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DYNAMICS OF *DETARIUM MICROCARPUM* GUILL. & PERR. IN BURKINA
FASO

Public defense on 13th March 2025

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DES POPULATIONS DE *DETARIUM MICROCARPUM* GUILL. & PERR. AU
BURKINA FASO**

Soutenance publique, le 13 Mars 2025

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DEDICATION

To my late father, Amadou Taonda, whose vision and decision to send me to school laid the foundation for my educational journey

To my mother Moniaga Setou, whose endless love, encouragement, and sacrifices have been the foundation of my success. This work is dedicated to you with all my heart

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ABBREVIATIONS AND ACRONYMS

ACCESS-CM2	Australian Community Climate and Earth System Simulator Climate Model Version 2
AGB	Above - Ground Biomass
AIC	Akaike information criterion
AUC	Receiver Operating Curve
BRT	Boosted Regression Trees
CFK	Classified Forest of Kou
CFN	Classified Forest of Nakambe
CMIP6	Coupled Model Intercomparison Project Phase 6
CD	Cell Density
CF	correction factors
CNRM-CM6–1	Centre National de Recherches Météorologiques model version 6
CPP	Consensus for Plant Part
EPS	Expressed Population Signal
DBH	Diameter at Breast Height
DEM	Digital Elevation Map
ENM	Ecological Nich Modelling
FAU	Friedrich-Alexander-University
GBIF	Global Biodiversity Information Facility
GCM	Global Climate Models
GLK:	Gleichläufigkeit
GPS	Global Position System
HadGEM3-GC3.1-LL	Third Hadley Centre Global Environment Model in the Global Coupled Configuration 3.1
INSD	Institut National des Sciences et de la Demographie
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
IVI	Importance Value Index
LH	Lorey's Height
MIROC6	Model for Interdisciplinary Research on Climate version 6
MVA	Mean Vessel lumen Area
NGR	Nazinga Game Ranch
NTFP	Non-Timber Forest Product

PGZs	Phytogeographique Zones
RF	Random Forest
RFC	Relative Frequency of Citation
RMSE	Root Mean Square Error
RSE	Residual Standard Error
SDM	Species Distribution Modelling
SSP	Shared Socioeconomic Pathways
TAGB	Total Above Ground Biomass
TSAP	Time Series Analysis and Presentation
TSS	True Skill Statistics
TVA	Total Vessel Area
TVAP	Total Vessel Area Percentage
VIF	Variance Inflation Factor
VN	Vessel Number
WRB	Wildlife Reserve of Bontoli
Wascal	West African Science Service Center on Climate Change and Adapted Land Use

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ABSTRACT

Climate threats and human activities on the population dynamics of *Detarium microcarpum* Guill. & Perr. in Burkina Faso

Tropical savanna species influence ecosystem multifunctionality through the ecological mechanisms underlying the provision of multiple ecosystem services. Despite this functionality, anthropogenic factors such as deforestation, overexploitation of natural resources, extension of agricultural lands, overgrazing, and bushfires, coupled with the adverse effects of climate change, contribute to the loss of *Detarium microcarpum*. Within this context, this study aimed to contribute to the sustainable management and conservation of *D. microcarpum* in Burkina Faso. To achieve these goals, the methods have consisted of semi-structured and focus group surveys of 465 people, 165 plots for forest inventories, tree rings and wood anatomy analysis, allometric equation and species modelling. The local population highlights the multipurpose uses of *Detarium* species and reveals the threats of the species are linked to the type of uses and the status of the site. A total of 102 woody species belonging to 79 genera rang in 28 families, were found in the natural habitats of *D. microcarpum*. The structure analysis reveals the unstable population of the species and the lack of regeneration. *D. microcarpum* showed distinct growth ring boundaries, the annual radial growth is positively related to precipitation during the end of the rainy for the current years but negatively to the previous years. Tree ring analysis revealed annual growth ring boundaries were 1.034 ± 0.425 mm. year⁻¹. The above-ground biomass and above-ground carbon allocation are greater in the Sudano-Sahelian than in the Sudanian climatic zone. The allometric models established to predict *D. microcarpum* biomass were $TAGB = e^{4.4002 (dbh*dbh*h) 0.9456} + e^{-3.5219 (dbh)2.4007} + e^{-2.8845(dbh)1.3465}$ in the Sudanian zone and $TAGB = e^{-4.1053 (dbh)2.4222} + e^{-5.2567(dbh)2.9539} + e^{-2.9894(dbh)1.5285}$ for the Sudano-Sahelian climatic zone. The current suitability area for the species covers 65.6 % of the country area with respectively high suitability (36.73%) and low suitability (29.16%). Models projections indicate that highly suitable areas for *Detarium microcarpum* conservation are expected to decline under future climate change scenarios, regardless of the models used. The only exception is the MIROC6 model under the SSP5-8.5 scenario, which predicts a slight expansion of suitable habitats. The shift was observed from both unsuitable and highly suitable areas to the low-suitability areas in the model results across all climatic zones, with a notable progression in the Sahelian zone. Overall, this study provides important information for the sustainable use of *D. microcarpum* and the conservation guide for forest practices.

Keywords: Anthropogenic threats, Allometric models, Parenchyma ring boundaries, climate change, Sustainable management

RÉSUMÉ

Menaces climatiques et activités humaines sur la dynamique des populations de *Detarium microcarpum* Guill. & Perr. au Burkina Faso

Les espèces des savanes tropicales influencent la multifonctionnalité des écosystèmes grâce aux mécanismes écologiques qui sous-tendent la fourniture de multiples services écosystémiques. Malgré cette fonctionnalité, des facteurs anthropiques tels que la déforestation, la surexploitation des ressources naturelles, l'extension des terres agricoles, le surpâturage et les feux de brousse, associés aux effets néfastes du changement climatique, contribuent à la disparition de *Detarium microcarpum*. Cette étude avait pour objectif contribuer à la gestion durable et à la conservation de *D. microcarpum* au Burkina Faso. Pour atteindre ces objectifs, les méthodes utilisées ont consisté en des enquêtes semi-structurées et des groupes de discussion auprès de 465 personnes, 165 plots pour les inventaires forestiers, l'analyse des cernes des arbres et de l'anatomie du bois, l'élaboration des modèles allométriques et la prédiction de l'espèce sous les menaces climatiques ont été menées. L'analyse des résultats ont révélées que les populations locale met en évidence les usages multiples de *Detarium microcarpum* et ont révélées que les menaces qui pèsent sur l'espèce sont liées aux types d'utilisation qui influencent le climat de la zone d'étude. Un total de 102 espèces ligneuses appartenant à 79 genres repartis en 28 familles ont été trouvées dans les habitats naturels de *D. microcarpum*. L'analyse de la structure a révélé que l'instabilité de la population de l'espèce et l'absence de régénération. L'analyse de la croissance chronologique de *D. microcarpum* a montré des cernes de croissance distinctes. La croissance radiale annuelle est positivement liée aux précipitations à la fin de la saison des pluies pour les années en cours, mais négativement pour les années précédentes. L'analyse des cernes de croissance a révélé que la croissance annuels de *D. microcarpum* étaient de $1,034 \pm 0,425 \text{ mm. an}^{-1}$. La biomasse et l'allocation de carbone sont plus importantes dans la zone climatique soudano-sahélienne que dans la zone climatique soudanienne. Les modèles allométriques établis pour prédire la biomasse de *D. microcarpum* sont $\text{TAGB} = e^{4.4002 (\text{dbh} \cdot \text{dbh} \cdot \text{h}) 0.9456} + e^{-3.5219 (\text{dbh})2.4007} + e^{-2.8845(\text{dbh})1.3465}$ dans la zone soudanienne et $\text{TAGB} = e^{-4.1053 (\text{dbh})2.4222} + e^{-5.2567(\text{dbh})2.9539} + e^{-2.9894(\text{dbh})1.5285}$ pour la zone climatique soudano-sahélienne. La zone favorable actuelle pour l'espèce couvre 65,6 % de la superficie du pays, repartis respectivement pour une forte favorable (36,73 %) et une faible favorable (29,16 %). Les résultats des modèles prévoient une réduction des zones très favorables à la conservation de *D. microcarpum* au profit des zones faiblement favorable dans le cadre d'impact climatique futur, quels que soient les scénarios et les modèles utilisés, à l'exception du modèle MIROC6 du scénario SSP5-8.5. Nous constatons que les résultats des modèles une reconversion des zones défavorables et très favorables vers la zone de faible favorable dans toutes les zones climatiques, avec une progression marquée dans la zone sahélienne. Dans l'ensemble, cette étude fournit des informations importantes pour l'utilisation durable de *D. microcarpum* et le guide de conservation pour les praticiens forestiers.

Mots-clés : Menaces anthropiques, Modèles allométriques, Cernes des anneaux de parenchyme, Changement climatique, Gestion durable.

INTRODUCTION

In the recent decade, several studies have focused on the conservation of multipurpose species due to anthropogenic activities and climate threats (**Kafoutchoni *et al.*, 2018**). Climate-induced land use change could indirectly drive species distribution through changes in forest stand composition and structure (**Bohn *et al.*, 2018**). However, climate change is a major global environmental challenge which negatively affects natural ecosystems (**Sintayehu, 2018**). It is a pervasive and growing global threat to biodiversity and ecosystems (**Díaz *et al.*, 2019**). The past decade has seen the rapid development of biodiversity loss due to climate change in many African countries. anthropogenic factors are increasingly altering landscapes and reducing the available space for species to exist (**Kamilar & Tecot, 2016**). Climate and habitat characteristics are among the most influential evolutionary forces shaping species. These factors also impact the species dynamic in their natural stand. **Balima *et al.* (2022)**, show that Global climate change represents unprecedented challenges for biodiversity conservation worldwide. One of the consequences of global warming is the loss of biodiversity. Based on scientific evidence, climate change and biodiversity loss are among humanity's most critical environmental challenges impacting food security (**Bilali *et al.*, 2020**), and education (**Filho *et al.*, 2023**). One of the most devastating threats to biodiversity is habitat destruction caused by human activities (**Sechrest, 2002; Agwu *et al.*, 2020; Avakoudjo *et al.*, 2021**). The magnitude of biodiversity loss worldwide is well documented and undergoing biodiversity decline is largely attributed to human-induced impacts (**Chapin *et al.*, 2000; M.E.A. 2005; Butchart *et al.* 2010; Lockwood *et al.*, 2014**). In the broader scope of conservation science, the fundamental mission of conservation ecology is to safeguard the diversity and health of all life forms on Earth, emphasizing the prevention of extinction, the preservation of ecosystems, and the maintenance of genetic diversity, as highlighted by **Lamy Lamy *et al.* (2021)**. In addition, Climate change and habitat loss are believed to interact in synergy (**García-Valdés *et al.*, 2015**).

In response to these threats, governments and private sector organisations in developing countries are implementing environmental conservation policies and programs to regulate and preserve biodiversity resources, while raising awareness of the challenges confronting biodiversity hotspots (**Ola & Benjamin, 2019**). According to **Kossi (2021)**, the degradation of tropical forests has reached such alarming levels that their sustainability is now in question. Forests are not only being converted to other land uses such as extensive agricultural, traditional mining exploitation, but are also subject to increased selective exploitation of key indigenous plant species (**Busmann *et al.*, 2018; Ouko *et al.*, 2018**). In any event, the population dynamics of woody species depend on several factors such as climate, soil type,

and human threat. Although the forests contribute directly to the health of communities, the quality of life in rural areas and the livelihood, natural resources are considerably impacted by climate change (**Nowak et al., 2001; Nowak et al., 2014; Leonel et al., 2021**). The unsustainable exploitation of forest products hurts the renewal capacity of the multipurpose species.

These threats, including habitat degradation, fragmentation, destruction, pollution, and climate change, disrupt and alter ecosystem structure and function (**Sechrest, 2002**). In addition, the loss of many important indigenous plant species crucial for population survival has been driven by human activities such as deforestation, overexploitation of natural resources, extensive agriculture, overgrazing, and bushfires by the effects of climate change. The erosion of biodiversity has severe implications for ecosystem services, global warming and human well-being (**Nunes et al., 2019**). **Traore et al. (2020)**, explain that many plant species are in a state of vulnerability despite their importance in the lives of local populations. In Burkina Faso, as in other tropical countries, forest resources play a crucial role in meeting the basic needs of local communities and contributing to the socio-economic development of the country (**Kagambega et al., 2019**). However, several tree species in the clear forests are now at high risk of extinction (**Ouattara et al., 2021**). According to various studies, including **Lamy et al. (2021)**, most plant extinctions have been driven by anthropogenic factors, either directly or indirectly, rather than natural causes. Due to resource scarcity, many multipurpose species have significantly declined.

In Burkina Faso, the extensive dependence on woody species like livelihood has profoundly affected the natural stand of these species (**Traore et al., 2020**). Knowledge of natural and semi-natural environments, therefore, appears today as a prerequisite for the proper management and protection of multipurpose species (**Kouyaté et al., 2002**). Although efforts are made to manage forest resources properly, Burkina Faso continues to lose its forest area. According to data from **IFN_{II} (2019)**, Burkina Faso loses an average of 243,450 hectares of plant formations annually. This study highlights that the current consumption and production patterns in the country are unsustainable. Climate change, coupled with changes in ecosystem composition and structure, is altering the dynamics of natural stands of multipurpose species (**Kapos et al., 2008**). These multipurpose species are undergoing severe degradation due to climatic hazards and anthropogenic pressure (**Badji et al., 2014**) which makes them highly attractive, particularly for the poverty in rural areas (**Leßmeister et al., 2018**). Therefore, sustainable harvesting of NTFP is essential for conserving plant species and for the livelihoods of many rural peoples (**Thiombiano et al., 2010; Agbo et al., 2020**). Forest ecosystems provide

local people with various products, including non-timber forest products (**Avakoudjo et al., 2020**). While studies on threats to species do exist (Balima et al., 2020; Zerbo et al., 2022), further research is needed in West Africa, particularly in Burkina Faso.

Among the savanna woody species, *Detarium microcarpum* is one of the most exploited tree species in West Africa, particularly in Burkina Faso (**Thiombiano et al., 2010**). The species has long been exploited for timber (**Bationo et al., 2001; Belem & Zoungrana, 2018; Dossa et al., 2020**) in Burkina Faso. Various parts of the tree, including its fruits, seeds, wood, and roots, are used by local communities (**Kouyate & Amadou, 2005; Dieng et al., 2019**) such as fruits, seeds, wood and roots. However, this species, which is among the most widely utilized by local populations, is increasingly threatened by climatic risks coupled with the security challenges. Given the crucial ecosystem services provided by this species, there remains a significant limitation in accurately on the scientific research. It is urgent to identify the factors which impact their dynamic through a depth research. This is a critical step in guiding management and conservation strategies, especially as the traditional uses of the species are often overlooked in some regions. Additionally, the development of specific allometric equations is needed to achieve more accurate estimates of above-ground biomass and to enhance our understanding of carbon storage and ecosystem productivity.

Additionally, these resources have faced multiple pressures from population growth, climate effects, and the uncontrolled exploitation of natural resources, rendering many species vulnerable. Effective conservation and sustainable use of these species require a thorough understanding of the key drivers of degradation. The multipurpose uses of these species pose significant threats to their population dynamics. Understanding the impacts of climate change on species characteristics is crucial for improving their management in their natural habitats. Investigating local communities' perceptions of the species will inform actions and policies for participatory management. The lack of information on anthropogenic pressures, coupled with climate effects, poses the greatest threat to their management. Any conservation initiative must be based on a comprehensive understanding of the species structural characteristics, the impacts of climate change, and the threats posed by human activities. In the perspective of curbing the disappearance of multipurpose forest species by setting up sustainable biodiversity management strategies, it is necessary to assess vulnerability by taking into account several factors such as climatic, anthropic and edaphic (**Kouyate et al., 2002; Agbo et al., 2017**). Several authors such as **Kouyate et al. (2002); Agbo et al. (2017); Dimobe et al. (2018)** have been interested in *Detarium microcarpum* from an ethnobotanical and morphological aspect, but information was lacking for their management. Previous studied (**Bationo et al., 2001;**

Bastide & Ouedraogo, 2008; Rizez, 2008; Ouédraogo & Thiombiano, 2012) have been dressed the regeneration patterns. This research has demonstrated a heightened focus on the economic aspects of conservation while overlooking the ecological aspects. It also explores the relationship between these two dimensions and the challenges posed by climate change. Studies carried out on this species did not provide information on the human threat and the climate hazard which impact the *D. microcarpum* conservation. Understanding how species respond to climate conditions can help identify the most efficient local sites for plant conservation, guiding sustainable in situ conservation efforts. Given the increasing pressures on the savanna multipurpose species such as *D. microcarpum* and the lack of data for their sustainable management, it is urgent to address how climate and human land use interact to affect its conservation. Despite its degree of vulnerability (**Traore et al., 2011**), the species has not yet been classified by the major concern of IUCN (**Contu, 2012**) but minor concern (RL), highlighting the importance of this study in addressing its conservation needs. In knowledge of the species reaction to the climate effect is important information for their conservation planning (**Adjonou et al., 2020**). In a broader sense, it will contribute positively to the development of management and conservation strategies for these species in Burkina Faso. This study seeks to fill a crucial gap in understanding, especially within this specific context. The various factors threatening *Detarium microcarpum* prompt us to ask the following questions: What are the perceptions of the local communities of the threats to *D. microcarpum*? Which factor influences the natural stand of *D. microcarpum*? How does climate impact the growth of savanna semi-arid species? What is the most appropriate allometric equation suitable for the carbon assessment? What factors influence their distribution? Indeed, studies like this are crucial for enhancing the management of *Detarium microcarpum*, especially given its vulnerability to climate-related hazards. These results can help mitigate the escalating threats to its survival by tackling the key conservation challenges facing the species. The present study which focuses on *D. microcarpum* is a response to the urgent need to collect and characterise the different factors to predict its perennially. The main goal of this study is to contribute to the sustainable management and conservation of *D. microcarpum* in Burkina Faso. To achieve this overarching goal, the following specific objectives have been outlined to provide a detailed framework for assessing the key factors influencing the natural stand of the *Detarium microcarpum* and its distribution:

- (i) Assess local perceptions of anthropogenic threats and climate effects on *Detarium microcarpum*.

- (ii) Characterise the effects of land use and climate on the diversity and population structure in natural stands of *Detarium microcarpum*.
- (iii) Assess the effects of climate on the growth of *Detarium microcarpum*.
- (iv) Develop a specific allometric model for predicting *D. microcarpum* aboveground biomass and carbon storage.
- (v) Assess the potential distribution of *Detarium microcarpum* in Burkina Faso under different Shared Socioeconomic Pathways (SSPs) projected by CMIP6 models. The following hypothesis has been tested
 - i. Perceptions of anthropogenic and climatic impacts on *Detarium microcarpum* vary among socio-cultural groups and across different climatic zones in Burkina Faso.
 - ii. Climate has a significant impact on the floristic composition of *Detarium microcarpum* in its natural habitats.
 - iii. Climatic factors influence the growth dynamics and anatomical structure of *Detarium microcarpum* species.
 - iv. Locally developed allometric models provide more accurate biomass estimates for *Detarium microcarpum* than the pantropical equations developed by **Chave et al. (2014)**.
 - v. Projected future climatic conditions are expected to impact significantly the distribution of *Detarium microcarpum* across Burkina Faso.

This dissertation consists of three parts, in addition to the introduction and conclusion sections. The general introduction outlines the study rationale and background, leading to the research objectives. Part one provides an overview of *Detarium microcarpum* and a literature review of the study area. Part two focuses on the materials and methodology, detailing the conceptual and theoretical frameworks, as well as the data collection and analysis processes. The study's results are presented and discussed in the final part. The dissertation concludes with a summary, recommendations, and suggestions for future research based on the findings

PART I: LITTERATURE REVIEW ON THE STUDY AREA, ON

Detarium microcarpum

CHAPTER 1. GENERALITIES OF *Detarium microcarpum*

1.1. Systematics and biogeography of the *Detarium* species.

The *Detarium* genus was first described as *Detar* of Sénégal by the Jussieu in 1789 (**Aubréville & Trochain, 1937**). It is a paleotropical taxon. The genus *Detarium* is in the Fabaceae family and the Subfamily of Caesalpiniaceae. According to **Savadogo et al. (2016)** and **Hassanin et al. (2019)**, the genus *Detarium* belongs to the class Magnoliopsida, the subclass Rosidae, and the order Fabales. It belongs to the tribe Detarieae. Native to the savanna species (**Keay, 1989**), the genus *Detarium* was first described in 1789 under the name "Detar" by De Jussieu in the *Genera Plantarum* (**Jussieu, 1789**). However, at present, many specialists agree that the genus *Detarium* comprises three species. According to **Hutchinson et al. (1958)**; **Aubréville (1970)**; **Lebrun and Stork (1991)** there are *D. microcarpum* Guill. & Perr., *D. senegalense* J.F. Gmel. and *D. macrocarpum* Harms. Since their description, the genus has undergone several revisions for its specific composition (**Aubréville & Trochain, 1937**; **Cavin, 2007**). The species of the *Detarium* genus are gallery and savanna forest species. According to the same authors, the areas of predominance of these species are the Sudanian and Sudano-Guinean sectors. These three species are very similar morphologically but appear to differ in ecological distribution. Among these species, two of its three species are the subject of several studies. For the area Distribution, the species of *D. microcarpum* occurs in Sudanian savannas on the African continent (**Keay, 1989**; **Lock, 1989**) from where its range extends from Senegal to Sudan. Only *D. macrocarpum* Harms and *D. senegalense* J.F. have been extensively studied genomically at the intron level of the tRNA-Leu (trnL) gene (**Bruneau et al., 2001**). Moreover, they are ecologically differentiated, as *D. microcarpum* occurs typically in dry savannas, whereas *D. senegalense* is more riparian and also occurs in dry forests. In Burkina Faso, *D. microcarpum* which is typically found in the Sudanian and Sudano-Sahelian climates, covers more than two-thirds of Burkina Faso (**Bationo et al., 2001**; **Thibaut, 2008**). The difference between the two species is found in leaf morphology, fruit flavour and flower arrangement (**Kouyaté, 2005**; **Cavin, 2007**; **Vautier et al., 2007**). The *D. microcarpum* is known by several common names including sweet dattock in English (**Woot-Tsuen, 1968**) and petit d'atar in French (**Burkill, 1995**). *D. microcarpum* and *D. senegalense* occur in the drier savannas and forests of Guinea-Congo and the wetter areas of the Sudanian savannas of the African continent respectively (**Lock, 1989**; **Keay, 1989**). According to the same authors, their natural range extends from tropical Africa from Senegal to the Republic of the Democratic Congo (ex-Zaire). The fruits of *D. microcarpum* are edible while *D. senegalensis* has both edible and poisonous fruits. The

main countries with the species are Benin, Burkina Faso, Cameroon, Central African Republic, Tchad, Côte d'Ivoire, Democratic Republic of Congo, Gambia, Ghana, Guinea, Guinea Bissau, Mali, Niger, Nigeria, Senegal, Sudan and Togo, **(Figure 1)**.

1.2. Description of the *Detarium microcarpum*

Native to tropical Africa, the genus *Detarium* was first described in 1789 under the name "Detar" by De Jussieu in the Genera Plantarum **(Jussieu, 1789)**. The natural range of species of the genus *Detarium* covers all of arid sub-Saharan Africa, from Senegal to Sudan. It is found in Benin, Burkina Faso, Cameroon, Chad, Côte d'Ivoire, the Gambia, Ghana, Guinea, Guinea-Bissau, Mali, Niger, Nigeria, Senegal, Sudan, and the Dominican Republic **(Keay 1989; Lock, 1989; Kouyate, 2006)** hence its area of distribution from Senegal to Sudan. The species *Detarium microcarpum* is a tree 8 to 12 m tall **(Kouyaté et al., 2002; Kouyate, 2005, Maré & Millogo, 2019; Lamy Lamy et al., 2021)** with pinnate leaves and has from 6 to 8 (-12) leaflets, arranged alternately or oppositely, **(Figure 2)**. According to the same authors, the characteristics of the leaflets are among others oval to elliptical, 7 to 11 cm long, 3 to 4 cm wide in the lower part. It is rounded at both ends and margined at the top. The blade is leathery, glaucous, whitish-grey below, and has translucent dots **(Kouyate, 2005)**.

The *Detarium microcarpum* is a tree which inhabits the driest to the wettest regions of the Sudanese sector **(Cavin, 2007a)**. It has a phytogeographical zone in the Sahelo-Sudanian to Sudano-Guinean zone with an annual rainfall varying from 600 to 1300 mm. According to the classification of **(Cavin, 2007a)**, the fruits of the *Detarium microcarpum* are edible for human consumption. Indeed, the *Detarium microcarpum* is one of the most exploited fruit species in Burkina Faso **(Bationo et al., 2001)** and is one of the most sought-after species in Mali **(Kouyate, 2005)** and Benin **(Agbo et al., 2017)**, Senegal **(Diop et al., 2010)**, Togo **(Kamou et al., 2017)** for *Detarium microcarpum*. In addition, **Calvin (2007)** also shows that *D. microcarpum* species occupy a prominent place and are used in several socio-cultural fields in Africa. Indeed, they are also part of the most sought-after species and are used by local populations because of the different ecosystem services they offer them. As for their ecological niches, they are distributed irregularly in the semi-arid parts of the Sahelian and Sudanese agroecological zones. It is widespread in wooded savannas, shrub savannas and semi-cleared dry forest areas.

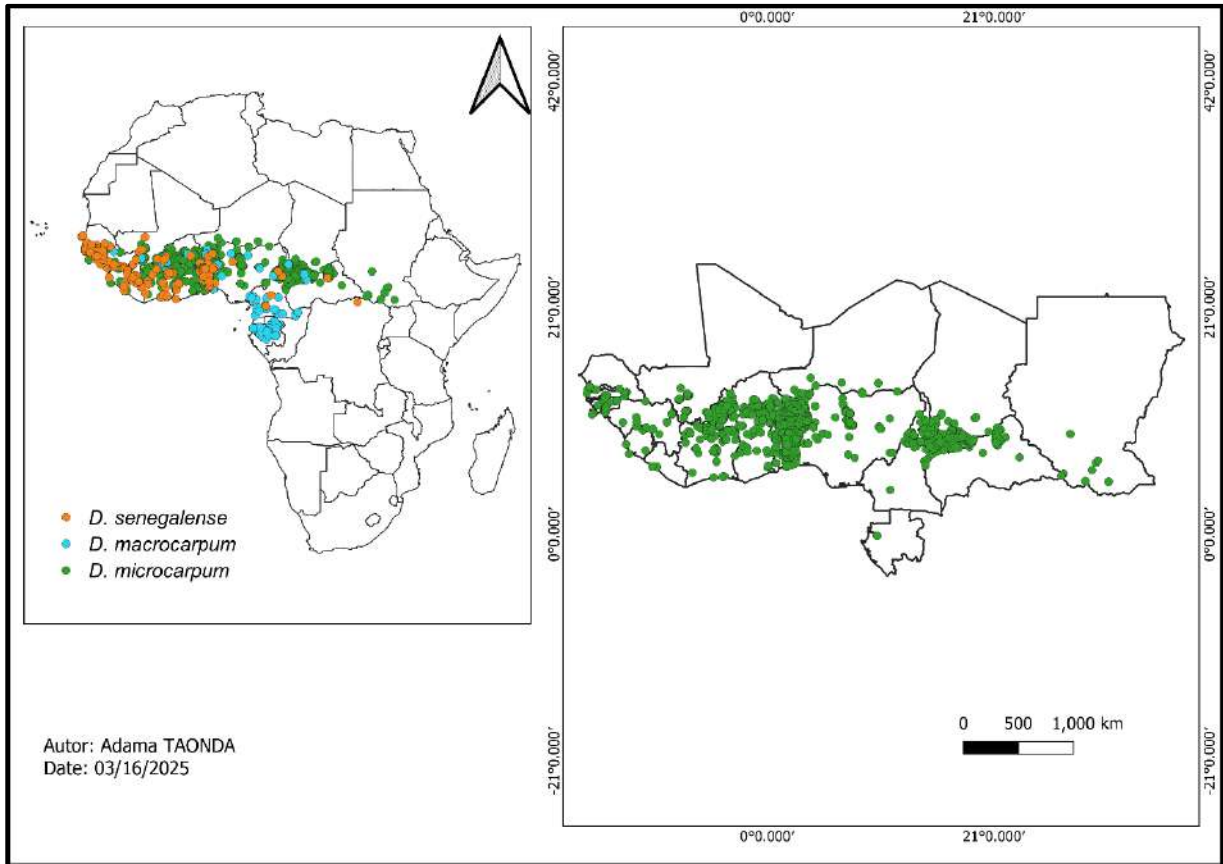


Figure 1: Distribution of *Detarium* species in Africa

In addition, the *Detarium microcarpum* is found in several habitats such as Guinean and Sudanese savannas, dry forests, and fallows, on sandy or lateritic soils (**Toli, 2018**). *Detarium microcarpum* is known by different local names depending on the country. They are refined according to local or regional uses. **Kouyaté & Lamien (2011)** in their work show that these species are known by different vernacular names depending on the country such as Benin and Togo, they are called Dapka (Fon), Napuhuri (Bassari), in Burkina Faso, we have Kaga (More), Bwa (O'O), Kwara (Dagara), Anakpaga ou Onakpagtigu (Gourmantchema), Népwo (Gourounsi), krou yaa (Bissa), konkairès ou Konkéhi (Fulfuldé), Kô (Samo) Tamacoumba (Bambara); in Côte d'Ivoire: Bidieu (Yacouba), Zama (Wobe), Senegal: Ndanh, Rahn (Serere); Daha, Dak, Danha (Wolof); Niger: Fantu (Zarma); Nigeria: Yoruba (Ogbogbo), Taoura (Hausa).



Figure 2: *Detarium microcarpum* trees in their natural stand

CHAPTER 2. Conceptual and theoretical frameworks on *Detarium microcarpum*

2.1. Socioeconomic of *Detarium microcarpum*.

Detarium microcarpum is a plant species that has been the subject of several scientific researches in Africa, particularly in Burkina Faso.

Like most tropical species, the species of the genus *Detarium* have been the subject of a botanical description as most of the species in French West Africa whose precursor is **Aubréville and Trochain (1937)**. The work of **Cavin (2007)** has contributed to the taxonomic and chemical knowledge of species of the *Detarium microcarpum*. **Kouyaté (2005)**; **Gning et al. (2013)** on ethnobotanical aspects and study of morphological, biochemical and phenological variability of *Detarium microcarpum* at Mali. The study of **Kouyate (2005)** showed that *D. microcarpum* plays a very important socio-economic, socio-cultural, food, medicinal, ecological, religious and environmental role in rural areas in southern Mali. The work of **Kouyaté et al. (2002)** on the farmers and the rural appreciation of *D. microcarpum* in southern Mali similarly, **Agbo et al. (2017)** notes a high frequency of wood use, thus explaining the high rate of vulnerability index (2.67). Other studies of **Kouyaté et al. (2002)**; **Kouyate (2005)** in Mali; in Benin, such as **Agbo et al. (2017; 2020)**; **Houénon et al. (2021)** ; in Sénégal for **Diop et al. (2010)**; **Dieng et al. (2019)**; **Diatta et al. (2021)**; in Togo, **Dangbo et al. (2019)**, have proven that the antlers of *D. microcarpum* are highly valued by the populations and that its wood and fruits are the most widely used organs and also confirm the uses character of these two species. Other studies are interested in ecological traits such as **Lamy Lamy et al. (2021)** in Cameroon, **(Agbo et al., 2018; Dossa et al., 2020)** in Benin. The work of **Agbo et al. (2018)** shows a need for the domestication of *D. microcarpum* for future generations. Concerning demographic characteristics, the work of **Agbo et al. (2019)**; **Houénon et al. (2021)** have shown the regression of the population dynamics of species of the *Detarium* genus. **Ndiaye et al. (2022)** showed that *D. microcarpum* (10 to 20 days) has a faster germination speed.

Its extensive use indicates a potential management issue for the species. **Lykke (2000)**; **Dossa et al. (2020)** have shown that the species fruits are rich in vitamin C and important nutrients that are indispensable in the food of rural and urban populations in Senegal and Benin.

The research of **Diatta et al. (2021)** shows that the forms of regeneration of both species are natural seeding and strain rejection. Thus, the work on nutritional contribution such as **Florence et al. (2014)** shows a good source of carbohydrates, fibre, minerals and vitamins and could also contribute to bold protein and fat needs. The antineutrinos contents of the fruit pulp

are below established toxic levels. Similarly, **David et al. (2017)** draw the same conclusions in their work on Phytochemical analysis, antidiabetic and toxicity studies of the methanolic leaf extract of *D. microcarpum* in Wistar albino rats in Nigeria.

In Burkina Faso, some studies have been done on species of *D. microcarpum*. **Wiersum & Slingerland (1997)** showed the importance of deepening the research on the species of *D. microcarpum*. The work of **Rietkerk et al. (1998)**; **Bationo et al., (2001)**, **Bationo (2007)** concluded that most *Detarium* species are characterized by cryptogenic germination. The same author agrees that cutting at ground level allows regeneration, which is the best method of exploiting *D. microcarpum* populations. The easy access to these fruits and their taste means that the dietary role of the two *Detarium microcarpum* makes them widely appreciated. **Guigma et al., (2012)** *Detarium micropum* is one of the species mostly solicited by rural communities. **Thiombiano et al. (2010)**, **Leßmeister et al. (2018)**, and **Kagambega et al. (2019)** have evaluated the impact of human activity on the dynamics of four utility species, including *D. microcarpum*, which makes it vulnerable and threatened. **Zida et al. (2007)**, **Millogo (2019)**, and **Traore et al. (2020)** have shown that the stocking density of species, including *Detarium microcarpum*, varies across different climatic zones. Without proper protective measures, this could lead to long-term management challenges for *D. microcarpum*. However, research on climate influence, community perception, economic assessment, evaluation of fruit and aboveground biomass, and population dynamics remains to be explored in Burkina Faso. Therefore, data on community perception is of great importance, especially for threatened plants experiencing severe human disturbance such as *D. microcarpum*. These data are undoubtedly fundamental for assessing the main threats to species conservation and for promoting sustainable management. Indeed, local perceptions and knowledge derived from ethnobotanical studies can complement the scientific approach in defining sustainable management plans for biodiversity conservation. Despite this broad range of previous studies on the species in the region, thus in Burkina Faso, there are huge knowledge gaps on *D. microcarpum* in Burkina Faso regarding the perception aspects, quantitative wood anatomy, dendrochronology analysis, carbon sequestration potential and distribution modelling. Such knowledge gaps contribute to the management of this threatened and highly valued tree species to ensure the continued provision of ecosystem services for future generations, **Figure 3**.

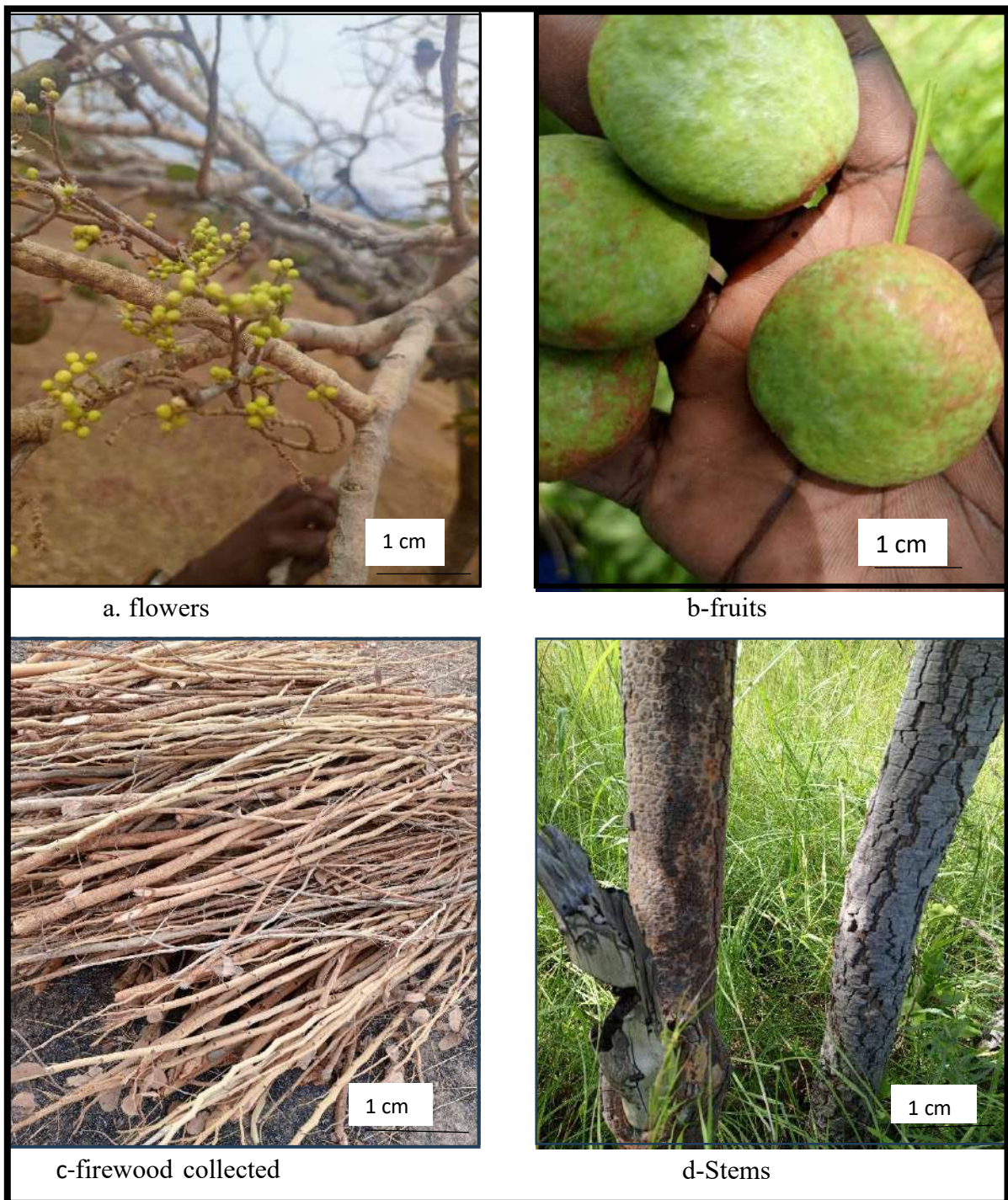


Figure 3: Different parts of *D. microcarpum* trees

2.2. Perception

Perceptions are an important way to assess conservation performance, of NTFP producing species is needed **(Abukari & Mwalyos, 2020)** to develop better strategies for effective biodiversity protection and the well-being of people living near protected areas. Perception implies a sense of the complexity of community conditions, images and stories that exist in thinking **(Ihsannudin et al., 2020)**. In underdevelopment countries like Burkina Faso, *Detarium microcarpum* is a multipurpose agroforestry plant still living *in situ* and highly valued by local populations **(Kouyaté et al., 2002 ; Kouyaté, 2005; Bastide & Ouedraogo 2008; Kouyaté et al., 2009; Diop et al., 2010 ; Dangbo et al., 2019a ; Ndiaye et al., 2022)**. These perceptions and beliefs may stem from ancestral traditions that mark the relationship of communities with the beings of nature as well as with natural resources, which is the modern vision **(Abukari & Mwalyosi, 2020)**. In the context of multipurpose species such as the genus of *Detarium microcarpum*, which coexists with the community and has a potential interest for their income, attention to the community structure is not enough **(Oldeland, 2011; Sanchez et al., 2012; Dey et al., 2017)**. Perception also plays a role in how community members perceive and respond to environmental changes **(Sanchez et al., 2012; Bonnemains, 2016; Rich, 2021)**. This includes increased awareness of the state of their local environment and the impact of these changes on their daily lives. Such perceptions can lead to a greater appreciation for the community and a willingness to take action to improve it.

However, understanding their possible perception of the community on the species' interest is required. With the increasing pressure on these indigenous species, which produce the NTFP, there is a need to provide the best management through new knowledge **(Mbayagone & Thiombiano, 2011)**. Moreover, the perception of nature is significantly shaped by the structure and dynamics of community solidarity **(Thompson et al., 1997)**. However, perception is not static but varies considerably across different communities. Some explanations show the importance of community perception of the multipurpose species in conservation activity, including in the conservation of *D. microcarpum* in underdeveloped countries like Burkina Faso. The study of perception plays a crucial role in identifying effective conservation strategies, fostering community engagement in conservation efforts, and rectifying past conservation failures **(Thaman et al., 2016)**. Regarding the anthropogenic pressure on natural resources and the increasing climate threat, there is a need to determine the interrelation between the community and its environment that affects the decision process.

Other perceptions, beliefs and acceptability criteria in non-ancestral communities may be related to risk perception, low level of trust and credibility.

2.3. The characteristics of the dendrometrics parameters

Forests play a vital role in climate change mitigation and contribute the soil and water epuration **(FAO, 2015; Deb *et al.*, 2021)**. Many authors emphasize that dendrometry parameters are the best indicators of the conservation status of a plant in its natural environment or *ex-situ* are missing **(Annapurna *et al.* 2013; Heywood, 2014; 2015)**. Dendrometric parameters refer to measurable characteristics of trees, such as diameter at breast height (DBH), tree height, crown diameter, and wood density **(Mensah *et al.*, 2014; Agwu *et al.*, 2020)**. These parameters are essential for assessing forest structure, growth, and biomass. The importance of the species characteristics in tree management lies in their ability to provide essential data for evaluating tree and forest health, productivity, and sustainability **(Dangbo *et al.*, 2019a)**. These measurable characteristics help forest managers make informed decisions about conservation, land use, and sustainable resource extraction **(Assogbadjo *et al.*, 2012)**. The knowledge of the species parameters helps in detecting changes in tree health and forest conditions, allowing for early intervention in their natural stand. In analyzing parameters such as DBH, height, and crown size, forest managers can plan thinning operations, harvest schedules, and regeneration efforts more effectively, ensuring that the species are used sustainably in their natural stand **(Donou Hounsode *et al.*, 2015; Bentsi-Enchill *et al.*, 2022;)**. In addition, understanding the structural attributes of forests through dendrometric measurements aids in biodiversity conservation, particularly in ecosystems with multipurpose species. By accurately estimating biomass and carbon storage through dendrometric data, forest managers could better participate in global carbon offset and climate change mitigation programs **(Sileshi, 2014)**. The species characteristics in their natural stand are foundational tools in tree management, providing critical data to guide sustainable practices, enhance productivity, and support conservation efforts.

However, Burkina Faso, like other tropical countries, has a remarkable biodiversity of endemic plants which are threatened by several factors including climate and human disturbances **(Sintayehu, 2018)**. In addition, several overexploited woody species with deficient regeneration were declining in savanna due to the lack of conservation and insufficiency of data on their status which could help to propose appropriate management solutions **(Bationo *et al.*, 2001)**. Indeed, among the woody species producing non-timber forest

products, *Detarium microcarpum* is one of the most exploited and vulnerable species in Burkina Faso (Traoré *et al.* 2011; Gaisberger *et al.*, 2017; Traore *et al.*, 2020). Despite the widely recognized importance of *D. microcarpum* for human uses (Bationo *et al.*, 2001; Dimobe *et al.*, 2018), little information is available on the effect of climate and land use on its populations' status. Previous studies on *D. microcarpum* focused on its regeneration pattern and population structure respectively in Burkina Faso (Bationo *et al.* 2001; Bastide & Ouedraogo, 2008; Maré & Millogo, 2019) and Cameroon (Lamy *et al.*, 2021). In addition, other studies have been conducted on the local uses and the conservation of the species in Benin (Sinadouwirou *et al.*, 2022; Houénon *et al.*, 2022) and in Mali (Kouyaté *et al.*, 2002; Kouyaté, 2005) and the fruits nutritional values in Burkina Faso (Cavin, 2007). Among all these studies, none focused implicitly on the impact of climate, land use, and their interaction in their natural stand diversity, their population dendrometric characteristics and structure. It has been acknowledged that climate conditions influence woody species population (Traore *et al.*, 2022, Zerbo *et al.*, 2023), and the dynamic of a stand is influenced more by the type of land use (Balima *et al.*, 2020; Zerbo *et al.* 2023). In addition, other authors pointed out that dendrometric parameters are real indicators of information on the conservation status of the species (Nichols *et al.*, 2008; Deluau & Van Damme, 2021). Given the increasing pressures on the savanna multipurpose species such as *D. microcarpum* and the lack of data for their sustainable management, it is urgent to address how climate and human land use interact to affect its conservation. When population densities increase, the competition for space and resources is impacted (Janovský *et al.*, 2013) and affects the species' survival (Atanasso *et al.*, 2019). In addition, the individuals that first occupy a given area may monopolize the most suitable habitats, which affects the structural parameters of the other species. In this context, assessing tree growth rates, stand dynamics, climate-growth relationships, and ecosystem productivity represents one of the most significant research challenges for ecologists (Balima *et al.*, 2020).

2.4. Dendroclimatology and Dendrochronology

The recent decade has been remarked by the development of tree-ring chronology studies in West Africa, which allows the reconstruction of the environmental history of the savanna species. However, Dendrochronology is the science of analyzing annual growth rings in trees and woody plants, linking the characteristics of these rings to the environmental conditions present during their formation (Acosta-Hernández *et al.*, 2017). One of the first researchers interested in the construction records of climates and climatic events passed through the

analysis of the growth characteristics of trees and in particular annual rings (**Mbow *et al.*, 2013**). This could contribute to understanding the climate events in West Africa. Whenever tree growth is limited directly or indirectly by climate variables (**Sheppard, 2010; Khaleghi, 2018; Upadhyay *et al.*, 2021**), which can be quantified and dated, dendroclimatological methods can be used to reconstruct past environmental conditions (**Dridder *et al.*, 2013**).

Dendroclimatology in the countries of savanna ecosystems is still at an early stage, although these ecosystems contribute enormously to attenuating greenhouse gas effects. Currently, major research gaps exist concerning the dynamics of tropical forests, their resilience to drought and their status as carbon sinks (**Fichtler, 2017**). Climate change refers to unexpected changes in the earth's climate characteristics that occur in the long term (**Goyal, 2004; Khaleghi, 2018**). Tree rings help in simulating tree growth following climate change (**Williams *et al.*, 2010**) and predicting the risk of increasing temperatures, altered precipitation, water stress, and drought (**Upadhyay *et al.*, 2021**). According to previous studies such as **Mbow *et al.* (2013); Gebrekirstos *et al.* (2014); Talla *et al.* (2021)** there is a relationship between precipitation, temperature, and tree rings and the climate variable. Whenever tree growth is influenced by climate variables, which can be quantified and dated through dendroclimatological methods and can be used to reconstruct past environmental conditions (**Gebrekirstos *et al.*, 2014; Fichtler, 2017**). Moreover, the tree rings have unique advantages compared to others as trees have a wide geographical distribution. These rings preserve a continuous record with an annual resolution and can consequentially be dated by ring counting (**Upadhyay *et al.*, 2021**). Better knowledge of other drivers of individual tree growth is necessary to understand the effects of environmental factors such as rainfall and temperature on tree dynamics (**Zhou *et al.*, 2013; Sanogo *et al.*, 2022**). In the semi-arid climatic zone of West Africa, the most critical issues are deforestation and forest degradation resulting from extensive farming practices, urbanisation, and artisanal mining (**Bayala & Harmand, 2023**). To understand past climate effects on the growth variability of savanna species and their resilience to climatic changes, studying climate–growth relationships and analysing their tree-ring variations is crucial. A recent study by **Upadhyay *et al.* (2021)** has shown that rapid climate change has significantly affected tropical forests' ecosystem structure and functioning. Therefore, detailed studies are needed to assess how climate variability drives growth patterns through ring analysis. Measuring ring width on stem discs or increment cores can reveal the long-term impact of climate on tree growth (**Rahman *et al.*, 2018; Talla *et al.*, 2021; Zuidema *et al.*, 2022**). Dendroecology is increasingly used in forestry research to evaluate the impact of climate on tree growth (**Bräuning *et al.*, 2016**). Tree rings are important for the long-term

assessment of the climate threat, which characterises climate variability (**David et al., 2016**). Tree rings are natural archives that preserve evidence of past climate changes and permit predicting the future climate through the species (**Mbow et al., 2013**).

The first tree ring study in Burkina Faso was based on the dendrochronology and wood anatomy of *Azizlia africana* (**Balima et al. 2020**). Moreover, tree ring analysis of savanna species presents specific challenges. The lack of a specific growth-limiting factor that synchronises cambial activity in a given species also leads to varying growth patterns among individual trees. With the presence of wedging rings and false rings in tropical trees, particularly in the savanna species, is a challenge to cross-date tree-ring series within and between trees (**Worbes, 2002; Sanogo et al., 2022**). In addition, the diminishing presence of the 'common signal' in tree growth also disrupts cross-dating processes and poses challenges to constructing chronologies for tree populations thriving in highly moist environments (**Williams et al., 2010; de Ridder et al., 2013**).

The high tree species diversity in the savanna allows a high diversity of reactions within the tree communities (**De Ridder et al., 2014**). In addition, illegal logging by the population combined with the adverse effects of bushfire, and cattle grazing impact the dynamic of the species (**Dimobe et al., 2017; Zerbo et al., 2023**). Precise knowledge of tree species' reaction to climate is crucial to assessing the growth behaviour of tree species under a changing climate (**Bräuning, 2017; Upadhyay et al., 2021**). However, the responses of tree species to climate may be species-specific and may also vary according to the site conditions (**Santos et al., 2021; Upadhyay et al., 2021**). Knowledge of the relationship between the climate–growth relationships of savanna species is almost missing. The formation of annual rings relates the annual growth characteristics of trees with local climatic conditions. Thus, for tree-ring studies in Semi-arid savanna species, identifying ring boundaries and assessing their annual character is essential before obtaining growth data and tree ages (**Brienen & Zuidema, 2006; Sánchez-Calderón et al., 2022**). It is necessary to quantify the relationship between climate and species growth to understand the growth dynamics of savanna species, as more arid conditions can limit growth rates. However, the alternation of a dry and a wet season and the seasonality in leaf phenology induce periodic cambial dormancy, causing the formation of tree-ring boundaries (**Balima et al., 2020**). In addition, the presence of drought during the rainy season in the semi-arid savanna induces the formation of ring boundaries by the species (**Avakoudjo et al., 2022**).

In semi-arid climatic conditions, tree rings are formed when trees experience cambial dormancy due to a long dry season and short times of cambial activity during the rainy season (Brienen & Zuidema, 2006; Mbow *et al.*, 2013).

As such, climate change is one of the most serious environmental changes that mankind faces. Specifically, how savanna species distribution would be affected by it is the most important question for the current researcher on climate change. However, understanding the impact of climatic events on the West African indigenous species growth through the tree's ring analyses, it is essential to apply the dendroclimatology analyses. Such data are essential for sustainable management and conservation strategies. Tropical dendroclimatology is experiencing significant advancements, particularly in the dry tropics. However, studies focusing on tropical tree-ring research in wet tropical forests remain relatively scarce, indicating a need for further exploration of these ecosystems. Tree ring analysis is a powerful tool for understanding past climate conditions and assessing the impact of climate. Tree rings, the concentric circles seen in the cross-section of a tree's trunk, provide a chronological record of environmental conditions, including temperature and precipitation, over the tree's lifetime.

In Burkina Faso, tree-ring studies are still scarce. However, these studies are necessary to better manage savanna species, which constitute the livelihood of rural communities. This study will enable the forest manager to estimate its adaptability to the changing climatic conditions in West Africa in general and in Burkina Faso particularly. However, studies focusing on tropical tree-ring research in wet tropical forests remain relatively scarce, indicating a need for further exploration of these ecosystems. Tree ring analysis is a powerful tool for understanding past climate conditions and assessing the impact of climate. By analysing these rings, scientists can reconstruct past climate patterns and identify potential threats through dendroclimatology.

2.5. Above-ground biomass and carbon quantification

Estimating the carbon stocked in forests is important to assess the mitigation effect of forests on global change and to predict the potential impact of mechanisms to reduce carbon emission (Ebuy *et al.*, 2011; Henry *et al.*, 2020; Ganamé *et al.*, 2021). Allometric models are necessary for estimating biomass of the multipurpose species like *Combretum glutinosum* and *Terminalia laxiflora* (Dimobe *et al.*, 2018), *Azelia africana* (Balima *et al.*, 2019), *Balanites aegyptiaca* (Ouedraogo *et al.*, 2020), *Diospyros mespiliformis* (Ouédraogo *et al.*, 2020), *Pterocarpus erinaceus* (Ganamé *et al.*, 2021) in Burkina Faso.

Estimation of biomass in Burkina Faso is constrained by a lack of allometric equations applicable to different. There is little information about the *Detarium* spp. above-ground biomass. Allometric equations are the most widely used means for estimating tree biomass (Williams *et al.*, 2010). Biomass can be estimated by direct or indirect methods. The most accurate method to estimate tree biomass is destructive sampling (Dimobe *et al.*, 2018; Balima *et al.*, 2019; Ouédraogo *et al.*, 2020; Ganamé *et al.*, 2021). Allometric equations exhibit diverse relationships depending on tree species, terrains, temperature and rainfall gradients (Chave *et al.*, 2014). The ability of the multipurpose species to sequester carbon could be known by the above-ground biomass estimation of some trees by an allometric model.

Biomass and carbon studies in savanna ecosystems are quite challenging on account of varying localities and difficulties in accessibility. No systematic data is available on studies on biomass/carbon of the savanna species and uniform estimation methodology for the multipurpose species. Although, many studies have been carried out on biomass and carbon stock estimations of the savanna species in Burkina Faso limited (Ganamé *et al.*, 2021a), they are sporadic and patchy, particularly for some species.

This complements the lack of knowledge in this area of allometric equations. Indeed, how biomass and carbon stocks vary spatially and temporally along the climate gradient remains poorly documented. In addition, whether climate influences carbon storage in tree aboveground biomass, and whether biomass allometric equations are climate-dependent remain unknown. Analysing the spatial distribution of tree biomass and carbon stocks of *Detarium* spp. could contribute to a better understanding of the relationship between biodiversity and climate change. The accuracy of the biomass estimation methods is crucial for various applications, including global carbon estimation. However, there is no universally robust method for biomass estimation, with existing methods showing variable accuracy ranges (Preece *et al.*, 2012; Djomo *et al.*, 2016). The species composition and the type of the species of the vegetation must be analysed, and all or at least a large proportion of vegetation components should be considered for biomass estimation, especially for the savanna species. Tree allometric equations are more accurate when applied to trees of the same species, especially those growing in identical climatic zones and soil environments, enhancing their applicability and reliability (Ehlers & Clark, 2000). Currently, the role of individual species in climate change mitigation through carbon sequestration requires further understanding. Additionally, there is no standardized method for estimating above-ground biomass (AGB), and the parameters used for biomass assessment in specific locations remain unclear. Given its rich savanna ecosystems, Burkina Faso is expected to play a significant role in carbon sequestration

and climate change mitigation through the management of its native species. Therefore, assessing the carbon stock and sequestration potential of the multipurpose species is imperative. However, developing allometric equations for estimating the biomass and carbon storage potential of the *Detarium microcarpum* is an important challenge in this regard. Establishing an allometric model of *Detarium* species for estimating biomass and carbon stock is important to support conservation and forest ecosystem management.

2.6. Species distribution modeling

Modelling species distributions and the demographics of populations is a mainstay of ecology (Lee-Yaw *et al.*, 2022). Species Distribution Models (SDMs) are recognized as a potent tool for predicting the potential impact of climate change on the geographic distribution of target species, utilizing environmental data and future outputs from Global Climate Models (GCMs) (Pecchi *et al.*, 2019). The geographic distribution of the species is strongly influenced by climate Ashrafzadeh *et al.* (2019) and there is particular concern about how future climates may increase the risk of extinction for species with narrow climate niches. These impacts are broadly characterised as changes in species distribution, forest composition and their structure (Deb *et al.*, 2018; Pramanik *et al.*, 2018). Projected climate change and the anthropogenic impacts on the multipurpose species have the potential to trigger significant ecosystem-level responses. Furthermore, for efficient planning, implementation of conservation measures, and sustainable land use, prioritizing efforts according to threats and vulnerabilities is important. Species distribution modeling (SDM) is one approach used to model the potential geographical distribution and ecological requirements of a species (Mishra *et al.*, 2021; Balima *et al.*, 2022). This method analyzes the environmental conditions of a species' known occurrence to predict potentially suitable habitats in different locations. Moreover, climate change has been reported to have significant implications for the habitat requirements of various species (Mishra *et al.*, 2021). The future dynamics and spatial distribution of the savanna species are pivotal for biodiversity conservation, especially in the face of the uncertainties posed by climate change. Climate change is expected to significantly alter forest ecosystems through various mechanisms, including changes in temperature, precipitation, and carbon dioxide levels, which can affect forest growth, productivity, and the distribution of tree species (Van Proosdij *et al.*, 2016). These changes can lead to shifts in species ranges, alterations in species compositions and interactions, and increased risks of species extinction (García-Callejas & Araújo, 2016). Estimation of the proportion of the species lost is essential for quantifying the effects of

anthropogenic change and disturbance and taking action to improve management and conservation to protect biodiversity (**He et al., 2018; Reis et al., 2019**). In addition, the Anthropogenic influence on the world's climate is very clear and has become more evident in recent decades (**Pramanik et al., 2018**). Species distribution modelling (SDM) and the impact of climate change are closely intertwined, with climate change significantly affecting the distribution and abundance of species across the globe. Therefore, determining whether climate change will affect the suitability of habitat for each species presents another critical problem linked to its economic value and ecological significance. Assessing the potential geographic distribution of multipurpose and threatened plants such as *Detarium* spp. is fundamental for anticipating conservation plans and their management. The modelling was performed for both the most optimistic and the most pessimistic IPCC scenarios in terms of temperature increment, projecting to 2070 and 2100. Statistical modelling techniques in species distribution modelling (SDM) can be categorized into three main types: empirical, correlative, and mechanistic (**Kearney et al., 2010**). Correlative SDMs, which are the most prevalent, utilize observed species occurrence data and environmental variables to generate maps predicting past, present, or future species distributions. Their simplicity and applicability make them a popular choice, accounting for approximately 90% of SDM publications (**Hijmans & Elith, 2013**). In addition, ecological Niche Modelling (ENM) is regarded as a valuable instrument for identifying habitats, predicting species populations, and assessing the impacts of climate change on various taxonomic groups (**Pecchi et al., 2019**). In contrast, mechanistic SDMs simulate biological processes based on ecological drivers, offering a more detailed understanding of species' fundamental niches. However, these models require extensive datasets and are not typically used at national or continental scales due to data limitations (**Horemans et al., 2024**). This review focuses on statistical SDMs as a means to overcome these limitations, with mechanistic models not being detailed here. Utilizing the MaxEnt modelling technique for *D. microcarpum* species distribution could significantly enhance our understanding of both current and future risks of climatic conditions. Species Distribution Models (SDMs) serve as a crucial instrument for forecasting the geographic distribution of species by correlating their presence with environmental factors (**Lompo et al., 2021**). Thus, with the current context of climate change and population growth, more attention has been given to predicting species distribution for future trends (**Phillips et al., 2006; Fan et al., 2022**). These modeling techniques offer a range of tools for predicting species distributions under different data conditions. MaxEnt tools developed by **Phillips et al. (2006)** are particularly suited for presence-only data, providing probability distributions across landscapes based on environmental factors. In contrast, GLMs

are versatile for presence/absence data and can handle various distributions, while GAMs extend this flexibility by allowing for non-linear relationships between predictors and outcomes (Nelder *et al.*, 1972; Segurado & Araújo, 2004 Thuiller *et al.*, 2009). For more complex interactions, Random Forest and Boosted Regression Trees (BRT) offer robust machine-learning approaches (Yang *et al.*, 2016). Random Forest uses an ensemble of decision trees to minimize overfitting and Boosted Regression Trees combines multiple tree predictions to enhance accuracy. All these models enable researchers to choose the most appropriate technique based on the nature of their data and the complexity of the relationships they are investigating. By using the occurrence data and the variety of environmental variables, the Maximum Entropy (MaxEnt) was chosen in this study to simulate the impact of climate change on their natural stand. Despite the research efforts and the importance of the species for the local communities, no research has been conducted to investigate how global climate change might affect the distribution of *D. microcarpum* across the country. Although information on its spatio-temporal dynamics is available in southern Guinea climatic zones like Benin (Agbo *et al.*, 2018), scientific knowledge of its geographical distribution and dynamics in semi-arid climatic zones, particularly in Burkina Faso is limited.

CHAPTER 3: Generality of the study location

3.1. Study area

This study was carried out in Burkina Faso which is a landlocked country located in West Africa located between the latitude 09°02' – 15°05' N and the longitudes 05°03' W – 02°02' E. The country is bounded by Mali to the north and west, Niger to the northeast, Benin to the southeast, and Côte d'Ivoire, Ghana, and Togo to the south. The country spans an area of 274,400 km², and according to the data of **INSD (2022)**, the population of Burkina Faso is 22,100,874 inhabitants with a density of 65.2 inhabitants per km² (65.2 hbts/km²). The terrain is mostly flat to dissected, undulating plains with hills in the west and southeast. The topography is plateau predominant with savannas-type geography, grassy in the north and gradually gives way to sparse forests in the southern region (**Schmidt et al., 2013**). The highest point in Burkina Faso is Tena Kourou, reaching 749 meters (2,457 feet), while the lowest point is the Mouhoun (Black Volta) River at 200 meters (656 feet). The country is characterised by its biogeography through its phytogeographic zones (PGZs) and the diversity of its vascular plant species (**Zizka et al., 2015**). The biogeography of Burkina Faso is characterized by its phytogeographic zones, each with distinct climate, vegetation, and plant diversity, reflecting the country's geographical location and climate gradient. The biogeography of Burkina Faso is marked by its distinct phytogeographic zones, each exhibiting unique climatic conditions, vegetation types, and levels of plant diversity (**Thiombiano et al., 2006**). These variations are a direct reflection of the country's geographical positioning and the prevailing climate gradient from South to North. This intricate biogeographical landscape significantly influences the ecosystems, biodiversity, and distribution patterns of plant species across the country. This biogeography plays a crucial role in the country's ecosystems, biodiversity, and the distribution of plant species. Due to this central position in West Africa, the country is a candidate for the ecological niche simulation at a large scale (**Schmidt et al., 2011**).

Across the country, this study was carried out in the Sudanian and the Sudano-Sahelian climatic zones of Burkina Faso, representing the natural occurrence areas of *D. microcarpum* (**Bationo et al., 2001; Thibaut, 2008**) (**Figure 4**). Along with the climatic gradient, four (04) sites were chosen based on the presence of the *Detarium microcarpum*, and their accessibility due to the security issue that the country is facing. In the Sudanian zone, the sites were the Wildlife Reserve of Bontioli (10°51'32'' N – 03°07'23'') (South-Western) and the Classified Forest of Kou (11°10'60'' N – 04°27'0'). In the Sudano – Sahelian climatic zone, the sites were

Nazinga Game Ranch (11°01' – 11°18'N / 1°18' – 1°43'W) and the classified forest of Nakambe (12°6'54'' N – 1° 6'56'' W) shown by **Figure 4**.

Administratively, the Wildlife Reserve of Bontioli (WRB) is situated in the southwestern region and belongs to the province of Ioba. The Classified Forest of Kou (CFK) belongs to the Western region in the province of Houet. Classified Forest of Nakambe (CFN) and Nazinga Game Ranch (NGR) are situated in the Centre–Southern of Burkina Faso belonging to the province of Bazega and in the province of Nahouri (Po). The choice of the site was based on the type of land use, the climatic gradient, and the accessibility according to the security issue the country faces; they shelter populations of *D. microcarpum* and cover the national stand of the species. In addition, NGR and WRB constitute the core research sites of the Wascal (West African Science Service Center on Climate Change and Adapted Land Use) Programme in the Competence Center of Burkina Faso.

3.2. Importance and conservation status of the study area.

Ever-growing human population and overexploitation lead globally to the ongoing degradation of ecological systems and their services, manifested by alarming rates of biodiversity loss. Pragmatically, protected areas are therefore seen as the core units of successful conservation of a minimum/maximum of this biodiversity in the long term and represent one of the most important forms of land use today. These sites have been protected at different periods but are all statued as "classified forests". However, they are all managed by annual early fires and the various types of land use. The four studied forests are conserved under specific regimes of protection. According to the World Database of Protected Areas (WDPA) of the International Union for Conservation of Nature (IUCN), the four protected areas are characterized by different conservation statuses based on their importance.

The Classified Forest of Nakambe was statued in 1953 and is in a state of advanced destruction as a result of human land use and climatic threat. With a total of 98000 ha and belonging to category IV is categorised in categorised as a forest development site co-managed by the State and the local forest management groups.

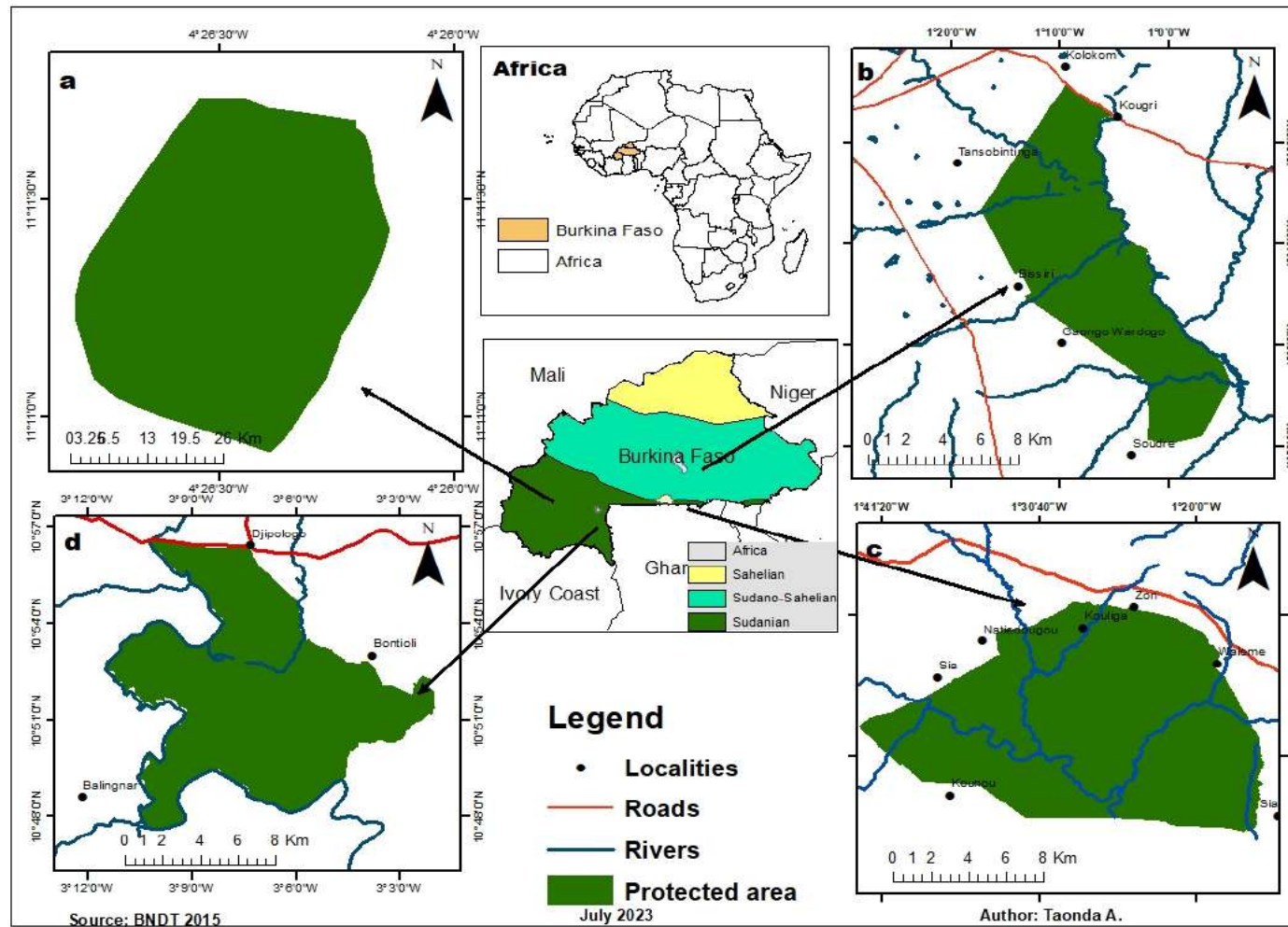


Figure 4: Map of study sites according to the 2012 Burkina Faso land occupation database

Legend: a = Classified Forest of Kou; b = Classified Forest of Nakambe; c = Classified Forest and Game Ranch of Nazinga; and d = Wildlife Reserve of Bontioli.

The Nazinga Game Ranch (NGR), established in 1979, is the first game ranch in West Africa, marking a significant milestone in conservation efforts. Classified under decree no 2000/0923/PRES/PM/MEE in 2000, the ranch spans a total area of 97,000 hectares, earning it a classification as a Category VI total faunal reserve. This designation underscores its importance in biodiversity conservation and supporting sustainable livelihoods through controlled human activities. The ranch's management includes the collection of non-timber forest products by local communities and regulated hunting, ensuring that these activities are conducted responsibly. As a leading faunal reserve dedicated to tourism, the NGR plays a crucial role in the country's economy, contributing significantly to its development and prosperity.

The Wildlife Reserve of Bontioli, also known as the "Classified Forest of Bontioli," is a significant conservation area in Burkina Faso, encompassing both a partial reserve and a total reserve. Established in 1957 under the decree no. 3147/SE/EF, dated 29/03/57, this reserve is classified under the IUCN categories as a total faunal reserve I and a partial faunal reserve IV. This study focuses only on the total reserve aspect of the Bontioli Wildlife Reserve

Classified Forest of Kou was classified by decree n^o132/FOR of 30/01/1951, in the application of the decree of 04/06/1935. It covers 115 ha. According to the text governing its classification, the main purpose of the CFK is to protect the Kou River and the "guinguette" springs. In terms of management, the FCK has benefited from various actions carried out by the Burkinabe National Tourist Office and the Forestry Service. The Kou name refers to the river that flows through the forest. The Kou Forest presents an essentially flat relief.

Despite the status of the protection, the Nakambe classify Forest, Wildlife Reserve of Bontioli and the Nazinga Game Ranch (NRG) are facing human disturbance. In these protected areas, illegal logging, extensive agriculture, bushfires, traditional mining exploitation and animal poaching are common threats. In addition, the farmlands are observed in inside of each site. The main disturbance in the Classify Forest of Nakambe is the illegal logging for firewood, and animal grazing, **(Figure 5)**; in the Wildlife Reserve of Bontioli, there is traditional mining exploitation and farming agriculture. The Nazinga Game Ranch is less disturbed and is relatively well protected like the Classify Forest of Kou. However, the classified forest of Kou is exempted from this disturbance because it is closely protected by a wall which avoids the local population disturbance.

Table 1: Characterization of the four protected areas

Protected Areas (P.A)	Area (ha)	IUCN	Sources
NGR	91.300	VI	Thiombiano & Kampmann, 2010
WRB	42.200	I & IV	Thiombiano & Kampmann, 2010
CFK	115	IV	Thiombiano & Kampmann, 2010
CFN	98.000	IV	Thiombiano & Kampmann, 2010

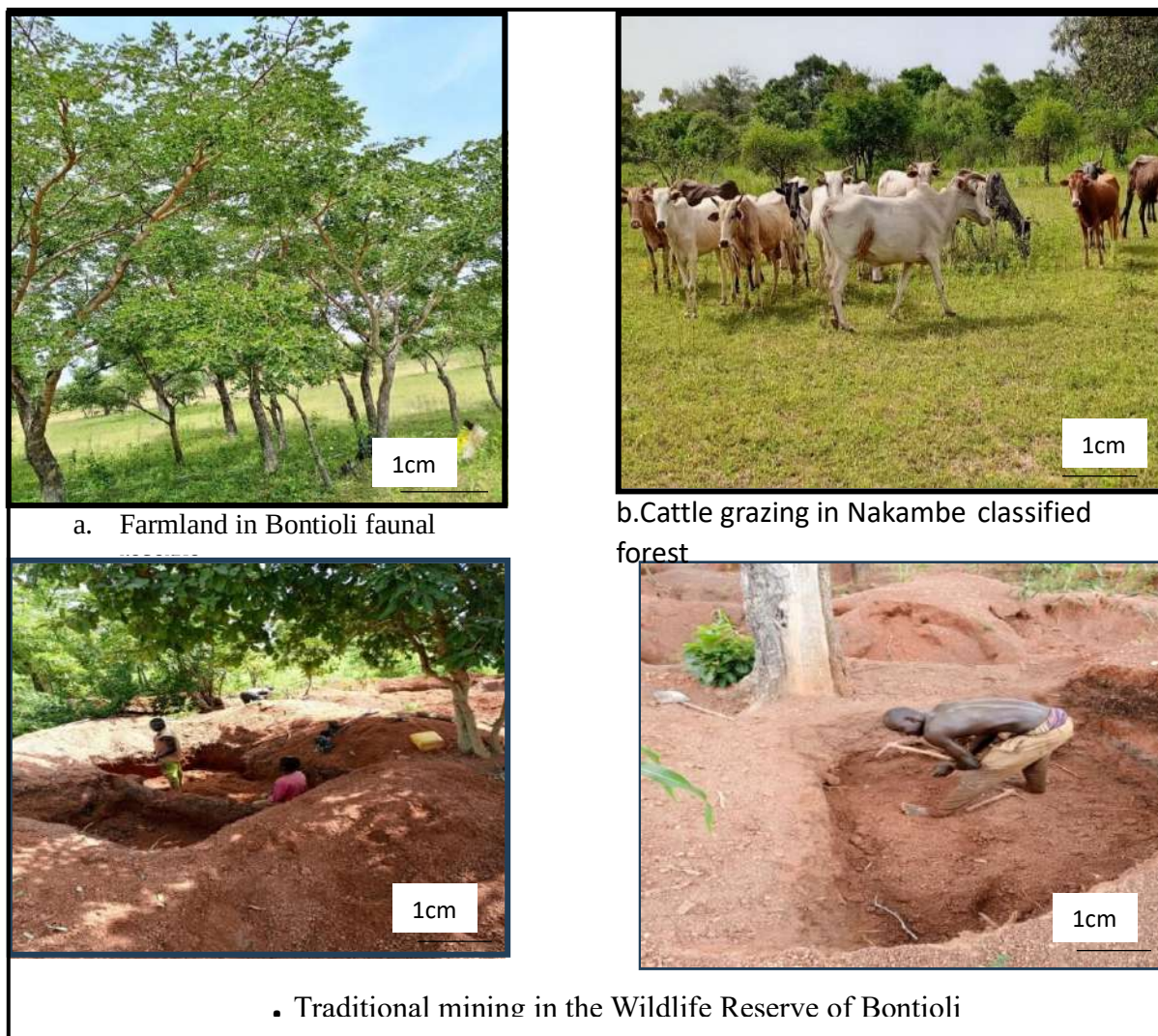


Figure 5: Different threats of the Protected areas

3.3. Climate

This area has mean annual rainfall between 952 mm/year⁻¹ and annual mean temperature varying from 29.8°C. The rainfall is very variable and irregular, which decreases from the southwest to the north, which influences the country's temperature. The study area spans two climatic zones: the Sudano-Sahelian climatic zone and the Sudanian climatic zone. The Nazinga Game Ranch and the classified Forest of Nakambe are located in the Sudano-Sahelian climatic zone **(Kristensen & Balslev, 2003)** This represents the country's transition climatic zone with 4 to 5 months of rainy season. The Wildlife Reserve of Bontioli and the Classified Forest of Kou are located in the Sudanian climatic zone **(Kangbéni, 2014; Yaovi *et al.*, 2021)** which represents the most humid climatic zone of the country with 5 to 6 rainy seasons. The regime of the climatic in the two climatic zones influences the mean temperature of the two climatic zones, which varied between 25 to 31 in the Sudano-Sahelian climatic zone and 20 – 26 in the Sudanian climatic zone. The anomalies of annual rainfall and temperature showed different trends in climate variations across the two climatic zones. Over the period 1991 – 2022, the two climatic zones have been characterized by frequent drought occurrence across the country **(Figure 6)**. The Classified Forest of Nakambe and Nazinga Game Ranch has been characterized by alternate periods of drought occurrences through the presence of the negative rainfall anomaly index in the Sudano-Sahelian climatic zone. The 1991 – 2001 has been characterized by the occurrence of a drought period both at the two climatic zones. In contrast, this period (drought period) corresponds to a hot period (negative temperature anomaly index) indicating an increasing temperature was also observed. The position rainfall anomaly index and positive anomaly index observed in each climatic zone indicate a return of rainfall. In the two climatic zones, the hotter zone was observed in the Sudano-Sahelian climatic zone and the positive anomaly index of the rainfall was observed better in the Sudanian climatic zone **(Figure 6)**.

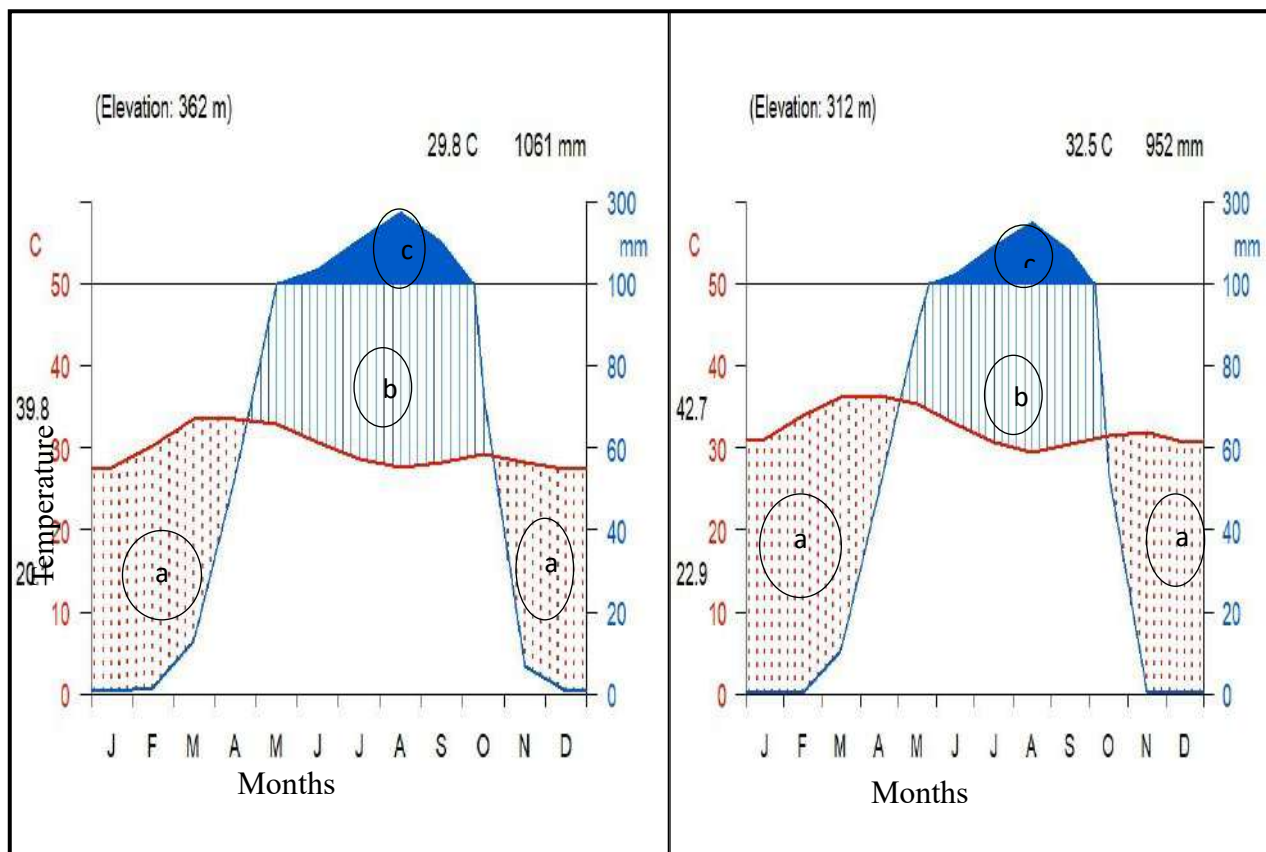


Figure 6: Walter and Lieth climate diagrams for Sudanian zone 1990 - 2022 and the Sudano -Sahelian 1992 -2022. a dry season, b rainy season, c major seasonal precipitation. Source of the data: National Direction of Meteorology Agency of Burkina Faso

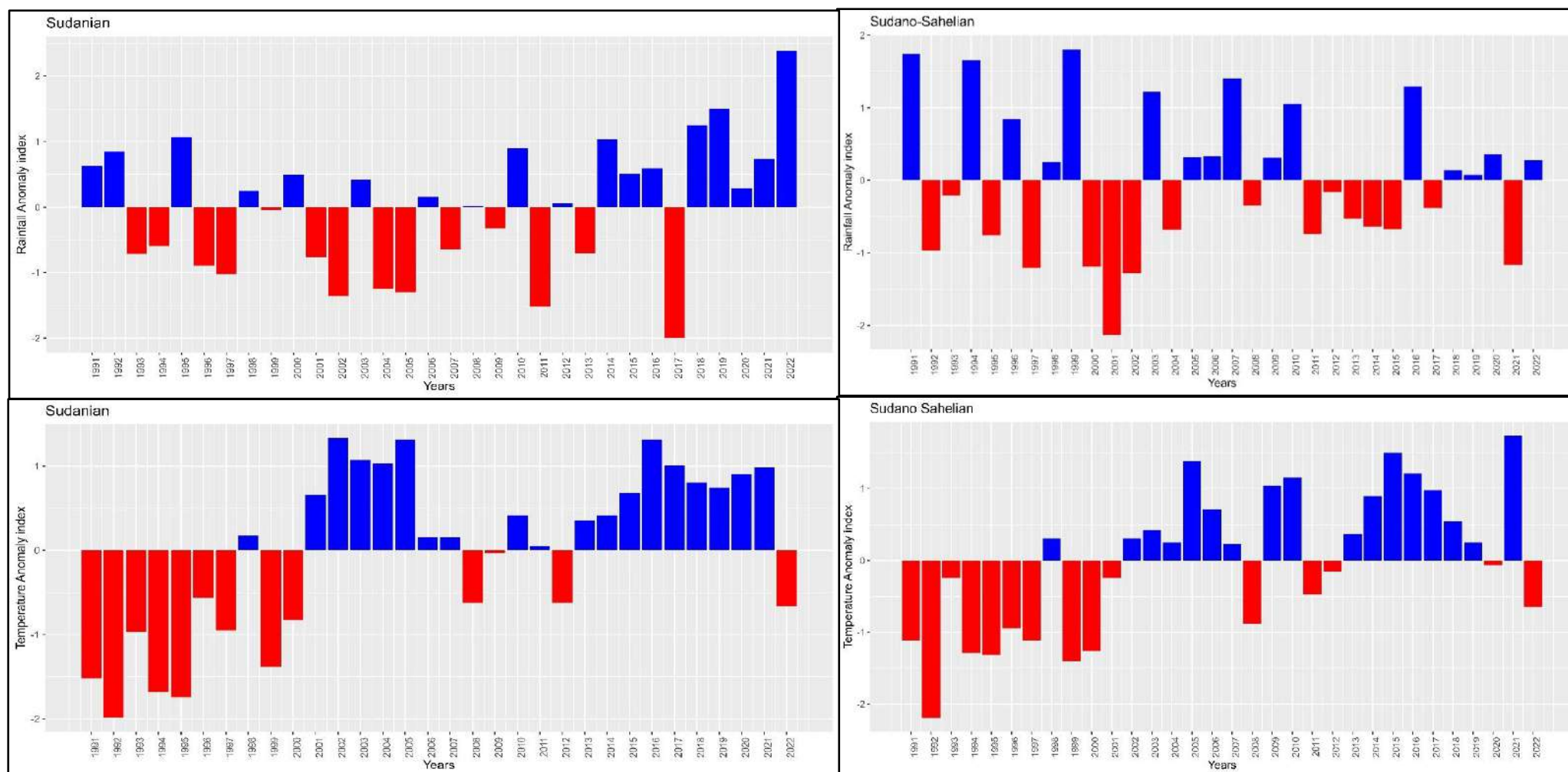


Figure 7: Annual rainfall and temperature anomalies index for Sudanian zone and Sudano-Sahelian zone.

Source of the data: National Direction of Meteorology Agency of Burkina Faso

3.4. Soils and Elevation

The four study sites vary in terms of soil types, which are influenced by their depth and physiographic position. Tropical ferruginous soil for Nakambe, ferruginous in Nazinga, lixisols in Bontioli and the Kou classified forest region is characterized by a predominantly flat landscape, with soils predominantly composed of loamy material, occasionally interspersed with rocky outcrops. The relief is more or less flat with some elevations across the study sites. The digital elevation map (DEM) shows that mean altitude varies slightly across the four sites with 304 m a.s.l (250 - 358) at Nakambe classify forest, 299 m a.s.l (233 - 365) at Nazinga, 291.5 m a.s.l (240–343) at Bontioli, and 354 m a.s.l (344 - 365) for Kou Classify Forest (**Figure 7**). The lowest altitude was found in Bontioli (291.5 m a.s.l.), whereas the highest altitude was found at Nazinga Ranch Game (365 m a.s.l.).

3.5. Vegetation, flora and fauna

The type of vegetation depends on the type of climate. Burkina Faso's vegetation is dominated by open forests, savannas and multi-facies steppes crisscrossed by gallery forests. In this order, the vegetation types in each study site are underlined with the type of climate in each environment. The four protected areas serve as crucial refuges for woody plant species, primarily from the Sudano-Sahelian climatic zone and the Sudano-Guinean zone respectively in the Sudano-Sahelian and the Sudanian climatic zone. These forests are distributed across the climatic zones with the vegetation cover becoming denser from the Sudano-Sahelian to the Sudanian climatic zone. The vegetation is made up of a mosaic of forest formations comprising: a gallery forest; an open forest; a plantation of *Tectona grandis*; a wooded savanna; a wooded savanna with a dense, continuous carpet of grasses and, lastly, aquatic vegetation characterised by *Nymphaea lotus* and *Potamogeton octandrus* (**Yaovi, 2017**). The main woody species encountered in Wildlife Reserve of Bontioli are *Daniellia oliveri* (Rolfe) Hutch. & Dalziel, *Detarium microcarpum* Guill. & Perr.; *Isobertinia doka* Craib & Stapf, *Pterocarpus erinaceus* Poir., *Terminalia laxiflora* Engl., *Terminalia macroptera* Guill. & Perr., *Terminalia avicennioides* Guill. & Perr., *Anogeissus leiocarpa* (DC.) Baill., *Burkea africana* Hook, *Mitragyna inermis* (Willd.) Kuntze, *Azelia Africana* Sm. ex Pers., *Lannea macrocarpa* Engl. & K.Krause, *Lannea acida* A.Rich., *Parkia biglobosa* (Jacq.) R.Br. ex G.Don and *Vitellaria paradoxa* C.F.Gaertn. (**Dimobe et al., 2015**).

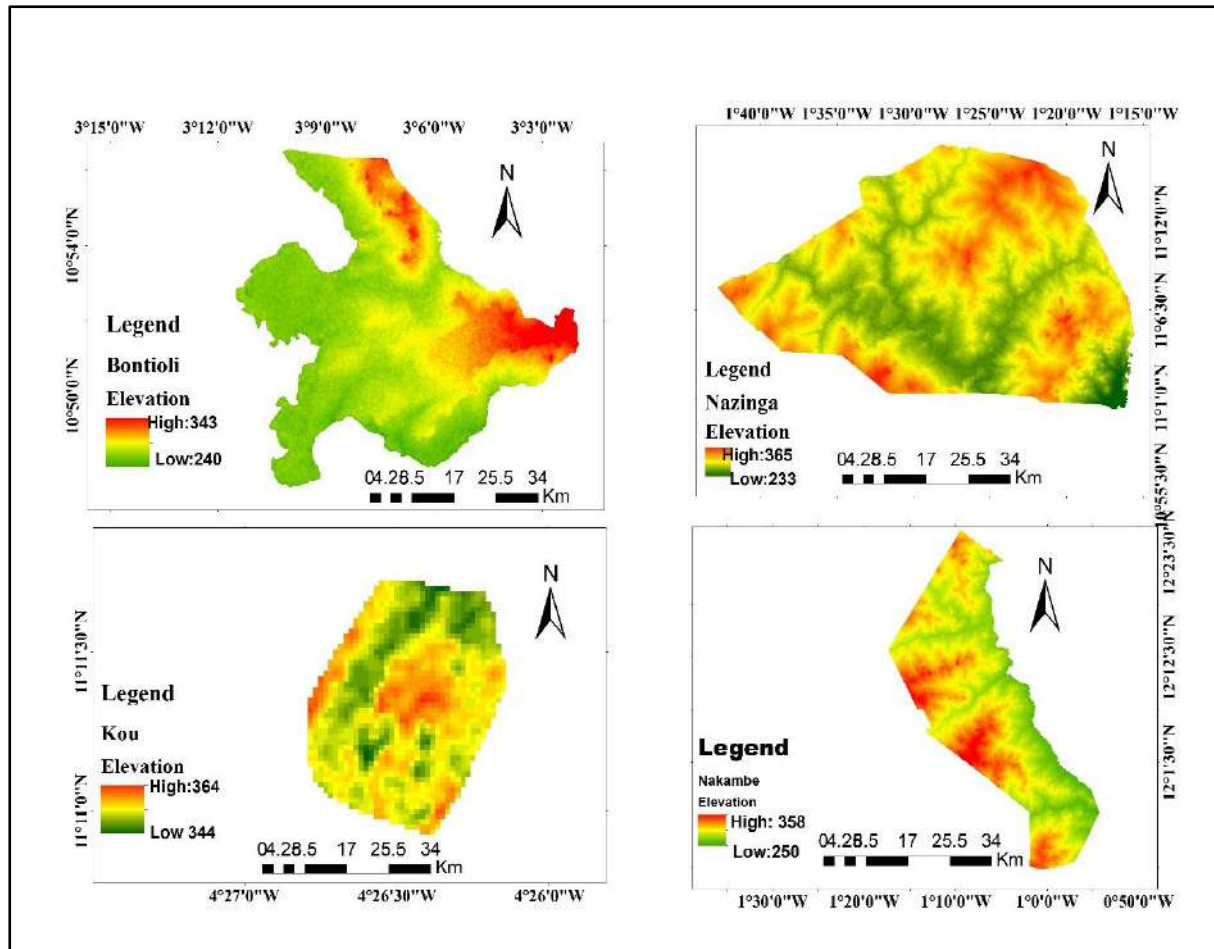


Figure 8: Digital Elevation Model (DEM) of the four study sites Source: SRTM (Shuttle Radar Topography Mission) data from <http://viewfinderpanoramas.org>; consulted on 11/01/2024.

In the Sudano-Sahelian climatic zone, the main vegetation is shrub savannas, tree savannas, woodlands and grass savannas with a grass layer dominated by annual herbaceous species. In the Nazinga Game Ranch is dominated by *Vitellaria paradoxa* C.F. Gaertn, *Terminalia laxiflora* Engl. & Diels, *Terminalia macroptera* Guill. & Perr., *Combretum glutinosum* Perr. ex DC., *Combretum micranthum* G. Don, *Combretum adenogonium* Steud. ex A.Rich., *Combretum collinum* Fresen., *Anogeissus leiocarpa* (DC.) Guill. & Perr., *Detarium microcarpum* Guill. & Perr., *Piliostigma thonningii* (Schum.) Milne-Redhead, *Isobertia doka* Craib & Stapf and *Lannea acida* A. Rich. The dominant grass species are *Andropogon gayanus* Kunth, *Hypparhenia rufa* (Nees) Stapf, *Loudetia togoensis* (Pilger) C.E. Hubbard and *Schizachyrium sanguineum* (Retz.) Alston (Nabaloum et al., 2022). The dominant woody species in the Nakambe Classified Forest include *Anogeissus leiocarpa* (DC.) Guill. & Perr., *Combretum glutinosum* Perr. ex DC., *Combretum micranthum* G. Don, *Combretum adenogonium* Steud. ex A.Rich., *Combretum collinum* Fresen., *Detarium microcarpum* Guill. & Perr., *Vitellaria paradoxa* C.F. Gaertn., *Annona senegalensis* var. *porpetac* (Boivin ex Baill.) Diels.

The fauna diversity of the four protected areas differs according to the disturbance level. In fact, the dominant fauna are elephants (*Loxodonta africana* Blumenbach, 1797), baboon (*Papio anubis* Erxleben, 1777), vervet (*Cercopithecus aethiops* Linnaeus, 1758), patas monkey (*Erythrocebus patas* Schreber, 1775) and hyenas (*Crocuta crocuta* Erxleben, 1777 and *Hyena hyena* Linnaeus, 1758). In the Nakambe Classified Forest, the main animals are the patas monkey (*Erythrocebus patas* Schreber, 1775), *Lepus europaeus*, Pallas 1778, *Varanus niloticus* (Linnaeus, 1766) and the different types of bird species. However, in the Sudanian climatic zone, the dominant fauna are *Tragelaphus scriptus*, *Kobus kob* (Erxleben, 1777); *Ourebia ourebi* (Zimmermann, 1783); *Redunca redunca* (Pallas, 1767), *Alcelaphus buselaphus* (Pallas, 1766), *Phacochoerus africanus* (Gmelin, 1788), *Sylvicapra grimmia* (Linnaeus, 1758); *Cephalophus rufilatus* Gray, 1846, *Papio ursinus* (Kerr, 1792); *Orycteropus afer* (Pallas, 1766) in the Wildlife Reserve Forest of Bontioli. According to his proximity to the villages of Kokorowe and Naso, the Classified forest of Kou contains a small amount of wildlife. The vertebrates that live there, as well as certain fish, reptiles and rodents, are subject to customary protection, which gives these animals a special status (Yaovi, 2017; 2021).

3.6. Population and socio-economic activities

The main ethnic groups residing around the four Protected areas in the study region are diverse: Mossi near the Classified Forest of Nakambe, Gourounsi around the Classified Forest and

Game Ranch of Nazinga, Dagara around the Wildlife Reserve of Bontioli and Bobo around the Classified Forest of Kou. Each Protected Area is surrounded by agricultural land. Predominantly, these communities engage in agriculture, relying on the cultivation of millet, Azia maize and sorghum, alongside herding and provisioning ecosystem services from trees. However, agriculture constitutes the main socio-economic activity of the rural people across the country and engages about 75% of the national population (**INSD, 2022**). In many West African countries, shifting cultivation, a method involving successive farming, is the prevalent agricultural practice in rural areas. This technique necessitates the selective cutting and burning of shrubs and trees during the preparation of fields for cultivation. This itinerant and extensive approach to farming not only consumes significant space but also contributes to the expansion of cultivated areas. Consequently, it exacerbates deforestation, ecosystem degradation, and biodiversity loss. Animal breeding serves as a critical socio-economic activity for rural communities, complementing agriculture. The herding system employed is a blend of sedentary and transhumant practices, adapting to the scarcity of forage during the dry season. Other socio-economic activities within these communities include fishing, hunting, trade, and craftsmanship.

PART II: MATERIAL AND METHODS

CHAPTER 4. Material

The material used in this study was composed of biological material, field equipment and laboratory equipment.

4.1. Biological material

The study focuses on *Detarium microcarpum*. Stem discs (wood samples) are collected for tree-ring analysis, while tree biomass, including branches, leaves, and stems, are used for biomass prediction. Biomass samples are analyzed to estimate carbon content.

4.2. Field equipment

A **motorbike** was used for local trips in the field, and a digital camera was utilized for photography. An **individual questionnaire** was administered for local surveys, while **50 m and 30 m ribbons** were employed for plot installation. A **forest compass** was used for diameter measurements, and a Suunto device was used to measure tree height. A **GPS** records coordinates and collects occurrence points for recorded and distribution modelling, while a chainsaw is used for tree felling. Finally, a **digital balance** is employed for biomass weighing.

4.3. Laboratory equipments

An **oven** was used to dry biomass samples, while a furnace was used to burn them. A **sanding belt** and sandpaper were applied for disc polishing, and a **microtome** was used for cutting wood samples. **Staining materials** were used for slide preparation, and a digital microscope is employed for slide examination. A **LINTAB** device was used to measure ring width, and a Smart Zoom Scanner was used to scan wood surfaces. The different software used for the data analysis were R software, PCord, and ArcGIS.

CHAPTER 5. Methodology

The methodology employed in this study is outlined as follows.

5.1. Local Perceptions of anthropogenic and climate factors affecting the use and the conservation of *Detarium microcarpum* in Burkina Faso

5.1.1 Sampling

A total of 465 individuals were interviewed using a simple random sampling technique, without gender considerations, based on their knowledge of plant parts of the *D. microcarpum* in question (Zerbo *et al.*, 2022). The number of interviewees varied from 65 to 185 individuals across different sites. Participants included residents of various ages, with a minimum age requirement of 30 years to ensure respondents had sufficient experience to identify changes in climate and anthropogenic threats to the species. Before conducting interviews, administrative and traditional leaders, as well as youth leaders at each site, were informed to aid in establishing a conducive environment for interactions with community members.

Data were collected through semi-structured interviews and focus group discussions from September to December 2022 (Naah & Guuroh, 2017; Balima *et al.*, 2018; Zerbo *et al.*, 2022). To ensure accurate identification, specimens of the *Detarium microcarpum* were provided to informants at each site. Interviews were conducted in local languages and translated by site-specific translators. Informants provided verbal consent before participation. The questionnaire included a combination of closed and open-ended questions and was designed to gather data on sociodemographic characteristics (ethnicity, sex, age, education level, and occupation) and the uses of different plant parts from the targeted species (Zerbo *et al.*, 2022). Additional questions related to areas of abundance, Type of threats and their impacts on the species related to the climate and human disturbance, and conservation solutions for sustainable resource management were also included. Informants provided insights into the current status of the species, including stability, decline or disappearance, and motivations for their conservation.

5.1.2. Data analysis

To determine the composition of the investigated population, the relative frequency of different sociodemographic characteristics, such as ethnic group, sex, age, education level, and activity sectors, were computed. Regarding age consideration, the informants were grouped into three age categories following Assogbadjo *et al.* (2008): young ($30 \leq \text{age} < 45$ years), adults ($45 \leq \text{age} < 60$), and old ($\text{age} \geq 60$ years).

To highlight which part of the species is used most often, the consensus value for the plant part (CPP) was considered (**Table 2**). It measures the degree of agreement among informants concerning the plant part used (**Monteiro et al., 2006**). In addition, the relative frequency of citation (RFC) for use categories was calculated to identify the most common uses. The Kruskal-Wallis non-parametric test was used to assess whether CPP and RFC varied significantly according to the sociodemographic factors (ethnic groups, sex, age, education levels, and activity sectors).

RFC was also used to evaluate local perceptions of presence areas, threats, and conservation solutions for the sustainable use of the species. Bar plots were created to visualise the areas of presence using the tidyr package (**Hadley et al., 2023**). Correspondence analyses were performed to highlight the relationship between local population perceptions of threat factors and their consequences relative to different sociodemographic characteristics, using the packages factoMiner version 2.8 (**Husson et al., 2023**) and factoshiny (**Vaissie et al., 2022**). Following **Zerbo et al. (2022)**, RFC calculations for different ethnic groups were depicted using Sankey diagrams using the networkD3 package (**Ellis et al., 2022**).

All statistical analyses were performed with R software version 4.2.2 (**R Development Core Team, 2022**).

5.2. Effects of land use and climate on the diversity and population structure in natural stands of *D. microcarpum* (Fabaceae) in Burkina Faso (West Africa)

5.2.1. Sampling design and data collection

The study was conducted in two climatic zones (Sudanian and Sudano-Sahelian). These climate zones were selected based on the presence of *Detarium microcarpum* natural stands. In each climate zone, data were collected in two protected areas and their surrounding areas (Unprotected areas) following an oriented sampling based on the presence of *D. microcarpum*. A total of 165 plots were set up in the two climatic zones. In the Sudanian zone, 75 plots comprising 45 plots in the Protected areas and 30 plots in the Unprotected areas were used. In the Sudano-Sahelian zone, 90 plots including 50 plots for Protected areas and 40 plots in Unprotected areas were established. The plots in the protected areas had a size of 1000 m² (50 m x 20 m) and those in unprotected areas had a size of 2500 m² (50 m x 50 m) adopted by **Thiombiano et al. (2016)** and **Balima et al. (2020)**. The plot sizes followed the standard guidelines established by **Thiombiano et al. (2016)** for West Africa savanna surveys according

to the the vegetation types. Within each site, the minimum distance between two plots was 100 m (**Ouédroogo et al., 2020**). In addition, unprotected areas include fallow land and grazing areas. In each plot, all woody species encountered were recorded for the assessment of *D. microcarpum* stand diversity and species composition. Forest inventories consisted of the measurements of the diameter at breast height (DBH) and the total height of each woody individual. Individuals with dbh less than 5 cm were considered juveniles. To characterize the regeneration of *D. microcarpum*, five sub-plots of 25 m² (5 m x 5 m) were installed (At the four corners of the plot, with a fifth plot located at its center) in each major plot to sample juvenile individuals (DBH < 5 cm). In each sub-plot, the height and the diameter of juvenile individuals of the species were measured using a diameter tape.

Table 2: Description of the calculated parameters for the local analysis of local perceptions

Nº	Parameters	Formula	Significations
1	Consensus value for plant part (CPP)	$CPP = P_x / P_t$	Number of times a given plant part was cited (P_x), divided by the total number of citations of all parts (P_t). Measures the degree of agreement among the informants concerning the plant part used (Monteiro <i>et al.</i>, 2006).
2	Relative Frequency of Citation (RFC)	$RFC = (S/N) * 100$	A measure is calculated as $RFC = (S/N)$, where ‘S’ represents the number of citations for a specific use of a plant part, and ‘N’ is the total number of informants. This metric provides insight into the relative importance of each plant part among the population for their provision of services.

5.2.2. Data analysis

5. 2.2.1. Variation in the stand's diversity and composition

All analyses were done with R statistical software (**R Core Team, 2023**). The taxonomic richness (number of species, genera, and families) of woody species associated with *D. microcarpum* was determined by investigating their co-occurrence in its natural stands (**Zerbo et al., 2016**). The recorded species names were further retrieved following the World Plant Names Index (<https://wfo.plantlist.org/plant-list/>) and the Catalogue of vascular plants of Burkina Faso (**Thiombiano et al., 2012**).

The woody stand diversity was assessed through the series of diversity numbers and evenness presented by **Hill (1973)**. The diversity indices were computed through the package Biodiversity R (**Kindt, 2011**) and were represented as follows:

- $N_0 = S$; with S the number of species in a plot
- $N_1 = e^{H'}$; with H' Shannon's index;
- $N_2 = 1/D$, D is the Simpson's index
- Evenness (E) = $H / \ln(S)$.

N_0 is the effective number of species in the sample regardless of their abundance. N_1 measure the number of abundant species in the sample. N_2 is the number of very abundant species

A Multi-Way Analysis of Variance (Multi-Way ANOVA) was used to assess the effect of climate, land use, and their interaction on the diversity indices described by N_0 , N_1 , N_2 , and the Evenness. The Tukey's post-hoc test (Tukey-PHT) was used to compare the mean values according to the climatic zone and land-use types when needed.

To quantify the similarity among the species' natural stand, the Jaccard similarity index (β -diversity) based on species data presence/absence was used to evaluate the variation in woody species composition according to the climatic zones and land use types.

The Importance Value Index (IVI) which is an indicator of species' ecological importance (Mueller-Dombois and Ellenberg 1974) was used to determine the pattern of variation in *D. microcarpum* stands composition. This index ranges between 0 and 300. The species having the highest IVI is considered dominant in the community. The IVI was calculated for each heterospecific woody species according to the following parameters:

- Frequency = number of plots in which the species occurs/total plot number $\times$ 100.
- Relative Frequency = frequency of a species/sum of all frequencies $\times$ 100.
- Relative density = (number of individuals of a species / total number of individuals) $\times$ 100.

- Relative Dominance = total basal area of a species/basal area of all species × 100.
- Importance Value Index = Relative density + Relative dominance + Relative frequency

In each climatic zone and land use type, the 20 species with the highest IVI were selected to highlight the variation patterns in dominant woody species.

5.2.2.2. Variation of *D. microcarpum* dendrometric structural parameters and effect of abiotic and biotic factors

The structural parameters of *D. microcarpum* included basal area (G), density (N), mean diameter (Dm), and Lorey's mean height (HL) were assessed.

The basal area G was calculated as the following formula:

- $G (m^2 \cdot ha^{-1}) = (\pi * DBH^2) / 4$.
- $N (individuals/ha) = n/S$, with n as the average number of individuals per plot and S as the area expressed in hectares.
- The average Lorey's height $m \left(\frac{\sum_{i=1}^k gihi}{\sum_{i=1}^k gi} \right)$ with $gi = \frac{\pi}{4} di^2$ expresses the height of the individuals adjusted by the basal area.

The variation in the species' structural parameters according to the climatic zones and land use types was analysed through the non-parametric Kruskal Wallis test due to the non-normal distribution of data.

To determine the effects of abiotic (mean annual temperature and mean annual precipitation) and biotic factors (“habitats specific richness” and “heterospecific density”) on the structural parameters of *D. microcarpum*, a generalized linear model assuming a Poisson distribution was applied. The “habitat heterospecific density” refers to the number of all individuals of the different species that occur within the same habitat with *Detarium microcarpum* stand. The “habitat-specific richness” refers to the number of different species found within the same habitat, with the *Detarium microcarpum* species. Based on geographical coordinates, abiotic factors including climate data such as mean annual temperature (°C) and mean annual precipitation (mm) were downloaded for each plot from WorldClim (<https://www.worldclim.org/data/worldclim21.html>) through the R packages raster (Etten *et al.*, 2023), SP (Hijmans *et al.*, 2023), rgdal (Daniel & Anderson, 2018), exactextractr (Daniel, 2020), sf (Cook & Baston, 2023), terra (Hijmans, 2023) with a spatial resolution of 0.5° for the analysis. Thus, abiotic (mean annual temperature and mean annual precipitation) and biotic (habitat heterospecific density and habitat-specific richness) factors were used as explanatory variables and *D. microcarpum* structural parameters (basal area, density, mean diameter and

Lorey's mean height) as response variables. In addition, the Pearson correlation was used to check the relationship between biotic factors (habitat-specific richness and heterospecific density) and abiotic factors (average temperature and mean annual precipitation) considered in the model as explanatory variables (Appendix 2).

5.2.2.3. Variation of *D. microcarpum* population structure

Diameter classes and height classes distribution based on the method of **Condit *et al.* (1998)** were used to interpret the status of *D. microcarpum* populations according to the climatic zones and land use types. This method provides a structured, detailed method for analysing forest ecosystems that is widely used in ecological studies, conservation planning, and forest management. Their method is crucial for providing insights into forest dynamics and biodiversity, which are all vital for understanding and mitigating the impacts of climate change. Thus, ten (10) diameter classes 5-10 cm, 10-15 cm, 15-20 cm, 20-25 cm, 25-30 cm, 30-35 cm, 35-40 cm, 40-45 cm, 45-50 cm and 50-55 cm for the adult stratum and five height classes 0-0.5 m, 0.5-1 m, 1-1.5 m, 1.5-2 m, 2-2.5 m for juvenile stratum were used. The resulting parameters, especially slope, R^2 coefficient of determination, and regression probability, were considered as indicators of distribution status (**Obiri *et al.*, 2002**). A negative slope indicates that small-diameter individuals are abundant, while a positive slope indicates an abundance of large-diameter individuals. In addition, values of the coefficient of determination (R^2) and their p-values make it possible to observe whether there is a stable transition between several individuals and diameter classes.

5. 3. The climate effect on *Detarium microcarpum* growth

5.3.1. Wood sample collection and processing

The trees were selected from protected areas to minimise possible human disturbances (cutting, pruning, grazing, etc.), which could impact the species' growth since individuals found in unprotected areas (fallow, farmlands, parklands, etc.) are more exposed to human disturbance. For each tree, the dendrometric parameters stem diameter at breast height in 1.3 m (DBH) and at 0.2 m above the ground, tree height (H), and the diameter of the crown (Hp) were measured in October – November 2022 through 12 plots in the protect area of in each climatic zone. The individual were chosen according to the GPS coordinate of the plot established during the field survey in. These plots were selected within the protected area to identify individuals subjected to minimal human impact. Before felling, the geographical coordinates of each stand were recorded and the dendrometric parameters were measured. In total, 12 trees of *D. microcarpum*

were chosen such as one disc per tree. Only trees, which were in good health condition were taken to minimise possible disturbances from human actions (bushfire, cutting, pruning, grazing, etc.). To reduce uncertainty related to identifying growth ring boundaries and distinguish wedging, false, or missing rings, we opted to collect stem discs instead of increment cores (**Gebrekirostos *et al.*, 2016; Sanogo *et al.*, 2016; Talla *et al.*, 2021**). The disc samples, ca. 2 cm thick were extracted from the bases of the trunks using a motorized chainsaw at heights ranging from 30 to 40 cm (**Brienen & Zuidema, 2006**). For all discs collected, information on felling date, geographical coordinates, diameter at breast height (DBH) and tree height were recorded. The samples were dried under shade to avoid cracking of the disks (**Balima *et al.*, 2020**), for the climatic analysis, gridded climate data with a spatial resolution of 0.5° provided by the Climate Research Unit (CRU, <https://climexp.knmi/>) University of East Anglia, UK, for mean temperature and total precipitation for 1929–2022 were used.

5.3.2. Identification of tree-ring chronologies and quality quantification analyses

To improve the legibility and the visibility of growth-ring boundaries of trees, the discs were both mechanically and manually polished using increasingly finer sandpapers (80 – 2000 grit). After sanding, the tree-ring boundaries were detected under a stereo-microscope and measurements to the nearest 0.01mm were carried out using a LINTAB 6 measuring table equipped with the Time Series Analysis and Presentation (TSAP) software (Rinntech, Heidelberg, Germany). Before conducting measurements, all tree ring boundaries were meticulously marked with a pencil under a stereo microscope. Every tenth ring was examined along the whole circumference to detect any missing or false rings. Should such anomalies be identified, the subsequent tree rings were traced to pinpoint the precise location of these irregularities. In some cases of missing or false rings, the radii rings were followed to identify the exact location of the tree-ring anomalies. After correct cross-dating, an average tree-ring series per tree was created, and then all individual mean tree-ring series were averaged within each climatic zone. This chronology encompasses all trees exhibiting a shared growth pattern, facilitating a comprehensive understanding of the site's growth dynamics. Cross-dating was done both visually and statistically. The visual cross-dating was conducted using pointer years (extremely wide or narrow rings). To determine the growth dynamic, internal synchronisation was applied to determine a wide and narrow ring. To detect wedding rings and false rings, every tenth ring inter-connects between the different radii of the same discs under the microscope (**Boakye *et al.*, 2019**). For statistically aided cross-dating, several statistical parameters were calculated in TSAP to check for optimal matching positions of cores (**Figure**

9). This tool offers the GLK (coefficient of parallel variations among tree-ring series, sign-test) and T-value, enhancing the reliability of the dating method (Baillie & Pilcher, 1973).



Figure 9: Tree-ring width measurement using LINTAB 6 supported by TSAP software

5.3.3. Wood anatomy description of *Detarium microcarpum*

5.3.3.1. Microsection preparations

In general, wood anatomy sample preparation typically entails creating microsections with a thickness ranging from 10 to 20 μm using a sledge or rotary microtome, followed by staining the pallid cell walls with agents like safranin or Astra blue (De Micco *et al.*, 2016; Pandey, 2021). The three best-fitting samples ($\text{GLK} \geq 65\%$ and $T\text{-value} > 2$) were chosen and used for the wood anatomical analysis. A cross-sectional subsample with a thickness of 20 μm , was extracted from two discs using a sliding microtome through subsections of each disc (Ayala-Usma *et al.*, 2019). These microsections underwent staining with a safranin solution for 2 hours, then dehydration using an ethyl alcohol series (50%, 70%, 96%, and 100%). According to the method described by Schweingruber & Büntgen (2013), Balima *et al.* (2020) and Sanogo *et al.* (2022), the permanent slides were then observed under a light microscope, and The micro-slides were subsequently examined under a digital microscope Zeiss Smartzoom 5 (Carl Zeiss Microscopy GmbH 2014, Jena, Germany) to identify the features that characterize the growth-ring boundaries. In each ring, the following wood-anatomical features were measured including vessel number (VN), mean vessel lumen area (MVA), total vessel area (TVA), total vessel area % (TVAP), mean tangential cell diameter (MVDt), and mean radial cell diameter (MVDr). In addition, vessel density (VD) was calculated as the ratio between the number of vessels and the size of the analysed area.

5.3.3.2. Wood density measurement

The method described by Balima *et al.* (2020) and Arnič *et al.* (2022), was used to determine the wood density of *D. microcarpum*. The wood samples were taken from main stems near ground level and stored in the laboratory air-dried to 72 h at 105 °C until the weight condition was obtained for the density determination. The wood density of each sample was calculated as the dry weight to the fresh volume ratio after drying the samples.

5.3.4. Statistical analysis

Several statistical tests were used to assess the quality of the derived chronology. These include the standard deviation, which indicates the variability of the data, the first-order autocorrelation, which measures the correlation of a variable with its own lagged values, and the mean sensitivity, which reflects the relative change in ring width from one year to the next (**López & Villalba, 2020**). This latter metric is particularly relevant as it often correlates with growth responses to climatic fluctuations. To determine the relationship between the climate and *D. microcarpum* growth, the indexed mean ring width curves of each disc and their chronology were compared with indexed precipitation values. The chronologies were developed using the "chron" function from the dplR package, based on the detrended ring-width index (RWI) series through the spline method. A robust mean was applied to minimise the influence of outliers (**Lebourgeois et al., 2017**). The reliability of the chronology was assessed using the expressed population signal (EPS), which reflects the fraction of common variance relative to a theoretical infinite population for the species (**Jing He & Li, 2010**). EPS was calculated using the number of sampled trees and the effective chronology signal (rbar.eff), a statistical parameter that measures chronology strength by incorporating both within- and between-tree correlations. To determine the most reliable portion of the regional chronology, the recommended threshold for the expressed population signal ($EPS > 0.85$) was applied. Pearson's correlation coefficients were computed to investigate the similarities in *D. microcarpum* growth patterns. Differences in wood anatomical features between trees were analyzed by measuring and comparing specific traits, such as vessel number (VN), mean vessel lumen area (MVA), total vessel area (TVA), total vessel area % (TVAP), mean tangential cell diameter (MVDt), and mean radial cell diameter (MVDr). In addition, vessel density (VD). Statistical tests were conducted to determine significant variations in these anatomical characteristics across the sampled trees. The Pearson's correlation coefficient was applied to assess the impact of the climate on the wood's anatomical traits. Annual and major seasonal precipitation (rainy season from May to October) and each climatic zone's mean annual temperature were considered.

5.4. Allometric models for estimating aboveground biomass and carbon stocks of the semi-arid savanna woody species, *Detarium microcarpum*

5.4.1. Sampling design and data collection

A total of 165 rectangular plots were established in the two climatic zones. To obtain an assessment of the biomass, the plots were selected in the protected areas to choose the individuals. In total, 90 plots were chosen, such as 50 in the Sudano-Sahelian zone and 40 plots in the Sudano-Sahelian area. The size of the plot was 1000 m² (50 m x 20 m) highlighted by **Thiombiano et al. (2016)** in West African savanna studies. For each plot for the harvesting, the diameter at the breast height (dbh), total height (ht), and mean crown diameter (Cd) were measured for the 30 individuals selected in each climatic zone. The mean Crown diameter (Cd) of each tree was calculated by measuring the two perpendicular crown diameters (east-west and north-south). The trees were selected to ensure a representative distribution of diameter classes within the sampling plots. Individuals were selected based on their availability and the absence of human exploitation (traces of pruning or debarking) or disease. A direct destructive sampling method was applied for the individual tree measurements. For biomass sampling, a total of 60 individual trees were grouped with 30 individuals in each climatic zone. These individuals were chosen according to the GPS coordinates that were established previously. The individuals were grouped in the size of class according to the method of Prodata highlighted by **Dimobe et al. (2018)**. The most abundant classes were sampled and were grouped into seven diameter classes as follows: 10–15 (8 individuals); 15–20 (8 individuals), 20–25 (4 individuals), 26–30 (4 individuals), 30–35 (2 individuals), 35–40 (2 individuals), and > 40 cm (one individual). Selected trees were cut at ground level using a chainsaw. Fell trees were separated into stems, branches, and leaves and weighed by organs kind. From each tree species, discs with bark were taken from the lower, middle, and upper parts of the stem for wood density determination along the length of the log, **(Figure 10a-b), (Abich et al., 2021)**. Discs were also taken from each branch diameter class for dry weight determination. Branches were removed from the stem and cut into weighable sections. Leaves were separated from branches and collected into bags for weighing. Fresh weights of stem, branches, and leaves for each tree were separately determined in the field using a 100 kg scale balance. Subsamples of leaves, stems and branches were taken, and their fresh weight was determined using a 5 kg electronic balance (precision 0.5 g). The subsamples of branches and stems were taken as discs of 5 cm thickness depending on the diameter of the trunk or branch. The fresh weight of each

disc was recorded in the field immediately after harvesting the trees. One hundred grams twenty (120 g) of leaf subsample for each tree was collected into bags to facilitate weighing.

The discs and leaf samples were transported to the laboratory where they were oven-dried to a constant weight at 105 °C (samples of branches and stems) or 75 °C (samples of leaves). The dry weight of the samples was recorded immediately after removal from the oven. The sample dry weight was divided by the corresponding fresh weight to obtain the dry-to-green weight ratio for each tree component. The dry biomass to fresh mass ratio was evaluated for each tree component, dividing the dry weight by the corresponding fresh weight. Component dry biomass was calculated by multiplying the dry mass to the fresh mass ratio by the component's corresponding fresh biomass. The TAGB of each tree was estimated by summing the dry biomass of the three components.

5.4.2. Carbon content assessment

The ash method was used to determine the proportion of carbon content of each tree of *D. microcarpum* (Dimobe *et al.*, 2018; Ouédraogo *et al.*, 2020; Ganamé *et al.*, 2021b). The leaves, branches, and stems of each individual were separated to estimate the amount of carbon. Composite samples were formed for each component by grinding stem, branches, and leaves sampled separately, after oven drying (Figure 10c). Five 2 g dry powder samples of each component were incinerated in a crucible in an oven at 550°C for 2 h, until complete calcination. This analysis was conducted in the Laboratory of Plants and Soils at the University Joseph KI-ZERBO, in Burkina Faso. The samples were then slowly cooled in a desiccator and weighed. After the completion of calcination and cooling in a desiccator, carbon contents were assessed following the method adopted by Bayen *et al.* (2016) and Ganamé *et al.* (2021b):

$$\text{Ash (\%)} = (W3 - W1) / (W2 - W1) \times 100$$

$$\text{Carbon \%} = (100 \% - \text{Ash \%}) \times 0.58$$

$$\text{Carbon} = \text{Biomass} \times \text{Carbon \%}$$

Where 0.58 is the carbon content in the organic matter, W1 is the weight of crucibles, W2 is the weight of the oven-dried grind samples + crucibles, and W3 is the weight of the ash with crucibles. The average Carbon content was calculated for each tree component based on the number of replicates and applied to each tree. The average C content of the three components (leaf, branch, and stem) was considered as the carbon content at the tree level. We computed the mean carbon content for each climatic zone based on the average carbon content stored in individual trees of the species.



a. *D. microcarpum* felled tree showing the length of the trunks



b. *D. microcarpum* trunks cut into sections



c. Weighing of *D. microcarpum*



d. Oven drying of samples.

Figure 10: Carbon sample data collection of *D. microcarpum*

5.4.3. Data analysis

The diameter at the breast height, stem height, crown diameter, total height, stem biomass, branch biomass, leaf biomass, branch density, and trunk density were compared among the two climatic zones using the independent Student t-test analysis. The comparison tests were preceded by the Shapiro-Wilk normality test to check the normality of the data. Data that were not normally distributed were normalised using log transformations. Before fitting the model, the Pearson correlation was made with the parameters to choose the parameters. In addition, the independent Student t-test analysis. was applied to assess if tree components biomasses are different between the two climatic zones, using multiple comparison tests. Allometric model were performed for each climatic zone to predict tree biomass components (leaf, branch, and stem) and the total aboveground biomass (TAGB). The unilateral t-test was performed to compare the average carbon content of *D. microcarpum* to the reference value suggested by the IPCC.

Before fitting the allometric models, data were checked for normality and a scatter plot was prepared to explore the relationships between above-ground biomass and independent variables dbh and H in each component. The scatter plot was graphically explored using several model types in each climatic zone. The power function was found to be an accurate equation and was then selected and presented in its linear form as: in each climate zone. The model was computed for each component and TAGB based on the non-linear equations with dbh, height (Ht), and ρ as independent variables. Certain of them were used as the lone predictors variable and some were combined in the equation.

The power function $y = \alpha x^\beta \varepsilon$ emerged as the best model that fit the observed data. Before developing the predictive model, the above equation is transformed into the following linear form using the natural logarithm (ln): $\ln(Y) = \ln(\alpha) + \beta \ln X + \varepsilon$.

The following allometric relationships were tested for aboveground biomass using dbh, basal diameter, height, crown diameter, and stem height) and the density.

where Y is the biomass, X the predictors, ε the random error, and β and β_1 the regression coefficients. This model was linearized for each component, as follows:

$$\ln(Y) = \ln(\alpha) + \beta \ln(\text{dbh}) + \varepsilon \quad (1)$$

$$\ln(Y) = \ln(\alpha) + \beta \ln(\text{dbh} * \text{ht}) + \varepsilon \quad (2)$$

$$\ln(Y) = \ln(\alpha) + \beta \ln(\text{dbh}^2 * \text{ht}) + \varepsilon \quad (3)$$

To compare the result of this model, the model defined by **Chave *et al.* (2014)** was developed as follows: $\ln(A) = \ln(\alpha) + b \ln(\text{dbh}) + c \ln(H) + d \ln(\rho)$

where Y is the biomass of the tree's compartment, α ; b, c, and d are the regression coefficients. The biomass of the species was established through the additive model between the three component (**Dimobe et al., 2018**). The best model of each climatic zone was established using the best model of each component selected.

$TAGB = \alpha_s X_s(\beta_1) + \alpha_b X_b(\beta_b) + \alpha_l X_l(\beta_l)$ with $\alpha_s X_s(\beta_1)$ is the stem biomass, $\alpha_b X_b(\beta_b)$ is the branch biomass, and $\alpha_l X_l(\beta_l)$ is the leaf biomass. In addition, the total biomass was dolloped with each parameter to make the comparison between the additive model and the model proposed by **Chave et al. (2014)**. The total carbon stock of a tree has been evaluated by the sum of all the carbon contents of the leaves, branches, and stems of the tree. The percentage of carbon in fresh biomass and each component of the tree, as well as in the whole tree were calculated based on carbon content percentage in the dry biomass of leaves, branches, and stems.

5.4.3.1. Evaluation of the quality of allometric selected models

To correct the bias introduced due to the back-transformation of the log-transformed response variable, the correction factors (CF) of these equations will be calculated. It is calculated from the following formula: $CF = e^{(RSE^2 / 2)}$ where RSE is the residual standard error of the regression. The best biomass equations were selected based on various goodness-of-fit statistics, namely the adjusted R-square ($Adj.R^2$), the Akaike information criterion (AIC) as well as the residual standard error (RSE) and root mean square error (RMSE). The root means square error (RMSE) and the Akaike information criteria (AIC) were used to evaluate the performance of each model. The high value of R^2 and the lowest values of RMSE and AIC (**Sileshi, 2014; Dong, Zhang and Li, 2018; Ganamé et al., 2021**) were selected as the most appropriate models.

$AIC = -2\ln(L) + 2p$ where L is the probability of the fitted model and p is the total number of parameters in the model.

$$RMSE = \frac{1}{n} \sqrt{\sum_{i=1}^n (y_i - \hat{y}_i)^2}$$

The best-fitting model in each component was compared to the pantropical allometric biomass model developed by **Chave et al. (2014)**. The AIC and RMSE values were used for comparison. However, a model efficiency close to 1 indicates a perfect fit and a value close to 0 indicates a prediction no better than the average of the observations. Negative values indicate a poor model. The best models were selected according to the high value of the $Adj. R^2$ and the low value of the AIC, RMSE, and RSE (**Dimobe et al., 2019b; Abich et al., 2021**)

The model developed by **Chave *et al.* (2014)** is widely used for AGB estimates for some species in Burkina Faso (**Balima *et al.*, 2019; Dimobe *et al.*, 2019; Ganamé *et al.*, 2021**). Graphical analyses were performed on both predicted and observed biomass values. A paired t-test was used to compare the predicted tree biomass with the observed tree biomass. The predicted and observed values of Above-ground Biomass (AGB) were plotted for each model to assess the model goodness fit. Pearson residual scatterplots were generated to analyse the model's performance. All statistical analyses were performed using the statistical software R 4.3.2 (**R Development Core Team 2022**).

5.5. Predicting the effect of climate change on the distribution of *Detarium microcarpum* (Fabaceae) in Burkina Faso

5.5.1. Data collection

5.5.1.1. Species occurrence records

Two hundred sixty-five (265) occurrences were recorded during the fieldwork using a GPS (Global Positioning System, Garmin 65) with a distance of at least 1 km between two trees. The additional occurrence points (354 points) were downloaded from the Global Biodiversity Information Facility repository (**GBIF**, <http://www.gbif.org/>; accessed on August 01, 2023) and the published relevant literature (203 points) through the article of **Schmidt *et al.* (2017)** after digitalizing the *D. microcarpum* distribution map. After controlling the quality of the data (removing incorrect and duplicate records), a total of 722 occurrence points of *D. microcarpum* were gathered from three sources that cover the country (**Figure 11**). Before using these data, they were merged in one database and outliers were removed.

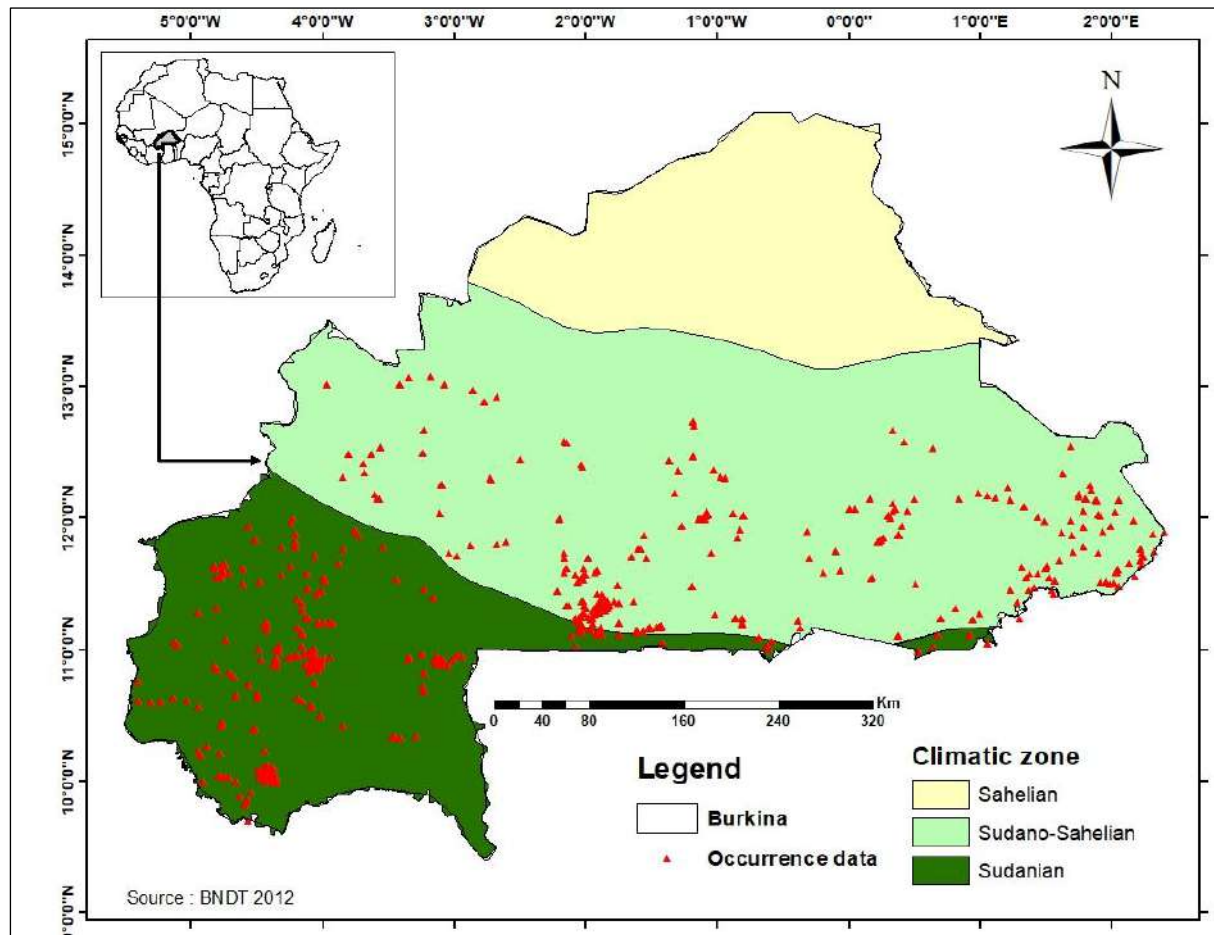


Figure 11: Occurrences points of *D. microcarpum* in Burkina Faso

5.5.1.2. Environmental data

Three sources of environmental data were used in this study. The variables were related to bioclimatic variables which influence the distribution of the species (**Heubes *et al.*, 2011**), elevation because it is mainly found on superficial, stony, and lateritic soils, and often on hills (**Kouyaté, 2005**) and soil variables which are important factors for the geographic distribution of tropical trees species (**Agbo *et al.*, 2018**). Soil variables (cation exchange capacity (Cec, mol/kg)) were obtained with 1-km² resolution from the Harmonized World Soil Database, version 1.2 (FAO/IIASA/ISRIC/ISSCAS/JRC 2012) at different horizons: 0–5 cm (Cec01), 5–15 cm (Cec02), 15–30 cm (Cec03), 30–60 cm (Cec04), 60–100 cm (Cec05). Nineteen (19) bioclimatic variables and the elevation were downloaded from the WorldClim platform (www.worldclim.org) version 2.1 with a spatial resolution of 30 seconds (approximately 1 × 1 km²). The current bioclimatic data obtained from the WorldClim website are derived from interpolated monthly averages of maximum and minimum temperature and rainfall, considering the historical series 1970–2000 (**Hijmans *et al.*, 2005**). To forecast the future distribution of the species, two Shared Socioeconomic Pathways (SSPs) from the updated CMIP6 scenarios were selected for analysis, the SSP2-4.5 and SSP5-8.5 for two times periods (2061–2080 averaged 2070, and 2081 – 2100 averaged 2090). Maximum temperature is expected to increase by 0.84–1.54 °C, and 0.98–1.73 °C, while minimum temperature would likely increase by 1.49–2.22 °C, and 1.75–4.83 °C under SSP2-4.5, and SSP5-8.5 scenarios, respectively (**Siabi *et al.*, 2023**). In addition, SSP2-4.5 represents a future world where there is an intermediate trajectory in which trends continue without substantial deviations whereas SSP5-8.5 represents a future world where there is high population growth, rapid economic expansion, and a heavy reliance on fossil fuels (**IPCC, 2021**). For future climate projections, four global climate models (GCMs) as ACCESS-CM2 (Australian Community Climate and Earth System Simulator Climate Model Version 2); HadGEM3-GC3.1-LL (Third Hadley Centre Global Environment Model in the Global Coupled Configuration 3.1), CNRM-CM6-1 (Centre National de Recherches Météorologiques model version 6); MIROC6 (Model for Interdisciplinary Research on Climate version 6) from the Coupled Model Inter-comparison Project phase 6 (CMIP6) were selected. These models are commonly used in climate research to assess the potential impacts of greenhouse gas emissions and inform climate change mitigation and adaptation strategies (**Peng *et al.*, 2023**). These models were selected because they were adapted for West African countries (**Diawara & Lobanov, 2019**) and were most

used for West African species distribution modeling in recent studies by several authors (Coulibaly *et al.*, 2023, Daï *et al.*, 2023).

5.5.2. Data analysis

5.5.2.1. Data processing

To reduce sampling bias, the occurrence records were spatially filtered using the function ‘spatially rarefy occurrence data in SDMtoolbox (Brown, 2017). This process enables to removal of all duplicate records within each grid. The processing of species data consisted mainly of cleaning the database (correction of species names, outliers, etc.) and converting it into the single CSV file format that is required by MaxEnt. The 19 bioclimatic variables were extracted at the Burkina Faso scale in GeoTIFF format and converted into ASCII format before their use. All environmental variables were converted to ASCII raster grids ArcGIS 10.8.1. To determine which variables affected the distribution of the *D. microcarpum* species, all the environmental variables (soil variables, elevation and climate variables) were rather performed to remove highly correlated variables to avoid autocorrelation ($r < 0.75$) modelling. From the bioclimatic variables and elevation data, different sets of predictors were tested by accounting for different thresholds of the autocorrelation coefficient. Based on the value of the variance inflation factor (VIF), a correlation that quantifies how strongly a variable predictor was identified through the highly correlated variable with the package “sdm” (Naimi, 2015). The three least correlated predictors were selected at the pairwise correlation coefficient of 0.75. These variables were bio3 (Isothermality), bio8 (Mean Temperature of Wettest Quarter), and bio14 (Precipitation of Driest Month). At the end of this method, a total of 722 presence records (CSV format) and the layers of the three bioclimatic variables (ASCII format) were used as input data to run the model.

5.5.2.2. Model fitting and evaluation

The process of the modelling was based on the principle of maximum entropy (MaxEnt, version 3.3.3k) proposed by Phillips *et al.*, 2006), considering only the occurrence data to predict the species' potential distribution from presence-only data and the different environmental variables. However, MaxEnt tools are one of the most powerful and widely used software programs for species distribution modelling (Elith *et al.*, 2006; Pearson *et al.*, 2007). In the region of West Africa, the MaxEnt algorithm was used by several authors (Achille *et al.*, 2016; Dimobe *et al.*, 2018; Balima *et al.*, 2022) to assess the impact of climate change on the

distribution of different plant species. To assess the importance of each variable in the model, the Jackknife test was used (**Phillips et al., 2006, Heubes et al., 2011; Guide & Brown, 2017**). The area under the Receiver Operating Curve (AUC) and true skill statistics (TSS) were used to estimate the goodness of fit of the model performance (**Pramanik et al., 2018**). In fact, in the MaxEnt model, AUC estimation is slightly different from other common methods (**Phillips et al., 2006**). The AUC values range from 0 to 1, representing the model's ability to differentiate between classes effectively. The quality of the model could be assessed at the five levels according to AUC values (**Rong et al., 2019**): excellent (> 0.9), good ($0.8-0.9$), accepted ($0.7-0.8$), bad ($0.6-0.7$), and invalid (<0.6) highlighted by **Elith et al. (2006)**. A total of three environmental variables were selected for model prediction. According to some criticism about the limitations of the AUC index by ecologists in assessing SDM performance (**Jiménez-Valverde et al., 2013**), the True Skill Statistics (TSS) for better evaluation of the model (**Allouche et al., 2006**) were calculated as well. TSS serves as a metric evaluating a model's capacity to accurately identify genuine absences (specificity) amidst true positives (sensitivity). TSS was used because it is a simple but robust and intuitive measure of the performance of species distribution models (**Lompo et al., 2021**).

The following formula was used to calculate this index: $TSS = \frac{ad-bc}{(a+b)(b+d)} = \text{Sensitivity} + \text{Specificity} - 1$

The value of the TSS varies from 0 to 1. If the value of the TSS < 0 indicates a random prediction, a value close to 1 ($TSS > 0.5$) suggests good predictive power (**Allouche et al., 2006; Thuiller et al., 2009**). However, if the TSS = 0, it suggests no skill at all. The model prediction is no better than random guessing. The TSS values were averaged for the 10 run replicates using the background predictions and the sample predictions of the MaxEnt outputs. In addition, the model performance was assessed by dividing the occurrence data at 75% for calibration and 25% for testing. To reduce overprediction and focus on the most suitable areas, the 10th Percentile Training Presence is used like the Threshold method (**Radosavljevic & Anderson, 2014**).

5.5.2.3. Assessing the area suitability of the species

To propose relevant conservation and some measures on the species, three categories of area classes were considered from the modelling output such as the unsuitability; low suitability and high suitability, through the polygonising of the raster files. A jackknife test was performed on the selected bioclimatic variables to determine the ones that best contribute to the model

prediction (**Berlioz *et al.*, 2021**). The probabilistic outputs were transformed into presence/absence classifications, utilizing the mean of predicted probabilities as the threshold to delineate the species' range (**Lawson *et al.*, 2014; Dimobe *et al.*, 2022**). The probability occurrence below the Maximum training sensitivity plus specificity is considered unsuitable for the conservation of the species. This threshold is chosen to maximize the alignment between observed and predicted distributions. For the habitat suitability class maps, the final logistic output was categorized into the following classes: (i) Unsuitability, (ii) lowly suitable, and (iii) highly suitable using the spatial analysis toolset in ArcGIS® software. The overlapped current and future habitat suitability maps within the country polygons were first assessed. In addition, the suitable area (km²) colonized by the species using the spatial analysis tools in ArcGIS was computed. The percentages of potential habitat suitability were calculated. In addition, the averaged outputs from the Maximum Entropy (MaxEnt) model, generated for each climate model under various scenarios across different time horizons, were first converted from ASCII format to raster format. These raster datasets were then classified into 'suitable habitats' and 'unsuitable habitats' based on the presence of data. To determine the current and projected boundaries of suitable and unsuitable habitats, the raster data were converted into polygons. This process facilitated the creation of comprehensive maps delineating the species' suitable areas under both present and anticipated climatic conditions, across two distinct scenarios and time horizons. All the processes of the modelling are shown in **Figure 12**.

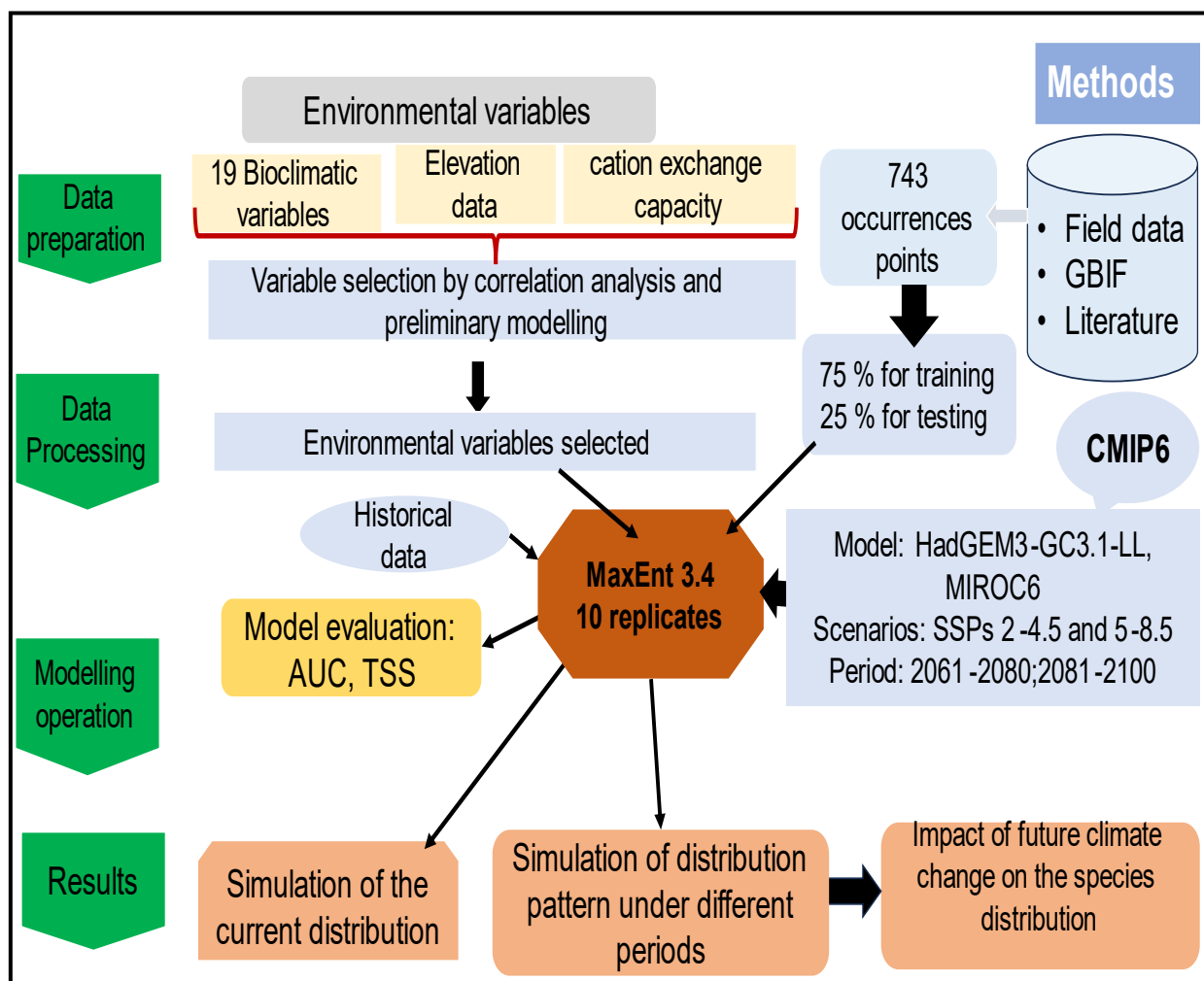


Figure 12: data calibration process for the modelling

PART III: RESULTS AND DISCUSSION

CHAPTER 6: RESULTS

6.1. Local perceptions of anthropogenic and climate factors affecting the use and the conservation of *Detarium microcarpum* in Burkina Faso (West Africa)

6.1.1. The profile of the surveyed populations

The survey engaged 465 individuals across the study sites, of which 63.22% were men (**Table 3**). The age group 30-44 years, which corresponds to the young, was the most represented among respondents (56.56 %). Mossi was the dominant ethnic group, comprising 38.49% of the total respondents and being the only group found at all sites. In terms of education, a significant proportion of the local population had no formal education (62.94%), followed by those with primary school education (27.31%). Occupationally, most of the respondents were farmers (43.44 %) and household members (31.61%;). According to the ethnic groups, the Mossi group were the most surveyed with 38.48% followed by the Dagara group (21.29%). The low representative ethnic groups such as Fulhani, Guin, Samo, Gourmantche, and Kacena have been grouped in Other ethnic groups with 13.66%, (**Table 3**).

6.1.2. Use patterns of *Detarium microcarpum* according to sociodemographic characteristics

6.1.2.1. Consensus of the plant parts used by the population

The survey identified six plant parts of *Detarium microcarpum* – fruits, bark, leaves, roots, branches, and trunks - utilised by the local population for various purposes (**Table 4**).

The CPP varied significantly according to the ethnic groups for bark use ($\chi^2 = 22.25$; $P = 0.0001$), trunks ($\chi^2 = 11.86$; $P = 0.0184$), leaves ($\chi^2 = 11.16$; $P = 0.0248$), and branches ($\chi^2 = 9.89$; $P = 0.0422$). However, this variation was not significant for fruits ($\chi^2 = 7.38$; $P = 0.1177$) or roots ($\chi^2 = 3.84$; $P = 0.4278$). Specifically, the Bobo group predominantly used leaves (CCP= 0.1384), while the Dagara group showed a higher usage of trunks (CPP=0.41), followed closely by the Gourounsi (CPP=0.33) and the Mossi (CPP=0.30). Both Dagara (CPP= 0.10) and Gourounsi (CPP= 0.10) communities also exhibited notable use of roots.

The CPP among the surveyed populations did not significantly vary with education level ($P > 0.05$) for most plant parts, including fruits ($\chi^2 = 3.20$; $P = 0.2018$), leaves ($\chi^2 = 4.53$; $P = 0.1039$) roots ($\chi^2 = 3.91$; $P = 0.1417$), branches ($\chi^2 = 2.47$; $P = 0.2906$), and trunks ($\chi^2 = 2.06$; $P = 0.3579$). However, a significant difference was observed for bark usage ($\chi^2 = 6.01$; $P = 0.0497$).

Table 3: The profile of the surveyed population

Sociodemographic parameters	Sites					Percentage (%)
	Bontioli	Kou	Nakambe	Nazinga	Total	
Ethnic group						
Bobo	0	63	0	0	63	13.55
Dagara	99	0	0	0	99	21.29
Gourounsi	0	0	0	60	60	12.90
Mossi	21	0	126	32	179	38.49
Others	0	2	59	3	64	13.76
Total	120	65	185	95	465	100
Sex						
Women	39	28	72	32	171	36.77
Men	81	37	113	63	294	63.23
Total	120	65	185	95	465	100
Age						
Young (30 > age ≤ 44 years)	73	18	101	71	263	56.56
Adult (45 > age ≤ 59 years)	33	39	74	15	161	34.62
Old (age >60 years)	14	8	10	9	41	8.82
Total	120	65	185	95	465	100
Education level						
High Primary	10	2	10	27	49	10.54
Illiterates	88	46	107	48	289	62.15
Primary level	22	17	68	20	127	27.31
Total	120	65	185	95	465	100
Occupation						
Farmers	35	27	95	45	202	43.44
Household	30	25	60	32	147	31.61
Official workers	5	3	3	7	18	3.87
Traditional mining exploitation	33	0	0	0	33	7.10
Traders	10	9	15	9	43	9.25
Traditional healer	7	1	2	2	12	2.58
Wood exploitation			10		10	2.15
Total	120	65	185	95	465	100

Despite this, branches (CPP= 0.14) and trunks (CPP=0.30) were primarily used by individuals with no formal education. No significant differences were found in the CPP between genders ($P > 0.05$).

On the other hand, occupation significantly influenced the CPP ($P < 0.05$). Trunks (CPP= 0.54) and fruits (CPP = 0.42) were commonly used by people from all sectors. However, specific sectors showed unique preferences; for instance, public workers reported no use of roots, leaves, or branches (CPP=0). Conversely, traditional healers (tradipraticiens) mostly used roots (CPP= 0.27), leaves (CPP= 0.23), and trunks (CPP= 0.20). Interestingly, bark was most used by those in the traditional mining exploitation sector (CPP = 0.41; **Table 4**).

6.1.2.2. Impact of sociodemographic parameters on use categories

The use of *Detarium microcarpum* parts spans various categories, including food, medicine, craft, energy, construction, and sales (**Table 5**).

The analysis of local population knowledge concerning the food use of *Detarium microcarpum* indicates a wide awareness across different sociodemographic groups, with no significant variation ($P \geq 0.05$) among ethnic groups, age groups, education levels, and gender. The activity sector presents a notable exception, where significant differences were observed ($\chi^2 = 81.16$ ($P \leq 0.05$)).

Gourounsi (RFC = 20.46%) and Bobo (RFC = 18.55%) ethnic groups emerged as the most knowledgeable in the use of the species for food. Similarly, younger (RFC = 18.91%) and adult age groups (RFC = 16.22%) knew more about food uses. Gender-wise, men (RFC = 19.05%) reported slightly more knowledge about food uses than women (RFC = 15.60%). Non-educated level respondents (RFC = 19.52%) reported higher use of *Detarium microcarpum* for food than other education levels. Farmers (RFC = 38.48%) and household members (RFC = 27.89%) reported more knowledge of food uses than those from other activity sectors. In the medicinal use category, the analysis revealed that while knowledge does not significantly differ among ethnic groups and ages ($P \geq 0.05$), it does vary with education level ($\chi^2 = 22.02$; $P = 0.0006$), gender ($\chi^2 = 12.54$; $P = P \leq 0.05$), and activity sector ($\chi^2 = 38.58$, $P = 0.0001$). The Dagara (RFC= 39.74) ethnic group exhibited the highest frequency of citation of medicinal uses, followed by the Mossi (RFC = 27.49%) and Bobo groups (RFC = 27.33%). Older individuals (RFC = 33.79%), followed by adults (RFC = 28.18%), knew more about the medicinal uses of *Detarium microcarpum*.

Table 4: Consensus of the plant parts used by the population.

Population profile	Bark	Fruits	Leaves	Roots	Branches	Trunks
Ethnic groups						
Bobo	0.02	0.41	0.14	0.09	0.19	0.15
Dagara	0.01	0.29	0.09	0.10	0.08	0.42
Gourounsi	0.14	0.35	0.05	0.10	0.03	0.33
Mossi	0.07	0.36	0.05	0.09	0.14	0.29
Others	0.01	0.52	0.11	0.06	0.14	0.18
Mean	0.05	0.38	0.09	0.09	0.12	0.28
χ^2	22.25	7.37	11.16	3.84	9.89	11.86
P-value	0.0001	0.1177	0.0248	0.4278	0.0422	0.0184
Education level						
High Primary	0.03	0.49	0.04	0.06	0.11	0.25
Primary	0.03	0.38	0.08	0.09	0.13	0.30
Non-educated	0.07	0.33	0.08	0.09	0.13	0.28
Mean	0.05	0.40	0.07	0.08	0.12	0.28
χ^2	6.01	3.20	4.53	3.91	2.47	2.05
P-value	0.0497	0.2018	0.1039	0.1417	0.2906	0.3579
Sex						
Women	0.03	0.39	0.08	0.08	0.15	0.27
Men	0.06	0.35	0.07	0.09	0.11	0.30
Mean	0.05	0.37	0.08	0.09	0.13	0.28
χ^2	1.67	0.54	0.01	1.20	0.66	0.12
P-value	0.1959	0.4621	0.9224	0.2729	0.4172	0.7276
Age						
Young	0.04	0.38	0.07	0.10	0.12	0.32
Adults	0.06	0.38	0.07	0.09	0.14	0.27
Old	0.11	0.33	0.13	0.12	0.12	0.19
Mean	0.07	0.34	0.09	0.10	0.13	0.26
χ^2	1.22	1.22	0.78	0.59	0.78	6.94
P-value	0.5433	0.5433	0.6786	0.7454	0.5444	0.0312
Occupation						
Farmers	0.09	0.77	0.15	0.17	0.33	0.49
Traders	0.04	0.73	0.13	0.22	0.26	0.62
Public workers	0.05	0.61	0.01	0.00	0.00	0.35
Household	0.04	0.47	0.04	0.02	0.06	0.38
Traditional mining exploitation	0.41	0.12	0.02	0.00	0.04	0.54
Wood exploitation	0.10	0.24	0.23	0.13	0.09	0.21
Traditional healer	0.07	0.12	0.23	0.27	0.109	0.21
Mean	0.11	0.42	0.11	0.12	0.13	0.54
χ^2	25.34	76.138	17.16	27.41	33.23	21.35
P-value	0.00473	0.0000	0.071	0.0022	0.0002	0.0188

Regarding education level, the non-educated (RFC = 40.38%) and primary-level educated (RFC = 28.71%) individuals cited the species for medicinal use. Gender differences were evident, with men (RFC = 34.19%) reporting a higher familiarity with the species' medicinal applications than women (RFC = 20.72%). Occupationally, farmers (RFC = 78.52%) and traditional healers (56.06%) were the most knowledgeable about the species in the medicine category.

In the craft category, knowledge varied significantly according to ethnic group ($\chi^2 = 20.44$; $P = 0.0004$), gender ($\chi^2 = 4.00$; $P = 0.0454$), and occupation ($\chi^2 = 19.37$; $P = 0.0222$), but not across age groups and education levels ($P \geq 0.05$). Farmers (RFC=45.06%) had the highest RFC, highlighting their prominent use of the species in the craft category.

In the energy use category, knowledge of the use of *Detarium microcarpum* did not differ significantly by ethnic group, age, or gender ($P \geq 0.05$). However, education level ($\chi^2 = 18.08$; $P = 0.0006$) and occupation ($\chi^2 = 44.79$, $P = 0.0001$) had significant effects. The Mossi (RFC = 25.94%) and Bobo (RFC = 22.56%) ethnic groups made the most use of the species in the energy category. Older individuals (RFC = 20.51%) cited uses for energy more frequently than other age groups. Non-educated individuals (RFC = 41.17%) reported using the species for energy more than those with higher levels of education. Women (RFC = 28.63%) reported using these species for energy purposes more than men (RFC = 20.09%). Farmers (RFC = 69.27%) and those involved in traditional mining exploitation (RFC = 45.56%) indicated more knowledge about the use of *Detarium microcarpum* in the energy category.

The use of the *Detarium microcarpum* in the sales category differed significantly based on gender ($\chi^2 = 105.87$, $P = < 2.2e^{-16}$) and the occupation ($\chi^2 = 25.21$; $P = 0.0027$). Despite variations in educational background, age, and ethnicity, participants shared similar knowledge ($P \geq 0.05$). The Mossi ethnic group (RFC = 27.45%), followed by the other ethnic groups (RFC = 22.40%), sold more parts of the *Detarium microcarpum*. Younger individuals (RFC = 25.37%), adults (RFC = 22.52%), women (RFC= 37.49), farmers (RFC = 32.80%), and traders (RFC = 32.44%) were more knowledgeable about the commercial importance of the species.

In the construction use category, knowledge varied significantly between ethnic groups ($\chi^2 = 20.44$; $P = 0.0004$), genders ($\chi^2 = 15.06$; $P = 0.0001$), and occupation ($\chi^2 = 23.44$; $P = 0.0053$). However, educational level and age did not significantly affect knowledge in this area ($P \geq 0.05$). The Dagara ethnic group (RFC= 13.43%) and farmers (RFC= 40.88%) demonstrated the most knowledge about using the species for construction (**Table 5**).

Table 5: Relative frequency of citation (%) of use categories of *Detarium microcarpum* according to the profile of the population surveyed

Poulation profile	Uses-categories					
	Food(%)	Medicine(%)	Craft(%)	Energy(%)	Seller(%)	Construction(%)
Ethnics groups						
Bobo	18.55	27.34	12.97	22.56	17.35	1.25
Dagara	13.94	39.74	1.59	14.48	19.00	13.43
Gourounsi	20.46	25.07	13.08	18.23	19.26	3.92
Mossi	17.14	27.49	7.34	25.94	27.45	9.59
Others	18.97	25.03	8.27	21.25	22.40	2.08
Mean	17.81	28.94	8.66	20.49	21.09	6.05
χ^2	3.88	9.25	20.44	3.43	1.10	22.52
<i>P-value</i>	0.4232	0.0552	0.0004	0.4882	0.8942	0.0002
Age						
Adults	16.22	28.18	6.20	19.91	22.52	6.96
Old	15.52	33.80	9.20	20.51	10.98	9.99
Youngs	18.91	26.84	9.14	17.88	25.37	6.54
Mean	16.88	29.61	8.18	19.43	19.63	7.83
χ^2	1.95	0.44	0.52	1.31	6.93	6.93
<i>P-value</i>	0.5827	0.9320	0.9136	0.7270	0.0743	0.6392
Education level						
High_Primary	17.43	26.68	10.14	17.09	21.40	9.19
Primary	17.61	28.72	8.26	21.22	21.53	8.68
Non-educated	19.52	40.37	7.26	41.17	19.25	5.44
Mean	18.18	31.92	8.55	26.49	20.73	7.77
χ^2	0.03	22.03	0.03	18.08	0.24	0.74
<i>P-value</i>	0.9860	0.0006	0.9835	0.0006	0.8863	0.6916
Sex						
Women	15.60	20.72	5.49	28.63	37.49	3.06
Men	19.05	34.20	10.16	20.07	6.77	10.36
Mean	17.33	27.46	7.82	24.34	22.13	6.71
χ^2	1.12	12.54	4.00	0.42	105.87	15.06
<i>P-value</i>	0.2896	0.0004	0.0455	0.5181	< 2.2e-16	0.0001
Occupation						
Farmers	38.48	78.52	45.06	69.26	32.80	40.88
Public workers	21.71	29.80	3.21	19.29	17.06	8.93
Household	27.89	21.88	4.31	21.03	29.45	4.44
Traditional mining exploitation	16.36	23.06	6.25	45.56	2.50	22.64
Trader	17.98	41.58	6.81	20.93	32.44	2.89
Traditional healer	7.25	56.06	7.97	9.68	17.60	1.45
Wood exploitation	15.14	31.09	14.46	11.43	23.79	4.09
Mean	20.69	40.28	12.58	28.17	22.23	12.19
χ^2	81.16	38.58	19.36	44.79	25.21	23.43
<i>P-value</i>	0.0010	0.0001	0.0223	0.0001	0.0027	0.0053

6.1.3. Local Knowledge on the areas of abundance, threat factors, and their effects on *Detarium microcarpum* conservation

The survey revealed five habitats identified by different ethnic groups as areas where *Detarium microcarpum* are found (**Figure 13**). Except for the Dagaras ethnic group, which predominantly located the species on granite rocky hills (31.97 %) and the agrosystem (27.50 %), other groups reported higher abundance in protected areas and fallows. The Bobo ethnic group observed the species most abundantly in the protected areas (50.81%) and fallows (33.61%). Similarly, the Gourounsi group found the species mainly in the protected areas (40.09%) and fallows (37.14%), while the Mossi group reported a significant presence in protected areas (40.09%). Across all groups, villages were cited less frequently as habitats for these species (**Figure 13**).

Local populations are aware that *Detarium* is under threat and have identified six factors that are impacting the survival of *D. microcarpum* within its natural habitats. The correspondence analysis, which explains a significant 82.68 % of the data distribution across two main axes, reveals how different sociodemographic groups perceive these threats (**Figure 14**). The first axis, accounting for 59.9% of the data distribution, correlates with the Mossi ethnic group, men, adults, youths, illiterate individuals, and those with primary education levels. These groups perceived wood overexploitation and bushfires as the primary threats to *Detarium microcarpum*. The Bobo and Gourounsi ethnic groups mentioned village expansions as a significant threat, while members of the category 'Other' ethnic groups highlighted extensive farming as a primary concern. On the second axis, which explains 22.80% of the variation, there is a distinction between the Mossi ethnic group and their associated sociodemographic parameters against the backdrop of other ethnic groups. Here, the Dagara ethnic group, along with individuals who have high primary education levels and are older, associated traditional mining exploitation and population growth as significant threats (**Figure 14**).

Nine (9) consequences associated with the threats to *Detarium microcarpum* were identified by the local populations (**Figure 15**), with their perceptions analysed through correspondence analysis, explaining 65.7 % of the data distribution across two main axes. The first axis, which accounts for 50.50% of the data distribution, groups the Mossi, Dagara and 'Others' category ethnic groups alongside individuals who are illiterate or only have primary education, as well as adults. These groups share the same opinion that the effects of threats include regrowth and degradation of the species, a decrease in rainfall, a reduction in medicinal species, loss of wild animals, and a decline in bee populations. On the second axis, explaining 15.2% of the

variation, the Bobo and Gourounsi ethnic groups noted a decrease in tourist visits as a consequence of threats to the *Detarium microcarpum* (**Figure 15**).

6.1.4. Local perceptions on conservation solutions and management strategies for *Detarium microcarpum* in Burkina Faso

Local populations proposed ten solutions aimed at mitigating a shift of *Detarium microcarpum*, with significant variation in preferences among different ethnic groups ($\chi^2 = 696.76$, $P < 0.0001$; **Figure 16a**). The Mossi ethnic group suggested the importance of demarcation (delimitation of the forest) (44%) and co-management, which represents the inclusion of the local population in the species management, which represents 36% as critical measures for preventing species shift. The Gourounsi highlighted the need for awareness (21.43 %) and monitoring of the species (23.19%). The Bobo expressed a preference for co-management (27.69 %) and the Introduction of financial penalties (introduction of fines; 22.45%), shown in **Figure 16a**.

For the sustainable management of *Detarium microcarpum*, six conservation strategies were mentioned (**Figure 16b**), with preferences varying significantly among ethnic groups ($\chi^2 = 696.76$, $P < 0.0001$). The strategies of co-management represent 53.29 %, financial support (48.79 %), and valorisation of the fruit value chain (47.38 %) were the most requested. The Mossi suggested co-management (43.41 %), financial support (37.23), and reforestation (23.37%), while the Gourounsi preferred reforestation (43,28%), co-management (41.32 %), and fruit value chain valorisation (35.67%). The Dagara ethnic group mentioned local community management (36.21%), co-management (31.62 %), and financial support. Members of the ‘Others’ ethnic group category requested valorisation of the fruit value chain and training, (**Figure 16b**).

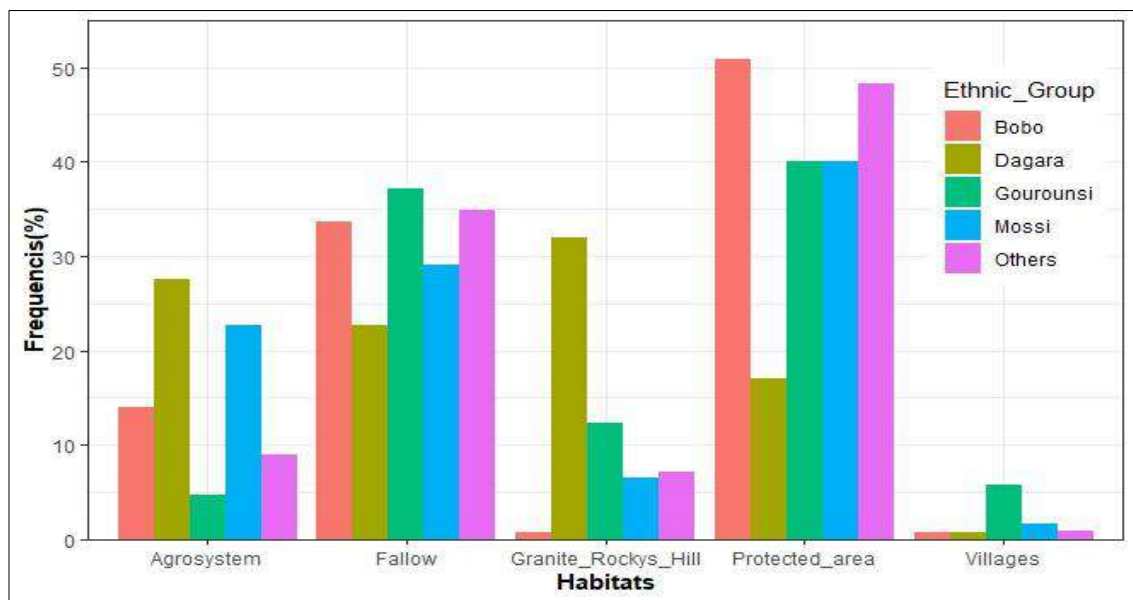


Figure 13: Local population perceptions on the areas of species abundance

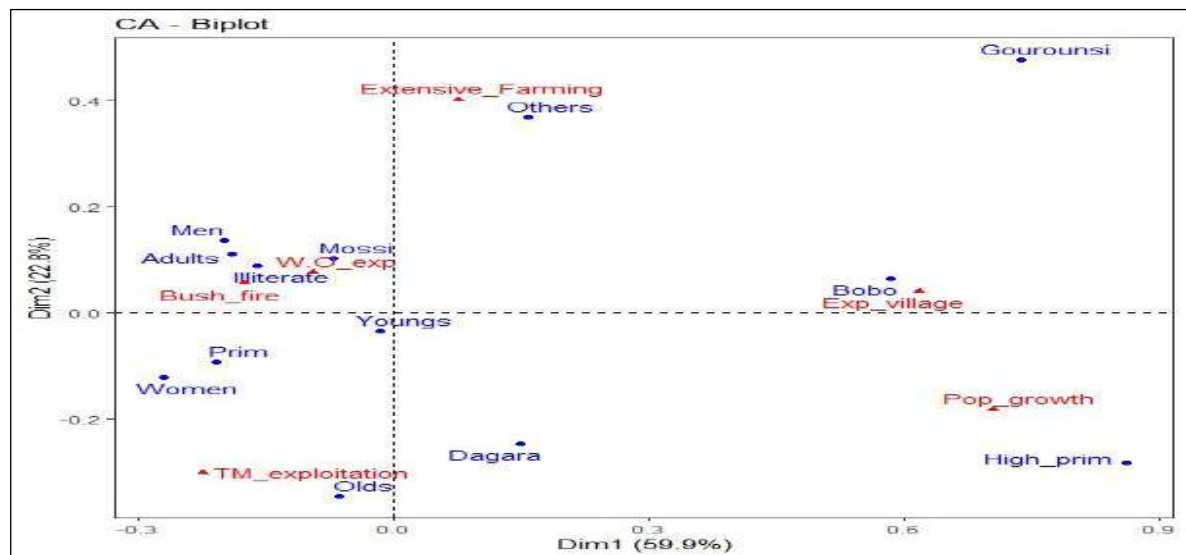


Figure 14: Correspondence analysis of local population perceptions on threats affecting *Detarium microcarpum* in Burkina Faso.

Legend = TM_exploitation: traditional mining exploitation; W.O_exp = wood overexploitation, Exp_village = village expansion; Pop_growth = population growth

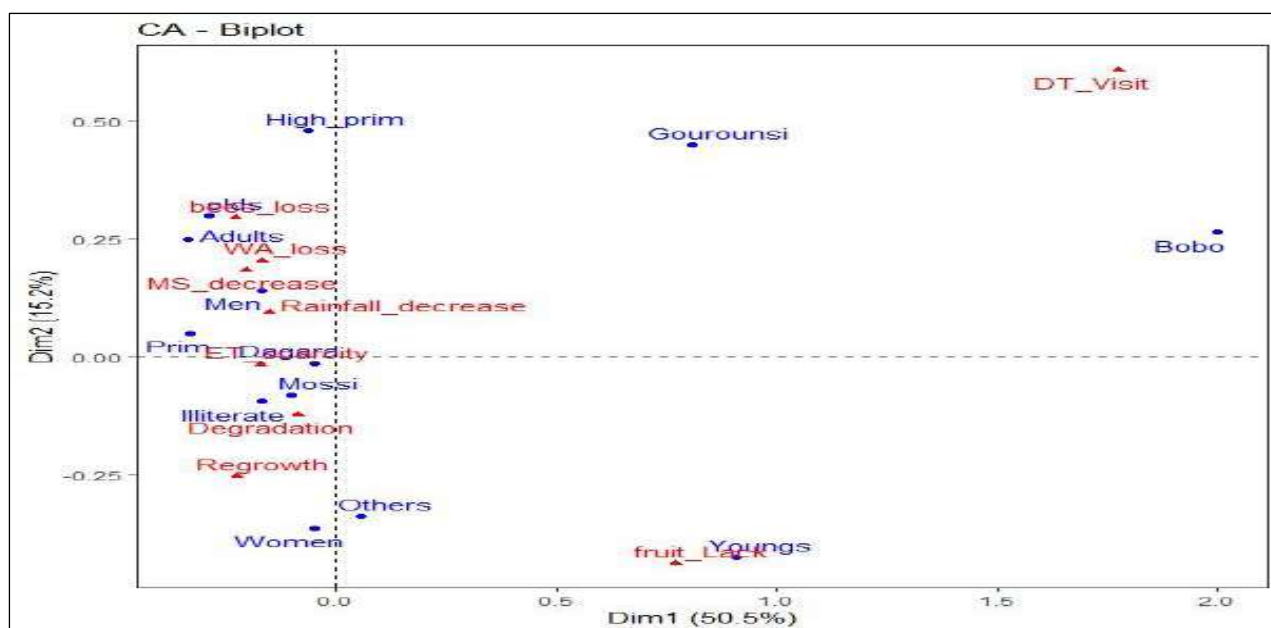


Figure 15: Correspondance analysis of local population perceptions on the consequences of threat factors on the *D. microcarpum*

Legend: MS_decrease = medicine species decrease; WA_loss = wild animal loss; High_prim = High primary education level; Prim= Primary education level, DT_visit = decrease tourist visits; ET_scarcity = Species decline.

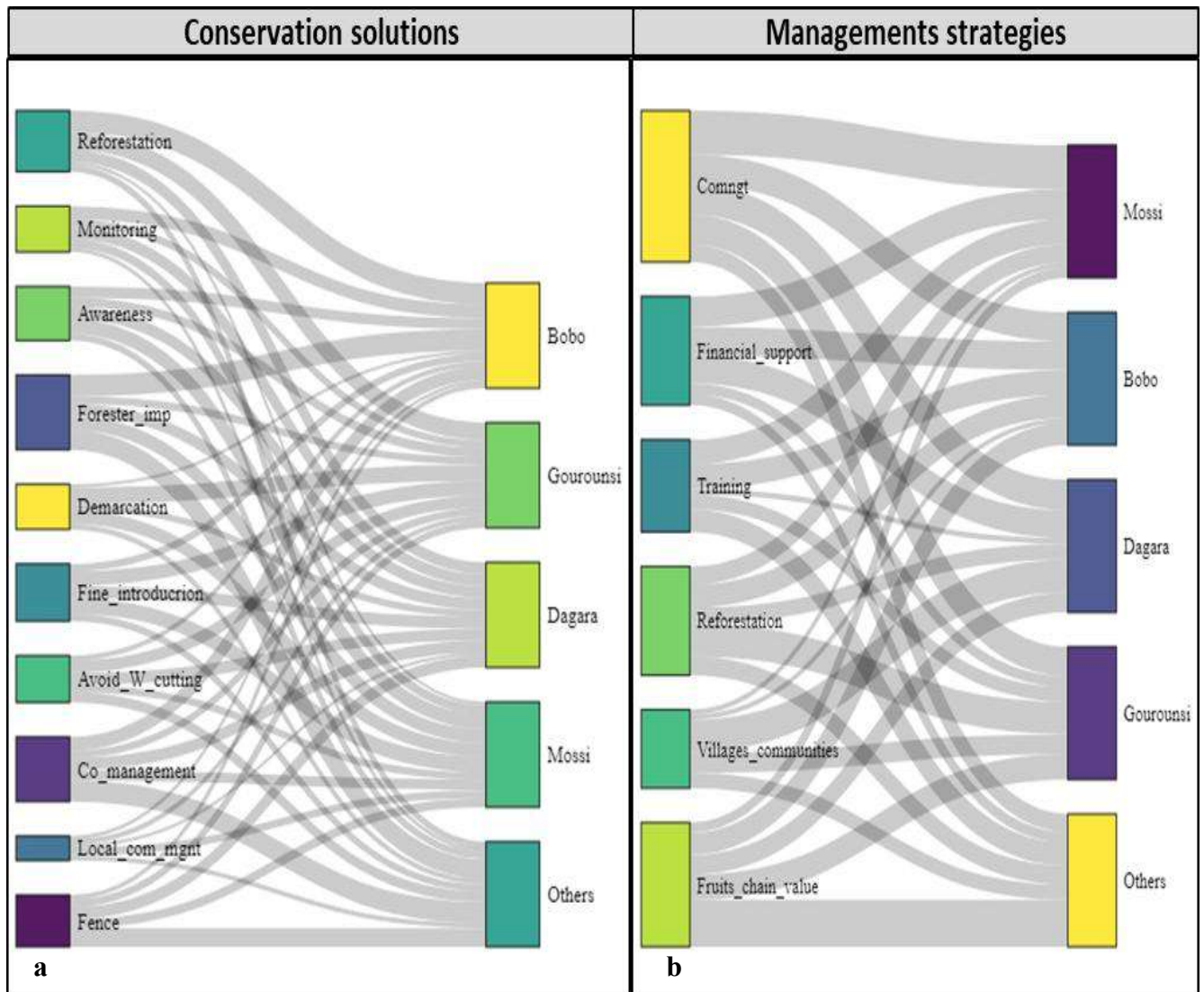


Figure 16: Local perceptions on conservation solutions and management strategies according to ethnic group

Legend: Forester_imp = Forester implication; Avoid_W_cutting = avoid wood cutting; Local_com_mngnt = local community management.

6.2. Effects of land use and climate on the diversity and population structure in natural stands of *Detarium microcarpum* Guill. & Perr. (Fabaceae) in Burkina Faso (West Africa)

6.2.1. Diversity and composition of *Detarium microcarpum* stands according to the climatic zones and land use types

6.2.1.1. Variation in *D. microcarpum* stands diversity according to the climatic zones and land use types.

A total of 102 woody species belonging to 79 genera rang in 28 families were found at the four study sites (Appendix A). The most represented families were Fabaceae (30.37 %), Anacardiaceae (6.32%), Combretaceae (6.32 %), Malvaceae (6.32%), Apocynaceae (5.06 %) and Phyllanthaceae (5.06 %).

The analysis of the stand diversity by Hill numbers allowed underlining the variations of mean species numbers (N_0), abundant species numbers (N_1), and very abundant species numbers (N_2) between climatic zones and land use types (**Table 6**). Species numbers, abundant species numbers, and very abundant species numbers decreased from the Sudanian zone to the Sudano-Sahelian zone.

Mean species numbers by plot (N_0) showed that the Sudanian zone was significantly ($F = 20.74$, $p < 0.0001$) more diverse than the Sudano-Sahelian zone (**Table 6**). By considering the land use types, there was only a significant difference ($F_2=44.584$, $P_2=< 0.0001$) between the mean species numbers by plot (N_0) found in the Protected areas (19.55 ± 5.82 species/plot) and the unprotected areas (12.43 ± 3.94 species/plot) of the Sudanian zone. However, no difference was observed between the mean species numbers by plot (N_0) found in the different land uses of the Sudano-Sahelian zone. In addition, the interaction between the climatic zone and the land use type influenced significantly (8.31 , $P_3=0.0044$) the mean number of species per plot.

The analysis of the abundant species numbers by N_1 revealed that the climatic zone ($F_1 = 17.27$, $P_1 < 0.0001$) and the land use types ($F_2=14.561$, $P_2=0.0001$), significantly affected the number of abundant species. Besides, in the Sudanian zone, the number of abundant species varied from 8.67 ± 3.96 species in the protected areas to 6.33 ± 2.57 in the unprotected areas but did not differ between land-protected and unprotected areas in the Sudano-Sahelian zone. By considering $1/D$ (N_2), the number of very abundant species decreased significantly from the Sudanian to the Sudano-Sahelian zone ($F_1 = 10.08$, $P_1 = 0.0017$). The type of land use also influenced significantly the number of very abundant species ($F_2= 5.1788$, $P_2 = 0.02417$). In the Sudanian zone, the number of very abundant species was 4.83 ± 2.7 in the Protected areas

and 3.97 ± 1.91 in the Unprotected areas. It varied from 3.74 ± 1.39 in the Protected to 3.27 ± 1.03 in the Unprotected areas in the Sudano-Sahelian climatic zone.

The Evenness pattern decreased significantly ($F1 = 4.42$, $P1 = 0.0371$) from the Sudanian to the Sudano-Sahelian zone. However, the type of land use ($F2 = 0.11$, $P = 0.7069$) and the interaction ($F3 = 0.00$ and $P3 = 0.9618$) between the climatic zone and the land use type did not influence the Evenness index. The value of the Evenness index ranges from 0.80 ± 0.10 in the Protected areas of the Sudanian zone to 0.72 ± 0.08 in the Unprotected areas of the Sudano-Sahelian zone.

6.2.1.2. Variation in *D. microcarpum* stands composition according to climatic zones and land use types

Jaccard's similarity index revealed a low similarity ($< 50\%$) between the different habitats of *Detarium microcarpum* across the two climatic zones and land use types (**Table 7**). The highest similarity (0.49) was observed between the Sudanian Protected areas and the Sudanian Unprotected areas. The lowest similarity (0.28) has been observed between the Sudanian Protected areas with the Sudano-Sahelian Unprotected areas.

The most dominant species associated with *D. microcarpum* varied according to climatic zones and land use types. In the protected areas of the Sudanian climatic zone, the most dominant species were *Combretum glutinosum*, *Vitellaria paradoxa*; *Burkea africana*, *Pterocarpus erinaceus*, *Hexalobus monopetalus*; *Entada africana*; while in the unprotected areas of the same climatic zone, there were *Vitellaria Paradoxa*, *Terminalia laxiflora*, *Combretum glutinosum*, *Entada africana*, *Lannea velutina* (**Table 8**). In the Sudano-Sahelian zone, *Crotopteryx febrifuga*, *Vitellaria Paradoxa*, *Terminalia avicennioides*, *Pericopsis laxiflora* and *Terminalia macroptera* were the most dominant in the Protected area, whereas in the Unprotected areas, the most dominant was *Balanites aegyptiaca*, *Lannea acida*, *Vitellaria paradoxa*, *Combretum collinum*, *Sterculia setigera* (**Table 8**). However, *Vitellaria paradoxa* and *Combretum glutinosum* were common species found in each climatic zone and land use type.

Table 6: Diversity indices of *Detarium microcarpum* stands (Mean $\pm$ standard deviation).

Parameters		Sudanian		Sudano-Sahelian		Anova multi-ways					
		protected areas	unprotected areas	protected areas	unprotected areas	F1	P1	F2	P2	F3	P3
N0 (Mean Richness)	mean	19.55 $\pm$ 5.82a	12.43 $\pm$ 3.94b	14.7 $\pm$ 3.93b	11.62 $\pm$ 3.41b	20.74	0.0001***	48.98	0.0001***	8.31	0.0044**
	Overall	103	80	76	61						
N1 (Exp. ^H).	mean	8.67 $\pm$ 3.96a	6.33 $\pm$ 2.57b	6.29 $\pm$ 2.14b	5.28 $\pm$ 1.55b	17.27	0.0001***	14.67	0.0001***	2.71	0.1016 ^{ns}
	Overall	19.08	14.74	11.5	9.28						
N2 (1/D)	mean	4.83 $\pm$ 2.7a	3.97 $\pm$ 1.91ab	3.74 $\pm$ 1.39b	3.27 $\pm$ 1.03b	10.08	0.0017**	4.79	0.0299*	0.45	0.5030 ^{ns}
	Overall	5.35	4.45	3.91	3.4						
Evenness (E)	mean	0.80 $\pm$ 0.10a	0.78 $\pm$ 0.11a	0.74 $\pm$ 0.09a	0.72 $\pm$ 0.08a	4.42	0.0371*	0.14	0.7069 ^{ns}	0.00	0.9618 ^{ns}
	Overall	0.636	0.614	0.564	0.542						

Legend: a, b, c = Tukey-HPT: value with different letters are significantly different; P= P value; P1 = P value of the difference climate zone, P2 = P value of the difference type of land use, P3 = P value of the interaction between climate zone and land use, *** P < 0.001, ** P < 0.01, * P < 0.05; ns = non-significant; F = F statistic of Fisher. F1= F statistic of the Sudanian zone; F2 = F statistic of the Sudano-Sahelian zone and F3 = F statistic of the interaction between the two climatic zones.

Table 7: Jaccard's similarity of *Detarium microcarpum* stands according to the climatic zones and land use types

Sites	SUPa	SPa	SSUPa	SSPa
SUPa	1			
SPa	0.4961	1		
SSUPa	0.3887	0.4619	1	
SSPa	0.2849	0.4438	0.4368	1

Legend: SUPa: Sudanian unprotected areas, SPa: Sudanian protected areas, SSUPa: Sudano-Sahelian unprotected areas, SSPa: Sudano-Sahelian protected area

Table 8: The first 20 dominant woody species encountered at the four sites along the climatic zones and land uses types based on importance value index (IVI).

Species	Sudanian climatic zone		Sudano-Sahelian climatic zone	
	protected areas	unprotected areas	protected areas	unprotected areas
<i>Azelia africana</i>	-	4.73	2.26	-
<i>Annona senegalensis</i>	-	4.07	-	-
<i>Balanites aegyptiaca</i>	-	-	-	29.78
<i>Bridelia ferruginea</i>	-	-	-	4.64
<i>Burkea africana</i>	12.12	7.27	3.44	-
<i>Cassia sieberiana</i>	-	4.73	-	-
<i>Combretum adenogonium</i>	-	-	4.06	-
<i>Combretum collinum</i>	-	-	6.49	16.99
<i>Combretum glutinosum</i>	13.11	13.26	4.37	4.52
<i>Combretum nigricans</i>	4.46	-	-	-
<i>Combretum paniculatum</i>	-	-	2.50	-
<i>Crotopteryx febrifuge</i>	7.63	8.30	25.69	-
<i>Daniella oliveri</i>	-	5.02	-	-
<i>Detarium microcarpum</i>	68.60	58.14	113.19	99.77
<i>Detarium senegalense</i>	6.37	-	-	-
<i>Diospyros mespiliformis</i>	-	5.00	-	-
<i>Entada africana</i>	8.81	10.67	-	-
<i>Gardenia erubescens</i>	-	8.73	-	3.91
<i>Gymnosporia senegalensis</i>	-	-	5.27	-
<i>Hexalobus monopetalus</i>	8.83	6.28	-	-
<i>Isoberlinia doka</i>	4.66	-	7.42	-
<i>Khaya senegalensis</i>	5.69	-	-	-
<i>Lannea acida</i>	7.86	-	7.47	19.02
<i>Lannea microcarpa</i>	6.10	20.39	-	-
<i>Lannea velutina</i>	-	8.80	-	-
<i>Pericopsis laxiflora</i>	5.28	-	12.63	-

<i>Piliostigma thonningii</i>	4.45	-	5.48	5.39
<i>Pterocarpus erinaceus</i>	9.81	9.82	-	6.74
<i>Senegalia gourmaensis</i>	7.73	-	-	11.87
<i>Senegalia macrostachya</i>	-	8.15	-	5.22
<i>Sclerocarya birrea</i>	-	-	-	2.96
<i>Sterculia setigera</i>	-	-	-	10.85
<i>Strychnos spinosa</i>	4.78	-	-	4.73
<i>Tamarindus indica</i>	-	5.84	-	9.23
<i>Terminalia avicennioides</i>	-	-	14.28	-
<i>Terminalia engleri</i>	4.38	-	2.73	-
<i>Terminalia laxiflora</i>	8.75	20.42	-	-
<i>Terminalia leiocarpa</i>	-	-	14.79	11.62
<i>Terminalia macroptera</i>	-	8.38	11.50	-
<i>Vachellia seyal</i>	-	-	3.23	5.24
<i>Vitellaria paradoxa</i>	12.17	32.27	22.59	17.66
<i>Vitex doniana</i>	-	-	-	3.39
<i>Xeroderiris stuhlmannii</i>	-	-	6.34	-

6.2.2. Effect of climate, land use, habitats specific richness, and heterospecific density on the dendrometric parameters of *D. microcarpum*

The analysis of the Kruskal Wallis test showed that the mean density ($\chi^2 = 85.864$; $p < 2.2e^{-16}$), mean diameter ($\chi^2 = 66.067$; $p < 2.965e^{-14}$), mean basal area ($\chi^2 = 94.043$; $p < 2.2e^{-16}$) and Lorey's mean height ($\chi^2 = 19.802$; $p = 0.0001865$) of *D. microcarpum* varied significantly ($P < 0.05$) between sites (**Figure 17**). The highest mean density (53.38 ± 17.22 individuals/ha) was recorded in Sudano-Sahelian protected areas, while the lowest density (16.4 ± 8.55 individuals/ha¹) was observed in Sudanian unprotected areas. Regarding mean diameter, the highest value (23.87 ± 2.85 cm) was recorded in the Protected areas of the Sudano-Sahelian zone and the lowest value (16.61 ± 4.41 cm) was observed in the unprotected areas of the same climatic zone. For the basal area, the highest mean value (2.73 ± 1.28) was observed in the protected areas of the Sudano-Sahelian zone, and the lowest value (0.53 ± 0.54) in the Unprotected areas of the Sudanian zone. In terms of Lorey's mean height, the lowest value (5.76 ± 0.95 m) was observed in the unprotected areas of the Sudano-Sahelian zone, and its highest value (6.13 ± 1.86 m) was observed in the protected areas of the Sudanian zone (**Figure 17**).

The habitat heterospecific density caused a significant increase in the basal area, the density, and the diameter but lead to a significant decrease in value of the Lorey's height (HL).

Habitat-specific richness did not influence the basal area but caused a significant increase in the diameter and Lorey's height. The Rainfall caused a significant decrease in the basal area, diameter, and the density, which increased from Sudanian to the Sudano-Sahelian, but increased with Lorey's height (HL). Temperature did not influence the basal area and Lorey's height but significantly influenced the value of diameter and species density, (**Table 9**). The correlogram of the explanatory variable based on Pearson correlation represented in **Appendix B** showed how each factors influence the dendrometric parameters of *D. microcarpum* in their natural stand.

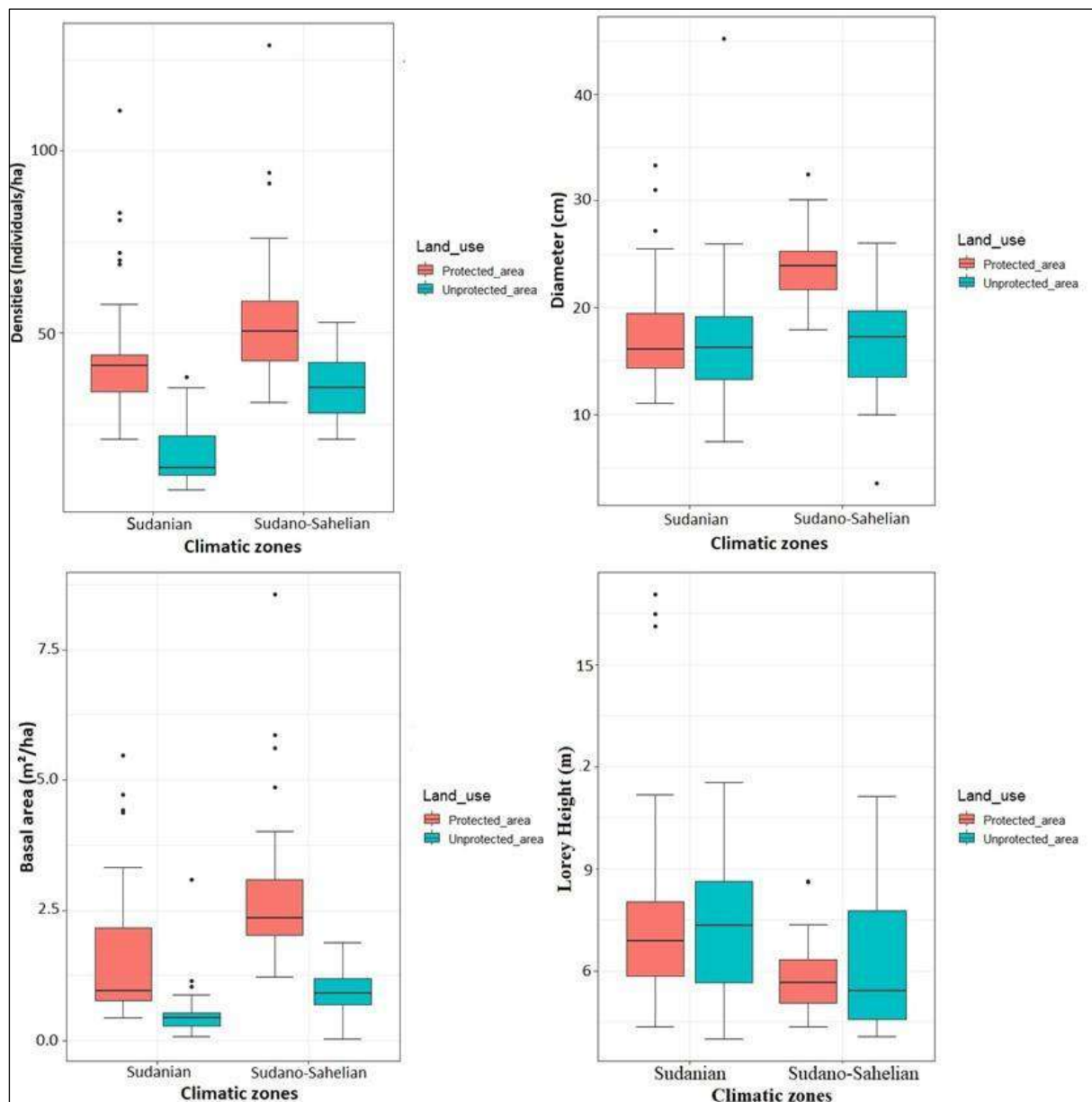


Figure 17: Differences in *Detarium microcarpum* structural parameters between climate and land use types

Table 9: Generalized linear models showing the effects of the biotic and abiotic factors on *Detarium microcarpum* structural parameters

Variables	Estimate (β)	Std. Error	z value	Pr(> z)
Basal area				
(Intercept)	14.59	10.90	1.34	0.181 ^{ns}
Habitat heterospecific density	0.01	0.01	6.64	0.0000***
Habitat specific richness	0.01	0.014	1.15	0.252 ^{ns}
Rainfall	-0.01	0.00	-2.54	0.011*
Temperature	-0.45	0.37	-1.24	0.217 ^{ns}
Density				
(Intercept)	11.24	1.99	5.64	0.0000***
Habitat heterospecific density	0.01	0.00	28.82	0.0000***
Habitat specific richness	0.00	0.00	1.36	0.1743 ^{ns}
Rainfall	-0.00	0.00	-8.05	0.0000***
Temperature	-0.25	0.07	-3.65	0.0002***
Stem Diameter				
(Intercept)	6.47	2.58	2.51	0.0121*
Habitat heterospecific density	0.00	0.00	1.29	0.1942 ^{ns}
Habitat specific richness	0.01	0.00	2.	0.0421*
Rainfall	-0.00	0.00	-2.55	0.0109*
Temperature	0.11	0.09	1.24	0.0216*
Lorey's height				
(Intercept)	0.33	4.16	0.08	0.9368 ^{ns}
Habitat heterospecific density	-0.01	0.00	-2.63	0.0085**
Habitat specific richness	0.02	0.01	2.89	0.0038**
Rainfall	0.01	0.00	1.67	0.0938 ^{ns}
Temperature	0.03	0.14	0.19	0.8510 ^{ns}

Legend: *** P < 0.001, ** P < 0.01, * P < 0.05. Std. Error: Standard Error; ns = non-significant

6.2.3. Population structure of *Detarium microcarpum* in their natural stands

The linear regression analyses of the diameter classes distribution revealed a negative slope in the different climatic zones and land use types (**Table 10**). The diameter classes of *D. microcarpum* individuals exhibited an irregular distribution, with a higher prevalence of individuals in the intermediate classes compared to those in the extreme classes (**Figure 18**). The predominance size class of the diameter class varied according to the climatic zones and land use type. The predominance class size was 15 -20 in the protected areas, and 10- 15 in the unprotected areas in the Sudano-Sahelian zone. In the Sudanian zone, the diameter abundance size class was 10- 15 in the protected areas, but there is a weak distribution in the unprotected areas (**Figure 18**). However, in the unprotected areas ($R^2 = 0.29$, $P = 0.1062$) of the Sudanian zone and both Protected ($R^2 = 0.26$, $P = 0.1303$) and Unprotected areas ($R^2 = 0.39$, $P = 0.0556$) of the Sudano-Sahelian zone, the R^2 values following with the probabilities P showed a weak relationship between the number of individuals and the diameter classes except for the Protected areas of Sudanian zone where strong relationship ($R^2 = 0.54$, $P = 0.0159$) were observed between the number of individuals and the diameter classes. Thus, the populations of *D. microcarpum* are unstable in the different climatic zones and land use types except for in the Protected areas of the Sudanian zone (**Table 10, Figure 18**).

The height class distribution of the juvenile stratum revealed a negative slope for the different climatic zones and land use types, which indicates the dominance of individuals of small height classes. Besides, a positive slope was observed in the unprotected areas of the Sudano-Sahelian zone. In addition, the R^2 values with the non-significant p-values ($P > 0.05$) reveal an unsuccessful transition of juveniles from the lower classes to the higher classes, reflecting difficulties of survival in juvenile individuals (**Figure 19**). Thus, the regeneration of *D. microcarpum* was characterized by unstable populations independent of the climatic zones and land use types.

Table 10: Regression slope values of height class distributions (Juvenile) and diameter Class according to the climatic zones and land use type

Climatic zones	Land use types	Regression parameters		
		Slope	R ²	P_value
Adult stratum				
Sudanian	Protected areas	-1.81	0.54	0.0159
	Unprotected areas	-0.57	0.29	0.1062
Sudano-Sahelian	Protected areas	-1.36	0.26	0.1303
	Unprotected areas	-1.24	0.39	0.0550
Juvenile stratum				
Sudanian	Protected areas	-0.29	0.06	0.7022
	Unprotected areas	-0.51	0.32	0.3230
Sudano-Sahelian	Protected areas	-0.90	0.05	0.7280
	Unprotected areas	0.39	0.29	0.3495

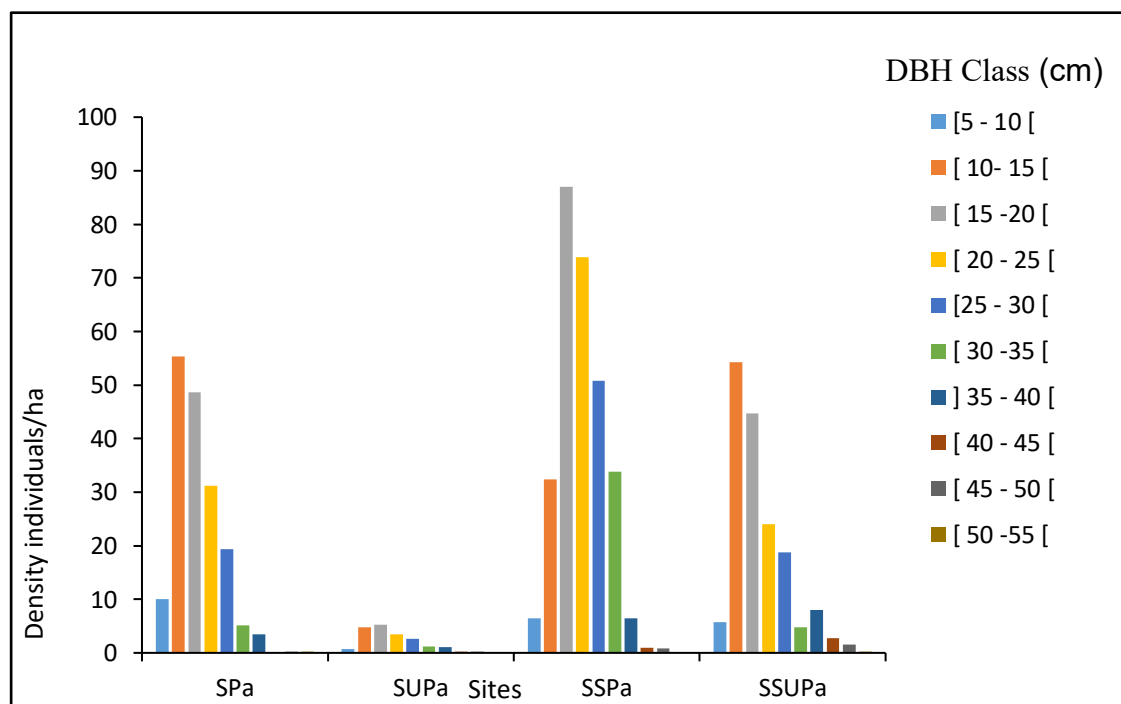


Figure 18: Horizontal structure of adult stands of *Detarium microcarpum* according to the climatic zones and land use type

Legend: Spa: Sudanian Protected areas, SUPa: Sudanian Unprotected areas, SSPa: Sudano-Sahelian Protected areas and SSUPa: Sudano-Sahelian Unprotected areas.

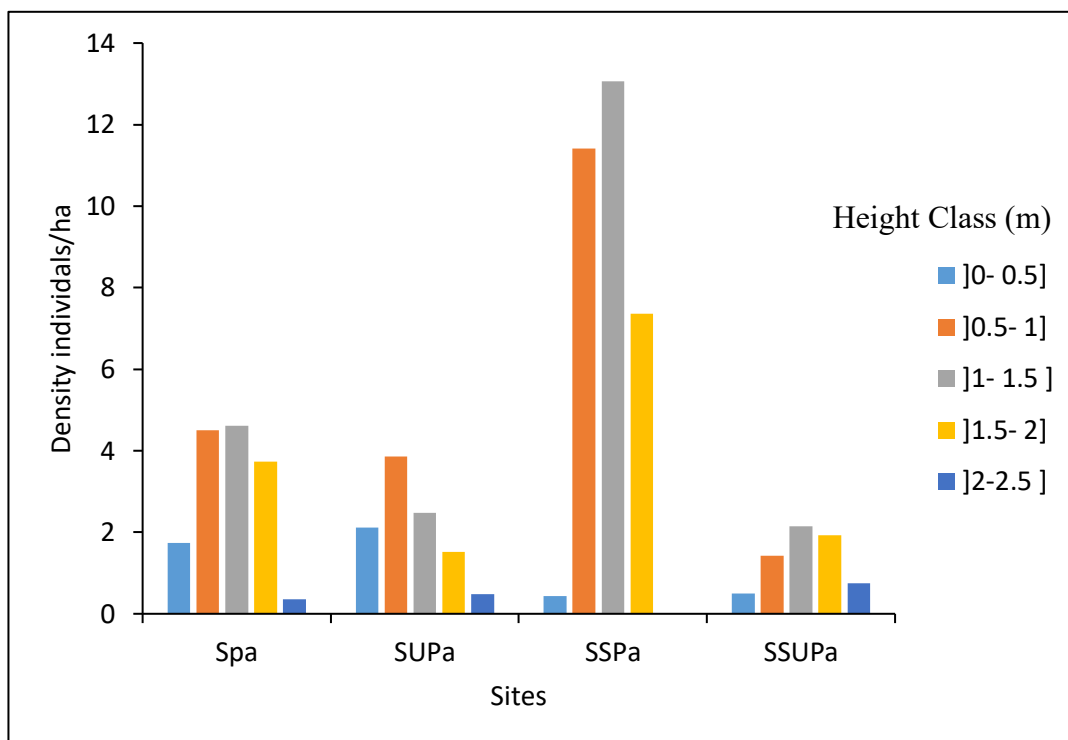


Figure 19 : Vertical structure of juvenile populations of *Detarium microcarpum* according to the climatic zones and land use type

Legend: Spa: Sudanian Protected areas, SUPa: Sudanian Unprotected areas, SSPa: Sudano-Sahelian Protected areas and SSUPa: Sudano-Sahelian Unprotected areas.

6.3. The effect of the climate on the growth of *Detarium microcarpum*

6.3.1. Xylem anatomy and anatomy of growth ring boundaries of *Detarium microcarpum*

Detarium microcarpum trees show clear diffuse-porous anatomy and the presence of (discontinuous) tangential parenchyma bands (**Figure 20**). In the cross-section, vessels occur solitary or grouped in pairs with an angular outline and are aligned in rows parallel to the rays. Fibres form a very dense and undifferentiated tissue, without a clear pattern between earlywood and latewood. Vessel distribution is diffuse-porous with the presence of the Gum duct. Wood parenchyma is often linked with vessels (paratracheal parenchyma). Besides, parenchyma cells form irregular tangential bands with a variable width. Several anatomical features have been identified, such as Fibres, which are elongated cells, that provide structural support and strength to the wood. Gum Ducts are often formed in response to injury or environmental stress. The presence of the Grouped Vessels facilitates the transport of water and nutrients, as shown in **Figure 20**. In addition, the solitary vessels individually enhanced the wood's ability to resist cavitation. Apotracheal Parenchyma occurred independently of the vessel and Paratracheal Parenchyma cells located adjacent to vessels support a vascular function of the vessel. The Marginal parenchyma showed the growth of the ring boundaries and the ray parenchyma which run radially across the wood, **Figure 20**. Tree-ring boundaries are delimited by marginal parenchyma bands, and thick-walled and radially compressed gum ducts. Earlywood rays were expanded. However, tangential parenchyma bands sometimes disappear on certain parts along the disc. Parenchyma bands that faded or vanished around the disc's circumference or along one of its radii were interpreted as interannual features, indicating the absence of genuine ring boundaries. Although all analysed discs presented some intra-annual ring fluctuations, they were not considered problematic for dating, since they were not present on the whole tree cross-section.

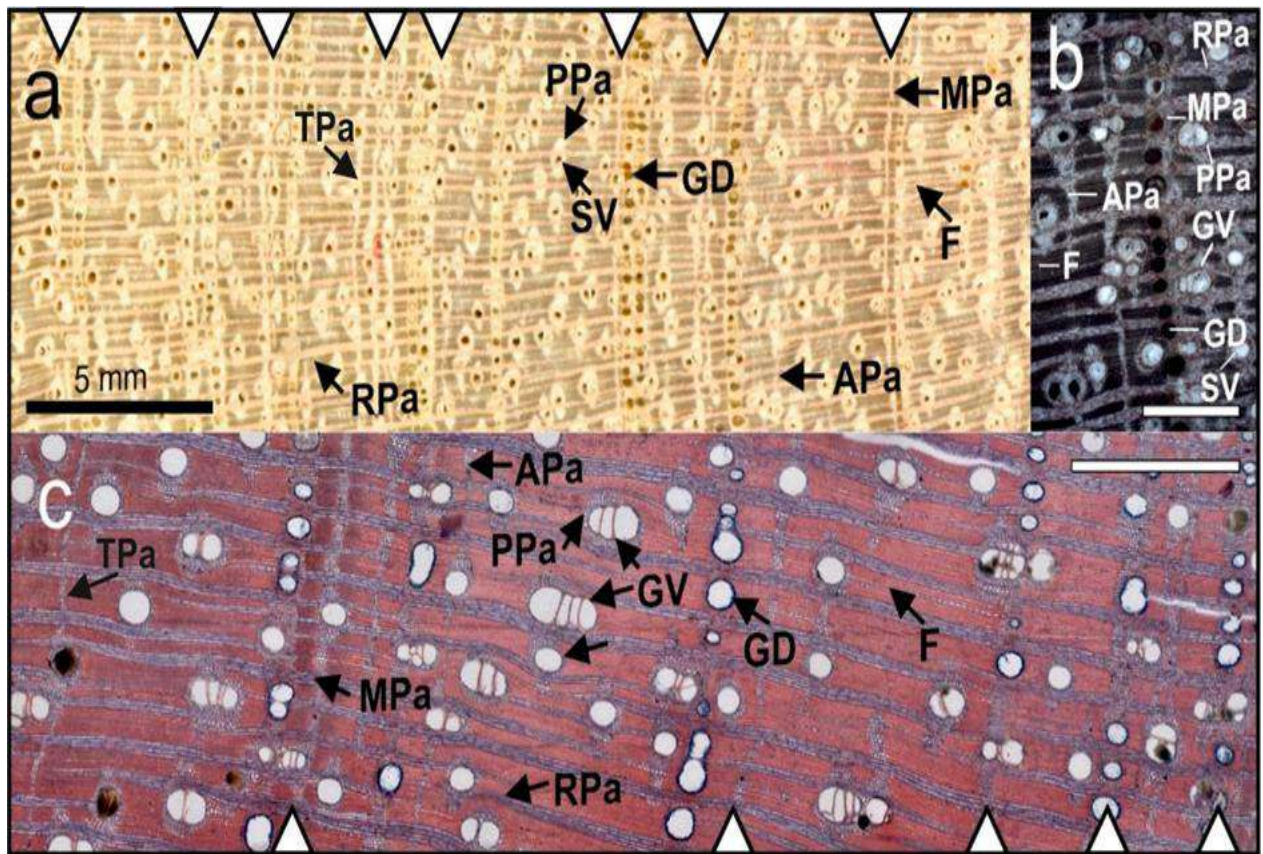


Figure 19: a. Macroscopic image of a disk cross-section of *Detarium microcarpum*. B. Detail of a. c. Microscopic image of a cross-section. White bars in b and c indicate a 1mm scale. White triangles in a and c indicate tree-ring boundaries. F, fibres; GD, gum ducts; GV, grouped vessels; SV, solitary vessels; APa, apotracheal parenchyma; PPa, paratracheal parenchyma; TPa tangential parenchyma; MPa, marginal parenchyma band; RPa, ray parenchyma.

6.3.2. Cross-dating, chronology quality and the response to the climate variable of *D. microcarpum*

Due to the complexity that we are encountered during the chronology process, data from the Sudano -Sahelian climatic zone were successfully correlated. However, Six of the twelve selected trees were successfully cross-dated between tree radii and trees and were averaged to construct the mean chronology. **Table 11** illustrates the statistics of the dendrochronological series in detail. The Pearson correlation ($r = 0.72$, $P = 0.0025$) showed a significant correlation between the common period (1937- 2022) and the total length of the chronology of 93 years (**Figure 21**). The result of the descriptive statistic of the chronology and cross-dating showed a high performance of the chronology. The expressed population signal (EPS) value of the chronology trees is (0.89), which is higher than the recommended threshold (0.85), indicating strong coherency among the different time series included in the final tree ring chronologies. Despite the small sample size, the EPS and the $\bar{r}$ values indicated the reliability of the chronology. The correlation coefficient values between all radii and between trees indicate similarity in annual growth patterns among sampled trees (**Table 11**). The common interval analysis of detrended series was established in a time span from 1937 to 2022 and subsequent dendrochronology analyses were conducted within this period, (**Figure 21**).

The result of the correlation analysis exhibited a significant negative correlation between the chronology and the precipitation index of the previous November and a positive correlation with the current year. The climate growth relationships of *D. microcarpum* revealed a negative correlation with the previous dry season. However, no correlation between growth and rainfall of the previous year was observed. In addition, the current year's September precipitation, which corresponded to the end of the rainy season influenced tree growth positively. Precipitation during the previous November influenced tree growth negatively whereas March temperature had a significant positive impact.

The growth of *D. microcarpum* is enhanced by low precipitation in May and the temperature in September, which is indicated by positive correlations (**Figure 21**). Regarding temperature, we only found a significant ($p < 0.05$) and negative correlation in November data in the Sudano-Sahelian climatic zone. A significant positive relationship was found between *D. microcarpum* tree growth and annual rainfall with ($r^2 = 0.4$, $n = 97$ years, $p < 0.001$), **Figure 21**. However, a

Table 11: Dendrometric data collected stem discs and characteristics of tree-ring series.

Parameters	Tree species: <i>D. microcarpum</i>
Number	13
Mean Diameter	36.12±10.4
Number of dated trees	12
Overall time span	1929 - 2022
Common interval time span	1937 -2022 (85)
Standard Deviation	0.308
Correlation between trees	0.41± 0.2
Autocorrelation	0.38
correlation between radii	0.89
Glk	0.76
Mean T value	4.7 ± 0.25
EPS	0.87
Pearson correlationof the radii	0.72 (P= 0.0025)

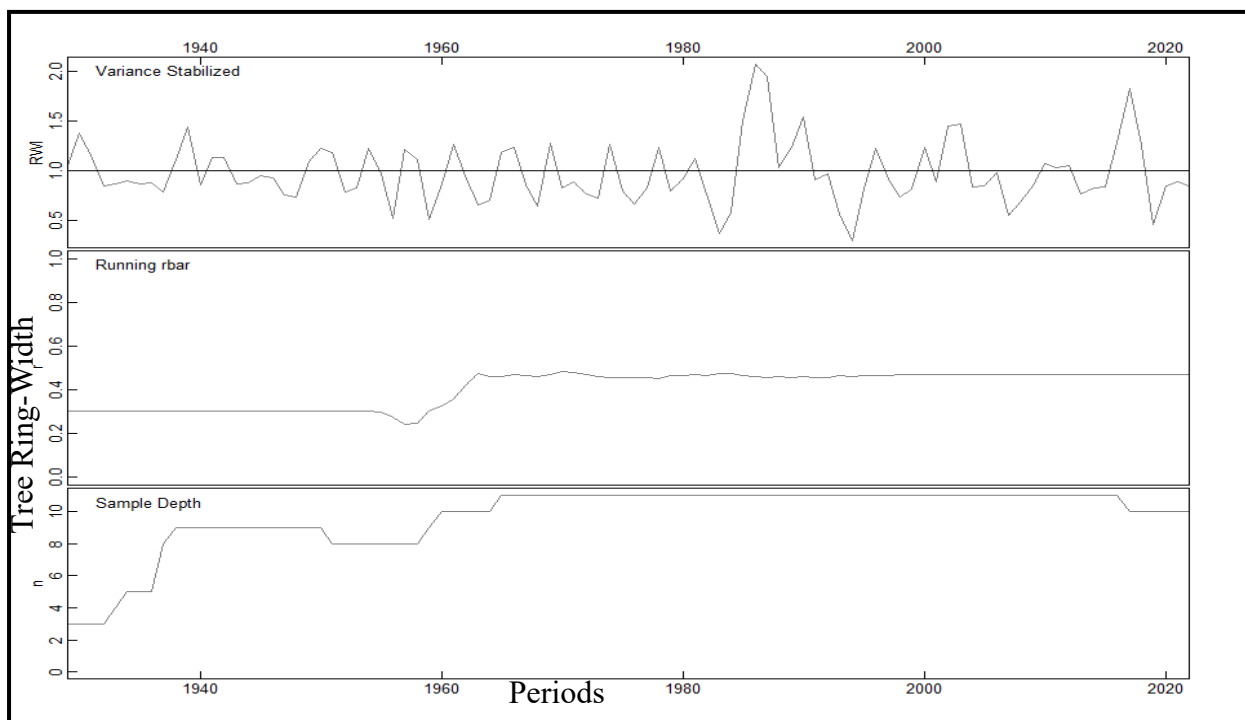


Figure 20: Mean series of ring-width indices (chronologies) of *D. microcarpum* obtained in the Sudano-Sahelian climate zone.

However, a significant ($p < 0.05$) positive correlation was found only for May, at the start of the rainy season.

The moving correlation analysis showed that the relationship between tree ring growth and climate changed during the analysed period (**Figure 22**). At the beginning of the study period, Tree-ring width responded positively to November rainfall, corresponding to the beginning of the dry season and June precipitation for many years. June precipitation had a stronger positive relation to tree growth with the decreased influence of August precipitation. From 1943 to 1984, June precipitation had a negative impact on tree growth; however, that trend increased over the years. The Precipitation of August impacts the growth of *D. microcarpum* negatively (**Figure 23**). February temperatures also showed a significant negative impact on tree growth throughout the period 1929 – 1984 (**Figure 24**). *D. microcarpum* growth has responded positively to the temperature of January in recent decades (1983 – 2022). However, in later years, there was a clear shift.

6.3.3. Vessel characteristics of *D. microcarpum* wood

The anatomical analyses of the wood formed during the last 35 years (1987 – 2022) enabled us to detect diffuse-porous ring boundaries delimited by marginal parenchyma. The mean vessel area (MVA), total vessel area (TVA), total vessel area percentage (TVAP), Vessel Density (VD), vessel diameter (MVD_r and Vessel Number (VN) weakly increased with tree age ($p < 0.05$) showed by **Table 12**. All anatomical variables showed strong correlations with each other (Table 12). The VN is positively correlated with MA and TVA. The VD shows a negative correlation with the tree ring width but a positive correlation with TVA.P. The tree Ring Width is positively correlated with MVA, TVA, and VN but negatively correlated with TVA.P and VD. Furthermore, TVA showed a negative correlation with VD but a positive correlation with VN and tree Ring width (**Table 13**). According to the climate variables, the temperature is negatively correlated with MVA, the precipitation is positively correlated with VN, TRW and negatively correlated with TVA

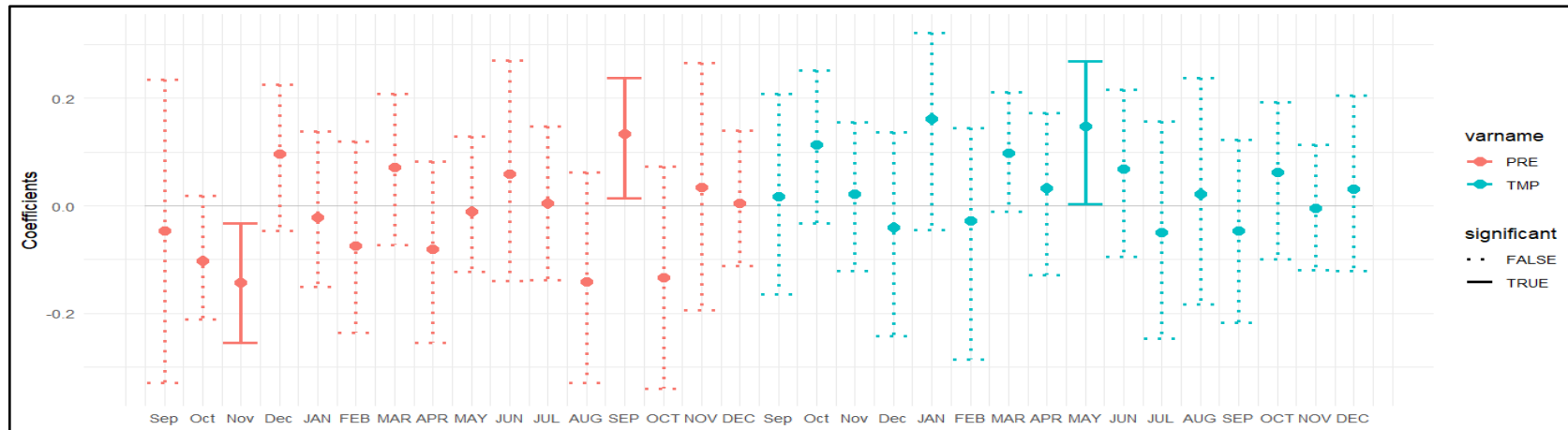


Figure 21:Plot of bootstrapped response function analysis relating tree ring growth of *Detarium microcarpum* to the precipitation and monthly temperature from previous September to current December

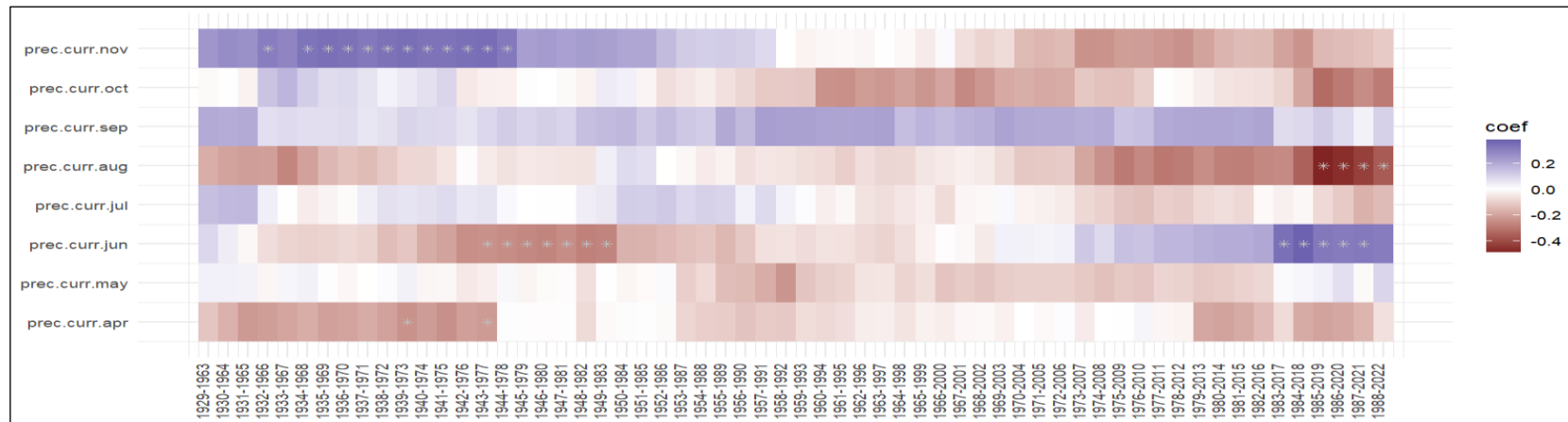


Figure 22: Plot of moving correlation function relating to tree ring growth of *D. microcarpum* to the temperature. Significant correlations ($p < 0.05$) are indicated by white asterisks.

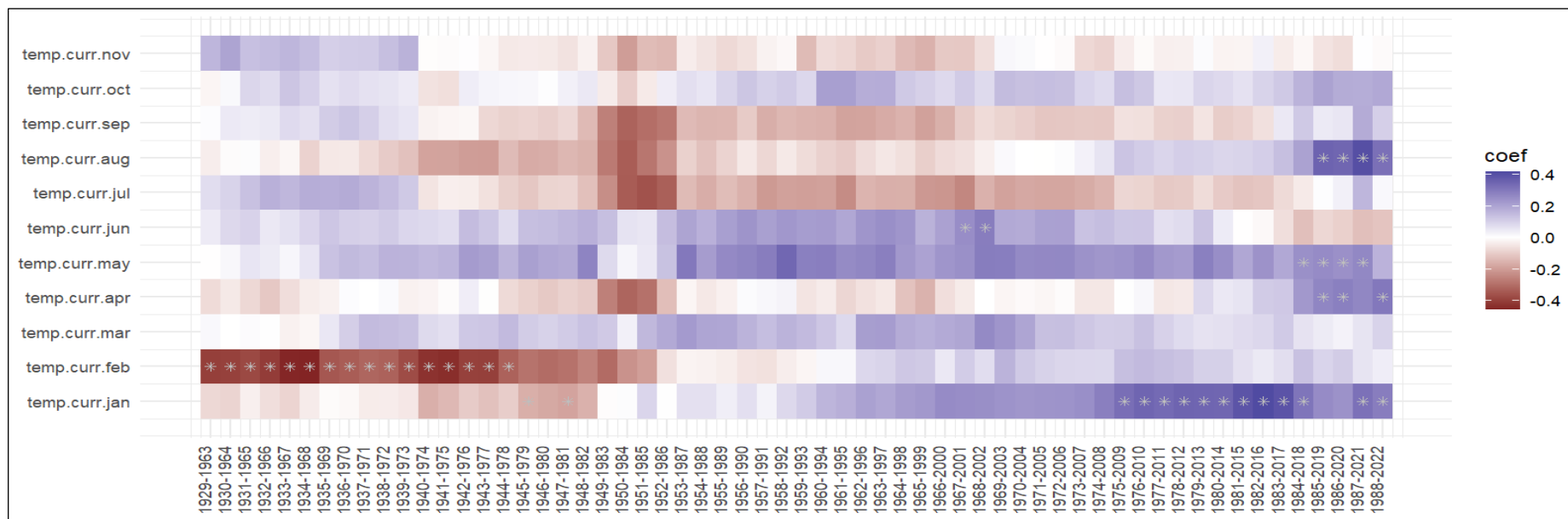


Figure 23: Plot of moving correlation function relating to tree ring growth of *D. microcarpum* to the precipitation. Significant correlations ($p < 0.05$) are indicated by white asterisks

Table 12: Variations of *Detarium microcarpum* vessel anatomical traits

	Mean $\pm$ sd	se(mean)	CV	p-value
MVA	266.78 $\pm$ 636.97	55.03	2.39	0.001
MVDr	0.187 $\pm$ 0.04	0.04	0.23	0.001
TVA	317.37 $\pm$ 212.26	18.34	0.67	0.001
TVA.P.	4.758 $\pm$ 1.55	0.134	0.33	0.001
VD	0.178 $\pm$ 0.14	0.012	0.8	0.001
VN	36.97 $\pm$ 13.23	1.14	0.36	0.001
Width	0.986 $\pm$ 0.31	0.032	0.33	0.001

Table 13: Pearson correlation matrix showing the relationships among anatomical traits

	Temp	MVA	MVDr	Precip	TVA	TVA.P.	VD	VN	TRW
Temp	1								
MVA	0.34	1							
MVDr	-0.56*	-0.45	1						
Precip	0.46	0.35	0.47	1					
TVA	-0.35	0.51	-0.35	-0.50*	1				
TVA.P.	-0.43	0.87***	-0.25	0.38	0.51	1			
VD	-0.47	-0.45	-0.64*	0.47	-0.51*	0.82**	1		
VN	-0.37	0.56*	-0.24	0.51*	0.76**	0.79**	-0.42	1	
TRW	0.44	0.75*	0.45	0.64*	0.55*	-0.62*	-0.72**	0.98***	1

Note: Temp: Temperature; MVA: Mean Vessel Area; MVDr: Mean Vessel Diameter, Precip: Precipitation; TVA: Total Vessel Area; TVAP: Total Vessel Area Percentage, VN: Vessel Number, VD: Vessel Diameter, TRW: Tree-Ring Width. $p < 0.05^*$, $p < 0.01^{**}$ and $p < 0.001^{***}$.

6.4. Allometric models for estimating aboveground biomass and carbon stocks of the semi-arid savanna woody species, *Detarium microcarpum*.

6.4.1. Statistical summary of the dendrometrics parameters and wood-specific density of *D. microcarpum*

The results indicated that the dendrometric parameters of *D. microcarpum* are well-distributed and differ significantly ($P \leq 0.001$) between the two climatic zones (**table 14**). The Pearson correlation shows that only the diameters at the breast height (dbh) and Total height (Ht) are lower correlated (0.45) than the other parameters which are highly correlated (≥ 0.52 , **Table 15**). This allowed us to establish the allometric equation according to the climatic zone using the diameter at the breast height (dbh) and the total height (ht).

In each climatic zone, the wood-specific density of *D. microcarpum* varied significantly between tree components ($F = 4.963$, $P = 0.0298$) for the Sudanian zone and ($F = 7.668$, $P = 0.00754$) in the Sudano-Sahelian zone. The branch had the highest density in each climatic zone with 0.88 ± 0.51 in the Sudanian zone and (0.98 ± 0.77) in the Sudano-Sahelian zone. For the stem density, they were 0.66 ± 0.19 in the Sudanian zone and 0.71 ± 0.12 in the Sudano-Sahelian zone. Based on mean species density, the value was 0.77 ± 0.25 in the Sudanian zone and (0.81 ± 0.12) in the Sudano-Sahelian zone.

Table 14: Statistical summary of the dendrometrics parameters of *D. microcarpum*

Parameters	Global data		Sudanian		Sudano-sahelian		P-Value
	Mean $\pm$ cv (%)	Range	Mean $\pm$ cv (%)	Range	Mean $\pm$ cv(%)	Range	
Basal diameter (d ₂₀ , cm)	23.68 $\pm$ 35.08	13 - 46	22.8 $\pm$ 34.92	13 - 42	24.57 $\pm$ 35.34	14 - 46	0.001
diameter at breast height (dbh, cm)	21.15 $\pm$ 40.05	10.5 - 44	20.09 $\pm$ 40.04	10.5 - 39.5	22.2 $\pm$ 40.01	11.99 - 44	0.001
Stem height (h, m)	2.83 $\pm$ 25.90	1.65 - 6	2.91 $\pm$ 26.93	1.9 - 6	2.75 $\pm$ 24.83	1.65 - 4.65	0.001
Tree height (h, m)	8.015 $\pm$ 26.8	3.85 - 15	8.215 $\pm$ 27.15	4.9 - 14	7.815 $\pm$ 26.62	3.85 - 13.75	0.001
Crown diameter (cd, m)	5.92 $\pm$ 41.52	2.275 - 13.025	6.01 $\pm$ 34.41	3.125 - 11.95	5.83 $\pm$ 48.50	2.275 - 13.025	0.001

Table 15: Pearson correlation of the dendrometric parameters of *D. microcarpum*

Dendrometric parameters	Basal diameter (d ₂₀)	Crown diameter	Diameter at the breast height (dbh).	Total height (ht)	Stem height
Basal diameter (d ₂₀)	1				
Crown diameter	0.81	1			
Diameter at the breast height (dbh)	0.99	0.89	1		
Total height (ht)	0.52	0.52	0.45	1	
Stem height	0.81	0.76	0.82	0.67	1

6.4.2. Allometric equations for predicting *D. microcarpum* above-ground biomass

All models were tested, and parameter estimates produced highly significant results with R^2 adj values over 0.80 in the two climatic zones. The coefficients obtained from the fitted models were highly significant ($P \leq 0.05$). In the Sudanian zone, allometric models predicted biomass components with AIC values ranging from 14.30 to 30.69184, RSE between 0.2365 and 0.4236, and RMSE between 0.0115 and 0.5088. Branch and leaf biomass were better predicted when using a dbh alone-like predictor with R^2 adj = 0.8657; AIC = 31.10; RSE = 0.3806 and RMSE = 0.4728 for the branch and R^2 = 0.8457; AIC = 27.37; RSE = 0.2365 and RMSE = 0.0115 for the leave. The best-fitted equation for stem biomass was fitted using $dbh^2 \cdot h$ with R^2 adj = 0.9094; RSE = 0.2876; AIC = 14.30 and RMSE were 0.1903 (**Table 16**).

In the Sudano-Sahelian climatic zone, the coefficients obtained from the fitted models were highly significant ($P < 0.05$). However, the higher Adj. R^2 values were recorded for the branch biomass (ranging from 0.8469 - 0.8796) with the AIC (40.43 – 51.37), RSE (0.4446 – 0.5526) and RMSE (0.4698 – 0.5203). For the stem biomass estimation, the Adj. R^2 varied between (0.8095 - 0.8763), AIC (26.72 – 39.68); RSE (0.3538 - 0.439), RMSE (0.1122 - 0.1526), and for the leaf biomass, the Adj. R^2 ranged from (0.8247 - 0.8473) with AIC (3.03 - 10.06); RSE (0.2384 - 0.268) and RMSE (0.0171 - 0.0220), (table 3). At each component (stem, branch, and leaves) in the Sudano-Sahelian zone, the best equation for leaf biomass was fitted using dbh alone. Adding tree total height to dbh as a compound variable ($dbh \times ht$) did not significantly improve the statistical fits in both of the two climatic zones when compared to the model based on dbh as a single predictor (**Table 16**).

The equations used to predict the total above-ground biomass (TGAB) showed a high adjusted R^2 value of each climatic zone. According to the low value of the RSE (0.2928); AIC (15.3655), and RMSE (0.5116), the dbh is the best predictor for the total biomass prediction with R^2 adj. (0.9013) in the Sudanian zone. For the Sudano-Sahelian climatic zone, the R^2 adj. ranged between (0.8488 - 0.9092) with AIC (22.21 - 37.50), RSE (0.3281 - 0.4234), and RMSE (0.4844 - 0.5332). The best-fitted model was found with dbh alone like the predictor, (**Table 16**). The model using single compound variables $dbh \cdot ht$ showed less efficient estimations than the model based on the multiple variables of $dbh^2 \cdot ht$ and a single predictor than dbh alone.

The most appropriate allometric equations for estimating biomass are presented in **Table 17**. In the Sudanian zone while in the Sudano-Sahelian zone, dbh alone was the good predictor for branch and leaf biomass. The differences were observed with the stem biomass prediction. In the Sudanian, the best predictors were $dbh^2 \cdot ht$ and dbh alone in the Sudano-Sahelian climatic

zone (**Table 16**). In each climatic zone, the appropriate allometric equation for the total aboveground biomass (TAGB) estimating was obtained by combining the best-performing models of each biomass component. For the Sudanian climatic, the model developed was $TAGB = e^{4.4002} (dbh \cdot dbh \cdot h)^{0.9456} + e^{-3.5219} (dbh)^{2.4007} + e^{-2.8845} (dbh)^{1.3465}$ in the Sudanian zone and $TAGB = e^{-4.1053} (dbh)^{2.4222} + e^{-5.2567} (dbh)^{2.9539} + e^{-2.9894} (dbh)^{1.5285}$ for the Sudano-Sahelian climatic zone. When comparing the additive model developed with the global biomass model developed in each climatic zone, the additive model performed the variance very well compared to the global model developed. In the Sudanian zone, the additive model performed well with $R^2_{adj} = 0.9099$, SSR = 2.6344, AIC = 14.7935, and RMSE = 0.3067 than the global biomass with ($R^2_{Adj} = 0.9013$, SSR = 3.0201; AIC = 16.9145 and RMSE = 0.3284 (table 4). In the Sudano-Sahelian climatic zone, they were $R^2_{adj} = 0.9099$, SSR = 2.6135; AIC = 21.9446 and RMSE = 0.3125 for the additive model and $R^2_{adj} = 0.9092$, SSR = 3.0147; AIC = 22.2054, and RMSE = 0.3281 for the global biomass model established (**Table 17**). These results indicate the selected allometric models present a good fit and better performance than the global model established and the model proposed by Chave *et al.* (2014) which includes the density in the model.

The scatter plots (**Figure 25**) of observed and predicted values of the three components were close to the linear trend which indicates the good performance of the models established in this study. No significant deviation was observed between observed and predicted biomass ($P > 0.05$) for the additive model like the global biomass established. For the additive model, they were ($t = 0.9358$; $P = 0.3088$) in the Sudanian zone and ($t = 1.116$; $P = 0.2736$) for the Sudano-Sahelian zone (**Table 17**). With the global biomass model established, they did not vary ($t = 0.8257$; $P = 0.4157$) in the Sudanian zone and ($t = 0.8390$; $P = 0.4083$) which is presented in **Table 17**. The error values from the above-ground biomass predictions using the SUR approach demonstrated enhanced performance compared to the models independently fitted (**Figure 26**)

Table 16: Summary of the best allometric models selected for *D. microcarpum* in Sudanian and Sudano-Sahelian climatic zone in Burkina Faso

Sudanian data														
		Regression coefficients					Goodness of fit						t-test	
Components	Predictor	Parameters	Est.	SE	t-value	Pr(> t)	adj R ²	RSE	CF	AIC	RMSE	P-Value	t	P-value
Stem (Eq1)	Intercept	lna	-4.0371	0.4564	-8.846	1.34e ⁻⁰⁹ ***	0.8951	0.3095	1.0491	18.7	0.1992	1.87e ⁻¹⁵	0.8063	0.4266
Stem (Eq1)	dbh	b	2.4362	0.1545	15.766	1.87e ⁻¹⁵ ***								
Stem (Eq2)	Intercept	lna	-4.4462	0.4824	-9.217	5.64e ⁻¹⁰ ***	0.895	0.3096	1.0491	18.73	0.2081	1.89e ⁻¹⁵	0.6324	0.5321
Stem (Eq2)	dbh*h	b	1.5087	0.0957	15.757	1.89e ⁻¹⁵ ***								
Stem (Eq3)	Intercept	lna	-4.4037	0.4423	-9.957	1.06e ⁻¹⁰ ***	0.9094	0.2876	1.0422	14.3	0.1903	2.39e ⁻¹⁶	0.6403	0.527
Stem (Eq3)	dbh ² *h	b	0.94606	0.05535	17.093	2.39e ⁻¹⁶ ***								
Stem (Eq4)	Intercept	lna	-4.3695	0.4633	-9.432	7.07e ⁻¹⁰ ***	0.9041	0.296	1.0184	17.8	0.1908	5.65e ⁻¹⁴	0.623	0.5382
Stem (Eq4)	dbh	b	2.0377	0.2634	7.735	3.31e ⁻⁰⁸ ***								
Stem (Eq4)	Ht	c	0.703	0.3916	1.795	0.0843								
Stem (Eq4)	density	d	-0.0945	0.2185	-0.432	0.0669								
Branch (Eq1)	Intercept	lna	-3.5301	0.5612	-6.29	8.41e ⁻⁰⁷ ***	0.8657	0.3806	1.075116	31.1	0.4728	4.26e ⁻¹³	0.8727	0.39
Branch (Eq1)	dbh	b	2.4035	0.19	12.65	4.26e ⁻¹³ ***								
Branch (Eq2)	Intercept	lna	-3.777	0.6598	-5.724	3.85e ⁻⁰⁶ ***	0.8089	0.4236	1.0939	37.52	0.5078	8.68e ⁻¹²	0.8524	0.401
Branch (Eq2)	dbh.ht		1.4571	0.131	11.126	8.68e ⁻¹² ***								
Branch (Eq3)	Intercept		-3.79557	0.60307	-6.294	8.33e-07 ***	0.8362	0.3922	1.079945	32.91	0.5088	9.95E-13	1.3323	0.1931
Branch (Eq3)	dbh ² *h		0.9212	0.0755	12.206	9.95e ⁻¹³ ***								
Branch (Eq4)	Intercept	lna	-3.6577	0.6096	-6.001	0.000002569 ***	0.8385	0.3894	1.1183	34.26	0.4728	4.79e ⁻¹¹	0.8516	0.4014
Branch (Eq4)	dbh	b	2.2472	0.3326	6.755	0.000000454 ***								
Branch (Eq4)	Ht	c	0.2957	0.4818	0.614	0.545								
Branch (Eq4)	density	d	0.1207	0.1804	0.669	0.509								
Leaf (Eq1)	Intercept	lna	-2.8943	1.0979	-2.636	0.01352 *	0.8457	0.2365	1.319351	27.37	0.0115	0.0011	1.1517	0.2589
Leaf (Eq1)	dbh	b	1.3494	0.3717	3.63	0.00112 **								
Leaf (Eq2)	Intercept	lna	-2.7464	1.2057	-2.278	0.03057 *	0.8419	0.2522	1.349235	30.69	0.0143	0.003589	1.5624	0.129
Leaf (Eq2)	dbh. ht	b	0.7608	0.2393	3.179	0.00359 **								
Leaf (Eq3)	Intercept	lna	-2.8674	1.1698	-2.451	0.02074 *	0.8425	0.2485	1.335637	29.66	0.0132	0.002142	1.5538	0.1311

Leaf (Eq3)	dbh ² *h	b	0.495	0.1464	3.382	0.00214 **								
Leaf (Eq4)	Intercept	lna	-2.6675	1.1719	-2.276	0.0313 *	0.8435	0.2425	1.000085	27.32	0.013	0.007443	1.2426	0.224
Leaf (Eq4)	dbh	b	1.6859	0.6434	2.62	0.0145 *								
Leaf (Eq4)	Ht	c	-0.5019	0.9505	-0.528	0.602								
Leaf (Eq4)	density	d	0.5737	0.5429	1.057	0.3003								
Global Biomass	Intercept	lna	-2.8815	0.4317	-6.675	3.04e-07 ***	0.9013	0.2928	1.043798	15.37	0.5116	7.94E-16	0.82566	0.4157
Global Biomass	dbh	b	2.3837	0.1462	16.307	7.94e-16 ***								
Global Biomass	Intercept	lna	-3.1821	0.5111	-6.226	9.99e-07 ***	0.8761	0.3281	1.0553	22.2	0.5896	1.95E-14	0.72703	0.473
Global Biomass	dbh. ht	b	1.4562	0.1014	14.355	1.95e-14 ***								
Global Biomass	Intercept	lna	-3.17895	0.45338	-7.012	1.26e-07 ***	0.8999	0.2949	1.044442	15.79	0.5436	9.71E-16	0.71097	0.4828
Global Biomass	dbh ² *h	b	0.91795	0.05674	16.179	9.71e-16 ***								
Global Biomass (Eq4)	Intercept	lna	-3.0908	0.4593	-6.729	3.86e-07 ***	0.9013	0.2929	1.043829	17.16	0.522	8.21E-14	0.76301	0.4516
	dbh	b	2.115	0.2522	8.387	7.21e-09 ***								
	Ht	c	0.5034	0.3726	1.351	0.188								
	density	d	0.155	0.2128	0.729	0.473								
Sudano-Sahelian data														
		Regression coefficients					Goodness of fit						t-test	
Components	Predictor	Parameters	Est.	SE	t-value	Pr(> t)	adj R2	RSE	CF	AIC	RMSE	P-Value	t	p-value
Stem (Eq1)	Intercept	lna	-4.1053	0.5142	-7.984	1.08e-08 ***	0.8763	0.3538	1.064587	26.72	0.1122	1.90E-14	-0.01804	0.9857
Stem (Eq1)	dbh	b	2.4222	0.1686	14.37	1.90e-14 ***								
Stem (Eq2)	Intercept	lna	-3.9659	0.6501	-6.101	1.40e-06 ***	0.8095	0.439	1.101156	39.68	0.1526	8.32E-12	0.38322	0.7044
Stem (Eq2)	DBH.Ht	b	1.4252	0.1279	11.146	8.32e-12 ***								
Stem (Eq3)	Intercept	lna	-4.16357	0.57493	-7.242	6.97e-08 ***	0.8518	0.3872	1.077843	32.14	0.1413	2.42E-13	0.081872	0.9353
Stem (Eq3)	dbh ² *h	b	0.91535	0.07069	12.949	2.42e-13 ***								
Stem (Eq4)	Intercept	lna	-4.0946	0.5458	-7.502	5.77e-08 ***	0.8683	0.365	1.007416	30.37	0.1216	3.41E-12	0.11204	0.9116
Stem (Eq4)	dbh	b	2.3828	0.2747	8.674	3.76e-09 ***								
Stem (Eq4)	Ht	c	0.1021	0.3784	0.27	0.789								
Stem (Eq4)	density	d	0.1734	0.3378	0.513	0.612								
Branch (Eq1)	Intercept	lna	-5.2567	0.6462	-8.135	7.42e-09 ***	0.8796	0.4446	1.1039	40.43	0.4698	4.00e-14	1.1265	0.2692

Branch (Eq1)	dbh	b	2.9538	0.2118	13.943	4.00e ⁻¹⁴ ***								
Branch (Eq2)	Intercept	lna	-5.1367	0.7886	-6.513	4.65e ⁻⁰⁷ ***	0.8469	0.5326	1.1524	51.27	0.5203	6.47e ⁻¹²	1.4809	0.1494
Branch (Eq2)	Dbh*h	b	1.7478	0.1551	11.268	6.47e ⁻¹² ***								
Branch (Eq3)	Intercept	lna	-5.3592	0.7046	-7.606	2.76e ⁻⁰⁸ ***	0.8514	0.4746	1.119209	44.35	0.5196	2.51e ⁻¹³	1.2766	0.2119
Branch (Eq3)	dbh ² *h	b	1.1201	0.0866	12.93	2.51e ⁻¹³ ***								
Branch (Eq4)	Intercept	lna	-5.1639	0.6665	-7.748	3.21e ⁻⁰⁸ ***	0.8685	0.4457	1.1404	41.95	0.5126	2.69e ⁻¹²	1.1404	0.2634
Branch (Eq4)	dbh	b	2.7453	0.3389	8.101	1.40e ⁻⁰⁸ ***								
Branch (Eq4)	Ht	c	0.2437	0.454	0.537	0.596								
Branch (Eq4)	density	d	-0.2122	0.149	-1.425	0.166								
Leaf (Eq1)	Intercept	lna	-2.9894	0.3465	-8.628	2.25e ⁻⁰⁹ ***	0.8473	0.2384	1.0288	3.03	0.0171	9.53e ⁻¹⁴	0.7681	0.4486
Leaf (Eq1)	dbh	b	1.5285	0.1136	13.457	9.53e ⁻¹⁴ ***								
Leaf (Eq2)	Intercept	lna	-2.9801	0.3968	-7.51	3.52e ⁻⁰⁸ ***	0.8247	0.268	1.0366	10.06	0.022	2.58e ⁻¹²	0.7921	0.4348
Leaf (Eq2)	Dbh*h	b	0.9149	0.0781	11.72	2.58e ⁻¹² ***								
Leaf (Eq3)	Intercept	lna	-3.0756	0.3608	-8.523	2.89e ⁻⁰⁹ ***	0.8358	0.243	1.03	4.2	0.0203	1.65e ⁻¹³	0.728	0.4725
Leaf (Eq3)	dbh ² *h	b	0.58373	0.04436	13.157	1.65e ⁻¹³ ***								
Leaf (Eq4)	Intercept	lna	-3.0954	0.3629	-8.529	5.22e ⁻⁰⁹ ***	0.8458	0.2414	1.0299	5.56	0.0187	9.23E-12	0.7404	0.465
Leaf (Eq4)	dbh	b	1.4137	0.18477	7.651	4.04e ⁻⁰⁸ ***								
Leaf (Eq4)	Ht	c	0.2369	0.2472	0.958	0.347								
Leaf (Eq4)	density	d	0.07539	0.12237	0.616	0.543								
Global Biomass (Eq1)	Intercept	lna	-3.7891	0.4769	-7.945	1.18e ⁻⁰⁸ ***	0.909	0.3281	1.0553	22.21	0.4844	2.49e ⁻¹⁶	0.8385	0.4086
Global Biomass (Eq1)	dbh	b	2.6683	0.1564	17.066	1.18e ⁻⁰⁸ ***								
Global Biomass (Eq2)	Intercept	lna	-3.6753	0.6269	-5.862	2.65e ⁻⁰⁶ ***	0.8488	0.4234	1.0938	37.5	0.5332	3.22e ⁻¹³	1.2081	0.2368
Global Biomass (Eq2)	Dbh*h	b	1.5778	0.1233	12.796	3.22e ⁻¹³ ***								
Global Biomass (Eq3)	Intercept	lna	-3.8783	0.5375	-7.215	7.46e ⁻⁰⁸ ***	0.8894	0.362	1.0677	28.11	0.4937	3.94e ⁻¹⁵	0.9545	0.3477
Global Biomass (Eq3)	dbh ² *h	b	1.0114	0.0661	15.305	3.94e ⁻¹⁵ ***								
Global Biomass (Eq4)	Intercept	lna	-3.8332	0.503	-7.621	4.34e ⁻⁰⁸ ***	0.9035	0.3381	1.0588	25.78	0.4852	6.08e ⁻¹⁴	0.7922	0.4347
Global Biomass (Eq4)	dbh	b	2.5818	0.2582	10	2.12e ⁻¹⁰ ***								

Global Biomass (Eq4)	Ht	c	0.1604	0.3501	0.458	0.651								
Global Biomass (Eq4)	density	d	0.0546	0.1674	0.326	0.747								

Table 17: Summary of the best allometric models selected for *D. microcarpum* in Sudanian and Sudano-Sahelian climatic zone in Burkina Faso

Sudanian									
		R ²	Adj-R ²	SSR	MSE	RMSE	AIC	Paired t-test	
								statistic	P.value
Stem	$\ln(\text{dbh}^2 \cdot h) = -4.4002 + 0.9456 \ln(\text{dbh}^2 \cdot h)$	0.9126	0.9094	2.3166	0.0827	0.2877	14.3034	0.5919	0.5585
Branch	$\ln(\text{dbh}) = -3.5219 + 2.4007 \ln(\text{dbh})$	0.8511	0.8657	4.0557	0.1448	0.3806	31.1038	0.8775	0.3874
leaf	$\ln(\text{dbh}) = -2.8845 + 1.3461 \ln(\text{dbh})$	0.8435	0.8457	1.5522	0.5543	0.2145	27.3672	1.5824	0.1244
Additive	$\text{TAGB} = e^{-4.1053(\text{dbh})^2.4222} + e^{-5.2567(\text{dbh})^2.9538} + e^{-2.9894(\text{dbh})^1.5285}$	0.9143	0.9099	2.6344	0.0941	0.3067	15.7935	0.9358	0.3088
Global model	$\text{AGB} = e^{-2.8815(\text{dbh})^2.3837}$	0.8901	0.9013	3.0201	0.1079	0.3284	16.9145	0.8257	0.4157
Sudano-Sahelian									
		R ²	Adj-R ²	SSR	MSE	RMSE	AIC	Paired t-test	
								statistic	p-value
Stem	$\ln(\text{dbh}) = -4.1053 + 2.4222 \ln(\text{dbh})$	0.8806	0.8763	3.5042	0.1252	0.3538	26.7189	-0.0206	0.9837
Branch	$\ln(\text{dbh}) = -5.2567 + 2.9539 \ln(\text{dbh})$	0.8796	0.8696	5.5346	0.1977	0.4446	40.4311	1.1272	0.2689
leaf	$\ln(\text{dbh}) = -2.9894 + 1.5285 \ln(\text{dbh})$	0.8661	0.8613	1.5910	0.0568	0.2384	3.0305	0.7683	0.4485
Additive	$\text{TAGB} = e^{-4.1053(\text{dbh})^2.4222} + e^{-5.2567(\text{dbh})^2.9539} + e^{-2.9894(\text{dbh})^1.5285}$	0.9132	0.9099	2.6135	0.0827	0.3125	21.9446	1.1162	0.2735
Global model	$\text{AGB} = e^{-3.7891(\text{dbh})^2.6683}$	0.9123	0.9092	3.0147	0.1077	0.3281	22.2054	0.8390	0.4083

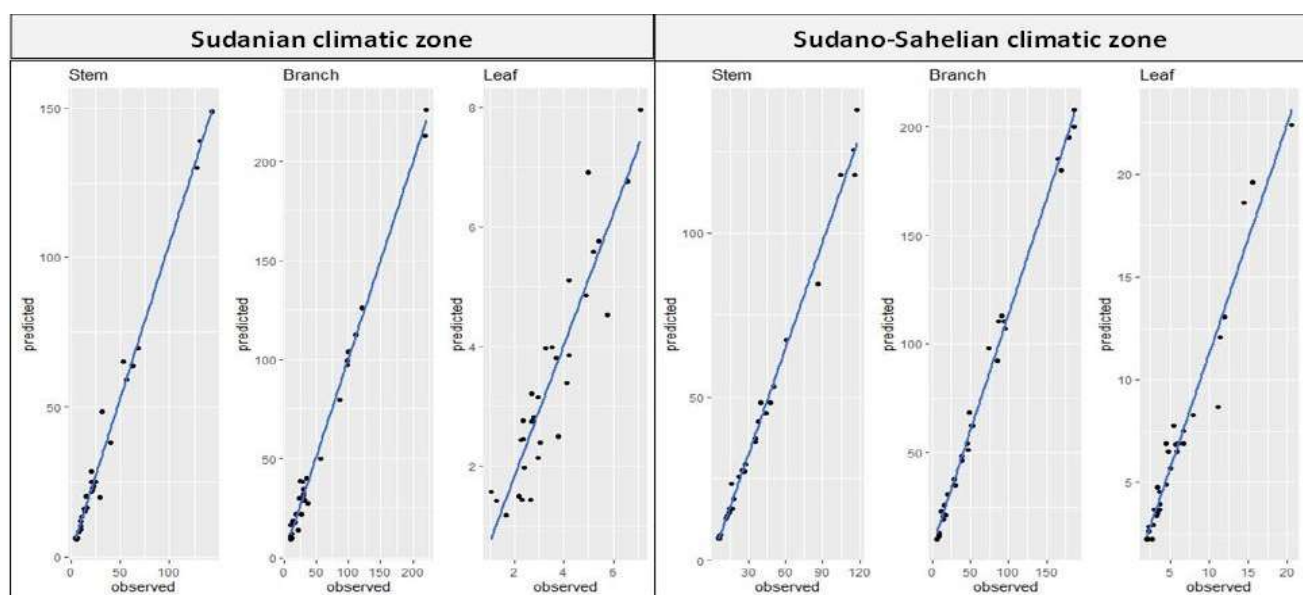


Figure 25: Scatter plots of observed and predicted aboveground biomass values of each component of *D. microcarpum* in Burkina Faso

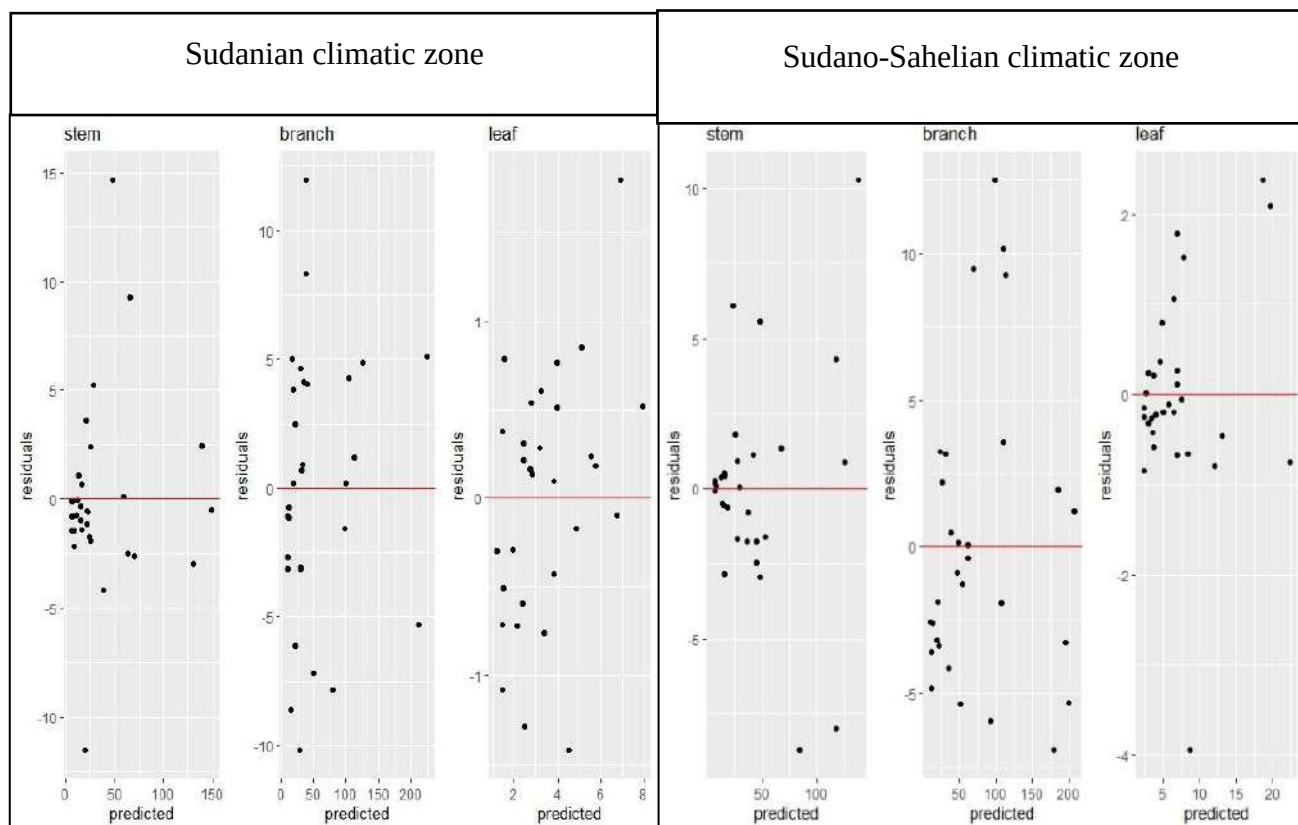


Figure 26: Residuals plot of each component of *D. microcarpum* in Burkina Faso

6.4.3. Aboveground biomass and carbon partition in tree components

The allocation of biomass among tree compartments varied with tree size and climatic zone, with the relative proportion of biomass showing significant differences ($P \leq 0.05$) across the three components of *Detarium microcarpum*. The analysis of the branch biomass showed a highly significant variation according to the climatic zones ($P \leq 0.001$). The biomass stored in the stem, branch, and leaves was also significantly varied according to the climate zones ($P \leq 0.001$) shown in **Figure 27**. According to the average biomass and the carbon partition, the analysis revealed that branches had the highest biomass fraction and carbon content among all tree components. In the Sudanian, the branch above-ground biomass partition was 210.52 ± 281.9 and 218 ± 151.94 for the Sudanian and Sudano-Sahelian climatic zone. The above-ground biomass of the stem was 149.84 ± 102.29 and 151 ± 61.23 in the Sudanian and Sudano-Sahelian zones respectively. The leaves had the lower allocation in the two zones with 6.04 ± 2.94 and 12.06 ± 5.05 in the Sudanian zone and Sudano-Sahelian zone, respectively. The Carbon content showed the same trend in both climatic zones with a lower content in leaves. The mean of leaves, branches, and stem carbon of *D. microcarpum* was 55.47 ± 0.22 ; 57.47 ± 0.37 , and 56.79 ± 0.07 in the Sudanian zone and, 55.62 ± 0.28 ; 57.56 ± 0.27 and 56.82 ± 0.34 in the Sudano-Sahelian zone. Moreover, the findings indicate that the biomass allocation among tree components is significantly higher in the Sudano-Sahelian zone compared to the Sudanian zone, as indicated in **Table 17** and illustrated in **Figure 27**. The significant variation in biomass and carbon content between the two climatic zones allowed us to establish the allometric model for each climatic zone.

Table 18: Biomass and carbon allocation for aboveground components for the ten trees of *D. microcarpum* in each climatic zone of Burkina Faso

Component	Sudanian zone			Sudano-Sahelian		
	Dry biomass $\pm$ sd	Mean carbon content $\pm$ sd	Carbon stock	Dry biomass $\pm$ sd	Mean carbon content $\pm$ sd	Carbon stock
stems	149.84 $\pm$ 102.29	56.79 $\pm$ 0.07	85.1	151 $\pm$ 61.23	56.82 $\pm$ 0.34	86.05
Branch	210.52 $\pm$ 281.9	57.47 $\pm$ 0.37	120.98	218 $\pm$ 151.94	57.56 $\pm$ 0.27	126.05
leaves	6.04 $\pm$ 2.94	55.47 $\pm$ 0.22	3.37	12.06 $\pm$ 5.05	55.62 $\pm$ 0.28	6.71
TAGB	366.41 $\pm$ 387.13	169.99 $\pm$ 0.66	209.45	382.51 $\pm$ 105.52	169.99 $\pm$ 0.88	218.81

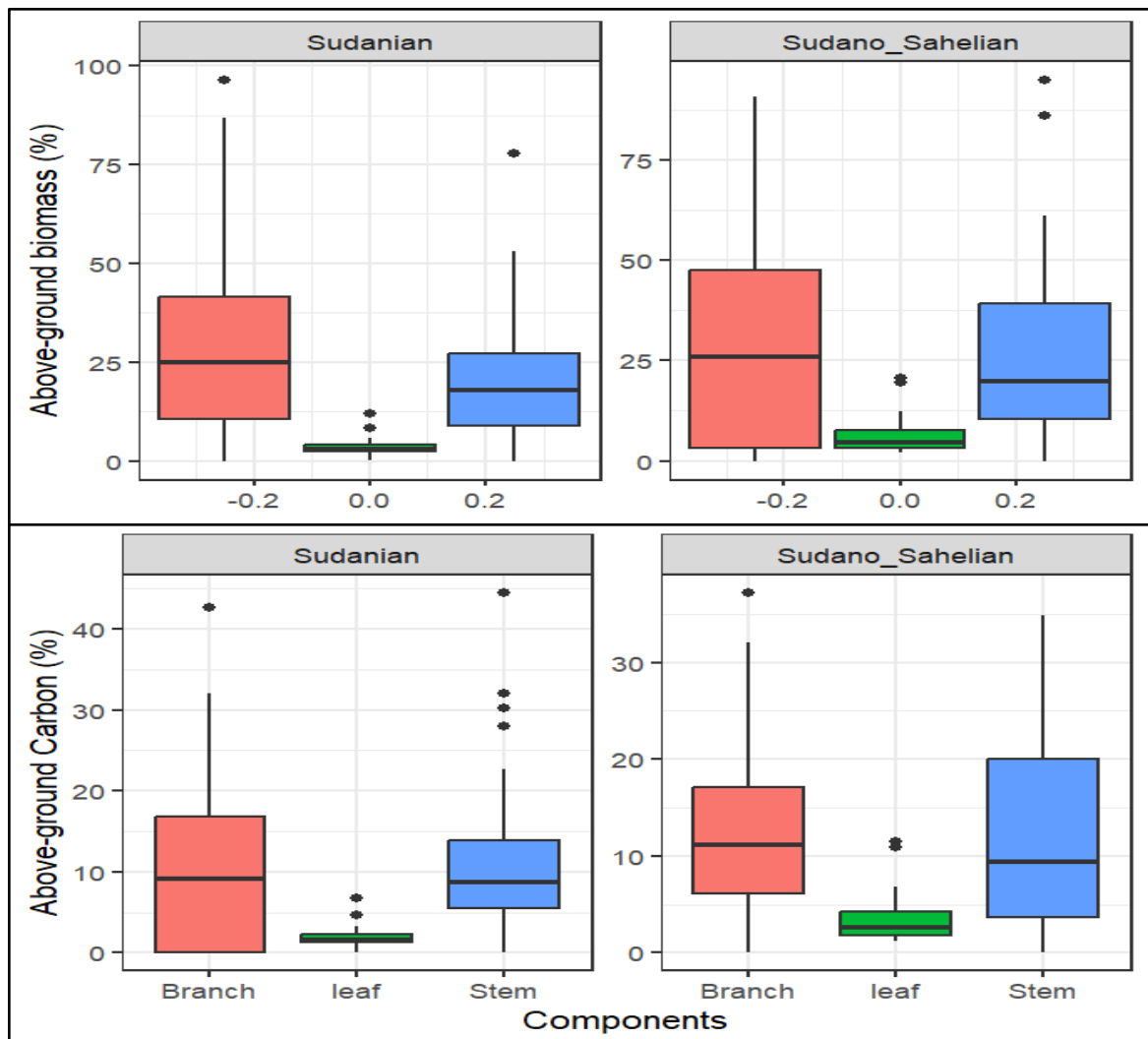


Figure 24: Biomass allocation and Carbon content in tree components of *Detarium microcarpum* in the two climatic zones in Burkina Faso

6.5. Predicting the Potential Distribution of *Detarium microcarpum* in Burkina Faso in response to different Shared Socioeconomic Pathways under CMIP6.

6.5.1. Bioclimatic variables contributions and model validation

The result of the MaxEnt output presented six variables which influence highly the distribution of the *Detarium microcarpum*. Among these variables, Isothermality (bio3), Mean Temperature of Wettest Quarter (bio8), Precipitation of driest month (bio14), cation exchange capacity at 0–5 cm (cec01), 15–30 cm (cec03) of the soil deeper, and the elevation influence the distribution of the species (**Table 18**). The variable Bio8 contributed most to the model while the variable cec01 (cation exchange capacity at 0–05 cm horizon) contributed the least. The Area Under the receiver operating characteristic Curve (**Figure 28**) showed good accuracy with a mean AUC of 0.845 which is better than random (0.5) indicating the high capability of the models. This value of AUC indicates the very good quality of the model for predicting the spatial distribution of the *Detarium microcarpum*. The value of the TSS is 0.661. This value > 0.5 confirms that the model performs better than random with a good performance.

The results of the Jackknife tests (**Figure 29**) showed that the dominant environmental variable which influenced the distribution of *Detarium microcarpum* is the Mean Temperature of the Wettest Quarter (bio8) compared to the other variables.

For each given prediction variable, the corresponding green bar shows how much the total gain is decreased in case this specific variable is excluded from the model. The blue bar shows the gain obtained if the variable considered is used in isolation and the others are excluded from the model and the red bar indicates the gain obtained using all variables. The curves of each variable are represented in **Appendix C**.

Table 19: Contribution of bioclimatic variables used for model running for prediction the distribution of *D. microcarpum* in Burkina Faso

Variable	Variable definition	Percent contribution
Bio8	Mean Temperature of Wettest Quarter	59
Bio3	Isothermality ((Bio1/Bio3) *100)	25.3
Elev	Elevation	9.9
Bio14	Precipitation of Driest Month	3.2
cec03	Cation exchange capacity (cec) horizon 15-30 cm	1.5
cec01	Cation exchange capacity (cec) horizon 0-5 cm	1.2

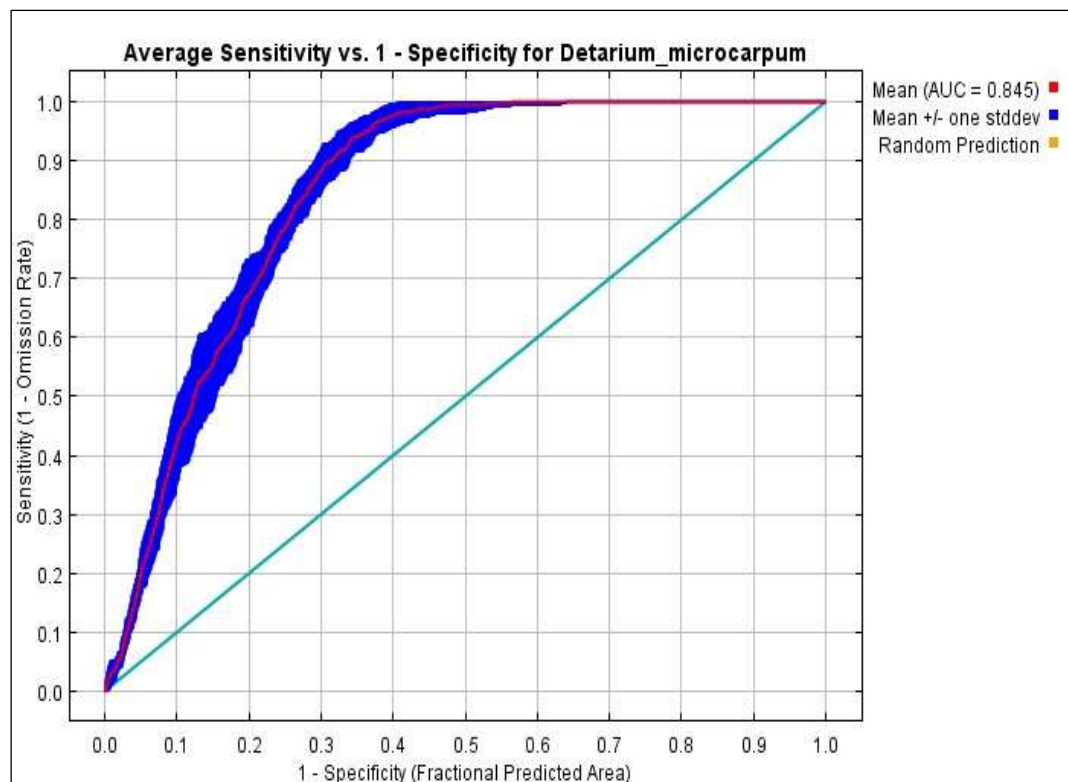


Figure 25: Average receiver operating characteristic curve and related AUC for prediction the spatial distribution of *D. microcarpum* in Burkina Faso

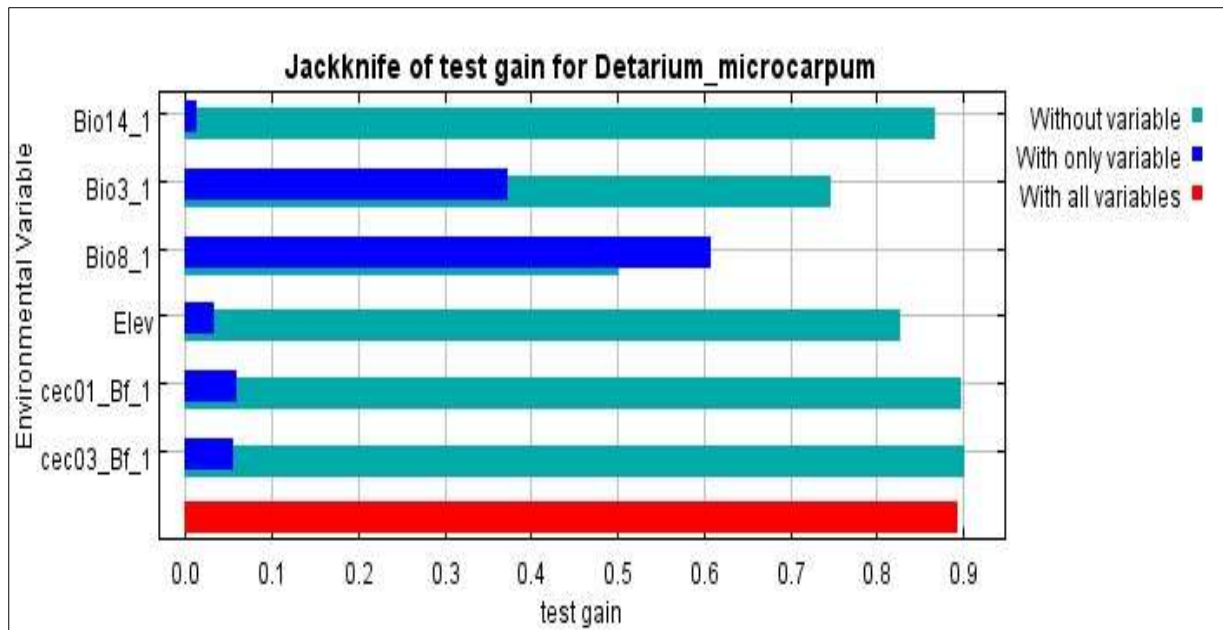


Figure 26: Results of a jackknife test for regularized training gain for *Detarium microcarpum*.
 Noted: Bio14_1: Precipitation of Driest Month, Bio3_1: Isothermality ((Bio1/Bio3) *100), Bio8_1: Mean Temperature of Wettest Quarter; Elev = elevation (slop), Cec01_Bf_1: cation exchange capacity (cec) horizons 0–5 cm, Cec03_Bf_1: cation exchange capacity (cec) horizons 15–30 cm.

The dark blue bars indicate that the gain from using each variable in isolation, the light blue bars indicate the gain lost by removing the single variable from the full model, and the red bar indicates the gain using all of the variables.

6.5.2. Current and future distribution of *D. microcarpum*.

The current distribution of *D. microcarpum* shows that the Sudano-Sahelian and the Sudanian zones are the most suitable zones (**Figure 30**). Currently, up to 180700 km² corresponding to 65.5% of the country are the suitable distribution areas of the species (**Table 20**). Besides, 100732.2 km² corresponding to 36.74% of the country represent currently the highly suitable habitats for species conservation (**Figure 31**). The low suitable areas under current climatic conditions for *D. microcarpum* conservation cover 79968.2 km² corresponding to 29.16 % of the country's territory. However, 93499.52 km², which corresponds to 34.099 % of the national territory, is revealed as an unsuitable area.

Under future climate conditions for the years 2070 and 2090, the low suitable habitats designated for conservation will increase because highly suitable areas will be reduced according to the models ACCESS-CM2, CNRM-CM6–1, HadGEM3-GC31-LL and MIROC6 respectively for the two scenarios. In addition, a reduction in unsuitable areas was recorded as a result of their conversion to low-suitable areas (**Figure 32, Table 2**).

In the MIROC6 model (**Figure 32**), the suitable areas which constitute the low suitable and high suitable areas were 73.55% and 73.15% at the country level, at the horizon 2070 and 2090, respectively, with the conversion of the high suitable area to the low suitable area under scenario SSP2-4.5 (**Table 20**). However, when considering the scenario SSP5-8.5 in the same model, the highly suitable areas were observed to increase for the benefit of the low-suitable areas. In addition, among the four models, the most habitat loss was expected in scenario SSP2-4.5 than the scenario SSP5-8.5.

Based on the **Figure 31** observation, the suitable area for the species conservation was mainly located in the Sudano-Sahelean climatic zone. Low Suitability areas for *D. microcarpum* will generally increase at horizon 2061-2080 and 2081-2100 under the two scenarios SSP2-4.5 and SSP5-8.5 regardless of the model. According to the future projection, the suitable areas for *D. microcarpum* differ from the four SSP scenarios. However, unsuitable areas become less suitable areas under the two scenarios according to the four models. The findings of this study showed the trend of low suitability will increase compared with the current distribution of the species. In both scenarios of the CNRM-CM6–1 model (**Figure 31**), the highly suitable areas were expected to be lost. For instance, the distribution of the species for the two scenarios of the ACCESS-CM2 (**Figure 31**) was expected to increase from 4.867% to 9.978%. For the SSP2-4.5 and SSP 5-8.5, future projections showed a high increase in low suitable habitats for the species with the decline of the high suitable areas.

Comparing the potential distributions of current and future scenarios for all models, the high suitable area was expected to decrease for the benefit of the low suitable and unsuitable area at the country level (**Figure 32**). The analysis showed a decrease of highly suitable habitats for the species for all the models except the scenario SSP5-8.5 of the MIROC6 (**Figure 31 and 32**) and (**Table 20**) model, which observed the increase in a suitable area. These analyses show that highly suitable and unsuitable areas in the Sudanian and Sudano-Sahelian climatic zones will shift to low suitable areas, with migration toward the currently unsuitable Sahelian climatic zone.

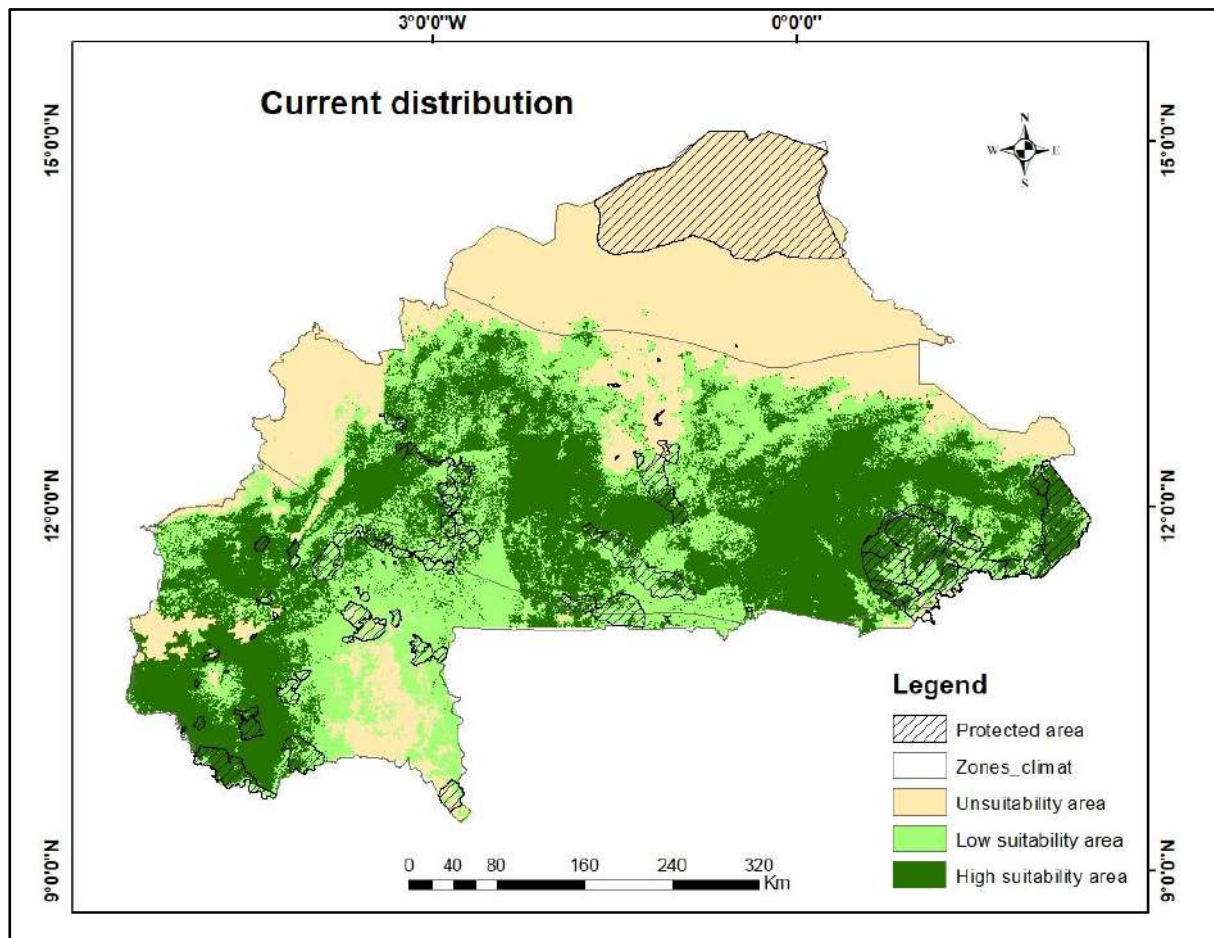


Figure 30: Maps showing the current distribution of *Detarium microcarpum* in Burkina Faso

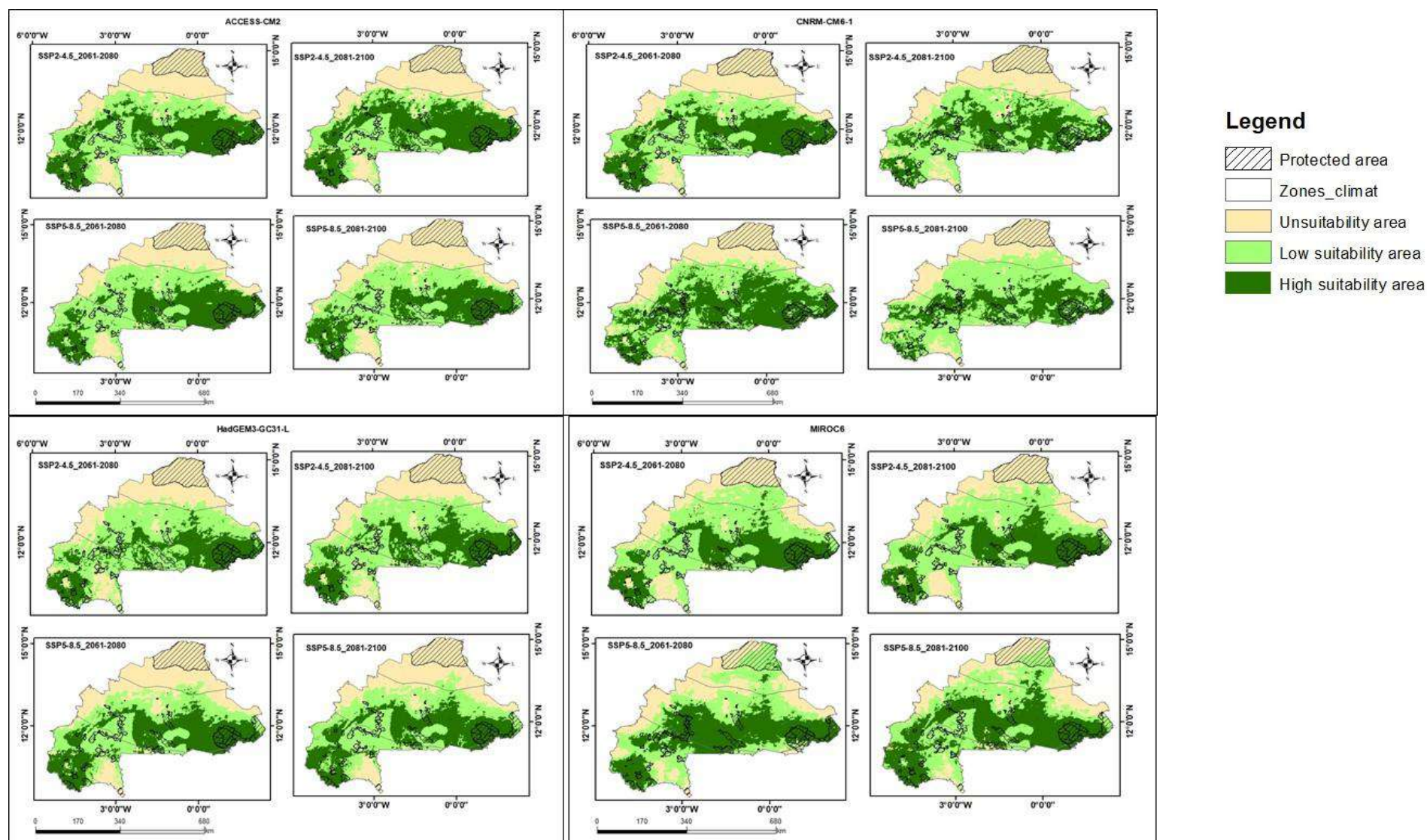


Figure 27: Distribution of *Detarium microcarpum* under the future change condition in Burkina Faso.

Table 20: Current and future distribution trend of *D. microcarpum* in Burkina Faso.

Model	Scenarios SSP	Horizon	Unsuitability		Low Suitability		High Suitability			Total suitability			
			Extent (Km²)	%	Extent (Km²)	%	Trend (%)	Extend (Km²)	%	Trend (%)	Extend (Km²)	%	Trend (%)
Current			93499.53	34.1	79968.28	29.16		100732.2	36.74		180700.48	65.5	
ACCESS-CM2	245	2061-2080	90703.13	33.08	93286.29	34.02	4.86	90210.58	32.89	-3.84	183496.87	66.91	1.41
	245	2081-2100	89342.56	32.58	95718.08	34.91	5.74	89139.36	32.51	-4.22	184857.44	67.42	1.92
	585	2061-2080	83794.09	30.56	104587.3	38.14	8.979	85818.63	31.3	-5.43	190.405.93	69.44	3.94
	585	2081-2100	91367.11	33.32	103586.3	37.78	8.61	79246.6	28.90	-7.83	182832.9	66.68	1.18
CNRM-CM6-1	245	2061-2080	68743.38	25.07	125169.7	45.65	16.49	80286.88	29.28	-7.46	205456.58	74.93	9.43
	245	2081-2100	83986.42	30.63	109717.6	40.01	10.85	80495.94	29.36	-7.38	190213.54	69.37	3.87
	585	2061-2080	72021.46	26.27	126251	46.04	16.88	75927.55	27.69	-9.05	202178.55	73.73	8.23
	585	2081-2100	66546.57	24.27	133687.7	48.77	19.59	73965.72	26.96	-9.76	207653.42	75.73	10.23
HadGEM3-GC31-LL	245	2061-2080	84416.25	30.79	115838.9	42.25	13.08	73944.81	26.97	-9.77	189783.71	69.22	3.72
	245	2081-2100	79403.81	28.96	116186.8	42.37	13.21	78609.38	28.67	-8.07	194796.18	71.04	5.54
	585	2061-2080	93666.78	34.16	94277.23	34.38	5.218	86255.99	31.46	-5.28	180533.22	65.84	0.34
	585	2081-2100	88183.53	32.16	102279.2	37.30	8.14	83737.22	30.54	-6.2	186016.42	67.84	2.34
MIROC6	245	2061-2081	72513.17	26.45	125868	45.90	16.74	75818.84	27.65	-9.09	201686.84	73.55	8.05
	245	2081-2100	73629.55	26.85	118524.9	43.23	14.06	82045.5	29.92	-6.82	200570.4	73.15	7.65
	585	2061-2080	73418.82	26.78	98503.61	35.92	6.76	102277.6	37.30	0.56	200781.21	73.22	7.72
	585	2081-2100	62163.82	22.67	106631.9	38.89	9.73	105404.3	38.44	1.70	212036.2	77.33	11.83

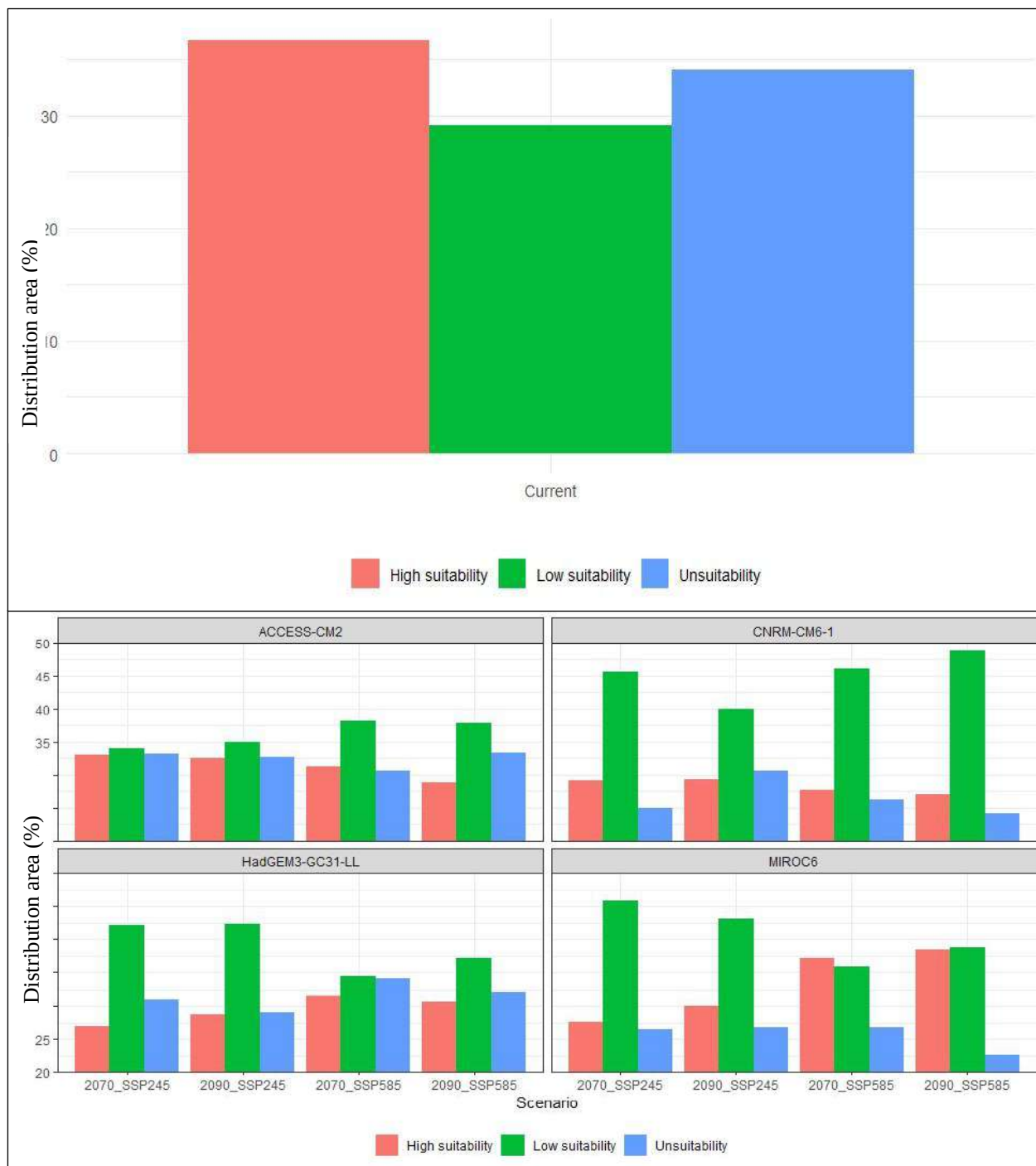


Figure 28: Dynamic of the suitable areas for *D. microcarpum*, in the present and the two future climate scenarios.

CHAPTER 7: DISCUSSION

This study showed that *Detarium microcarpum* is a species with multiple uses, with local communities exploiting nearly every part of the plant such as roots, bark, trunk, fruit, leaves, and branches for a variety of purposes. This extensive use underscores the significant value of *Detarium* species as multipurpose resources for the local population (**Gaisberger et al., 2017**). The broad spectrum of applications for these species confirms their importance in supporting rural livelihoods (**Sreekumar et al., 2020; Houénon et al., 2021**). **Dimobe et al. (2018)** identified *Detarium* species among the priority multipurpose species in Burkina Faso, a designation also accorded to other species like *Azizelia africana* (**Balima et al., 2018**) and *Bombax costatum* (**Zerbo et al., 2022**). These results show that species provide non-timber forest products which help the rural population to improve their livelihoods.

Informants mostly mentioned the use of fruits and trunks of the *Detarium microcarpum*. The high fruit usage indicates that the species play a role in food security, contributing to the resilience of rural populations. Similarly, the extensive use of trunks indicates the dependency on the species for timber (**Sinadouwirou et al., 2022**).

The study also revealed that sociodemographic factors influence the use patterns of *Detarium microcarpum*. Women's focus on trunks and branches underlines the use of the species as firewood and is indicative of their role in gathering firewood, a task integral to cooking responsibilities within households. This pattern aligns with observations made by **Kouyaté (2005)** in Mali and **Agbo et al. (2020)** in Benin, highlighting this gendered knowledge and use of firewood trees. This particular interest in trunks poses a considerable challenge to the conservation of the species (**Biara et al., 2021**), as it directly impacts the availability of mature trees. Harvesting leaves, fruits, and bark could also potentially affect the reproductive performance of the species, further stressing the need for sustainable management practices (**Nacoulma et al., 2017**).

The distinct consensus value for plant parts reported by individuals with higher levels of education, compared to the lower values associated with branches and trunks, suggests that the level of education influences choices regarding energy sources. **Gkargkavouzi et al. (2020)** illustrated that a higher education level is often correlated with a positive stance towards species conservation, implying that education plays a crucial role in promoting conservation efforts. However, the impact of modernisation and development seems to be affecting traditional knowledge systems concerning the use of multipurpose species in the region.

Monteiro et al. (2006) explained how progress in modernisation has influenced the dynamics of plant use, potentially diminishing the transmission and application of indigenous knowledge concerning these species.

The pronounced preference for fruit among traders and farmers, as indicated by the high CPP values, underscores the dual role of *Detarium microcarpum* as both a nutritional supplement for farmers and a source of income. This observation aligns with the work of **Lykke et al. (2004)**, which showed that the importance attached to a species often depends on its utility to different user groups. Furthermore, **Monteiro et al. (2006)** and **Zerbo et al. (2022)**, observed that preferences for specific plant parts differ among communities, highlighting the diverse ways in which multipurpose species support the resilience and food security of rural communities. The importance of such species in the livelihoods of rural populations is further supported by **Kuhlman et al. (2010)**; **Guigma et al. (2012)**, and **Balima et al. (2018)** studies. The broad involvement of the different parts of *Detarium microcarpum* across six categories of use highlights their importance to the local population. This study found that gender, age, and occupation influence knowledge about the species' uses, in line with results reported by **Monteiro et al. (2006)**. The exploitation of different parts was strongly linked to occupation and education levels. Notably, fruit sales are dominated by young people and women, highlighting their active participation in utilising these species for economic benefits. Younger individuals, full of energy and driven by the pursuit of wealth, show a keen interest in collecting the fruit of *D. microcarpum* (**Biara et al., 2021**). **Kristensen & Balslev (2003)** suggest that sociocultural and demographic factors such as gender, age, and education level correlate with the knowledge and use of plant parts. **Malleson et al. (2014)**, demonstrated that NTFPs offer new income sources for many women in the rural areas of Cameroon and Nigeria.

The high frequency of use reported by women in the energy category (firewood) underlines the species' value to households, likely due to the wood's flame intensity and low smoke emission (**Ramos et al., 2008**; **Sinadouwirou et al., 2022**). Other studies like **Dao et al. (2020)** and **Sinadouwirou et al. (2022)**, have also emphasised wood characteristics as a primary factor in firewood selection. Moreover, another study pointed out the dependence of local populations on forest resources for various needs and income generation, exacerbating deforestation and forest degradation highlighted by **Hesselberga & Iversenb (2011)**.

Ethnic groups and age-related preferences were observed, with the Mossi using the species for firewood and the younger population engaging in fruit selling, indicating usage variations based on ethnic groups and age. **Diatla (2021)**, mentioned that *Detarium microcarpum* was at the heart of local income activities in Thiobon, Senegal. Their use in traditional medicine

constitutes a significant degradation factor (**David et al., 2017**). This medicinal importance can be attributed to antimicrobial, anti-inflammatory, and antimalarial effects, as well as nutritional components (**Kini et al., 2010; Dieng et al., 2016**). **Dogara (2022)**, found that each part of the *D. microcarpum* plant has a therapeutic application, and the plant is often referred to as a miracle plant by traditional herbalists. In addition, the widespread use of bark and roots in traditional medicine illustrates the species' therapeutic significance, aligning with global reliance on traditional medicine as a source of primary health care (**Houénon et al., 2021**).

The use of the *Detarium microcarpum* for crafts and construction reflects their wood quality, which **Sawadogo (2007)** identified as a factor contributing to their vulnerability. Members of the Dagara ethnic group mentioned that cultural practices, such as rituals conducted by traditional healers, also influence the use of these species. The extensive use of bark, branches, roots, and fruits, as highlighted in this study, poses a serious threat to the sustainability of these species. Rural communities, particularly women and young people, heavily depend on multipurpose species like *Detarium microcarpum* for income, especially through activities such as fruit harvesting and selling (**Kagambega, 2019**).

Moreover, the findings show that *Detarium microcarpum* are highly valued by local populations, underscoring their critical role in areas of natural occurrence. The consensus among these communities indicates that protected areas and fallows are key zones of abundance, further emphasising the importance of these regions for the conservation of the species (**Assogbadjo et al., 2012**). This follows **FAO (2015)** findings which highlight a positive relationship between species abundance and habitat protection. The species' presence on hills and granite rocks corroborates previous studies indicating a preference for granitic soils (**Aubréville & Trochain, 1937; Diop et al., 2010; Dossa et al., 2020**). In contrast, the diminished presence of *Detarium microcarpum* in villages underscores the adverse impact of unregulated exploitation and habitat degradation in non-protected areas. This observation is consistent with **Agbo et al. (2017)** and other studies, which highlight the complex interplay between species protection, uses, proximity, and cultural practices (**Avakoudjo et al., 2020; Coulibaly et al., 2021; Dogara, 2022**). These findings suggest an urgent need for the domestication of *Detarium microcarpum* to mitigate the risks associated with their overexploitation and to promote sustainable use (**Kouyaté et al., 2002; Sinadouwirou et al., 2022**).

The surveys revealed that local populations are aware of the decline and the disappearance of *Detarium microcarpum* from their habitat, primarily attributed to the overexploitation of plant parts, such as the bark and the trunk, alongside habitat destruction for

agricultural expansion. This indiscriminate exploitation across all plant parts significantly jeopardises the species' survival (**Yaovi et al., 2021**). The major threats identified in Burkina Faso include bushfires, population growth, wood over-exploitation, and traditional mining exploitation. **López-Carr (2021)**, shows the impact of urban development related to population growth on species dynamics, while **Gaisberger et al. (2017)**, explain that overexploitation is due to the vulnerability of local populations. Extensive farming is one of the most common causes of forest exploitation, with illegal logging for firewood contributing to the species' scarcity. Traditional mining exploitation, particularly at the Bontioli site, further exacerbates these threats. Consequently, the combined effect of these pressures constitutes a major challenge to the sustainable management of *Detarium microcarpum*, underlining the need for effective conservation strategies to mitigate the ongoing risks to their survival, as noted by **Avakoudjo et al. (2020)**.

In addition to the anthropogenic factors mentioned, local populations pointed out that climate events such as flood effects, drought during the rainy season impact the livelihood of the population which contributes to the vulnerability of *Detarium microcarpum*. Communities residing near protected areas perceive climate events like drought, high winds, and rising temperature as threat factors which impact *Detarium microcarpum* populations. **Nunes (2019)** and **Deb et al. (2021)** support this observation, indicating that local populations are often the first to notice the effects of climate change and forest degradation. **Gross-Camp et al. (2015)** and **Dey et al. (2017)** pointed out that the experiential knowledge of local communities, shaped by their livelihoods and direct interactions with their environment, plays a crucial role in recognising and understanding these impacts. Furthermore, the decline in fruit availability is largely attributed to illegal logging, which targets mature *Detarium microcarpum* trees, and to climatic hazards. These factors not only reduce the number of adult trees capable of fruit production but also negatively impact the overall health and reproductive capacity of the species (**Kamou et al., 2017; Kagambega, 2019; Fontodji et al., 2019**).

To ensure the sustainable conservation of *Detarium microcarpum*, local populations have emphasized the importance of raising awareness, implementing community management, and co-managing resources with forestry authorities. These approaches highlight the crucial role local stakeholders play in the sustainable use of ecosystem goods and services provided by woody species (**Badjaré et al., 2018**). However, the diversity of solutions proposed, influenced by occupations, showed the integral part forests play in supplementing community livelihoods. Local communities advocate for awareness, monitoring to protect against overexploitation, and the introduction of alternative species like almonds, which can help

combat overexploitation and the illegal exploitation of forest resources. Engaging local communities in species management enhances security through sustainable participatory management (**Delvingt & Doucet, 2000; FAO, 2013; 2015**), offering a unique opportunity to educate them on natural resource depletion and ecosystem service provision (**Gning et al., 2013**).

Site status influences management type, with suggestions including wood-cutting regulations, the promotion of more effective stoves, and alternative village energy solutions. To reduce the rate of species decline, local populations propose multiple conservation strategies to ensure sustainable use, such as financial support, product valorisation, training capacity building, and reforestation. This initiative proves that the sustainable management of indigenous species contributes to improving the livelihoods of rural communities. However, community contribution to forest management is highly variable and often dependent on their main occupation (**Lawin et al., 2019; Mugisho et al., 2022**). While some communities have a high degree of knowledge concerning species management, others require basic training specifically tailored to align with local knowledge and practices. **Kristensen & Balslev (2003)** explain that the local communities' opinion is the guideline to ensure the best management of natural resources. Despite the species not receiving much attention, species managers are taking steps to enhance the sustainable management of certain versatile species, including *Detarium microcarpum* productivity (**Jones & Lynch, 2007; Bowler et al., 2012; Wouyo et al., 2014**). Income diversification, especially for women and youths involved in the collection, is key to forest protection, as illustrated by studies from **Tiétiambou et al. (2016)** and **Hounsou-Dindin et al. (2022)**. Developing effective management strategies that consider the opinions and needs of local communities is essential for their conservation. The valorisation of *Detarium microcarpum* fruit, particularly by women, could integrate them into the value chain, boosting their incomes. The success of these initiatives requires collaboration among all stakeholders, including policymakers, local communities, researchers, extension agencies, and funding bodies. While the valorization of *Detarium microcarpum* fruit offers economic opportunities for local communities, particularly the rural population, it is equally important to consider the biodiversity within these stands to ensure sustainable management practices.

Overall, 102 woody species were recorded in *D. microcarpum* stands, divided into 79 genera ranging in 28 families. This species richness represents 19.21 % of the woody flora of Burkina. According to **Thiombiano et al. (2012)**, Burkina Faso contains 531 woody species. This result corroborates with **Balima et al. (2020)** which found 107 species divided into 73 genera ranged in 35 families on the natural stand of *Azelia africana* in the same climate zones.

These similarities characterise the predominance of the species to the Fabaceae family in the savannas ecosystem. The dominance of Fabaceae, Anacardiaceae, Combretaceae, and Malvaceae families characterizes dry climates (**Tindano et al., 2015**) and reveals the savanna character of these plant communities (**Ganamé et al., 2019**) associated with human pressures and climate pejoration (**Lankoandé et al., 2017**). Hill's diversity numbers revealed that species diversity decreased significantly from the Sudanian to Sudano-Sahelian zone and from protected to unprotected areas. In each climatic zone, the highest species diversity of *D. microcarpum* stands was recorded in Protected areas. Similar results were found by authors who demonstrated that Protected areas host higher diversity for stands of Combretaceae species (**Bognounou et al., 2009; Ganamé et al., 2019**); *Azelia africana* (**Balima et al., 2020**) and *Lannea microcarpa* (**Tinguéri et al., 2021**) in Burkina Faso and *Strychnos spinosa* (**Avakoudjo et al., 2022**) in Benin. The significant difference in mean species number and abundant species numbers between climate zones shows that the species richness increases with rainfall level in the Savanna ecosystem. **Li et al. (2015)** reported that human disturbance affected vegetation at the local scale and modified the ecosystem function. **Balima et al. (2020)** pointed out that agricultural land use contributes to the disturbance of species diversity. When comparing species richness according to the climatic zone and type of land use, the species richness gradually declines from Sudanian to Sudano-Sahelian zones and from protected areas to unprotected areas. The findings of this study indicate that protected areas have a significant positive impact on species diversity. Following that, the higher diversity found in Protected areas highlights the great potential of these non-disturbed ecosystems in biodiversity conservation (**Nacoulma et al., 2011**). This proves the positive effect of protecting forests, especially in the tropics (**Gray et al., 2016**) like Burkina Faso. The higher Hill index in the Sudanian climatic zone is due to the Kou classified forest. This forest minimizes cropland expansion and pasture while still retaining natural forest characteristics (**Yaovi et al., 2021**) and reveals the influence of better management practices. **Maryo & Wendawek (2014)** reported that the low evenness can be attributed to excessive environmental disturbances, variable conditions for regeneration, and selective exploitation.

Jaccard's index values showed little similarity in species composition in *D. microcarpum* plant formations along the two climatic zones. The low values of the similarity index indicate a high β -diversity between populations and could be related to the climatic effect.

The higher IVI values of *D. microcarpum* obtained for the Sudano-Sahelian zone highlight the ecological importance of the species in this climate zone. On the contrary, the lower IVI values obtained on the Sudanian zone for the same species indicate that *D. microcarpum* is not adapted

to the humid zone (**Lamy et al., 2021**). This corroborates the results of **Chejanovski & Wiens (2014)** who explained that the climatic gradient influences the species niche. According to **Zerbo et al. (2016)**, the low percentage of frequent species and the high rate of occasional and rare species implies on the one hand a great heterogeneity among plant communities of each climatic and land use condition with the human disturbance. Therefore, in the Sudanian and Sudano-Sahelian, the presence of some species (*Combretum glutinosum*, *Vittelaria paradoxa*, *Burkea africana*, *Piliostigma thonningii*, *crosopteryx februfiga*, *Entada africana*, *Terminalia laxiflora*) would be an indicator the presence of *D. microcarpum*. In the North of Ivory Coast, it has been reported that *Piliostigma thonningii* is an indicator of the presence of *D. microcarpum* on silty-clay soils (**Fournier, 1991**). Understanding the ecological indicators of *Detarium microcarpum* presence, along with the species response to climatic and land use factors, is essential for effective conservation and management strategies

Regarding the stand structure of *Detarium microcarpum*, the results show that climate and land use have a significant influence on the structural parameters. The high tree densities observed in the Sudano-Sahelian zones indicate that *D. microcarpum* is a savanna species that thrives in low humidity. This is underlined with **Lamy et al. (2021)** who pointed out that the high density of *D. microcarpum* in the Sudano-Sahelian zone could be due to the autecology of the species. In addition, the Sudano-Sahelian climate zone characterizes a lower rainfall quantity than the Sudanian zone. This is in line with previous studies such as **Nacoulma et al., (2011)**; **Zerbo et al. (2018)**; **Kabre et al. (2020)**; **Houénou et al. (2022)** showed that the differences in stand diversity in forests may be attributed to the climate effect and anthropogenic disturbances. This leads to a high development of the structural parameters of the woody species in this zone, especially *D. microcarpum* which is an important fodder species. In protected areas, the density of *D. microcarpum* was significantly higher than in unprotected areas. Human pressure contributes to the fragmentation of plant formations (**Sinadouwirou et al., 2022**) which leads to the loss of biodiversity. This result corroborates with **Nouhoun et al. (2019)** and **Kabré et al. (2020)** who explains that human activities such as extensive agricultural, illegal logging, and traditional mining exploitation reduce the density of the species. In fact, the lower number of large trees observed in the land use area compared with the protected area may be explained by logging, which mostly affects individuals of large diameter.

The effect of the abiotic factors (temperature, precipitation) and biotic factors (habitat heterospecific density and habitat-specific richness) on the *D. microcarpum* dendrometric parameters suggests a competitive interaction between the two factors. The abiotic have mainly

negative effects on the dendrometric parameters, while biotic factors show positive effects. This finding corroborates with **Atanasso et al. (2019)** who found that the heterospecific tree density influences the structure of *Afzelia africana* individual trees in the Pendjari Biosphere (Benin). The mean diameter, mean height, mean density, and basal area values were higher in the Sudano-Sahelian than in the Sudanian zone. This may be due to the climatic regime in the Sudano-Sahelian which favours the growth of the species. This corroborates with **Amoako & Gambiza (2021)** who pointed out that the regime of the climate influences the diameter size of *Anogeissus leiocarpa* Baill. in Guinea savannas of Ghana. In addition, The high population density found in this zone may be due to the quality of the soil which influences the symbiotic relationship between the roots of Leguminosae and mycorrhizal fungi (**Raddad et al., 2005; Houénon et al., 2022**).

The difference in the basal area between the protected and unprotected areas may be attributed to disparity in the surrounding species composition, degree of disturbances, age of trees, and the influence of the climate. **Kacholi (2019)** pointed out that the species composition influences the basal area of the species. The low basal area values in the unprotected area were related to high accessibility due to the nearby population's lack of enough protection (**Lamy et al., 2021**) and illegal logging (**Sinadouwirou et al., 2022**). Consequently, the conservation of *D. microcarpum* is not sustainable.

The Habitat heterospecific density, Habitat species richness, temperature, and Rainfall influence the structure of the *D. microcarpum* population at different levels. The negative impact of rainfall and temperature on the density and basal area of *D. microcarpum* indicates that the two variables have a contrasting influence on the recruitment and growth of the other species. However, higher rainfall decreases the temperature at the special scale (**Du et al., 2019; Rodrigo, 2022**) and influences the richness of the species and the basal area (**Bognounou et al., 2009; Premavani et al., 2014**). These results indicate that the decrease in diameter is related to the increase in tree competition. According to **Traoré et al. (2022)**, rainfall is one of the main climate variables which affect the species' population status.

Concerning population structure, rainfall is the main abiotic variable affecting the structure of *D. microcarpum*. This suggests that an increase in rainfall can disturb the recruitment process of *D. microcarpum* juveniles. **Traore et al. (2022)** found that the density of the *Faidherbia albida* species which is the savanna species was influenced by the rainfall. **Ostonen et al. (2011)** and **Mensah et al. (2020)** pointed out that climate variation affects several characteristics of adult tree species such as the timing of leaf growth, the duration of the

growing season, and the intensity of stress experienced by the trees in their natural stand. Likewise, the growth rate of the tree trunk is linked with the level of precipitation and temperature, which increase the photosynthesis rate and, then, cambial activity (**Schaffner, 2017**). The negative effect of habitat heterospecific density on Lorey's mean height can be explained by the competition of the species with other species occurring in the same habitat. This can be related to the competition for light and nutrients. According to **Aubréville & Trochain (1937)**, *D. microcarpum* is a medium-sized tree (8 m -12 m), and taller trees can affect their competitiveness for light. In fact, the light is one of the most limiting resources that impact the growth of the species in the forest (**Reuger et al., 2012; Azquez, 2020**) and the increased light levels affected juvenile recruitment. The availability of light, a key factor affecting growth and recruitment in forest species, further compounds the instability seen in the populations of *Detarium microcarpum*.

The distributions of diameter and height classes of *D. microcarpum* reveal unstable populations in all the study areas. The instability of the species populations observed in the two climatic zones was generally characterized by a low number of small-diameter individuals and an irregularity of the transition in their size class distribution. The same trend was found by **Kouyaté (2005); Houénon et al. (2022); Lamy et al. (2021); Agbo et al. (2018)** who explains that the weakness of the forests' protection has caused the species' threat. **Bentsi-Enchill et al. (2022)** pointed out that the overexploitation of the species in the Unprotected areas could be the reason for the instability of the species structure and the lack of protection. Usually, when trees are logged without replacement, their structures decrease (Rivero et al., 2008). Similar results indicating the degradation of tree populations were reported by **Traore et al. (2022)** for *Faidherbia albida* and **Mensah et al. (2020)** for *Azelaia africana* in Africa. The lack of individuals in the larger size classes in the Sudano-Sahelian could be due to the excessive exploitation of bigger trees by the locals for timber and construction purposes. This excessive exploitation should be linked to the preference of the ethnic group. In fact, In the Sudanian zone, the Mossi people are notably dominant and highly value the quality of *D. microcarpum* wood. The local population depends on forest resources for firewood, building materials, livestock, and income generation (**Kouyaté, 2011; Dossa et al., 2020**). This can reduce the availability of seeds and may thereby lead to a lack of regeneration (**Thomas, 2006**). According to **Bouché et al. (2011)** The elephant population was affected negatively by the recruitment of the species.

The size class distributions of the juvenile individuals suggest that the species are in a crucial stage of regeneration and recovering from disturbances.

The instability reported for the regeneration independent of the climate zone and the land use type indicated difficulties in recruitment and transition between the different classes in the species juvenile population (**Zerbo et al., 2023**). This instability would be linked to the pressures that the species faces, leading to its poor regeneration and then constitutes a threat to its survival. **Bationo et al. (2001)** pointed out that human pressure and bushfires impacted the recruitment of the *D. microcarpum* juvenile species. In addition, **Sinadouwirou et al. (2022)** explained that the seed of *D. microcarpum* has a natural germination difficulty compared to the other species due to the tegument dormancy. Besides, according to the same authors, the low individual number observed in the size class 0- 0.5 could also be explained by bushfires, which affected the fruit germination capacity due to burning. In addition, land clearing and tree density reduction for agricultural purposes may be detrimental to the seedling establishment and, hence, threaten the species (**Fandohan et al., 2011**). The illegal logging of *Detarium microcarpum* for firewood contributes also to the reduction of mature tree density, influencing the species' fruits and seed production. Previous studies showed that *D. microcarpum* wood was highly appreciated by the population, particularly by women because of its high flame intensity (**Kouyaté, 2005; Agbo et al., 2017**). The fruit harvest reduces the seed potential of edible tree species. Indeed, Taïta (2003) stated that species whose fruits and seeds are consumed often face regeneration issues. This is underlined with the findings of several authors who reported that the fruits of *D. microcarpum* are highly valued and consumed by the local populations (**Kouyaté, 2005; Dieng et al., 2016; Dieng et al., 2019; Agbo et al., 2020**). This study suggests that protecting *D. microcarpum* populations within Protected areas does not guarantee successful species recruitment across all size classes. The instability structure of the juvenile would also be due to the regime of the bushfire which impacted the recruitment of the species. While fire regimes, human threats, climate effects and protection within designated areas affect the recruitment and structure of *D. microcarpum* populations, insights from wood anatomy offer an additional understanding of the species' growth dynamics

Anatomical observation of the cross-section of the wood of *D. microcarpum* species showed that growth rings were visible and characterized by lines of tangential parenchyma band. The demarcation of *D. microcarpum* growth-ring boundaries by marginal parenchyma bands is common in tropical areas. Nevertheless, discerning tree-ring boundaries was challenging due to the wide variation of the wood's anatomical features. The anatomical characteristics of the growth ring boundaries of *D. microcarpum* were similar in each tree and corroborated with the previous descriptions for the savanna species (**Sanogo et al., 2016; Balima et al., 2020**). In addition, the growth rates exhibited considerable variation between

trees, which is probably influenced by the ecological site conditions. **Müller (2000)** points out that the ecological conditions are the main factor, which influences tree ring growth. The growth-ring boundaries of *D. microcarpum* are commonly marked by the presence of marginal parenchyma bands, which has already been noted by several studies (**David et al., 2014; Sanogo et al., 2016; Talla et al., 2021**) for African savanna species. **David et al. (2014)** and **Talla et al. (2021)** highlight that parenchyma bands are the main characteristic of the Fabaceae wood anatomy. The ring boundaries of the *D. microcarpum* are demarcated by thickened cell walls but distinctiveness declined with decreasing ring width. The distinction of the growth ring boundary may be due to the dormancy of the cambial activity during the dry season. **Hall (1976)** pointed out that cambial activity influences the growth of the species. The anatomy observed with *D. microcarpum* is underlined by *Azelia africana* anatomy (**Boakye et al., 2016**). The distinct growth boundaries of *D. microcarpum* indicate periodic dormancy, likely associated with seasonal climate, which is common with the savanna species (**Fichtler, 2017; López & Villalba, 2020; Gauli et al., 2022**). The presence of a false ring may be due to drought events and disturbances like forest fires interrupting the normal growth of the trees. Due to its economic value, the *D. microcarpum* is disturbed by local people through firewood exploitation (**Dogara, 2022**). The occurrence of false rings and missing rings causes difficulties in the cross-dating process. **Copenheaver et al. (2006)** highlight that the position of the canopy also influences the radial growth of the species and influences the frequency of false rings. Despite the issue of ring misidentification, we believe that measuring the rings of *D. microcarpum* can still yield valuable basic information about the growth rates of this species. However, Cross-dating procedures are needed to ensure a consistent growth response across many ring series. Although challenges in accurately identifying growth rings exist, the application of cross-dating methods can enhance the reliability of growth data, as demonstrated by the comprehensive tree-ring chronology developed in this study.

Twelve radii from five trees were used to develop a comprehensive tree-ring-width chronology. The number of individuals used in this study is higher than those in earlier studies (**Sanogo et al., 2014; 2023**), which developed tree-ring chronologies of *Vitellaria paradoxa* and *Lannea microcarpa* with only four (4) trees. Traditional dendrochronological statistics indicate that our *D. microcarpum* chronology is of high quality and contains a significant common signal. Despite the difficulties encountered with tropical savanna species, cross-dating is essential to ensure the correct assignments of annual growth rates for correlation with environmental variables. These difficulties are common for tropical species (**Mbow et al., 2013; Gebrekirstos et al., 2014; Sanogo et al., 2016**). Due to the lack of reference

chronologies for *D. microcarpum*, this study is compared with the other species occurring in the savanna area. The tree-ring chronologies presented in this study are the first for *D. microcarpum* in Burkina Faso. The oldest tree found in this study is 93 years old. This tree is younger than *Afzelia africana* (Balima *et al.*, 2020), but older than *Vitelaria paradoxa* and *Daniella oliveri* (Sanogo *et al.*, 2016; 2022). The successful cross-dating and correlation between growth rings and annual climate variables (precipitation and temperature) confirmed the formation of annual growth rings, indicating that dendrochronology can be applied to this species. However, the GLK and T values found in this study are within the range of those reported by previous authors (David *et al.*, 2014; Ridder *et al.*, 2014; Khan *et al.*, 2022; Talla, *et al.*, 2021). The cross-dating difficulties may partly result from anthropogenic use (fodder, food, medicine, etc.) of *D. microcarpum*. This human impact (pruning, bark wounds) causes the formation of discontinuous, incomplete and sometimes blurred rings that alter the quality of the cross-dating. The statistical parameters of the cross-dating found with *D. microcarpum* suggest that the trees show a common signal caused by local environmental factors. This is underlined by Gebrekirstos *et al.* (2016), who reported that the annual formation of growth rings depends on the successful cross-dating of ring width series and their correlation with climate data. In addition, the EPS value found in this study is greater than the other savanna species such as *Lannea microcarpa* (Sanogo *et al.*, 2022) in Burkina Faso and Mali, or *Afzelia africana* (Balima *et al.*, 2020) in Burkina Faso. However, the regions with a single passage of the intertropical convergence zone (ITCZ) per year experience only an unimodal precipitation pattern, resulting in the formation of one annual ring per calendar year (Mbow *et al.*, 2013). The annual nature of tree rings in *D. microcarpum* and the cross-dating confirm the potential for dendrochronological studies in semi-arid species from Africa. However, our study challenges earlier arguments that distinct annual rings are absent in African trees, particularly in tropical regions, due to the lack of low temperatures and dormant winter seasons (Baillie & Pilcher, 1973; Stahle *et al.*, 1999; Brienens & Zuidema, 2006). The presence of false ring boundaries may also be due to episodic drought effects during the rainy season (Pallardy, 2008). Despite these significant challenges, average reference chronologies have been developed due to satisfactory inter-tree correlation results. The successful cross-dating between individuals demonstrates that the similar variation in their growth patterns is not coincidental (Stahle *et al.*, 1999), but rather indicates an external factor consistently influencing periodic wood formation in these trees (Therrell *et al.*, 2006; Sun & Liu, 2016). However, the three species exhibited significant and distinct responses to rainfall and temperature during specific periods of the year. The chronology shows significant correlations between ring width and

climatic factors, suggesting that tree growth of *D. microcarpum* is sensitive to climate. Similar findings have been reported in many tropical forests, particularly in the dry tropics, including the dry savannas of West Africa (**Brienen et al., 2016; Sanogo et al., 2023**). The correlations found here are in the range reported from other studies (**López & Villalba, 2020; Santos et al., 2021**). The variation in the correlation between the temperature and precipitation indicates that there is a relationship between the two variables and the growth of *D. microcarpum*. This showed that during the vegetation period, the temperature has a strong influence on all tree-ring components of *D. microcarpum* and is underlined by **Altieri et al. (2024)** who explained that the temperature appeared to be the factors which influence the growth of the species. Temperatures in May and precipitation in September, marking the onset of the rainy and dry seasons at our study site, respectively, reduce the transpiration rate, inhibit chloroplast function, and cause stomatal closure, all of which influence the growth of *D. microcarpum*. These conditions lead to increased photosynthesis and promote radial growth. This response of the species to temperature and rainfall in the two specific periods indicates that there is a specific growth period of *D. microcarpum*. This finding is underlined by **Bréda & Granier (1996)** and **Therrell et al. (2006)**, who highlight that seasonal climate fluctuation influences the growth of the species. In addition, the dry season of the previous years (November to April) leads to low photosynthetic rates with the loss of the leaves which the *D. microcarpum* a deciduous species. We found a significant correlation between tree growth and the end of the current year September precipitation. The soils are less water-saturated at the end of the rainy season, particularly during September precipitation with low precipitation. This behaviour suggests that the species has a preference for semi-arid regions and granitic soils (**Kouyaté et al., 2002; Lamy Lamy et al., 2021**). A second explanation for the sensitivity at the end of the rainy season could be the gradual depletion of water reserves stored in the soil. During this period, species adapted to low rainfall begin to grow. This explains why only the temperatures at the beginning of the rainy season and the rainfall at the end of the season significantly impact the diameter growth of *D. microcarpum*. Similar behaviour was observed with *Dichrostachys cinerea* by **Shikangalah et al. (2020)**, who showed that the temperature is the most important factor which influences their ring growth. The negative correlation between rainfall in November of the previous year and growth can be attributed to hydraulic stress caused by high temperatures and soil water depletion. This reaction showed that there is a species-specific variation in the timing of tree-ring growth in response to water balance in the soil. These results lead to the conclusion that the cambium of *D. microcarpum* is active from May to September, corresponding to the beginning and termination of the rainy season in the study site.

The influence of climatic factors on cambial activity, as highlighted by **Upadhyay et al. (2021)** and supported by **Brienen & Zuidema (2005)**, emphasizes the importance of understanding the interdependence of anatomical traits in *Detarium microcarpum*, particularly when drawing comparisons with studies from tropical savanna ecosystems. The statistical correlation between anatomy traits shows the interdependence of different characteristics. Due to the lack of specific references on *D. microcarpum* wood anatomy and the focus of our study on a single climatic zone, these results were compared with similar studies conducted in tropical savanna ecosystems. However, some anatomical characteristics found in this study vary from those of the other savanna species such as *Strychnos spinosa* and *Azelia africana* by **Avakoudjo et al. (2022)** and **Balima et al. (2020)** respectively. The difference founded between *Strichnos spinosa* and *D. microcarpum* would be linked to the difference between the families of the two species respectively Loganiaceae and Fabaceae. In the case of *Azelia africana*, the two species are from the same family (Fabaceae).

In examining tree-ring patterns and wood anatomical characteristics, a negative correlation between tree ring width and vessel density was observed; this indicates that wider tree rings contain fewer vessels. Consequently, a reduced vessel count within a single growth ring corresponds to a decrease in the relative conductive area (**Arnič et al., 2022**). The vessel density observed in this study aligned with *A. africana* vessel density in dry site found by **Balima et al. (2020)**. These similarities may be attributed to the effect of the climate (**Fichtler & Worbes, 2012; Pandey, 2021**) pointed out that the climate influences the size of the tropical species vessel. The size of the vessel trait of this study differs according to the age of the ring. These variations of vessel traits reflect the “universal” characteristic of the vessel traits (**Lechthaler et al., 2019**) and the water availability influences the size of the vessel (**Ayala-Usma et al., 2019**). Moreover, the size of the vessels regulates the potential water conductivity of the trees in their natural habitat (**Steppe & Lemeur, 2007**). The vessel number found in this study is greater than the species mentioned above. This variation will be due to ecological conditions such as soil type, climate regime, human threats and the type of the species. However, *D. microcarpum* is found in dry savannas on rocky soils (**Kouyaté, 2011; Lamy Lamy et al., 2021**). This finding showed that the ecological condition influences the size of the vessels and their number. In addition, when plants frequently encounter increased drought stress, they often develop a greater number of smaller vessels to secure their water supply and avoid vessel embolism (**Djomo et al., 2017**). Additionally, the presence of heterogeneous rays in the xylem enhances the radial conduction of water, minerals, and other organic substances (**Bräuning et al., 2016**). Insights from tree-ring analysis through the dendrochronology and

wood anatomy analysis, particularly regarding vessel structure and density, provide a critical foundation for developing accurate allometric models for *Detarium microcarpum* biomass assessment.

The specific density of the species analysed showed a significant difference between the two climatic zones and the tree components. The higher density was recorded in the Sudano-Sahelian zone than in the Sudanian zone. This result indicates that the climate pattern influences the wood density. **Bouslimi et al. (2022)** emphasise that trees which grow in warmer locations with more sunlight and water generally produce denser wood and are influenced by the geographic location. Compared to the stem density, the branch has the highest density. This difference would be due to the anatomical function of the different organs of the trees (**Ganamé et al., 2020**). The mean density found in this study is less than the *Pterocarpus erinaceus* density found by (**Ganamé et al., 2020**). This would be due that *Pterocarpus erinaceus* is a wood timber species, unlike *D. microcarpum*. In addition, in each climatic zone, the mean density is higher than the density suggested by **IPCC (2003)** for the tropical species. **Djomo et al. (2017)** pointed out that drying temperature affects the variation of the wood density. This corroborates with **Landau (2004)** which showed that rainfall, seasonality, and temperature influence the density of tropical wood species. This result showed that the climatic characteristics of each climatic zone appear to be the main factors affecting the density of *D. microcarpum*. However, the plant's physiological mechanisms control the exchange activity of wood formation which influences its density (**Rocha et al., 2020**). In addition, (**Shaiek et al., 2011**) pointed out that, the high density of the branch could also be related to a higher concentration of inorganic elements than stem. The study developed the allometric equations for estimating the aboveground using the diameter at the breast height (dbh) and the total height (H) which performed the model very well. To develop *D. microcarpum* allometric models for biomass estimation, the sample size was 30 individuals for each climatic zone. The size of the sample used in this study (30 samples /climatic zone) was sufficient and was underlined with several published studies in the tropical African savanna species such as *Azelia africana* (**Balima et al., 2019**), and *Pterocarpus erinaceus* (**Ganamé et al., 2020**) in West Africa. The harvested sample trees were selected in each climatic zone and the mean diameter size class ranged from $20.09 \pm 40.04\text{cm}$ for the Sudanian zone and $22.2 \pm 40.01\text{cm}$ for the Sudano-Sahelian zone. This information is essential for developing and testing the biomass assessment process, as highlighted by **Mäkelä & Vanninen (1998)**. Additionally, the precision of the predictor variable measurements is critical for ensuring the accuracy of the biomass assessment, as emphasized by **Cui et al. (2020)**.

With a robust sample size and accurate predictor variable measurements, as supported by the dendrometrics parameters, the next step in this research focused on applying power law models to forecast biomass, revealing a strong relationship between tree parameters such as diameter and height and the overall biomass of *D. microcarpum*.

The findings showed a strong relationship between the tree parameters and biomass. In this study, the power law model was applied to forecast the biomass of tree components which is underlined with the previous studies scored in West African savanna species (**Moussa & Mahamane, 2018; Ouédraogo et al., 2020a**). Power models, which are log-transformed equations, were established using variables that demonstrate a strong predictive capability for biomass, such as total height and diameter at breast height (dbh). **Chave et al. (2005)** underscored the necessity of applying log transformations to variables to satisfy the assumptions of normality and homoscedasticity, given that biological data are inherently heteroscedastic. The models demonstrated good performance with high explained variance ($p < 0.05$; Adj. $R^2 > 0.8089$) for all tree components in the two climatic zones. At the tree level, including ht additional predictor improved the stem biomass equations in the Sudanian climatic zone, but this had no significant improvement for the branch, leaves, and Sudano-Sahelian climatic zone equation. This suggests that equation improvement through the incorporation of additional dendrometric parameters is not a general case for tropical species. This is in line with the previous study in West Africa (**Mbow et al., 2013; Awé et al., 2017; Ouédraogo et al., 2020**) who explained that the allometric equation varied between the species. The best allometric equations developed with the two explanatory variables varied according to the climatic zone and the three components. The accuracy of the estimated parameters has a significant effect on the predictive power of the models particularly the model which has been selected as the best model among the models. The best model selected varies according to the climate zone. The power law model selected in this study to predict tree components' biomass was in line with the previous such (**Ouédraogo et al., 2020; Balima et al., 2022**). Diameter at Breast Height (dbh) and total height (ht) were used as compound variables that serve as effective predictors of stem biomass in the Sudanian climatic zone. Additionally, dbh alone is a reliable indicator for estimating branch and leaf biomass. This result corroborates the finding of **Miah et al. (2020)** who explained that dbh^2 and ht performed better in the *Mangifera stem* biomass than the other types of models. Dbh and the total height of the tree is a more comfortable inventory practice for biomass prediction and have an essential advantage for biomass estimation. However, the total height and dbh influence the variability of tree biomass because of their close correlation with structural tree characteristics and physiological and

mechanical properties of woody species. Tree height and diameter at breast height (dbh) are recognized as key indicators of species status (**Puc-Kauil et al., 2020**). Including both dbh and height (ht) in regression models for biomass estimation is often suggested, particularly for tropical species where these variables may be more reliably measured. The model using the two compound variables ($\text{dbh}^2 \times \text{H}$) showed less efficient estimations than the model using a single variable (dbh) for the branch and leaves biomass estimation. The fact that the species structure varies according to climatic type and that the biomass variations around the trees may be unique to the species in their ecological zone (**Mugasha et al., 2016; Addi et al., 2022**). Moreover, variations in allometric equations can be attributed to climatic factors. As climate impacts a tree's growth and biomass accumulation, it can alter allometric relationships even within the same species (**Diédhiou et al., 2017**). It was found that using the diameter at breast height (dbh) as a predictor variable explained $> 86\%$ of the variations in biomass and produced the lowest AIC. This may be due to many trees in the Sudano-Sahelian zone having branchy patterns that allow for significant biomass accumulation in the branches. Consequently, diameter at breast height (dbh) proved to be a superior predictor of biomass variation compared to the inclusion of total height (ht) alone. The dbh is a dendrometric parameter that is easily physically measurable during the species inventories (**Miah et al., 2020**). In addition, using tree height as an additive predictor did not improve equation parameters. **Mugasha et al. (2016)** elucidate that fluctuations in climate significantly impact tree height, which subsequently influences the estimation of their above-ground biomass. If dbh were recognised as the best predictor in this study, some authors argue that the accuracy of the dbh in predicting biomass is dependent on the conditions of its use rather than the variable itself (**Ouédraogo et al., 2020**). The above-ground allometric equation developed in this study has applicability for the non-destructive assessment of biomass. Therefore, using the logarithmic form on the power model produced a strong accuracy in biomass estimation for *D. microcarpum* tree components. The comparison of the best-selected specific allometric models developed with the general pantropical allometric model developed by **Chave et al. (2014)** showed that the pantropical model did not provide accurate above-ground biomass estimation both at the two climatic zones. The coefficient of determination ($\text{Adj. } R^2$) for the total above-ground biomass allometric model found in this study for each climatic zone is higher ($\text{Adj. } R^2 > 0.90$) than the general coefficient of variation ($\text{adj. } R^2$) proposed by (**Savaresi, 2013**) for the biomass prediction. The results of this study demonstrate that the pantropical model could not accurately estimate the biomass of different species. Consequently, it is more reliable to develop species-specific and local site-specific allometric models separately. These findings align with the work of **Talla**

et al. (2020) and **Ganamé *et al.* (2021a)** who demonstrated that species-specific allometric equations are more accurate in predicting aboveground biomass than pantropical equations developed by **Chave *et al.* (2014)**. The discrepancies between the two models suggest that environmental factors significantly affect the tree allometry model more than the species functional type, as highlighted by **Rahman *et al.* (2021)**.

These findings, highlighting the superiority of *D. microcarpum* allometric equations, set the stage for a deeper exploration of biomass and carbon storage, which are critical for climate mitigation efforts.

Evaluating biomass and carbon storage is essential for global climate mitigation efforts, as they are integral to assessing the impacts of climate change and devising mitigation strategies. This investigation underscores the significant contribution of woody components, especially stems and branches, to aboveground biomass across various climates. Notably, branches emerge as the primary contributor to above-ground biomass in both studied climates, echoing findings from previous studies in Burkina Faso involving species like *Balanites aegyptiaca* and *Pterocarpus erunaceus*. Contrarily, earlier research by **Henry *et al.* (2011)** and **Bouslimi *et al.* (2022)** highlighted the stem influence greatly the total above-ground mass than the two other components. The differences found in the present study could be linked to the species-specific physiological traits and ecological conditions (**Djomo *et al.*, 2016**).

The resilience of *Detarium microcarpum* to extreme heat and drought, as noted by **Kouyaté *et al.* (2002)**, further supports the variability in biomass contributions. The relationship between increased biomass fractions and diameter at breast height (dbh) correlates with the growth of new branches and leaf loss (**Mensah *et al.*, 2016**). Among the three components (stem, branch, and leaves), the leaves exhibit lower carbon content, indicating a significant disparity in carbon distribution between foliage and woody parts (branches and stem). This observation aligns with previous research on *Vitellaria paradoxa* and *Balanites aegyptiaca* but suggests a higher carbon content in the current study, potentially attributed to species-specific physiology (**Dimobe *et al.*, 2019b; Ouédraogo *et al.*, 2020**).

However, under conditions of nutrient or water scarcity, plants allocate more biomass to the branches than the leaves to ensure survival and structural integrity. This may result in fewer, smaller leaves while the branches continue to grow for the savanna species (**Shackleton & Scholes, 2011; Abreu *et al.*, 2017; Amara *et al.*, 2020**). This contributes to the differential carbon allocation within trees. Biomass and carbon levels are significantly higher in the Sudano-Sahelian zone than in the Sudanian zone, driven by differences in environmental conditions and nutrient availability (**Bouslimi *et al.*, 2022; Nyamukuru *et al.*, 2023**). This

finding shows that, in dry conditions, the species sequester more above-ground biomass than the high rainfall areas. Environmental factors such as temperature, rainfall, and general weather patterns significantly affect carbon sequestration processes, with savanna species exhibiting adaptive mechanisms to enhance carbon absorption under reduced precipitation (**Abebe et al., 2022; Bentsi-Enchill et al., 2022**). These adaptations minimize water loss and optimise photosynthetic efficiency, impacting both carbon uptake and ecosystem respiration (**Miah et al., 2020; Taylor et al., 2017; Xiang et al., 2021**). Foliage is pivotal in a tree's productivity by facilitating carbon absorption through photosynthesis (**Goudiaby et al., 2012**). Consequently, understanding these dynamics is crucial for optimising species management and productivity, offering valuable insights for carbon assessment and mitigation strategies.

Given that environmental factors like temperature and rainfall significantly influence carbon sequestration processes, it is essential to recognize how these bioclimatic variables, should shape the distribution of *D. microcarpum* in the future under climate change.

The result of this study showed that the bioclimatic variables (Wettest Quarte (bio8) and Isothermality (bio3)) contributed more to the distribution of *D. microcarpum* than other variables. This finding showed that temperature is a crucial factor which impacts the distribution of *D. microcarpum*. This is underlined by **Bueno et al. (2017)**, who pointed out that the temperature influences the savanna species distribution. In addition, this investigation has reported that average temperature for the wettest quarter (bio8) and Isothermality (bio3) are the main environmental predictors which most affected the current distribution of *D. microcarpum*. These results also corroborate previous studies which have shown that solar radiation and air temperature have the greatest effects on the metabolic rates of plants in tropical forests (**Jiménez-Valverde et al., 2013; Guidigan et al., 2018b**). As reported by **Agbo et al. (2018)**, the influence of the two bioclimatic variables (bio3 and bio8) shows that water availability and low temperature might remarkably alter *D. microcarpum* seed germination and regeneration, plant height and cover, leaf area, phenology, pollination, reproduction, dispersal of propagules, and physiological processes like photosynthesis. Consequently, the future distribution area of the species is expected to increase in the Sudano–Sahelian climatic zone than in the Sudanian zone. As **Sinadouwirou et al. (2023)** explain in their research, these bioclimatic variables influence significantly the species distribution patterns, shaping various aspects of ecological dynamics. In addition, these variables (bio8 and bio14) combined with the capacity exchange cation at the different scales affected the distribution of *D. microcarpum*. Moreover, **Idohou et al. (2017); Guidigan et al. (2018b); and Dimobe et al. (2020)** pointed out that climatic factors and soil texture determine the ecological zone of the species. The

output of the model found a good performance ($AUC > 0.8$ and $TSS > 0.6$). These findings suggest that the MaxEnt algorithm effectively captures variations in environmental data, indicating its good performance (Araújo *et al.*, 2005).

The findings of this study show that, the elevation influence significantly the distribution of *D. microcarpum*. These results were underlined by the conclusion of Cavin (2007), Lamy *et al.* (2021), and Houénon *et al.* (2022) who showed that *D. microcarpum* is an altitudinal species which could be also found on the laterite and the granitic zone. However, the integration of the elevation and cation exchange capacity variables in the process increases the model performance functionally and more accurately (Agbo *et al.*, 2018) and the development of the species. Indeed, Lamy *et al.* (2021) and Michel *et al.* (2023), explained that the elevation influences the distribution of the savanna species. Besides, Agbo *et al.* (2018) showed that *D. microcarpum* species prefers the soil which is rich in cation exchange capacity. Regarding the findings of this study, the variables which influence the ecological optimum of *D. microcarpum* are bio8 and bio3. In addition, *D. microcarpum* is generally grown in warm and sub-arid regions with temperature and rainfall ranges of 25 to 37 and 600 to 900 mm/year respectively and is underlined by the known climatic preferences of the species (Sinadouwirou *et al.*, 2023). This could affect its ability to establish new seedlings and may lead to dieback in areas where it currently grows (Kataoka *et al.*, 2020; Gao *et al.*, 2022; Yebeyen *et al.*, 2022). Among the environmental variables, cation exchange capacity (cec) had lower contribution rates than others. Identifying the dominant environmental variables that affect species distribution provides a better indicator for understanding the effects of global change on species suitability and its suitable management (Xie *et al.*, 2022, Wang *et al.*, 2023).

Understanding the environmental variables influencing *D. microcarpum* distribution is crucial, particularly as habitat loss patterns emerge from various climate models, indicating the species' current and future suitability across different climatic zones.

The distribution of *D. microcarpum* followed a favourable climatic pattern, although the models indicated variations in the extent of habitat loss. The four climate models showed different levels of habitat loss within each horizon and each emission scenario. The current suitable habitat of *D. microcarpum* is 65.5 % of the country area and 29.16 % is revealed to be low suitable for the species conservation. Indeed, the current distribution of *D. microcarpum* showed that the species is widespread in two climatic zones (Sudanian and Sudano-Sahelian). In the literature review coupled with the ecological observation, the species were not found in the Sahel climate zone (Schmidt *et al.*, 2017). As part of the current distribution, the fundamental niche of the species is larger than the realized niche and some suitable habitats

were located in some areas where the species is not currently predicted. This observation corroborates with **Lompo et al. (2021)** and **Daï et al. (2023)**, explained that the fundamental niche is larger than the realized niche and is the future environmental conditions favourable for species conservation (**Fandohan et al., 2015; Mellert et al., 2015; Coulibaly et al., 2023**). Some areas may become suitable for this species' conservation in favour of the highly suitable area.

The future predictions indicate that climate change will affect the distribution of *D. microcarpum*, resulting in a decrease in highly suitable habitats throughout the country. Although the ACCESS-CM2, CNRM-CM6–1, and HadGEM3-GC31-LL model with the type of the scenario predict a significant regression of the high suitable area in aid of low suitable habitats area of *D. microcarpum*. The expansion of low-suitable habitat is predicted to increase in all scenarios compared to the current area.

However, there are variations in trends depending on the model and scenario. The prediction of species distribution under future climate conditions in West Africa, as shown by studies such as **Idohou et al. (2017); Agbo et al. (2018); Lompo et al. (2021); Balima et al. (2022); Dimobe et al. (2020, 2022)**, and **Daï et al. (2023)**, highlights the variation in the distribution of savanna species. The future projection suggests that suitable habitats for *D. microcarpum* will shift, with low-suitability areas increasing and suitability-high-suitability areas decreasing. **Ma & Sun (2018)** and **Wouyou et al. (2022)** pointed out that the loss of suitable habitat can directly reduce the distribution of species like *D. microcarpum*. This decline can be further intensified by human activities like deforestation and land conversion, which amplify the impacts of climate change. This situation may be due to fluctuations in precipitation and temperature variables, which are predicted to change in projected SSPs (**Mkala et al., 2023**). However, the findings from the SSP5-8.5 scenario under the MIROC6 model indicate an increase in suitable and highly suitable areas for *D. microcarpum*. These results align with previous studies that have suggested a positive impact of climate change on the distribution of *Parkia biglobosa* in Mali (**Coulibaly et al., 2023**) and *Pterocarpus erinaceus* in West Africa under climate threat (**Adjonou et al., 2020**). In contrast, other research by **Balima et al. (2022)** and **Dimobe et al. (2022)** has shown that future climate conditions are likely to reduce the suitable areas for *Azelia africana* and *Pterocarpus erinaceus* in the sub-arid savanna, as predicted through the MaxEnt approach. This indicates that *D. microcarpum* should show a latitudinal and longitudinal shift in its current range in response to climate change. In addition, the regressive trends of *D. microcarpum* suitable habitats suggest the threat of the climate will have an adverse impact on the habitat distribution which is already threatened by its

multipurpose uses (Agbo *et al.*, 2017; Dossa *et al.*, 2020; Leakey *et al.*, 2022). Previous modeling studies in West Africa suggest that climate change is one of the most important factors that affect habitat losses which increases the decline of the species (Rey & Carlos, 2014; Peng *et al.*, 2023). The reduction of suitable habitats for this species at the 2070 and 2090 horizon could be linked to the type of model. Fandohan *et al.* (2015) and Dimobe *et al.* (2020) made the same observation of the distribution of *Chromolaena odorata* and *Vitellaria paradoxa* respectively using the HadGEM2-ES and MIROC5 under CMIP5. The future range of the species under future climate projections could be explained by significant changes in precipitation and temperature, which are the key drivers of species distribution (Thiombiano *et al.*, 2006; Bellard *et al.*, 2012; Brown *et al.*, 2016). The differences observed in the species distribution would depend on the future climate conditions and could be attributed to the local differences in the change predicted by each climate model (Balima *et al.*, 2022a; Çoban *et al.*, 2020).

In contrast, the expected shift of the geographical range of *D. microcarpum* in the Northern part of the country under the model MIROC6 in Scenario SSP5-8.5 is probably due to the humid and moderate climatic conditions with increasingly frequent precipitation events area. However, the area average precipitation is expected to increase by 8.5 % and 15.2 % respectively for SSP2-4.5 and SSP5-8.5 under the CMIP6 model in Africa (Almazroui *et al.*, 2020; Ama *et al.*, 2021). Several previous studies have suggested that climate change might affect *Lebrunia bushaie* Staner (Clusiaceae) distribution Imani & Won, (2023), *Lebrunia bushie* in RDC, Coulibaly *et al.* (2023), for *Bombax costatum* in Mali, Vihotogbé *et al.*, (2021) for *Mondia whitei* in Benin. Jean *et al.* (2017) Highlighted that a specific species may be predicted to be extinct by some climate models, whereas other models suggest it could survive due to habitat loss or range expansion. The expansion of suitable areas indicates that projected climatic conditions could benefit some species found in savanna regions. Mirhashemi & Ahmadi, (2024) explain that the extent of habitat changes is determined by a species' ability to adapt to the climatic conditions of the new environment. Given the differing predictions across climate models regarding species survival and extinction, understanding the specific impacts of climate change on *Detarium microcarpum* distribution becomes essential, particularly as various models suggest changes in habitat suitability.

This research explores the impact of climate change, as modelled under CMIP6, on the distribution of *Detarium microcarpum* across the country. The distribution patterns differed significantly among the four climate models across two emission scenarios (SSP2_4.5 and SSP5-8.5) and two time horizons (2061-2080 and 2081-2100). The findings of this study

aligned with previous research such as **Fandohan et al. (2013)**, **Guidigian et al. (2018b)**, **Agwu et al. (2020)**, **Issoufou et al. (2022)**, and **Mirhashemi & Ahmadi (2024)** shows that climatic variables, along with factors such as model type, soil type, elevation, and human impact, influence species distribution. Consequently, bioclimatic projections suggest that *D. microcarpum* should experience a slight loss of highly suitable habitats but gain areas of moderate suitability by 2070 and 2090 under the two scenarios. Meanwhile, unsuitable habitats are expected to transition to low suitability. These findings are consistent with previous studies on similar species in Africa, such as *Kigelia africana* in Benin (**Guidigian et al., 2018a**) and *Afzelia africana* in Burkina Faso (**Balima et al., 2022**).

Interestingly, under the SSP5-8.5 scenario, the MIROC6 model predicts an increase in suitable areas for *D. microcarpum* in Burkina by 2090. Climate Change and the expansion of climate allowed the tropical and subtropical species to expand their ranges significantly (Leakey et al., 2022). Changing would be due to the fluctuations in precipitation and temperature projected SSPs (Mkala et al., 2023).

The predictions of the future distribution suggest that areas highly favourable to *D. microcarpum* will revert to areas less favourable under the different scenarios tested. However, these variations highlight the discrepancies among global climate models and the challenges posed by model uncertainties, influenced by factors such as modelling techniques, constructed model processes, and uncertainties in climate scenarios.

These insights underline the potential effects of future climate warming on *D. microcarpum*, exacerbated by habitat destruction from human activities and natural disasters (**Agwu et al., 2020; Dimobe et al., 2022**). In addition, determining the factors which influence the species' distribution is useful knowledge for conservation and management efforts (**Radha & Khwarahm, 2022; Hama & Khwarahm, 2023**), as well as for the related biodiversity of the multipurpose species across the country. The application of this study offers significant advantages in identifying priority zones for *D. microcarpum* conservation. The result of this study suggests that applying modeling techniques, such as MaxEnt offers significant benefits in establishing priority zones for biodiversity conservation. These models improve the accuracy of identifying critical habitats by integrating environmental and climatic data, allowing for precise species distribution predictions (**Mirhashemi & Ahmadi, 2024**). These models enable the precise mapping of current and future distribution patterns, providing insights into the species' ecological requirements and potential shifts due to climate change. They also enable the projection of future suitable areas of *D. microcarpum* under various climate scenarios, helping to allocate conservation resources more efficiently. This allows conservation planners

to prioritize these stable habitats as key zones for protection (**Ararat et al., 2023**). The integration of these modeling approaches with existing biodiversity data facilitates the creation of comprehensive conservation strategies (**Agwu et al., 2020**). By simulating various climate scenarios, these techniques can predict areas that are likely to remain suitable area for *D. microcarpum* in the future, even as environmental conditions change. This allows conservation planners to prioritize these stable habitats as key zones for protection (**Boria et al., 2014; Mkala et al., 2023**). This research is an invaluable tool in the conservation of *D. microcarpum*, providing a scientific basis for prioritizing areas that are crucial for the species' survival and for maintaining overall biodiversity in the face of ongoing environmental changes. In addition, it provides a scientific basis for decision-making, these models facilitate collaboration among stakeholders involved in conservation efforts. Several strategies such as mitigating the impacts of human activities and climate change, preserving biodiversity, and ensuring the sustainable use of *D. microcarpum*, in the socioeconomic context of Burkina Faso through a specific action. These specific actions could include establishing protected areas, community-based forest management, climate-resilient agroforestry, restoration and reforestation programs, and research and monitoring. Indeed, it is essential to examine the specific threats facing this species such as deforestation, habitat loss, land conversion, agricultural expansion, overexploitation, and altered fire regimes and to develop strategies for mitigating these threats to ensure its conservation. The results of this study aligned with the idea of **Radha & Khwarahm (2022)** which showed that the management actions of the species require detailed categorised maps of the target species that will possibly convince policymakers. In addition, Habitat reversion could be linked to the type of model, scenario; species, and type of climatic zone (Fandohan et al., 2015; Mellert et al., 2015; Coulibaly et al., 2023).

Conclusion, Perspectives and Recommendations

Conclusion

This study showed the significant influence sociodemographic factors have on the uses of *Detarium microcarpum*, demonstrating the rural population's awareness of the decline of these species within their environment. It has highlighted the significant economic value of *D. microcarpum*. Conserving *D. microcarpum* will also preserve the cultural heritage and traditional knowledge surrounding its uses, especially for the medicinal or nutritional significance of local populations. This study underscored the negative consequences of species overexploitation on their survival, revealing that threats to the *D. microcarpum* are closely linked to site-specific activities and the status of the site. Moreover, rural communities demonstrated awareness of these threats, proposing certain solutions and management strategies to avoid the disturbance of the species. The floristic diversity and composition of *D. microcarpum* natural stand vary according to the climatic zones and the land use types. Climate patterns and land use type influenced the dendrometric parameters of and the population trend of the *D. microcarpum* stand. The degradation of the *D. microcarpum* dendrometric parameters and diversity associated with land use has significant implications for biodiversity conservation related to target 15 of the sustainable development goals. The analysis of dendrometric parameters revealed an unstable population, indicating the need for targeted protection measures to prevent overharvesting and ensure the species' recruitment. The tree-ring chronologies were significantly correlated differently with precipitation and temperature indicating that the two climatic variables affect differently the growth patterns of the species. This study complements the dendrochronological database conducted in Burkina Faso. The finding of the anatomy wood quantitative analysis suggests that the anatomical traits react differently in response to climate variability than ring width. The tree-ring chronologies were significantly correlated differently with precipitation and temperature indicating that the two climatic variables affect differently the growth patterns of the species. Despite the external factors (climate effect, human disturbance) which impacted the cross-dating process, this result complements the dendrochronological database conducted in Burkina Faso. The anatomy wood quantitative analysis suggests that the anatomical traits react differently in response to climate variability than ring width. The finding of this study revealed that the diameter at breast height alone is a perfect predictor in the Sudano-Sahelian climatic zone and for the branch and foliage biomass estimation in the Sudanian climatic zone, while the stem requires tree height as an additional predictor ($dbh^2 \cdot ht$). Despite the equivalence between the two climatic zones,

the best allometric model in each climatic zone performed better above-ground than the pantropical model proposed for the tropical species. However, the above-ground production and carbon contents vary between the Sudanian and the Sudano-Sahelian climatic zones. This reflects that dbh is more important for estimating the above-ground than the other dendrometric parameters. These results support the hypothesis that local equations can better explain above-ground variability when both total height and diameter at the breast are included in the fitting process since these parameters are highly correlated with growth type and wood physical properties of trees. This equation may also be usable in other similar multipurpose species in West Africa. Promoting the sustainable management of *D. microcarpum* like the other species could also stimulate scientific research on its ecological role, economic value, and potential for new uses, contributing to the knowledge base of both local communities and researchers. The use of equations can help achieve this goal and can be a valuable tool in the implementation of the Greenhouse Gas Monitoring System in Burkina Faso. The findings highlighted that climate might influence above-ground production and carbon storage in the savanna woody species. The potential range of the currently suitable habitats of the species was 65.5 % across the country total area. The results indicate that in response to climate change, the species will primarily inhabit the Sudano-Sahelian climate zone, with highly suitable and unsuitable areas converting to marginally suitable ones. Under climate change scenarios, the climatic niche of *D. microcarpum* will shrink geographically from south to north across the country. Across all selected climate models under the SSPs 2-4.5 and SSPs 2-8.5, the highly suitable areas were predicted to decrease at the horizon 2061 – 2080 and 2081 – 2100. This study provides essential empirical knowledge to guide the future sustainable uses of *D. microcarpum* resources. A focus on sustainable management can guide the creation or improvement of policies and regulations that protect *D. microcarpum*, ensuring its conservation while balancing development needs and ecosystem health. Promoting the conservation of *D. microcarpum* could lead to ecotourism initiatives, where the species could become a point of interest for both educational purposes and income-generating activities.

Perspectives

Given the strong human pressure on resources and the unstable population of *Detarium microcarpum* in their natural stand, it is imperative to consider their sustainability in the face of population growth and the effects of climate change. While additional data on *D. microcarpum* are needed, different types of study in the savanna-threatened are essential to develop efficient conservation and management plans for savanna species and ecosystems. Identifying the economic value chain of *D. microcarpum* products. High morphological variations of *D. microcarpum* trees were noted during local surveys and forest inventories between the two climatic zones. However, this study did not investigate the reasons behind the observed morphological diversity. Therefore, molecular analyses are needed to assess the morpho-genetic diversity of *D. microcarpum* in Burkina Faso. These investigations will also contribute to understanding the species' morphological adaptations to environmental factors, which is crucial for restoration and domestication programs. In addition, the assessment of the co-occurrence species surrounding the natural stand needs to know the reel indicator species of *D. microcarpum*. The evaluation of the below-ground biomass (root biomass) and their contribution to the total carbon storage of *D. microcarpum* could help to establish a long-term monitoring program for the *D. microcarpum* carbon dynamics under changing climate and land use conditions. Due to the poor cross-dating potential of ring series among trees within, further investigations were needed on radiocarbon dating and climate-growth correlations to verify the annual growth-ring boundaries of *D. microcarpum* in Burkina Faso. This will also help to build the species' chronology and improve the chronology data in West Africa. The increasing need for ecological insights in tropical forest management demands heightened efforts in tree-ring studies, especially for semi-arid savanna species like *D. microcarpum*. Conducting a dendroclimatological analysis will help estimate the species' growth variations in response to climate factors, enhancing our understanding of its ecological dynamics. Furthermore, examining how projected changes in temperature and precipitation influence the phenology specifically the timing of leafing, flowering, and fruiting could provide critical information on how these changes impact *D. microcarpum* reproductive success and survival rates. Additionally, modeling the interactions between *D. microcarpum* and other key savanna species under future climate conditions will offer a more comprehensive understanding of how the ecosystem might evolve, guiding sustainable management and conservation strategies. Extending this kind of study to other savanna multipurpose species is essential for their best conservation.

Recommendations

The results of this study suggest the need for formulating and implementing recommendations to enhance the sustainable management of the species. Establishing a platform or exchange framework to update and consolidate all national research activities on NTFP production through multipurpose species is recommended. This platform should enable researchers to access regular information and share their findings, allowing them to focus their efforts more effectively and develop relevant research projects. Ultimately, this approach will generate new knowledge and identify appropriate solutions for the challenges associated with the management and development of these species. Involving local communities in the conservation process through **community-based conservation**. This will provide education on the importance of sustainable management and create opportunities for them to benefit economically from these practices. Promoting the conservation of biodiversity by protecting a variety of species and their habitats ensures a balanced ecosystem that supports multipurpose species. Developing and implementing restoration programs for degraded areas to re-establish native species and restore ecosystem functions are essential steps. Establishing monitoring and research programs to track the health and growth of multipurpose species, assess the impacts of climate change, and adapt management practices based on scientific findings is also vital. Advocating for and supporting the development of policies and legislation that promote the sustainable use and conservation of multipurpose species is necessary. Creating economic incentives, such as payment for ecosystem services (PES) or certification schemes, will encourage the sustainable management of multipurpose species. Fostering collaborative partnerships between government agencies, non-governmental organisations, research institutions, and local communities to share knowledge, resources, and best practices is beneficial. Develop guidelines for sustainable harvesting of *Detarium microcarpum* fruits, leaves, and wood to prevent over-exploitation. Enhance the conservation and restoration of *Detarium microcarpum* populations, contributing to biodiversity and ecosystem services. Provide alternative income sources for local communities through the sustainable use and sale of *Detarium microcarpum* products. Strengthen community engagement and ownership in conservation efforts, fostering long-term stewardship of natural resources

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APPENDIX

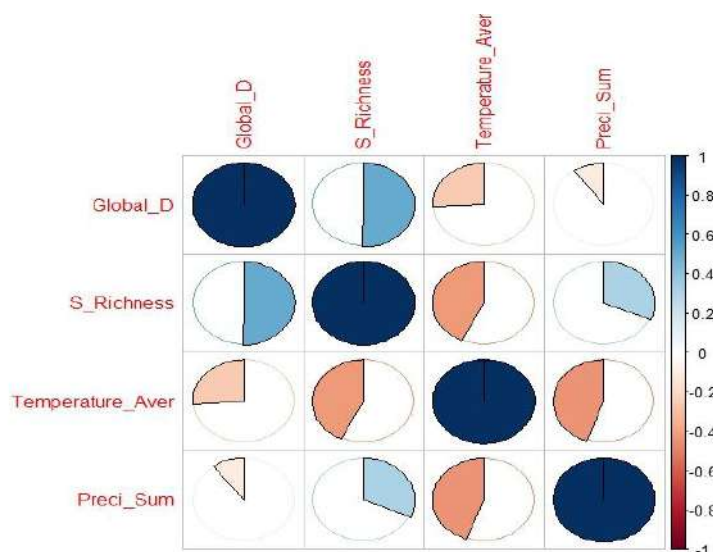
Appendix A: List of woody species across climatic zones and land use types

Families	Genera	Species	Sudanian climate zone		Sudano Sahelian climate zone	
			Protecte d areas	Unprotecte d area	Protecte d area	Unprotecte d area
Anacardiaceae	Anacardium	<i>Anacardium occidentale</i> L.		X		
Anacardiaceae	Lannea	<i>Lannea acida</i> A.Rich.	X	X	X	X
Anacardiaceae	Lannea	<i>Lannea microcarpa</i> Engl. & K.Krause	X	X		X
Anacardiaceae	Lannea	<i>Lannea velutina</i> A.Rich.	X	X	X	
Anacardiaceae	Mangifera	<i>Mangifera indica</i> L.	X	X		X
Anacardiaceae	Ozoroa	<i>Ozoroa insignis</i> Delile	X	X		
Anacardiaceae	Sclerocarea	<i>Sclerocarya birrea</i> Hochst.				X
Annonaceae	Annona	<i>Annona senegalensis</i> Pers.	X	X	X	X
Annonaceae	Hexalobus	<i>Hexalobus monopetalus</i> Engl. & Diels	X	X		
Apocynaceae	Ancylobotrys	<i>Ancylobotrys amoena</i> Hua	X			
Apocynaceae	Calotropis	<i>Calotropis procera</i> (Aiton) Dryand.		X	X	
Apocynaceae	Holarrhena	<i>Holarrhena floribunda</i> T.Durand & Schinz	X			
Apocynaceae	Londolfia	<i>Londolfia heudelotii</i> A.DC.	X	X		
Apocynaceae	Saba	<i>Saba senegalensis</i> (A.DC.) Pichon	X	X		
Apocynaceae	Tacazzea	<i>Tacazzea apiculata</i> Oliv.	X			
Arecaceae	Borassus	<i>Borassus aethiopum</i> Mart.		X		
Arecaceae	Elaeis	<i>Elaeis guineensis</i> Jacq.	X	X		
Bignoniaceae	Stereospermum	<i>Stereospermum kunthianum</i> Cham.	X	X	X	X
Capparaceae	Capparis	<i>Capparis fascicularis</i> DC.	X		X	
Celastraceae	Gymnosporia	<i>Gymnosporia senegalensis</i> Loes.			X	
Chrisobalanaceae	Parinari	<i>Parinari curatellifolia</i> Planch. ex Benth.	X			
Combretaceae	Combretum	<i>Combretum adenogonium</i> Steud. ex A.Rich.	X		X	
Combretaceae	Combretum	<i>Combretum collinum</i> Fresen.	X	X	X	X
Combretaceae	Combretum	<i>Combretum glutinosum</i> Fresen.	X	X	X	X
Combretaceae	Combretum	<i>Combretum micranthum</i> G. Don			X	X
Combretaceae	Combretum	<i>Combretum molle</i> R.Br. ex G.Don	X			
Combretaceae	Combretum	<i>Combretum nigricans</i> Leprieur ex Guill. & Perr.	X			
Combretaceae	Combretum	<i>Combretum paniculatum</i> Vent.			X	X
Combretaceae	Guiera	<i>Guiera senegalensis</i> JFGmel.				X
Combretaceae	Terminalia	<i>Terminalia engleri</i> Gere & Boatwr.	X		X	X
Combretaceae	Terminalia	<i>Terminalia leiocarpa</i> Baill.	X	X	X	X
Combretaceae	Terminalia	<i>Terminalia avicennioides</i> Guill. & Perr.	X		X	
Combretaceae	Terminalia	<i>Terminalia laxiflora</i> Engl.	X	X	X	
Combretaceae	Terminalia	<i>Terminalia macroptera</i> Guill. & Perr.	X	X	X	
Combretaceae	Terminalia	<i>Terminalia mollis</i> Malawson	X			
Delleniaceae	Tetracera	<i>Tetracera alnifolia</i> Willd.	X			
Ebenaceae	Diospyros	<i>Diospyros mespiliformis</i> Hochst. ex A.DC.	X	X	X	X
Fabaceae	Afzelia	<i>Afzelia africana</i> Pers.	X	X	X	
Fabaceae	Aganope	<i>Aganope stuhlmannii</i> (Taub.) Adema	X	X	X	

Fabaceae	Albizia	<i>Albizia zygia</i> (DC.) JF Macbr.	X			
Fabaceae	Bernilia	<i>Bernilia grandiflora</i> (Vahl) Hutch. & Dalziel	X			
Fabaceae	Burkea	<i>Burkea africana</i> Hameçon.	X	X	X	
Fabaceae	Cassia	<i>Cassia sieberiana</i> DC.	X	X	X	
Fabaceae	Daniella	<i>Daniella oliveri</i> Hutch. & Dalziel	X	X		
Fabaceae	Detarium	<i>Detarium microcarpum</i> Guill. & Perr.	X	X	X	X
Fabaceae	Detarium	<i>Detarium senegalense</i> JFGmel.	X			
Fabaceae	Dichrostachys	<i>Dichrostachys cinerea</i> (L.) Wight & Arn.	X			
Fabaceae	Entada	<i>Entada africana</i> Guill. & Perr.	X	X		
Fabaceae	Erythrina	<i>Erythrina senegalensis</i> DC.		X		
Fabaceae	Isoberlinia	<i>Isoberlinia doka</i> Craib & Stapf	X		X	
Fabaceae	Ormocarpum	<i>Ormocarpum pubescens</i> (Hochst.) Cufod.	X			
Fabaceae	Parkia	<i>Parkia biglobosa</i> (Jacq.) R.Br. ex G.Don	X	X		
Fabaceae	Pterocarpus	<i>Pterocarpus lucens</i> Lepr. ex Guill. & Perr.	X			
Fabaceae	Pericopsis	<i>Pericopsis laxiflora</i> (Benth. ex Baker) Meeuwen	X		X	
Fabaceae	Philenoptera	<i>Philenoptera laxiflora</i> (Guill. & Perr.) Roberty			X	X
Fabaceae	Piliostigma	<i>Piliostigma reticulatum</i> (DC.) Hochst.	X		X	X
Fabaceae	Piliostigma	<i>Piliostigma thonningii</i> (Schumach.) Milne-Redh.	X		X	X
Fabaceae	Prosopis	<i>Prosopis africana</i> (Guill. & Perr.) Taub.	X	X		X
Fabaceae	Pterocarpus	<i>Pterocarpus erinaceus</i> Poir.	X	X	X	X
Fabaceae	Senegal	<i>Senegalia gourmaensis</i> (A.Chev.) Kyal. & Boatwr			X	X
Fabaceae	Senegalia	<i>Senegalia dudgeonii</i> (Craib) Kyal. & Boatwr.	X			X
Fabaceae	Senegalia	<i>Senegalia gourmaensis</i> (A.Chev.) Kyal. & Boatwr.	X	X	X	X
Fabaceae	Senna	<i>Senna singueana</i> (Delile)			X	X
Fabaceae	Tamarindus	<i>Tamarindus indica</i> L.	X	X	X	X
Fabaceae	Vachellia	<i>Vachellia seyal</i> (Delile) P.J.H.Hurter			X	X
Fabaceae	Vachellia	<i>Vachellia sieberiana</i> (DC.) Kyal. & Boatwr.		X	X	
Lamiaceae	Gmelina	<i>Gmelina arborea</i> Roxb.		X		
Lamiaceae	Tectona	<i>Tectona grandis</i> LF	X			
Lamiaceae	Vitex	<i>Vitex doniana</i> Doux	X	X	X	X
Loganiaceae	Strychnos	<i>Strychnos spinosa</i> Lam.	X	X	X	X
Malvaceae	adansonia	<i>Adansonia digitata</i> L.	X			X
Malvaceae	Bombax	<i>Bombax costatum</i> Pellegr. & Vuillet	X	X	X	X
Malvaceae	Ceiba	<i>Ceiba pentandra</i> (L.) Gaertn.	X			
Malvaceae	Cola	<i>Cola cordifolia</i> (Cav.)R. Br.	X			
Malvaceae	Grewia	<i>Grewia rotii</i> DC.	X	X		
Malvaceae	Grewia	<i>Grewia lasiodiscus</i> K. Schum.	X			
Meliaceae	Azadirachta	<i>Azadirachta indica</i> A.Juss.		X		
Meliaceae	Khaya	<i>Khaya senegalensis</i> A. Juss.	X			
Moraceae	Ficus	<i>Ficus crocata</i> Mart. ex Miq.	X		X	

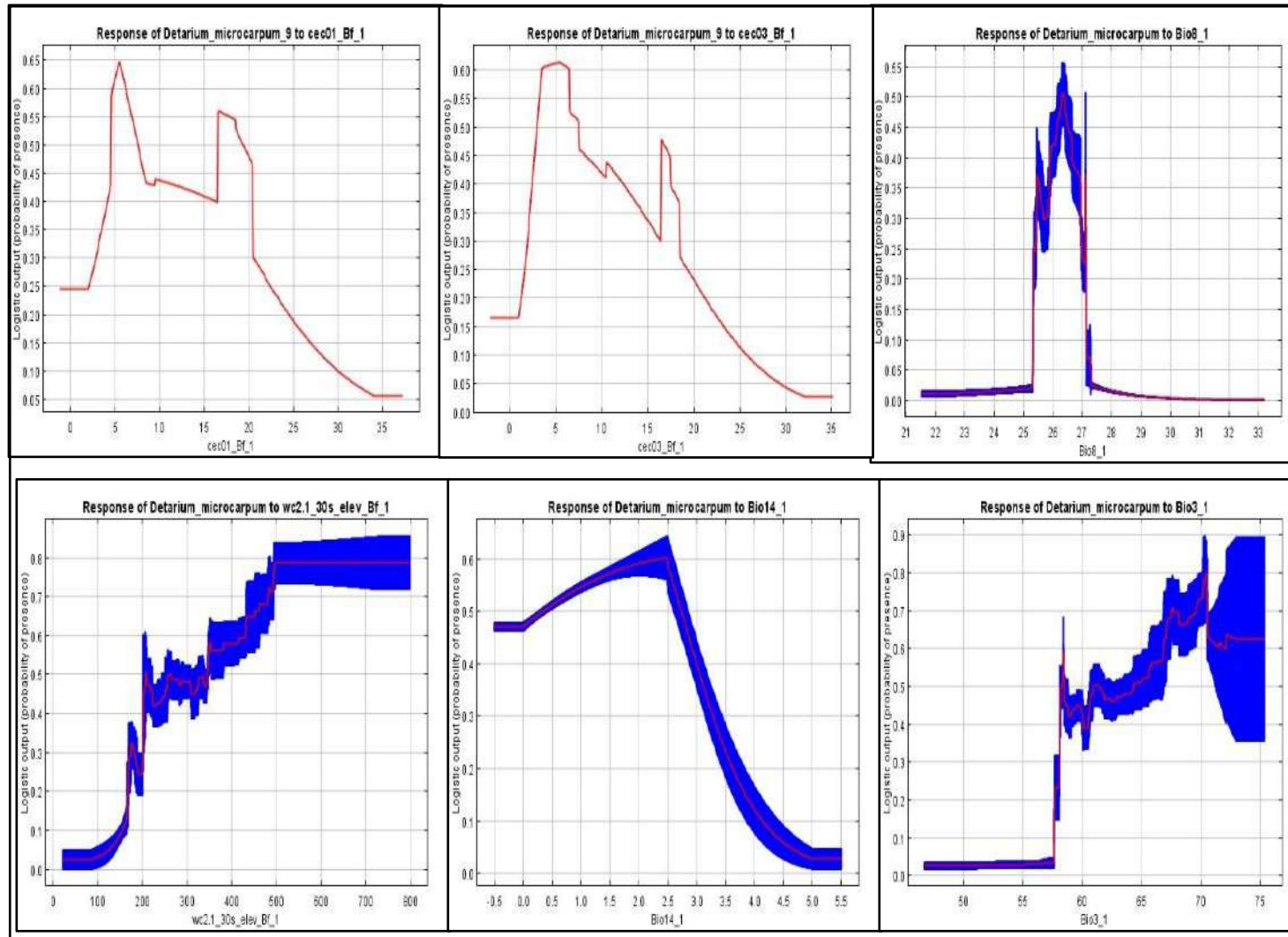
Moraceae	Ficus	<i>Ficus thonningii</i> Blume				X
Moraceae	Ficus	<i>Ficus Sycomorus</i> L.				
Myrtaceae	Eucalyptus	<i>Eucalyptus camaldulensis</i> Dehnh.	X	X		
Ochnaceae	Lophira	<i>Lophira lanceolata</i> Van Tiegh. Ex keay		X		
Olacaceae	Ximenia	<i>Ximenia americana</i> L.	X		X	X
Phyllanthaceae	Bridelia	<i>Bridelia micrantha</i> (Hochst.) Baill.	X		X	X
Phyllanthaceae	Fluggea	<i>Fluggea virosa</i> (Roxb.ex Wild.) Royle.	X		X	
Phyllanthaceae	Hymenocardi a	<i>Hymenocardia acida</i> Tul.	X	X		
Phyllanthaceae	Margaritaria	<i>Margaritaria discoidea</i> (Baill.) GLWebster	X			
Polygalaceae	Securidaca	<i>Securidaca longepedunculata</i> Fresen.	X			
Rhamnaceae	Ziziphus	<i>Ziziphus spina-christi</i> (L.) Willd.			X	X
Rubiaceae	Crotopteryx	<i>Crotopteryx febrifuga</i> (Afz ex G.Don)Benth	X	X	X	
Rubiaceae	Feretia	<i>Feretia apodanthera</i> Delile	X		X	
Rubiaceae	Gardenia	<i>Gardenia aqualla</i> Stapf & Hutch.	X			
Rubiaceae	Gardenia	<i>Gardenia erubescens</i> Stapf & Hutch.	X	X	X	X
Rubiaceae	Gardenia	<i>Gardenia ternifolia</i> Schumach. & Thônn.	X	X		
Sapindaceae	Allophyle	<i>Allophylus africanus</i> P.Beauv.	X			
Sapindaceae	Bligia	<i>Blighia sapida</i> KDKoenig	X			
Sapotaceae	Manilkara	<i>Manilkara obovata</i> (Sabine & G.Don) J.H.Hemsl .	X			
Sapotaceae	Pouteria	<i>Pouteria alnifolia</i> (Baker) Roberty	X			
Sapotaceae	Vitellaria	<i>Vitellaria paradoxa</i> CFGaertn.	X	X	X	X
Sterculiaceae	Sterculia	<i>Sterculia setigera</i> Delile	X	X		X
Zygophyllaceae	Balanites	<i>Balanites aegyptiaca</i> (L.) Delile	X	X	X	X

Appendix B. Correlogram of the explanatory variable



Legend: Global_D = habitat heterospecific density; S_Richness = habitat-specific richness, Temperature_Aver = mea

Appendix C: Response curves of the variables used to model the distribution of *D. microcarpum*.



Publication 1

Local perceptions of anthropogenic and climate factors affecting the use and the conservation of *Detarium microcarpum* and *Detarium senegalense* in Burkina Faso (West Africa)

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Abstract

Understanding local perceptions and the different uses of multi-purpose plant species is essential for their sustainable management. Despite this, anthropogenic factors such as deforestation, over-exploitation of natural resources, extension of agricultural lands, overgrazing, and bushfires, coupled with the adverse effects of climate change, are contributing to the loss of these species. This study analyses the perceptions of local communities in Burkina Faso regarding the threats to *Detarium microcarpum* and *Detarium senegalense* and their implications, aiming to contribute to the effective management and conservation of such species. Through individual semi-structured and focus group interviews with 465 local people, data were collected on sociodemographic characteristics, plant parts used, use categories, threats and their effects, proposed solutions, and perceived conservation strategies. Descriptive statistics (consensus for plant part and relative frequency of citation), component analysis, and non-parametric analyses were used for data analysis. Results indicated that ethnicity, age, education level, and occupation were the most influential sociodemographic factors in relation to the use of these species. Six plant parts from both *Detarium* species are used across seven use categories, with fruits (0.40), trunks (0.16), and bark (0.27) being the most exploited. There was consensus among local populations regarding areas of abundance. Threat factors, their effects, and conservation solutions varied significantly according to site status. This study highlights the multipurpose uses of *Detarium* species throughout Burkina Faso and reveals that threats to these species are linked to the occupation and the status of each site. Sustainable use, effective conservation, and domestication of *Detarium* species should be considered to promote and sustain the exploitation of non-timber forest products.

KEYWORDS

climate change, *Detarium* species, plant parts, sustainable use, threat factors

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Plain language summary

Understanding rural populations' perceptions of the use and conservation of multipurpose species is crucial for effective and sustainable management of the resources these species provide. The valorisation and domestication of plant species require a scientific approach based on indigenous knowledge of their uses combined with conservation strategies. This study aims to contribute to the sustainable management of *Detarium microcarpum* and *Detarium senegalense* by analysing the perceptions of local populations regarding threats and potential solutions for their conservation. Data were gathered on informants' sociodemographic characteristics, plant use categories, plant parts used and conservation issues. Descriptive statistics (consensus for plant part and relative frequency of citation), component analysis and nonparametric analyses were used for data analysis. Ethnicity, age, education level and main activity were sociodemographic factors that had the most influence on species use. Through the exploitation of nontimber forest products, *Detarium* species contribute to improving the livelihoods of rural populations. Local populations are aware of the decline and the disappearance of *Detarium* species in their surrounding habitats, potentially caused by increasing use and the effects of climate change. These species have high social value due to their diverse applications, including food, traditional medicine, construction and crafts, which utilise all parts of the plant. This study shows that threats to these species are linked to activities in the surrounding areas and to forest status. This research provides a foundation for scientifically informed insights into the potential risks these species face. Rural communities are aware of potential threats and have developed management strategies and solutions to ensure sustainable use practices.

1 | INTRODUCTION

Climate change constitutes a critical environmental factor that significantly impacts natural habitats, compromising the development of African countries with limited and fragile resources (Liu et al., 2022). This situation adversely affects the livelihoods of most rural populations, which rely on natural resources such as nontimber forest products (NTFPs). Forests serve as biodiversity reservoirs, playing a vital role in providing ecosystem services to local communities (Agbo et al., 2017). These services, which humans derive from ecosystems in various ways (Leßmeister et al., 2018), contribute to rural communities' resilience against the effects of climate change (Gning et al., 2013). Mensah et al. (2014) reported that increasing human populations have led to intensified forest degradation due to the rising demand for forest products. Tan (2022) also found that the world's ecosystems are changing more rapidly with global population growth. Human actions such as deforestation, overexploitation of natural resources, agriculture, overgrazing and bushfires, coupled with the adverse effects of climate change, contribute to the loss of many multipurpose species. This loss affects natural ecosystems, diminishing their ability to provide goods and services to West African communities (Fontodji et al., 2019). The irreversible loss of

Practitioner points

- Local populations are aware of the decline and disappearance of *Detarium* species in their habitats, attributing this trend to excessive human exploitation and the effects of climate change.
- The challenges faced by *Detarium* species are correlated with activities in the surrounding area and individual forest status. *Detarium* plant resources may face challenges in forests with different levels of protection status due to habitat fragmentation and the effects of climate change.
- Rural communities have devised strategies and solutions which can contribute to the conservation of *Detarium* species.

plant species biodiversity leads to ecosystem degradation, impacting both ecosystem services and human well-being (Sintayehu, 2018).

The decline of multipurpose species in Sub-Saharan Africa greatly impacts communities and societal groups most dependent on forest resources (IPCC-IPBES, 2020). Maja and Ayano (2021) explain that population growth, urbanisation and economic

development have exacerbated food insecurity, increasing pressure on multipurpose woody species. *Detarium microcarpum* Guill. & Perr. and *Detarium senegalense* J.F. Gmel. are among the most exploited species in Burkina Faso (Bationo et al., 2001), Benin (Agbo et al., 2019) and Mali (Kouyaté, 2005). These species face vulnerabilities in their occurrence areas, yet their conservation status remains unclassified by the International Union for the Conservation of Nature (IUCN) (Lamy Lamy et al., 2021).

In recent years, much research effort has focused on the socioeconomic contributions (Kouyaté et al., 2002; Florence et al., 2014) and regeneration concerns (Agbo et al., 2019; Bationo et al., 2001; Lamy Lamy et al., 2021; Ricez, 2008) of *D. microcarpum* and *D. senegalense*. While several studies have shown the importance of *Detarium* species in food and economic sectors through the exploitation of NTFPs, less attention has been given to local perceptions of the threats to these species. The exploitation of plant parts from species such as *D. microcarpum* and *D. senegalense* serves as a resilience strategy through the ecosystem services provision for rural populations. With increasing populations, NTFP market values have risen, putting greater pressure on these woody multipurpose species. This pressure contributes to the vulnerability of *D. microcarpum* and *D. senegalense* (Ouédraogo et al., 2021; Yaovi et al., 2021). In addition, the lack of effective management strategies and insecurity in West African Sahelian countries amplify the threats to these species (Zerbo et al., 2022). Understanding local communities' resilience, alongside their perceptions of climate effects and current threats to *Detarium* species, is essential for assessing their adaption potential (Houndonougbo et al., 2020; Ouko et al., 2018; Tiétiambou et al., 2015).

Given the significant role of *Detarium* species in Burkina Faso (Bationo et al., 2001; Maré & Millogo, 2019), it is necessary to investigate local perceptions regarding the degradation of these plant resources in the current context of climate change and over-exploitation. Knowledge of human perceptions towards plant species is a key factor in understanding ecosystem dynamics for sustainable biodiversity management. Moreover, the valorisation and the domestication of plant species require a scientific approach that incorporates indigenous knowledge of their uses into conservation strategies (Balima et al., 2018). In Burkina Faso, several studies have been carried out on the sociocultural, economic and ecological significance of multipurpose woody species such as *Balanites aegyptiaca* (L.) Delile (Kouyaté et al., 2002), *Azelia africana* Sm. ex Pers. (Balima et al., 2018) and *Bombax costatum* Pellegr. & Vuillet (Zerbo et al., 2022). While previous ethnobotanical studies on *Detarium* species have been carried out across West Africa in countries like Benin (Agbo et al., 2017), Togo (Dangbo et al., 2019), Senegal (Diop et al., 2010), Mali (Kouyaté et al., 2002) and Burkina Faso (Bationo et al., 2001), many

aspects remain unexplored. This study aims to fill some of these gaps by analysing local population perceptions regarding the threats to *D. microcarpum* and *D. senegalense*, and their implications for management. Specifically, it aims to (i) identify the specific parts of these species that are exploited, (ii) assess the impact of sociodemographic characteristics on their use, (iii) analyse the local perceptions of species decline and (iv) assess local conservation strategies to ensure their sustainable use in Burkina Faso.

2 | MATERIALS AND METHODS

2.1 | Materials

2.1.1 | Study area

The study was conducted along a climatic gradient in Burkina Faso, a country in West Africa, located between the latitudes 09°02'–15°05'N and the longitudes 05°03'W 02°02'E. With a total area of 274,400 km², the population is estimated at 20,487,979 habitants, resulting in a density of 51.08 inhabitants/km² (INSD, 2020) (Figure 1). The research focused on villages surrounding four protected areas (PAs) known to harbour natural populations of *Detarium* species. These areas include the Classified Forest of Nakambe (located in the Sudano-Sahelian climatic zone), the Classified Forest and Game Ranch of Nazinga (located in the transition zone between the Sudanian and Sudano-Sahelian climatic zones), the Wildlife Reserve of Bontioli and the Classified Forest of Kou (both located in the Sudanian climatic zone). These classified forests were selected based on their accessibility stemming from the current security challenges the country is facing.

The main ethnic groups residing around the PAs in the study region are diverse: Mossi near the Classified Forest of Nakambe, Gourounsi around the Classified Forest and Game Ranch of Nazinga, Dagara around the Wildlife Reserve of Bontioli and Bobo around the Classified Forest of Kou. Predominantly, these communities engage in agriculture, relying on the cultivation of millet, Azia maize and sorghum, alongside herding and provisioning ecosystem services from trees (Dimobe et al., 2015).

According to National Meteorological Office data, the Sudano-Sahelian zone experiences annual rainfall ranging from 600 to 900 mm spread over 4–5 months, with average temperatures around 30°C. The Sudanian zone receives an annual rainfall of 900–1200 mm over a longer rainy season lasting 5–6 months, with a cooler average annual temperature of 26°C. The vegetation in the four PAs is characterised by various vegetation types, including shrub savannas, tree savannas, woodlands, dry forests and gallery forests (Nacoulma et al., 2018).

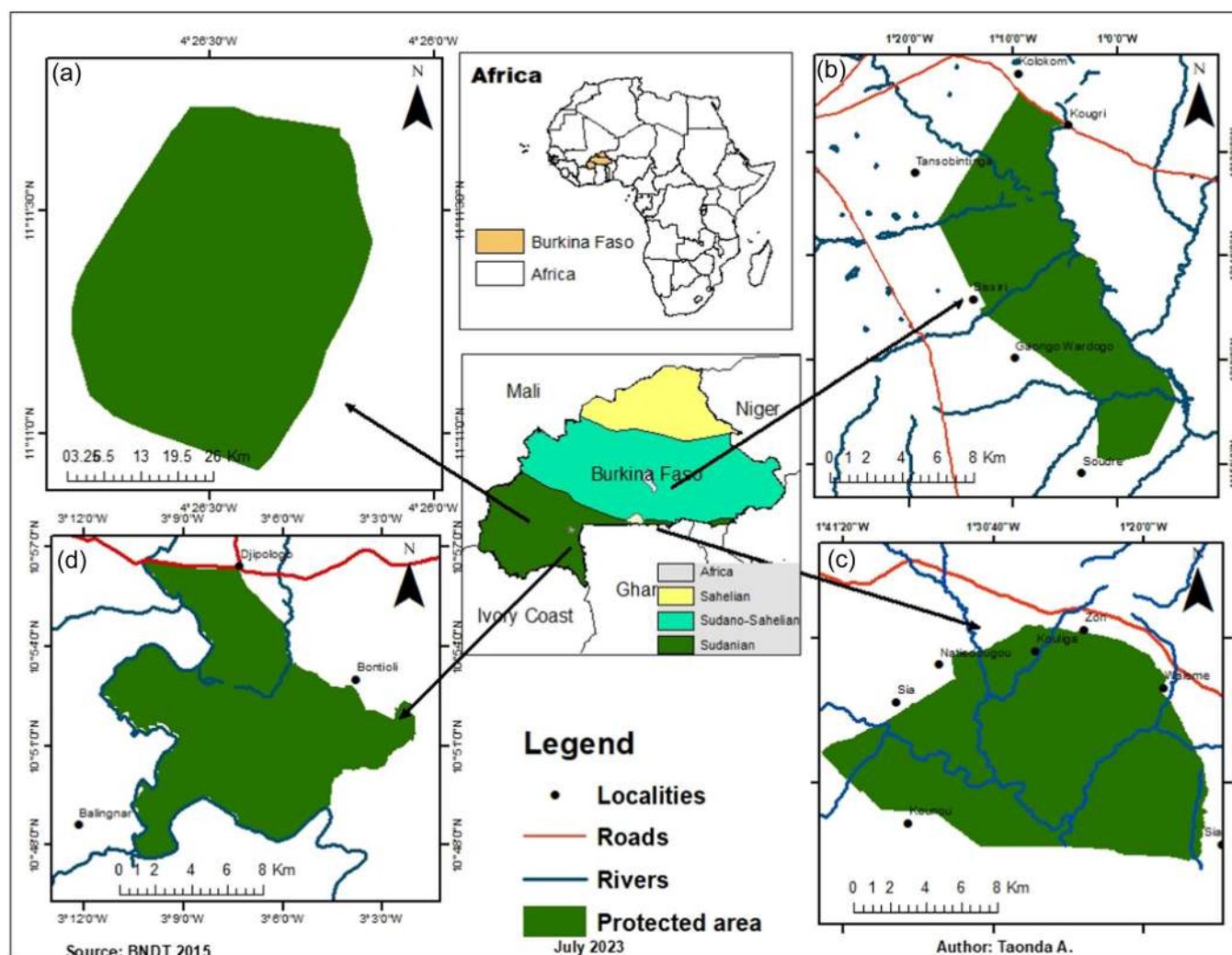


FIGURE 1 Map of study sites according to the 2012 Burkina Faso land occupation database. (a) Classified Forest of Kou; (b) Classified Forest of Nakambe; (c) Classified Forest and Game Ranch of Nazinga; and (d) Wildlife Reserve of Bontioli.

2.1.2 | Study species

D. microcarpum and *D. senegalense* are woody species belonging to the Fabaceae family (Arbonnier, 2009). *D. microcarpum*, a medium-sized tree, can reach up to 12 m in height and is distinguished by its dense spherical crown (Maré & Millogo, 2019; Thiombiano et al., 2012). *D. senegalense* is larger, usually growing to between 15 and 30 m, and even reaching 40 m within forest galleries (Houénou et al., 2021). The two species differ in several morphological aspects: *D. microcarpum* typically has fewer, larger and tougher leaflets, more compact inflorescences, externally hairy sepals and slightly smaller fruits compared to *D. senegalense* (Dangbo et al., 2019; Diop, 2013; Dossa, Gouwakinnou, et al., 2020). Both species feature paripinnate leaves with 5–6 pairs of opposite leaflets arranged alternately. The leaflets are 4–6 cm long and 3–4 cm wide, oval to elliptical, rounded at the ends and emarginate at the top. The limb is thin, flexible, finely leathery, pinnate and green on the underside. Their inflorescence form in axillary panicles and measure between 5 and 8 cm in length. The creamy white flowers, in raceme, have a glabrous or glabrescent calyx. They have four elliptical sepals

with an ovoid and pubescent ovary, supported by 10 white bilocular stamens. These species are mainly dispersed by animals and exhibit distinct habitats (Bationo et al., 2001; Kamou et al., 2017).

D. microcarpum thrives in dry savannas, dry forests and fallow lands on sandy or iron-rich hard soils (Houénou et al., 2021; Kouyaté et al., 2006). *Detarium senegalense* prefers dry lowland forests, gallery forests in savannah areas (Cavin, 2007; Diop et al., 2010) and humid forests (Sanusi, 2022). Notably, certain *Detarium* species, like *D. microcarpum*, have shown some resistance to fire (Diatta et al., 2021). Propagation of these species can occur both vegetatively and from seeds (Bationo et al., 2001; Ricez, 2008).

2.2 | Method

2.2.1 | Sampling

A total of 465 individuals were interviewed using a simple random sampling technique, without gender considerations, based on their knowledge of plant parts of the two species in question (Zerbo

et al., 2022). The number of interviewees varied from 65 to 185 individuals across different sites, determined by the population density of each area. Participants included local residents of various ages, with a minimum age requirement of 30 years to ensure respondents had sufficient experience to identify changes in climate and anthropogenic threats to the species. Before conducting interviews, administrative and traditional leaders, as well as youth leaders at each site, were informed to aid in establishing a conducive environment for interactions with community members.

2.2.2 | Data collection

Data were collected through semi-structured interviews and focus group discussions from September to December 2022 (Balima et al., 2018; Naah & Guuroh, 2017; Zerbo et al., 2022). To ensure accurate identification, specimens of the *Detarium* species were provided to informants at each site. Interviews were conducted in local languages and translated by site-specific translators. Informants provided verbal consent before participation. The questionnaire included a combination of closed and open-ended questions and was designed to gather data on sociodemographic characteristics (ethnicity, sex, age, education level and occupation) and the uses of different plant parts from the targeted species (Zerbo et al., 2022). Additional questions related to areas of abundance, threats and their impacts on the species and conservation solutions for sustainable resource management were also included. Informants provided insights into the current status of the species, including stability, decline or disappearance and motivations for their conservation.

2.2.3 | Data analyses

To determine the composition of the investigated population, the relative frequency of different sociodemographic characteristics, such as ethnic group, sex, age, education level and activity sectors, were computed. Regarding age consideration, the informants were grouped into three age categories following Assogbadjo et al. (2008): young ($30 \leq \text{age} < 45$ years), adults ($45 \leq \text{age} < 60$) and old ($\text{age} \geq 60$ years).

To highlight which part of the species is used most often, the consensus value for plant part (CPP) was considered (Table 1). It measures the degree of agreement among informants concerning the plant part used (Monteiro et al., 2006). In addition, the relative frequency of citation (RFC) for use categories was calculated to identify the most common uses. The Kruskal–Wallis nonparametric test was used to assess whether CPP and RFC varied significantly according to the sociodemographic factors (ethnic groups, sex, age, education levels and activity sectors).

RFC was also used to evaluate local perceptions of presence areas, threats and conservation solutions for the sustainable use of the species. Bar plots were created to visualise the areas of presence using the *tidyr* package (Hadley et al., 2023). Correspondence analyses were performed to highlight the relationship between local population perceptions of threat factors and their consequences relative to different sociodemographic characteristics, using the packages *factoMiner* version 2.8 (Husson et al., 2023) and *factoshiny* (Vaissie et al., 2022).

Following Zerbo et al. (2022), RFC calculations for different ethnic groups were depicted using Sankey diagrams using the *networkD3* package (Ellis et al., 2013).

All statistical analyses were performed with R software version 4.2.2 (R Core Team, 2022).

3 | RESULTS

3.1 | Sociodemographic characteristics of the surveyed populations

The survey engaged 465 individuals across the study sites, of which 63.22% were men (Table 2). The age group 30–44 years was the most represented among respondents (56.56%). Mossi was the dominant ethnic group, comprising 38.49% of the total respondents and being the only group found at all sites. In terms of education, a significant proportion of the local population had no formal education (62.94%), followed by those with primary school education (27.31%). Occupationally, most of the respondents were farmers (43.44%) and household members (31.61%) (Table 2).

TABLE 1 Description of the calculated parameters.

No.	Parameters	Formula	Significations
1	Consensus value for plant part (CPP)	$CPP = P_x / P_t$	Number of times a given plant part was cited (P_x), divided by the total number of citations of all parts (P_t). Measures the degree of agreement among the informants concerning the plant part used (Monteiro et al., 2006).
2	Relative frequency of citation (RFC)	$RFC = (S/N) \times 100$	A measure calculated as $RFC = (S/N)$, where 'S' represents the number of citations for a specific use of a plant part, and 'N' is the total number of informants. This metric provides insight into the relative importance of each plant part among the population for their provision of services.

TABLE 2 Sociodemographic characteristics.

	Sites					
Sociodemographic parameters	Bontoli	Kou	Nakambe	Nazinga	Total	Percentage (%)
Ethnic group						
Bobo	0	63	0	0	63	13.55
Dagara	99	0	0	0	99	21.29
Gourounsi	0	0	0	60	60	12.90
Mossi	21	0	126	32	179	38.49
Others	0	2	59	3	64	13.76
Total	120	65	185	95	465	100
Sex						
Women	39	28	72	32	171	36.77
Men	81	37	113	63	294	63.23
Total	120	65	185	95	465	100
Age						
Young (30 > age ≤ 44 years)	73	18	101	71	263	56.56
Adult (45 > age ≤ 59 years)	33	39	74	15	161	34.62
Old (age >60 years)	14	8	10	9	41	8.82
Total	120	65	185	95	465	100
Education level						
High primary	10	2	10	27	49	10.54
Illiterates	88	46	107	48	289	62.15
Primary level	22	17	68	20	127	27.31
Total	120	65	185	95	465	100
Occupation						
Farmers	35	27	95	45	202	43.44
Household	30	25	60	32	147	31.61
Official workers	5	3	3	7	18	3.87
Traditional mining exploitation	33				33	7.10
Traders	10	9	15	9	43	9.25
Traditional healer	7	1	2	2	12	2.58
Wood exploitation			10		10	2.15
Total	120	65	185	95	465	100

3.2 | Use patterns of *Detarium* species according to sociodemographic characteristics

3.2.1 | Impact of sociodemographic parameters on plant parts used

The survey identified six plant parts of *Detarium* species—fruits, bark, leaves, roots, branches and trunks—utilised by the local population for various purposes (Table 3).

The CPP varied significantly according to the ethnic groups for bark ($\chi^2 = 22.25$; $p = 0.0001$), trunks ($\chi^2 = 11.86$; $p = 0.0184$), leaves ($\chi^2 = 11.16$;

$p = 0.0248$) and branches ($\chi^2 = 9.89$; $p = 0.0422$), indicating distinct preferences and uses among different cultural backgrounds. However, this variation was not significant for fruits ($\chi^2 = 7.38$; $p = 0.1177$) or roots ($\chi^2 = 3.84$; $p = 0.4278$). Specifically, the Bobo group predominantly used leaves (CCP = 0.1384), while the Dagara group showed a higher usage of trunks (CPP = 0.41), followed closely by the Gourounsi (CPP = 0.33) and the Mossi (CPP = 0.30). Both Dagara (CPP = 0.10) and Gourounsi (CPP = 0.10) communities also exhibited notable use of roots.

The CPP among the surveyed populations did not significantly vary with education level

TABLE 3 Impact of sociodemographic parameters on plant part used.

Sociodemographic factors	Bark	Fruits	Leaves	Roots	Branches	Trunks
Ethnic groups						
Bobo	0.02	0.41	0.14	0.09	0.19	0.15
Dagara	0.01	0.29	0.09	0.10	0.08	0.42
Gourounsi	0.14	0.35	0.05	0.10	0.03	0.33
Mossi	0.07	0.36	0.05	0.09	0.14	0.29
Others	0.01	0.52	0.11	0.06	0.14	0.18
Mean	0.05	0.38	0.09	0.09	0.12	0.28
χ^2	22.25	7.37	11.16	3.84	9.89	11.86
p-Value	0.0001	0.1177	0.0248	0.4278	0.0422	0.0184
Education level						
High Primary	0.03	0.49	0.04	0.06	0.11	0.25
Primary	0.03	0.38	0.08	0.09	0.13	0.30
Noneducated	0.07	0.33	0.08	0.09	0.13	0.28
Mean	0.05	0.40	0.07	0.08	0.12	0.28
χ^2	6.01	3.20	4.53	3.91	2.47	2.05
p-Value	0.0497	0.2018	0.1039	0.1417	0.2906	0.3579
Sex						
Women	0.03	0.39	0.08	0.08	0.15	0.27
Men	0.06	0.35	0.07	0.09	0.11	0.30
Mean	0.05	0.37	0.08	0.09	0.13	0.28
χ^2	1.67	0.54	0.01	1.20	0.66	0.12
p-Value	0.1959	0.4621	0.9224	0.2729	0.4172	0.7276
Age						
Young	0.04	0.38	0.07	0.10	0.12	0.32
Adults	0.06	0.38	0.07	0.09	0.14	0.27
Old	0.11	0.33	0.13	0.12	0.12	0.19
Mean	0.07	0.34	0.09	0.10	0.13	0.26
χ^2	1.22	1.22	0.78	0.59	0.78	6.94
p-Value	0.5433	0.5433	0.6786	0.7454	0.5444	0.0312
Occupation						
Farmers	0.09	0.77	0.15	0.17	0.33	0.49
Traders	0.04	0.73	0.13	0.22	0.26	0.62
Public workers	0.05	0.61	0.01	0.00	0.00	0.35
Household	0.04	0.47	0.04	0.02	0.06	0.38
Traditional mining exploitation	0.41	0.12	0.02	0.00	0.04	0.54
Wood exploitation	0.10	0.24	0.23	0.13	0.09	0.21
Traditional healer	0.07	0.12	0.23	0.27	0.109	0.21
Mean	0.11	0.42	0.11	0.12	0.13	0.54
χ^2	25.34	76.138	17.16	27.41	33.23	21.35
p-Value	0.00473	0.0000	0.071	0.0022	0.0002	0.0188

($p > 0.05$) for most plant parts, including fruits ($\chi^2 = 3.20$; $p = 0.0218$), leaves ($\chi^2 = 4.53$; $p = 0.1039$), roots ($\chi^2 = 3.91$; $p = 0.1417$), branches ($\chi^2 = 2.47$; $p = 0.2906$) and trunks ($\chi^2 = 2.06$; $p = 0.3579$), indicating a uniformity in the use of *Detarium* species across different educational backgrounds. However, a significant difference was observed for bark usage ($\chi^2 = 6.01$; $p = 0.0497$), suggesting that certain knowledge or preferences related to bark use might be influenced by education. Despite this, branches (CPP = 0.14) and trunks (CPP = 0.30) were primarily used by individuals with no formal education, perhaps reflecting traditional knowledge passed down through generations that do not rely on formal education systems. No significant differences were found in the CPP between genders ($p > 0.05$).

On the other hand, occupation significantly influenced the CPP ($p < 0.05$). Trunks (CPP = 0.54) and fruits (CPP = 0.42) were commonly used by people from all sectors. However, specific sectors showed unique preferences; for instance, public workers reported no use of roots, leaves, or branches (CPP = 0), possibly reflecting a disconnection from the traditional use of plants. Conversely, traditional healers (tradipraticiens) mostly used roots (CPP = 0.27), leaves (CPP = 0.23) and trunks (CPP = 0.20), suggesting a specific application in this sector. Interestingly, bark was most used by those in the traditional mining exploitation sector (CPP = 0.41) (Table 3).

3.2.2 | Impact of sociodemographic parameters on use categories

The use of *Detarium* species parts spans various categories, including food, medicine, craft, energy, construction and sales (Table 4).

The analysis of local population knowledge concerning the food use of *Detarium* species indicates a wide awareness across different socio-demographic groups, with no significant variation ($p \geq 0.05$) among ethnic groups, age groups, education levels and gender. The activity sector presents a notable exception, where significant differences were observed ($\chi^2 = 81.16$, $p \leq 0.05$).

Gourounsi (RFC = 20.46%) and Bobo (RFC = 18.55%) ethnic groups emerged as the most knowledgeable in the use of the species for food. Similarly, younger (RFC = 18.91%) and adult age groups (RFC = 16.22%) knew more about food uses. Gender-wise, men (RFC = 19.05%) reported slightly more knowledge about food uses than women (RFC = 15.60%). Noneducated level respondents (RFC = 19.52%) reported higher use of *Detarium* species for food than other education levels. Farmers (RFC = 38.48%) and household members (RFC = 27.89%) reported more knowledge of food uses than those from other activity sectors.

In the medicinal use category, the analysis revealed that while knowledge does not significantly differ among ethnic groups and ages

($p \geq 0.05$), it does vary with education level ($\chi^2 = 22.02$; $p = 0.0006$), gender ($\chi^2 = 12.54$; $P = p \leq 0.05$) and activity sector ($\chi^2 = 38.58$, $p = 0.0001$). The Dagara (RFC = 39.74) ethnic group exhibited the highest frequency of citation of medicinal uses, followed by the Mossi (RFC = 27.49%) and Bobo groups (RFC = 27.33%). Older individuals (RFC = 33.79%), followed by adults (RFC = 28.18%), knew more about the medicinal uses of *Detarium* species. Regarding education level, the noneducated (RFC = 40.38%) and primary-level educated (RFC = 28.71%) individuals cited the species for medicinal use. Gender differences were evident, with men (RFC = 34.19%) reporting a higher familiarity with the species' medicinal applications than women (RFC = 20.72%). Occupationally, farmers (RFC = 78.52%) and traditional healers (56.06%) were the most knowledgeable about the species in the medicine category.

In the craft category, knowledge varied significantly according to ethnic group ($\chi^2 = 20.44$; $p = 0.0004$), gender ($\chi^2 = 4.00$; $p = 0.0454$) and occupation ($\chi^2 = 19.37$; $p = 0.0222$), but not across age groups and education levels ($p \geq 0.05$). Farmers (RFC = 45.06%) had the highest RFC, highlighting their prominent use of the species in the craft category.

In the energy use category, knowledge of the use of *Detarium* species did not differ significantly by ethnic group, age, or gender ($p \geq 0.05$). However, education level ($\chi^2 = 18.08$; $p = 0.0006$) and the occupation ($\chi^2 = 44.79$; $p = 0.0001$) had significant effects. The Mossi (RFC = 25.94%) and Bobo (RFC = 22.56%) ethnic groups made the most use of the species in the energy category. Older individuals (RFC = 20.51%) cited uses for energy more frequently than other age groups. Noneducated individuals (RFC = 41.17%) reported using the species for energy more than those with higher levels of education. Women (RFC = 28.63%) reported using these species for energy purposes more than men (RFC = 20.09%). Farmers (RFC = 69.27%) and those involved in traditional mining exploitation (RFC = 45.56%) indicated more knowledge about the use of *Detarium* species in the energy category.

The use of the *Detarium* species in the sales category differed significantly based on gender ($\chi^2 = 105.87$; $p = < 2.2e-16$) and the occupation ($\chi^2 = 25.21$; $p = 0.0027$). Despite variations in educational background, age and ethnicity, participants shared similar knowledge ($p \geq 0.05$). The Mossi ethnic group (RFC = 27.45%), followed by the other ethnic groups (RFC = 22.40%), sold more parts of the *Detarium* species. Younger individuals (RFC = 25.37%), adults (RFC = 22.52%), women (RFC = 37.49), farmers (RFC = 32.80%) and traders (RFC = 32.44%) were more knowledgeable about the commercial importance of the species.

In the construction use category, knowledge varied significantly between ethnic groups ($\chi^2 = 20.44$; $p = 0.0004$), genders ($\chi^2 = 15.06$; $p = 0.0001$) and occupation ($\chi^2 = 23.44$; $p = 0.0053$). However, educational level and age did not significantly affect knowledge in

TABLE 4 Impact of sociodemographic parameters on usage categories.

Sociodemographic factors	Uses-categories					
	Food	Medicine	Craft	Energy	Seller	Construction
Ethnics groups						
Bobo	18.55	27.34	12.97	22.56	17.35	1.25
Dagara	13.94	39.74	1.59	14.48	19.00	13.43
Gourounsi	20.46	25.07	13.08	18.23	19.26	3.92
Mossi	17.14	27.49	7.34	25.94	27.45	9.59
Others	18.97	25.03	8.27	21.25	22.40	2.08
Mean	17.81	28.94	8.66	20.49	21.09	6.05
χ^2	3.88	9.25	20.44	3.43	1.10	22.52
<i>p</i> -Value	0.4232	0.0552	0.0004	0.4882	0.8942	0.0002
Age						
Adults	16.22	28.18	6.20	19.91	22.52	6.96
Old	15.52	33.80	9.20	20.51	10.98	9.99
Youngs	18.91	26.84	9.14	17.88	25.37	6.54
Mean	16.88	29.61	8.18	19.43	19.63	7.83
χ^2	1.95	0.44	0.52	1.31	6.93	6.93
<i>p</i> -Value	0.5827	0.9320	0.9136	0.7270	0.0743	0.6392
Education level						
High primary	17.43	26.68	10.14	17.09	21.40	9.19
Primary	17.61	28.72	8.26	21.22	21.53	8.68
Noneducated	19.52	40.37	7.26	41.17	19.25	5.44
Mean	18.18	31.92	8.55	26.49	20.73	7.77
χ^2	0.03	22.03	0.03	18.08	0.24	0.74
<i>p</i> -Value	0.9860	0.0006	0.9835	0.0006	0.8863	0.6916
Sex						
Women	15.60	20.72	5.49	28.63	37.49	3.06
Men	19.05	34.20	10.16	20.07	6.77	10.36
Mean	17.33	27.46	7.82	24.34	22.13	6.71
χ^2	1.12	12.54	4.00	0.42	105.87	15.06
<i>p</i> -Value	0.2896	0.0004	0.0455	0.5181	<2.2e-16	0.0001
Occupation						
Farmers	38.48	78.52	45.06	69.26	32.80	40.88
Public workers	21.71	29.80	3.21	19.29	17.06	8.93
Household	27.89	21.88	4.31	21.03	29.45	4.44
Traditional mining exploitation	16.36	23.06	6.25	45.56	2.50	22.64
Trader	17.98	41.58	6.81	20.93	32.44	2.89
Traditional healer	7.25	56.06	7.97	9.68	17.60	1.45
Wood exploitation	15.14	31.09	14.46	11.43	23.79	4.09
Mean	20.69	40.28	12.58	28.17	22.23	12.19
χ^2	81.16	38.58	19.36	44.79	25.21	23.43
<i>p</i> -Value	0.0010	0.0001	0.0223	0.0001	0.0027	0.0053

this area ($p \geq 0.05$). The Dagara ethnic group (RFC = 13.43) and farmers (RFC = 40.88%) demonstrated the most knowledge about using the species for construction (Table 4).

3.3 | Local perceptions on the areas of abundance, threat factors and their effects on *Detarium* species conservation

The survey revealed five habitats identified by different ethnic groups as areas where *Detarium* species are found (Figure 2). Except for the Dagaras ethnic group, which predominantly located the species on granite rocky hills (31.97%) and the agrosystem (27.50%), other groups reported higher abundance in PAs and fallows. The Bobo ethnic group observed the species most abundantly in the PAs (50.81%) and fallows (33.61%). Similarly, the Gourounsi group found the species mainly in the PAs (40.09%) and fallows (37.14%), while the Mossi group reported a significant presence in PAs (40.09%). Across all groups, villages were cited less frequently as habitats for these species, indicating a consensus on the species' rarity in village environments (Figure 2).

Local populations are aware that *Detarium* is under threat and have identified six factors that are impacting the survival of these species within their natural habitats. The correspondence analysis, which explains a significant 82.68% of the data distribution across two main axes, reveals how different socio-demographic groups perceive these threats (Figure 3). The first axis, accounting for 59.9% of the data distribution, correlates with the Mossi ethnic group, men, adults, youths, illiterate individuals and those with primary education levels. These groups perceived wood overexploitation and bushfires as the primary threats to *Detarium* species. The Bobo and

Gourounsi ethnic groups mentioned village expansions as a significant threat, while members of the category 'Other' ethnic groups highlighted extensive farming as a primary concern. On the second axis, which explains 22.80% of the variation, there is a distinction between the Mossi ethnic group and their associated sociodemographic parameters against the backdrop of other ethnic groups. Here, the Dagara ethnic group, along with individuals who have high primary education levels and are older, associated traditional mining exploitation and population growth as significant threats (Figure 3).

Nine consequences associated with the threats to *Detarium* species were identified by the local populations (Figure 4), with their perceptions analysed through correspondence analysis, explaining 65.7% of the data distribution across two main axes. The first axis, which accounts for 50.50% of the data distribution, groups the Mossi, Dagara and 'Others' category ethnic groups alongside individuals who are illiterate or only have primary education, as well as adults. These groups share the same opinion that the effects of threats include regrowth and degradation of the species, a decrease in rainfall, a reduction in medicinal species decrease, loss of wild animals and a decline in bee populations'. On the second axis, explaining 15.2% of the variation, the Bobo and Gourounsi ethnic groups noted a decrease in tourist visits as a consequence of threats to the *Detarium* species (Figure 4).

3.4 | Local perceptions on conservation solutions and management strategies for *Detarium* species

Local populations proposed 10 solutions aimed at mitigating the decline of *Detarium* species, with

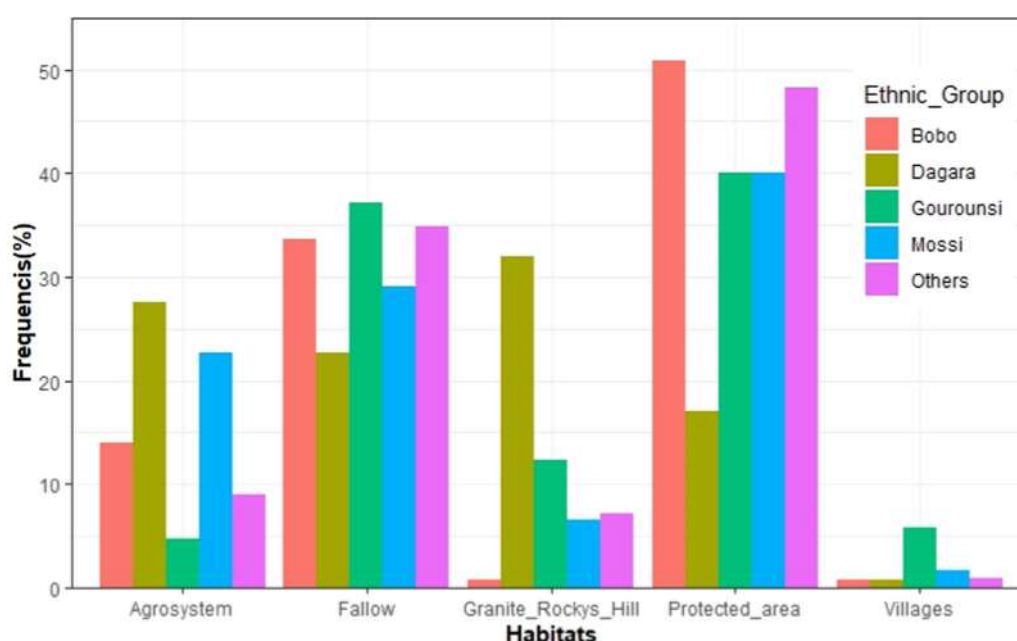


FIGURE 2 Local population perceptions on the areas of species abundance.

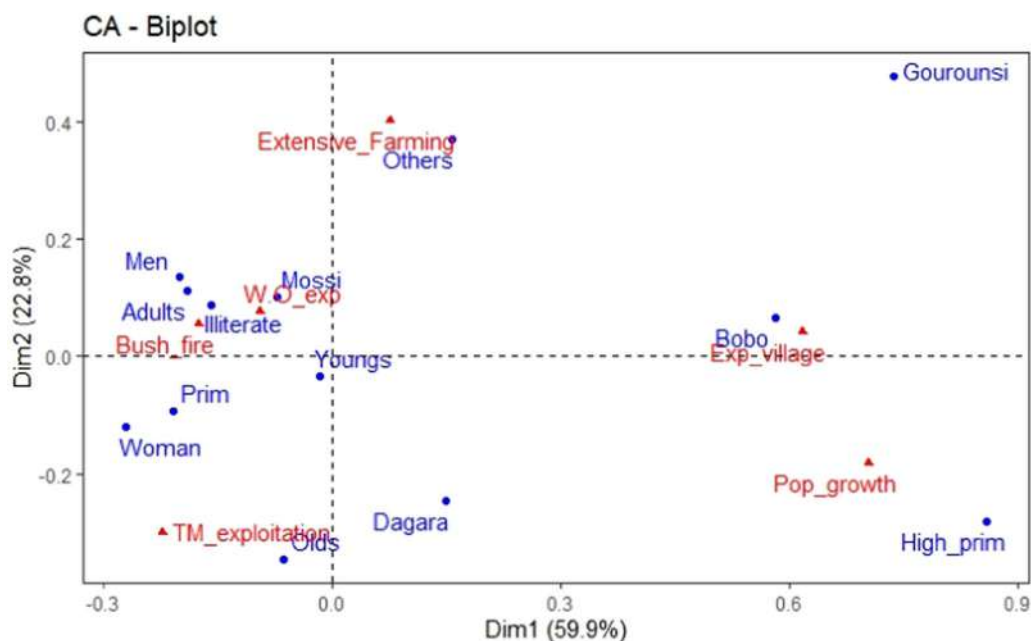


FIGURE 3 Local population perceptions on threats affecting the species. Exp_village, village expansion; Pop_growth, population growth; TM_exploitation, traditional mining exploitation; W.O_exp, wood overexploitation.

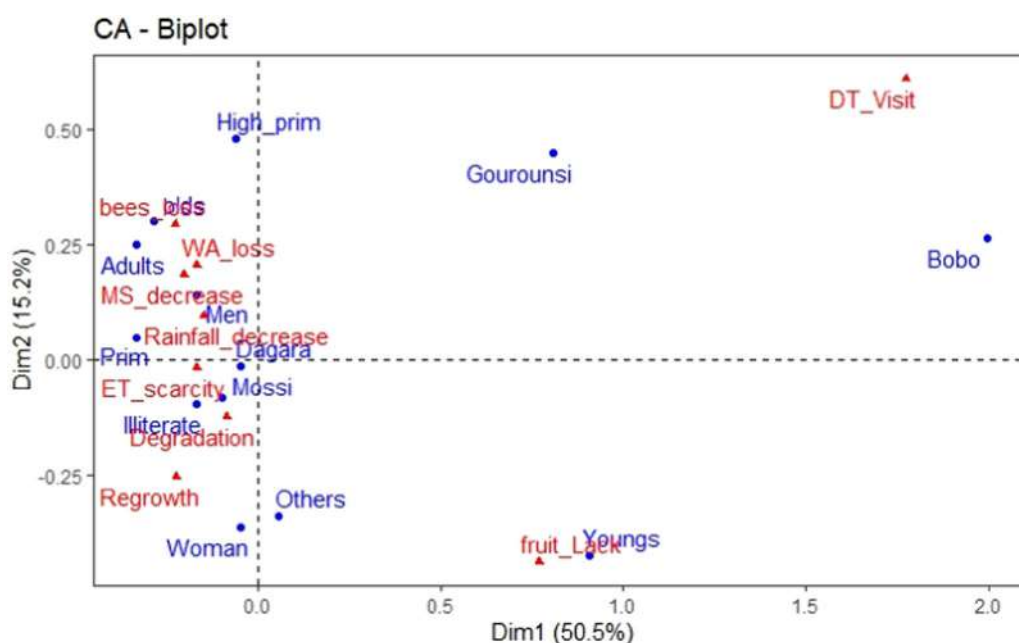


FIGURE 4 Local population perceptions on the consequences of threat factors on the species. DT_visit, decrease tourist visits; ET_scarcity, species decline; High_prim, high primary education level; MS_decrease, medicine species decrease; Prim, primary education level; WA_loss, wild animal loss.

significant variation in preferences among different ethnic groups ($\chi^2 = 696.76$; $p < 0.0001$) (Figure 5). The Mossi ethnic group suggested the importance of demarcation (44%) and comanagement (36%) as critical measures for preventing species decline. The Gourounsi highlighted the need for awareness (21.43%) and monitoring of the species (23.19%). The Bobo expressed a preference for comanagement (27.69%) and the introduction of fines (22.45%) (Figure 5).

For the sustainable management of *Detarium* species, six conservation strategies were mentioned (Figure 5), with preferences varying significantly among ethnic groups ($\chi^2 = 696.76$; $p < 0.0001$). The strategies of comanagement (53.29%), financial support (48.79%) and valorisation of the fruit value chain (47.38%) were the most requested. The Mossi suggested comanagement (43.41%), financial support (37.23) and reforestation (23.37%), while the Gourounsi preferred reforestation (43.28%), comanagement

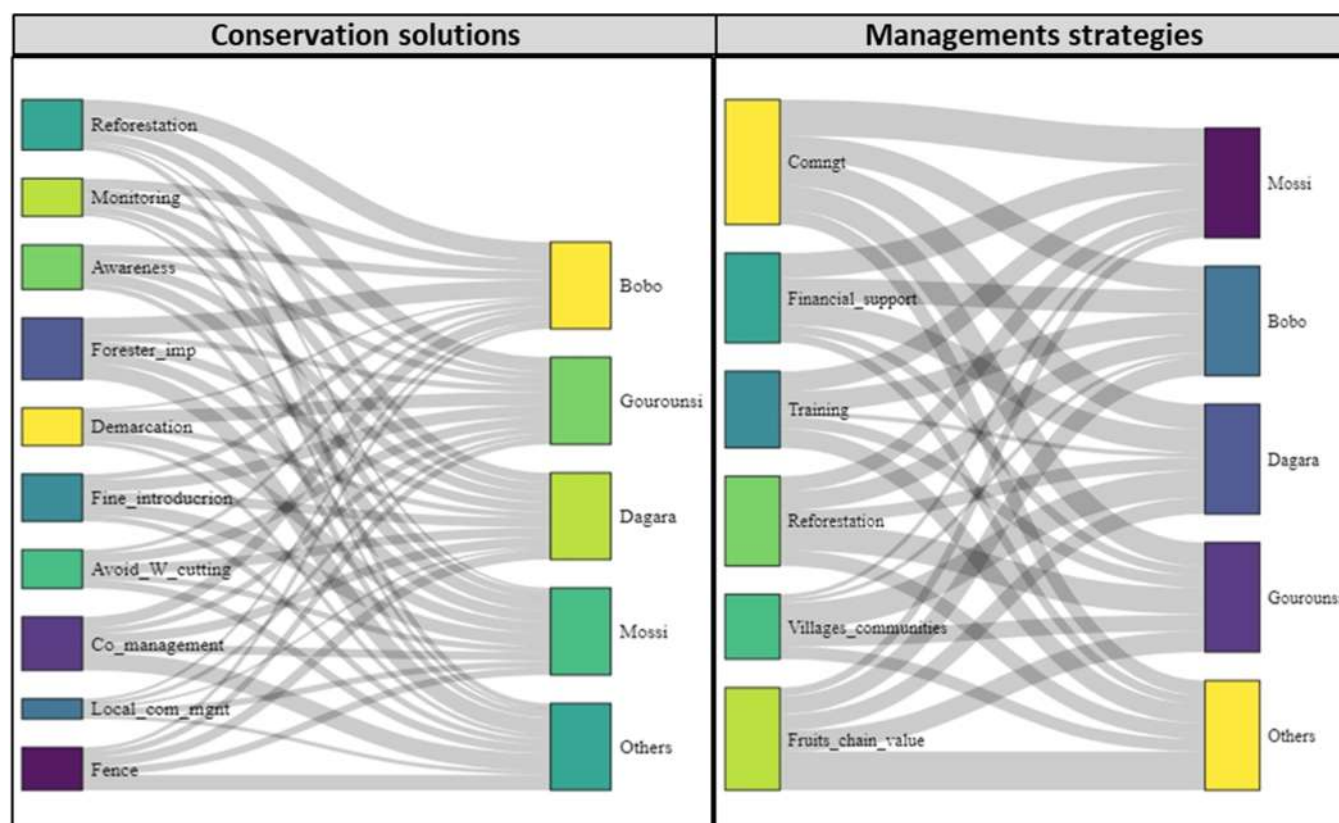


FIGURE 5 Local perceptions on conservation solutions and management strategies according to ethnic group. Avoid_W_cutting, avoid wood cutting; Forester_imp, forester implication; Local_com_mngt, local community management.

(41.32%) and fruit value chain valorisation (35.67%). The Dagara ethnic group mentioned local community management (36.21%), comanagement (31.62%) and financial support. Members of the 'Others' ethnic group category requested valorisation of the fruit value chain and training.

4 | DISCUSSION

4.1 | Variations in *Detarium* species use

This study showed that *D. microcarpum* and *D. senegalense* are species with multiple uses, with local communities exploiting nearly every part of these plants—roots, bark, trunk, fruit, leaves and branches—for a variety of purposes. This extensive use underscores the significant value of *Detarium* species as multipurpose resources for the local population (Gaisberger et al., 2017). The broad spectrum of applications for these species confirms their importance in supporting rural livelihoods (Houénou et al., 2021; Sreekumar et al., 2020). Dimobe et al. (2018) identified *Detarium* species among the priority multipurpose species in Burkina Faso, a designation also accorded to other species like *A. africa* (Balima et al., 2018) and *B. costatum* (Zerbo et al., 2022).

Informants mostly mentioned the use of fruits and trunks of the *Detarium* species. This high fruit usage indicates that the species play a role in food

security, contributing to the resilience of rural populations. Similarly, the extensive use of trunks indicates the dependency on these species for timber (Sinadouwirou et al., 2022).

The study also revealed that sociodemographic factors influence the exploitation patterns of *Detarium* species. Women's focus on trunks and branches underlines the use of the species as firewood and is indicative of their role in gathering firewood, a task integral to cooking responsibilities within households. This pattern aligns with observations made by Kouyaté (2005) in Mali and Agbo et al. (2020) in Benin, highlighting this gendered knowledge and use of firewood trees. This particular interest in trunks poses a considerable challenge to the conservation of the species (Biara et al., 2021), as it directly impacts the availability of mature trees. Harvesting leaves, fruits and bark could also potentially affect the reproductive performance of the species, further stressing the need for sustainable management practices (Nacoulma et al., 2017).

The distinct CPPs reported by individuals with higher levels of education, compared to the lower values associated with branches and trunks, suggests that the level of education influences choices regarding energy sources. Gkargkavouzi et al. (2020) illustrated that a higher education level is often correlated with a positive stance towards species conservation, implying that education plays a crucial role in promoting conservation efforts.

However, the impact of modernisation and development seems to be affecting traditional knowledge systems concerning the use of multipurpose species in the region. Monteiro et al. (2006) explained how progress in modernisation has influenced the dynamics of plant use, potentially diminishing the transmission and application of indigenous knowledge concerning these species.

The pronounced preference for fruit among traders and farmers, as indicated by the high CPP values, underscores the dual role of *Detarium* species as both a nutritional supplement for farmers and a source of income. This observation aligns with Lykke et al. (2004), who showed that the importance attached to a species often depends on its utility to different user groups. Furthermore, Monteiro et al. (2006) and Zerbo et al. (2022) observed that preferences for specific plant parts differ among communities, highlighting the diverse ways in which multipurpose species support the resilience and food security of rural communities. The importance of such species in the livelihoods of rural populations is further supported by studies from Kuhlman et al. (2010), Guigma et al. (2012) and Balima et al. (2018).

The broad involvement of the different parts of *Detarium* species across six categories of use highlights their importance to the local population. This study found that gender, age and occupation influence knowledge about the species' uses, in line with results reported by Monteiro et al. (2006). The exploitation of different parts was strongly linked to occupation and education levels. Notably, fruit sales are dominated by young people and women, highlighting their active participation in utilising these species for economic benefits. Younger individuals, full of energy and driven by the pursuit of wealth, show a keen interest in collecting the fruit of these species (Biara et al., 2021). Kristensen and Balslev (2003) suggest that sociocultural and demographic factors such as gender, age and education level correlate with the knowledge and use of plant parts. Ahenkan and Boon (2011) show women's essential role in the commercialisation of NTFPs in West Africa, contributing to rural community resilience by opening new economic opportunities. Malleon et al. (2014) demonstrated that NTFPs offer new income sources for many women in the rural areas of Cameroon and Nigeria.

The high frequency of use reported by women in the energy category (firewood) underlines the species' value to households, likely due to the wood's flame intensity and low smoke emission (Ramos et al., 2008; Sinadouwirou et al., 2022). Other studies like Dao et al. (2020) and Sinadouwirou et al. (2022) have also emphasised wood characteristics as a primary factor in firewood selection. Moreover, another study pointed out the dependence of local populations on forest resources for various needs and income generation, exacerbating deforestation and forest degradation (Hesselberga & Iversenb, 2011).

Ethnic- and age-related preferences were observed, with the Mossi using the species for firewood and the younger population engaging in fruit selling, indicating usage variations based on ethnic group and age. Diatta et al. (2021) mentioned that *D. microcarpum* and *D. senegalense* were at the heart of local income activities in Thiobon, Senegal. Their use in traditional medicine constitutes a significant degradation factor (David et al., 2017). This medicinal importance can be attributed to antimicrobial, anti-inflammatory and antimalarial effects, as well as nutritional components (Dieng et al., 2016; Kini et al., 2010). Dogara (2022) found that each part of the *D. microcarpum* plant has a therapeutic application and the plant is often referred to as a miracle plant by traditional herbalists. In addition, the widespread use of bark and roots in traditional medicine illustrates the species' therapeutic significance, aligning with global reliance on traditional medicine as a source of primary health care (Houénon et al., 2021).

The use of the *Detarium* species for crafts and construction reflects their wood quality, which Sawadogo (2007) identified as a factor contributing to their vulnerability. Members of the Dagara ethnic group mentioned that cultural practices, such as rituals conducted by traditional healers, also influence the use of these species. The extensive use of bark, branches, roots and fruits found in this study poses a great threat to their sustainability, with rural communities heavily relying on multipurpose species such as *Detarium* for income, particularly women and young people involved in fruit picking and selling (Kagambega, 2019).

4.2 | Local perceptions of areas of abundance, threat factors and threat effects of *Detarium* species

This study shows that *Detarium* species are highly valued by local populations, underscoring their critical role within areas of natural occurrence. The consensus among local populations indicates that PAs and fallows are key zones of abundance, affirming the significance of these areas for species conservation (Assogbadjo et al., 2012). This is in accordance with FAO (2015) findings that highlight a positive relationship between species abundance and the level of habitat protection. The species' presence on hills and granite rocks corroborates previous studies indicating a preference for granitic soils (Aubréville & Trochain, 1937; Diop et al., 2010; Dossa, Ouinsavi, et al., 2020).

In contrast, the diminished presence of *Detarium* species in villages underscores the adverse impact of unregulated exploitation and habitat degradation in non-PAs. This observation is consistent with Agbo et al. (2017) and other studies, which highlight the complex interplay between species protection, uses, proximity and cultural practices (Avakoudjo et al., 2020; Coulibaly et al., 2021; Dogara, 2022). These findings suggest an urgent need for the domestication of *Detarium*

species to mitigate the risks associated with their overexploitation and to promote sustainable use (Kouyaté et al., 2002; Sinadouwirou et al., 2022).

The study revealed that local populations are aware of the decline and the disappearance of *Detarium* species from their habitat, primarily attributed to the overexploitation of plant parts, such as the bark and the trunk, alongside habitat destruction for agricultural expansion. This indiscriminate exploitation across all plant parts significantly jeopardises the species' survival (Yaovi et al., 2021). The major threats identified in Burkina Faso include bushfires, population growth, wood overexploitation and traditional mining exploitation. López-Carr (2021) shows the impact of urban development related to population growth on species dynamics, while Gaisberger et al. (2017) explain that overexploitation is due to the vulnerability of local populations. Extensive farming is one of the most common causes of forest exploitation, with illegal logging for firewood contributing to the species' scarcity. Traditional mining exploitation, particularly at the Bontioli site, further exacerbates these threats. Consequently, the combined effect of these pressures constitutes a major challenge to the sustainable management of *Detarium* species, underlining the need for effective conservation strategies to mitigate the ongoing risks to their survival, as noted by Avakoudjo et al. (2020).

In addition to the anthropogenic factors mentioned, local populations pointed out that climate change contributes to the vulnerability of *Detarium* species (Agossou et al., 2012). Communities residing near PAs perceive climate events like drought, high winds and rising temperature as threat factors which impact *Detarium* species populations. Nunes et al. (2019) and Deb et al. (2021) support this observation, indicating that local populations are often the first to notice the effects of climate change and forest degradation. Gross-Camp et al. (2015) and Dey et al. (2017) pointed out that the experiential knowledge of local communities, shaped by their livelihoods and direct interactions with their environment, plays a crucial role in recognising and understanding these impacts.

Furthermore, the decline in fruit availability is attributed to illegal logging, targeting mature *Detarium* trees and climatic hazards. These events not only lead to a decrease in the number of adult trees capable of fruit production but also affect the overall health and reproductive capacity of the species (Kamou et al., 2017; Kagambega, 2019; Fontodji et al., 2019).

4.3 | Local people's perceptions on conservation strategies and valorisation of *Detarium* species

For the sustainable conservation of *Detarium* species, awareness, local community management and comanagement with the foresters have been emphasised by local populations. These approaches

underscore the vital role local stakeholders play in the sustainable use of ecosystem goods and services of woody species (Badjaré et al., 2018). However, the diversity of solutions proposed, influenced by occupations, showed the integral part forests play in supplementing community livelihoods. Local communities advocate for awareness, monitoring to protect against overexploitation and the introduction of alternative species like almonds, which can help combat overexploitation and the illegal exploitation of forest resources. Engaging local communities in species management enhances security through sustainable participatory management (Delvingt & Doucet, 2000; FAO, 2013, 2015), offering a unique opportunity to educate them on natural resource depletion and ecosystem service provision (Gning et al., 2013).

Site status influences management type, with suggestions including wood-cutting regulations, the promotion of more effective stoves and alternative village energy solutions. To reduce the rate of species decline, local populations propose multiple conservation strategies to ensure sustainable use, such as financial support, product valorisation, training capacity building and reforestation. This initiative proves that the sustainable management of indigenous species contributes to improving the livelihoods of rural communities. However, community contribution to forest management is highly variable and often dependent on their main occupation (Lawin et al., 2019; Mugisho et al., 2022). While some communities have a high degree of knowledge concerning species management, others require basic training specifically tailored to align with local knowledge and practices. Kristensen and Balslev (2003) explain that the local communities' opinion is the guideline to ensure the best management of the natural resources. Despite the species not receiving much attention, species managers are taking steps to enhance the sustainable management of certain versatile species, including *Detarium* productivity (Bowler et al., 2012; Jones & Lynch, 2007; Wouyo et al., 2014). Income diversification, especially for women and youths involved in the collection, is key to forest protection, as illustrated by studies from Tiétiambou et al. (2015) and Hounsou-Dindin et al. (2022). The development of effective management strategies that consider the opinions and needs of local communities is essential. The valorisation of *Detarium* fruit, particularly by women, could integrate them into the value chain, boosting their incomes. The success of these initiatives requires collaboration among all stakeholders, including policymakers, local communities, researchers, extension agencies and funding bodies.

5 | CONCLUSION

This study showed the significant influence sociodemographic factors have on the uses of *D. microcarpum* and *D. senegalense*, demonstrating

the rural population's awareness of the decline of these species within their environment. *Detarium* species have high social value, especially in use categories such as food, traditional medicine, construction and crafts, with all plant parts being exploited, reflecting their diverse application. Among the ethnic groups studied, the Mossi showed the most extensive knowledge of the utilisation of plant parts and application forms for *D. microcarpum*, with the Bobo similarly knowledgeable about *D. senegalense*.

This study underscored the negative consequences of species overexploitation on their survival, revealing that threats to these species are closely linked to site-specific activities and the status of individual forests. Moreover, rural communities demonstrated awareness of these threats, proposing certain solutions and management strategies to address them. This study also aims to provide a scientific foundation for a better understanding of the challenges facing these species. For effective conservation of the two *Detarium* species, it is imperative that environmental authorities, NTFP associations and nongovernmental organisations involved in plant conservation initiate training programmes and diversify the economic income of local populations through financial support. Such measures are essential for mitigating the impacts of overexploitation and ensuring the sustainable management of *D. microcarpum* and *D. senegalense*.

AUTHOR CONTRIBUTIONS

Adama Taonda conceived the work with advice from Issouf Zerbo, Anny Estelle N'guessan, Justin N'Dja Kassi and Adjima Thiombiano. Adama Taonda collected and Issouf Zerbo curated the data. Issouf ZERBO performed a formal analysis. Adama Taonda and Issouf Zerbo drafted the manuscript with the contribution of Anny Estelle N'guessan, Justin N'Dja Kassi and Adjima Thiombiano. All authors validated the study, reviewed and edited the manuscript and read and approved the final manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data are available if the request need after the publication. Data in WASCAL are open access and are made available upon the receipt of an official request to the institution through the Data Management Department and the corresponding author (taonda.a@edu.wascal.org).

ETHICS STATEMENT

All local people involved in this research consented to the use of their information during data collection, in compliance with ethical and legal standards.

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Publication 2



Effects of land use and climate on the diversity and population structure in natural stands of *Detarium microcarpum* Guill. & Perr. (Fabaceae) in Burkina Faso (West Africa)

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ABSTRACT

Detarium microcarpum Guill. & Perr. is a multipurpose species, providing many ecosystem services. However, in its geographical range, its multiple uses represent a major challenge to the sustainable management and conservation of its resources. This study aimed to determine the effect of climatic zones, land uses, and their interaction on the natural stands of *D. microcarpum*. Inventories were conducted in 165 plots in two climatic zones and land use types in Burkina Faso. Hill diversity indices were used to determine the effects of climatic zones, land uses, and their interaction on *D. microcarpum* stand diversity. Generalized linear models were used to assess the effect of the abiotic and biotic factors on the species' structural parameters. Land uses and climatic zones significantly affected *D. microcarpum* stand diversity and structure. The lowest stand diversity was recorded in the unprotected areas. The similarity in woody species composition between land uses and climatic zones was low, indicating high beta diversity. The generalized linear model showed that rainfall, temperature, habitat heterospecific density, and habitat-specific richness significantly influenced the structural parameters of the *D. microcarpum* population. The diameter classes' distribution revealed unstable populations for the adult stratum, independent of climatic zones and land use types, except for the protected area in the Sudanian zone. The height class distribution of the juvenile stratum highlighted the instability regeneration of *D. microcarpum* populations. This study highlighted the instability of *D. microcarpum* populations and the specific effects of biotic and abiotic variables on the species' structural parameters. Thus, the findings suggest urgent conservation measures to ensure sustainable utilisation and management of the species.

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1. Introduction

In the recent decade, several studies have focused on the conservation of multipurpose species due to the anthropogenic activities and climate threats (Kafoutchoni et al., 2018). These species have faced serious threats with the increasing agricultural intensification and the supply of non-timber forest products (NTFP) (Mensah et al., 2014; Gogoi, 2018). In addition, climate-induced land use change could indirectly drive species distribution via changes in forest stand composition and structure (Bohn et al., 2018). Climate change affects individual species and the way they interact with other organisms and their habitats, which alters the structure and function of ecosystems and the goods and services that natural systems provide to society (Diaz et al., 2019; Trisurat et al., 2023). In developing countries like Burkina Faso, the expansion of agriculture has additional impacts on the species composition and population dynamics (Kumar et al., 2023). Environmental deterioration, changes in habitat, inappropriate vegetation management, fragmentation, and deforestation modify biotic and abiotic conditions which affect the species dynamics (Zida et al., 2007; Bedair et al., 2021).

The human population growth has increased agricultural intensification and the demand for forest products (Maryo and Wendawek, 2014) which affects biodiversity through the loss of species (Lompo et al., 2021). Deforestation leads to biodiversity loss and forest degradation, which contributes to global climate change (Coulibaly et al., 2021). The overexploitation of multipurpose species related to the strong demographic growth in Sub-Saharan African countries impairs the survival of many woody species (Zerbo et al., 2023) and impacts the ecological functions of savanna ecosystems (Balima et al., 2020).

However, at smaller scales, microclimatic conditions and species' competitive abilities influence the species structure and their composition (Mensah et al., 2018; Atanasso et al., 2019). Understanding the direction and magnitude of ecological responses allows forest manager to better anticipate these changes and their adaptation (Sirakaya, 2022). With human population pressure and climate change, it is expected that more natural landscapes will be converted into farmlands to further worsen the current state of biodiversity (Shiferaw et al., 2004). The intensive use of land for agriculture and the high demand for the species of wood for different purposes combined with the climate threat is leading to the loss of multipurpose species (Maryo and Wendawek, 2014).

Burkina Faso, like other tropical countries, has a remarkable biodiversity of endemic plants which are threatened by several factors including climate and human disturbances (Sintayehu, 2018). In addition, several overexploited woody species with deficient regeneration were declining in savanna due to the lack of conservation and insufficiency of data on their status which could help to propose appropriate management solutions (Bationo, Ouedraogo, et al., 2001). Indeed, among the woody species producing non-timber forest products, *Detarium microcarpum* is one of the most exploited and vulnerable species in Burkina Faso (Traoré et al., 2011; Gaisberger et al., 2017; Traore et al., 2020). Despite the widely recognized importance of *D. microcarpum* for the human uses (Bationo et al., 2001; Dimobe et al., 2018), little information is available for the effect of climate and land use on its populations' status.

Previous studies on *D. microcarpum* focused on its regeneration pattern and population structure in Burkina Faso (Bationo et al., 2001; Bastide and Ouedraogo, 2008; Maré and Millogo, 2019) and in Cameroon (Lamy et al., 2021). In addition others studies have been conducted on the local uses and the conservation of the species in Benin (Sinadouwirou et al., 2022; Houénon et al., 2022) and in Mali (Kouyaté et al., 2002; Kouyaté, 2005) and the fruits nutritional values in Burkina Faso (Cavin, 2007). Among all these studies, none focused implicitly on the impact of climate, land use, and their interaction in their natural stand diversity, their population dendrometric characteristics and structure. It has been acknowledged that climate conditions influence woody species population (Traore et al., 2022; Zerbo et al., 2023), and the dynamic of a stand is influenced more by the type of land use (Balima et al., 2020; Zerbo et al., 2023). In addition, others authors pointed that dendrometric parameters are valid indicators of information on the conservation status of the species (Nichols et al., 2008; Deluau and Van Damme, 2021). Given the increasing pressures on the savannah multipurpose species such as *D. microcarpum* and the lack of data for their sustainable management, it is urgent to assess how climate and human land use interact to affect its conservation. When population densities increase, the competition for space and resources is impacted (Janovský et al., 2013) and affects the species' survival (Atanasso et al., 2019). In addition, the individuals that first occupy a given area may monopolize the most suitable habitats which affects the structural parameters of the other species. In this context, it is crucial to understand how abiotic factors (temperature and precipitation) and biotic drivers (Habitat heterospecific tree density, habitat-specific richness) influence the structure and composition of tree species in their natural stand. This study expected that climatic variables (mean temperature, sum of precipitation) and biotic factors (Global density of the species, species richness) influence the dendrometric parameters of *D. microcarpum* on their natural stand. Knowledge of the species reaction to the climate effect is an important information for their conservation planning (Adjonou et al., 2020). Additionally, understanding the relationships between the species, stand structure, human disturbance and climate effect is essential for its sustainable management. This study aims to determine the effect of climatic zones, land uses, and their interaction on the natural stand's diversity and the population structure of *D. microcarpum*. Specifically, it:

- i. Assess the influence of land uses and climatic zones on the diversity and the composition of woody species associated with *D. microcarpum* stands;
- ii. determine how the *D. microcarpum* population responds to abiotic factors (temperature, precipitation) and biotic factors (habitat heterospecific density and habitat-specific richness) through its structural parameters.
- iii. analyze the population structure of *D. microcarpum* across the land use types and the climatic zones.

2. Material and methods

2.1. Study sites

The study was carried out in the Sudanian and the Sudano-Sahelian climatic zones of Burkina Faso, which represent the natural occurrence areas of *D. microcarpum* in the country (Fig. 1). It was done from September to December 2022. Along to the climatic gradient, four study sites in protected and unprotected areas were chosen based on the presence of the *Detarium microcarpum*, and their accessibility due to the security issue that the country is facing. In each climatic zone, the distance between sites was more than 60 km. Besides, in each climate zone, the distance between sites representing protected and unprotected areas was 500 m.

In the Soudanian zone, the Protected areas were the Wildlife Reserve of Bontioli (South-Western) and the Classified Forest of Kou. The main ethnic groups encountered around the Classified Forest of Kou are Bobo, while the ones found around the Wildlife Reserve of Bontioli are Dagara. In the Sudano-Sahelian zone, the Protected areas consisted of the Game Ranch of Nazinga and the Classified Forest of Nakambe. The main ethnic groups of the two sites are Mossi for the Classified Forest of Nakambe and Gourounsi for the Game Ranch of Nazinga.

The vegetation in the four Protected areas is characterized by various savanna types including shrub savannas, tree savannas, woodlands, dry forests, and gallery forests (Nacoulma et al., 2018). The Protected areas such as the Classified Forest of Kou, the Wildlife Reserve of Bontioli, and the Classified Forest of Nakambe were found along the rivers of Kou, Bougouriba, and Nakambe. The Unprotected areas were dominated by agroforestry parks.

The mean annual rainfall increases from the Sudano-Sahelian zone to the Sudanian zone in contrast to the mean annual temperature which decreases. According to the climate data from the National Meteorological Office, the annual rainfall ranges between 900 and 1100 mm in the Sudanian zone and between 600 and 900 mm in the Sudano-Sahelian zone. The mean annual temperature in the Sudanian zone was 27.5 °C and the found in the Sudano-Sahelian zone was 28.9 °C. In the Sudanian zone, the main activities of the population in the unprotected areas were the traditional mining exploitation around the Wildlife Reserve of Bontioli and the

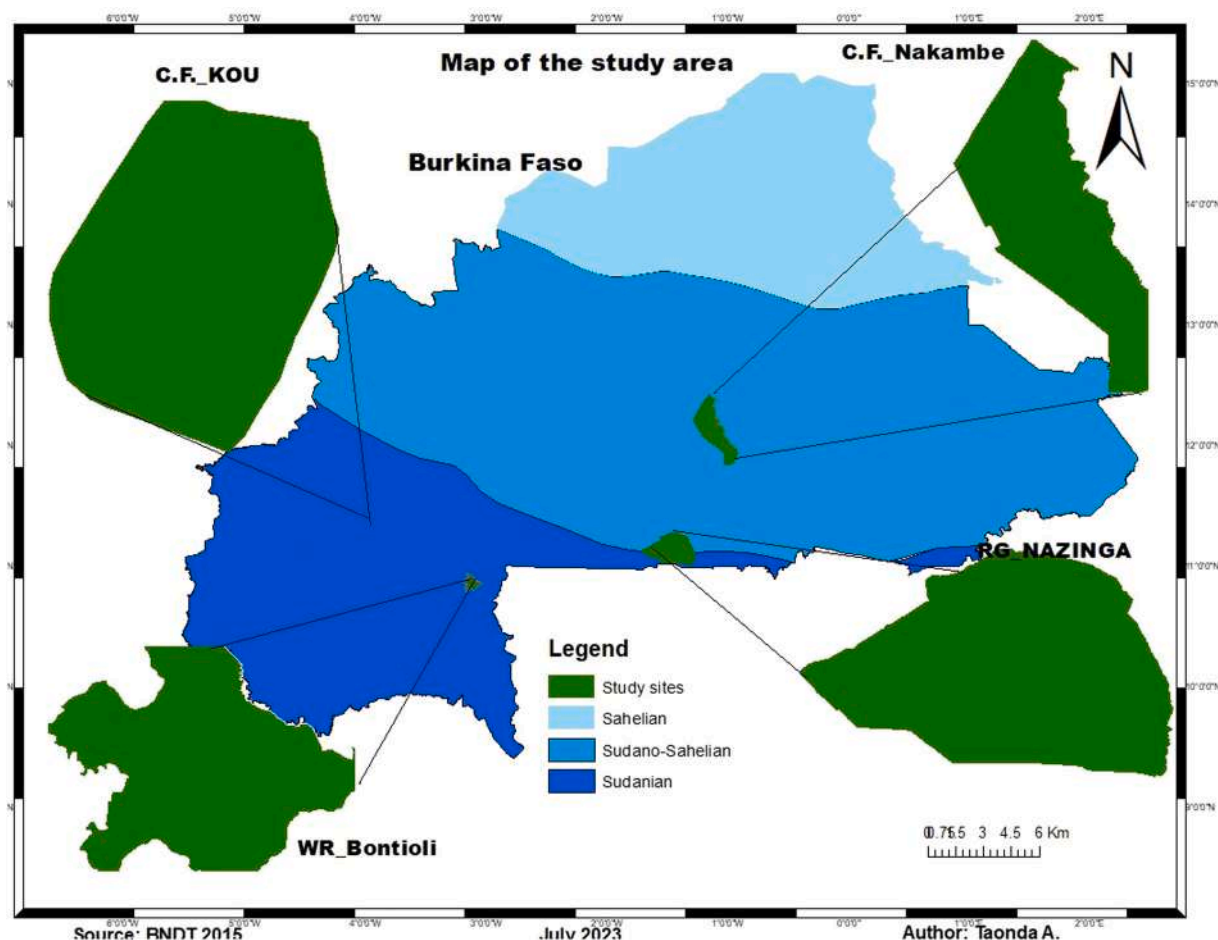


Fig. 1. Map of studied sites according to land occupation database of Burkina Faso in 2012. Legend: FC kou: Kou classified Forest; FC Nakambe: Nakambe Classified Forest; WR - Bontioli: wildlife reserve of Bontioli; RG Nazinga: Game Ranch of Nazinga

agriculture around the Classified Forest of Kou. In the Sudano-Sahelian zone, the main activities of the population living the surrounding the Game Ranch of Nazinga were agriculture, while around the Classified Forest of Nakambe, the main population activities were agriculture, wood exploitation and trading.

2.2. Study species

Detarium microcarpum is a woody species belonging to the Fabaceae family (Arbonnier, 2009). It is a medium-sized tree and can reach up to 12 m high with a fairly dense spherical crown (Kouyaté, 2005; Maré and Millogo, 2019). The leaves of the species are composed of paripinnate with 5–6 pairs of opposite leaflets arranged alternately (Aubréville and Trochain, 1937). The flyers are 4–6 cm long and 3–4 cm wide, oval to elliptical, rounded at the ends, and emarginated at the top. The fruit is an ovoid or rounded pod, similar to a drupe, indehiscent with 2.5–4.5 cm in diameter (Aubréville and Trochain, 1937). The seed dispersers are often by animals (Bationo et al., 2001; Kamou et al., 2017). The species is found in dry savannas, dry forests, and fallow lands on sandy or iron-rich hard soils as well as scattered trees on farms (Kouyate et al., 2006; Houénou et al., 2021).

2.3. Sampling design and data collection

The study was conducted in two climatic zones (Sudano and Sudano-Sahelian). These climate zones were selected based on the presence of *Detarium microcarpum* natural stands. In each climate zone, data were collected in two protected areas and their surrounding areas (Unprotected areas) following an oriented sampling based on the presence of *D. microcarpum*. A total of 165 plots were set up in the two climatic zones. In the Sudanian zone, 75 plots comprising 45 plots in the Protected areas and 30 plots in the unprotected areas were used. In the Sudano-Sahelian zone, 90 plots including 50 plots for Protected areas and 40 plots in Unprotected areas were established. The plots in the protected areas had a size of 1000 m² (50 m x 20 m) and those in unprotected areas had a size of 2500 m² (50 m x 50 m) (Thiombiano et al., 2016; Balima et al., 2020). The plot sizes were followed the standard guidelines established by Thiombiano et al. (2016) for West Africa vegetation surveys. Within each site, the minimum distance between two plots was 100 m (Ouédroogo et al., 2020). In each plot, all woody species encountered were recorded for the assessment of *D. microcarpum* stand diversity and species composition. Forest inventories consisted of the measurements of the diameter at breast height (DBH) and the total height of each woody individual.

To characterize the regeneration of *D. microcarpum*, five sub-plots of 25 m² (5 m x 5 m) were installed in each major plot to sample juvenile individuals (DBH < 5 cm). In each sub-plot, the height of juvenile individuals of the species was measured using a diameter tape.

2.4. Data analyses

2.4.1. Variation in the stand's diversity and composition

All analyses were done with R statistical software (R Core Team, 2023). The taxonomic richness (number of species, genera, and families) of woody species associated with *D. microcarpum* was determined by investigating their co-occurrence in its natural stands (Zerbo et al., 2016). The recorded species names were further retrieved following the World Plant Names Index (<https://wfoplantlist.org/plant-list/>) and the Catalogue of vascular plants of Burkina Faso (Thiombiano et al., 2012).

The woody stand diversity was assessed through the series of diversity numbers and evenness presented by Hill (1973). The diversity indices were computed through the package Biodiversity R (Kindt, 2011) and were represented as follows:

- No = S; with S the number of species in a plot
- N1 = e^{H'}; with H' Shannon's index;
- N2 = 1/D, D is the Simpson's index
- Evenness (E) = H' / ln(S).

A Multi-Way Analysis of Variance (Multi-Way ANOVA) was used to assess the effect of climate, land use, and their interaction on the diversity indices described by N0, N1, N2, and the Evenness. The Tukey's post-hoc test (Tukey-PHT) was used to compare the mean values according to the climatic zone and land-use types when needed.

To quantify the similarity among the species' natural stand, Jaccard similarity index (β -diversity) based on species data presence/absence was used to evaluate the variation in woody species composition according to the climatic zones and land use types.

The Importance Value Index (IVI) which is an indicator of species' ecological importance (Mueller-Dombois and Ellenberg, 1974) was used to determine the pattern of variation in *D. microcarpum* stands composition. This index ranges between 0 and 300. The species having the highest IVI is considered dominant in the community. The IVI was calculated for each heterospecific woody species according to the following parameters:

- Frequency = number of plots in which the species occurs/total plot number × 100.
- Relative Frequency = frequency of a species/sum of all frequencies × 100.
- Relative density = (number of individuals of a species / total number of individuals) × 100.
- Relative Dominance = total basal area of a species/basal area of all species × 100.
- Importance Value Index = Relative density + Relative dominance + Relative frequency

Table 1Diversity indices of *Detarium microcarpum* stands (Mean $\pm$ standard deviation).

Parameters		Sudanian		Sudano-Sahelian		Anova multi-ways					
		protected areas	unprotected areas	protected areas	unprotected areas	F1	P1	F2	P2	F3	P3
N0 (Richness)	mean	19.55 $\pm$ 5.82a	12.43 $\pm$ 3.94b	14.7 $\pm$ 3.93b	11.62 $\pm$ 3.41b	20.74	0.0001***	48.98	0.0001***	8.31	0.0044**
	Overall	103	80	76	61						
N1 (Exp. ^H).	mean	8.67 $\pm$ 3.96a	6.33 $\pm$ 2.57b	6.29 $\pm$ 2.14b	5.28 $\pm$ 1.55b	17.27	0.0001***	14.67	0.0001***	2.71	0.1016 ^{ns}
	Overall	19.08	14.74	11.5	9.28						
N2 (1/D)	mean	4.83 $\pm$ 2.7a	3.97 $\pm$ 1.91ab	3.74 $\pm$ 1.39b	3.27 $\pm$ 1.03b	10.08	0.0017**	4.79	0.0299*	0.45	0.5030 ^{ns}
	Overall	5.35	4.45	3.91	3.4						
Evenness (E)	mean	0.80 $\pm$ 0.10a	0.78 $\pm$ 0.11a	0.74 $\pm$ 0.09a	0.72 $\pm$ 0.08a	4.42	0.0371*	0.14	0.7069 ^{ns}	0.00	0.9618 ^{ns}
	Overall	0.636	0.614	0.564	0.542						

Legend: a, b = Tukey-HPT: Levels with different letters are significantly different; P = P value (line 358); P1 = P value of the difference climate zone, P2 = P value of the difference type of land use, P3 = P value of the interaction between climate zone and land use, *** P < 0.001, ** P < 0.01, * P < 0.05; ns = non-significant; F = F statistic of Fisher. F1 = F statistic of the Sudanian zone; F2 = F statistic of the Sudano-Sahelian zone and F3 = F statistic of the interaction between the two climatic zones.

In each climatic zone and land use type, the 20 species with the highest IVI were selected to highlight the variation patterns in dominant woody species.

2.4.2. Variation of *D. microcarpum* structural parameters and effect of abiotic and biotic factors

The structural parameters of *D. microcarpum* included basal area (G), density (N), mean diameter (Dm), and Lorey's mean height (HL).

The basal area G was calculated as the following formula:

- $G \text{ (m}^2\text{.ha}^{-1}\text{)} = (\pi * DBH^2) / 4$.
- $N \text{ (individuals/ha)} = n/S$, with n as the average number of individuals per plot and S as the area expressed in hectares.
- The average Lorey's height $m \left(\frac{\sum_{i=1}^k g_i h_i}{\sum_{i=1}^k g_i} \right)$ with $g_i = \frac{\pi d_i^2}{4}$ expresses the height of the individuals adjusted by the basal area.

The variation in the species' structural parameters according to the climatic zones and land use types were analysed through the non-parametric Kruskal Wallis test due to the non-normal distribution of data.

To determine the effects of abiotic (mean annual temperature and mean annual precipitation) and biotic factors ("habitats specific richness" and "heterospecific density") on the structural parameters of *D. microcarpum*, a generalized linear model assuming a Poisson distribution was applied. The "habitat heterospecific density" refers to the number of all individuals of the different species that occur within the same habitat with *Detarium microcarpum* stand. The "habitat-specific richness" refers to the number of the different species found within the same habitat with *Detarium microcarpum* species. Based on geographical coordinates, abiotic factors including climate data such as mean annual temperature (°C) and mean annual precipitation (mm) were downloaded for each plot from WorldClim (<https://www.worldclim.org/data/worldclim21.html>) through the R packages raster (Etten et al., 2023), SP (Hijmans et al., 2023), rgdal (Daniel and Anderson, 2018), exactextractr (Daniel, 2020), sf (Cook and Baston, 2023), terra (Hijmans, 2023) with a spatial resolution of 0.5.

Thus, abiotic (mean annual temperature and mean annual precipitation) and biotic (habitat heterospecific density and habitat specific richness) factors were used as explanatory variables and *D. microcarpum* structural parameters (basal area, density, mean diameter and Lorey's mean height) as response variables. In addition, the Pearson correlation was used to check the relationship between biotic factors (habitat-specific richness and heterospecific density) and abiotic factors (average temperature and mean annual precipitation) considered in the model as explanatory variables (Appendix 2).

2.4.3. Variation of *D. microcarpum* population structure

Diameter classes and height class distribution based on the method of Condit et al. (1998) were used to interpret the status of *D. microcarpum* populations according to the climatic zones and land use types. Thus, ten (10) diameter classes 5–10 cm, 10–15 cm, 15–20 cm, 20–25 cm, 25–30 cm, 30–35 cm, 35–40 cm, 40–45 cm, 45–50 cm and 50–55 cm for the adult stratum and five height classes 0–0.5 m, 0.5–1 m, 1–1.5 m, 1.5–2 m, 2–2.5 m for juvenile stratum were used. The resulting parameters, especially slope, R^2 coefficient of determination, and regression probability were considered as indicators of distribution status (Obiri et al., 2002). A negative slope indicates that small-diameter individuals are abundant, while a positive slope indicates an abundance of large-diameter individuals. In addition, values of the coefficient of determination (R^2) and their p-values make it possible to observe whether there is a stable transition between several individuals and diameter classes.

3. Results

3.1. Diversity and composition of *Detarium microcarpum* stands according to the climatic zones and land use types

3.1.1. Variation in *D. microcarpum* stands diversity according to the climatic zones and land use types

A total of 102 woody species belonging to 79 genera and 28 families were found at the four study sites (Appendix A). The most represented families were Fabaceae (30.37%), Anacardiaceae (6.32%), Combretaceae (6.32%), Malvaceae (6.32%), Apocynaceae (5.06%) and Phyllanthaceae (5.06%).

The analysis of the stand diversity by Hill numbers allowed underlining the variations of mean species numbers (N0), abundant species numbers (N1), and very abundant species numbers (N2) between climatic zones and land use types (Table 1). Species numbers, abundant species numbers, and very abundant species numbers decreased from the Sudanian zone to the Sudano-Sahelian zone.

Mean species numbers by plot (N0) showed that the Sudanian zone was significantly ($F = 20.74$, $p < 0.0001$) more diverse than the Sudano-Sahelian zone (Table 1). By considering the land use types, there was only a significant difference ($F_2 = 44.584$, $P_2 < 0.0001$) between the mean species numbers by plot (N0) found in the Protected areas (19.55 ± 5.82 species/plot) and the unprotected areas (12.43 ± 3.94 species/plot) of the Sudanian zone. However, no difference was observed between the mean species numbers by plot (N0) found in the different land uses of the Sudano-Sahelian zone. In addition, the interaction between the climatic zone and the land use type influenced significantly (8.31 , $P_3 = 0.0044$) the mean number of species per plot.

The analysis of the vegetation by N1 revealed that the climatic zone ($F_1 = 17.27$, $P_1 < 0.0001$) and the land use types ($F_2 = 14.561$, $P_2 = 0.0001$), significantly affected the number of abundant species. Besides, in the Sudanian zone, the number of abundant species varied from 8.67 ± 3.96 species in the protected areas to 6.33 ± 2.57 in the unprotected areas but did not differ between land protected

and unprotected areas in the Sudano-Sahelian zone.

By considering $1/D$ (N_2), the number of very abundant species decreased significantly from the Sudanian to the Sudano-Sahelian zone ($F_1 = 10.08$, $P_1 = 0.0017$). The type of land use also influenced significantly the number of very abundant species ($F_2 = 5.1788$, $P_2 = 0.02417$). In the Sudanian zone, the number of very abundant species was 4.83 ± 2.7 in the Protected areas and 3.97 ± 1.91 in the Unprotected areas. It varied from 3.74 ± 1.39 in the Protected to 3.27 ± 1.03 in the Unprotected areas in the Sudano-Sahelian climatic zone.

The Evenness pattern decreased significantly ($F_1 = 4.42$, $P_1 = 0.0371$) from the Sudanian to the Sudano-Sahelian zone. However, the type of land use ($F_2 = 0.11$, $P = 0.7069$) and the interaction ($F_3 = 0.00$ and $P_3 = 0.9618$) between the climatic zone and the land use type did not influence the Evenness index. The value of the Evenness index ranges from 0.80 ± 0.10 in the Protected areas of the Sudanian zone to 0.72 ± 0.08 in the Unprotected areas of the Sudano-Sahelian zone.

3.1.2. Variation in *D. microcarpum* stands composition according to climatic zones and land use types

Jaccard's similarity index revealed a low similarity ($< 50\%$) between the different habitats of *Detarium microcarpum* across the two climatic zones and land use types (Table 2). The highest similarity (0.49) were observed between the Sudanian Protected areas and Sudanian Unprotected areas. The lowest similarity (0.28) has been observed between the Sudanian Protected areas with the Sudano-Sahelian Unprotected areas.

The most dominant species associated with *D. microcarpum* varied according to climatic zones and land use types. In the protected areas of the Sudanian climatic zone, the most dominant species were *Combretum glutinosum*, *Vitellaria paradoxa*; *Burkea africana*, *Pterocarpus erinaceus*, *Hexalobus monopetalus*; *Entada Africana*; while in the unprotected areas of the same climatic zone, there were

Table 2

The first 20 dominant woody species encountered at the four sites along the climatic zones and land uses types based on importance value index (IVI).

Species	Sudanian climatic zone		Sudano-Sahelian climatic zone	
	protected areas	unprotected areas	protected areas	unprotected areas
<i>Azizelia africana</i>	-	4.73	2.26	-
<i>Annona senegalensis</i>	-	4.07	-	-
<i>Balanites aegyptiaca</i>	-	-	-	29.78
<i>Bridelia ferruginea</i>	-	-	-	4.64
<i>Burkea africana</i>	12.12	7.27	3.44	-
<i>Cassia sieberiana</i>	-	4.73	-	-
<i>Combretum adenogonium</i>	-	-	4.06	-
<i>Combretum collinum</i>	-	-	6.49	16.99
<i>Combretum glutinosum</i>	13.11	13.26	4.37	4.52
<i>Combretum nigricans</i>	4.46	-	-	-
<i>Combretum paniculatum</i>	-	-	2.50	-
<i>Crotophyx febrifuge</i>	7.63	8.30	25.69	-
<i>Daniella oliveri</i>	-	5.02	-	-
<i>Detarium microcarpum</i>	68.60	58.14	113.19	99.77
<i>Detarium senegalense</i>	6.37	-	-	-
<i>Diospyros mespiliformis</i>	-	5.00	-	-
<i>Entada africana</i>	8.81	10.67	-	-
<i>Gardenia erubescens</i>	-	8.73	-	3.91
<i>Gymnosporia senegalensis</i>	-	-	5.27	-
<i>Hexalobus monopetalus</i>	8.83	6.28	-	-
<i>Isobertlinia doka</i>	4.66	-	7.42	-
<i>Khaya senegalensis</i>	5.69	-	-	-
<i>Lannea acida</i>	7.86	-	7.47	19.02
<i>Lannea microcarpa</i>	6.10	20.39	-	-
<i>Lannea velutina</i>	-	8.80	-	-
<i>Pericopsis laxiflora</i>	5.28	-	12.63	-
<i>Piliostigma thonningii</i>	4.45	-	5.48	5.39
<i>Pterocarpus erinaceus</i>	9.81	9.82	-	6.74
<i>Senegalia gourmaensis</i>	7.73	-	-	11.87
<i>Senegalia macrostachya</i>	-	8.15	-	5.22
<i>Sclerocarya birrea</i>	-	-	-	2.96
<i>Sterculia setigera</i>	-	-	-	10.85
<i>Strychnos spinosa</i>	4.78	-	-	4.73
<i>Tamarindus indica</i>	-	5.84	-	9.23
<i>Terminalia avicennoides</i>	-	-	14.28	-
<i>Terminalia engleri</i>	4.38	-	2.73	-
<i>Terminalia laxiflora</i>	8.75	20.42	-	-
<i>Terminalia leiocarpa</i>	-	-	14.79	11.62
<i>Terminalia macroptera</i>	-	8.38	11.50	-
<i>Vachellia seyal</i>	-	-	3.23	5.24
<i>Vitellaria paradoxa</i>	12.17	32.27	22.59	17.66
<i>Vitex doniana</i>	-	-	-	3.39
<i>Xeroderis stuhlmannii</i>	-	-	6.34	-

Vitellaria paradoxa, *Terminalia laxiflora*, *Combretum glutinosum*, *Entada africana*, *Lannea velutina* (Table 3). In the Sudano-Sahelian zone, *Crotophyx febrifuga*, *Vitellaria paradoxa*, *Terminalia avicennioides*, *Pericopsis laxiflora* and *Terminalia macroptera* were the most dominant in the Protected area whereas in the Unprotected areas, the most dominant was *Balanites aegyptiaca*, *Lannea acida*, *Vitellaria paradoxa*, *Combretum collinum*, *Sterculia setigera* (Table 2). However, *Vitellaria paradoxa* and *Combretum glutinosum* were common species found in each climatic zone and land use type.

3.2. Effect of climate, land use, habitats specific richness, and heterospecific density on the structural parameters of *D. microcarpum*

The analysis of the Kruskal Wallis test showed that the mean density ($\chi^2 = 85.864$; $P < 0.001$), mean diameter ($\chi^2 = 66.067$; $P < 0.001$), mean basal area ($\chi^2 = 94.043$; $P < 0.001$) and Lorey's mean height ($\chi^2 = 19.802$; $P < 0.001$) of *D. microcarpum* varied significantly ($P < 0.05$) between sites (Fig. 2). The highest mean density (53.38 ± 17.22 individuals/ha) was recorded in Sudano-Sahelian protected areas, while the lowest density (16.4 ± 8.55 individuals/ha¹) was observed in Sudanian unprotected areas. Regarding mean diameter, the highest value (23.87 ± 2.85 cm) was recorded in the Protected areas of the Sudano-Sahelian zone and the lowest value (16.61 ± 4.41 cm) was observed in the unprotected areas of the same climatic zone. For the basal area, the highest mean value (2.73 ± 1.28) was observed in the protected areas of the Sudano-Sahelian zone, and the lowest value (0.53 ± 0.54) in the Unprotected areas of the Sudanian zone. In terms of Lorey's mean height, the lowest value (5.76 ± 0.95 m) was observed in the unprotected areas of the Sudano-Sahelian zone, and its highest value (6.13 ± 1.86 m) was observed in the protected areas of the Sudanian zone (Fig. 2).

The habitat heterospecific density caused a significant increase in the basal area, the density, and the diameter but lead a significant decrease in value of the Lorey's height (HL).

Habitat specific richness did not influence the basal area but caused a significant increase in the diameter and the Lorey's height. Rainfall significantly decreased the basal area, diameter and density, and increased the Lorey's height, although not significantly. Temperature did not influence the basal area and the Lorey's height but significantly influence the value of diameter and the species density (Table 4).

3.2.1. Population structure of *Detarium microcarpum*

The linear regression analyses of the diameter classes distribution revealed a negative slope in the different climatic zones and land use types (Table 5). The diameter classes of *D. microcarpum* individuals showed an irregular distribution of individuals, with a predominance of individuals of intermediate classes compared to those of extreme classes (Fig. 3). The predominance size class varied according to the climatic zones and land use type. The predominance class size was 15–20 in the protected areas, and 10–15 in the unprotected areas in the Sudano-Sahelian zone. In the Sudanian zone, the abundance size class was 10–15 in the protected areas, but there is a weak distribution in the unprotected areas (Fig. 3). Across the Sudanian zone, unprotected areas showed a weak correlation ($R^2 = 0.29$, $P = 0.1062$) between the number of individuals and their diameter classes. Similarly, both protected and unprotected areas within the Sudano-Sahelian zone showed a weak relationship ($R^2 = 0.26$, $P = 0.1303$ for protected areas and $R^2 = 0.39$, $P = 0.0556$ for unprotected areas). However, a notable exception was observed in the protected areas of the Sudanian zone, where a strong correlation ($R^2 = 0.54$, $P = 0.0159$) was found between the number of individuals and their diameter classes. Thus, the populations of *D. microcarpum* are unstable in the different climatic zones and land use types except for in the Protected areas of Sudanian zone (Table 5, Fig. 3).

The height classes distribution of the juvenile stratum revealed a negative slope for the different climatic zones and land use types, which indicate the dominance of individuals of small height classes. Besides, a positive slope was observed in the unprotected areas of the Sudano-Sahelian zone. In addition, the R^2 values with the non-significant p-values ($P > 0.05$) reveal an unsuccessful transition of juveniles from the lower classes to the higher classes, reflecting difficulties of survival in juvenile individuals (Fig. 4). Thus, the regeneration of *D. microcarpum* was characterized by unstable populations independent of the climatic zones and land use types.

4. Discussion

4.1. Effect of climate and land use on *Detarium microcarpum* stand diversity and composition

Overall, 102 woody species were recorded in *D. microcarpum* stands, divided into 79 genera and 28 families. This species richness represents 19.21% of the woody flora of Burkina. According to (Thiombiano et al., 2012), Burkina Faso contains 531 woody species.

Table 3

Jaccard's similarity of *Detarium microcarpum* stands according to the climatic zones and land use types.

Sites	SUPa	SPa	SSUPa	SSPa
SUPa	1			
SPa	0.4961	1		
SSUPa	0.3887	0.4619	1	
SSPa	0.2849	0.4438	0.4368	1

Legend: SUPa: Sudanian unprotected areas, SPa: Sudanian protected areas, SSUPa: Sudano-Sahelian unprotected areas, SSPa: Sudano-Sahelian protected areas

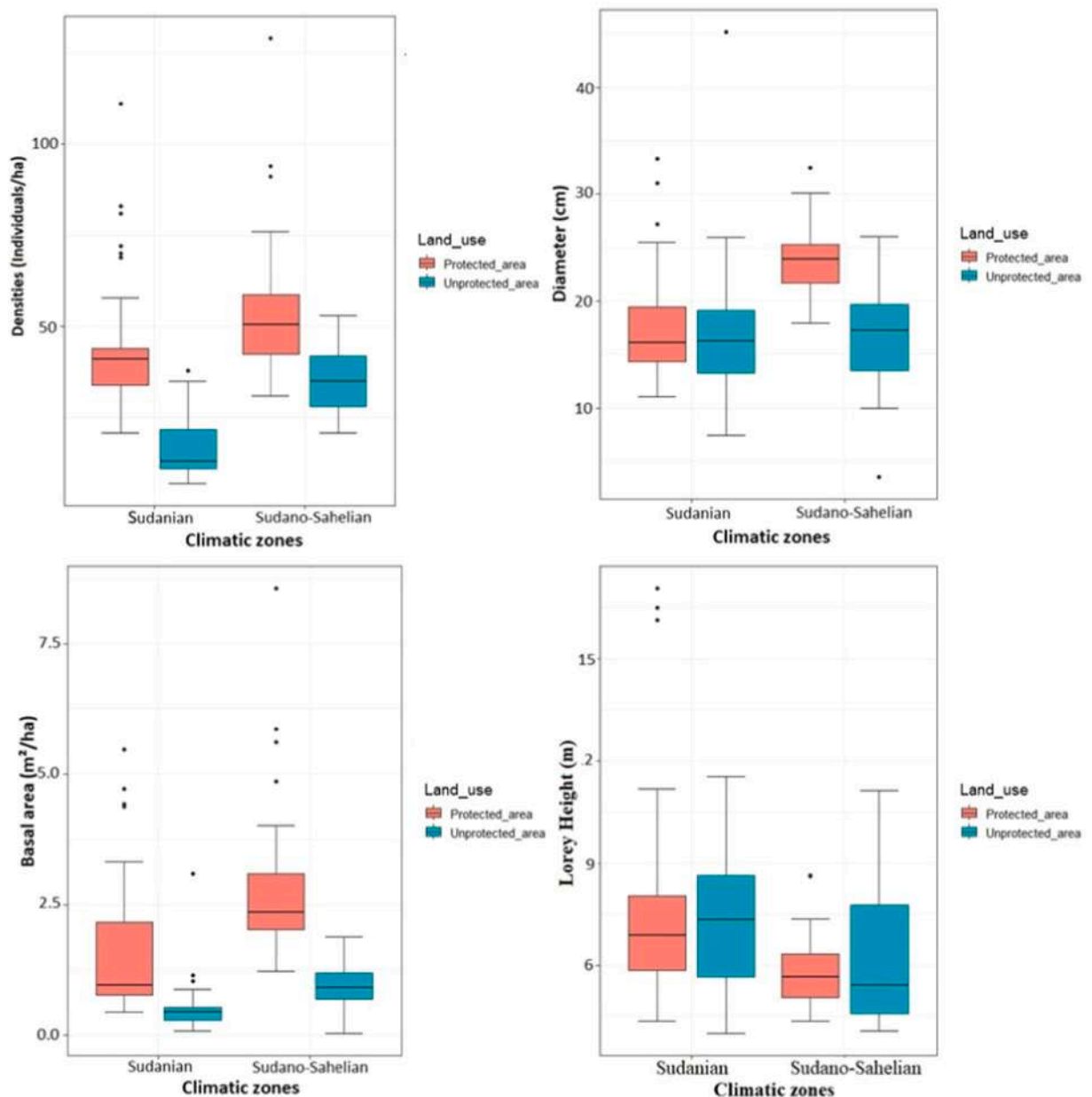


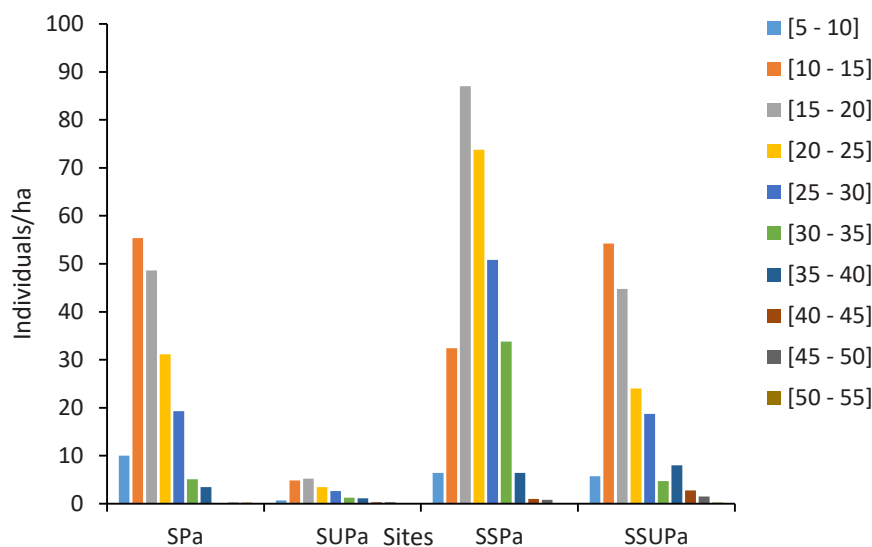
Fig. 2. Differences in *Detarium microcarpum* structural parameters between climate and land use types.

This result corroborates with Balima et al. (2020) which found 107 species divided into 73 genera and 35 families on the natural stand of *Azelia africana* in the same climate zones. The dominance of Fabaceae, Anacardiaceae, Combretaceae, and Malvaceae families characterize dry climates (Tindano et al., 2015) and reveals the savanna character of these plant communities (Ganamé et al., 2019) associated with human pressures and climate peioration (Lankoandé et al., 2017). Hill's diversity numbers revealed that species diversity decreased significantly from Sudanian to Sudano-Sahelian zone and from protected to unprotected areas. In each climatic zone, the highest species diversity of *D. microcarpum* stands was recorded in Protected areas. Similar results were found by authors who demonstrated that Protected areas host higher diversity for stands of Combretaceae species (Bognounou et al., 2009; (Ganamé et al., 2019)Ganamé et al., 2019); *Azelia africana* (Balima et al., 2020) and *Lannea macrocarpa* (Tinguéri et al., 2021) in Burkina Faso and *Strychnos spinosa* (Avakoudjo et al., 2022) in Benin. The significant difference in mean species and abundant species numbers between climate zones shows that the species richness increases with rainfall level in the Savanna ecosystem. Li et al. (2015) reported that human disturbance affected vegetation at the local scale and modified the ecosystem function. Balima et al. (2020) pointed out that agricultural land use contributes to the disturbance of species diversity. When comparing species richness according to the climatic zone and the land use type, the species richness gradually declines from Sudanian to Sudano-Sahelian zones and from protected areas

Table 4Generalized linear models showing the effects of the biotic and abiotic factors on *Detarium microcarpum* structural parameters.

Variables	Estimate (β)	Std. Error	z value	Pr(> z)
Basal area				
(Intercept)	14.59	10.90	1.34	0.181 ^{ns}
Habitat heterospecific density	0.01	0.01	6.64	0.0000 ^{***}
Habitat specific richness	0.01	0.014	1.15	0.252 ^{ns}
Rainfall	-0.01	0.00	-2.54	0.011 [*]
Temperature	-0.45	0.37	-1.24	0.217 ^{ns}
Density				
(Intercept)	11.24	1.99	5.64	0.0000 ^{***}
Habitat heterospecific density	0.01	0.00	28.82	0.0000 ^{***}
Habitat specific richness	0.00	0.00	1.36	0.1743 ^{ns}
Rainfall	-0.00	0.00	-8.05	0.0000 ^{***}
Temperature	-0.25	0.07	-3.65	0.0002 ^{***}
Diameter				
(Intercept)	6.47	2.58	2.51	0.0121 [*]
Habitat heterospecific density	0.00	0.00	1.29	0.1942 ^{ns}
Habitat specific richness	0.01	0.00	2.	0.0421 [*]
Rainfall	-0.00	0.00	-2.55	0.0109 [*]
Temperature	0.11	0.09	1.24	0.0216 [*]
Lorey's height				
(Intercept)	0.33	4.16	0.08	0.9368 ^{ns}
Habitat heterospecific density	-0.01	0.00	-2.63	0.0085 ^{**}
Habitat specific richness	0.02	0.01	2.89	0.0038 ^{**}
Rainfall	0.01	0.00	1.67	0.0938 ^{ns}
Temperature	0.03	0.14	0.19	0.8510 ^{ns}

Legend: *** P < 0.001, ** P < 0.01, * P < 0.05. Std. Error: Standard Error; ns = non-significant

**Fig. 3.** Horizontal structure of adult stands of *Detarium microcarpum* Legend: SPa: Sudanian Protected areas, SUPa: Sudanian Unprotected areas, SSPa: Sudano-Sahelian Protected areas and SSUPa: Sudano-Sahelian Unprotected areas.

to unprotected areas. The findings of this study indicate that protected areas have a significant positive impact on species abundance. Following that, the higher diversity found in Protected areas highlights the great potential of these non-disturbed ecosystems in biodiversity conservation (Nacoulma et al., 2011). This proves the positive effect of protecting forests, especially in the tropics (Gray et al., 2016) like Burkina Faso. The higher Hill index in the Sudanian climatic zone is due to the Kou classified forest. This forest minimizes cropland expansion and pasture while still retaining natural forest characteristics (Yaovi et al., 2021) and reveals the influence of better management practices. Maryo and Wendawek (2014) reported that the low evenness can be attributed to excessive environmental disturbances, variable conditions for regeneration, and selective exploitation.

Jaccard's index values showed little similarity in species composition in *D. microcarpum* plant formations along the two climatic zones. The low values of the similarity index indicate a high β -diversity between populations and could be related to the climatic effect.

The higher IVI values of *D. microcarpum* obtained for the Sudano-Sahelian zone highlight the ecological importance of the species in this climate zone. On the contrary, the lower IVI values obtained on the Sudanian zone for the same species indicate that the species are

Table 5

Regression slope values of height class distributions (Juvenile) and diameter Class distribution (adults) of *Detarium microcarpum* stand according to climatic zones and land use types.

Climatic zones	Land use types	Regression parameters		
		Slope	R ²	P_value
Adult stratum				
Sudanian	Protected areas	-1.81	0.54	0.0159
	Unprotected areas	-0.57	0.29	0.1062
Sudano-Sahelian	Protected areas	-1.36	0.26	0.1303
	Unprotected areas	-1.24	0.39	0.0550
Juvenile stratum				
Sudanian	Protected areas	-0.29	0.06	0.7022
	Unprotected areas	-0.51	0.32	0.3230
Sudano-Sahelian	Protected areas	-0.90	0.05	0.7280
	Unprotected areas	0.39	0.29	0.3495

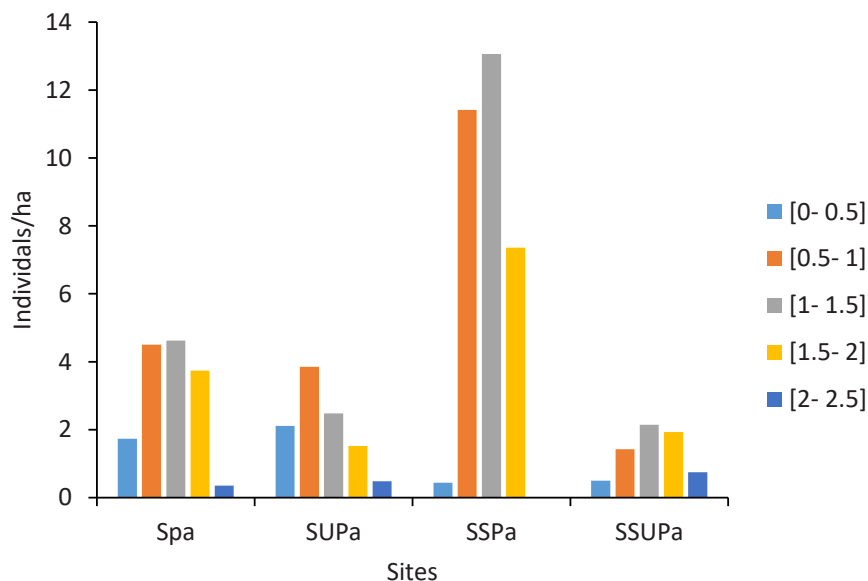


Fig. 4. Vertical structure of juvenile populations of *Detarium microcarpum* Legend: Spa: Sudanian Protected areas, SUPa: Sudanian Unprotected areas, SSPa: Sudano-Sahelian Protected areas and SSUPa: Sudano-Sahelian Unprotected areas.

not adapted to the humid zone (Lamy et al., 2021). This corroborates the results of Chejanovski and Wiens (2014) who explained that the climatic gradient influences the species niche. According to Zerbo et al. (2016), the low percentage of frequent species and the high rate of occasional and rare species implies on the one hand a great heterogeneity among plant communities of each climatic and land use condition with the human disturbance. Therefore, in the Sudanian and Sudano-Sahelian, the presence of some species (*Combretum glutinosum*, *Vittelaria paradoxa*, *Burkea africana*, *Piliostigma thonningii*, *crosopteryx februfiga*, *Entada africana*, *Terminalia laxiflora*) would be an indicator of sites suitable for *D. microcarpum* stand. In the Ivory Coast, it has been reported that, *Piliostigma thonningii* is an indicator of the presence of *D. microcarpum* on silty-clay soils (Fournier, 1991).

4.2. Effect of climate and land use on the structural parameters of *Detarium microcarpum*

Regarding the stand structure of *Detarium microcarpum*, the results show that the climate and land use have a significant influence on the structural parameters. The high densities of trees observed in the Sudano-Sahelian zones showed that the *D. microcarpum* is the savanna species that prefers low humidity. Lamy et al. (2021) pointed out that, the high density of *D. microcarpum* in the Sudano-Sahelian zone could be due to the autecology of the species. In addition, the Sudano-Sahelian climate zone characterizes a lower rainfall quantity than the Sudanian zone. This is in line with previous studies such as Nacoulma et al. (2011); Zerbo et al. (2018); Kabre et al. (2020); Houénon et al. (2022) showed that the differences in stand diversity in forests may be attributed to natural and anthropogenic disturbances. This leads to a high development of the structural parameters of the woody species in this zone, especially *D. microcarpum* which is an important fodder species. In protected areas, the density of *D. microcarpum* was significantly higher than in unprotected areas. Human pressure contributes to the fragmentation of plant formations (Sinadouwirou, Dicko, et al., 2022) which

leads the loss of the biodiversity. This result corroborates with [Nouhou et al. \(2019\)](#) and [Kabré et al. \(2020\)](#) who explain that human activities reduce the density of the species. In fact, the lower number of large trees observed in the land use area compared with the protected area may be explained by logging, which mostly affects individuals of large diameter.

Contrasting effects of abiotic and biotic factors were found, as temperature and precipitation have mainly negative effects on the species dendrometric parameters, while habitat heterospecific density and richness show positive effects. This finding corroborates with [\(Atanasso et al., 2019\)](#) who find that the heterospecific tree density influences the structure of *Afzelia africana* individual trees in the Pendjari Biosphere (Benin). The mean diameter, mean height, mean density, and basal area values were higher in the Sudano-Sahelian than in the Sudanian zone. This may be due to the climatic regime in the Sudano-Sahelian which favours the growth of the species. This corroborates with [Amoako and Gambiza \(2021\)](#) who pointed out that the regime of the climate influence the diameter size of *Anogeissus leiocarpa* Baill. in Guinea savannah of Ghana. In addition, The high population density found in this zone may be due to the quality of the soil which influences the symbiotic relationship between the roots of Leguminosae and mycorrhizal fungi ([Raddad et al., 2005](#); [Houénou et al., 2022](#)).

The difference in the basal area between the protected and unprotected areas may be attributed to disparity in the surrounding species composition, degree of disturbances, age of trees, and the influence of the climate. [Kacholi, \(2019\)](#) pointed out that the species composition influences the basal area of the species. The low basal area values in the unprotected area were related to high accessibility due to the nearby population's lack of enough protection ([Lamy et al., 2021](#)) and illegal logging ([Sinadouwirou et al., 2022](#)). Consequently, the conservation of *D. microcarpum* is not sustainable.

The Habitat heterospecific density, Habitat species richness, temperature, and Rainfall influence the structure of *D. microcarpum* population at different levels. The negative impact of rainfall and temperature on the density and basal area of *D. microcarpum* indicates that the two variables have a contrasting influence on the recruitment and growth of the other species. However, the higher rainfall decreases the temperature at the special scale ([Du et al., 2019](#); [Rodrigo, 2022](#)) and influences the richness of the species and the basal area ([Bognounou et al., 2009](#); [Premavani et al., 2014](#)). These results indicate that the decrease in diameter is related to the increase in tree competition. According to [Traoré et al. \(2022\)](#), rainfall is one of the main climate variables which affect the species' population status.

Concerning population structure, rainfall is the main abiotic variable affecting the structure of *D. microcarpum*. This suggest that an increasing in rainfall can disturb the recruitment process of *D. microcarpum* juveniles. [Traore et al., \(2022\)](#) found that the density of the *Faidherbia albida* species which is the savannah species was influenced by the rainfall. [Ostonen et al. \(2011\)](#) and [Mensah et al. \(2020\)](#) pointed out that climate variation affect several characteristics of adult tree species such as the timing of leaf growth, the duration of the growing season, and the intensity of stress experienced by the trees in their natural stand. Likewise, the growth rate of the tree trunk is linked with the level of the precipitation and temperature, which increase the photosynthesis rate and, then, cambial activity ([Schaffner, 2017](#)).

The negative effect of habitat heterospecific density on the Lorey's mean height can be explained by the competition of the species with other species occurred in the same habitat. This can be related to the competition for light and nutrients. According to [Aubréville and Trochain, \(1937\)](#), *D. microcarpum* is a medium size tree (8 m –12 m), and taller trees can affect their competitiveness for light. In fact, the light is one of the most limiting resources that impact the growth of the species in the forest ([Reuger et al., 2012](#); [Azquez, 2020](#)) and the increased light levels affected juvenile recruitment.

4.3. Effect of climate and land use on the population structure of *Detarium microcarpum*

The distributions of diameter and height classes of *D. microcarpum* reveals unstable populations in all the study areas. The instability of the species populations observed in the two climatic zones was generally characterized by a low number of small-diameter individuals and an irregularity of the transition in their size class distribution. The same trend was found by [Kouyaté \(2005\)](#); [Houénou et al. \(2022\)](#); [Lamy et al. \(2021\)](#); [Agbo et al. \(2018\)](#) who explain that the weakness of the forests' protection has caused the species threat. [Bentsi-Enchill et al. \(2022\)](#) pointed out that the overexploitation of the species in the Unprotected areas could be the reason for instability of the species structure and the lack of protection. Usually, when trees are logged without replacement, their structures decrease ([Rivero et al., 2008](#)). Similar results indicating the degradation of tree populations were reported by [Traore et al. \(2022\)](#) for *Faidherbia albida* and [Mensah et al. \(2020\)](#) for *Afzelia africana* in Africa. The lack of individuals in the larger size classes in the Sudano-Sahelian could be due to the illegal logging of bigger trees by the locals for timber and construction purposes. In fact, the local population depends on forest resources for firewood, building materials, livestock as well and income generation ([Kouyaté, 2011](#); [Dossa et al., 2020](#)). This can reduce the availability of seeds and may thereby lead to a lack of regeneration ([Thomas, 2006](#)). According to [Bouché et al. \(2011\)](#), the elephant impacts affected negatively the recruitment of the species.

The size class distributions of the juvenile individuals suggest that the species are in a crucial stage of regeneration and recovering from disturbances.

The instability reported for the regeneration independent of the climate zone and the land use type indicated difficulties in recruitment and transition between the different classes in the species juvenile population ([Zerbo et al., 2023](#)). This instability would be linked to the pressures that the species faces, leading to its poor regeneration and then constitutes a threat to its survival. [Bationo et al. \(2001\)](#) pointed out that human pressure and the bushfire impacted the recruitment of the *D. microcarpum* juvenile species. In addition, [Sinadouwirou et al. \(2022\)](#) explained that the seed of *D. microcarpum* has a natural germination difficulty compared to the other species due to the tegument dormancy. Besides, according to the same authors, the low individuals number observed in the size class 0–0.5 could be also explained by bushfires which affected the fruit germination capacity due to burning. In addition, land clearing and tree density reduction for agricultural purposes may be detrimental to the seedling establishment and, hence, threaten the species

(Fandohan et al., 2011). The illegal logging of *D. microcarpum* for fire wood also contribute to the reduction of mature trees density, influencing the species fruits and seeds production. In fact, previous studies showed that *D. microcarpum* wood was highly appreciated by the population in particular by the women because of its high flame intensity (Agbo et al., 2017; Kouyaté, 2005). The fruits harvest reduce seed potential of edible tree species. Indeed, Taïta (2003) stated that species whose fruits and/or seeds are consumed often face regeneration issues. This is in line with the findings of authors who reported that the fruits of *D. microcarpum* are highly valued and consumed by the local populations (Agbo et al., 2020; Dieng et al., 2019; Dieng et al., 2016; Kouyaté, 2005). This study suggests that protecting *D. microcarpum* populations within Protected areas does not guarantee successful species recruitment across all size classes.

5. Conclusion

The floristic diversity and composition of *D. macrocarpum* natural stands vary according to the climatic zones and the land use types. Climate patterns and land use type influenced the structural parameters of and the population trend of the *D. microcarpum* stand. The degradation of the species stands structure and diversity due to land use have significant implications for biodiversity conservation related to the target 15 of the sustainable development goals. This study indicated that *D. microcarpum* has unstable populations and specific protection actions must be enforced to avoid full harvesting to ensure the recruitment of the species. It would be preferable to develop a good policy for integrating the species into the agroforestry system. To ensure the sustainable use of the species, it is crucial to implement institutional and managerial policies including the local population which could contribute to preserving the multi-purpose species.

CRedit authorship contribution statement

Adama Taonda: Writing- original draft, Visualization, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation and Conceptualization. **Issouf Zerbo:** Writing- Original draft, Visualization, Validation, Software, Methodology, Data curation, Conceptualization and draft editing. **Anny Estelle N'Guessan:** Visualization, Methodology, Formal analysis and conceptualization. **Innocent Charles Emmanuel Traoré:** Visualization, Formal analysis, Data curation, Writing - review editing, Supervision and Project administration. **Justin N'Dja Kassi:** Writing review and editing, Visualization, Validation, Supervision, Project administration.

Declaration of Competing Interest

This article is an original research and the authors declare that they have known competing financial interest or personal relationships that could have appeared to influence this work.

Data availability

Data will be made available on request.

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Consent for publication

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

Appendix A. List of woody species across climatic zones and land use types

Famillies	Genera	Species	Sudanian climate zone		Sudano Sahelian climate zone	
			Protected areas	Unprotected area	Protected area	Unprotected area
Anacardiaceae	Anacardium	<i>Anacardium occidentale</i> L.		X		
Anacardiaceae	Lannea	<i>Lannea acida</i> A.Rich.	X	X	X	X
Anacardiaceae	Lannea	<i>Lannea microcarpa</i> Engl. & K.Krause	X	X		X
Anacardiaceae	Lannea	<i>Lannea velutina</i> A.Rich.	X	X	X	
Anacardiaceae	Mangifera	<i>Mangifera indica</i> L.	X	X		X
Anacardiaceae	Ozoroa	<i>Ozoroa insignis</i> Delile	X	X		

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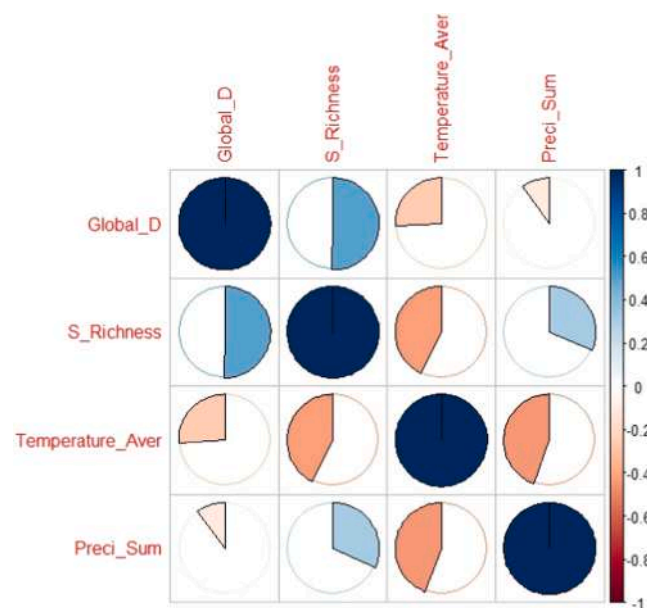
Families	Genera	Species	Sudanian climate zone		Sudano Sahelian climate zone	
			Protected areas	Unprotected area	Protected area	Unprotected area
Anacardiaceae	Sclerocarea	<i>Sclerocarya birrea</i> Hochst.				X
Annonaceae	Annona	<i>Annona senegalensis</i> Pers.	X	X	X	X
Annonaceae	Hexalobus	<i>Hexalobus monopetalus</i> Engl. & Diels	X	X		
Apocynaceae	Ancylobotrys	<i>Ancylobotrys amoena</i> Hua	X			
Apocynaceae	Calotropis	<i>Calotropis procera</i> (Aiton) Dryand.		X	X	
Apocynaceae	Holarrhena	<i>Holarrhena floribunda</i> T.Durand & Schinz	X			
Apocynaceae	Londolfia	<i>Londolfia heudelotii</i> A.DC.	X	X		
Apocynaceae	Saba	<i>Saba senegalensis</i> (A.DC.) Pichon	X	X		
Apocynaceae	Tacazzea	<i>Tacazzea apiculata</i> Oliv.	X			
Arecaceae	Borassus	<i>Borassus aethiopum</i> Mart.		X		
Arecaceae	Elaeis	<i>Elaeis guineensis</i> Jacq.	X	X		
Bignoniaceae	Stereospermum	<i>Stereospermum kunthianum</i> Cham.	X	X	X	X
Capparidaceae	Capparis	<i>Capparis fascicularis</i> DC.	X		X	
Celastraceae	Gymnosporia	<i>Gymnosporia senegalensis</i> Loes.			X	
Chrisobalanaceae	Parinari	<i>Parinari curatellifolia</i> Planch. ex Benth.	X			
Combretaceae	Combretum	<i>Combretum adenogonium</i> Steud.ex A.Rich.	X		X	
Combretaceae	Combretum	<i>Combretum collinum</i> Fresen.	X	X	X	X
Combretaceae	Combretum	<i>Combretum glutinosum</i> Fresen.	X	X	X	X
Combretaceae	Combretum	<i>Combretum micranthum</i> G. Don			X	X
Combretaceae	Combretum	<i>Combretum molle</i> R.Br. ex G.Don	X			
Combretaceae	Combretum	<i>Combretum nigricans</i> Leprieur ex Guill. & Perr.	X			
Combretaceae	Combretum	<i>Combretum paniculatum</i> Vent.			X	X
Combretaceae	Guiera	<i>Guiera senegalensis</i> JFGmel.				X
Combretaceae	Terminalia	<i>Terminalia engleri</i> Gere & Boatwr.	X		X	X
Combretaceae	Terminalia	<i>Terminalia leiocarpa</i> Baill.	X	X	X	X
Combretaceae	Terminalia	<i>Terminalia avicennioides</i> Guill. & Perr.	X		X	
Combretaceae	Terminalia	<i>Terminalia laxiflora</i> Engl.	X	X	X	
Combretaceae	Terminalia	<i>Terminalia macroptera</i> Guill. & Perr.	X	X	X	
Combretaceae	Terminalia	<i>Terminalia mollis</i> Malawson	X			
Delleniaceae	Tetracera	<i>Tetracera alnifolia</i> Willd.	X			
Ebenaceae	Diospyros	<i>Diospyros mespiliformis</i> Hochst. ex A.DC.	X	X	X	X
Fabaceae	Afzelia	<i>Afzelia africana</i> Pers.	X	X	X	
Fabaceae	Aganope	<i>Aganope stuhlmannii</i> (Taub.) Adema	X	X	X	
Fabaceae	Albizia	<i>Albizia zygia</i> (DC.) JF Macbr.	X			
Fabaceae	Bernilia	<i>Bernilia grandiflora</i> (Vahl)Hutch.&Dalziel	X			
Fabaceae	Burkea	<i>Burkea africana</i> Hameçon.	X	X	X	
Fabaceae	Cassia	<i>Cassia sieberiana</i> DC.	X	X	X	
Fabaceae	Daniella	<i>Daniella oliveri</i> Hutch. & Dalziel	X	X		
Fabaceae	Detarium	<i>Detarium microcarpum</i> Guill. & Perr.	X	X	X	X
Fabaceae	Detarium	<i>Detarium senegalense</i> JFGmel.	X			
Fabaceae	Dichrostachys	<i>Dichrostachys cinerea</i> (L.) Wight & Arn.	X			
Fabaceae	Entada	<i>Entada africana</i> Guill. & Perr.	X	X		
Fabaceae	Erythrina	<i>Erythrina senegalensis</i> DC.		X		
Fabaceae	Isobrerlinia	<i>Isobrerlinia doka</i> Craib & Stapf	X		X	
Fabaceae	Ormocarpum	<i>Ormocarpum pubescens</i> (Hochst.) Cufod.	X			
Fabaceae	Parkia	<i>Parkia biglobosa</i> (Jacq.) R.Br. ex G.Don	X	X		
Fabaceae	Pterocarpus	<i>Pterocarpus lucens</i> Lepr. ex Guill. & Perr.	X			
Fabaceae	Pericopsis	<i>Pericopsis laxiflora</i> (Benth. ex Baker) Meeuwen	X		X	
Fabaceae	Philenoptera	<i>Philenoptera laxiflora</i> (Guill. & Perr.) Roberty			X	X
Fabaceae	Piliostigma	<i>Piliostigma reticulatum</i> (DC.) Hochst.	X		X	X
Fabaceae	Piliostigma	<i>Piliostigma thonningii</i> (Schumach.) Milne-Redh.	X		X	X
Fabaceae	Prosopis	<i>Prosopis africana</i> (Guill. & Perr.) Taub.	X	X		X
Fabaceae	Pterocarpus	<i>Pterocarpus erinaceus</i> Poire.	X	X	X	X
Fabaceae	Senegal	<i>Senegalia gourmaensis</i> (A.Chev.) kyal. \$Boatwr			X	X
Fabaceae	Senegalia	<i>Senegalia dudgeonii</i> (Craib) Kyal. & Boatwr.	X			X
Fabaceae	Senegalia	<i>Senegalia gourmaensis</i> (A.Chev.) Kyal. & Boatwr.	X	X	X	X
Fabaceae	Senna	<i>Senna singueana</i> (Delile)			X	X
Fabaceae	Tamarindus	<i>Tamarindus indica</i> L.	X	X	X	X
Fabaceae	Vachellia	<i>Vachellia seyal</i> (Delile) PJHHurter			X	X
Fabaceae	Vachellia	<i>Vachellia sieberiana</i> (DC.) Kyal. & Boatwr.		X	X	
Lamiaceae	Gmelina	<i>Gmelina arborea</i> Roxb.		X		

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Famillies	Genera	Species	Sudanian climate zone		Sudano Sahelian climate zone	
			Protected areas	Unprotected area	Protected area	Unprotected area
Lamiaceae	Tectona	<i>Tectona grandis</i> LF	X			
Lamiaceae	Vitex	<i>Vitex doniana</i> Doux	X	X	X	X
Loganiaceae	Strychnos	<i>Strychnos spinosa</i> Lam.	X	X	X	X
Malvaceae	adansonia	<i>Adansonia digitata</i> L.	X			X
Malvaceae	Bombax	<i>Bombax costatum</i> Pellegr. & Vuillet	X	X	X	X
Malvaceae	Ceiba	<i>Ceiba pentandra</i> (L.) Gaertn.	X			
Malvaceae	Cola	<i>Cola cordifolia</i> (Cav.)R. Br.	X			
Malvaceae	Grewia	<i>Grewia rotii</i> DC.	X	X		
Malvaceae	Grewia	<i>Grewia lasiodiscus</i> K. Schum.	X			
Meliaceae	Azadirachta	<i>Azadirachta indica</i> A.Juss.		X		
Meliaceae	Khaya	<i>Khaya senegalensis</i> A. Juss.	X			
Moraceae	Ficus	<i>Ficus crocata</i> Mart. ex Miq.	X		X	
Moraceae	Ficus	<i>Ficus thonningii</i> Blume				X
Moraceae	Ficus	<i>Ficus sycomorus</i> L.				
Myrtaceae	Eucalyptus	<i>Eucalyptus camaldulensis</i> Dehnh.	X	X		
Ochnaceae	Lophira	<i>Lophira lanceolata</i> Van Tiegh. Ex keay		X		
Olacaceae	Ximenia	<i>Ximenia americana</i> L.	X		X	
Phyllanthaceae	Bridelia	<i>Bridelia micrantha</i> (Hochst.) Baill.	X		X	X
Phyllanthaceae	Fluggea	<i>Fluggea virosa</i> (Roxb.ex Wild.) Royle.	X		X	
Phyllanthaceae	Hymenocardia	<i>Hymenocardia acida</i> Tul.	X	X		
Phyllanthaceae	Margaritaria	<i>Margaritaria discoidea</i> (Baill.) GLWebster	X			
Polygalaceae	Securidaca	<i>Securidaca longepedunculata</i> Fresen.	X			
Rhamnaceae	Ziziphus	<i>Ziziphus spina-christi</i> (L.) Willd.			X	X
Rubiaceae	Crotopteryx	<i>Crotopteryx febrifuga</i> (Afz ex G.Don)Benth	X	X	X	
Rubiaceae	Feretia	<i>Feretia apodanthera</i> Delile	X		X	
Rubiaceae	Gardenia	<i>Gardenia aqualla</i> Stapf & Hutch.	X			
Rubiaceae	Gardenia	<i>Gardenia erubescens</i> Stapf & Hutch.	X	X	X	X
Rubiaceae	Gardenia	<i>Gardenia ternifolia</i> Schumach. & Thönn.	X	X		
Sapindaceae	Allophyle	<i>Allophylus africanus</i> P.Beauv.	X			
Sapindaceae	Blighia	<i>Blighia sapida</i> KDKoenig	X			
Sapotaceae	Manilkara	<i>Manilkara obovata</i> (Sabine & G.Don) JHHemsl.	X			
Sapotaceae	Pouteria	<i>Pouteria alnifolia</i> (Baker) Roberty	X			
Sapotaceae	Vitellaria	<i>Vitellaria paradoxa</i> CFGaertn.	X	X	X	X
Sterculiaceae	Sterculia	<i>Sterculia setigera</i> Delile	X	X		X
Zygophyllaceae	Balanites	<i>Balanites aegyptiaca</i> (L.) Delile	X	X	X	X

Appendix B. correlogram of the explanatory variable based on Pearson correlation



Legend: Global_D = habitat heterospecific density; S_Richness = habitat-specific richness, Temperature_Aver = mean annual temperature; Preci_Sum = Precipitation

Colored proportions reflect the values of the correlation coefficients.

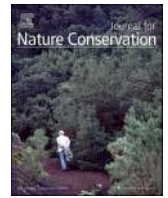
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Publication 3



Potential distribution of *Detarium microcarpum* under different climate change scenarios in Burkina Faso

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ABSTRACT

Climate change and human activities are major drivers influencing species distribution, posing significant challenges for woody species that provide essential ecosystem goods and services. Therefore, a thorough understanding of climate impacts on species distribution is crucial for more effective management. This study aims to assess the effect of climate change on the current and future distribution of *Detarium microcarpum*. This study was conducted in Burkina Faso. The maximum entropy (MaxEnt) approach was used to simulate the current and future distributions of the species. The future distribution of the species was assessed through four global climate models: HadGEM3-GC3.1-LL, ACCESS-CM2, CNRM-CM6-1 and MIROC6 under two Shared Socioeconomic Pathways (SSPs) scenarios, SSP2-4.5 and SSP5-8.5 at the horizons 2061–2080 and 2081–2100. The area under the curve (AUC > 0.80) and True Skill Statistic (TSS=0.7) revealed a high level of prediction for the current and future scenarios. The results showed that the mean temperature of the Wettest Quarter (bio8) and Isothermality (bio3) were the most important environmental variables which affect *D. microcarpum* distribution. The results show that the current suitability area for the species covers 65.6 % of the country area with respectively high suitability (36.73 %) and low suitability (29.16 %). Based on the outcomes of the prediction, the high suitable areas for *D. microcarpum* conservation will decrease on average by 5.92 % of their current area under future climate change, regardless of the scenario and model used, except for the MIROC6 model under the SSP5-8.5 scenario, which will increase its current area from 0.56 % to 1.7 %. The result of this study underscores the significant effect of the future climate on the suitable area of *D. microcarpum*. Specific actions should be taken to ensure the suitable conservation of this valuable multipurpose species.

1. Introduction

Climate is the main factor influencing species distribution in the savannah ecosystems (Ren et al., 2020). Changes in precipitation patterns influence water availability, altering ecosystems' structure and composition (Hattab et al., 2014). For instance, rainfall patterns may partly influence the tree density of a certain number of species (Issoufou et al., 2022). Climate threats represent a major challenge to biodiversity conservation (Pecchi et al., 2019; Requena-Mullor et al., 2019). In Sub-Saharan Africa, these threats are exacerbated by complex natural

disasters, endemic poverty and human conflicts, which are very challenging for many countries (Lompo et al., 2021). The manifestation of climate change exacerbates human pressure on forests through fragmentation and degradation, which in turn contribute to biodiversity loss, and negatively impact food security, human health, and the economy (Dimobe et al., 2020, 2022; Ren et al., 2020). McClean et al. (2006) explain that at the horizon 2085; approximately 25 % to 42 % of African plant species may become extinct due to habitat loss and fragmentation. According to the data from Monographie Nationale (2020), Burkina Faso lost an average of 243,450 ha/year of its forest area. With the

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increasing human pressure and the loss of the species' natural habitats, the multipurpose species which provide several types of ecosystem services are subject to be threatened by the lack of long-term strategic management (Schumann et al., 2012; Gurung et al., 2021; Dai et al., 2023). Climatic stress, driven by severe environmental changes, significantly impacts species dynamics (Balima et al., 2022). The conservation of the species must therefore consider how various climate change scenarios may impact their distribution (Mkala et al., 2023).

One of the major challenges in species conservation is predicting the future suitability of habitats for tree species (Mkala et al., 2023). The current ecologist's challenges are to understand how species interact with the environment and the future effects of the climate (Gurung et al., 2021; Zhang et al., 2022). Species predictions play an important role in alerting scientists and decision-makers to the potential future impact of climate threats (Bellard et al., 2012; Parmesan et al., 2013). However, the most effective tool for predicting the impact of climate change on species distribution is Species Distribution Modeling (SDM) (Issoufou et al., 2022). Species Distribution Models (SDMs) serve as a crucial instrument for forecasting the geographic distribution of species by correlating their presence with environmental factors (Lompo et al., 2021). Thus, with the current context of climate change and population growth, more attention has been given to predicting species distribution for future trends (Phillips et al., 2006; Fan et al., 2022). These modeling techniques offer a range of tools for predicting species distributions under different data conditions. MaxEnt tools developed by Phillips et al. (2006) is particularly suited for presence-only data, providing probability distributions across landscapes based on environmental factors. In contrast, GLMs are versatile for presence/absence data and can handle various distributions, while GAMs extend this flexibility by allowing for non-linear relationships between predictors and outcomes (Nelder et al., 1972; Segurado & Araújo, 2004; Thuiller et al., 2009). For more complex interactions, Random Forest and Boosted Regression Trees (BRT) offer robust machine-learning approaches (Yang et al., 2016). Random Forest uses an ensemble of decision trees to minimize overfitting and Boosted Regression Trees combines multiple tree predictions to enhance accuracy. All these models enable researchers to choose the most appropriate technique based on the nature of their data and the complexity of the relationships they are investigating. By using the occurrence data and the variety of environmental variables, the Maximum Entropy (MaxEnt) were chosen in this study to simulate the impact of climate change in their natural stand. Furthermore, understanding the factors which influence species distribution is crucial for developing effective strategies for sustainable management.

Among the savanna species, *Detarium microcarpum* Guill et al. (2006) is a vulnerable species because it is extremely exploited (Sinadouwirou et al., 2022) by humans for several purposes (Agbo et al., 2020; Sinadouwirou et al., 2022; Amoussa et al., 2023). Indeed, previous ethnobotanical studies in West Africa (Kouyaté et al., 2002; Dieng et al., 2019; Agbo et al., 2020; Amoussa et al., 2023; Sinadouwirou et al., 2022), demonstrated that *D. microcarpum* is a key multipurpose fruit tree species that provide vital goods and services for the communities. In addition, in Burkina Faso, several authors indicated the regeneration concerns of the species (Rietkerk et al., 1998; Bationo et al., 2001; Bastide et al. 2008; Ki-Dembélé et al., 2008; Ki-Dembélé et al., 2010), the impacts of fire on its fruits production (Bastide and Ouédraogo, 2009) and human exploitation on population conservation (Wiersum et al. 1997; Taonda et al., 2024a; Taonda et al., 2024b). The species fruits are consumed by the population (Kouyaté, 2005) and its wood is used for firewood (Sinadouwirou et al., 2022). In addition, *D. microcarpum* finds application in traditional medicinal practices (Dogara, 2022). The leaves, bark, stem and roots of the species are used to treat tuberculosis, meningitis, itching, syphilis, and diarrhoea (Dieng et al., 2019). The stems and branches of the species are used for firewood (Rietkerk et al., 1998; Kouyaté et al., 2002; Sinadouwirou et al., 2022, Taonda et al., 2024a; Taonda et al., 2024b). Given the importance of *D. microcarpum* to rural communities, the species is under significant pressure from

overexploitation, which is a major factor contributing to its decline. Additionally, climate change poses various threats to its distribution and abundance, with extreme weather events even affecting pollination processes (Rong et al., 2019). *D. microcarpum*, a member of the Fabaceae family, is recognized for its woody nature (Arbonnier, 2009) and is found in particular in Benin, Burkina Faso, Cameroon, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Mali, Niger, Nigeria, Central African Republic, Senegal, Sudan and Tchad (Lamy et al., 2021).

Despite the research efforts and the importance of the species to local communities, no studies have been conducted to investigate how environmental variables and their potential future statuses under climate change scenarios might affect the distribution of *D. microcarpum* in Burkina Faso. Although information on its spatiotemporal dynamics is available in southern Guinea climatic zones like Benin (Agbo et al., 2018), scientific knowledge of its geographical distribution and dynamics in semi-arid climatic zones, particularly in Burkina Faso is limited. Without the climatic preferences and potential geographical distribution of *D. microcarpum*, formulating a management strategy and practical conservation becomes challenging. Thus, identifying a suitable area for the species should provide robust information on the species' variability, occurrence, and distribution in the semi-arid country. To provide the best management of *D. microcarpum* in West Africa particularly in Burkina Faso, this research focused on assessing how the geographic distribution will change in response to the future climate threat. To achieve this research, the following questions were addressed:

- (i) Which environmental variables affect the distribution of *D. microcarpum*?
- (ii) What is the current spatial extent of the suitable area of *D. microcarpum*?
- (iii) What are the dynamics of the suitable area of *D. microcarpum* under the future climate projection?

2. Materials and methods

2.1. Study area

The study was carried out in Burkina Faso, which is a West African tropical semi-arid country located between the latitude of 09° 02'–15° 05' N and longitudes 02° 02'E – 05° 03 W and over an area of 274,200 km². The country has three climatic zones which are the Sudanian zone, the Sudano-Sahelian zone and the Sahelian Zone (Thiombiano et al., 2006; Dayamba, 2019). In terms of vegetation, four phytogeographic sectors are found: South-Sudanian, North-Sudanian, Sub-Sahelian, and North-Sahelian (Fontès et Guinko, 1995; Nacoulma et al. 2018). According to the 5th report of the Ministry of Economy and Planning, the population of Burkina Faso is 20,505,155 with 73.9 % live in rural areas and are dependent on multipurpose species (MEFP, 2022). According to the data from the National Meteorological Office, in the Sahelian zone, the annual rainfall ranges between 400 mm and 600 mm and the temperature ranges from 20°C – 42°C. For the Sudano-Sahelian zone, the annual rainfall varies between 600 and 900 mm over 4 to 5 months while the average annual temperature ranges from 20°C to 40°C. The Sudanian zone has annual rainfall between 900 and 1200 mm with a rainy season of 5 to 6 months and a temperature between 18°C – 37°C. The country's climate leads to a similarly broad gradient in plant diversity and composition of taxonomic and functional groups. Previous studies such as Thiombiano et al. (2012) and Schmidt et al. (2017) mentioned that the diversity of plant species increased with the rainfall gradient from the Sahelian to the Sudanian zones across the country.

2.2. Study species

The natural range of *D. microcarpum* covers all of the arid sub-Saharan Africa, from Senegal to Sudan (Aubréville & Trochain, 1937). *D. microcarpum* thrives in environments ranging from dry savannas and

dry forests to fallow lands, typically on sandy or iron-rich soils, and occasionally as isolated trees within farming landscapes. (Kouyate et al., 2006; Houénon et al., 2021). *D. microcarpum* is a heat and drought-tolerant species capable of thriving on infertile sites (Lamy Lamy et al., 2021). It grows on dry soil in wooded savanna and open woodland and is locally very common (Cavin, 2007a; Lamy Lamy et al., 2021). It is most common in regions with an annual rainfall of 600–1000 mm (Kouyaté, 2005). This tree reaches heights of up to 12 m, characterized by a full, compact canopy (Kouyaté, 2005; Maré and Millogo, 2019).

2.3. Data collection

2.3.1. Species occurrence records

Two hundred and sixty-five (265) occurrences were recorded during the fieldwork using a GPS (Global Positioning System, Garmin 65) with a distance of at least 1 km between two trees. The additional occurrence points, the three hundred and fifty-four occurrences (354 points) were downloaded from the Global Biodiversity Information Facility repertory (GBIF, <https://www.gbif.org/>; accessed on August 01, 2023) and the published relevant literature two hundred and three (203 points) through the article of Schmidt et al., 2017) after digitalizing the *D. microcarpum* distribution map. After controlling the quality of the data (removing incorrect and duplicate records), a total of seven hundred and twenty-two (722) occurrence points of *D. microcarpum* were gathered from three sources that cover the country (Fig. 1).

2.3.2. Environmental data

Three sources of environmental data were used in this study. These data included the bioclimatic variables which influence the distribution of the species (Heubès et al., 2011), elevation because it is mainly found on superficial, stony, and lateritic soils, and often on hills (Kouyaté, 2005) and soil variables which are important factors for the geographic distribution of tropics tree species (Agbo et al., 2018). Soil variables (cation exchange capacity (Cec, mol/kg)) were obtained with 1-km² resolution from the Harmonized World Soil Database, version 1.2 (FAO/IIASA/ISRIC/ISSCAS/JRC 2012) at different horizons: 0–5 cm (Cec01), 5–15 cm (Cec02), 15–30 cm (Cec03), 30–60 cm (Cec04), 60–100 cm (Cec05). Nineteen (19) bioclimatic variables and the elevation were downloaded from the WorldClim platform (<https://www.worldclim.org>) version 2.1 with a spatial resolution of 30 s (approximately 1 × 1 km²). The current bioclimatic data obtained from the WorldClim website are derived from interpolated monthly averages of maximum and minimum temperature and rainfall, considering the historical series 1970–2000 (Hijmans et al., 2005). To forecast the future distribution of the species, two Shared Socioeconomic Pathways (SSPs) from the updated CMIP6 scenarios were selected for analysis, the SSP2-4.5 and SSP5-8.5 for two times periods (2061–2080 averaged 2070, and 2081–2100 averaged 2090). Maximum temperature is expected to increase by 0.84–1.54 °C, and 0.98–1.73 °C, while minimum temperature would likely increase by 1.49–2.22 °C, and 1.75–4.83 °C under SSP2-4.5, and SSP5-8.5 scenarios, respectively (Siabi et al., 2023). SSP2-4.5 represents a future world where there is an intermediate trajectory in which trends continue without substantial deviations whereas SSP5-8.5 represents a

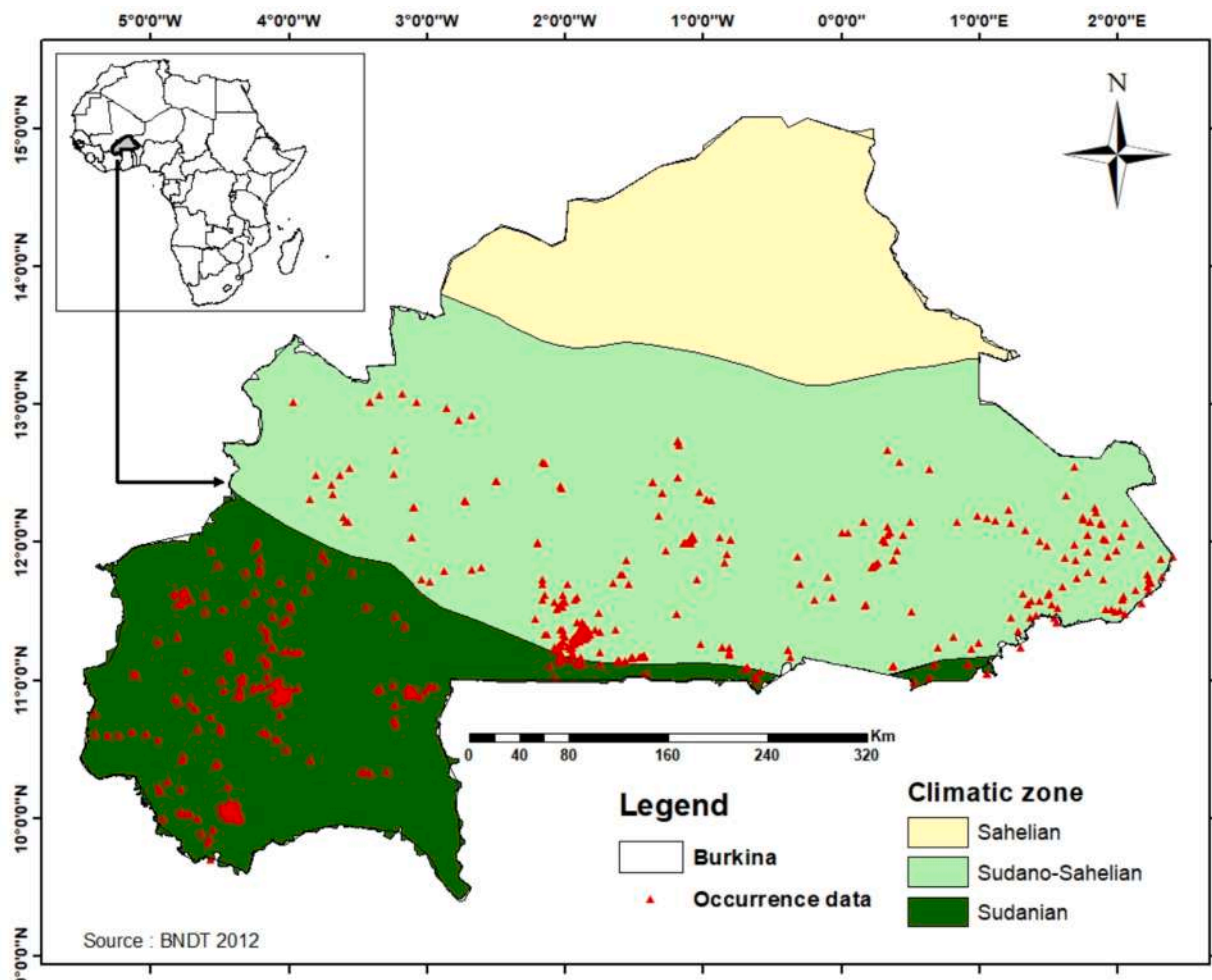


Fig. 1. Study area and occurrences of *D. microcarpum* in Burkina Faso.

future world where there is high population growth, rapid economic expansion, and a heavy reliance on fossil fuels. In addition, SSP2-4.5 represents a more balanced approach to emissions reduction, leading to moderate warming, while SSP5-8.5 assumes continued high emissions and results in severe warming (IPCC, 2021; Tebaldi et al., 2021). The latter scenario, SSP5-8.5, would lead to more extreme climate impacts, including higher temperatures, more frequent extreme weather events, and greater stress on ecosystems and human systems, compared to SSP2-4.5. While SSP2-4.5 includes some progress toward sustainable practices, SSP5-8.5 largely ignores sustainability in favor of economic growth driven by fossil fuels (Riahi, 2016; van Vuuren et al., 2017). These two scenarios represent contrasting futures, with the former assuming moderate progress in climate mitigation and the latter depicting a world with unchecked emissions growth. The choice between these scenarios is crucial for understanding potential climate impacts and informing policy decisions about climate change mitigation and adaptation. To explore these potential futures, four global climate models (GCMs) such as ACCESS-CM2, HadGEM3-GC3.1-LL, CNRM-CM6-1, and MIROC6 were selected from the Coupled Model Inter-comparison Project phase 6 (CMIP6). These models are commonly used in climate research to assess the potential impacts of greenhouse gas emissions under different scenarios on species distribution in order to provide valuable information for developing climate change mitigation and adaptation strategies (Peng et al., 2023). In addition, these models were selected because they were adapted for West African countries (Diawara & Lobanov, 2019) and were most used for West African species distribution modelling in recent studies by several authors (Coulilaly et al., 2023; Daï et al., 2023).

2.4. Data analysis

2.4.1. Data processing

To reduce sampling bias, the occurrence records were spatially filtered with a distance of at least 1 km between two trees using the function spatially rarefy occurrence data in SDMtoolbox through ArcGIS 10.8.1 software (Brown, 2017). This process enables to removal of all duplicate records within each grid. The processing of species data consisted mainly of cleaning the database (correction of species names, outliers, etc.) and converting it into the single CSV file format that is required by MaxEnt.

The 19 bioclimatic variables were extracted at the Burkina Faso scale in GeoTIFF format and converted into ASCII format before their use. All environmental variables were converted to ASCII raster grids ArcGIS 10.8.1. To determine which variables affected the distribution of the *D. microcarpum* species, all the environmental variables (soil variables, elevation and climate variables) were rather performed to remove highly correlated variables to avoid autocorrelation ($r < 0.75$) modelling. These variables also contribute to directly impacting the micro-climatic conditions that *Detarium microcarpum* experiences, which in turn determine its distribution, survival, and ability to cope with climate variability. In addition, the ecological condition of the species was considered. From the bioclimatic variables and elevation data, different sets of predictors were tested by accounting for different thresholds of the autocorrelation coefficient. Based on the value of the variance inflation factor (VIF), a correlation that quantifies how strongly a variable predictor was identified through the highly correlated variable with the package "sdm" (Naimi, 2015). Six variables were selected through the Pearson pairwise correlation coefficient of 0.75 (Naghipour et al., 2021). These variables were bio3 (Isothermality), bio8 (Mean Temperature of Wettest Quarter), and bio14 (Precipitation of Driest Month), Elevation, Cation exchange capacity (cec01 (0–5 cm)) and Cation exchange capacity (cec03 (15–30 cm)). Finally, a total of 722 presence records (CSV format) and the layers of the six environmental variables (ASCII format) were used as input data to run the model.

2.4.2. Model fitting and evaluation

The process of the modelling was based on the principle of maximum entropy (MaxEnt, version 3.3.3 k) (Phillips et al., 2006), considering only the occurrence data to predict the species' potential distribution from presence-only data and the different environmental variables. However, MaxEnt tools are one of the most powerful and widely used software programs for species distribution modeling (Elith et al., 2006; Pearson et al., 2007). In the region of West Africa, the MaxEnt algorithm was used by several authors (Achille et al., 2016; Dimobe et al., 2018; Balima et al., 2022) to assess the impact of climate change on the distribution of different plant species. To assess the importance of each variable in the model, the Jackknife test was applied (Phillips et al., 2006; Heubers et al., 2011; Guide & Brown, 2017). The area under the Receiver Operating Curve (AUC) and true skill statistics (TSS) were used to estimate the goodness of fit of the model performance (Pramanik et al., 2018). In fact, in the MaxEnt model, AUC estimation is slightly different from other common methods (Phillips et al., 2006). The AUC values range from 0 to 1, representing the model's ability to differentiate between classes effectively. The quality of the model could be assessed at the five levels according to AUC values (Rong et al., 2019): excellent (>0.9), good (0.8–0.9), accepted (0.7–0.8), bad (0.6–0.7), and invalid (<0.6) (Elith et al., 2006). A total of six environmental variables were selected for model prediction. According to some criticism about the limitations of the AUC index by ecologists in assessing SDM performance (Jiménez-Valverde et al., 2013), the True Skill Statistics (TSS) for better evaluation of the model (Allouche et al., 2006) were calculated as well. TSS serves as a metric evaluating a model's capacity to accurately identify genuine absences (specificity) amidst true positives (sensitivity). TSS was used because it is a simple but robust and intuitive measure of the performance of species distribution models (Lompo et al., 2021).

The following formula was used to calculate this index: $TSS = (ad - bc) / [(a + b)(b + d)] = \text{Sensitivity} + \text{Specificity} - 1$.

The value of the TSS varies from 0 to 1. If the value of the TSS < 0 indicates a random prediction, a value close to 1 ($TSS > 0.5$) suggests good predictive power (Allouche et al., 2006; Thuiller et al., 2009). However, if the TSS = 0, it suggests no skill at all. The model prediction is no better than random guessing. The TSS values were averaged for the 10 run replicates using the background predictions and the sample predictions of the MaxEnt outputs. In addition, the model performance was assessed by dividing the occurrence data at 75 % for calibration and 25 % for testing. To reduce overprediction and focus on the most suitable areas, the 10th Percentile Training Presence is used like the Threshold method (Radosavljevic & Anderson, 2014).

2.4.3. Assessing the area suitability of the species

To propose relevant conservation and some measures on the species, three categories of area classes were considered from the modelling output such as the unsuitability; low suitability and high suitability through the polygonising of the raster files. A jackknife test was performed on the selected bioclimatic variables to determine the ones that best contribute to the model prediction (Berlioz et al., 2021). The probabilistic outputs were transformed into presence/absence classifications, utilizing the mean of predicted probabilities as the threshold to delineate the species' range (Lawson et al., 2014; Dimobe et al., 2022). The probability occurrence below the Maximum training sensitivity plus specificity is considered unsuitable for the conservation of the species. This threshold is chosen to maximize the alignment between observed and predicted distributions. For the habitat suitability class maps, the final logistic output was categorized into the following classes: (i) Unsuitability, (ii) lowly suitable, and (iii) highly suitable using the spatial analysis toolset in ArcGIS® software. The overlapped current and future habitat suitability maps within the country polygons were first assessed. In addition, the suitable area (km^2) colonized by the species using the spatial analysis tools in ArcGIS was computed. The percentages of potential habitat suitability were calculated.

3. Results

3.1. Bioclimatic variables contributions and model validation

The result of the MaxEnt output presented six (6) variables that highly contributed to the distribution of the *Detarium microcarpum*. Among these variables, Isothermality (bio3), Mean Temperature of Wettest Quarter (bio8), Precipitation of driest month (bio14), cation exchange capacity at 0–5 cm (cec01), 15–30 cm (cec03) horizon, and the elevation influence the distribution of the species (Table 1). The variable Bio8 contributed most to the model while the variable cec01 (cation exchange capacity at 0–05 cm horizon) contributed the least.

The Area Under the receiver operating characteristic Curve (Fig. 2) showed good accuracy with a mean AUC of 0.845 which is better than random (0.5) indicating the high capability of the models. This value of AUC indicates the very good quality of the model for predicting the spatial distribution of the *Detarium microcarpum*. The value of the TSS is 0.7. This value > 0.5 confirms the best performance of the model.

The results of the Jackknife tests (Fig. 3) showed that the dominant environmental variable which influenced the distribution of *D. microcarpum* is the Mean Temperature of the Wettest Quarter (bio8) compared to the other variables. For every prediction variable analysed, the green bar represents the decrease in total gain when excluding that particular variable from the model. The blue bar illustrates the gain achieved by using only the variable in question, with all other variables excluded. Conversely, the red bar signifies the gain realized through the inclusion of all variables in the model.

3.2. Current and future distribution of *d. Microcarpum*.

The current potential distribution of *D. microcarpum* shows that the Sudano-Sahelian and the Sudanian zones are the most suitable zones (Fig. 4). Currently, up to 180,700 km² corresponding to 65.5 % of the country are the suitable distribution areas of the species (Appendix 2). Besides, 100,732.2 km² corresponding to 36.74 % of the country represent currently highly suitable habitats for species conservation (Fig. 5). The low suitable areas under current climatic conditions for *D. microcarpum* conservations cover 79,968.2 km² corresponding to 29.16 % of the country's territory. However, 93,499.52 km², which corresponds to 34.099 % of the national territory, is revealed as unsuitable.

Under future climate conditions projection for 2061–2080 (average 2070) and 2081 – 2100 (average 2090) years, the suitable habitats designated for conservation will increase because highly suitable areas will be reduced according to the models ACCESS-CM2, CNRM-CM6–1, HadGEM3-GC31-LL and MIROC6 respectively for the two scenarios with the conversion of high suitable areas into low suitable areas with a different partition. In addition, a reduction in unsuitable areas was recorded as a result of their conversion to moderately suitable areas (Fig. 5, Appendix 2).

In the MIROC6 model (Fig. 5), the suitable areas were 73.55 % and 73.15 % at the country level at the horizon 2070 and 2090 respectively with the conversion of the high suitable area to the low suitable area

under scenario SSP2-4.5 (Appendix 2). However, when considering the scenario SSP5-8.5 in the same model, the highly suitable areas were observed to increase for the benefit of the low-suitable areas. In addition, among the four models, the most habitat loss was expected in scenario SSP2-4.5 than the scenario SSP5-8.5.

Based on the Fig. 5 observation, the suitable area for the species conservation was mainly located in the Sudano-Sahelean climatic zone. Low Suitability areas for *D. microcarpum* will generally increase at horizon 2061–2080 and 2081–2100 under the two scenarios SSP2-4.5 and SPP5-8.5 regardless of the model. According to the future projection, the suitable areas for *D. microcarpum* differ according to the four SSP scenarios. However, unsuitable areas become low suitable areas under the two scenarios according to the four models. The findings of this study showed the trend of low suitability will increase compared with the current distribution of the species. In both scenarios of the CNRM-CM6–1 model (Fig. 5), the highly suitable areas were expected to be lost. For instance, the distribution of the species for the two scenarios of the ACCESS-CM2 (Fig. 5) was expected to increase from 4.867 % to 9.978 %. For the SSP2-4.5 and SSP 5–8.5 respectively, future projections showed a high increase in low suitable habitats for the species with the decline of the high suitable areas.

Comparing the potential distributions of current and future scenarios for all models, the high suitable area was expected to decrease for the benefit of the low suitable and unsuitable area at the country level (Fig. 5, Appendix 2 and 3). The analysis showed a decrease of highly suitable habitats for the species for all the models except the scenario SSP5-8.5 of the MIROC6 (Fig. 5; Appendix 2 and 3) model which observed the increase in a suitable area.

4. Discussion

4.1. Model performance and variable contribution

The result of this study showed that the bioclimatic variables (Mean Temperature of the Wettest Quarter (bio8) and Isothermality (bio3)) contributed more to the distribution of *D. microcarpum* than other variables. This finding showed that temperature is a crucial factor which impacts the distribution of *D. microcarpum*. This is underlined with Bueno *et al.*, (2017) who pointed out that the temperature influences the savanna species distribution. In addition, this investigation has reported that average temperature for the wettest quarter (bio8) and Isothermality (bio3) are the main environmental predictors which most affected the current distribution of *D. microcarpum*. As reported by Agbo *et al.* (2018), the influence of the two bioclimatic variables (bio3 and bio8) shows that water availability and low temperature might remarkably alter *D. microcarpum* seed germination and regeneration, plant height and cover, leaf area, phenology, pollination, reproduction, dispersal of propagules, and physiological processes like photosynthesis. Consequently, the future distribution area of the species is expected to increase in the Sudano–Sahelian climatic zone than in the Sudanian zone. As Sinadouwirou *et al.* (2023) explain in their research, these bioclimatic variables influence significantly the species distribution patterns, shaping various aspects of ecological dynamics. In addition, these variables (bio8 and bio14) combined with the capacity exchange cation at the different scales affected the distribution of *D. microcarpum*. Moreover, Ibdohou *et al.* (2017); Guidigan *et al.* (2018); and Dimobe *et al.* (2020) pointed out that climatic factors and soil texture determine the ecological zone of the species. The output of the model found a good performance (AUC > 0.8 and TSS > 0.6). These findings suggest that the MaxEnt algorithm effectively captures variations in environmental data, indicating its good performance (Araújo *et al.*, 2005).

The findings of this study show that, the elevation influence significantly the natural habitat of *D. microcarpum*. This is underlined with the conclusion of Cavin (2007b), Lamy *et al.* (2021), and Houénon *et al.* (2022) who showed that *D. microcarpum* is an altitudinal species which could be found on the laterite and the granitic zone. However, the

Table 1
Contribution of bioclimatic variables used for model running.

Variable	Variable definition	Percent contribution (%)
Bio8	Mean Temperature of Wettest Quarter	59
Bio3	Isothermality ((Bio1/Bio3) *100)	25.3
Elev	Elevation	9.9
Bio14	Precipitation of Driest Month	3.2
cec03	Cation exchange capacity (cec) horizon 15–30 cm	1.5
cec01	Cation exchange capacity (cec) horizon 0–5 cm	1.2

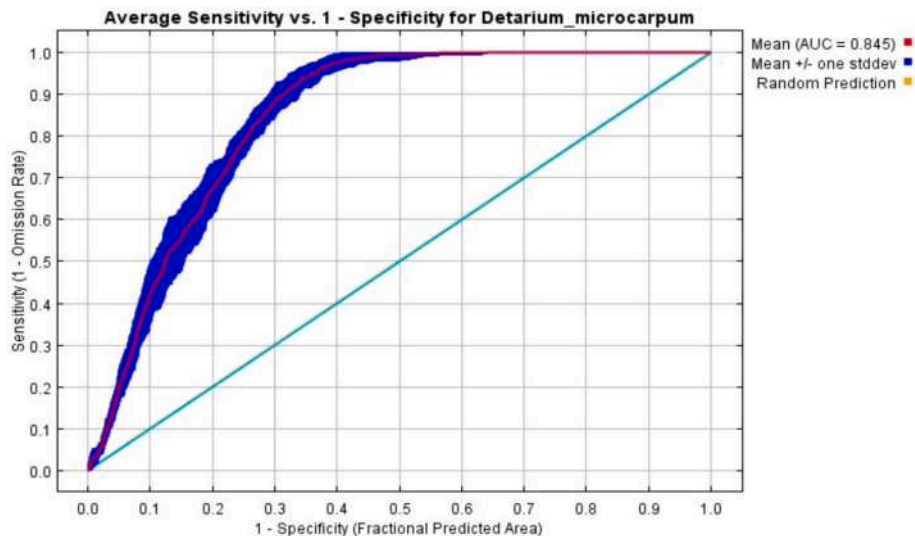


Fig. 2. Average receiver operating characteristic curve and related AUC.

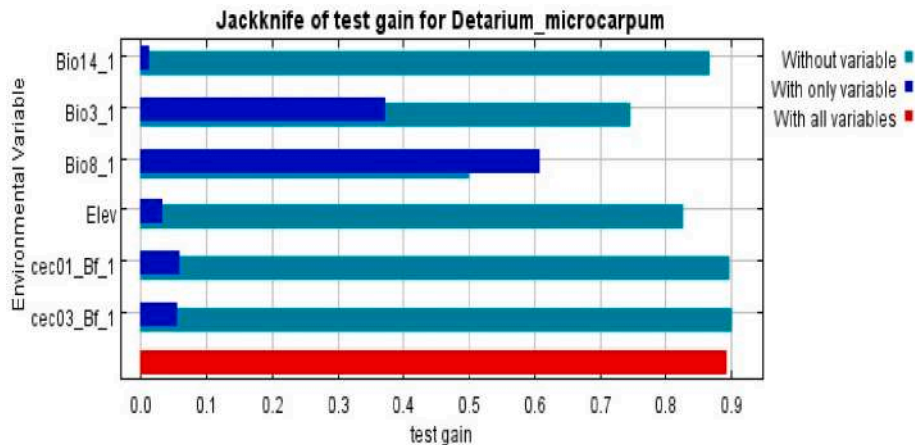


Fig. 3. Results of a jackknife test for regularized training gain for *Detarium microcarpum* Noted: Bio14_1: Precipitation of Driest Month, Bio3_1: Isothermality ((Bio1/Bio3) *100), Bio8_1: Mean Temperature of Wettest Quarter; Elev = elevation (slop), Cec01_Bf_1: cation exchange capacity (cec) horizons 0–5 cm, Cec03_Bf_1: cation exchange capacity (cec) horizons 15–30 cm.

integration of the elevation and cation exchange capacity variables in the process increases the model performance functionally and more accurately (Agbo et al., 2018) and the development of the species. Indeed, Lamy et al. (2021) and Michel et al., (2023), explained that the elevation influences the distribution of the savanna species. Besides, Agbo et al. (2018) showed that *D. microcarpum* species prefers the soil which is rich in cation exchange capacity. In addition, *D. microcarpum* is generally grown in warm and sub-arid regions with temperature and rainfall ranges of 25 to 37°C and 600 to 900 mm/year respectively (Taonda et al., 2024a; Taonda et al., 2024b) and this finding is underlined with the known climatic preferences of the species (Sinadouwirou et al., 2023). This could affect its ability to establish new seedlings and may lead to dieback in areas where it currently grows (Kataoka et al., 2020; Gao et al., 2022; Yebeyen et al., 2022). Identifying the dominant environmental variables that affect species distribution provides a better indicator for understanding the effects of global change on species suitability and its suitable management (Xie et al., 2022, Wang et al., 2023).

4.2. Potential effects of the current and future climate on the distribution of *d. Microcarpum*

The distribution of the species showed a general pattern, although there were some differences in the extent of habitat loss according to the model. The four climate models showed different levels of habitat loss within each horizon and each emission scenario. The current suitable habitat of *D. microcarpum* is 65.5 % of the country area and 29.16 % is revealed to be low suitable for the species conservation. Indeed, the prediction of the current distribution of *D. microcarpum* showed that the species is widespread in two climatic zones (Sudanian and Sudano-Saharan). In the literature review coupled with the ecological observation, the species were not found in the Sahel climate zone (Schmidt et al., 2017). As part of the current distribution, the fundamental niche of the species is larger than the realized niche and some suitable habitats were located in some areas where the species is not currently predicted. This observation corroborates with Lompo et al. (2021) and Dai et al. (2023) explained that the fundamental niche is larger than the realized niche and is the future environmental conditions favourable for species conservation (Fandohan et al., 2015; Mellert et al., 2015; Coulibaly et al., 2023). Some areas may become suitable for this species' conservation in favour of the highly suitable area.

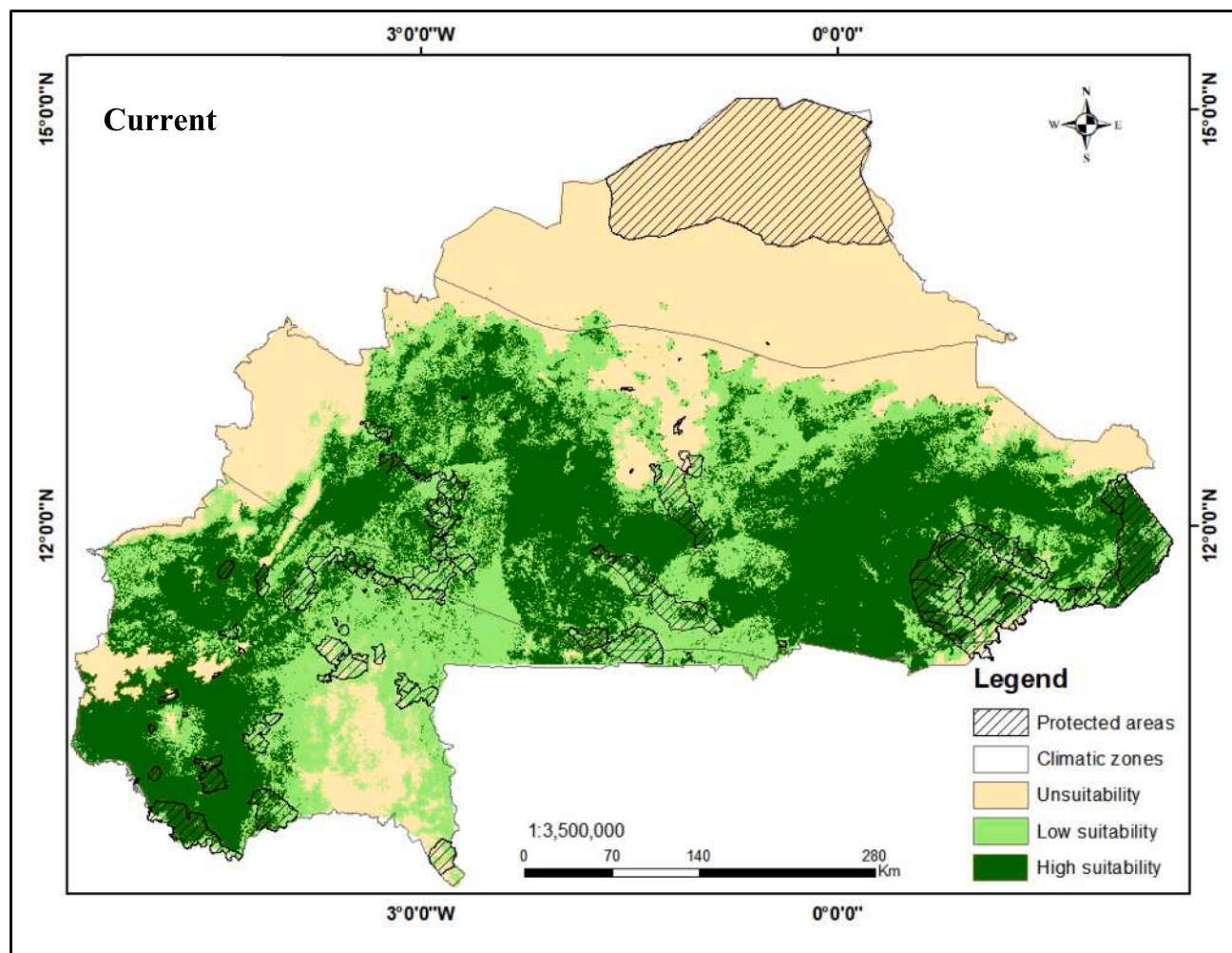


Fig. 4. Maps showing the current distribution of *Detarium microcarpum*.

The future predictions indicate that climate change will affect the distribution of *D. microcarpum*, resulting in a decrease in highly suitable habitats throughout the country. Although the ACCESS-CM2, CNRM-CM6-1, and HadGEM3-GC31-LL model with the type of the scenario predict a significant regression of the high suitable area in aid of low suitable habitats area of *D. microcarpum*. The expansion of low-suitable habitat is predicted to increase in all scenarios compared to the current area.

However, there are variations in trends depending on the model and scenario. The prediction of species distribution under future climate conditions in West Africa, as shown by studies such as Idohou et al. (2017), Agbo et al. (2018), Lompo et al. (2021), Balima et al. (2022), Dimobe et al. (2020, 2022), and Dai et al. (2023), highlights the variation in the distribution of savanna species. The future projection suggests that suitable habitats for *D. microcarpum* will shift, with low-suitability areas increasing and suitability-high-suitability areas decreasing. Ma and Sun (2018) and Wouyou et al. (2022) pointed out that the loss of suitable habitat can directly reduce the distribution of species like *D. microcarpum*. This decline can be further intensified by human activities like deforestation and land conversion, which amplify the impacts of climate change. This situation may be due to fluctuations in precipitation and temperature variables, which are predicted to change in projected SSPs (Mkala et al., 2023). However, the findings from the SSP5-8.5 scenario under the MIROC6 model indicate an increase in suitable and highly suitable areas for *D. microcarpum*. These results align with previous studies that have suggested a positive impact of climate change on the distribution of *Parkia biglobosa* in Mali

(Coulibaly et al., 2023) and *Pterocarpus erinaceus* in West Africa under climate threat (Adjonou et al., 2020). In contrast, other research by Balima et al. (2022) and Dimobe et al. (2022) has shown that future climate conditions are likely to reduce the suitable areas for *Azelia africana* and *Pterocarpus erinaceus* in the sub-arid savanna, as predicted through the MaxEnt approach. This indicates that *D. microcarpum* should show a latitudinal and longitudinal shift in its current range in response to climate change. In addition, the regressive trends of *D. microcarpum* suitable habitats suggest the threat of the climate will have an adverse impact on the habitat distribution which is already threatened by its multipurpose uses (Agbo et al., 2017; Dossa et al., 2020; Leakey et al., 2022). Previous modeling studies in West Africa suggest that climate change is one of the most important factors that affect habitat losses which increases the decline of the species (Rey & Carlos, 2014; Peng et al., 2023). The reduction of suitable habitats for this species at the 2070 and 2090 horizon could be linked to the type of model. Fandohan et al. (2015) and Dimobe et al. (2020) made the same observation of the distribution of *Chromolaena odorata* and *Vitellaria paradoxa* respectively using the HadGEM2-ES and MIROC5 under CMIP5. The future range of the species under future climate projections could be explained by significant changes in precipitation and temperature, which are the key drivers of species distribution (Thiombiano et al., 2006; Bellard et al., 2012; Brown et al., 2016). The differences observed in the species distribution would depend on the future climate conditions and could be attributed to the local differences in the change predicted by each climate model (Balima et al., 2022; Çoban et al., 2020).

In contrast, the expected shift of the geographical range of

D. microcarpum in the Northern part of the country under the model MIROC6 in Scenario SSP5-8.5 is probably due to the humid and moderate climatic conditions with increasingly frequent precipitation events area. However, the area average precipitation is expected to increase by 8.5 % and 15.2 % respectively for SSP2-4.5 and SSP5-8.5 under the CMIP6 model in Africa (Almazroui et al., 2020; Ama et al., 2021). Several previous studies have suggested that climate change might affect *Lebrunia bushaie* Staner (Clusiaceae) distribution Imani & Won, (2023) *Lebrunia bushie* in RDC, Coulibaly et al., (2023) for *Bombax costatum* in Mali, Vihotogbé et al., (2021) for *Mondia whitei* in Benin. Jean et al. (2017) Highlighted that a specific species may be predicted to be extinct by some climate models, whereas other models suggest it could survive due to habitat loss or range expansion. The expansion of suitable areas indicates that projected climatic conditions could benefit some species found in savanna regions. Mirhashemi & Ahmadi, (2024) explain that the extent of habitat changes is determined by a species' ability to adapt to the climatic conditions of the new environment.

4.3. The implication of the study for species conservation

This research explores the impact of climate change, as modelled under CMIP6, on the distribution of *Detarium microcarpum* across the country. The distribution patterns differed significantly among the four climate models across two emission scenarios (SSP2_4.5 and SSP5-8.5) and two-time horizons (2061–2080 and 2081–2100). The findings of this study aligned with previous research such as Fandohan et al., (2013), Guidigan et al. (2018), Agwu et al. (2020), and Issoufou et al. (2022), Mirhashemi & Ahmadi, (2024) shows that climatic variables, along with factors such as model type, soil type, elevation, and human impact, influence species distribution. Consequently, bioclimatic projections suggest that *D. microcarpum* should experience a slight loss of highly suitable habitats but gain areas of moderate suitability by 2070

and 2090 under the two scenarios. Meanwhile, unsuitable habitats are expected to transition to low suitability. These findings are consistent with previous studies on similar species in Africa, such as *Kigelia africana* in Benin (Guidigan et al., 2018) and *Azelia africana* in Burkina Faso (Balima et al., 2022).

Interestingly, under the SSP5-8.5 scenario, the MIROC6 model predicts an increase in suitable areas for *D. microcarpum* in Burkina by 2090. The predictions of the future distribution suggest that areas highly favourable to *D. microcarpum* will revert to areas less favourable under the different scenarios tested. However, these variations highlight the discrepancies among global climate models and the challenges posed by model uncertainties, influenced by factors such as modeling techniques, constructed model processes, and uncertainties in climate scenarios.

These insights underline the potential effects of future climate warming on *D. microcarpum*, exacerbated by habitat destruction from human activities and natural disasters (Agwu et al., 2020; Dimobe et al., 2022). In addition, determining the factors which influence the species' distribution is useful knowledge for conservation and management efforts (Radha & Khwarahm, 2022; Hama & Khwarahm, 2023), as well as for the related biodiversity of the multipurpose species across the country. The application of this study offers significant advantages in identifying priority zones for *D. microcarpum* conservation. The result of this study suggests that applying modeling techniques, such as MaxEnt offers significant benefits in establishing priority zones for biodiversity conservation. These models improve the accuracy of identifying critical habitats by integrating environmental and climatic data, allowing for precise species distribution predictions (Mirhashemi & Ahmadi, 2024). These models enable the precise mapping of current and future distribution patterns, providing insights into the species' ecological requirements and potential shifts due to climate change. They also enable the projection of future suitable areas of *D. microcarpum* under various climate scenarios, helping to allocate conservation resources more

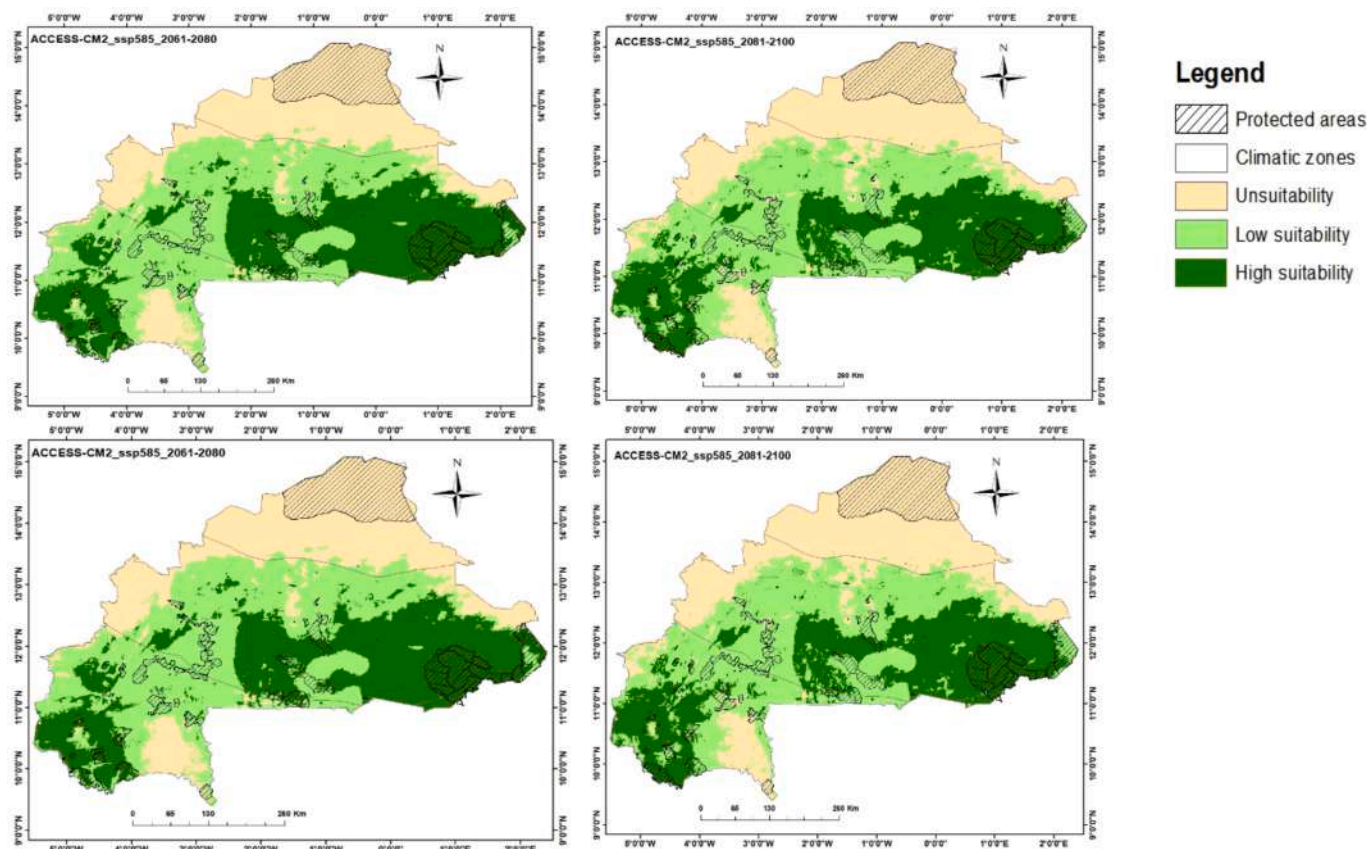


Fig. 5. Future distribution of *Detarium microcarpum* under the different models tested.

efficiently. This allows conservation planners to prioritize these stable habitats as key zones for protection (Ararat et al., 2023). The integration of these modeling approaches with existing biodiversity data facilitates the creation of comprehensive conservation strategies (Agwu et al., 2020). By simulating various climate scenarios, these techniques can predict areas that are likely to remain suitable area for *D. microcarpum* in the future, even as environmental conditions change. This allows conservation planners to prioritize these stable habitats as key zones for protection (Boria et al., 2014; Mkala et al., 2023). This research is an invaluable tool in the conservation of *D. microcarpum*, providing a scientific basis for prioritizing areas that are crucial for the species' survival and for maintaining overall biodiversity in the face of ongoing environmental changes. In addition, it provides a scientific basis for decision-making, these models facilitate collaboration among stakeholders involved in conservation efforts. Several strategies such as mitigating the impacts of human activities and climate change, preserving biodiversity, and ensuring the sustainable use of *D. microcarpum*, in the socioeconomic context of Burkina Faso through a specific action. These specific actions could include establishing protected areas, community-based forest management, climate-resilient agroforestry, restoration and reforestation programs, and research and monitoring. Indeed, it is essential to examine the specific threats facing this species

such as deforestation, habitat loss, land conversion, agricultural expansion, overexploitation, and altered fire regimes and to develop strategies for mitigating these threats to ensure its conservation. The results of this study aligned with the idea of Radha & Khwarahm, (2022) which showed that the management actions of the species require detailed categorized maps of the target species that will possibly convince policymakers.

5. Conclusion

This study estimates the potential range of *Detarium microcarpum* under current, and future climate conditions by 2061–2080 and 2081–2100. The current suitable habitats of the species were 65.5 % across the country total area. The results of this study show that the species should be found in the Sudano-Sahelian climate in response to climate change with the conversion of the highly suitable and unsuitable areas to low suitable areas. Under climate change scenarios, the *D. microcarpum* climatic niche will be geographically reduced from south to north across the country. Overall, this study provides important empirical knowledge to guide the conservation and sustainable cultivation of *D. microcarpum* resources in the future.

The suitable area identified through this study would help to

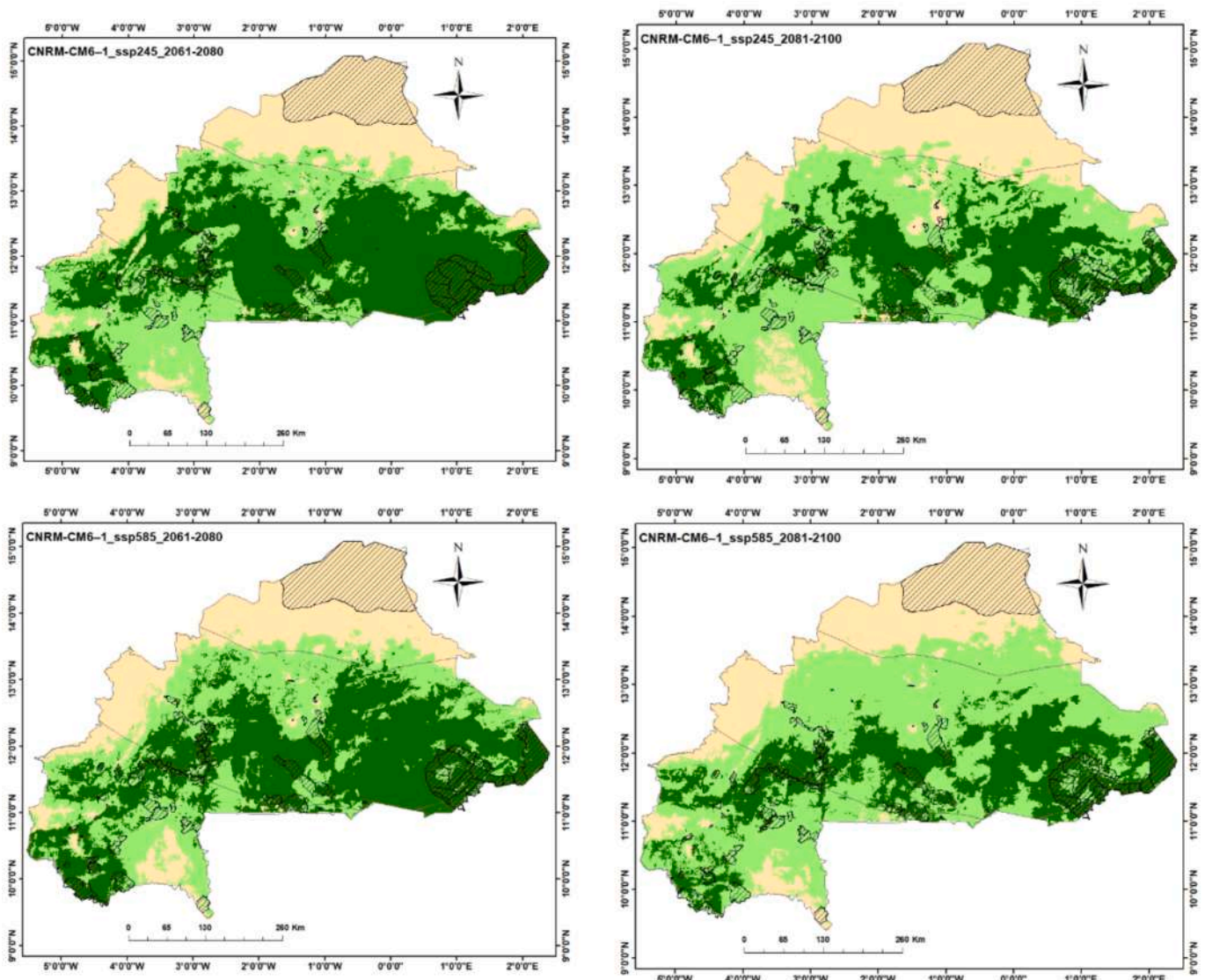


Fig. 5. (continued).

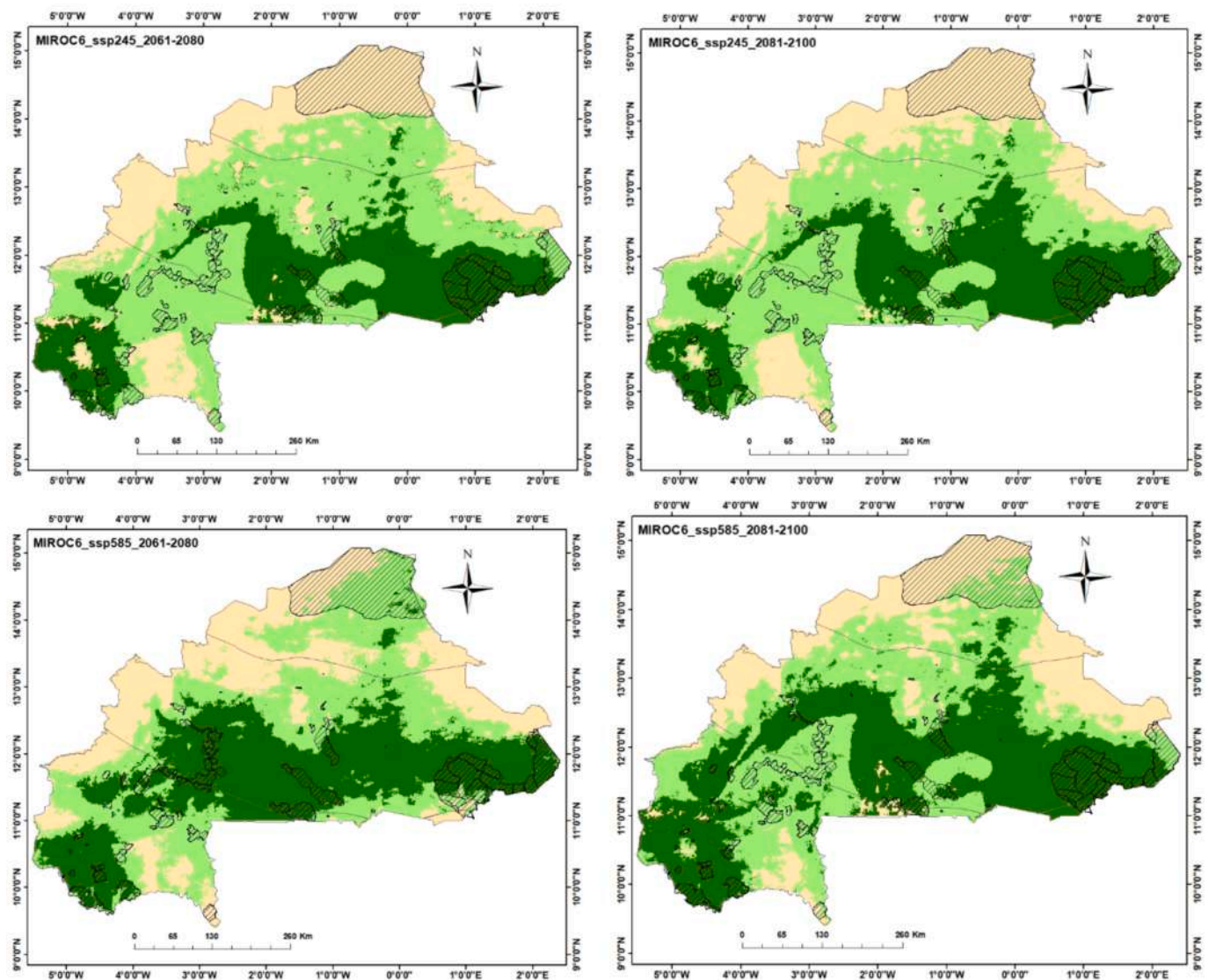


Fig. 5. (continued).

improve the conservation status of *D. microcarpum* across the country. Improving the knowledge of the climate projections effect on the species is essential to inform decision-makers to improve the political guidelines for species conservation. This research offers vital insights for forest management and serves as an important alert for preserving biodiversity in regions where specific species could be at risk of extinction in the future. By accurately forecasting the temporal and spatial shifts in the range of *Detarium microcarpum* within its natural habitat, the study highlights the need for proactive conservation strategies. Modeling application combined with geospatial analysis emerges as an effective approach for evaluating species distribution patterns across different regions and periods in Burkina Faso. In addition, to ensure accuracy in determining a distribution area, it would be advisable to compare these results with other models, such as RF, GAM, GLM, and Ensemble Suitability Models; Investigating how shifts in the distribution of *Detarium microcarpum* impact its interactions with other species.

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CRediT authorship contribution statement

Taonda Adama: . **Issouf Zerbo**: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Sie Sylvestre Da**: Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Innocent Charles Emmanuel Traoré**: Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Anny Estelle N'Guessan**: Visualization, Software, Investigation, Formal analysis, Data curation, Conceptualization. **Justin N'Dja Kassi**: Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Adjima Thiombiano**: Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

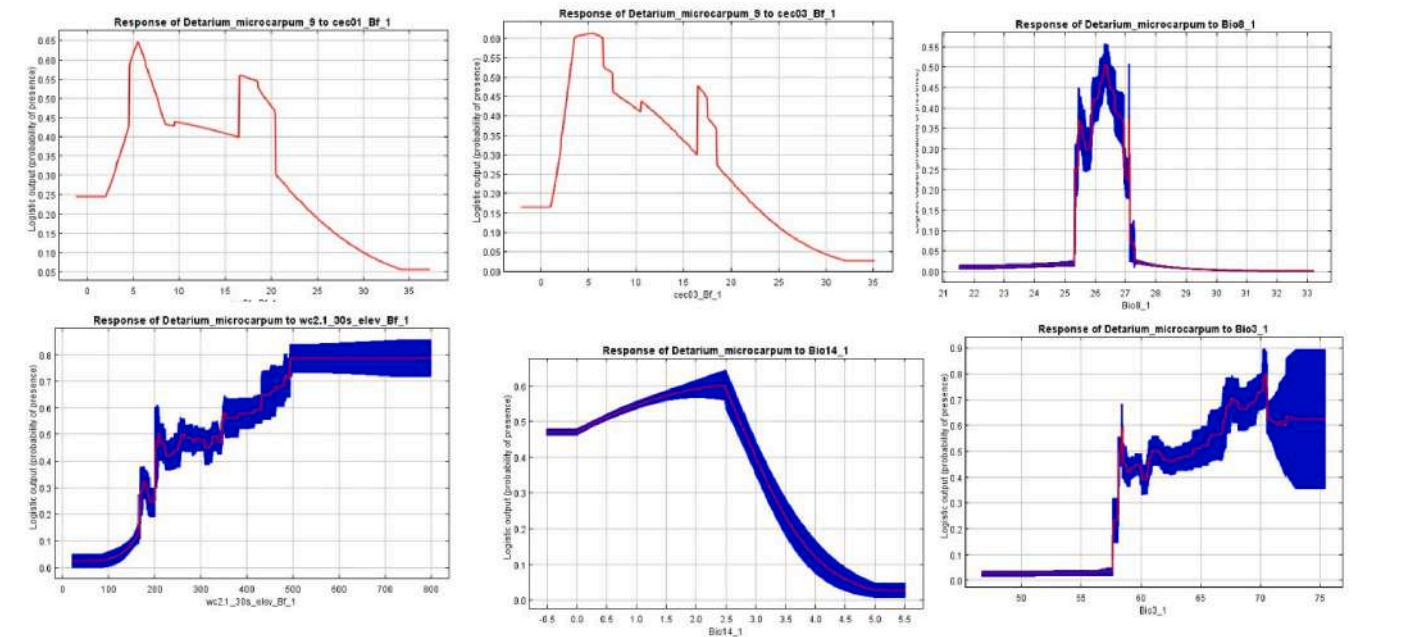
Data will be made available on request.

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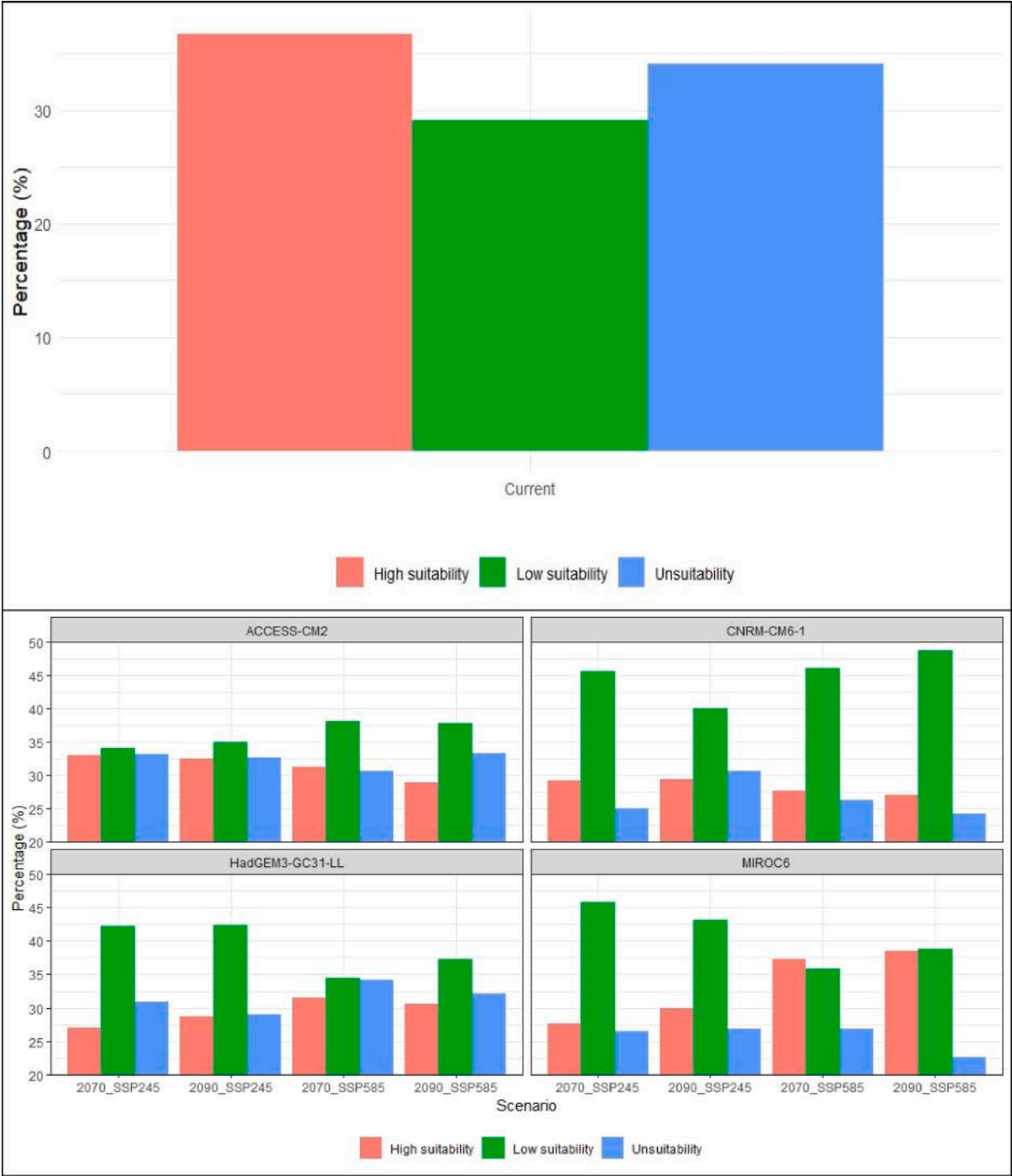
Appendix 1. . Response curves of the variables used to model the distribution of *d. Microcarpum*



Appendix 2. . Current and future trend *d. Microcarpum* in Burkina Faso

Model	Scenarios SSP	Horizon	Unsuitability		Low Suitability			High Suitability			Total suitability		
			Extent (Km ²)	%	Extent (Km ²)	%	Trend (%)	Extend (Km ²)	%	Trend (%)	Extend (Km ²)	%	Trend (%)
Current			93,499.53	34.1	79968.28	29.16		100732.2	36.74		180700.48	65.5	
ACCESS-CM2	245	2061–2080	90,703.13	33.08	93,286.29	34.02	4.86	90,210.58	32.89	−3.84	183,496.87	66.91	1.41
	245	2081–2100	89,342.56	32.58	95,718.08	34.91	5.74	89,139.36	32.51	−4.22	184,857.44	67.42	1.92
	585	2061–2080	83,794.09	30.56	10,4587.3	38.14	8.979	85,818.63	31.3	−5.43	190,405.93	69.44	3.94
	585	2081–2100	91,367.11	33.32	10,3586.3	37.78	8.61	79,246.6	28.90	−7.83	182,832.9	66.68	1.18
CNRM-CM6–1	245	2061–2080	68,743.38	25.07	125,169.7	45.65	16.49	80,286.88	29.28	−7.46	205,456.58	74.93	9.43
	245	2081–2100	83,986.42	30.63	109,717.6	40.01	10.85	80,495.94	29.36	−7.38	190,213.54	69.37	3.87
	585	2061–2080	72,021.46	26.27	126,251	46.04	16.88	75,927.55	27.69	−9.05	202,178.55	73.73	8.23
	585	2081–2100	66,546.57	24.27	133,687.7	48.77	19.59	73,965.72	26.96	−9.76	207,653.42	75.73	10.23
HadGEM3- GC31-LL	245	2061–2080	84,416.25	30.79	115,838.9	42.25	13.08	73,944.81	26.97	−9.77	189783.71	69.22	3.72
	245	2081–2100	79,403.81	28.96	116,186.8	42.37	13.21	78,609.38	28.67	−8.07	194796.18	71.04	5.54
	585	2061–2080	93,666.78	34.16	942,77.23	34.38	5.218	86,255.99	31.46	−5.28	180533.22	65.84	0.34
	585	2081–2100	88,183.53	32.16	102,279.2	37.30	8.14	83,737.22	30.54	−6.2	186016.42	67.84	2.34
MIROC6	245	2061–2081	72,513.17	26.45	125,868	45.90	16.74	75,818.84	27.65	−9.09	201686.84	73.55	8.05
	245	2081–2100	73,629.55	26.85	118,524.9	43.23	14.06	82,045.5	29.92	−6.82	200570.4	73.15	7.65
	585	2061–2080	73,418.82	26.78	98,503.61	35.92	6.76	102,277.6	37.30	0.56	200781.21	73.22	7.72
	585	2081–2100	62,163.82	22.67	106,631.9	38.89	9.73	105,404.3	38.44	1.70	212036.2	77.33	11.83

Appendix 3. . Dynamic of the suitable areas for *d. Microcarpum* in the present and the three future scenarios



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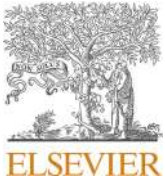
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Publication 4



Allometric models for estimating aboveground biomass and carbon stocks of the semi-arid savanna woody species, *Detarium microcarpum* Guill. et Perr.

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ABSTRACT

Quantification of plant biomass and carbon is critical for the savanna species. The lack of accurate biomass tools is a challenge for the savanna species. Information on allometric equations is limited for *Detarium microcarpum* species. This study aimed to develop an allometric equation for the aboveground biomass of *D. microcarpum* across the two climatic zones. A total of 60 trees were considered using the destructive method. Three equations were tested with a diameter at the breast (dbh) alone, height (ht) as additional (dbh*ht), and diameter in combination with height (dbh²*ht) as predictors using log-transformed data with a power function. Their performance was assessed with the adjusted R-square (Adj.R²), Akaike Information Criteria (AIC), correction factors (CF), and the Root Mean Square Error (RMSE). The performance of the validated allometric models was compared with the generalized pantropical equation (Chave et al., 2014). The results revealed that the diameter is a good predictor in the Sudano-Sahelian zone and for branches and leaves biomass estimates in the Sudanian zone. The stem requires ht with the dbh (dbh²*ht) in the Sudano-Sahelian zone.

The allometric models established to predict *D. microcarpum* biomass were
TAGB = $e^{4.4002} (dbh*dbh*ht)^{0.9456} + e^{-3.5219} (dbh)^{2.4007} + e^{-2.8845} (dbh)^{1.3465}$ in the Sudanian zone
and TAGB = $e^{-4.1053} (dbh)^{2.4222} + e^{-5.2567} (dbh)^{2.9539} + e^{-2.9894} (dbh)^{1.5285}$ for the Sudano-Sahelian climatic zone. The equations developed in this study are useful tools for assessing the aboveground biomass and the carbon of the savanna multipurpose species.

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Introduction

Forests and savannas serve as vital carbon sinks, playing a crucial role in mitigating global warming through sustainable practices. Their conservation is recognised as a key strategy in addressing the escalating challenges posed by climate change [1–3]. Forest ecosystems are instrumental in the global carbon cycle, absorbing CO₂ during photosynthesis and storing it in both above and belowground biomass [4]. By capturing atmospheric carbon through photosynthesis, trees and forests help decrease greenhouse gas concentrations and contribute to climate regulation [5]. Accurate biomass estimations are paramount for evaluating a species' carbon sequestration capacity, a fundamental component of effective climate change mitigation strategies and sustainable land management [6,7].

Mitigation efforts encompass enhancing carbon storage, promoting sustainable ecosystem management, and conserving biodiversity [8]. Over the past decade, the significance of carbon assessment through biomass has grown, partly due to the emergence of market-based incentives for afforestation and reforestation as climate change solutions [9]. However, the imprecision of biomass estimates is a shortcoming in the assessment of plant species [10]. Estimating carbon stored in forests is also crucial for gauging their mitigation effectiveness against global change and forecasting the outcomes of carbon emission reduction initiatives [11].

To address these challenges, allometric equations are employed for efficient biomass estimation [12]. Nonetheless, the methodology chosen for biomass estimation can significantly influence the accuracy of the results [13]. Human-induced disturbances complicate the application of generalized models for estimating the biomass of savannah and multipurpose species. Despite these complexities, the Paris Agreement (COP21) has underscored the importance of forest and agricultural landscapes in mitigating greenhouse gas emissions [14]. Post-COP21, numerous countries have endeavoured to refine carbon assessment methodologies. To achieve this, precise biomass estimates remain elusive in many African tropical regions due to the difficulty in collecting field data for developing suitable models for individual tree biomass prediction in species-rich ecosystems [15]. Ecological conditions, particularly climate, significantly affect the applicability of allometric equations [16].

Enhancing the nation's climate data requires creating predictive models that could accurately estimate biomass. At present, the contribution of each species to climate change mitigation and carbon sequestration is unclear, often inaccurately represented due to reliance on specific allometric models for biomass and carbon calculations [10,17,18].

Accurate biomass estimation can also contribute to understanding the ecosystem's long-term structure and functionality, potentially enhancing ecosystem services [15]. However, these estimations can be achieved through direct, indirect, or remote sensing methods, each with its advantages and limitations. Many approaches are grounded in relationships between plant components [19–21], yet these models frequently neglect considering the density within individual components, posing a significant drawback. Consequently, indirect methods like biomass estimation equations, geographic information systems, or remote sensing have been developed to circumvent the shortcomings of direct methods [22]. The indirect method is often used for taller trees [23]. The disadvantage of these methods is that the relationships between the indirect attribute and biomass are generally limited to the specific time and place where the preliminary data was collected [24]. In addition, the result of the indirect method needs to be validated by the direct method [25]. The local allometric equations are crucial for precisely determining forest biomass, enabling the country to leverage carbon market opportunities [26] and enhance biomass estimate precision.

Three-based methods, such as the destructive method [10,27–30], indirect (non-destructive) methods [31–33], and remote sensing techniques [14,34] are commonly used to measure woody biomass. While each method offers unique benefits and challenges, the development of specialized allometric equations for biomass estimation remains limited, especially for African semi-arid savannah species. Examples include *Azvelia africana* [27], *Pterocarpus erinaceus* [28], *Vitellaria paradoxa* [32], *Balanites aegyptiaca* [18], *Diospyros mespiliformis* [18], *Jatropha curcas* [35], *Senegalia dudgeonii*, *Senegalia gourmaensis*, *Vachellia nilotica*, and *Vachellia tortilis* [36] in Burkina Faso, *Jatropha curcas* L. [16]; *Sclerocarya birrea* (A.Rich) Hoscht and *Boscia senegalensis* (Pers.) Lam. ex Poir [37] in Senegal, *Faidherbia albida* (Delile) A.Chev. and *Prosopis africana* Guill. & Perr. Taub. [38] in Niger. However, the reliability of these global models is debatable, as allometric models are highly influenced by site-specific abiotic conditions and the structural traits of the species [7,16,39]. Despite these efforts, the carbon storage potential of several multipurpose species, including *Detarium microcarpum*, remains underestimated.

However, the overexploitation of *D. microcarpum* species coupled with the bush fire affected the dynamic of the species which could affect its ecosystem services provision capacity such as carbon sequestration. In addition, forest fragmentation through illegal exploitation and extensive agriculture is the most significant threat to the multipurpose species in Burkina Faso [40]. The natural stand of the *D. microcarpum* has been strongly influenced by human impacts which contribute to their decline [41]. Despite the scientist's interest in *D. microcarpum* species in Burkina Faso, few studies have been made to assess the species' biomass and carbon sequestration. Given this consideration, it is important to develop accurate estimates of Carbon stored by *D. microcarpum* individual trees in their natural stand. Thus, developing tools for estimating the above-ground of *D. microcarpum* as the savanna multipurpose species within these savannas is useful for determining their contribution to climate change mitigation. In addition, Knowledge of above-ground biomass is essential for understanding the role of this savanna multipurpose species in carbon sequestration and climate change mitigation, as well as their contribution to the production of non-timber forest products [42,43]. The development of the species allometric models will significantly improve the quality of biomass estimates at the country level for the international carbon market. Hence, the interest of this work is to provide quantitative data on the carbon potential of *D. microcarpum* to better understand their contributory role in mitigating the adverse effects of global warming in Burkina Faso. The present study aimed to develop an allometric equation for the aboveground biomass estimation and carbon-sequestered of *D. microcarpum* species in their natural stand in Burkina Faso. To achieve this objective, we hypothesise that the aboveground biomass of *D. microcarpum* is related to dendrometric parameters in their natural stand.

Materials and methods

Study area and study species

This investigation took place across four protected areas (PAs) in Burkina Faso, spanning two distinct climatic zones: the Sudano-Sahelian zone, home to the Nazinga Game Ranch (NGR) and the Nakambe Classified Forest (NCF), and the Soudanian zone, housing the Wildlife Reserve of Bontioli (WRB) and the Kou Classified Forest. These locations were chosen due to the presence of the target species (Fig. 1).

The vegetation across these four PAs encompasses a variety of habitats, ranging from shrub savannas and tree savannas to woodlands, dry forests, and gallery forests [44]. Within the Sudano-Sahelian zone, aside from *Detarium microcarpum* (Guill. & Perr.), notable woody species include *Senegalia gourmaensis* (A.Chev.) Kyal. & Boatwr., *Vachellia seyal* (Delile) P. J. H. Hurter, *Terminalia leiocarpa* Baill., *Balanites aegyptiaca* (L.) Delile, *Combretum collinum* Fresen., *Lannea acida* A.Rich., *Sterculia setigera* Delile, *Pericopsis laxiflora* (Benth. ex Baker) Meeuwen, *Crossopteryx febrifuga* Benth., *Isobrerlinia doka* Craib & Stapf., and *Senegalia gourmaensis* (A.Chev.) Kyal. & Boatwr. Dominant species in the Soudanian zone include *Azvelia africana* Pers., *Annona senegalensis* Pers., *Burkea africana* Hook., *Combretum glutinosum* Perr. ex-DC., *Crossopteryx febrifuga* Benth., *Hexalobus monopetalus* Engl. & Diels, *Isobrerlinia doka* Craib & Stapf. and *Pterocarpus erinaceus* Poir.

Climate-wise, the Sudano-Sahelian zone experiences an increase in mean annual rainfall, ranging from 600 to 900 mm over 4 to 5 months, accompanied by an annual temperature fluctuation between 20 and 30 °C. In contrast, the Soudanian zone receives a slightly higher annual rainfall of 900 to 1100 mm, spread over 5 to 6 months, and is characterized by cooler temperatures, typically between 20 and 26 °C, compared to the Sudano-Sahelian zone.

Detarium microcarpum, one of the Fabaceae family, exhibits characteristics typical of woody plants [45]. It typically reaches heights of up to 12 m, featuring a densely packed, spherical crown [46,47]. The plant's foliage consists of paripinnate leaves, bearing 5 to 6 pairs of opposite leaflets arranged alternately. Its inflorescence takes the form of a somewhat branched axillary panicle, extending approximately 5 to 8 cm in length. Seed dispersal for this species is primarily facilitated by animal agents [48,49].

Detarium microcarpum is commonly encountered in environments such as dry savannas, dry forests, and abandoned fields, thriving on sandy or iron-rich substrates. It also appears sporadically in agricultural settings, particularly in orchards [50,51].

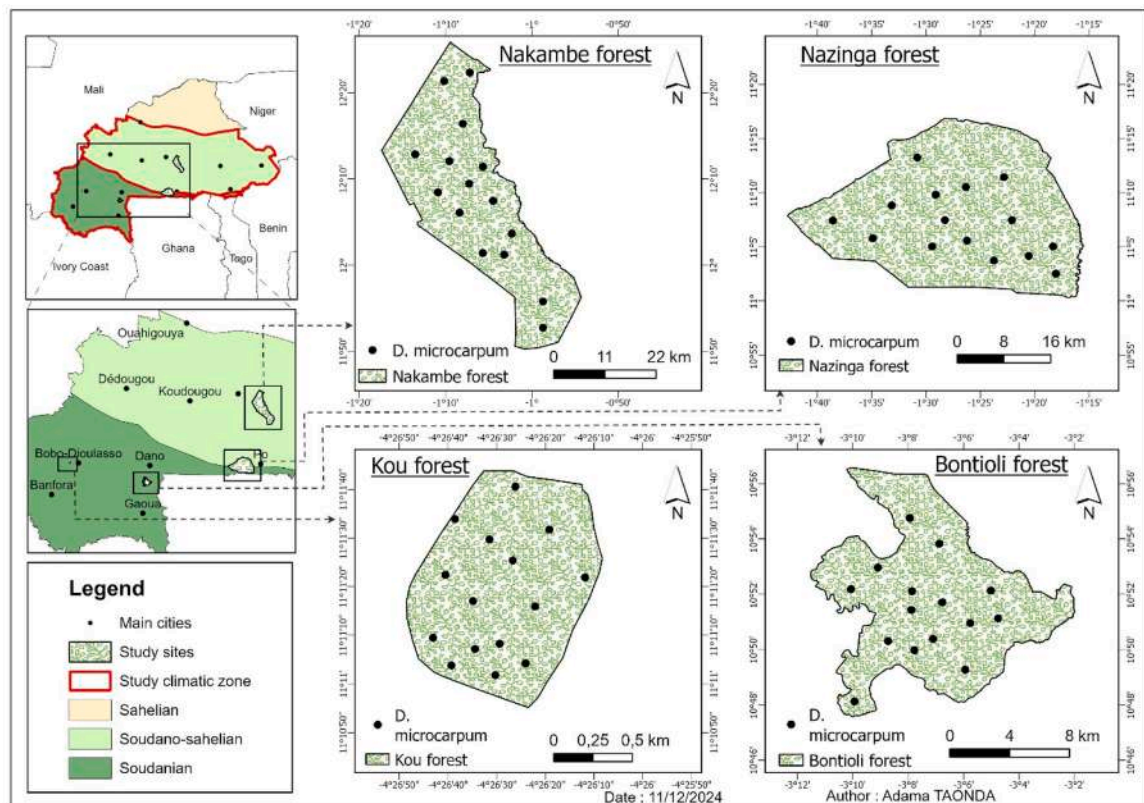


Fig. 1. Location of the study sites across the country (Burkina Faso).

Sampling design and data collection

A comprehensive study encompassing 165 plots across two distinct climatic zones was undertaken. These plots were selected based on the presence of *Detarium microcarpum*, following an oriented sampling method highlighted by Thiombiano et al. [52]. Within the Sudano-Sahelian zone, 90 plots were strategically placed, comprising 50 plots of 1000 m² (50 m x 20 m) in the protected areas and 40 plots of 2500 m² (50 m x 50 m) in the unprotected area. In the Sudanian climatic zone, 75 plots with 45 in the protected area and 35 in the unprotected areas. These plot sizes adhered to the guidelines outlined by Thiombiano et al. [52] for research in West African savannas. Each plot featured the measurement of key parameters (harvesting, diameter at breast height (dbh), total height (ht), and mean crown diameter (Cd)) on each mature individual of *D. microcarpum* (dbh ≥ 5 cm). The Cd of each tree was determined by averaging the two perpendicular crown diameters (east-west and north-south).

In addition, the basal diameter which refers to the diameter of a plant stem or trunk at its base, typically measured near ground level at 20 cm was measured. For biomass collection, according to the climatic zone, trees of *D. microcarpum* were categorized into seven different diameter classes (10–15 cm, 15–20 cm, 20–25 cm, 26–30 cm, 30–35 cm, 35–40 cm and > 40 cm) to ensure a balanced representation within the sampling areas. The 165 plots provided a robust dataset, enabling the selection of diameter classes through the Prodata method highlighted by [10]. In each climate zone, 30 individuals were selected based on their availability and abundance according to the different diameter classes, the absence of human interference (such as pruning marks or signs of debarking), and health status. The size of the sample is underlined with the previous studies in the semi-arid savanna species for their biomass and carbon assessment [10,20,27,36].

Trees from the most prevalent diameter classes were sampled and grouped into seven categories: 10–15 cm (8 individuals), 15–20 cm (8 individuals), 20–25 cm (4 individuals), 26–30 cm (4 individuals), 30–35 cm (2 individuals), 35–40 cm (2 individuals), and > 40 cm (2 individual). A direct destructive sampling method was employed for individual tree measurements, with 60 trees (30 per climatic zone) chosen for biomass sampling. Trees were felled using a chainsaw, and their components (stems, branches, and leaves) were individually weighed [20,27,32,53].

Wood density was assessed by extracting discs from various segments of the stem and branches, which were then dried and weighed. Fresh weights of stems, branches, and leaves were recorded in the field using a 100 kg scale balance, with subsamples analysed using a 5 kg electronic balance for precise measurements. Leaf subsamples were collected in bags for easy weighing, and the process concluded with the transportation of discs and leaf samples to the lab for drying and subsequent analysis.

Upon arrival at the lab, samples underwent drying at 105 °C for branches and stems, or 75 °C for leaves, until achieving a stable weight. Post-drying, the dry weights were noted, and the dry-to-green weight ratios for each component were calculated. The dry biomass of each component was then calculated by multiplying the dry-to-green weight ratio by the component's fresh biomass, culminating in the estimation of the Total Above-ground Biomass (TAGB) for each tree by summing the dry biomass of the three components.

Data analysis

The diameter at the breast height, stem height, crown diameter, total height, stem biomass, branch biomass, leaf biomass, branch density, basal diameter, and trunk density were compared between the two climatic zones using an independent Student's *t*-test. Comparison tests were performed using the Shapiro-Wilk normality test to check the normality of the data. Data that were not normally distributed were normalized using log transformation. Before fitting the model, a Pearson correlation was performed to avoid collinearity problems between the chosen parameters. Allometric developed were performed for each climatic zone to predict tree biomass components (leaf, branch, and stem) and the total aboveground biomass (TAGB).

Before fitting the allometric equations, data were checked for normality, and a scatter plot was prepared to explore the relationships between aboveground biomass and the independent variables diameter at breast height (dbh and total height (ht) in each component. The scatter plot was graphically explored using several model types for each climatic zone. The power function ($y = \alpha x^\beta e^\epsilon$) was found to be an accurate equation and was then selected and presented in its linear form in each climate zone as follows: the equations were computed for each component and TAGB based on nonlinear equations with dbh, height (Ht), and ρ as independent variables. Certain variables were used as the lone predictor variable, and some were combined in the equation. Before developing the predictive model, the above equation was transformed into the following linear form using the natural logarithm (ln): $\ln(Y) = \ln\alpha + \beta \ln X + \epsilon$.

The following allometric relationships were tested for above-ground biomass using dbh, basal diameter, height, crown diameter, and stem height) and density. where Y is the biomass, X is the predictor, ϵ is the random error, and β and β_1 are regression coefficients. The model was linearized for each component, as follows:

$$\ln(Y) = \ln(\alpha) + \beta \ln(dbh) + \epsilon \quad (1)$$

$$\ln(Y) = \ln(\alpha) + \beta \ln(dbh * ht) + \epsilon \quad (2)$$

$$\ln(Y) = \ln(\alpha) + \beta \ln(dbh^2 * ht) + \epsilon \quad (3)$$

With Y is the biomass of the tree compartment and α , β , γ , and δ are the regression coefficients.

The biomass of the species was established using an additive model of the three components [10]. The best model for each climatic zone was established by using the best model for each selected component.

$$\text{TAGB} = \alpha\text{Xs}(\beta\text{s}) + \alpha\text{Xb}(\beta\text{b}) + \alpha\text{Xl}(\beta\text{l})$$

where $\alpha\text{Xs}(\beta\text{s})$ is the stem biomass, $\alpha\text{Xb}(\beta\text{b})$ is the branch biomass, and $\alpha\text{Xl}(\beta\text{l})$ is the leaf biomass.

In addition, the total biomass was calculated for each climate zone to compare the additive model with the model proposed by Chave et al. [17]. The model defined by Chave et al. [17] as follows: $\ln(A) = \ln(\alpha) + \text{bln}(\text{dbh}) + \text{cln}(\text{ht}) + \text{dln}(\rho)$ with ρ a species density

The total carbon stock of a tree was evaluated as the sum of all the carbon contents of the leaves, branches, and stems of the tree. The percentage of carbon in fresh biomass and each component of the tree and the whole tree was calculated based on the percentage of carbon in the dry biomass of leaves, branches, and stems.

Evaluation of the quality of allometric selected models

To address the issue of bias resulting from the back-transformation of the log-transformed response variable, correction factors (CF) were computed for these equations. The calculation employs the formula: $\text{CF} = e^{(\text{RSE}^2 / 2)}$ where RSE represents the residual standard error of the regression. The selection of the optimal above-ground model was guided by several metrics of goodness-of-fit, including the adjusted R-square (Adj.R^2), Akaike Information Criterion (AIC), residual standard error (RSE), and root mean square error (RMSE). Both RMSE and AIC served as indicators of each model's performance. Models exhibiting high R^2 values and minimal RMSE and AIC scores were identified as the most fitting [54,55].

The Akaike Information Criterion (AIC) is defined as $\text{AIC} = -2\ln(L) + 2p$, where L denotes the likelihood of the fitted model, and p signifies the total number of parameters in the model. Root Mean Square Error (RMSE) is calculated as $\text{RMSE} = \frac{1}{n} \sqrt{\sum_{i=1}^n (y_i - \hat{y}_i)^2}$

The best-fitting model for each component was compared to that of the pantropical allometric biomass model developed by Chave et al. [17]. AIC and RMSE values were used for comparison. Model efficiency near 1 indicates an excellent fit, whereas values approaching 0 suggest predictions equivalent to the average of the observations. Negative values signify a subpar model. Selection of the top models was based on high Adj. R^2 values and low AIC, RMSE, and RSE scores [53,56].

The model by Chave et al. [17] is commonly applied for estimating Above-ground Biomass (AGB) for certain species in Burkina Faso [20,27,32]. Graphical analyses were conducted on both predicted and observed biomass values. A paired *t*-test was employed to contrast the predicted tree biomass with the observed tree biomass. Plots of predicted versus observed AGB values for each model were generated to gauge the model's fit. Pearson residual scatterplots were utilized to scrutinize the model's performance. Statistical analyses were executed using R version 4.3.2 [57].

Carbon content assessment

The ash method was employed to access the carbon content percentage of each tree of *D. microcarpum*, as detailed by Abeyir et al. [1] and Rahman et al. [58]. Individual trees were dissected to isolate their leaves, branches, and stems, facilitating the quantification of carbon. Following oven drying, composite samples were prepared by grinding separate samples of stems, branches, and leaves. Each composite sample consisted of five 2 g portions of dried powder, which were subsequently incinerated in a crucible at 550 °C for two hours to achieve complete calcination. After calcination, the samples were gradually cooled in a desiccator and their weights were measured. Upon completion of the calcination process and subsequent cooling, the carbon content was determined using the formulas provided by Bayen et al. [35] and Ganamé et al. [20]:

$$\text{Ash (\%)} = [(W3 - W1) / (W2 - W1)] \times 100$$

$$\text{Carbon \%} = (100 \% - \text{Ash \%}) \times 0.58; \text{Carbon} = \text{Biomass} \times \text{Carbon\%}$$

In these calculations, 0.58 represents the carbon content in organic matter, W1 is the weight of the crucibles, W2 is the combined weight of the oven-dried ground samples plus the crucibles, and W3 is the weight of the ash along with the crucibles. The average carbon content for each tree component was computed based on replicate numbers and applied across each tree. The average carbon content of the three components (leaves, branches, and stems) was treated as the carbon content at the tree level. Furthermore, the mean carbon content for each climatic zone was calculated based on the average carbon content stored in individual trees of the

Table 1

Statistical summary of the dendrometrics parameters.

Parameters	Global data		Sudanian		Sudano-sahelian		P-Value
	Mean $\pm$ cv (%)	Range	Mean $\pm$ cv (%)	Range	Mean $\pm$ cv (%)	Range	
Basal diameter (d_{20} , cm)	23.68 $\pm$ 35.08	13–46	22.8 $\pm$ 34.92	13–42	24.57 $\pm$ 35.34	14–46	0.001
diameter at breast height (dbh, cm)	21.15 $\pm$ 40.05	10.5–44	20.09 $\pm$ 40.04	10.5–39.5	22.2 $\pm$ 40.01	11.99–44	0.001
Stem height (h, m)	2.83 $\pm$ 25.90	1.65–6	2.91 $\pm$ 26.93	1.9–6	2.75 $\pm$ 24.83	1.65–4.65	0.001
Tree height (ht, m)	8.015 $\pm$ 26.8	3.85–15	8.215 $\pm$ 27.15	4.9–14	7.815 $\pm$ 26.62	3.85–13.75	0.001
Crown diameter (cd, m)	5.92 $\pm$ 41.52	2.275–13.025	6.01 $\pm$ 34.41	3.125–11.95	5.83 $\pm$ 48.50	2.275–13.025	0.001
Density (branch)	0.93 $\pm$ 69.91	0.4–1.22	0.88 $\pm$ 57.45	0.44–0.98	0.98 $\pm$ 79.06	0.4–1.22	0.001
Density(stem)	0.62 $\pm$ 26.66	0.32–1.38	0.66 $\pm$ 29.79	0.35–1.38	0.81 $\pm$ 0.12	0.71–0.12	0.001

species. A unilateral *t*-test was performed to compare the average carbon content of *D. microcarpum* to the reference value suggested by the IPCC. In addition, an independent Student's *t*-test was used to assess if tree component biomass was different between the two climatic zones. These analyses were made in the Plant and Soil Laboratory of Joseph KI-ZERBO University (Burkina Faso).

Result

Statistical summary of the dendrometrics parameters and wood-specific density

The results showed that the dendrometric parameters of *D. microcarpum* distribution were very well distributed and differed significantly ($P \leq 0.001$) between the two climatic zones (Table 1). The Pearson correlation shows that only the diameters at the breast height (dbh) and Total height (Ht) are lower correlated (0.45) than the other parameters which are highly correlated (≥ 0.52) (Table 2). This allowed us to establish an allometric equation using the diameter at breast height (dbh) and total height (ht) according to the climatic zone.

In each climatic zone, the wood-specific density of *D. microcarpum* varied significantly between tree components in the Sudanian zone ($F = 4.963$, $P = 0.0298$) and the Sudano-Sahelian zone ($F = 7.668$, $P = 0.00754$). The branch had the highest density in each climatic zone with (0.88 ± 57.45) in the Sudanian zone and (0.98 ± 79.06) in the Sudano-Sahelian zone. The stem densities were (0.66 ± 29.79) and (0.71 ± 0.12) in the Sudanian and Sudano-Sahelian climatic zones respectively. The main density of the stem was 0.93 ± 69.91 , and 0.62 ± 26.66 for the branch and stem respectively. Based on mean species density, the value was 0.77 ± 0.25 in the Sudanian zone and 0.81 ± 0.12 in the Sudano-Sahelian zone.

Allometric model for predicting *D. microcarpum* above-ground biomass

All models were tested, and parameter estimates produced highly significant results, with R^2 adj values over 0.80 in the two climatic zones. The coefficients obtained from the fitted models were highly significant ($P \leq 0.05$). In the Sudanian zone, allometric models predicted biomass components, with AIC values ranging from 14.30 to 30.69184, RSE between 0.2365 and 0.4236, and RMSE between 0.0115 and 0.5088. branch and leaf biomass were better predicted when using a dbh alone-like predictor, with R^2 adj = 0.8657, AIC = 31.10, RSE = 0.3806, and RMSE = 0.4728 for the branch and R^2 = 0.8457, AIC = 27.37, RSE = 0.2365, and RMSE = 0.0115 for the leaves. The best-fit model for steam biomass was fitted using $\text{dbh}^2 \times \text{ht}$, with R^2 adj = 0.9094, RSE = 0.2876, AIC = 14.30, and RMSE = 0.1903 (Table 3).

In the Sudano-Sahelian climatic zone, the coefficients obtained from the fitted models were highly significant ($P < 0.05$). However, higher Adj. R^2 values were recorded for branch biomass (ranging from 0.8469 to 0.8796) with AIC (40.43 – 51.37), RSE (0.4446 – 0.5526), and RMSE (0.4698 – 0.5203). For the stem biomass estimation, the Adj. R^2 varied between (0.8095–0.8763), AIC (26.72 – 39.68); RSE (0.3538–0.439), and RMSE (0.1122–0.1526), and for the leaf biomass, the Adj. R^2 ranged from (0.8247–0.8473) with AIC (3.03–10.06), RSE (0.2384–0.268), and RMSE (0.0171–0.0220) (Table 3). For each component (stem, branch, and leaves) in the Sudano-Sahelian zone, the best model for leaf biomass was fitted using dbh alone. Adding total tree height to dbh as a compound variable ($\text{dbh} \times \text{ht}$) did not significantly improve the statistical fits in either climatic zone when compared to the model based on dbh as a single predictor (Table 3).

The model used to predict the total above-ground biomass (TGAB) showed a high adjusted R^2 value for each climate zone. According to the low value of the RSE (0.2928), AIC (15.3655), and RMSE (0.5116), dbh was the best predictor for the total biomass prediction with R^2 adj. (0.9013) for the Sudanian zone. For the Sudano-Sahelian climatic zone, the R^2 adj. ranged between (0.8488 - 0.9092) with AIC (22.21 - 37.50), RSE (0.3281 - 0.4234), and RMSE (0.4844 - 0.5332). The best-fit model was found using dbh alone as the predictor (Table 3). The model using single compound variables $\text{dbh}^2 \times \text{ht}$ showed less efficient estimations than the model based on multiple variables of $\text{dbh}^2 \times \text{ht}$ and a single predictor than dbh alone.

The most appropriate allometric models for estimating the biomass are presented in Table 4. In the Sudanian and Sudano-Sahelian zones, dbh alone was a good predictor of branch and leaf biomass. Differences were observed in stem biomass prediction. In Sudanian, the best predictors were $\text{dbh}^2 \times \text{ht}$ and dbh alone in the Sudano-Sahelian climatic zone (Table 4). In each climatic zone, an appropriate allometric model for the total aboveground biomass (TAGB) estimation was obtained by combining the best-performing models of each biomass component. For the Sudanian climatic zone, the model developed was $\text{TAGB} = e^{4.4002} (\text{dbh} \times \text{dbh} \times \text{ht})^{0.9456} + e^{-3.5219} (\text{dbh})^{2.4007} + e^{-2.8845} (\text{dbh})^{1.3465}$ in the Sudanian zone and $\text{TAGB} = e^{-4.1053} (\text{dbh})^{2.4222} + e^{-5.2567} (\text{dbh})^{2.9539} + e^{-2.9894} (\text{dbh})^{1.5285}$ for the Sudano-Sahelian climatic zone. When comparing the additive model developed with the global biomass model developed in each climatic zone, the additive model performed better than the global model. In the Sudanian zone, the additive model performed better with R^2 .adj =

Table 2
Pearson correlation of the dendrometric parameters.

Dendrometric parameters	Basal diameter (d_{20})	Crown diameter	Diameter at the breast height (dbh)	Total height (ht)	Steam height
Basal diameter (d_{20})	1				
Crown diameter	0.81	1			
Diameter at the breast height (dbh)	0.99	0.89	1		
Total height (ht)	0.52	0.52	0.45	1	
Steam height	0.81	0.76	0.82	0.67	1

Table 3

Summary of the best allometric models selected.

Sudanian data														
Components	Regression coefficients						Goodness of fit						t-test	
	Predictor	Parameters	Est.	SE	t-value	Pr(> t)	adj R2	RSE	CF	AIC	RMSE	P-Value	t	P-value
Stem (Eq1)	Intercept	lna	−4.0371	0.4564	−8.846	1.34e ^{−09} ***	0.8951	0.3095	1.0490	18.7	0.1992	1.87e ^{−15}	0.8063	0.4266
Stem (Eq1)	dbh	B	2.4362	0.1545	15.766	1.87e ^{−15} ***								
Stem (Eq2)	Intercept	lna	−4.4462	0.4824	−9.217	5.64e ^{−10} ***	0.895	0.3096	1.0491	18.73	0.2081	1.89e ^{−15}	0.6324	0.5321
Stem (Eq2)	dbh ² *h	B	1.5087	0.0957	15.757	1.89e ^{−15} ***								
Stem (Eq3)	Intercept	lna	−4.40372	0.4423	−9.957	1.06e ^{−10} ***	0.9094	0.2876	1.0422	14.3	0.1903	2.39e ^{−16}	0.6403	0.527
Stem (Eq3)	dbh ² *h	b	0.9461	0.0554	17.093	2.39e ^{−16} ***								
Stem (Eq4)	Intercept	lna	−4.3694	0.4634	−9.432	7.07e ^{−10} ***	0.9041	0.296	1.0184	17.8	0.1908	5.65e ^{−14}	0.623	0.5382
Stem (Eq4)	dbh	b	2.0377	0.2634	7.735	3.31e ^{−08} ***								
Stem (Eq4)	Ht	c	0.703	0.3916	1.795	0.0843								
Stem (Eq4)	density	d	−0.0945	0.2185	−0.432	0.0669								
Branch (Eq1)	Intercept	lna	−3.5301	0.5612	−6.29	8.41e ^{−07} ***	0.8657	0.3806	1.0751	31.1	0.4728	4.26e ^{−13}	0.8727	0.39
Branch (Eq1)	dbh	b	2.4035	0.19	12.65	4.26e ^{−13} ***								
Branch (Eq2)	Intercept	lna	−3.777	0.6598	−5.724	3.85e ^{−06} ***	0.8089	0.4236	1.0939	37.52	0.5078	8.68e ^{−12}	0.8524	0.401
Branch (Eq2)	dbh. ht		1.4571	0.131	11.126	8.68e ^{−12} ***								
Branch (Eq3)	Intercept		−3.7956	0.603	−6.294	8.33e ^{−07} ***	0.8362	0.3922	1.0799	32.91	0.5088	9.95e ^{−13}	1.3323	0.1931
Branch (Eq3)	dbh ² *h		0.92124	0.07547	12.206	9.95e ^{−13} ***								
Branch (Eq4)	Intercept	lna	−3.6577	0.6096	−6.001	2.569e ^{−5} ***	0.8385	0.3894	1.1183	34.26	0.4728	4.79e ^{−11}	0.85163	0.4014
Branch (Eq4)	dbh	b	2.2472	0.3326	6.755	4.54 e ^{−7} ***								
Branch (Eq4)	Ht	c	0.2957	0.4818	0.614	0.545								
Branch (Eq4)	density	d	0.1207	0.1804	0.669	0.509								
Leaf (Eq1)	Intercept	lna	−2.8943	1.0979	−2.636	0.0135 *	0.8457	0.2365	1.3194	27.37	0.0115	0.0011	1.1517	0.2589
Leaf (Eq1)	dbh	b	1.3494	0.3717	3.63	0.0011 **								
Leaf (Eq2)	Intercept	lna	−2.7464	1.2057	−2.278	0.0306*	0.8419	0.2522	1.3494	30.69	0.0143	0.0034	1.5624	0.129
Leaf (Eq2)	dbh. ht	b	0.7608	0.2393	3.179	0.0036 **								
Leaf (Eq3)	Intercept	lna	−2.8674	1.1698	−2.451	0.0207 *	0.8425	0.2485	1.3357	29.66	0.0132	0.002142	1.5538	0.1311
Leaf (Eq3)	dbh ² *h	b	0.495	0.1464	3.382	0.0021**								
Leaf (Eq4)	Intercept	lna	−2.6675	1.1719	−2.276	0.0313 *	0.8435	0.2425	1.001	27.32	0.013	0.0074	1.2426	0.224
Leaf (Eq4)	dbh	b	1.6859	0.6434	2.62	0.0145 *								
Leaf (Eq4)	Ht	c	−0.5019	0.9505	−0.528	0.602								
Leaf (Eq4)	density	d	0.5737	0.5429	1.057	0.3003								
Global Biomass	Intercept	lna	−2.8815	0.4317	−6.675	3.04e ^{−07} ***	0.9013	0.2928	1.0438	15.37	0.5116	7.94e ^{−16}	0.8257	0.4157
Global Biomass	dbh	b	2.3837	0.1462	16.307	7.94e ^{−16} ***								
Global Biomass	Intercept	lna	−3.1821	0.5111	−6.226	9.99e ^{−07} ***	0.8761	0.3281	1.0553	22.2	0.5896	1.95e ^{−14}	0.7270	0.473
Global Biomass	dbh. ht	b	1.4562	0.1014	14.355	1.95e ^{−14} ***								
Global Biomass	Intercept	lna	−3.1789	0.4534	−7.012	1.26e ^{−07} ***	0.8999	0.2949	1.0444	15.79	0.5436	9.71e ^{−16}	0.7109	0.4828
Global Biomass	dbh ² *h	b	0.9179	0.0567	16.179	9.71e ^{−16} ***								
Global Biomass (Eq4)	Intercept	lna	−3.0908	0.4593	−6.729	3.86e ^{−07} ***	0.9013	0.2929	1.043829	17.16	0.522	8.21e ^{−14}	0.7630	0.4516
Global Biomass (Eq4)	dbh	b	2.115	0.2522	8.387	7.21e ^{−09} ***								
Global Biomass (Eq4)	Ht	c	0.5034	0.3726	1.351	0.188								
Global Biomass (Eq4)	density	d	0.155	0.2128	0.729	0.473								
Sudano-Sahelian data														
Components	Regression coefficients						Goodness of fit						t-test	
	Predictor	Parameters	Est.	SE	t-value	Pr(> t)	adj R2	RSE	CF	AIC	RMSE	P-Value	t	p-value
Stem (Eq1)	Intercept	lna	−4.1053	0.5142	−7.984	1.08e ^{−08} ***	0.8763	0.3538	1.0646	26.72	0.1122	1.90e ^{−14}	−0.0180	0.9857
Stem (Eq1)	dbh	b	2.4222	0.1686	14.37	1.90e ^{−14} ***								
Stem (Eq2)	Intercept	lna	−3.9659	0.6501	−6.101	1.40e ^{−06} ***	0.8095	0.439	1.1012	39.68	0.1526	8.32e ^{−12}	0.3832	0.7044

(continued on next page)

Table 3 (continued)

Sudanian data														
Components	Regression coefficients						Goodness of fit						t-test	
	Predictor	Parameters	Est.	SE	t-value	Pr(> t)	adj R2	RSE	CF	AIC	RMSE	P-Value	t	P-value
∞	Stem (Eq2)	DBH.Ht	b	1.4252	0.1279	11.146	8.32e ⁻¹² ***							
	Stem (Eq3)	Intercept	lna	-4.1634	0.57493	-7.242	6.97e ⁻⁰⁸ ***	0.8518	0.3872	1.0779	32.14	0.1413	2.42e ⁻¹³	0.0819
	Stem (Eq3)	dbh ² *h	b	0.91535	0.0707	12.949	2.42e ⁻¹³ ***							0.9353
	Stem (Eq4)	Intercept	lna	-4.0946	0.5458	-7.502	5.77e-08 ***	0.8683	0.365	1.0075	30.37	0.1216	3.41e ⁻¹²	0.1120
	Stem (Eq4)	dbh	b	2.3828	0.2747	8.674	3.76e ⁻⁰⁹ ***							0.9116
	Stem (Eq4)	Ht	c	0.1021	0.3784	0.27	0.789							
	Stem (Eq4)	density	d	0.1734	0.3378	0.513	0.612							
	Branch (Eq1)	Intercept	lna	-5.2567	0.6462	-8.135	7.42e ⁻⁰⁹ ***	0.8796	0.4446	1.1039	40.43	0.4698	4.00e ⁻¹⁴	1.1265
	Branch (Eq1)	dbh	b	2.9538	0.2118	13.943	4.00e ⁻¹⁴ ***							0.2692
	Branch (Eq2)	Intercept	lna	-5.1367	0.7886	-6.513	4.65e ⁻⁰⁷ ***	0.8469	0.5326	1.152382	51.27	0.5203	6.47e ⁻¹²	1.4809
	Branch (Eq2)	Dbh*h	b	1.7478	0.1551	11.268	6.47e ⁻¹² ***							0.1494
	Branch (Eq3)	Intercept	lna	-5.35919	0.7046	-7.606	2.76e ⁻⁰⁸ ***	0.8514	0.4746	1.1193	44.35	0.5196	2.51e ⁻¹³	1.2766
	Branch (Eq3)	dbh ² *h	b	1.1201	0.0867	12.93	2.51e ⁻¹³ ***							0.2119
	Branch (Eq4)	Intercept	lna	-5.1639	0.6665	-7.748	3.21e ⁻⁰⁸ ***	0.8685	0.4457	1.1404	41.95	0.5126	2.69e ⁻¹²	1.1404
	Branch (Eq4)	dbh	b	2.7453	0.3389	8.101	1.40e ⁻⁰⁸ ***							0.2634
	Branch (Eq4)	Ht	c	0.2437	0.454	0.537	0.596							
	Branch (Eq4)	density	d	-0.2122	0.149	-1.425	0.166							
	Leaf (Eq1)	Intercept	lna	-2.9894	0.3465	-8.628	2.25e ⁻⁰⁹ ***	0.8473	0.2384	1.0289	3.03	0.0171	9.53e ⁻¹⁴	0.7681
	Leaf (Eq1)	dbh	b	1.5285	0.1136	13.457	9.53e ⁻¹⁴ ***							0.4486
	Leaf (Eq2)	Intercept	lna	-2.9801	0.3968	-7.51	3.52e ⁻⁰⁸ ***	0.8247	0.268	1.0367	10.06	0.022	2.58e ⁻¹²	0.7921
	Leaf (Eq2)	Dbh*h	b	0.9149	0.0781	11.72	2.58e ⁻¹² ***							0.4348
	Leaf (Eq3)	Intercept	lna	-3.0751	0.3608	-8.523	2.89e ⁻⁰⁹ ***	0.8358	0.243	1.0299	4.2	0.0203	1.65e ⁻¹³	0.7279
	Leaf (Eq3)	dbh ² *h	b	0.5838	0.0441	13.157	1.65e ⁻¹³ ***							0.4725
	Leaf (Eq4)	Intercept	lna	-3.0954	0.3629	-8.529	5.22e ⁻⁰⁹ ***	0.8458	0.2414	1.029867	5.56	0.0187	9.23e ⁻¹²	0.74038
	Leaf (Eq4)	dbh	b	1.4137	0.1848	7.651	4.04e ⁻⁰⁸ ***							0.465
	Leaf (Eq4)	Ht	c	0.2369	0.2472	0.958	0.347							
	Leaf (Eq4)	density	d	0.0754	0.1224	0.616	0.543							
	Global Biomass (Eq1)	Intercept	lna	-3.7891	0.4769	-7.945	1.18e ⁻⁰⁸ ***	0.9092	0.3281	1.0553	22.21	0.484352	2.49e ⁻¹⁶	0.8385
	Global Biomass (Eq1)	dbh	b	2.6683	0.1564	17.066	1.18e ⁻⁰⁸ ***							0.4086
	Global Biomass (Eq2)	Intercept	lna	-3.6753	0.6269	-5.862	2.65e ⁻⁰⁶ ***	0.8488	0.4234	1.0938	37.5	0.5332	3.22e ⁻¹³	1.2081
	Global Biomass (Eq2)	Dbh*h	b	1.5778	0.1233	12.796	3.22e ⁻¹³ ***							0.2368
	Global Biomass (Eq3)	Intercept	lna	-3.8783	0.5375	-7.215	7.46e ⁻⁰⁸ ***	0.8894	0.362	1.0677	28.11	0.4937	3.94e ⁻¹⁵	0.9545
	Global Biomass (Eq3)	dbh ² *h	b	1.0114	0.0661	15.305	3.94e ⁻¹⁵ ***							0.3477
	Global Biomass (Eq4)	Intercept	lna	-3.8332	0.503	-7.621	4.34e ⁻⁰⁸ ***	0.9035	0.3381	1.0588	25.78	0.4852	6.08e ⁻¹⁴	0.7922
	Global Biomass (Eq4)	dbh	b	2.5818	0.2582	10	2.12e ⁻¹⁰ ***							0.4347
	Global Biomass (Eq4)	Ht	c	0.1604	0.3501	0.458	0.651							
	Global Biomass (Eq4)	density	d	0.0546	0.1674	0.326	0.747							

Table 4
Summary of the best allometric models selected.

Sudanian		Regression parameters						Paired t-test	
Parameters	Equations	R ²	Adj-R ²	SSR	MSE	RMSE	AIC	statistic	P-value
Stem	$\ln(\text{dbh}^2 \cdot h) = -4.4002 + 0.9456 \ln(\text{dbh}^2 \cdot h)$	0.9126	0.9094	2.3166	0.0827	0.2877	14.3034	0.5919	0.5585
Branch	$\ln(\text{dbh}) = -3.5219 + 2.4007 \ln(\text{dbh})$	0.8511	0.8657	4.0557	0.1448	0.3806	31.1038	0.8775	0.3874
leaf	$\ln(\text{dbh}) = -2.8845 + 1.3461 \ln(\text{dbh})$	0.8435	0.8457	1.5522	0.5543	0.2145	27.3672	1.5824	0.1244
Additive	$\text{TAGB} = e^{4.1053 (\text{dbh})^{2.4222}} + e^{-5.2567 (\text{dbh})^{2.9538}} + e^{-2.9894 (\text{dbh})^{1.5285}}$	0.9143	0.9099	2.6344	0.0941	0.3067	15.7935	0.9358	0.3088
Global model	$\text{AGB} = e^{-2.8815 (\text{dbh})^{2.3837}}$	0.8901	0.9013	3.0201	0.1079	0.3284	16.9145	0.8257	0.4157
Sudano-Sahelian		Regression parameters						Paired t-test	
Parameters	Equations	R ²	Adj-R ²	SSR	MSE	RMSE	AIC	statistic	p-value
Stem	$\ln(\text{dbh}) = -4.1053 + 2.4222 \ln(\text{dbh})$	0.8806	0.8763	3.5042	0.1252	0.3538	26.7189	-0.0206	0.9837
Branch	$\ln(\text{dbh}) = -5.2567 + 2.9539 \ln(\text{dbh})$	0.8796	0.8696	5.5346	0.1977	0.4446	40.4311	1.1272	0.2689
leaf	$\ln(\text{dbh}) = -2.9894 + 1.5285 \ln(\text{dbh})$	0.8661	0.8613	1.5910	0.0568	0.2384	3.0305	0.7683	0.4485
Additive	$\text{TAGB} = e^{-4.1053 (\text{dbh})^{2.4222}} + e^{-5.2567 (\text{dbh})^{2.9539}} + e^{-2.9894 (\text{dbh})^{1.5285}}$	0.9132	0.9099	2.6135	0.0827	0.3125	21.9446	1.1162	0.2735
Global model	$\text{AGB} = e^{-3.7891 (\text{dbh})^{2.6683}}$	0.9123	0.9092	3.0147	0.1077	0.3281	22.2054	0.8390	0.4083

0.9099, SSR = 2.6344, AIC = 14.7935, and RMSE = 0.3067 than the global biomass (R^2 Adj. = 0.9013, SSR = 3.0201; AIC = 16.9145, and RMSE = 0.3284 (Table 4). The Sudano-Sahelian climatic zone is R^2 .adj. = 0.9099, SSR = 2.6135, AIC = 21.9446, and RMSE = 0.3125 for the additive model, and R^2 .adj. = 0.9092, SSR = 3.0147; AIC = 22.2054, and RMSE = 0.3281 for the global biomass model established, (Table 4). These results indicate that the selected allometric model presents a good fit and better performance than the established global model and the model proposed by Chave et al. [17], which includes density in the model.

The scatter plots (Fig. 2) of the observed and predicted values of the three components were close to a linear trend, which indicates the good performance of the models established in this study. No significant deviation was observed between the observed and predicted biomass ($P > 0.05$) for the additive model, similar to the global biomass established. For the additive model, they were ($t = 0.9358$ ($P = 0.3088$)) in the Sudanian zone and ($t = 1.116$; $P = 0.2736$) in the Sudano-Sahelian zone (Table 4). With the global biomass model established, they did not vary ($t = 0.8257$; $P = 0.4157$) in the Sudanian zone or ($t = 0.8390$; $P = 0.4083$) (Table 4). The error values from the biomass predictions using the SUR approach demonstrated enhanced performance compared to the models independently fitted (Fig. 3).

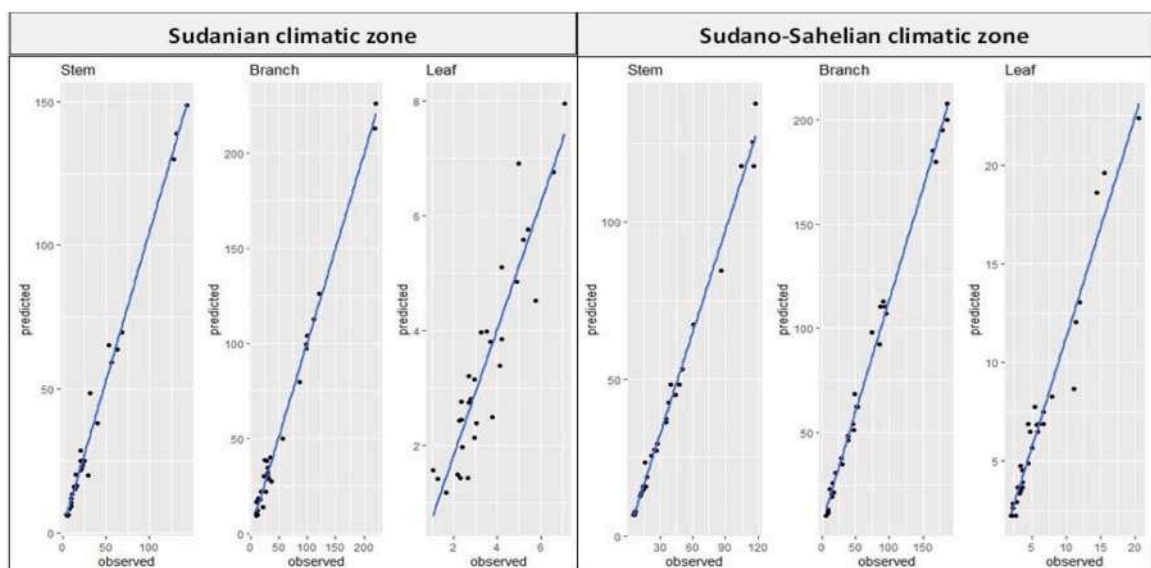


Fig. 2. Relationship between observed and predicted biomass values of each component.

Caption. Stem: Stem above-ground biomass, Branch: Branch above-ground biomass, Leaf: Leaf above-ground biomass, Predicted values are obtained through the equations selected for each component in each climatic zone.

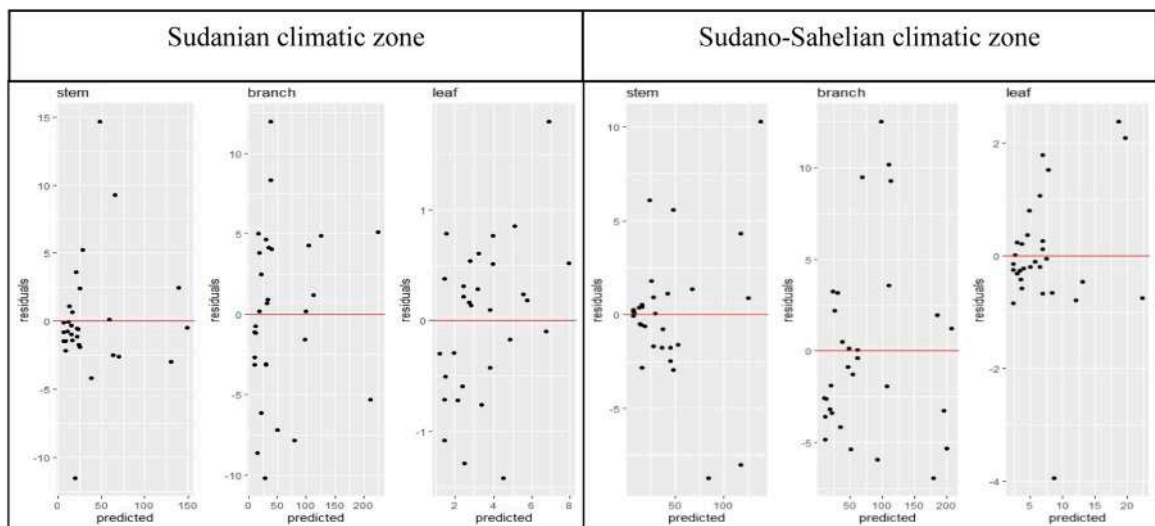


Fig. 3. Residuals plot of each component Above-ground biomass predicted. Caption Stem: Stem aboveground biomass. Branch: Branch above-ground biomass. Leaf: Leaf above-ground biomass.

Above-ground biomass and carbon partition in tree components

The allocation of biomass among tree compartments varied between the tree size and the climatic zone. The relative proportion of biomass varied significantly ($P \leq 0.05$) across the three components of the species. The analysis of the branch biomass shows a highly significant variation according to the climatic zone ($P \leq 0.001$). The biomass stored in the stem, branch, and leaves was also significantly varied according to the climate zones ($P \leq 0.001$) (Fig. 4). According to the biomass and the carbon partition, the analysis revealed that branches had the highest biomass fraction and carbon content among all tree components (Table 5 and Fig. 4). In the Sudanian, the biomass partition was 210.52 ± 281.9 , and 218 ± 151.94 for the Sudanian and Sudano-Sahelian climatic zone. The mean dry biomass of the stem was 149.84 ± 102.29 and 151 ± 61.23 in the Sudanian and Sudano-Sahelian zones respectively. The leaves had the lower allocation in the two zones with 6.04 ± 2.94 and 12.06 ± 5.05 in the Sudanian zone and Sudano-Sahelian zone, respectively. The Carbon content showed the same trend in both climatic zones with a lower content in leaves. The mean of leaves, branches, and stem carbon of *D. microcarpum* was 55.47 ± 0.22 ; 57.47 ± 0.37 , and 56.79 ± 0.07 in the Sudanian zone and 55.62 ± 0.28 ; 57.56 ± 0.27 ; and 56.82 ± 0.34 in the Sudano-Sahelian zone. Moreover, the findings indicate that the biomass allocation among tree components is significantly higher in the Sudano-Sahelian zone compared to the Sudanian zone, as indicated the Table 5 and illustrated in Fig. 4. The significant variation in the biomass and carbon content between the two climatic zones allowed us to establish the allometric model in each climatic zone.

Discussion

Dendrometric parameters and wood specific density

The specific density of the species analysed showed a significant difference between the two climatic zones and the tree components. The higher density was recorded in the Sudano-Sahelian zone than in the Sudanian zone. This result indicates that the climate pattern influences the wood density. Bouslimi et al. [59] emphasize that trees that grow in warmer locations with more sunlight and water generally produce denser wood and are influenced by the geographic location. Compared to the stem density, the branch has the highest density. This difference would be due to the anatomical function of the different organs of the trees [28]. The mean density found in this study is less than the *Pterocarpus erinaceus* density found by [28]. This would be due that *Pterocarpus erinaceus* is a wood timber species, unlike *D. microcarpum*. In addition, in each climatic zone, the mean density is higher than the density suggested by [60] for the tropical species. Djomo et al. [61] pointed out that drying temperature affects the variation of the wood density. This corroborates with [62] which showed that rainfall, seasonality, and temperature influence the density of tropical wood species. This result showed that the climatic characteristics of each climatic zone appear to be the main factors affecting the density of *D. microcarpum*. However, the plant's physiological mechanisms control the exchange activity of wood formation which influences its density [63]. In addition, [64] pointed out that, the high density of the branch could also be related to a higher concentration of inorganic elements than stem. The study developed the allometric model for estimating the aboveground using the diameter at the breast height (dbh) and the total height (H) which performed the model very well. To develop allometric models for biomass estimation of *Detarium microcarpum*, a sample size of 30 individuals was selected for each climatic zone. This sample size was deemed adequate, as supported by several published studies on tropical African savanna species, including *Azizelia africana* [27] and *Pterocarpus erinaceus* [28] in West Africa. The harvested sample trees were selected in each climatic zone and the mean diameter size class ranged from 20.09 ± 40.04 cm

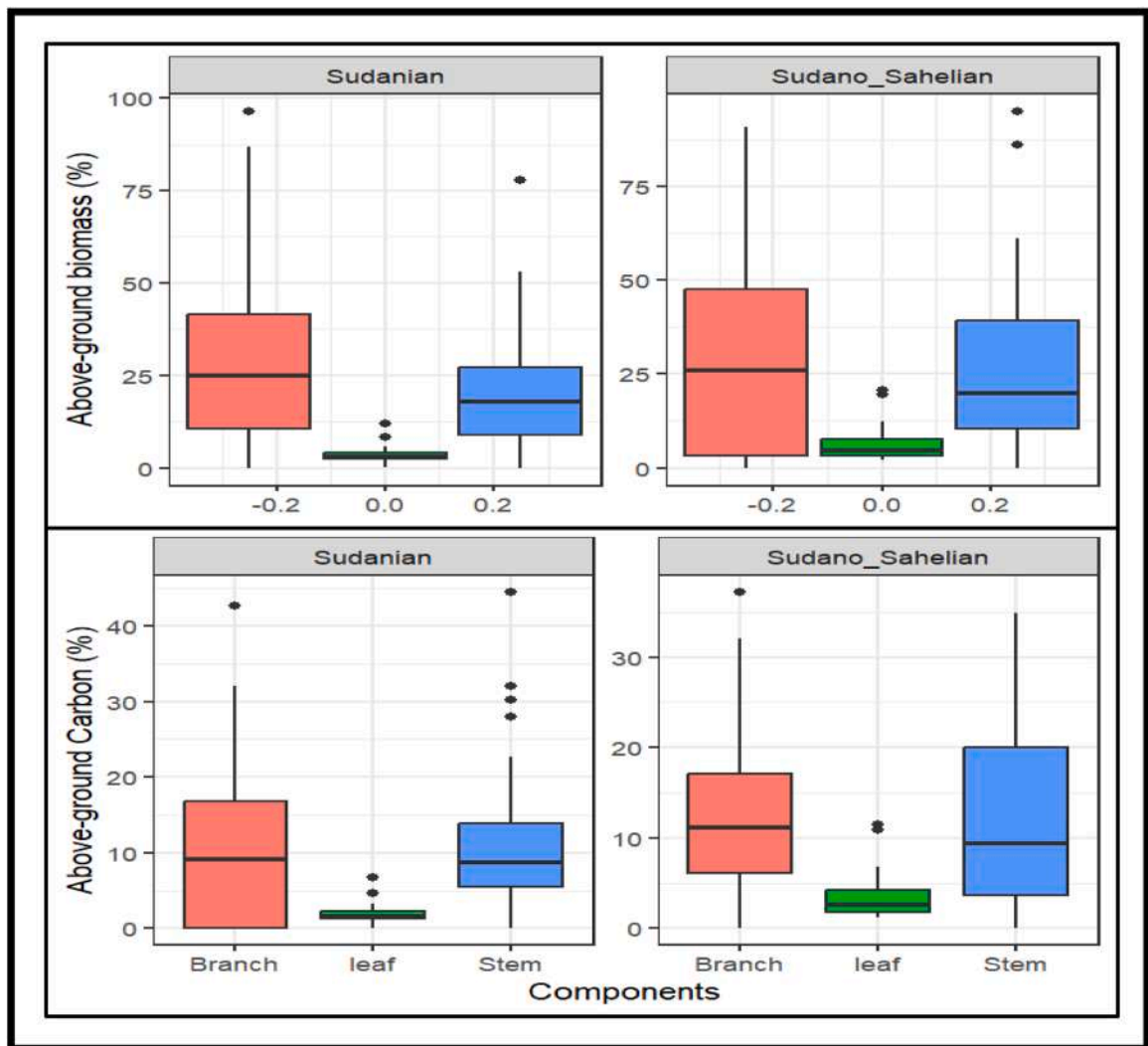


Fig. 4. Biomass allocation and Carbon content in tree components of *Detarium microcarpum* in the two climatic zones of Burkina Faso. Caption Stem: Stem above-ground biomass, Branch: Branch above-ground biomass, Leaf: Leaf above-ground biomass.

Table 5

Biomass and carbon allocation for aboveground components for the ten species.

Component	Sudanian zone			Sudano-Sahelian		
	Dry biomass $\pm$ sd	Mean carbon content $\pm$ sd	Carbon stock	Dry biomass $\pm$ sd	Mean carbon content $\pm$ sd	Carbon stock
stems	149.84 $\pm$ 102.29	56.79 $\pm$ 0.07	85.1	151 $\pm$ 61.23	56.82 $\pm$ 0.34	86.05
Branch	210.52 $\pm$ 281.9	57.47 $\pm$ 0.37	120.98	218 $\pm$ 151.94	57.56 $\pm$ 0.27	126.05
leaves	6.04 $\pm$ 2.94	55.47 $\pm$ 0.22	3.37	12.06 $\pm$ 5.05	55.62 $\pm$ 0.28	6.71
TAGB	366.41 $\pm$ 387.13	169.99 $\pm$ 0.66	209.45	382.51 $\pm$ 105.52	169.99 $\pm$ 0.88	218.81

for the Sudanian zone and 22.2 ± 40.01 cm for the Sudano-Sahelian zone. This information is essential for developing and testing the biomass assessment process, as highlighted by Mäkelä & Vanninen [65]. Additionally, the precision of the predictor variable measurements is critical for ensuring the accuracy of the biomass assessment, as emphasized by Cui et al. [66].

Allometric biomass components models

The findings of this study indicate a strong relationship between the tree parameters and biomass. In this study, the power law model was applied to forecast the biomass of tree components which is underlined with the previous studies scored in West African

savanna species [38,67]. Power models, which are log-transformed equations, were established using variables that demonstrate a strong predictive capability for biomass, such as total height and diameter at breast height (dbh). Chave et al. [15] underscored the necessity of applying log transformations to variables to satisfy the assumptions of normality and homoscedasticity, given that biological data are inherently heteroscedastic. The models performed well with high explained variance ($p < 0.05$; Adj. R^2 0.8089) for all tree components in the two climatic zones. At the tree level, including an additional predictor, the stem biomass equations in the Sudanian climatic zone improved, but this was no significant improvement in the branch, leaves, and Sudano-Sahelian climatic zone equation. This suggests that the model improvement by incorporating additional dendrometric parameters is not a general case for tropical species. This is underlined with the previous study in West Africa [18,68,69] who explained that the allometric model varied between the species. The best allometric model developed with the two explanatory variables varied according to the climatic zone and the tree components. The accuracy of the estimated parameters has a significant effect on the predictive power of the models particularly the model which has been selected as the best model among the models. The power law model selected in this study to predict tree components' biomass was in line with the previous such [70,18]. Diameter at Breast Height (dbh) and total height (ht) were used as compound variables that serve as effective predictors of stem biomass in the Sudanian climatic zone. Additionally, dbh alone is a reliable indicator for estimating branch and leaf biomass. This result corroborates the finding of Miah et al. [71] who explained that dbh² and ht performed better in the *Mangifera steam* biomass than the other types of models. Dbh and the total height of the tree is a more comfortable inventory practice for biomass prediction and have an essential advantage for biomass estimation. However, the total height and dbh influence the variability of tree biomass because of their close correlation with structural tree characteristics and physiological and mechanical properties of woody species. Tree height and diameter at breast height (dbh) are recognized as key indicators of species status [72]. Including both dbh and height (ht) in regression models for biomass estimation is often suggested, particularly for tropical species where these variables may be more reliably measured. The model using the two compound variables (dbh²*H) showed less efficient estimations than the model using a single variable (dbh) for the branch and leaves biomass estimation. However, Vorster et al. [73] explained that the model with dbh² × ht as a predictor produces the best fits probably because the use of dbh and height as a compound variable solves the problem of collinearity while still accounting for the within-species variation of height for a given value of dbh like the Sudano-Sahelian climatic zone. The fact that, the species structure varies according to climatic type and that the biomass variations around the trees may be unique to the species in their ecological zone [42,74]. Moreover, variations in allometric equations can be attributed to climatic factors. In addition, resource allocation and ecological conditions are influenced by the quantity of rainfall in each climatic zone influencing the biomass allocation [75]. As climate impacts a tree's growth and biomass accumulation, it can alter allometric relationships even within the same species [16]. The finding of this study showed that, using the diameter at breast height (dbh) as a predictor variable explained > 86 % of the variations in biomass and produced the lowest AIC. Even though dbh alone provided a fitting proxy for estimating above-ground and stem biomass, its performance was enhanced by including height in the Sudano-Sahelian climatic zone. This may be due to the fact that many trees in the Sudano-Sahelian zone have branchy patterns that allow for significant biomass accumulation in the branches and climate conditions. Consequently, diameter at breast height (dbh) proved to be a superior predictor of biomass variation compared to the inclusion of total height (ht) alone. The dbh is a dendrometric parameter that is easily physically measurable during the species inventories [71]. In addition, using tree height as an additive predictor did not improve equation parameters. Mugasha et al. [74] elucidate that fluctuations in climate significantly impact tree height, which subsequently influences the estimation of their aboveground biomass. If dbh were recognised as the best predictor in this study, some authors suggest that the accuracy of the dbh in predicting biomass is dependent on the conditions of its use rather than the variable itself [18].

The comparison of the best-selected specific allometric models developed with the general pantropical allometric model developed by Chave et al. [17] showed that the pantropical model did not provide accurate above-ground biomass estimation both at the two climatic zones. The coefficient of determination (Adj. R^2) for the total above-ground biomass allometric model found in this study for each climatic zone is higher (Adj. $R^2 > 0.90$) than the general coefficient of variation (adj. R^2) proposed by Savaresi [76] for the biomass prediction. Despite the wood density is a supporting parameter when developing an allometric equation for the species biomass, its inclusion did not improve the *D. microcarpum* biomass. This showed that the pantropical model could not accurately estimate the biomass of different species such as savanna species. Consequently, it is more reliable to develop species-specific and local site-specific allometric models separately. These findings align with the work of Talla et al. [37] and Ganamé et al. [6] who demonstrated that species-specific allometric equations are more accurate in predicting aboveground biomass than pantropical equations developed by Chave et al. [17]. The above-ground allometric equation developed in this study has applicability for the non-destructive assessment of biomass.

Detarium microcarpum biomass and carbon partition

Evaluating biomass and carbon storage is essential for global climate mitigation efforts, as they are integral to assessing the impacts of climate change and devising mitigation strategies. This investigation underscores the significant contribution of woody components, especially stems and branches, to aboveground biomass across various climates. Notably, branches emerge as the primary contributor to aboveground biomass in both studied climates, echoing findings from previous studies in Burkina Faso involving species like *Balanites aegyptiaca* and *Pterocarpus erunaceus*. Contrarily, earlier research by Henry et al. [77] and Bouslimi et al. [59] highlighted the dominance of stem biomass in total aboveground mass, suggesting that differences could stem from species-specific physiological traits and ecological factors [39].

The resilience of *Detarium microcarpum* to extreme heat and drought, as noted by Kouyaté et al. [78], further supports the variability in biomass contributions in the Sudano-Sahelian climatic zone. The relationship between increased biomass fractions and diameter at

breast height (dbh) correlates with the growth of new branches and leaf loss [79] revealing that the dbh influenced the model precision than the other parameters in the Sudanian climatic zone. Among the three components (stem, branch, and leaves), the leaves exhibit lower carbon content, indicating a significant disparity in carbon distribution between foliage and woody parts (branches and stem). This observation aligns with previous research on *Vitellaria paradoxa* and *Balanites aegyptiaca* but suggests a higher carbon content in the current study, potentially attributed to species-specific physiology [18,32].

The presence of lignin in woody tissues and its absence in foliage, as identified by Ganamé et al. [20], contributes to the differential carbon allocation within trees. Biomass and carbon levels are notably higher in the Sudano-Sahelian zone compared to the Sudanian zone, influenced by environmental conditions and nutrient availability [21,59]. Environmental factors such as temperature, rainfall, and general weather patterns significantly affect carbon sequestration processes, with savanna species exhibiting adaptive mechanisms to enhance carbon absorption under reduced precipitation [80,81].

Conclusion

The diameter at breast height is the best predictor in the Sudano-Sahelian climatic zone and for the branch and foliage biomass estimation in the Sudanian climatic zone, while the stem requires tree height as an additional predictor ($\text{dbh}^2 \times \text{ht}$). In each climate zone, the best allometric model outperformed the pantropical model developed by Chave et al. [17] for estimating biomass in tropical species. These results support the hypothesis that the local allometric model could better explain biomass variability when total height and diameter at the breast are included in the fitting process since these parameters are highly correlated with growth type and the physical properties of trees. The findings highlighted that the biomass production, and carbon contents, vary between the Sudanian and the Sudano-Sahelian climatic zones and the three components of the *Detarium microcarpum* trees. The use of the model could help achieve this goal and can be a valuable tool in the implementation of the Greenhouse Gas Monitoring System in Burkina Faso.

Availability of data and materials

Data will be made available on request.

Consent for publication

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

CRediT authorship contribution statement

Adama Taonda: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Issouf Zerbo:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Innocent Charles Emmanuel Traore:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Fousseni Folega:** Conceptualization, Data curation, Methodology, Validation, Visualization, Writing – original draft. **Anny Estelle N'Guessan:** Conceptualization, Data curation, Methodology, Validation, Visualization, Writing – original draft. **Justin N'Dja Kassi:** Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing. **Adjima Thiombiano:** Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Declaration of interests

The authors declare no conflict of interest of this article.

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UNIVERSITE JOSEPH KI-ZERBO

LABORATOIRE DE BIOLOGIE ET ECOLOGIE VEGETALES



ATTESTATION DE COMMUNICATION

Taonda Adama

a présenté une communication orale intitulée «*Local perceptions of anthropogenic and climate factors affecting the use and conservation of Detarium microcarpum (Guill. & Perr.) and Detarium senegalense (J.F. Gmel.) in Burkina Faso (West Africa)*», lors du **Colloque scientifique International en Hommage au Professeur Sita GUINKO** tenu du 20 au 22 septembre 2023 à l'Université Joseph KI-ZERBO, Burkina Faso.

En foi de quoi, la présente attestation lui est délivrée pour servir et valoir ce que de droit.

Le Président du Comité d'organisation

Prof. Amadé OUEDRAOGO

Chevalier de l'ordre des Palmes Academiques





UNIVERSITÉ
THOMAS SANKARA

SCIENCE - INTEGRITÉ - SOCIÉTÉ

CENTRE UNIVERSITAIRE DE TENKODOGO

JOURNÉES SCIENTIFIQUES DU CENTRE UNIVERSITAIRE DE TENKODOGO

1^{re} ÉDITION LES 25, 26 ET 27 NOVEMBRE 2024 À TENKODOGO (BURKINA FASO)

THÈME GÉNÉRAL : Le développement rural à l'intersection des sciences humaines et agronomiques :
quelles problématiques pertinentes pour un développement local intégré ?

ATTESTATION DE COMMUNICATION

Monsieur **TAONDA Adama**

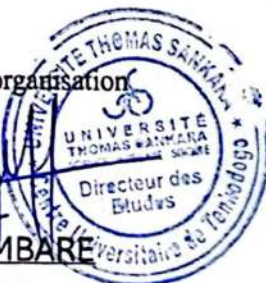
a présenté une communication orale sur « Dendrochronology Potential of the Savanna
Multipurpose Species for Ecological Studies in Burkina Faso: Case of *Detarium microcarpum* ».

En foi de quoi la présente attestation lui est délivrée pour servir et valoir ce que de droit.

Pour le comité d'organisation

Dr Oumarou SAMBARE

Maitre de Conférences



Fait à Tenkodogo, le 27 novembre 2024



Pour le comité scientifique

Pr Joseph Issiaka BOUSSIM

Officier de l'ordre des Palmes Académiques





Direction de la Recherche et de l'Innovation
Journées Scientifiques Internationales de Lomé



ATTESTATION DE COMMUNICATION

délivrée à :

TAONDA Adama

Sur le thème :

Allometric models for estimating aboveground biomass and carbon stocks of the semi

A l'occasion des **JOURNÉES SCIENTIFIQUES INTERNATIONALES DE LOMÉ XX^e ÉDITION**

placées sous le thème :

**RECHERCHE ET INNOVATIONS AU SERVICE DE LA TRANSFORMATION
STRUCTURELLE ET DU DÉVELOPPEMENT DES PAYS AFRICAINS**

Le Directeur de la Recherche et de l'Innovation

LOME DU 07 AU 11 OCTOBRE 2024



Prof. Essohanam BOKO



Société Nouvelle des
Phosphates du Togo





COLLOQUE INTERNATIONAL PLURIDISCIPLINAIRE AWACLIM 2024

Changements climatiques, ressources naturelles, agriculture, santé et développement durable

ATTESTATION DE COMMUNICATION

Délivrée à

TAONDA Adama

Pour sa participation au colloque et sa communication intitulée :

« USING ALLOMETRIC EQUATIONS TO ESTIMATE CARBON STOCKS IN TREE BIOMASS OF DETARIUM MICROCARPUM GUILL. ET PERR. IN BURKINA FASO, WEST AFRICA »,

les 15, 16 et 17 octobre 2024 à l'Université Peleforo GON COULIBALY (Korhogo / Côte d'Ivoire).

En foi de quoi, cette attestation est délivrée pour servir et valoir ce que de droit.

Fait à Korhogo, le 17 octobre 2024

Président de l'AWACLIM



Professeur VISSIN EXPEDIT WILFRID

Présidente du Comité d'Organisation



Dr (MC) TAPE SOPHIE PULCHERIE

Doyen de l'UFR des Sciences Sociales



Dr (MC) KONAN KOUAME HYACINTHE



Université des Sciences, des Techniques
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4^{ème} Journée Scientifique
DER DE BIOLOGIE FST/USTTB



Faculté des Sciences
Techniques (FST)

ATTESTATION DE COMMUNICATION

Je Soussigné, Professeur Alhousseini BRETAUDEAU, Président de la Commission Scientifique, atteste que

Adama TAONDA

a pris part à la 4^{ème} Journée Scientifique du DER de Biologie de la FST-USTTB tenue le 25 novembre 2023 à Bamako (Mali) et y a présenté la/les communication(s) numéro(s) **JSDB4-CO-129**.

Thème « Sciences Biologiques et Développement Durable »

En foi de quoi la présente attestation lui est délivrée pour servir et valoir ce que de droit.

Fait à Bamako, le 25 Novembre 2023



Pr Alhousseini BRETAUDEAU
Président de la Commission Scientifique



Pr Issiaka TOGOLA
Chef de DER de Biologie FST-USTTB



Pr Bernard A. SODIO
Doyen de la FST-USTTB



UNIVERSITE
DE KARA

Projet de semaine
Écologique

ATTESTATION DE COMMUNICATION

Décernée à

M. TAONDA Adama

pour avoir participé et communiqué au Colloque Scientifique International dans le cadre de la troisième édition du Projet de Semaine Écologique du 18 au 19 janvier 2024 à l'Université de Kara, Togo.

Thème du colloque : La transition écologique en Afrique : entre dynamiques et perspectives

Titre de la communication : Predicting the distribution of Detarium microcarpum (Fabaceae) under the current and future effects of the climate in Burkina Faso (West Africa)

Type de la communication : Orale

En foi de quoi, la présente attestation lui est délivrée pour servir et valoir ce que de droit.

Fait à Kara, le 19 janvier 2024

Le Président du comité d'organisation,



BINI Essonam (MC)

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- <http://viewfinderpanoramas.org>
- <https://wfoplantlist.org/plant-list/>
- <https://www.worldclim.org/data/worldclim21.html>
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- <http://www.gbif.org/>