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ETHNOBOTANY AND ECOLOGICAL ADAPTATION OF THE BLACK PLUM (*VITEX DONIANA* SWEET) TO CLIMATIC CONDITIONS IN BENIN, WEST AFRICA: IMPLICATIONS FOR CONSERVATION AND DOMESTICATION

Achille HOUNKPEVI

Public defence on December, 21st 2016

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ECOLE DOCTORALE CHANGEMENT CLIMATIQUE ET BIODIVERSITE

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THESE

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Spécialité: Changement climatique et biodiversité

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Achille HOUNKPEVI

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DEDICATION

To

My parents: Pierre A. Hounkpèvi and Agnès A. Yazin, as a reward of your sacrifices

My wife: J. Chantale V. Ahokpè, as a consolation for your support and sacrifices during my several long absences from home

To my sons: A. Ronel Dodji and A. Rostan Dona, as an example to follow

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FOREWORD

This dissertation is submitted to the Graduate Research Programme Climate Change and Biodiversity as a requirement to obtain the Doctorate grade of Félix Houphouët-Boigny University (Abidjan, Côte d'Ivoire). It is the result of three years of research activities in Benin and was financially supported by the German Ministry of Education and Research (BMBF) through the West African Service Centre on Climate Change and Adapted Land use (WASCAL).

In this work, we studied *Vitex doniana* Sweet, an important multipurpose plant species in tropical Africa, in order to improve knowledge on its ethnobotany and on its adaptive mechanisms to fit in various climatic zones of Benin. The study was conducted in order to provide baseline information for the implementation of ecosystem-based adaptation approaches using *V. doniana* to face climate change. Firstly, traditional ecological knowledge on uses values and perceptions of climate change and its impacts on the biology and productivity of the species was capitalized. Secondly, the ecological and structural characteristics of the species were studied along a climatic gradient. Morphological characterization of the species was thereafter carried out in relation to climatic parameters with focus on its trunk, canopy, leaves and fruits. Furthermore, the radial growth patterns and wood anatomy including size, shape and density of vessels were evaluated in the two contrasting climatic zones of the country. Finally, impacts of current and future climate on the habitat suitability for cultivation and conservation of the species were assessed through species distribution modelling.

The study highlighted the ecological, morphological and geographical range adaptations developed by the species in its occurrence zones. It provided relevant information for the integration of the species in ecosystem-based adaptation strategies through domestication and sustainable management schemes development for the species in the context of climate change.

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LIST OF ACCRONYMS

AIC	:	Akaike's Information Criterion
AMS	:	American Meteorology Society
ANOVA	:	Analysis of Variance
ASECNA	:	Agence pour la Sécurité de la Navigation Aérienne
AUC	:	Area Under the receiver operating characteristic Curve
CMIP5	:	Coupled Model Intercomparison Project phase 5
CNRA	:	Centre National de Recherche Agronomique
dbh	:	diameter at breast height
EBA	:	Ecosystem-Based Adaptation
ENMT	:	Environmental Niche Modelling Tools
EPS	:	Expressed Population Signal
GBIF	:	Global Biodiversity Information Facility
GDP	:	Gross Domestic Product
GLK	:	*Gleichläufigkeit* (coefficient of uniformity)
GLM	:	Generalized Linear Models
GPS	:	Global Positioning System
HadGEM2-ES	:	Hadley Global Environment Model version 2 – Earth System
IATS	:	Indigenous Agroforestry Tree Species
IPCC	:	Intergovernmental Panel on Climate Change
MASS	:	Modern Applied Statistics with S
MaxEnt	:	Maximum Entropy
MIROC5	:	Model for Interdisciplinary Research on Climate Change version 5
MS	:	Mean Sensitivity
NMDS	:	Non-metric Multidimensional Scaling
PAN	:	Protected Areas Network
PCA	:	Principal Components Analysis
PPUV	:	Plant Part Use Value
RCP	:	Representative Concentration Pathway
RDA	:	Redundancy Analysis
RUV	:	Reported Use Value
SDM	:	Species Distribution Modelling
TEK	:	Traditional Ecological Knowledge
TRW	:	Tree-Ring Width
TSAP	:	Time Series Analysis and Presentation
TSS	:	True Skill Statistic
UAC	:	Université d'Abomey-Calavi
UDA	:	Université de Diffa
UFHB	:	Université Félix Hounphouët-Boigny
UFV	:	Use Form Value
UNA	:	Université Nangui Abrogoua

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ABSTRACT

Climate change is projected to highly impact biodiversity components such as ecosystems and organisms. Through this work, *Vitex doniana* Sweet, one of the top ten priority species for domestication programs in West Africa was used to understand some of the mechanisms developed by plants to fit in various climatic environments. Uses values and perceptions of local people on climate change and its impacts on the biology and productivity of species were assessed through ethnobotanical survey. Ecology, structural parameters and the morphological variability of the species were assessed along transects within climatic zones of Benin. Radial growth and wood anatomical patterns of the species were studied in the two extreme (wet vs. dry) climatic zones using tree rings. Finally, impacts of current and future climates on the habitat suitability for cultivation and *in situ* conservation of the species were assessed through species distribution modelling using the Maximum Entropy algorithm (MaxEnt). The findings confirmed that *V. doniana* is an important agroforestry species diversely appreciated by local people depending on their ethnicity and age category. Shortening of rainy season's length and temperature raising are the most reported perceptions on climate change. According to local people, these changes affect negatively the biology and productivity of the species. Regarding the ecology of the species, whatever the climatic zone, the species is more frequent in mosaics of croplands and fallows, and in areas close to river (less than 500 m). Structural parameters, mainly mean diameter (Dg) and basal area (Ba) of the species are under combined effects of climatic zone and land cover. The study revealed a relatively low climate-induced variability of morphological traits. Trees from the Sudanian region are the biggest, with fruits producing little pulp while individuals from the Guinean zone present a higher amount of pulp. Sudano-Guinean trees are the tallest with larger leaves. As far as the tree-ring analysis is concerned, trees from both climatic zones show common signal with a similar annual radial growth rate (0.8 cm/year). Vessels features vary significantly between stands with larger and more circular vessels in the Guinean zone. However, vessels are more abundant in rings from Sudanian trees. Finally, under current climatic conditions, about 85 % of Benin area is potentially suitable for the cultivation of *V. doniana* and, increase of 3 to 12 % of this habitat is projected under future climatic conditions for the year 2050. Moreover, a large proportion (76.28 %) of the national PAN was reported as potentially suitable for the *in situ* conservation of the species under current climate. This proportion is also projected to increase by 14 to 23 % under future climate. These findings highlighted some of the opportunities of integrating the black plum in the formal production systems of Benin and also its potentialities for ecosystem-based adaptation approaches implementation.

Keywords: Benin, climate change, neglected and underutilized species, plant ecology, plant morphology, species distribution, *Vitex doniana*, wood anatomy

RESUME

Les changements climatiques ont d'importants impacts sur les composantes de la biodiversité tels que les écosystèmes et les organismes. A travers ce travail, *Vitex doniana* Sweet, une des dix espèces agroforestières prioritaires pour les programmes de domestication en Afrique occidentale, a été utilisée pour comprendre certains des mécanismes développés par les plantes pour s'adapter à différents environnements climatiques. Les valeurs d'usage et les perceptions des populations locales sur les changements climatiques et ses impacts sur la biologie et la productivité de l'espèce ont été évaluées à travers des enquêtes ethnobotaniques. L'écologie, les paramètres structuraux et la variabilité morphologique de l'espèce ont été évalués le long de transects au sein des zones climatiques du Benin. La croissance radiale et l'anatomie du bois de l'espèce ont été étudiées dans les deux zones climatiques extrêmes (humide vs. sèche) du pays en utilisant les cernes de bois. Enfin, les impacts des climats actuel et futur sur les habitats favorables à la culture et la conservation de l'espèce ont été évalués à travers la modélisation de sa niche climatique en utilisant l'algorithme du maximum d'entropie (MaxEnt). Les résultats confirment que *V. doniana* est une importante espèce agroforestière diversement appréciée par les populations locales selon leur ethnie et âge. Le raccourcissement de la longueur de la saison pluvieuse et l'élévation de la température sont les perceptions locales les plus signalées en ce qui concerne les changements climatiques. Selon la population locale, ces changements affectent négativement la biologie et la productivité de l'espèce. En ce qui concerne l'écologie de l'espèce, quelle que soit la zone climatique, l'espèce est plus fréquente dans les champs et jachères, et à proximité des rivières (moins de 500 m). Ses paramètres structuraux, notamment le diamètre moyen (Dg) et la surface terrière (Ba) sont sous les effets combinés de la zone climatique et du couvert végétal. L'étude a révélé que le climat induit une variabilité relativement faible des traits morphologiques. Les arbres de la zone soudanienne sont les plus gros, avec des fruits produisant peu de pulpe, alors que ceux de la zone guinéenne présentent une plus grande quantité de pulpe. Ceux de la zone soudano-guinéenne sont les plus grands avec de plus large feuilles. En ce qui concerne l'analyse des cernes, les arbres des deux zones climatiques présentent des signaux communs avec une croissance radiale annuelle similaire (0,8 cm/an). Les caractéristiques des vaisseaux varient significativement entre les zones avec les plus larges et circulaires vaisseaux dans la zone Guinéenne. Toutefois, les vaisseaux sont plus abondants dans les cernes des arbres du Soudanien. Enfin, sous les conditions climatiques actuelles, environ 85% de la superficie du Bénin est potentiellement favorable à la culture de *V. doniana* et, une augmentation de 3 à 12% de cet habitat est projetée sous les conditions climatiques de l'année 2050. De plus, une grande proportion (76,28%) du réseau national d'aires protégées du pays est potentiellement favorable à la conservation de l'espèce sous le climat actuel. Cette proportion aussi augmentera de 14 à 23% sous le futur climat. Ces résultats mettent en évidence quelques-unes des possibilités d'intégration du prunier noir dans les systèmes formels de production au Bénin et aussi ses potentialités pour la mise en œuvre des approches basées sur les écosystèmes pour l'adaptation aux changements climatiques.

Mots clés: Anatomie du bois, Bénin, changements climatiques, espèces négligées et sous-utilisées, écologie des plantes, morphologie des plantes, distribution des espèces, *Vitex doniana*

PART I: INTRODUCTION

1.1. Problem statement and justification of the study

Climate change, one of the biggest challenges affecting our planet since decades, is mainly viewed as changes over time in weather parameters such as temperature, precipitation and wind. Yet, increases in temperature are considered the most illustrative indicator **(de Chazal and Rounsevell, 2009)**. Despite well acknowledged conflicting views, there is evidence of a strong correlation between rises in emissions of greenhouse gases, mainly carbon dioxid (CO_2) by human activities (deforestation, industrialisation, etc.) and global warming **(IPCC, 2014)**. Although emissions from developing countries, particularly in Sub-Saharan Africa, are quite low, this region is expected not only to be the most affected but also the least capable to face the projected negative impacts of climate change **(IPCC, 2014)**. Climate proofing key sectors in sub-Sahara Africa, such as agroforestry, should therefore be given high global priority.

Several reportedly promising approaches are being considered to ensure local adaptation to climate change, including ecosystem-based adaptation (EBA) approaches **(Doswald and Osti, 2011; Fandohan *et al.*, 2015a)**. These ecosystem-based approaches for adaptation to climate change imply the use of local biodiversity and ecosystem services as adaptive strategy to help people in facing the adverse impacts of climate change **(Convention on Biological Diversity, 2009; Doswald and Osti, 2011; Munang *et al.*, 2013)**. Within this EBA framework, indigenous agroforestry trees species (IATS) are seen as key components because of their potential role in buffering the sociocultural and economic impacts of climate change, and their strong ability for environment stabilization and ecological restoration **(Akinnifesi *et al.*, 2008; Bayala *et al.*, 2014; Fandohan *et al.*, 2015a)**. For instance, maintaining these IATS in agricultural lands, is a strategy adopted by many farmers to satisfy their needs for essential resources like food, medicine, fodder, fuel and other market commodities. In the same time, these species contribute to important environmental services provision such as soil fertility improvement, water catchment protection, carbon sequestration, biodiversity conservation and ecosystems restoration **(Akinnifesi *et al.*, 2008; Garrity *et al.*, 2010)**. Although it is still unclear which of these species are more likely to withstand climate change, their integration into formal production systems could play a key role in the implementation of EBA approaches to climate change **(Fandohan *et al.*, 2015a)**. Therefore, it is crucial to document traditional ecological knowledge (TEK) on these plant species with regard to climate change, and to assess adaptive mechanisms developed by them in facing threats like land cover and climate changes in order to promote their integration in EBA approaches.

Regardless of the approach, there is an increasing agreement that traditional ecological knowledge (TEK) on plant species on one hand, and on climate change on the other hand, is relevant for conservation and domestication strategies formulation and implementation **(Ishaya and Abaje, 2008)**. Indeed, TEK could provide useful information, e.g., on how changes in the environmental conditions are affecting plant species and how local people are coping with the impacts resulting from these changes. Studies on perceptions of local people on climate change are now routine, yet, agroforestry species have so far received little attention **(Brou *et al.*, 2005; Fandohan *et al.*, 2015a)**. Previous attempts to fill in this gap (e.g. in Benin) have illustrated local awareness on changes in the climate and some perceived impacts on agroforestry systems including *Vitellaria paradoxa* dominated parklands **(Gnanglè *et al.*, 2011; Gnanglè *et al.*, 2012; Teka *et al.*, 2013)**. In addition to this TEK, taking into account the mechanisms developed by plant species to fit in various habitats is crucial for their efficient integration in EBA approaches.

Indeed, several mechanisms are developed by plant species to survive to climate change depending on the species and their geographic location **(FAO, 2012)**. These mechanisms imply phenotypic and or genetic adjustments, with the phenotypic processes being the most rapid and important **(Hoffmann and Sgro, 2011; Bellard *et al.*, 2012)**. Regarding these phenotypic processes, variation in morphological, physiological or behavioural characteristics are the most relevant **(Chevin *et al.*, 2010)**. Thus, morphotypes development has been reported to favour species fitness in the changing environment **(Visser, 2008)**. Also, wood anatomy adjustment (vessels size and distribution) is suggested to be relevant for water transport and use **(Fernandez *et al.*, 2012)**. Furthermore, geographical range expansion or contraction could help species in finding suitable climatic conditions **(Hannah *et al.*, 2002; Fandohan *et al.*, 2013)**. However, do all plant species use the same strategies of adaptation? It is therefore, important to assess the ecology, the morphology, the wood anatomy and the geographical range of given species occurring under various climatic conditions in order to predict some of its responses to climate change and foster its domestication and conservation which can be valued in EBA approaches.

The black plum (*Vitex doniana* Sweet) is one of the key agroforestry species spared by farmers during land clearing activities. It is a plant species widespread in savannah regions, of which most organs are valued as food and or in traditional pharmacopoeias. Previous research endeavours on this species have yielded substantial information. Its young leaves are used in sauce preparation, and ripened fruits are consumed fresh or used for jam and for some locally made drinks preparation **(Ky, 2008; Dadjo *et al.*, 2012)**. The mature leaves, the bark and the roots are common ingredients in traditional healing systems **(Kilani, 2006; Padmalatha *et al.*, 2009)**.

In Benin, the black plum is known as an agroforestry fruit tree widespread in the three climatic zones of the country and, it has a high socio-economic value **(Oumorou *et al.*, 2010; Achigan-Dako *et al.*, 2011; Dadjo *et al.*, 2012)**. According to **Dadjo *et al.* (2012**), knowledge on the species is well distributed among communities in the southern part of Benin, with people showing diverse interests in its uses and management. Food and medicine are however its major use categories. These previous findings cannot however be representative of the national body of knowledge on this species, provided that data were collected in a couple of socio-culturally related villages. Since the black plum is a nation-widely distributed species, it is important to have the nation body knowledge if a climate proofed sustainable use plan is to be developed for such a species across three different ecological regions.

In addition, although the black plum ranks among the top ten priority species for domestication programs in West Africa **(Akinnifesi *et al.*, 2008)**, it is not certain whether it has a high climate change adaptation value (e.g., resilience or capacity to withstand critical climatic changes in its native habitats). In the current context and the foreseeable changes in the climate, screening agroforestry species for climate change value is of prime importance for maintaining productivity of agroforestry systems **(Fandohan *et al.*, 2015a)**.

Indeed, with the high plasticity of *V. doniana* in habitat selection **(Arbonnier, 2004; Ky, 2008)**, the species may have developed specific patterns in regard to its environment **(Anyomi *et al.*, 2012; Mensah *et al.*, 2014)**. For instance, following insights from previous studies which showed impacts of climatic variability on structural parameters of some plant species **(Fandohan *et al.*, 2011c; Glèlè Kakaï *et al.*, 2011; Nacoulma *et al.*, 2011; Ouédraogo *et al.*, 2013; Mensah *et al.*, 2014)**, we expect that *V. doniana* shows heterogeneity in its ecological, morphological and growth patterns regarding the climatic environment. Therefore, a countrywide assessment on the black plum with focus on its ethnobotany, ecology, morphology, growth and wood anatomy, and geographic climatic range, could help in capitalizing information on its capacities to adapt to climate change. Moreover, such information might be of high importance for future domestication and conservation programmes on the species and therefore for EBA approaches implementation.

1.2. Objectives of the study

The overall goal of this study is to improve knowledge on the ethnobotany of *Vitex doniana* and on the adaptive mechanisms used by the species to fit in various climatic zones of Benin in order to provide baseline information for the implementation of ecosystem-based adaptation approaches using *V. doniana* to face climate change. Specifically, its objectives are to:

(i) Capitalize traditional ecological knowledge on uses of the black plum and on perceptions of local people on climate change and its impacts on the biology and productivity of the species

(ii) Elucidate the ecological conditions under which the black plum occurs and characterize the structure of its population

(iii) Assess the climate-induced morphological variability of the species

(iv) Analyse the radial growth and wood anatomical patterns of the species in relation with climatic conditions

(v) Model habitat suitability for cultivation and *in situ* conservation of the species under current and future climates.

These objectives were addressed in order to develop a consistent database for the sustainable management and domestication policies of *Vitex doniana*. Thus, use values of the species and perceptions of local people about climate change and its potential impacts on the species were firstly evaluated for a better understanding of its ethnobotany. After that, its ecology, morphology, radial growth and wood anatomy (size, shape and density of vessels) were studied in relation with climatic conditions to identify the coping mechanisms developed by the species to survive in different climatic habitats. Finally, impacts of current and future climates on habitat suitability for cultivation and *in situ* conservation of the species were assessed to highlight its potentialities in facing climate change.

1.3. Research questions

To address the objectives of the study, the following research questions were answered:

- How do local people value the black plum in Benin?
- Are local people aware of changes in climatic parameters and, do they relate some disturbances on *V. doniana* to these changes?
- What are the important occurrence areas of the black plum regarding climatic zone, land cover type and distance to river?
- What are the impacts of those environmental parameters on the population structure of the species?
- Does climate affect the morphology of the species?
- What are the morphological traits that discriminate *V. doniana* trees regarding climatic zones, and what are the relationships between those traits and bioclimatic parameters?
- Do the growth and wood anatomical patterns of the species vary between climatic zones?
- What are the effects of climatic parameters on tree ring and vessel characteristics of the species?
- What are the most important bioclimatic predictors of the distribution of *V. doniana*?

- How do current and future climate affect the habitat suitability for the cultivation and *in situ* conservation of the species in Benin?

1.4. Organisation of the thesis

This dissertation is organised in six parts:

- The first part (current section) presents the problem and justification of the study through a global overview on climate change and importance of IATS in local adaptation and mitigations strategies. It also describes the objectives of the research, and it presents the structure of the thesis.
- The second part deals with a literature review with focus on climate change and its impacts on ecosystems and organisms. It presents also a review of the botanical, ecological and morphological description, and the socio-economic importance of the black plum.
- The third part describes the study area, material and methods used to address the objectives of the study.
- The fourth and fifth parts present the findings of the study and their discussion, respectively.
- The sixth part concludes the study. It presents the implications of the study and gives some perspectives for future research.

PART II: LITERATURE REVIEW

2.1. Climate change and its impacts on ecosystems and organisms

Climate change refers to the change and or to the variability in average of weather patterns persisting for an extended period of time, typically decades to millions of years in a statistical point of view **(IPCC, 2014)**. It may be caused by some natural internal processes (i.e. natural features of the land – ocean – atmosphere climate system) or by other external forces such as solar radiations, volcanic eruptions and the persistent changes in the composition of the atmosphere due to certain human activities such as fossil fuels burning, agriculture, deforestation, etc. **(IPCC, 2013, 2014)**. The implications of this climate variability and change are significant for the long-term stability of natural ecosystems and for the many benefits and services that humans take from them **(Lucier *et al.*, 2009)**. For that, several studies have been undertaken in order to better explain its impacts on biological systems i.e. ecosystems and organisms for developing strategies for adaptation and mitigation **(Parmesan, 2006)**.

It is obvious that climate change is negatively impacting biodiversity components such as ecosystems and organisms **(Campbell *et al.*, 2009; FAO, 2012; IPCC, 2014)**. Most of these impacts have been predicted and several are being observed already **(Walther *et al.*, 2002; Campbell *et al.*, 2009; FAO, 2012)**. These impacts occurred at all the scales of biodiversity from individual (organism) to biome, and they are potentially driving ecosystem services provision for human's well-being **(IPCC, 2014)**. The most extreme and irreversible impact is obviously species extinction and, to avoid or reduce its amplitude, biodiversity components mainly organisms, must produce adaptive responses. Whatever the adaptation mechanism used, species responses to climate change have been observed along three distinct and non-exclusive axes: time (e.g. phenology), space (e.g. range) and self (e.g. physiology), with the first two axes being the most easily observable and well documented proofs **(Parmesan, 2006)**.

In the temporal point of view, to respond to changing abiotic factors, individuals can shift in time (on a daily to seasonal basis) by adjusting their phenology. Phenology is the timing of life cycle events such as leafing, flowering and fruiting as far as plant species are concerned. Shift in key phenological events is one of the most ubiquitous responses to the 20th century climate warming and, it has already been documented in many species **(Parmesan, 2006; Charmantier *et al.*, 2008)**. These phenological changes could help species to keep synchrony with critical abiotic factors, and they can occur at a small temporal scale **(Bellard *et al.*, 2012)**.

Regarding the spatial axis, through dispersion, species can track appropriate conditions and follow them. Species shift then their distribution to stay in quasi-equilibrium with the climatic conditions they are adapted to **(Bellard *et al.*, 2012)**. Modelling studies combined with experimental trials on species tolerance showed significant changes in the distribution of some species and ecosystems, principally due to the increasing temperature and/or to the alteration of precipitation regimes **(Walther *et al.*, 2002; Campbell *et al.*, 2009)**. Several reports and studies have predicted that in addition to shifting ecosystems locations, climate change will alter the composition of many ecosystems **(FAO, 2012)**. In this sense, there will be decreases in plant species richness in some areas and increases in others regions **(Sommer *et al.*, 2010)**. Also, there will be changes in vegetation density according to the characteristics of each ecosystem **(Kalame *et al.*, 2009; FAO, 2012)**. At species level, recent observed evidences showed that climate change has already caused changes in the distribution of many plants and animals species **(Campbell *et al.*, 2009; Lucier *et al.*, 2009)**. Indeed, some studies revealed that geographical shifts due to climate change will likely occur on an individual species level, rather than on forest type level and this is mainly because some species will be able to adapt better to changing conditions than others. Moreover, this will allow changes in species composition of forest types, rather than geographic shifts of forest types **(FAO, 2012)**. In West Africa for instance, forests ecosystems are already facing impacts of climate change and climate variability with increases in trees mortality, and decreases in forest species richness and trees density **(Kalame *et al.*, 2009)**. Southward shift of Sudanian and Guinean tree species and a southward expansion of Sahelian tree species have also been reported in the region **(Gonzalez, 2001)**. However, these species may not be adapted to other abiotic variables such as photoperiod or novel biotic interactions. In such cases, they can undergo either plastic or micro-evolution to fit in the new environment **(Visser, 2008; Bellard *et al.*, 2012)**. It has been well documented that species distribution is driven by climatic and non-climatic factors, with climate playing a determinant role **(Walther, 2003; Adomou *et al.*, 2006; Sommer *et al.*, 2010)**. There are evidences that change in climate will impose physiological constraints on species and therefore affect their distributions **(Busby *et al.*, 2012)**. Species distribution modelling (SDM) are widely used to determine habitat suitability patterns at large spatial scales and to produce spatially explicit and comprehensive maps that are particularly useful for identifying areas where conservation efforts are most needed or effective. Generally, these SDM techniques taking into account information on habitat requirements derived from known occurrence sites are widely used to predict potential habitat of species under current or future conditions. Even if these models can not indicate the realised distribution, they provide relevant habitat suitability information for given species and, they can guide sustainable management plans **(Phillips *et al.*, 2006; Sommer *et al.*, 2010; Schwartz, 2012)**. This information on the derived distribution map of a species is useful in identifying suitable areas for cultivation and assessing conservation status of a target species by protected areas networks **(Fandohan *et al.*, 2011b; Schwartz, 2012; Fandohan *et al.*, 2013; Tantipisanuh *et al.*, 2016)**.

As far as the third axis is concerned, through physiological adjustments allowing tolerance to wetter or drier conditions, or through behavioural modifications of diet, activity and energy budget, species cope with changing climatic conditions by adjusting their metabolism to new conditions in their local range. The underlying mechanisms of these responses are of several time-dependent types such as plastic (i.e. phenotypic) and or genetic adjustments **(Parmesan, 2006; Bellard *et al.*, 2012)**. The plastic mechanisms occur through very short-term (within individual's lifetime) responses to environmental changes **(Charmantier *et al.*, 2008)**. They imply mostly intraspecific variation in morphological, physiological or behavioural traits, and they can occur on different time scales within the species' spatial range **(Chevin *et al.*, 2010)**. Long-term processes can also be genetically developed (mutations or selection of existing genotypes) to adapt to new conditions **(Salamin *et al.*, 2010)**. Empirical evidences suggested that plastic adaptations are often more important than genetic contribution **(Hoffmann and Sgro, 2011)**. However, these plastic or genetic adaptations are often less obvious than time or space dependent responses **(Bellard *et al.*, 2012)**.

2.2. Taxonomy, botany, ecology and socio-economic importance of the black plum

2.2.1. Taxonomy

The genus *Vitex* was previously classified in Verbenaceae family, but based upon several phylogenetic studies, it has been transferred to Lamiaceae family (subfamily Viticoideae), as well as other genera such as *Clerodendrum* and *Tectona* **(Harley *et al.*, 2004; Cabral, 2013)**. Lamiaceae is one of the 23 families of the Lamiales order **(Angiosperm Phylogeny Group, 2009)**. It includes about 236 genera and is one of the most important families of the order **(Harley *et al.*, 2004)**. *Vitex* is among the largest genera of the family (3.6% of Lamiaceae) and comprises about 250 pan-tropical, subtropical and a few temperate species. Most of these species are shrubs and trees from 1 to 35 m tall. Among these species, about 60 occur in tropical Africa, with *Vitex doniana* Sweet being the most abundant and widespread **(Ky, 2008; Orwa *et al.*, 2009)**.

Vitex doniana is also called *V. cuneata* Schumach. & Thonn., *V. cienkowskii* Kotschy & Peyr., *V. paludosa* Vatke, *V. dewevrei* De Wild. & T. Durand, *V. pachyphylla* Baker, *V. hornei* Hemsl., *V. homblei* De Wild, *V. puberula* Baker or *V. umbrosa* G. Don ex Sabine **(The Plant List, 2013)**. In English, the species is named “Black plum”, “West African plum” or “African oak” while in French it is called “Prune des savanes” or “Prunier noir” **(Akoegninou *et al.*, 2006; Ky, 2008)**.

2.2.3. Botany

The black plum exhibits an important variability regarding its morphology. It is a deciduous plant species with a small to medium size, up to 25 m tall. It often presents a branchless trunk for up to 11 m, often slightly fluted at base, and with a diameter which can reach 160 cm. Its crown is heavy and rounded (Photo 1a). The bark surface is greyish white to pale brown, often rough with narrow vertical fissures (Photo 1b). The inner bark is yellowish white darkening to brown in contact with air. Leaves are glabrous, without stipules, 14-34 cm long, opposite and digitately compound with usually 5 or rarely 7 leaflets (Photos 1c & d). Leaflets are distinctly stalked, ovate to obovate-elliptic, entire, 8-22 cm long and 2-9 cm wide, notched to rounded or shortly acuminate at apex and nearly glabrous. Petiole length ranges from 5 to 20 cm and that of petiolule varies from 0.5 to 2.5 cm. Its inflorescence is an axillary cyme up to 10 cm long and 16 cm wide, orange-brown hairy (Photo 1e). Flowers are numerous, small (3-12 mm in diameter), bisexual and zygomorphic with white pinkish to purple corolla, tube 6-8 mm long, limb 4-lobed and pubescent 5-teeth conical calyx. The fruit is an obovoid to oblong-ellipsoid drupe (2–3 cm long), green when young and turning purplish-black once ripe (Photo 1f) with a starchy black pulp. It is surrounded at the base with a persistent calyx expanded in cup. It contains a hard conical core (1.5-2 cm long, 1-1.2 cm wide) with up to four seeds **(Arbonnier, 2004; Ky, 2008; Orwa *et al.*, 2009)**. Regarding the wood anatomy, the black plum presents a diffuse porous wood in which vessels exhibit little or no variation in size within growth ring. Ring boundaries are distinct or indistinct. The density of vessels in the wood varies from 5 to 20 vessels per square millimetre **(Ky, 2008)**.

a. Overview

b. Bark surface

c. Young leaves

d. Leaves and unripe fruits

e. Leaves and flowers

f. Ripe fruits

Photo 1: Overview, bark surface, leaves, flowers and fruits of *Vitex doniana*

Photos by Hounkpèvi (fieldwork in 2014)

2.2.4. Ecology, biogeography and propagation

Vitex doniana occurs in various habitats from savannahs to forests, including farmlands and fallows, often in wet localities and along rivers, and on termite mounds. It is found on various soil types but more often on alluvial soils. It occurs in regions with altitude ranging from 0 to 2000 m, mean annual rainfall between 750-2000 mm, and temperature from 10 to 30°C **(Arbonnier, 2004; Ky, 2008; Orwa *et al.*, 2009)**.

The black plum is naturally widespread in tropical Africa, from Senegal to Somalia and to South Africa, also in Comoros and Seychelles (Figure 1). It is occasionally cultivated in Mauritius **(Arbonnier, 2004; Ky, 2008; Orwa *et al.*, 2009)**. It is an African Pluri-regional species belonging to the Isoberliniondokae ecosociological group **(Akoegninou *et al.*, 2006; Djégo, 2006)**. In Benin, it has been mentioned as naturally occurring in all climatic zones **(Assogbadjo *et al.*, 2012)**.

It propagates naturally by seeds, coppices and root suckers. However, its regeneration by seeds is always challenging because of the orthodox seed storage behaviour exhibited by the species (i.e. seed with hard coat, often called stones). In the nature, given that *V. doniana* is a sarcochore i.e. plant dispersing fleshy fruits, its seeds are dispersed by animals mainly monkeys (zoochory). Seed dormancy is therefore often broken after passing through the intestinal canal of those dispersers. Forest fires also help in inducing its seeds germination **(Ky, 2008; Orwa *et al.*, 2009)**. Several studies have proved the very weak germinative capacity of the species through experimental trials. Most of these studies revealed low germination rates and the importance of seed treatment for dormancy breaking **(Ahoton *et al.*, 2011; N'Danikou *et al.*, 2014; N'Danikou *et al.*, 2015)**. Other studies proved the use of stem and root cuttings as interesting alternative propagation methods for growing black plum trees **(Mapongmetsem *et al.*, 2012; Sanoussi *et al.*, 2012; Achigan-Dako *et al.*, 2014)**.

The species has a moderate growth rate with seedlings which can reach in average 70-90 cm tall after three years **(Ky, 2008)**. In West Africa, the black plum flowers in the second half of the dry season or onset of the rainy season (February to April). The fructification occurs from May to October and the renewal of leaves intervenes during the dry season, often between December and February **(Akoegninou *et al.*, 2006; Ky, 2008)**.

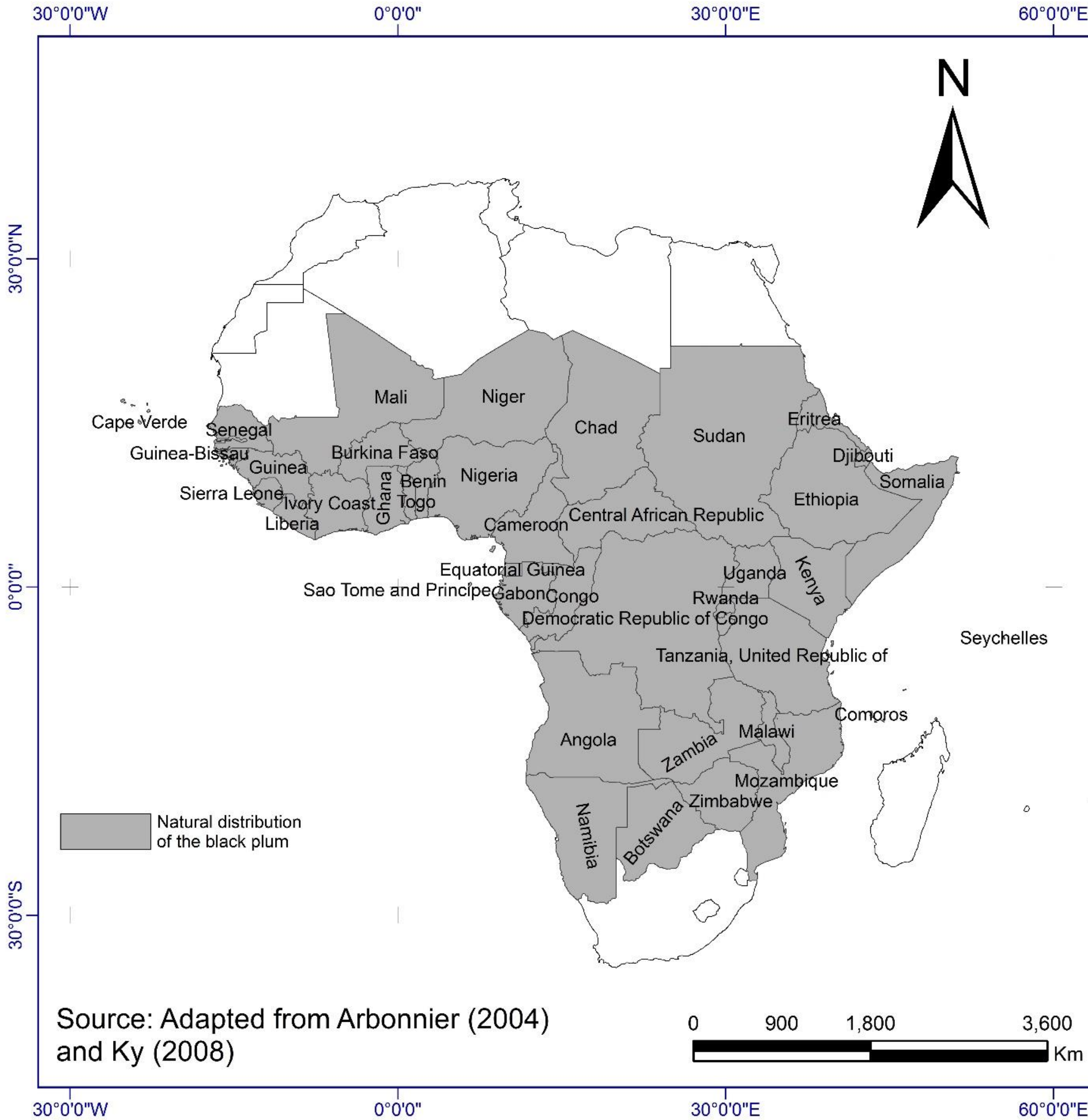


Figure 1: Distribution of the black plum

2.2.5. Socio-economic importance of the black plum

The black plum is an agroforestry species valued by people in many parts of Africa for several purposes such as food (fruits and young leaves), medicine, building material, firewood, fodder, etc. **(Arbonnier, 2004; Ky, 2008; Orwa *et al.*, 2009)**. The black pulp of ripe fruit is edible and tastes like prunes, it is often eaten raw and sometimes used to make jam or juice. Boiled fruits are also used in preparation of some alcoholic liquors and wine. The young leaves are used as leafy vegetables for sauces preparation **(Ky, 2008; Orwa *et al.*, 2009)**. The species has several applications in traditional medicine. The fruit is used to improve human fertility and to treat anaemia and dysentery. The root is used to heal gonorrhoea, and its decoction for backaches relief. The sap of young leaves is used as eye drop to treat conjunctivitis and other eye troubles. Powdered bark added to water is a remedy for colic; bark extract is used to treat stomach complaints and kidney troubles. The bark is also used against liver diseases and to control bleeding after childbirth. Pastes of pounded leaves and bark are effective for wounds and burns treatment. The twigs are used as chewing sticks for teeth cleaning **(Ky, 2008; Orwa *et al.*, 2009)**.

Vitex doniana produces a teak-like and termite-resistant timber (Photo 2 a & b). It is suitable for light building material, furniture, light flooring, joinery, stools, drums, guitars, carvings, shipbuilding and several other wood-made stuffs. The wood is also used as firewood and for production of charcoal **(Arbonnier, 2004; Ky, 2008)**. Leaves, pods and seeds of the species are used as fodder. Its flowers are favourite for bee-keeping. The tree has nitrogen-fixing roots, and its leaves can be used for mulching. It contributes therefore to soil fertility improvement. The blackish extract obtained by boiling leaves, bark, roots or fruits is used as ink, tannin and as dye for clothes **(Ky, 2008; Orwa *et al.*, 2009)**.

In Benin, the black plum has been reported as one of the ten most important agroforestry species valued by local people **(Assogbadjo *et al.*, 2012)**. The species is known as a particular multipurpose tree with a high socio-economic value. The young leaves are the most widely commercialised part **(Oumorou *et al.*, 2010; Dadjo *et al.*, 2012)**. The black plum, like many other agroforestry plant species contributes to rural households' cash income and values of these species for local people have resulted in many cultures sparing them when cleaning lands for agriculture **(Achigan-Dako *et al.*, 2011; Assogbadjo *et al.*, 2012)**.

a. Longitudinal section

b. Transversal section

Photo 2: Wood of *Vitex doniana*

Photos by Hounkpèvi (fieldwork in 2015)

PART III: MATERIAL AND METHODS

3.1. Study area

3.1.1. Location

The study was carried out in Benin Republic, located in West Africa, between 6°25’ and 12°50’ North and 0°45’ and 3°50’ East. It covers 114,763 km^2 and, it is neighboured by Togo in the West, Nigeria in the East, Burkina Faso and Niger in the North. It has an opening of about 120 km on the Atlantic Ocean in its southern part (Figure 2). The physical and anthropogenic characteristics of the country with potential effects on ecology, morphology, growth, distribution and conservation of plant species including *Vitex doniana* are described below.

3.1.2. Climate

Benin’s climatic profile shows three climatic zones. These climatic zones are from South to North: the Guinean zone (between 6°25’ and 7°30’ N), the Sudano-Guinean zone (from 7°30’ to 9°45’ N) and the Sudanian zone (between 9°45’ to 12°50’ N). Regarding the particularities of these zones, two contrasting regions (Guinean and Sudanian) and one transitional region (Sudano-Guinean) can be identified.

The Guinean zone is characterised by a subequatorial climate with four seasons (two rainy and two dry). The rainfall of about 1200 mm per year is bimodal, mostly from March to July and from September to November (Figure 3a). The temperature varies between 25 and 29 °C, and the relative humidity is between 69 % and 97 %.

The Sudano-Guinean zone is a transitional area with two rainy seasons merging in a unimodal regime (Figure 3b). The annual rainfall varies between 900 and 1110 mm. The temperature is between 25 and 29°C, and the relative humidity varies from 31 % to 98 %.

The Sudanian zone has a tropical dry climate with two equal length seasons (rainy and dry). The mean annual rainfall in this zone is often less than 1000 mm and, it occurs mainly from May to September (Figure 3c). The relative humidity varies from 18% to 99% and, the temperature ranges from 24 to 31°C **(Adam and Boko, 1993)**.

3.1.3. Hydrography

The hydrographic network of the country is structured in four major sets which are parts of the sub-regional river-catchments (Niger, Volta, Mono Couffo and Ouémé Yewa). It is a very dense hydrographic network covering the whole country (Figure 4) and, it is composed of seven permanent rivers (Ouémé, Mono, Couffo, Pendjari, Mékrou, Alibori and Sota) and several seasonal and temporary rivers **(Le Barbé *et al.*, 1993)**.

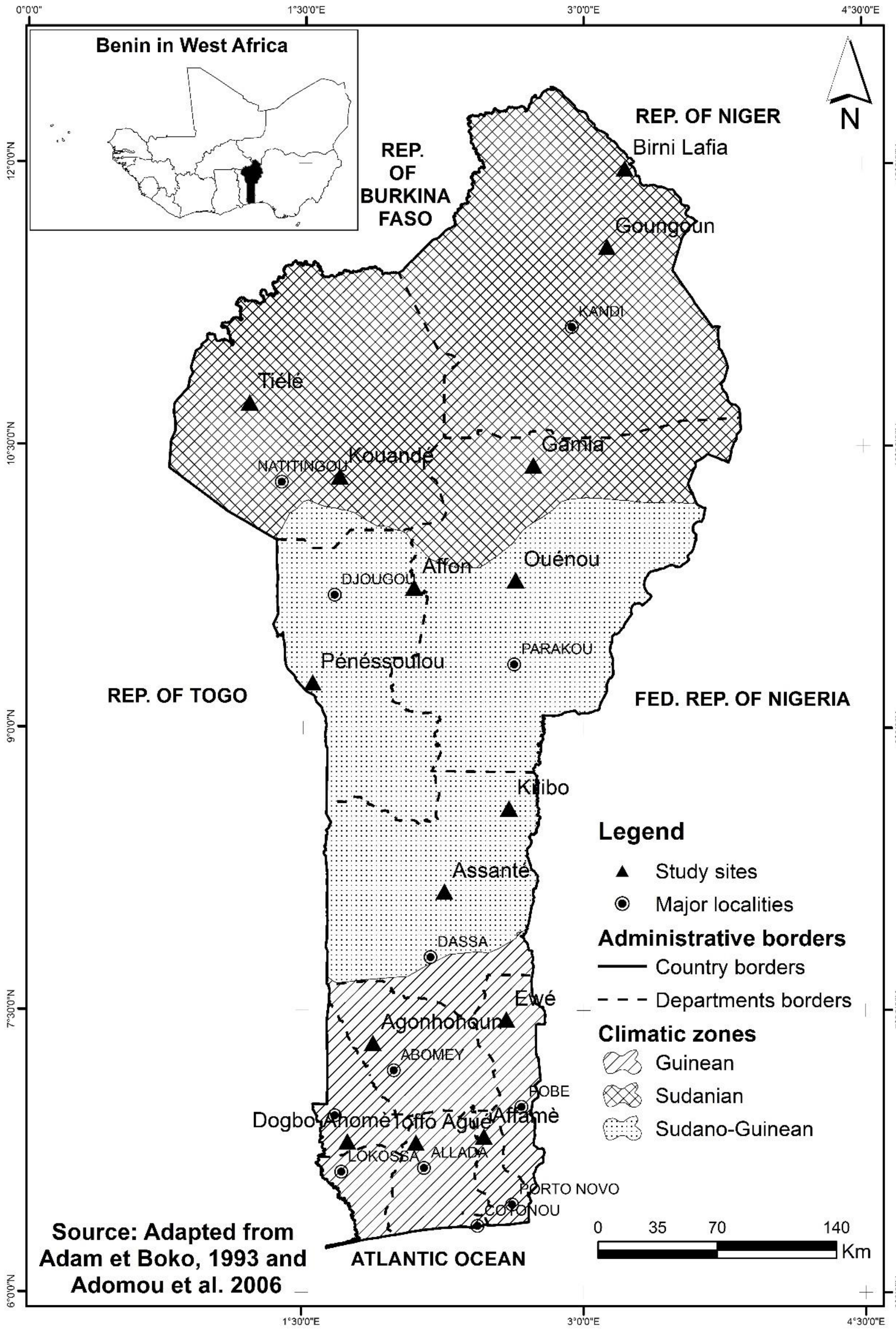
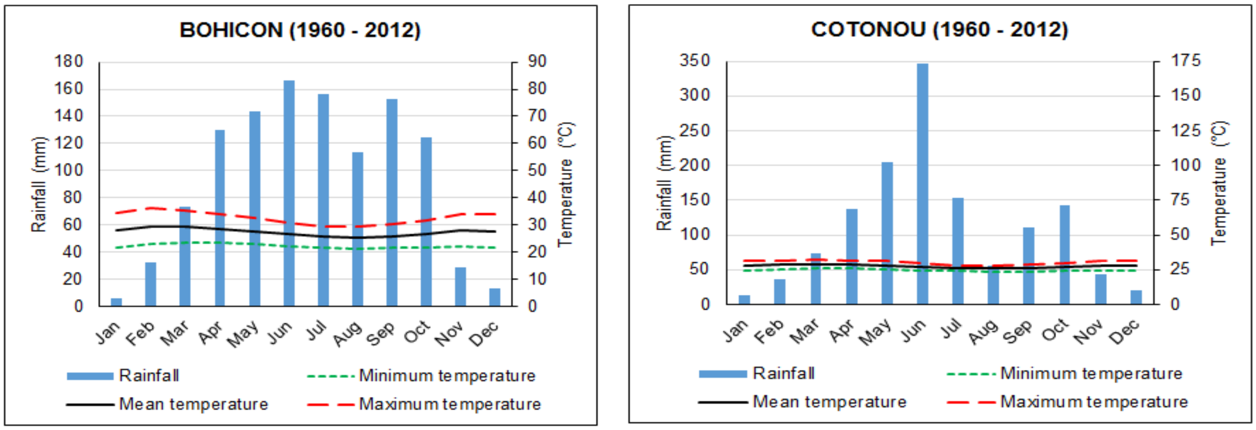
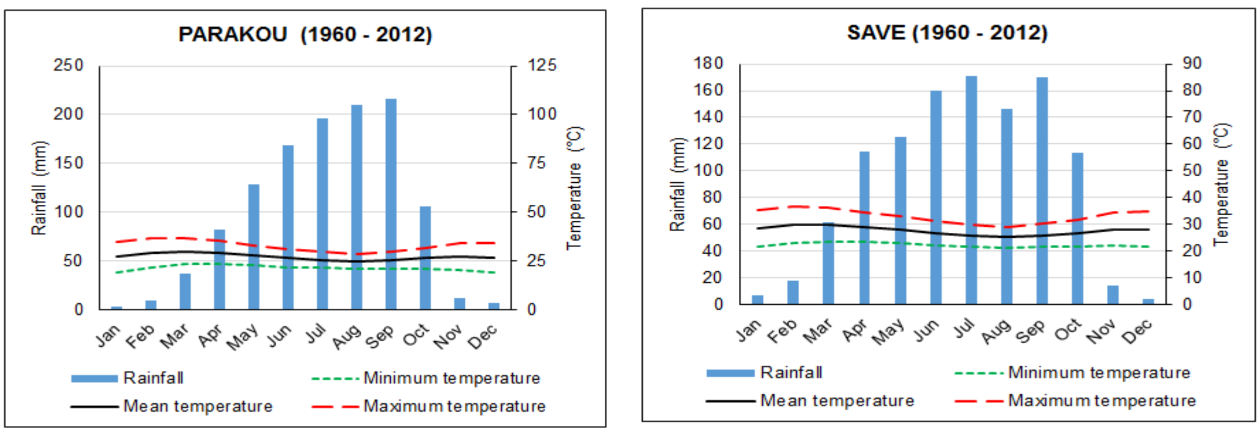


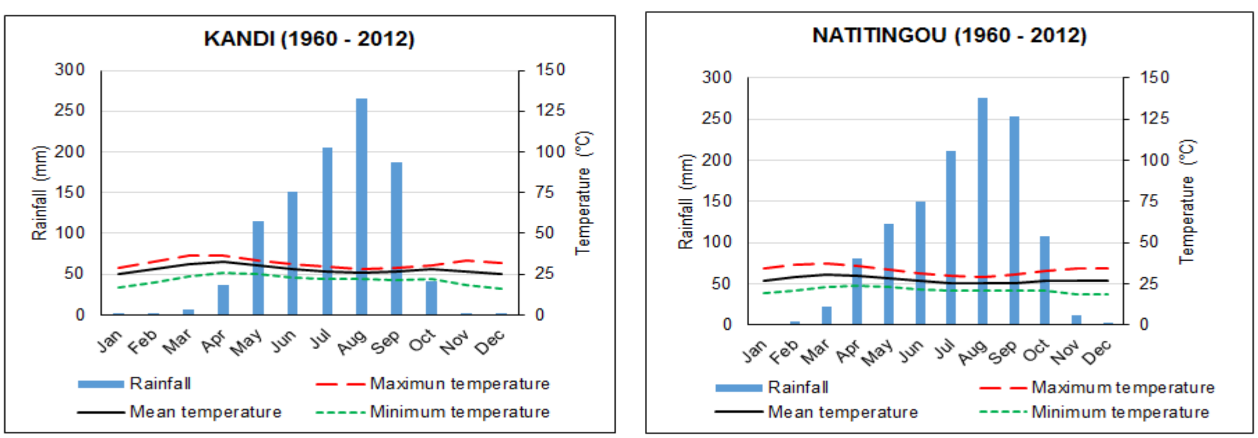
Figure 2: Map of Benin Republic with climatic zones and studied sites



a. Guinean zone



b. Sudano-Guinean zone



c. Sudanian zone

Figure 3: Climatic diagrams of the Guinean (a), Sudano-Guinean (b) and Sudanian (c) zones of Benin

Source: ASECNA-Benin (Data from 1960-2012)

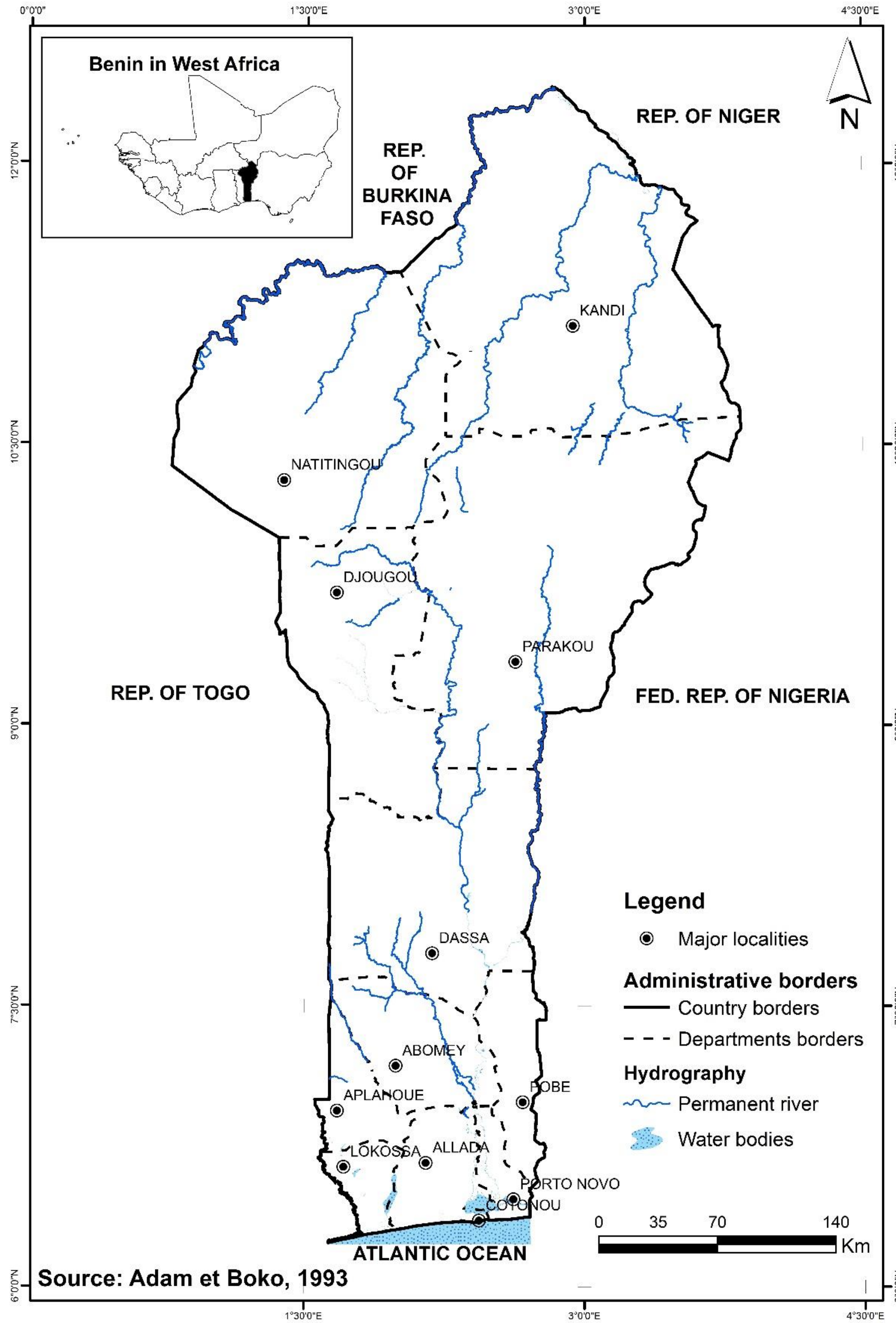


Figure 4: Hydrographic map of Benin

3.1.4. Soil and geology

Several soil types have been distinguished in Benin (Figure 5) among which five have been considered as major **(Willaime and Volkoff, 1967; Adomou, 2005)**. These major soil types are:

(i) Tropical ferruginous soils with several variations – They are developed on granito-gneissic formations of Central and Northern part of Benin, and on schists of the Northwest Benin. They occupy approximately 70% of the territory, mainly in the Sudano-Guinean and Sudanian zones. They are mostly covered by dry forests, woodlands, and savannahs.

(ii) Ferralitic soils – They are formed on the Continental terminal and Cretaceous sandstone. They cover approximately 7 to 10% of the country's area and, and they are mostly found in the Guinean zone. They host mainly semi-deciduous forests.

(iii) Hydromorphic soils – They cover between 5 and 8% of the country. The most important part of this soil type is found in the Guinean zone. They are typical to valleys, basins and alluvial plains. They are the main support for swamp and gallery forests.

(iv) Rough and undeveloped mineral soils – They occupy between 5 and 7% of the country. They are mostly found in coastal areas and on rocky outcrops of central and northern parts of the country.

(v) Vertic green soils – they cover approximately 5% of the country and they are mostly found in the depression of Lama. They host a particular dry type of semi-deciduous forest.

Two major geological domains are defined in the country. These domains are : the West African Continental Terminal with sedimentary rock in the Southern part and, the Precambrian Shield with granito-gneissic rock, seen as outcrops (inselbergs) from the Central to the Northern part of the country **(Adam and Boko, 1993; Adomou, 2005)**.

3.1.5. Land cover, vegetation and protected areas network

The country presents different land cover types. These land cover types can be grouped in four major units **(Orekan, 2007)**: (i) natural formations, (ii) anthropogenic formations, (iii) agglomerations and (iv) bare terrain (water surfaces, rocky surfaces, and sandy beaches). The predominant units are natural vegetation and anthropogenic plant communities (Figure 6). The natural vegetation covering more than half of the country includes: tree and shrub savannahs (50.35 % of the country area), woodlands (13.12 %), gallery forests (2.49 %), swamp forests (1.66 %) and dense forests (0.62 %). The anthropogenic plant communities are composed of mosaics of croplands and fallows (28.31 %) and plantations (2.11 %).

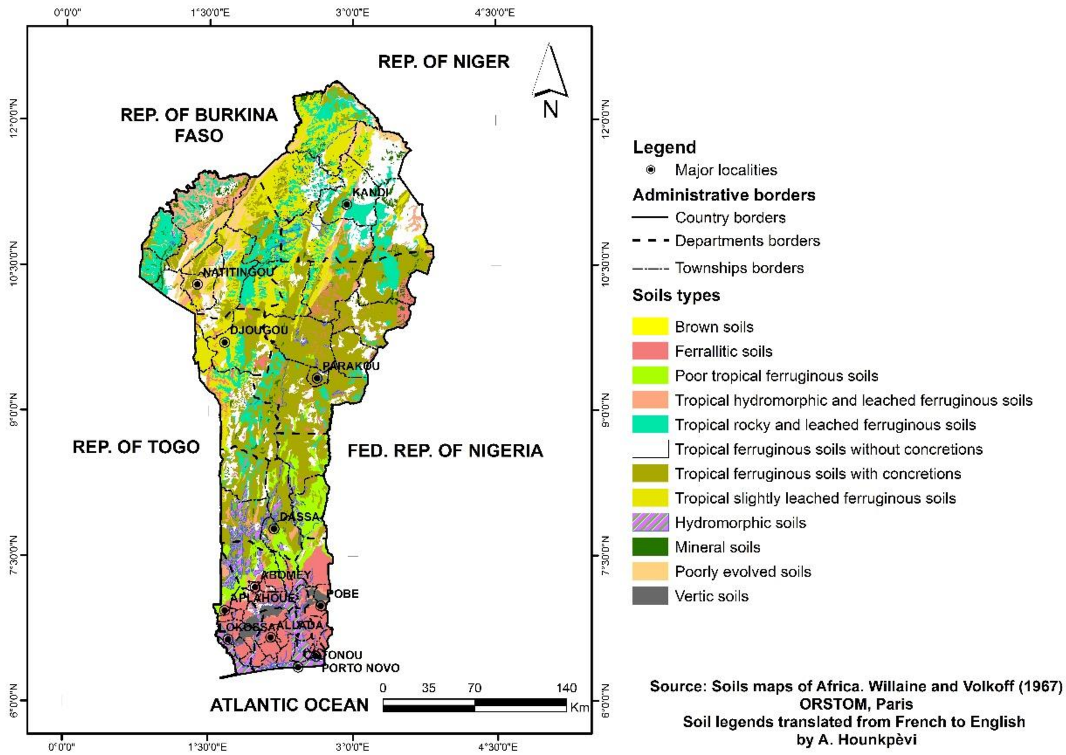


Figure 5: Soil map of Benin

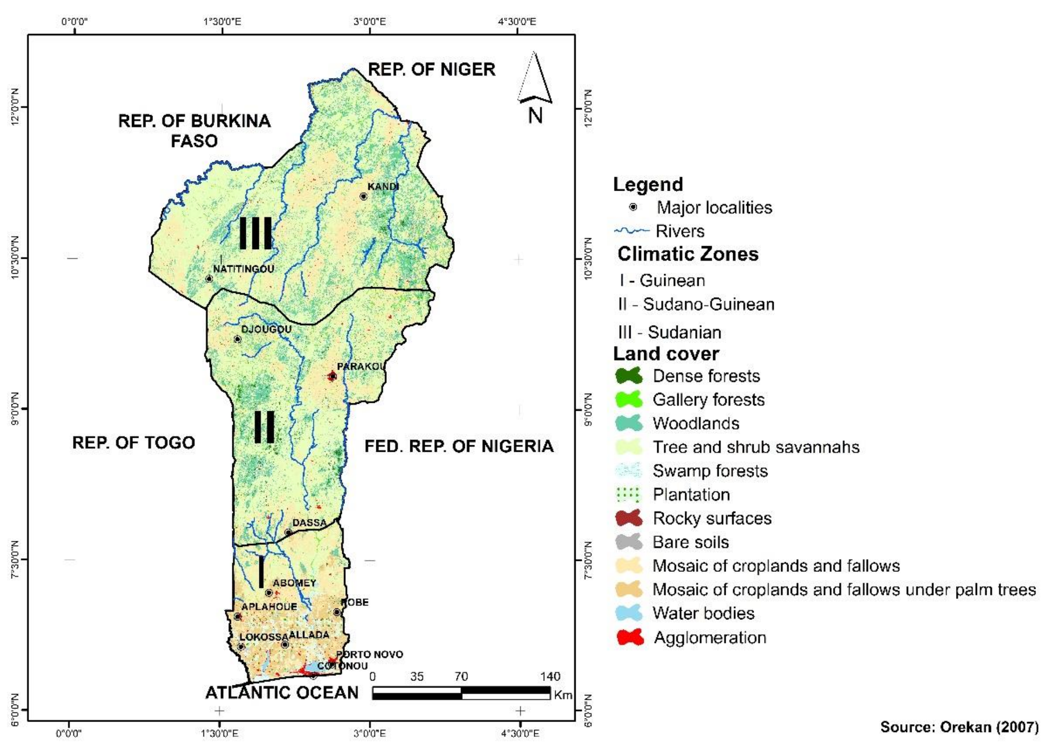


Figure 6: Land cover map of Benin

The natural vegetation of the country is climate-dependent. The Guinean zone for instance, is the domain of mosaic of lowland rain forests and secondary grasslands. The natural plant formation in this zone is dominated by patches of semi-deciduous and swamp forests. The common species include *Triplochiton scleroxylon*, *Celtis zenkeri*, *Cola gigantea*, *Milicia excelsa*, *Antiaris toxicaria*, *Ceiba pentandra*, and *Albizia spp*. The Sudano-Guinean zone is occupied by *Isoberlinia*-dominated woodlands. Associated species include *Anogeissus leiocarpa, Pterocarpus erinaceus, Monotes kerstingii* and *Uapaca togoensis*. The zone is also suitable for parklands with the dominance of *Vitellaria paradoxa*, *Parkia biglobosa*, *Khaya senegalensis* and *Afzelia africana*. The Sudanian zone is dominated by undifferentiated woodland lacking in *Isoberlinia* except in few small patches. The dominant species include *Combretum spp.*, *Acacia spp.*, *Balanites aegyptiaca*, *Hyparrhenia spp.*, *Loudetia spp.* and *Andropogon spp.* **(Adjanohoun *et al.*, 1989; Adomou, 2005; Aregheore, 2009)**.

About 24% of the country (approximately 27,310.47 km^2) is legally preserved in a Protected Areas Network (PAN). This PAN is constituted of two national parks (Pendjari in the North-Western part and W in the extreme Northern part of the country), three hunting zones (the hunting zone of Djona bordering W National park, the hunting zone of Atakora between the two parks and the hunting zone of Pendjari) and several classified forests **(IUCN and UNEP-WCMC, 2015)**. These protected areas are mainly located in the Sudanian and Sudano-Guinean zones (Figure 7).

3.1.6. Human population and economic activities

Benin's resident population was of about 10 million inhabitants in 2013. The population growth rate is of 3.51% between 2002 and 2013 **(INSAE, 2013)**. This population belongs to several ethnic groups (Figure 8). These ethnic groups are clustered into six socio-linguistic families namely *Kwa*, *Gur*, *Yoruboïd*, *Mandé*, *Songhaï* and *Senegambia.* The *Kwa* socio-linguistic family is geographically located in the Southern and Central parts of the country (Guinean and Sudano-Guinean zone respectively). This socio-linguistic family is represented by *Fon*, *Mahi*, *Adja*, *Xwéda*, *Sahouè* and relatives, *Mina*, *Anii*, *Windji-windji and relatives, Aïzo, Kotafon and relatives, and Goun, Tofin, Xwla* and relatives ethnic groups. The *Gur* socio-linguistic family, located in the Northern part of the country (Sudanian zone and upper area of the Sudano-Guinean zone), includes *Bariba*, *Ditammari*, *Berba*, *Waama* and relatives, *Gourmantché*, *Natimba* and relatives, *Lokpa*, *Kotokoli*, *Kabyè* and relatives, *Yom*, *Yoa*, *Tanéka* and relatives. The *Yoruba*, *Idaatcha*, *Nagot* and relatives ethnic groups making up the *Yoruboïd* socio-linguistic family, are mostly found in the Central (Sudano-Guinean zone) and Southeastern (Guinean

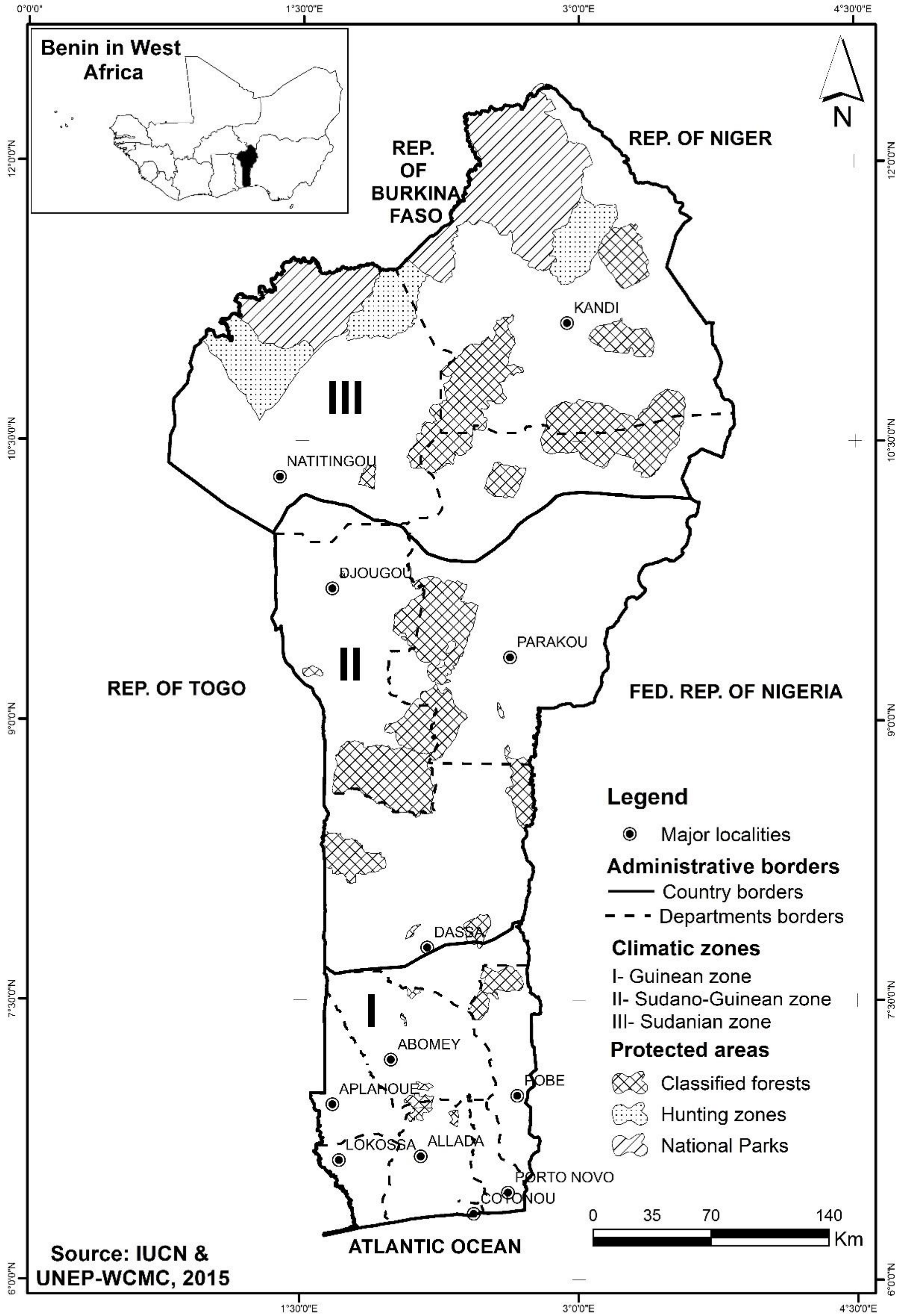


Figure 7: Climatic zones and protected areas network of Benin

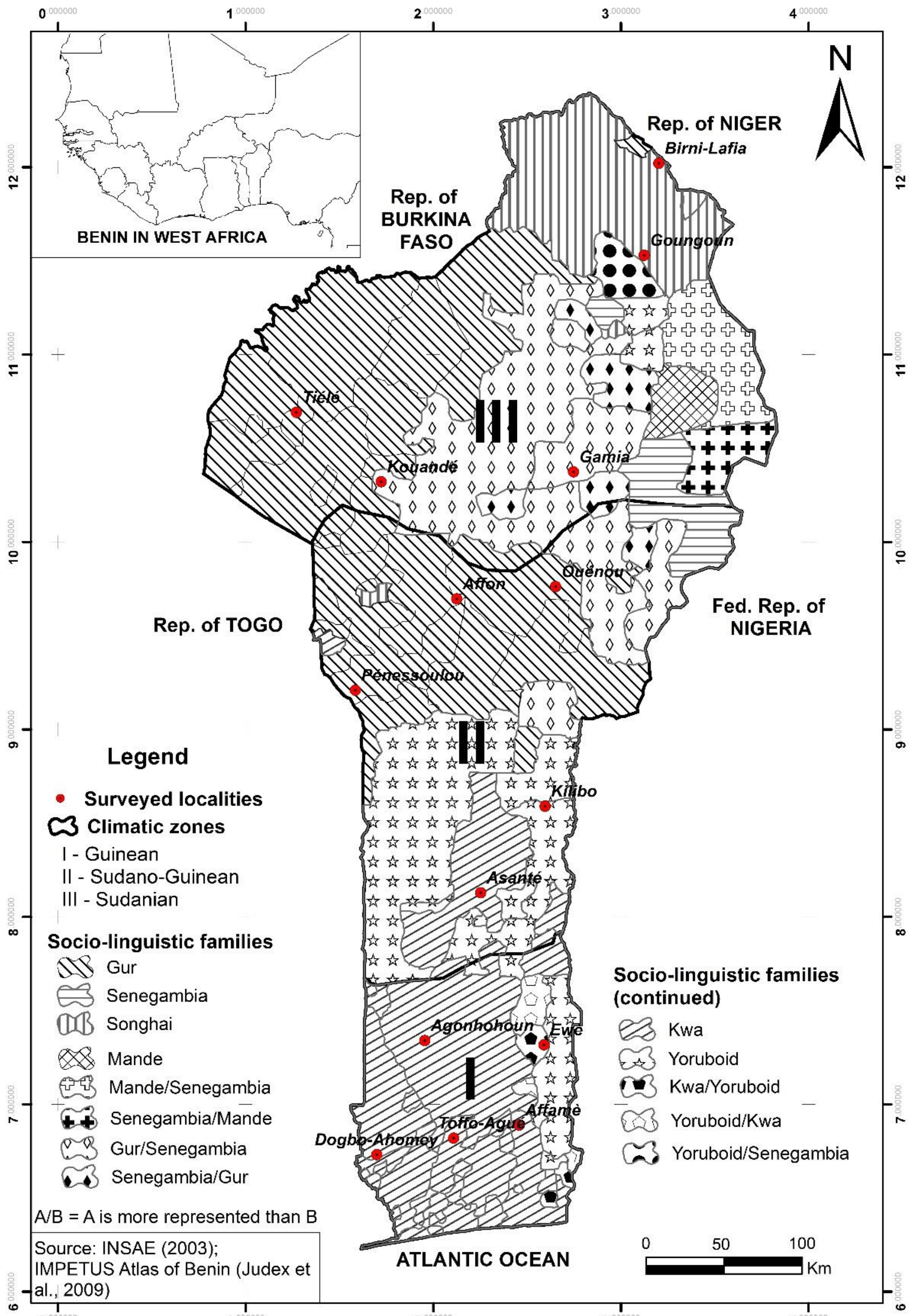


Figure 8: Distribution of socio-linguistic families in Benin

zone) parts of the country. The *Mandé* socio-linguistic family including only *Boko* ethnic group, is mainly found in the Northeastern part of the country (Sudanian zone). The *Songhaï* linguistic family is constituted by *Dendi* and *Jerma* ethnic groups and is mostly located in the extreme Northern part of the country (Sudanian zone). The *Senegambia* socio-linguistic family is made up by *Peulh* ethnic group and is located mainly in the Sudanian zone. However, people belonging to this ethnic group are also found in the Sudano-Guinean zone **(INSAE, 2003; Judex *et al.*, 2009)**. Four of these ethnic groups including the *Fon*, the *Adja*, the *Bariba* and the *Yoruba* are the most represented with about 54 % of the country's population **(Aregheore, 2009)**. Except *Peulh* ethnic group whose main activity is pastoralism, most of the ethnic groups are farmers.

The economy of the country is agriculture-dependent. Cotton is the major cash crop accounting for about 40 % of Gross Domestic Product (GDP) and roughly 80 % of country's official total exports. Subsistence agriculture employs an important part of the active population. It produces maize, cowpeas and beans, rice, groundnuts, cassava, yams, fruits and vegetables for mainly home consumption and local market **(Aregheore, 2009; Awoyé, 2015)**

3.2. Data collection and analysis

3.2.1. Evaluation of use values and perceptions of local people on climate change and its impacts on the black plum

3.2.1.1. Data collection

Data were collected in the three climatic zones of Benin using questionnaires through semi-structured interviews. In each zone, five localities were randomly selected from an administrative map of the country (see Figure 2, p.19, and Figure 8, p. 26). In each locality, the number of informants to consider for the survey was determined using the normal approximation of the binomial distribution **(Dagnelie, 1998)**. Following a short preliminary survey on 30 individuals, the proportion of people knowing and using regularly any part of the plant, was determined and used to compute the number of informants to be interviewed to reach a minimum of representativeness in the given locality, based on equation 1 **(Dagnelie, 1998)**:

$$n = \frac{U_{1-\alpha/2}^{2} \times p(1-p)}{d^{2}} \qquad \text{(Equation 1)}$$

where *n* is the number of individuals to interview in the locality; $U_{1-\alpha/2}$ is the value of the normal random variable for a probability value of 1-α/2, for α = 5%, $U_{1-\alpha/2}^{2} = 3.84$; *p* is the proportion of people knowing and using regularly the plant; and *d* is the expected error margin ranging from 1% to 15%. For practical reasons, we considered a margin error of 10 % ($d = 10\%$).

During the survey, only people above 30 years old were interviewed. This is because previous studies have illustrated that younger people have limited knowledge on use of agroforestry trees species **(Ayantunde *et al.*, 2008; Camou-Guerrero *et al.*, 2008; Beltrán-Rodríguez *et al.*, 2014)** and poor perceptions of climate change **(Teka *et al.*, 2013)**. Informants were randomly selected among people freely willing to participate in the study. These people were identified during group discussion in each locality. Finally, a total of 441 people belonging to 19 ethnic groups were interviewed across the country. Some of these ethnic groups like *Bariba*, *Mahi* and *Peulh* were met in more than one bioclimatic zone. They were therefore considered separately in order to take into account possible effects of climatic zone on the factors under study. Thus, instead of 19 ethnic groups, 22 groups were overall considered (Table I). Since only people above 30 years old were surveyed, we considered only two age categories following **Teka *et al.* (2013)**: adult (< 60 years) and old (≥ 60 years).

The questionnaire used during the survey focused on socio-cultural traits (ethnicity, gender, age), uses of the species, and perceptions of informants on climate change and its impacts on the biology and productivity of the species. Ethnicity, gender, age and location were considered in assessing the species use values and local perceptions on climate change because of their well-evidenced role in shaping traditional ecological knowledge (TEK) on agroforestry species **(Ayantunde *et al.*, 2008; Camou-Guerrero *et al.*, 2008; Avouhou *et al.*, 2012)** and also local perceptions on climate change **(Gnanglè *et al.*, 2012; Teka *et al.*, 2013)**. According to the uses of the species, informants were asked to list parts of the species that they use and the use forms. For perceptions on climate change, based on preliminaries results from pilot studies, the study focused on how informants perceive (i) current ambient temperature compared to past decades, (ii) current rainy season's length and (iii) current rainfall intensity. For the rainfall intensity, the definition provided by the American Meteorology Society (AMS) was used during interviews with local people. According to this definition, the rainfall intensity is the ratio of rainfall amount on a given period, usually millimetre per hour **(American Meteorology Society, 2015)**. Three eventualities of perception (increase, no change and, decrease) were considered for each of the climatic factors. Then, informants were asked to describe how they perceive the impacts of these changes on the species.

3.2.1.2. Data analysis

In order to describe patterns of the use value of the species across socio-cultural groups, three use value indices were used following **Gomez-Beloz (2002**). These indices were : (i) the Reported Use Value (RUV), defined as the total number of uses reported by an informant; (ii) the Plant Part Use Value (PPUV), taken as the ratio of the total number of uses reported by all informants of a given group for each plant part (young leaves, matures leaves, flowers, bark, root, trunk) to the total number of reported uses (RU) mentioned for the species; and (iii) the Use Form Value (UFV) defined similarly to the PPUV by considering the following form of uses - food, medicine, fodder, magical/cultural, fire (wood and charcoal) and handicraft making (furniture, building, …).

Mean values and standard deviation were calculated for RUV and used to assess how it varies according to climatic zone, ethnic group, gender and age category. The non-parametric Kruskal–Wallis rank sum test was performed to test statistical differences among groups because normality assumption was not fulfilled **(Glèlè Kakaï *et al.*, 2006)**. A Principal Components Analysis (PCA) was performed on the matrices of ethnic groups (in rows) and, the PPUV and UFV (in columns) to assess similarities amongst ethnic groups regarding uses of plant parts and use forms respectively.

Table I: Sample size according to climatic zone, ethnic group, gender and age category

Factors	Number of informants	Proportion of sample size (%)
Bioclimatic zone		
Guinean	160	36.28
Sudano-Guinean	139	31.52
Sudanian	142	32.20
Ethnic group (Climatic zone)		
Adja (Guinean)	35	7.94
Aïzo (Guinean)	29	6.58
Fon (Guinean)	26	5.9
Holli (Guinean)	23	5.22
Wémènou (Guinean)	35	7.94
Anii (Guinean)	25	5.67
Mahi (Guinean)	12	2.72
Mahi (Sudano-Guinean)	25	5.67
Bariba (Sudano-Guinean)	31	7.03
Ishabè (Sudano-Guinean)	26	5.9
Kotokoli (Sudano-Guinean)	6	1.36
Peulh (Sudano-Guinean)	5	1.13
Yom (Sudano-Guinean)	21	4.76
Bariba (Sudanian)	27	6.12
Berba (Sudanian)	27	6.12
Biali (Sudanian)	14	3.17
Gourmantché (Sudanian)	6	1.36
Jerma (Sudanian)	25	5.67
Monkolé (Sudanian)	26	5.9
Natimba (Sudanian)	10	2.27
Peulh (Sudanian)	3	0.68
Waama (Sudanian)	4	0.91
Gender		
Female	166	37.64
Male	275	62.36
Age category		
Adult (< 60 years)	257	58.28
Old (> 60 years)	184	41.72

Perceptions of local people on climate change and its impacts on the biology and productivity of the species were assessed through a correspondence analysis. According to perceptions on climate change, number of informants reporting eventualities of perception (increase, no perceptible change or decrease) for the considered factors (temperature, length of rainy season and intensity of rains) were computed for each ethnic group and used to build a perceptions matrix. A similar matrix was also built for the potential impacts assessment. Impacts mentioned by interviewees were organised in four categories: reduction of fruiting period's length (RLF), growth disturbance (GD), delay in flowering/fruiting (DFF) and decrease of productivity (DP). In order to assess the dependence of perception/impact regarding ethnic group, climatic zone, gender and age category, Chi-squared test was used where its assumptions where satisfied (all expected counts are greater than zero, and more than 80% of the expected counts are above or at least equal to 5) otherwise, the Fisher's exact test for count data was preferred **(Agresti, 2002)**. Finally, correlations between organ uses and perceptions on climate change, and potential impacts of climate change on the species were assessed. The same analyses were performed on use forms and the above mentioned parameters. Since these analyses were performed on dichotomous data (1/0), the recommended tetrachoric correlations were computed **(Brown, 1977; Revelle, 2016)**. For that, the psych package **(Revelle, 2016)** was used. All the analyses were run in R software, version 3.2.2 **(R Core Team, 2016)**.

3.2.2. Identification of ecological conditions of the black plum and characterisation of structural parameters of its population

3.2.2.1. Data collection

Ecological and structural data on the species were collected in the 15 localities considered during the ethnobotanical survey (see Figure 2, p.19, and Figure 8, p. 26). In each locality, a point was randomly chosen on a map as the centre of the site. Coordinates (longitude and latitude) of the chosen point were saved in a Global Positioning System (GPS) and used on field to locate its position. From this point, four transects of 3 km each were set (Figure 9a) in the four directions (North, South, East and West). A Global Positioning System (GPS) and a compass were used for the transect orientation. Investigations were carried out within a band of 100 m of width (50 m on each side) along each transect (Figure 9a). In order to correctly cover the 100 m band along each transect, the GPS operator and a field assistant walked following the centre of the observation band, while a field guide walked at about 25 m apart of each side. Within observation bands, plot of 50 m x 20 m following **Ouédraogo *et al.* (2013)** were laid around each encountered adult individual of the black plum (i.e. individual with a diameter at breast height (dbh) equal or greater than 5 cm).

Within each 50 x 20 m^2 plot, the dbh of adult individuals (dbh ≥ 5 cm) of all woody species was recorded with a diameter tape. All woody species was considered in order to compute the contribution of the black plum to the stand's basal area. The total height of adult individuals (dbh ≥ 5 cm) of the black plum was recorded with a SUNNTO clinometer. Five sub-plots (10 x 10 m^2) were set in each plot to study the regeneration (dhb < 5 cm) of the species. One sub-plot was set at each corner, and at the centre of the 50 x 20 m^2 plot (Figure 9b). Within each 10 x 10 m^2 sub-plot, the regeneration of the species (dbh < 5 cm) was assessed by counting the total number of the black plum plants. A measuring tape was used for distance measuring during plots and sub-plots setting.

For each plot, land cover type was recorded in field. Soil samples were collected in a total of 55 randomly selected plots in order to determine the particles size (percentage of clay, silt and sand), total nitrogen content, organic carbon content and pH. Moreover, geographic coordinates were also recorded at the centre of each plot with a GPS. These recorded GPS coordinates were projected on a land cover map, soil map, and hydrographic map of Benin in ArcGIS 10.3 **(ESRI, 2014)** in order to update the land cover type and soil information, and to determine the distance of the plot to the closest river. From these data, five land cover types were observed and considered: riparian forests (RF), woodlands (Woodl), tree and shrub savannahs (TSS), mosaics of croplands and fallows (MCF) and, plantations (Plt). According to the distance to the closest river, four classes of distance were built and considered: class1 (less than 500 m), class2 (500-1000 m), class3 (1000-1500 m) and class4 (more than 1500 m). Finally, 226 plots were laid in total along 60 transects through the country. The distribution of those plots according to climatic zone, land cover type and distance to the closest river is presented in Table II.

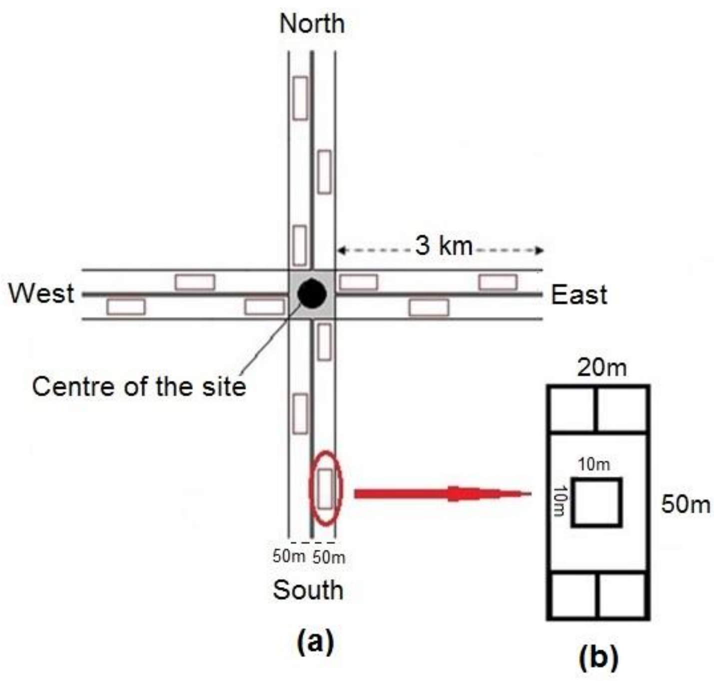


Figure 9: Research design for ecology and structural parameters assessment on the black plum

(a) Transects orientation; (b) Plot design

Table II: Number of plots per climatic zone, land cover type and per class of distance to the closest river

	Guinean	Sudano-Guinean	Sudanian	TOTAL
Land cover				
MCF	82	24	37	**143**
Plt	1	7	0	**8**
RF	0	8	3	**11**
TSS	6	27	22	**55**
Woodl	2	4	3	**9**
TOTAL	**91**	**70**	**65**	**226**
Distance class				
Class1	43	65	35	**143**
Class2	15	5	17	**37**
Class3	16	0	6	**22**
Class4	17	0	7	**24**
TOTAL	**91**	**70**	**65**	**226**

MCF = Mosaics of croplands and fallows; Woodl = woodlands; Plt = Plantation; RF = Riparian forests; TSS = Tree and shrub savannahs.

Class1 = less than 500m; Class2 = between 500 and 1000 m; Class3 = between 1000 and 1500 m; Class4 = more than 1500 m.

3.2.2.2. Data analysis

- **Identification of high occurrence habitats of the black plum**

Absolute frequency of observation and abundance of adult individuals of the black plum along transects were used to identify high occurrence habitats with regard to the local environmental patterns (climatic zones, land cover types and distance to the closest river). For that, numbers of contacts with adult individuals (dbh ≥ 5 cm) and numbers of adult individuals per contact were analysed through generalized linear models (GLM), particularly the negative binomial model because normality and homogeneity of variance assumptions were not fulfilled **(Madsen and Thyregod, 2011)**. The Modern Applied Statistics with S (MASS) package **(Venables and Ripley, 2002)** was used for the analysis in the R software **(R Core Team, 2016)**.

- **Description of floristic assemblages around the black plum**

A non-metric multidimensional scaling (NMDS) based on the metaMDS procedure was performed in order to assess the woody floristic assemblages within which the black plum occurs regarding the climatic zone, land cover type, and proximity to river. The analysis was performed on a dissimilarity matrix derived from an abundance matrix (226 plots and 65 woody plant species, except *V. doniana*). This dissimilarity matrix was built based on the Bray-Curtis index **(Bray and Curtis, 1957)**. Pairwise Jaccard's similarity index **(Chao *et al.*, 2005)** was computed, and was used to test for difference in the floristic composition around *V. doniana* regarding climatic zones, land cover types and distance to the closest river classes. Moreover, indicator woody plant species around the target species regarding the considered environmental parameters were identified through an indicator species analysis **(De Caceres *et al.*, 2012)**. All analyses were run in the R software **(R Core Team, 2016)** with specific packages. For instance, Vegan package **(Oksanen *et al.*, 2013)** was used for NMDS, while fossil package **(Vavrek, 2011)**, and indicspecies **(De Cáceres and Legendre, 2009)** were used for Jaccard's similarity index calculation and indicator species analysis respectively.

- **Structural parameters of the black plum**

Tree density (N, stem/ha), basal area (Ba, m^2/ha), mean diameter (Dg, cm), Lorey's mean height (HL, m), contribution of *V. doniana* to stand basal area (Cs, %), and density of regeneration (Nreg, stems/ha) were computed per plot. Mean values and coefficient of variation of each of these parameters were calculated according to the environmental patterns. Two-way analysis of variance was used to test for mean differences (Dg, Ba, Cs and HL) regarding land cover type and climatic zone, and class of distance to the closest river and climatic zone. Data were log-transformed (log(x)) to fulfil the assumption of normality and homogeneity of variance **(Madsen and Thyregod, 2011)**. In the case of a significant effect, Tukey's post'hoc test was used for pair-wise comparison. For the density data (adult and regeneration), the negative binomial model was used with MASS package **(Venables and Ripley, 2002)** for testing differences regarding the considered environmental factors.

Within climatic zones, the stem diameter structure of the black plum was established for each land cover type and for each class of distance to the closest river. The observed diameter structures were adjusted to the Weibull's 3-parameter theoretical distribution in order to describe the life conditions of stands, and to propose sustainable management strategies for the species **(Johnson and Kotz, 1970; Glèlè Kakaï *et al.*, 2016)**. This theoretical distribution was preferred because of its simplicity in usage, and mainly because it can present several forms (exponential, bell, beta) according to the values of its theoretical parameters **(Glèlè Kakaï *et al.*, 2016)**. The probability density function of the distribution is given by equation 2 **(Rondeux, 1999)** as following:

$$f(x) = \frac{c}{b}\left(\frac{x-a}{b}\right)^{c-1} exp\left[-\left(\frac{x-a}{b}\right)^{c}\right] \quad \text{(Equation 2)}$$

In this equation, x is the diameter of trees; a, b and c are the theoretical parameters of the distribution. They are threshold, scale and shape respectively. The form of the Weibull distribution depends on the value of the shape parameter (c). For $c < 1$, the distribution is of a reversed-J form, describing multispecific stands with a high regeneration potential. For $c = 1$, it is a decreasing exponential distribution, describing populations near extinction. When $1 < c < 3.6$, the distribution is left-skewed (left asymmetric) and it describes monospecific stands with predominance of young trees with small diameter, but a relatively low regeneration potential. For $c = 3.6$, the distribution is bell shaped (symmetric), describing monospecific stands with a low regeneration potential. When $c > 3.6$, the distribution is right-skewed (right asymmetric), and it describes monospecific stands with predominance of aged trees, big diameters and a very low regeneration potential **(Husch *et al.*, 2003)**.

Since only adult individuals with dbh ≥ 5cm were considered in the study, a threshold of 5 cm was used to estimate the two other parameters of the Weibull distribution (scale and shape) in Minitab 17 **(Minitab Inc., 2010)**. A log-linear analysis was performed in SAS 9.1 **(SAS Institute Inc., 2003)** to test the adequacy of adjustments and to compare diameter classes based on their densities **(Glèlè Kakaï *et al.*, 2016)**.

3.2.3. Analysis of morphological traits of the black plum in relation to climate

3.2.3.1. Data collection

Morphological data were collected from July to October 2014 in the three climatic zones following unfixed transects (length varying from 1 to 6 km). Seven, six and nine transects were followed in the Guinean, Sudano-Guinean and Sudanian zone, respectively. A distance of at least 20 m was left between fruiting trees in order to avoid genetically close individuals **(Gbèmavo *et al.*, 2015)**. A total of 102 fruiting individuals of *Vitex doniana* were assessed (35, 31, and 36 respectively in the Guinean, Sudano-Guinean and Sudanian zone). The number of fruiting trees assessed was not the same in all climatic zones because of the scarcity of healthy and less impacted trees by human activities in the zones. Ten leaves and ten fruits were randomly selected in the middle part of the canopy of each fruiting tree for morphological description **(Cornelissen *et al.*, 2003)**. Morphological data were collected on the trunk, canopy, leaves and fruits in the field (Figure 10). On the trunk, circumference at 1.3 m (*circ*, cm), total height (*htree*, m) and bole height (*hbole*, m) i.e height from ground to the first big branch were measured (Figure 10a) using diameter tape and SUNNTO clinometer, respectively. Concerning the Canopy, four radii (r_i) were measured from the projection of the crown on ground using a measuring tape (Figure 10a). On the leaves, leaf length (*Llgth*, mm), length and width of the main leaflet (*llgth* and *lwdth*, mm), petiole length and diameter (*petlgth* and *petdiam*, mm) and number of leaflets (*lnumb*) were recorded (Figure 10b). Regarding the fruits, length and width of fruit (*flgth* and *fwdth*, mm) and fruit fresh mass (*ffmass*, g) were measured (Figure 10c).

After measuring the above described parameters, fruits were oven dried at 65°C during 48 hours for determination of their dry mass (*fdmass*, g) following **Fandohan *et al.* (2011a)**. The pulp and fibres were removed from the dried fruits in order to have the endocarp for which length (*endolgth*, mm), width (*endowdth*, mm) and mass (*endomass*, g) were measured. All these morphological parameters were measured using an electronic digital calliper (0.01 mm resolution) for length and width parameters and, a 0.01g-precision scale for weight parameters.

Finally, the GPS coordinates of each fruiting tree were recorded and used in ArcGIS 10.3 **(ESRI, 2014)** to extract bioclimatic data for each tree. The bioclimatic data were extracted from WorldClim database (available at www.worldclim.org/bioclim), Version 1.4 database at 2.5-minute grid resolution (approximately 4.62 x 4.62 km^2 in West Africa). This database included 19 bioclimatic variables (Bio1 to Bio19) derived from average minimum and maximum temperature and rainfall data **(Hijmans *et al.*, 2005)**.

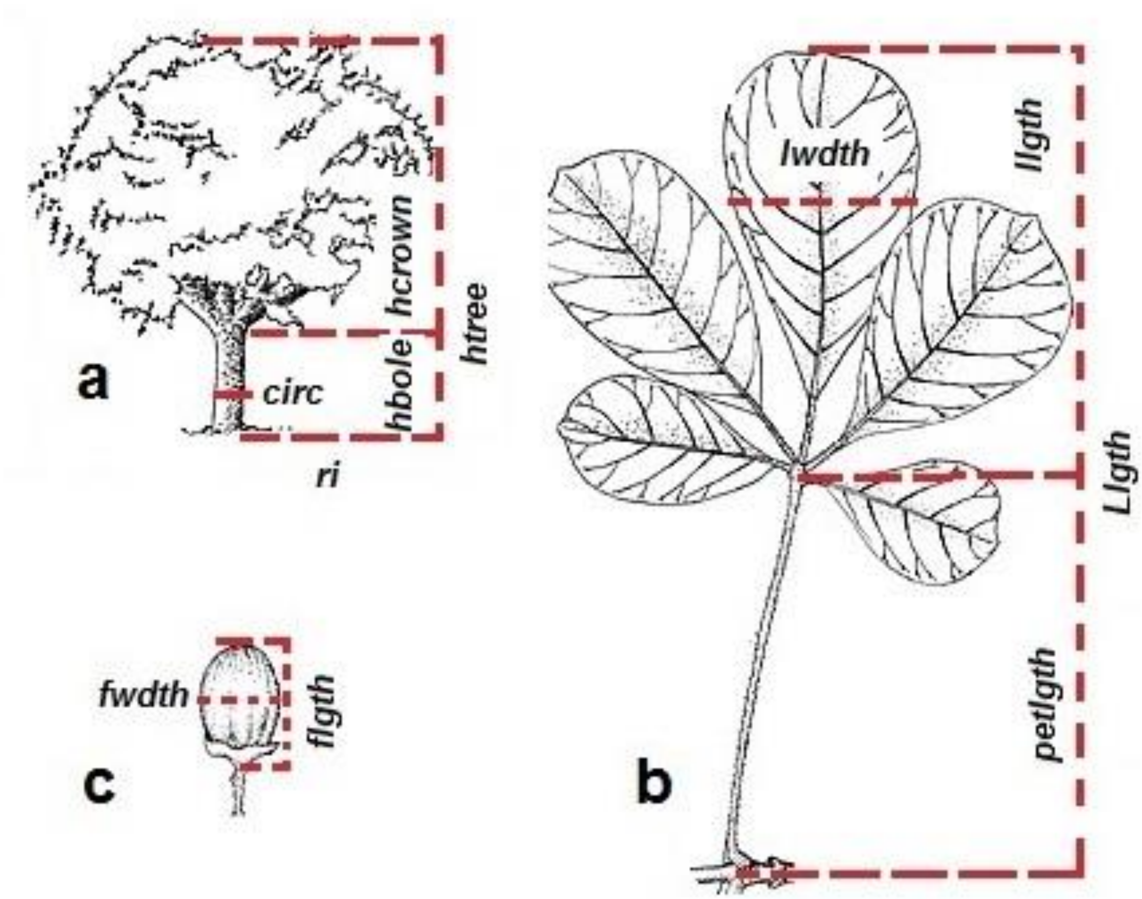


Figure 10: Morphological descriptors measured on the black plum

a- Tree: circumference at 1.3m (*circ*, cm); total height (*htree*, m); bole height (*hbole*, m) and crown height (*hcrown*, m) and crown radii (r_i, m). **b- Leaf:** leaf length (*Llgth*, mm), length and width of the main leaflet (*llgth* and *lwdth*, mm), petiole length (*petlgth*, mm). **c- Fruit:** length and width of fruit (*flgth* and *fwdth*, mm)

3.2.3.2. Data processing and analysis

From the measured parameters, the following variables were computed:

- Mean diameter of canopy (*dcrown*, m): It was computed from the four measured radii (r_i, *i* from *1* to *4*) using the following formula **(Glèlè Kakaï *et al.*, 2011)**:

$$dcrown = 2\sqrt{\sum \frac{{r_i}^2}{4}} \quad \text{(Equation 3)}$$

- Height of canopy (*hcrown*, m): It is the difference between total height and bole height

$$hcrown = htree - hbole \quad \text{(Equation 4)}$$

- Canopy shape (*shcrown*): It is a ratio of canopy height over mean diameter of canopy

$$shcrown = \frac{hcrown}{dcrown} \quad \text{(Equation 5)}$$

- Pulp thickness (*pulpthick*, mm): It is the difference between fruit width and endocarp width divided by 2

$$pulpthick = \frac{fwdth - endowdth}{2} \quad \text{(Equation 6)}$$

- Pulp mass (*pulpmass*, g): It is the difference between dry mass of fruit and endocarp mass

$$pulpwght = fdwght - endowght \quad \text{(Equation 7)}$$

- Fruit shape (fshape): It is the ratio of fruit length over fruit width

$$fshape = \frac{flgth}{fwdth} \quad \text{(Equation 8)}$$

- Endocarp shape (endshape): It is the ratio of endocarp length over endocarp width

$$endoshape = \frac{endolgth}{endowdth} \quad \text{(Equation 9)}$$

From equations 5, 8 and 9, the computed ratio was used as a simple proxy of the crown, fruit and endocarp shape respectively. When the ratio is below 1, the given object was considered as having an ellipsoid shape (numerator in the equation is greater than the denominator). For ratio equal to 1, the shape was considered as round. The shape was taken as oblong when the ratio is greater than 1.

Mean, standard error of mean and coefficient of variation were computed for trunk and canopy traits per climatic zone. The same descriptive statistics were calculated for each morphological parameter of leaves and fruits per climatic zone taking into account variation in leaves/fruits by using the two-stage sampling formulas of **Cochran (1977)**. The skewness was also calculated for each morphological trait to appreciate normality of its distribution within climatic zone. One way-ANOVA was used to test for differences in trunk/canopy morphological traits between climatic zones. The analysis was performed on log transformed data except for crown diameter in order to meet normality and homogeneity of variance assumptions. Student-Newman-Keuls' posthoc test was used to classify mean values of those morphological traits. Meanwhile, linear mixed effects models using the restricted maximum likelihood (REML) from lme4 **(Bates *et al.*, 2015)** and lmerTest **(Kuznetsova *et al.*, 2014)** packages were performed on leaves and fruits morphological traits for the same comparison purpose and to estimate the part of their variability explained by between-climatic zone effect and within-climatic zone effect (tree-within climatic zone, tree-within transect and within-tree effects). Since sample sizes (number of transects per climatic zone, number of trees considered per climatic zone and per transect) were unequal, Satterthwaite approximation was used as correction formula for the degrees of freedom in order to have accurate p-values **(Mason *et al.*, 2003)**. Tukey's contrasts for multiple comparisons of means from multcomp package **(Hothorn *et al.*, 2008)** was used for means classification **(Mangiafico, 2015)**. For these linear mixed effects models, climatic zone with its three modalities (Guinean, Sudano-Guinean and Sudanian) was considered as fixed factor while transect (7, 6 and 9 respectively in the Guinean, Sudano-Guinean and Sudanian zones) and fruiting tree (from which ten leaves/fruits were measured) were considered as nested factors.

A stepwise linear discriminant analysis was performed in order to find out the most important morphological traits that discriminate trees regarding climatic zones. For this analysis, morphological traits at trunk and canopy levels and mean values per tree for leaves and fruits characteristics were used.

Finally, a redundancy analysis (RDA) was performed to assess relationships between morphological descriptors and bioclimatic variables. The analysis was run on the standardized means values of the previously selected discriminant morphological traits and all the 19 bioclimatic variables extracted from WorldClim database. The best model was selected by removing sequentially bioclimatic variables with the step function in Vegan package **(Oksanen *et al.*, 2013)**. The model selection was based on the Akaike's Information Criterion (AIC) which measures the goodness of fit, with the best model showing the small AIC **(Burnham and Anderson, 2003)**. For the selected model, significance of canonical axes was tested using the marginal permutation test from Vegan package. Moreover, the significance of each bioclimatic variables in the model was tested using the permutation ANOVA test. R 3.2.2 software **(R Core Team, 2016)** was used for the one-way ANOVA, linear mixed effects models and RDA while SPSS 20 **(SPSS IBM, 2011)** was used for the stepwise discriminant analysis.

3.2.4. Assessment of radial growth and wood anatomical patterns of the black plum in regard to climatic conditions

3.2.4.1. Data collection and processing

Radial growth and wood anatomical patterns of the black plum were assessed through tree ring analysis on stem discs. Seven stem discs were collected in January 2015 from each of the extreme (wet vs. dry) climatic zones of Benin: Guinean and Sudanian zones. The discs were taken from trees at 1.3 m from the ground. The diameter at breast height (dbh), total height and bole height were recorded on trees before cutting stem discs (Table III).

- ***Stem discs processing and tree-ring boundaries marking***

Stem discs were processed following the protocol of **Gärtner *et al.* (2015**). The surface of discs were sanded and polished using an electric belt sander with sequence of increasingly sanding papers (80, 120, 180, 240, 320, 400, 800 and 1200 grits) for easy identification of rings boundaries. Air compressor machine was used to clean disc surface from the resulting dust (Photo 3).

- ***Tree-ring boundaries marking and width measuring***

Tree-ring boundaries were marked macroscopically and updated microscopically along three radii per disc (Photo 4). Visual check-up were performed on each disc by counting rings along each radius and viewing their growth patterns. Tree-ring widths (TRW) were measured along each radius from pith to bark with the precision of 0.01 mm. Time Series Analysis and Presentation (TSAP) software combined with the digital measuring device LINTAB 5 (RinnTECH, Heidelberg, Germany) connected to a stereomicroscope (Wild M3Z, Leica, Germany) was used for the measuring process. Growth chronologies were then built from the measured TRW.

Table III: Characteristics of the collected stem discs of *Vitex doniana*

		Climatic zones	
Parameters		**Guinean**	**Sudanian**
DBH (cm)	Mean	36.24	32.6
	Range	34-40	28-37
Total height (m)	Mean	10.14	8.79
	Range	7.5-12.5	6.5-11.5
Bole height (m)	Mean	3.93	3.21
	Range	2-5.5	2-4.5
Bark thickness (mm)	Mean	12.29	11.94
	Range	10.5-13.5	10.5-13.5

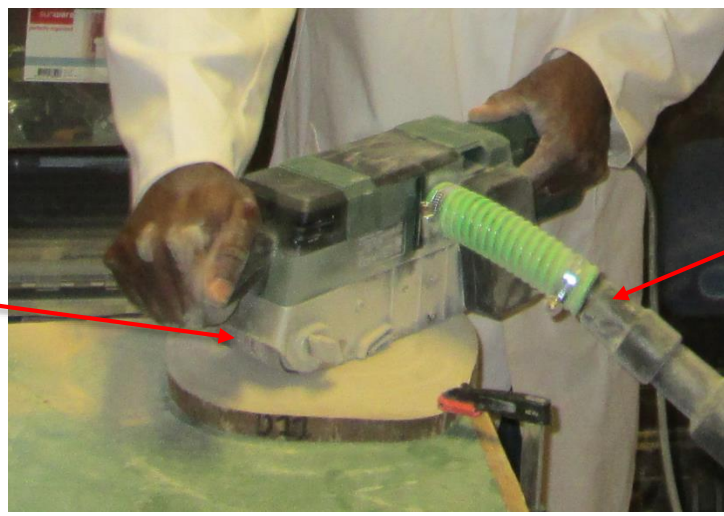


Photo 3: Disc surface polishing with an electric belt sander combined to an air compressor machine

Photos by Hounkpèvi (Laboratory work, in 2015)

Photo 4: Stem disc with tree-ring boundaries marked along three radii

Photos by Hounkpèvi (Laboratory work, in 2015)

- ***Wood sections cutting***

For anatomical data acquisition, mainly conduits (vessels) size and shape within rings, thin sections were cut along one radius per disc. The selected radius was split into overlapping pieces (Photo 5) from last rings (bark) to almost first rings (near the pith). From each piece, 15 µm thin section was cut from the cross-sectional plane with a Lab-microtome. The thin sections were used for slides preparation **(Gärtner *et al.*, 2015)**. Only the five most representative discs were selected in each of the considered climatic zones (Sudanian and Guinean). Before cutting the thin section, the surface of the piece of wood was covered with a corn-starch solution (10 g of corn-starch, 8 ml of water, and 7 g of 100% glycerol) to stabilize the structures within the thin section **(Gärtner *et al.*, 2015)**. To prevent the thin sections from drying, some drops of glycerol solution (one part of 100% glycerol and two parts of distilled water) were added on them.

- ***Slides preparation***

Permanent slides of the thin sections were prepared following steps developed by **Gärtner *et al.* (2015)**. The glycerol was washed away from the thin sections using pipette and distilled water. Drops of Safranin (1 g of Safranin powder + 100 ml of water) and Astra blue (0.5 g of Astra blue powder + 2 ml of 100% acetic acid + 100 ml of water) were added on the micro sections to distinguish between lignified and non-lignified structures and also to enhance the contrast for the subsequent image analysis. After about 5 minutes, the micro sections covered by dye were washed again with pipette and distilled water until the excessive dye is removed. In order to prevent sections from breaking, they were dehydrated by washing them with pipette and a sequence of alcohol solutions: 50 % diluted (one part of pure alcohol + one part of distilled water), 96% alcohol and finally 100% ethanol (pure alcohol + 10% Dimethoxypropan). The micro sections were rinsed thereafter with pipette and 100% Rotihistol. Few drops of 100% Canada balsam were used to cover the micro sections before placing a cover glass on the slides. The resulting slides were gently pressed with soft paper tissue to remove air bubbles. The resulting micro slides were placed between two strips of heat-resistant plastics and the set on a metal plate. Magnets were fixed on top of the slides to press them down in order to keep them flat during drying process. The slides were finally placed in oven at 60 °C for 24 hours. After removing the slides from the oven, they were let for cooling down. When cool, they were cleaned using razor blades to remove the surplus of Canada balsam.

- ***Image and anatomical data acquisition***

Overlapping images were taken from the entire section of each slide using camera (LEICA DFC 420 C) mounted on a microscope (LEICA DM 1000). The magnification of 40X was used for picture capturing. The overlapping images were merged in Photoshop programme in order to have one full image of each slide.

ImageJ software **(Abràmoff *et al.*, 2004)** was used for anatomical data acquisition from the microscopic images. The last annual rings (2004-2014) were measured for each of the selected discs. Tree-ring limits were identified by the differences in vessel lumen area and by the marginal parenchyma bands (Photo 6). Within each tree-ring, individual vessel lumen area (mm^2) and shape i.e. circularity (Equation 10, **Abràmoff *et al.* (2004)**) were measured (Photo 7).

$$circularity = 4\pi \frac{Area}{Perimeter^2} \qquad \text{(Equation 10)}$$

Misrecognized vessels were manually corrected. Such corrections consisted of adding non-recognized vessels, deleting misrecognized vessels, splitting clustered vessels and correcting misrecognized vessel contours. Edging vessels were not considered in the measuring process. In order to determine the density of vessels (number of vessels per area unit), the area of each ring was also measured.

3.2.4.2. Data analysis

- ***Radial growth patterns***

Tree-ring width (TRW) chronologies were cross-dated in TSAPWin through synchronization of paired radii using one as reference and vice-versa. The cross-dating was performed at two levels: for each stem disc by considering the three radii, and for each climatic zone by considering all radii (3 radii x 7 discs). The TRW chronologies, showing low matching patterns with the rest of the dataset were rejected from the dataset rather than corrected **(Šēnhofa *et al.*, 2016)**. Then, only the best matching radii have been considered for each climatic zone. In case of more than one best matching radii for a given disc, an average TRW chronology was built. The computer programme COFECHA was used on the set of tree-ring width measurements to evaluate the cross-dating accuracy **(Holmes, 1986; Grissino-Mayer, 2001)**.

Residual chronologies of TRW were established through a standardization of raw TRW with the computer programme ARSTAN **(Cook and Holmes, 1986)**. A negative exponential curve was used for the standardization process in order to remove biological growth trends from raw TRW chronologies **(Axelson *et al.*, 2014)**. Stand-level chronologies were developed by computing a bi-weight robust mean

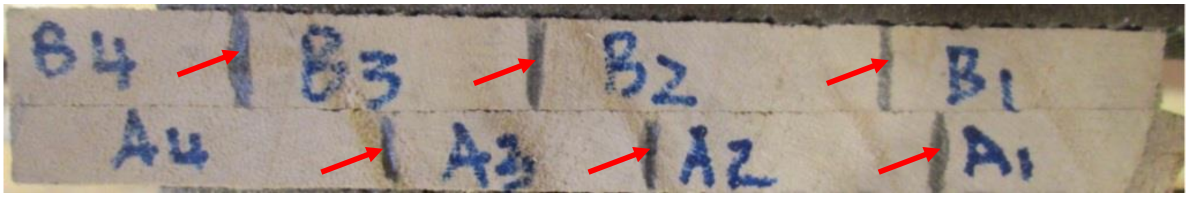


Photo 5: Splitting of wood portion along radius with overlap

Arrows show sawing lines; A1-A4 & B1-B4 codes of overlapping wood pieces for thin sections cutting.
Photos by Hounkpèvi (Laboratory work, in 2015)

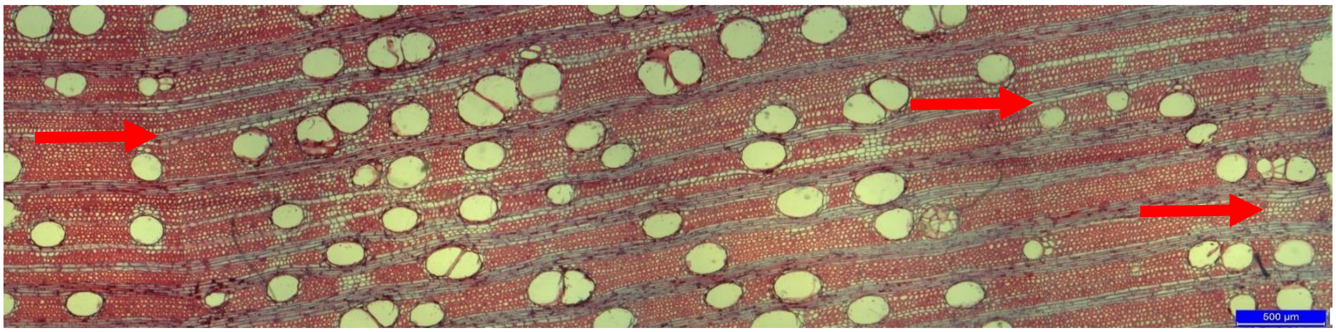


Photo 6: Tree-ring boundaries in wood section
From left to right, rings of 2008 and 2009. Disc D16 from the Guinean zone.
Magnification 40X. Arrows showed rings boundaries and growth direction
Photos by Hounkpèvi (Laboratory work, in 2015)

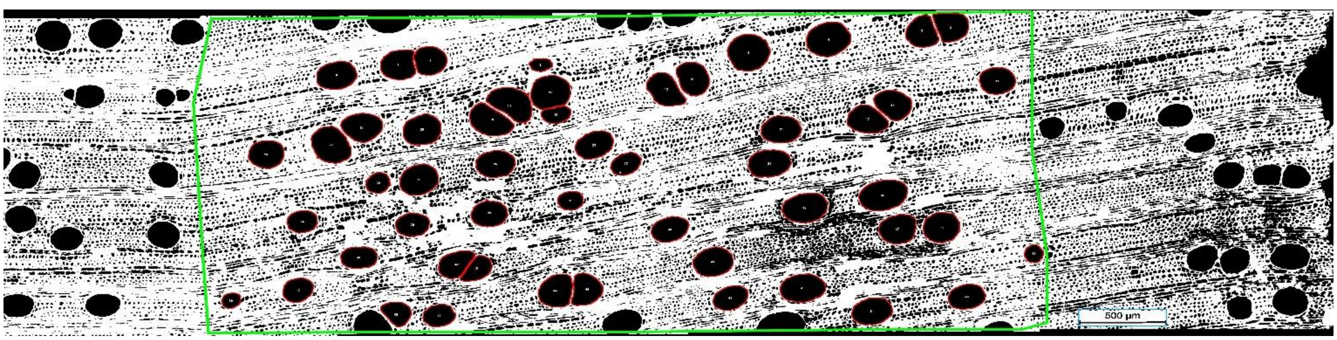


Photo 7: Vessel lumen measuring with ImageJ

Ring of 2008 of the disc D16 from the Guinean zone. Polygon in green is the measuring area. Contour of individual vessel is highlighted in red. Each vessel was automatically labelled during the measuring process.
Photos by Hounkpèvi (Laboratory work, in 2015)

(no autoregressive modelling) of the residual chronologies of each climatic zone. This approach was preferred because it minimizes the effect of outliers and produces a dimensionless stationary index with a defined mean of 1.0 **(Axelson *et al.*, 2014)**.

The following parameters were used to describe the chronologies: (i) *Gleichläufigkeit* (GLK) i.e. coefficient of uniformity provided by the TSAPWin software, it was used as overall measure of similarity between series; (ii) Mean sensitivity (MS), it measures the relative difference between tree-ring variables of consecutive rings; (iii) First-order autocorrelation (AR1), it is a measure of the degree to which growth in a given year is similar to growth in the preceding year; (iv) Expressed population signal (EPS), it measures how well a chronology based on a finite number of trees represents the hypothetical population chronology. Higher between-trees correlation (R_{bt}) and sample size imply a higher EPS **(Fritts, 2001)**. The EPS was computed as:

$$EPS = (n_t \ x \ R_{bt})/((R_{bt} \ x \ n_t) + (1 - R_{bt})) \qquad \text{(Equation 11)}$$

Where n_t is the number of cross-dated trees and R_{bt} is the mean correlation between trees.

The annual radial growth rate (ARG, cm/year) was also computed for each cross-dated tree and averaged for each stand. It was computed as:

$$ARG = 0.1 \ x \ 2mrw \qquad \text{(Equation 12)}$$

with *mrw* being the mean ring width (cm) for each cross-dated tree.

Student's t test was used to compare stands based on the annual radial growth.

- ***Wood anatomical features***

From the measured parameters, minimum, maximum and mean vessel area, vessel density (number of vessels per area unit), lumen fraction (percentage of vessels total area), minimum, maximum and mean vessel circularity were computed for each tree-ring. Differences in wood anatomical features were tested between rings at tree level and also between trees within climatic zone. Moreover, stands were compared regarding these wood anatomical features. For all these analyses, the non-parametric Kruskal-Wallis test was used because normality and variance homogeneity assumptions were not satisfied **(Glèlè Kakaï *et al.*, 2006)**.

- ***Effects of tree morphology and climatic parameters on the tree-ring index and anatomical features***

Pearson's correlation analysis was used to explore relationships between morphological variables of trees (dbh, bole height, tree total height and bark thickness) and wood anatomical variables (vessel size, shape and density). The same analysis was performed to assess the relationships between the residual chronologies of TRW, wood anatomical features and climatic factors. The analysis was run for the period of 1960 – 2012 for TRW and 2004 – 2012 for vessel data. Monthly rainfall and temperature (maximum, minimum and mean) were obtained from the meteorological stations near the sites. Thus, for the Sudanian zone, climatic data from Kandi's station were used while for the Guinean zone, climatic data from Bohicon's station was preferred. All the analyses were run in R software **(R Core Team, 2016)**.

3.2.5. Modelling the habitat suitability for the cultivation and *in situ* conservation of the black plum under current and future climates

3.2.5.1. Data collection

A total of 227 occurrence points (longitude and latitude) were obtained from fieldwork in Benin. Additional occurrence data were also downloaded from the Global Biodiversity Information Facility portal **(GBIF, 2015)** for the West African region (Table IV, Figure 11).

Bioclimatic data for current (1950-2000) and projections for 2050 were extracted from WorldClim database (as described in ***3.2.3.1***). According to the future climate (2050), projections from two models of the Coupled Model Intercomparison Project phase 5 (CMIP5) were preferred because of their commonness use and satisfactory features for simulating the global climate response to increasing greenhouse gas concentration **(Fandohan *et al.*, 2015b)**. These models were the Hadley Global Environment Model version 2 – Earth System (HadGEM2-ES) and the Model for Interdisciplinary Research on Climate Change, Version 5 (MIROC5). They were considered under two of the four Representative Concentration Pathway (RCP) developed by the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report: RCP 4.5 and RCP 8.5. These RCP were preferred because they projected the most divergent trends for the West African region compared to the others **(IPCC, 2013)**. With this divergent trend (low vs. high emissions scenario), the range of emissions uncertainty is well captured **(Harris *et al.*, 2014)**. For instance, temperature is projected to rise above industrial level by at least 1.4°C under RCP 4.5 in West Africa by mid-21st century, with atmospheric CO_2 reaching 500 ppm and by 2°C with atmospheric CO_2 over 550 ppm under the more drastic RCP 8.5 **(IPCC, 2013)**.

Table IV: Source, type, geographic location of occurrence points used in the modelling process

Source and type	Geographic location	Number of points
GBIF (H & F)	Burkina-Faso	22
GBIF (H & F)	Benin	30
GBIF (H & F)	Cote d'Ivoire	13
GBIF (H & F)	Ghana	21
GBIF (H & F)	Guinea	15
GBIF (H & F)	Gambia	1
GBIF (H & F)	Mali	10
GBIF (H & F)	Nigeria	21
GBIF (H & F)	Sierra Leone	7
GBIF (H & F)	Togo	8
GBIF (H & F)	Senegal	1
Fieldwork	Benin	78

GBIF (Global Biodiversity Information Facility, www.gbif.org); H = herbarium, F = Fieldwork

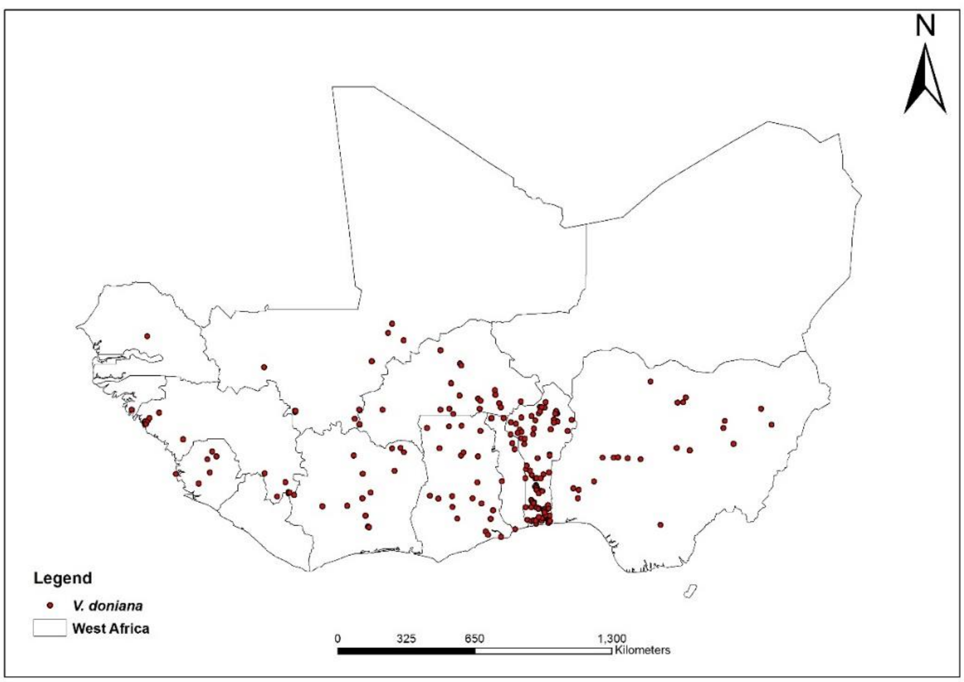


Figure 11: Occurrence of the black plum in West Africa

(Data source: GBIF and fieldwork in Benin)

The Protected Area Network (PAN) map of Benin was downloaded from the World Database on Protected Areas **(IUCN and UNEP-WCMC, 2015)**. This map was used to assess the *in situ* conservation of the species within PAN in the country under current and future climates.

3.2.5.2. Data analysis

The Maximum Entropy (MaxEnt, version 3.3.3k") species distribution model algorithm **(Phillips *et al.*, 2006)** was used for the habitat suitability modelling. This modelling tool requiring presence-only data is one of the best-performing modelling approaches among those using climate modelling approaches **(Phillips *et al.*, 2006)** and it is relatively robust for small sample sizes **(Pearson *et al.*, 2007)**. It is a machine learning method that estimates a species' distribution across a study area by calculating the probability distribution of maximum entropy subject to the constraint that the expected value of each feature under this estimated distribution should match its empirical average **(Phillips *et al.*, 2006)**. Although there are several conceptual ambiguities and uncertainties about bioclimatic envelope modelling **(Schwartz, 2012)**, MaxEnt remains an important modelling tool in assessing potential impacts of climate change on species distribution **(Elith *et al.*, 2011a)**.

During the modelling process, presence data were cleaned up by removing duplicate records in grids in order to reduce sampling bias which may result from the over sampling of some sites in the study area **(Elith *et al.*, 2006)**. Only the less-correlated ($r < 0.85$) bioclimatic variables were selected with the environmental niche modelling tools (ENMTs) and used for the modelling **(Elith *et al.*, 2011b)**. During the variables selection process, priority was given to bioclimatic variables reflecting water availability since plants distribution in the study area is known to be under the influence of mainly soil moisture, total rainfall, air humidity and the length of the dry season **(Adomou *et al.*, 2006)**. MaxEnt's internal Jackknife test was performed to assess the contribution of the selected variables in the distribution of the species **(Pearson *et al.*, 2007)**.

Twenty five percent of the occurrence points was used for model testing and 75% for model calibration in five replicates. The five replicates were averaged through cross-validation. Two criteria were used to evaluate the performance i.e. goodness-of-fit and predictive power of the model: (i) the area under the receiver operating characteristic curve (AUC) and (ii) the true skill statistic (TSS) **(Allouche *et al.*, 2006; Elith *et al.*, 2006; Pearson *et al.*, 2007)**. The AUC is the probability that a randomly chosen presence point of the species will be ranked as more suitable than a randomly chosen absence point. A model is considered as having a good fit when its AUC is close to 1 ($AUC \geq 0.75$) **(Elith *et al.*, 2006)**. The TSS is the capacity of the model to accurately detect true presences (sensitivity) and true absences (specificity). A model with TSS ≤ 0 indicates a random prediction, while a model with a TSS close to 1 (Tss > 0.5) has a good predictive power **(Allouche *et al.*, 2006)**.

To capture the correct range of each bioclimatic factor, the modelling process was performed using occurrence and climatic data for the whole West Africa. The outputs of MaxEnt were then clipped on Benin, to mark out the study area. The habitat suitability of the species across the study area was assessed based on the logistic probability distributions generated by the model using the 10 percentile training presence logistic threshold. Thus, areas with occurrence probability above the threshold value were considered as suitable for the species and areas with occurrence probability below the threshold value were taken as unsuitable habitats **(Scheldeman and van Zonneveld, 2010; Fandohan *et al.*, 2015b)**. Suitable/unsuitable habitats of the species for current and future climate were mapped in ArcGIS 10.3 **(ESRI, 2014)**.

Representation gap analysis was used to assess the *in situ* conservation status of the species by the national protected areas network **(Fandohan *et al.*, 2011b; Fandohan *et al.*, 2013; Tantipisanuh *et al.*, 2016)**. For that, PAN of Benin was overlain on the present and future habitat suitability maps and proportions of suitable and unsuitable areas within the PAN were estimated in ArcGIS 10.3 **(ESRI, 2014)**.

PART IV: RESULTS

4.1. Use values and perceptions of local people on climate change and its impacts on the black plum

4.1.1. Use values of the black plum

4.1.1.1. Reported use values

Reported used values (RUV) per interviewee varied weakly between climatic zones (Kruskal-Wallis chi-squared = 6.19; df = 2; p-value = 0.045). Informants from the Guinean and Sudanian zones reported slightly more usages than those in the Sudano-Guinean zone (Table V). Conversely, the results revealed a strong effect of the ethnic group (Kruskal-Wallis chi-squared = 140.01; df = 21; p-value = <0.001) and age category (Kruskal-Wallis Chi-squared = 8.68; df = 1; p-value = 0.003) on the RUV. No significant gender influence was detected (Kruskal-Wallis chi-squared = 0.26, df = 1, p-value = 0.608). *Gourmantché* (4.83 ± 1.60) and *Jerma* (4.44 ± 1.04) ethnic groups (both from the Sudanian zone) reported relatively more usages of the species than the other ethnic groups, the lowest values being reported by *Waama* (1.75 ± 0.50) and *Natimba* (1.50 ± 1.35) groups also from the Sudanian zone. There seemed to be a positive relationship between age of informants and the RUV, with old people (above 60 years) reporting more usages of the species than adults (below 60 years).

4.1.1.2. Plant part use values

Overall, fruits and young leaves were the most used parts of the black plum in Benin (Figure 12). However, the plant parts did not have the same importance across the country, particularly regarding climatic zones. In the Guinean and Sudanian zones, fruits seemed to be the most used plants parts while in the Sudano-Guinean zone, young leaves appeared the most used part.

The Principal Components Analysis (PCA) performed on the plant part use values showed that the first two principal components explained 54.66 % of the total variance. The first principal component (PC1) was negatively correlated with fruits and young leaves and, positively correlated with mature leaves. The second principal component (PC2) was negatively correlated with trunk and, positively with mature leaves, bark and flowers (Table VI). The projection of ethnic groups in the system axis (Figure 13) showed, regarding PC1, that *Aïzo*, *Anii*, *Bariba* in the Sudano-Guinean zone (*BaribaSG*), *Holli*, *Biali* and *Ishabè* ethnic groups valued fruits and young leaves more than other parts of the plant. On the counterpart, *Gourmantché*, *Jerma*, *Peulh* met in the Sudanian zone (*PeulhS*) and *Mahi* in the Sudano-Guinean zone (*MahiSG*) gave more importance to mature leaves than the other parts of the plant. Regarding PC2, *Adja*, *Bariba* from the Sudanian zone (*BaribaS*), *Mahi* from the Guinean zone (*MahiG*), *Natimba* and *Wémènou* ethnic groups gave more importance to mature leaves, bark and flowers than the

Table V: Reported use values based on climatic zone, ethnic group, gender and age category

Factors	Mean ± SD	p-value
Bioclimatic zone		
Guinean	3.15 ± 1.28	
Sudano-Guinean	2.89 ± 1.27	0.045
Sudanian	3.16 ± 1.41	
Ethnic group (Bioclimatic zone)		
Adja (Guinean zone)	2.80 ± 1.47	
Aïzo (Guinean zone)	2.55 ± 0.74	
Fon (Guinean zone)	3.42 ± 1.14	
Holli (Guinean zone)	2.65 ± 1.03	
Mahi (Guinean zone)	3.58 ± 1.00	
Wémènou (Guinean zone)	3.97 ± 1.32	
Anii (Sudano-Guinean zone)	2.2 ± 0.82	
Bariba (Sudano-Guinean zone)	2.48 ± 1.21	
Ishabè (Sudano-Guinean zone)	2.50 ± 0.95	
Kotokoli (Sudano-Guinean zone)	2.17 ± 1.60	
Mahi (Sudano-Guinean zone)	3.44 ± 1.12	<0.001
Peulh (Sudano-Guinean zone)	4.00 ± 1.22	
Yom (Sudano-Guinean zone)	4.10 ± 1.04	
Bariba (Sudanian zone)	2.41 ± 1.39	
Berba (Sudanian zone)	3.07 ± 0.96	
Biali (Sudanian zone)	2.64 ± 1.22	
Gourmantché (Sudanian zone)	4.83 ± 1.60	
Jerma (Sudanian zone)	4.44 ± 1.04	
Peulh (Sudanian zone)	4.00 ± 0.00	
Monkolé (Sudanian zone)	3.27 ± 1.00	
Natimba (Sudanian zone)	1.50 ± 1.35	
Waama (Sudanian zone)	1.75 ± 0.50	
Gender		
Female	3.02 ± 1.26	0.608
Male	3.11 ± 1.36	
Age category		
Adult (< 60 years)	2.92 ± 1.31	0.003
Old (> 60 years)	3.29 ± 1.31	

SD = Standard deviation; p-value = probability of significance from Kruskal-Wallis rank sum test

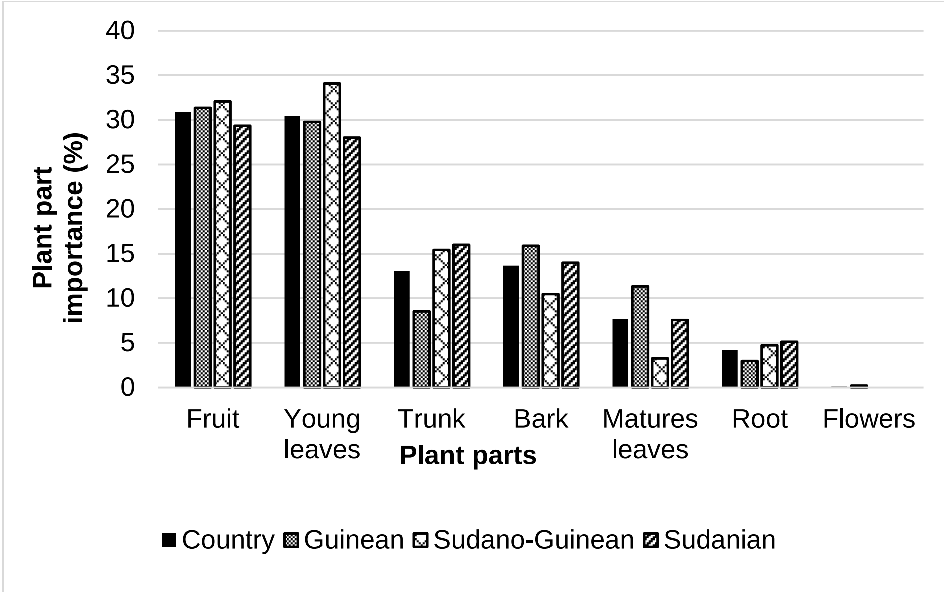


Figure 12: Relative importance (%) of used plant parts of the black plum in Benin

Table VI: Correlations between used parts of the black plum and principal components (PC1 and PC2)

	PC1 (30.17%)	**PC2 (24.48%)**
Fruit	-0.87***	0.44*
Young leaves	-0.87***	0.30ns
Mature leaves	0.56**	0.69***
Bark	0.41ns	0.54**
Root	0.29ns	0.27ns
Flowers	0.08ns	0.63***
Trunk	0.20ns	-0.45*

***: Significant at p-value < 0.001; **: Significant at p-value < 0.01; *: Significant at p-value < 0.05, ns: Non significant (p-value > 0.05)

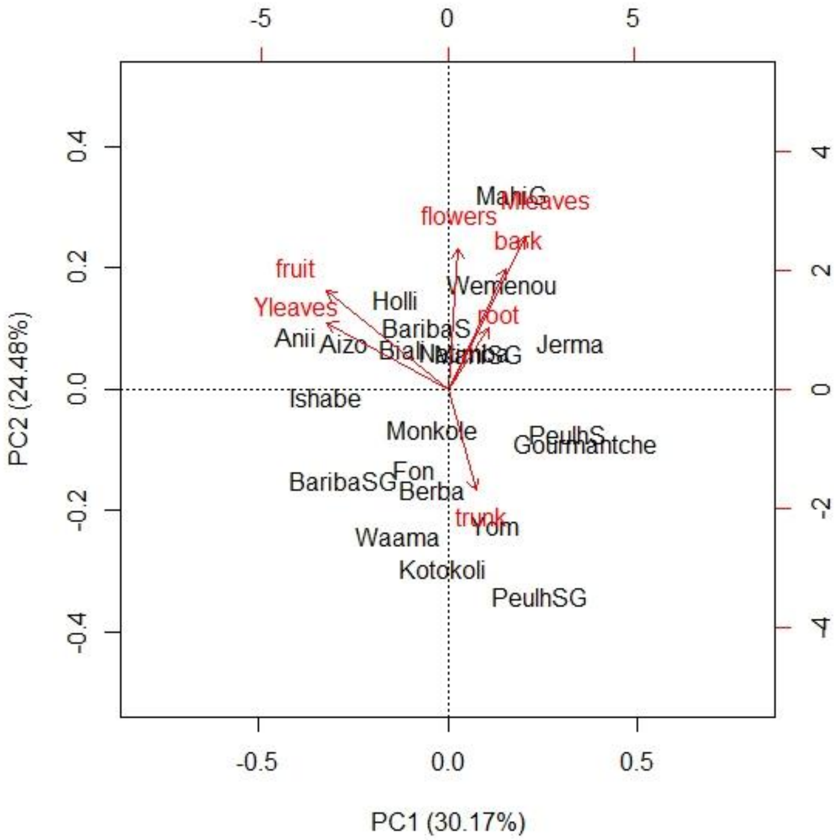


Figure 13: Projection of ethnic groups of Benin in the system axis defined by the first two principal components showing correlations between these groups and uses of the black plum parts

other parts of the species. The trunk was more valued by *Berba*, *Fon*, *Kotokoli, Peulh* from the Sudano-Guinean zone (*PeulhSG*), *Monkolé*, *Waama* and *Yom* ethnic groups (see contributions of ethnic groups on PC1 and PC2 in Appendix 1).

4.1.1.3. Use forms

The black plum is used for several purposes among which food and medicine were the most reported irrespective of the bioclimatic zone (Figure 14). This species was more valued for consumption in the Sudano-Guinean zone (65.36%) than in the other zones. The Principal Components Analysis performed on use form values indicated that the first three principal components explain 68.44 % of the total variance. The first component was negatively correlated with uses for food, while uses for fodder and magical/cultural purposes were positively linked to the same component. The second component was negatively correlated with uses for fire (firewood and charcoal) and handicraft making purposes. The third component was positively correlated with medicinal uses and negatively associated with handicraft making purposes (Table VII).

Figure 15a showed that *Adja*, *Bariba* in the Sudanian zone (*BaribaS*), *Biali*, *Holli*, *Ishabè* and *Wémènou* ethnic groups used the black plum mostly for food purposes. *Gourmantché*, *Peulh* in the Sudanian zone (*PeulhS*) and *Monkolé* groups seemed interested in the black plum mostly for fodder and magical/cultural uses. *Yom, Fon, Peulh* in the Sudano-Guinean zone *(PeulhSG)* and *Berba* groups valued the species mostly for fire (wood and charcoal) and handicraft making purposes. Regarding figure 15b, *Bariba* people living in the Sudano-Guinean zone (*BaribaSG*), *Waama*, *Aïzo,* and *Kotokoli* groups considered the black plum as an important plant for handicraft making. *Mahi* in Guinean and Sudano-Guinean zones (*MahiG*, *MahiSG*) and *Jerma* ethnic groups used the species mostly in traditional pharmacopeia (see contributions of ethnic groups on PC1, PC2 and PC3 in Appendix 2).

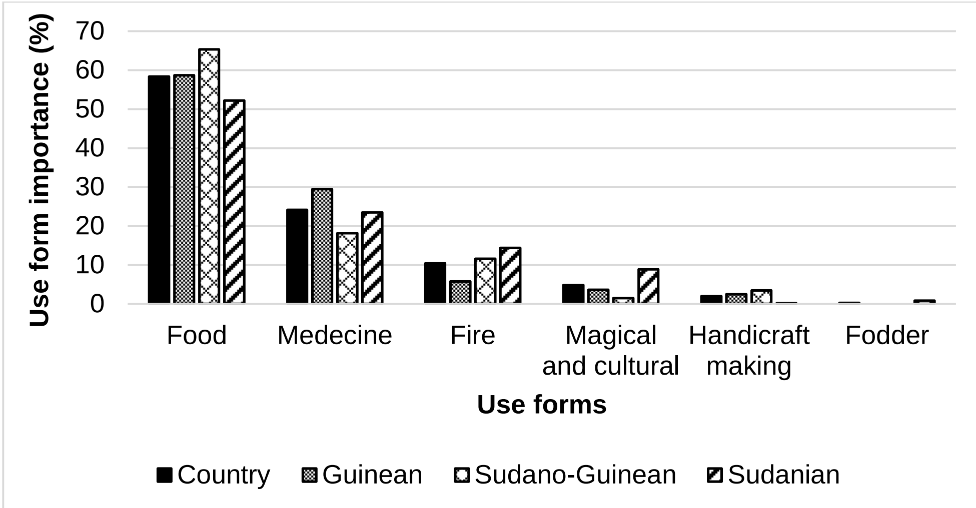


Figure 14: Relative importance (%) of use forms of the black plum in Benin

Table VII: Correlations between use forms of the black plum and Principal Components (PC1, PC2 and PC3)

	PC1 (29.60 %)	**PC2 (21.44 %)**	**PC3 (17.40 %)**
Food	-0.75***	0.22ns	-0.23ns
Medicine	-0.33ns	0.01ns	0.84***
Fodder	0.74***	0.39ns	-0.08ns
Fire (wood and charcoal)	0.12ns	-0.86***	0.21ns
Handicraft making	-0.22ns	-0.55**	-0.49*
Magical and cultural	0.71***	-0.20ns	0.05ns

***: Significant at p-value < 0.001; **: Significant at p-value < 0.01; *: Significant at p-value < 0.05, ns: Non significant (p-value > 0.05).

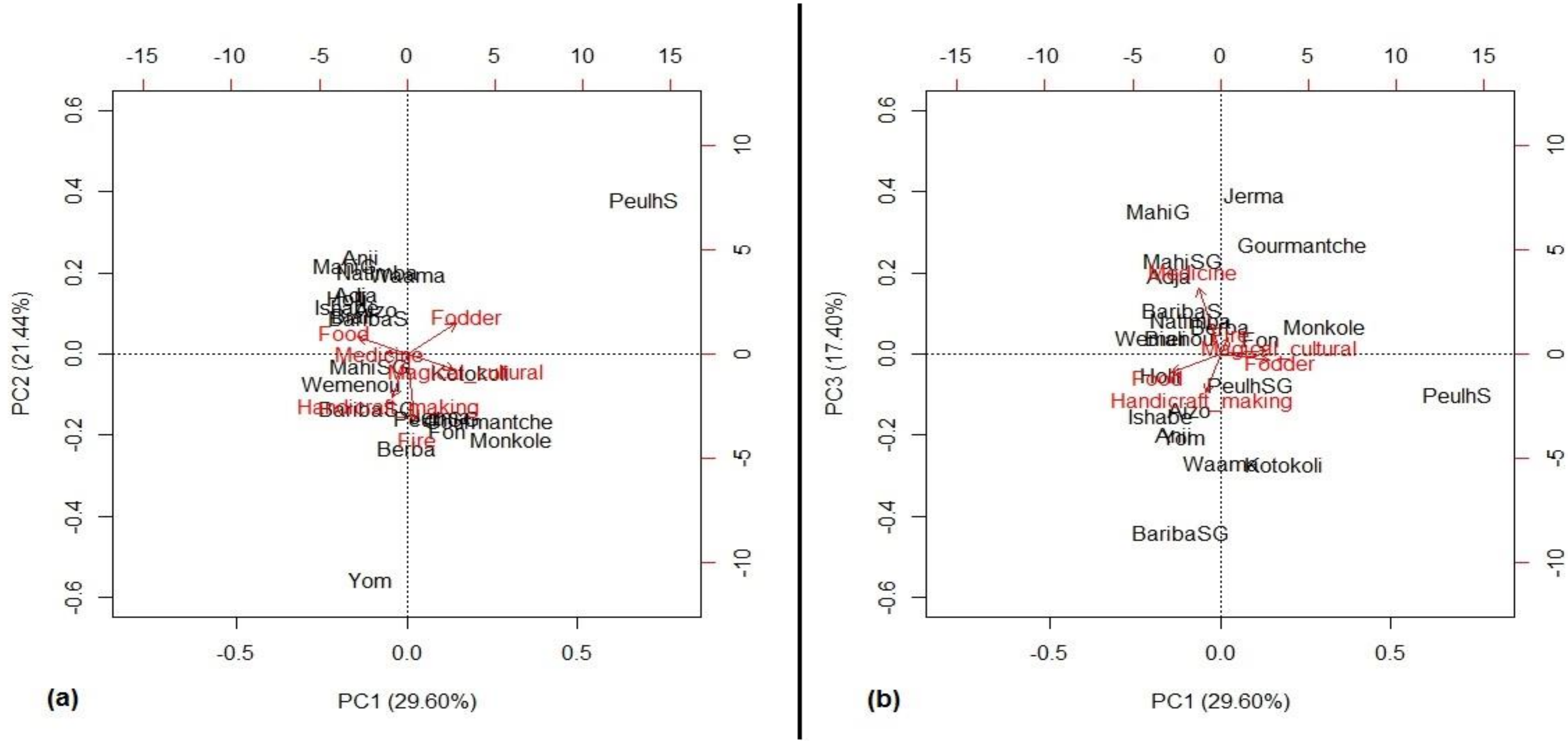


Figure 15: Projection of ethnic groups of Benin in the system axis defined by principal components showing correlations between these groups and use forms of the black plum

(a) PC1 X PC2; (b) PC1 X PC3

4.1.2. Local people perceptions of on climate change and its impacts on the black plum

4.1.2.1. Local perceptions on climate change

At country scale, 95 % of respondents perceived changes in the climatic parameters considered in this study. Regarding the climatic zones, 88.13, 98.56 and 99.30 % of interviewees reported changes in the climatic factors in the Guinean, Sudano-Guinean and Sudanian zones respectively. The most reported perceptions were reduction of the rainy season's length (27.46 %), temperature raising (26.1 %) and reduction of rain intensity (23.45 %). Perceptions of people on climate change depended on their ethnicity (p-value < 0.001 from Fisher's exact test), and on their belonging climatic zone (Chi-squared = 166.72, df = 16, p-value < 0.001). However, gender (Chi-squared = 2.89, df = 8, p-value = 0.941) and age (Chi-squared = 13.55, df = 8, p-value = 0.094) did not significantly affect perceptions of local people on climate change. In the Sudanian zone, about 28 % of people perceiving changes in the climatic parameters reported that temperature is decreasing while in the other zones, a relatively low proportion of respondents mentioned this decrease in temperature. Moreover, 15 % of respondents reported no changes in rainy season length in the Guinean zone, while only 1.41 of respondents in the Sudanian and 5.04 % in the Sudano-Guinean zone noted this observation. Regarding the other parameters (gender and age category), the proportions of respondents are quite similar for each of the perceptions on the climatic factors (Table VIII).

From the correspondence analysis on perceptions of local people on climate change, it appeared that the system axis defined by the first two dimensions holds 70.02 % of the total information in the data. The best represented perceptions on dimension 1 were the "no perceptible changes" in the considered parameters whereas on dimension 2, "increase in rainy season length" and "increase in rainfall intensity" were the well represented perceptions (Table IX). The projection of perceptions and ethnic groups in this axis systems showed that *Aïzo* people did not mostly perceive any changes in the climatic parameters and that *Bariba* in the Sudano-Guinean zone, *Kotokoli* and *Anii* people perceived that rainy season length and rainfall intensity have increased (Figure 16, Appendix 3).

Regarding relationships between organ uses and perceptions on climate change, there were no significant correlations between organ uses and perceptions on climate change. Similar trends were also noticed between use forms and perceptions on climate change (Figure 17).

Table VIII: Percentage of respondents regarding changes in climatic parameters in Benin

	Temperature			Length of rainy season			Rainfall intensity		
	Warming	Cooling	No change	Longer	Shorter	No change	Decrease	Increase	No change
Climatic zones									
Guinean	84.38	1.88	13.75	1.25	83.75	15.00	70.00	8.75	21.25
Sudano-Guinean	87.05	10.79	2.16	25.90	69.06	5.04	68.35	21.58	10.07
Sudanian	62.68	28.17	9.15	4.93	93.66	1.41	72.54	2.82	24.65
Gender									
Female	78.92	12.65	8.43	9.04	83.13	7.83	66.27	11.45	22.29
Male	77.82	13.45	8.73	10.91	81.82	7.27	72.73	10.55	16.73
Age category									
Adult (< 60)	76.23	16.60	7.17	12.08	80.00	7.92	71.32	12.08	16.60
Old (≥ 60)	81.25	7.95	10.80	7.39	85.80	6.82	68.75	9.09	22.16

Table IX: Representation of local perceptions on climate change in the first two dimensions system

	Dim 1 (40.48%)		Dim 2 (29.54%)	
Local perceptions	**Contribution**	**Cos^2**	**Contribution**	**Cos^2**
Increase of temperature	2.997	0.301	0.401	0.030
Temperature decrease	0.125	0.003	2.878	0.057
No change in temperature	**31.844**	**0.913**	0.076	0.002
Increase of rainy season length	0.547	0.014	**46.675**	**0.891**
Decrease of rainy season length	2.294	0.307	5.868	0.581
No change of rainy season length	**34.546**	**0.869**	0.022	0.000
Decrease of rainfall intensity	5.840	0.475	3.655	0.220
Increase of rainfall intensity	0.000	0.000	**39.145**	**0.899**
No changes in rainfall intensity	**21.807**	**0.622**	1.280	0.027

Values in bold are the best representation of variables in the considered dimension (contribution > 100/9 = 11.11 % and squared cosine > 0.5)

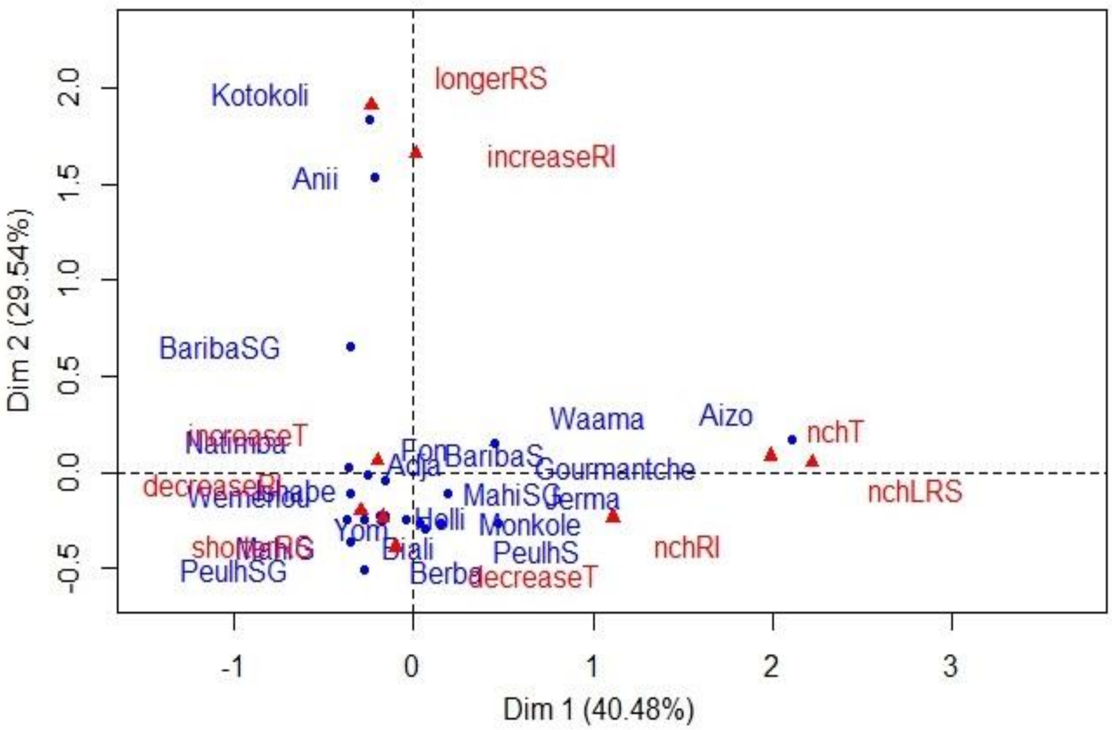


Figure 16: Projection of ethnic groups of Benin and local perception on climate change in the axis system defined by the correspondence analysis

Ethnic groups are in blue and local perception in red (nchRI = no perceptible changes of rainfall intensity; nchT = no perceptible changes of temperature; nchLRS = no perceptible changes of rainy season length; increaseRI = increase of rainfall intensity; decreaseRI = decrease of rainfall intensity; increaseT = increase of temperature; decreaseT = decrease of temperature; longerRS = increase of rainy season length; shorterRS = decrease of rainy season length).

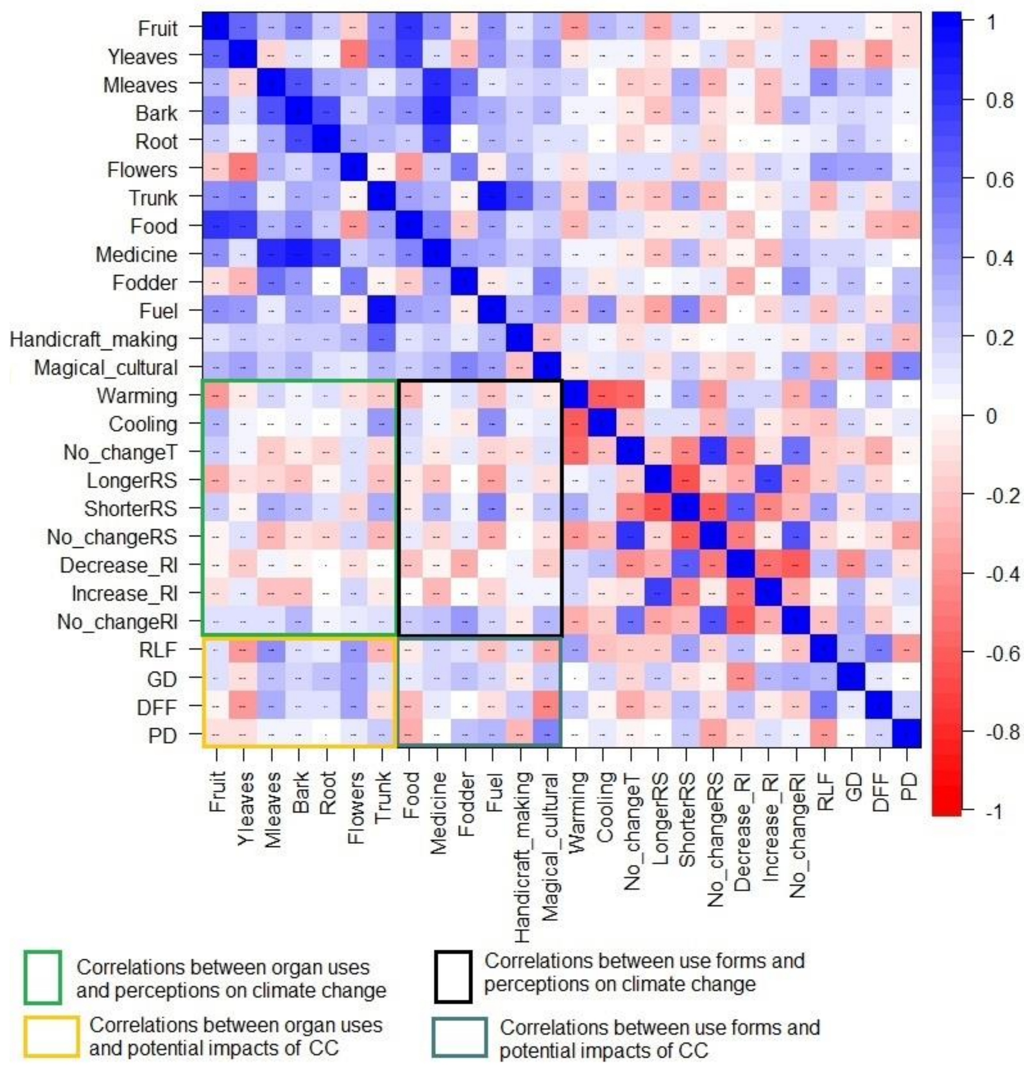


Figure 17: Correlations plot (Tetrachoric correlations)

No_changeRI = no perceptible changes of rainfall intensity; No_changeT = no perceptible changes of temperature; No_changeRS = no perceptible changes of rainy season length; Increase_RI = increase of rainfall intensity; Decrease_RI = decrease of rainfall intensity; Warming = increase of temperature; Cooling = decrease of temperature; Increase_RS = increase of rainy season length; Decrease_RS = decrease of rainy season length.
RLF = reduction of fruiting period's length; GD = growth disturbance; DFF = delay in flowering/fruiting; PD = decrease of productivity.

4.1.2.2. Impacts of climate change on the biology and productivity of the species according to local people

Overall, thirty five percent of people perceiving changes in the climate, associated these changes to some perceived impacts on *V. doniana* trees. In each of the Guinean and Sudanian zones, 42.55 % of those perceiving changes in climate associated these changes with some stresses on *V. doniana* trees, versus 19.71 % in the Sudano-Guinean zone. The reported impacts on the black plum due to climate change were: decreasing productivity (52.22 %), delay in flowering/fruiting (29.56 %), reduction of fruiting period's length (10.34 %) and growth disturbance i.e. growth stress (7.88 %). These reported impacts depended on ethnicity and on bioclimatic zone where respondents live (p-value < 0.001 from Fisher's exact test). But there was no signal of gender effect (Chi-squared = 3.99, df = 3, p-value = 0.262) or age effect (Chi-squared = 0.21, df = 3, p-value = 0.977) on the reported impacts. In the Guinean zone for example, 20.62 % of informants mentioned reduction of fruiting period's length of while in the other zones, less than 2 % of the respondents reported this impact. Similarly, growth disturbance and decrease of productivity were mostly mentioned by interviewees in Sudano-Guinean and Sudanian zones (Table X).

The correspondence analysis on reported impacts of climate change on the species shows that the first two dimensions store 88.46 % of the total information in the data. Reduction of fruiting period, delay in flowering/fruiting and decrease of productivity were well represented in the first dimension while growth disturbance was represented in the second dimension (Table XI). The projection of impacts and ethnic groups in the axis system (Figure 18) showed that *Gourmantché* and *Kotokoli* groups associated growth disturbance of *Vitex doniana* with climate change while almost all the other groups attributed the reduction of fruiting period, delay in flowering/fruiting and decrease of productivity to climate change (see contributions of ethnic groups on Dimensions 1 and 2 in Appendix 4).

Similarly to the case of the perceptions on climate change, no significant correlations were found between organ uses and potential impacts of climate change on the species. It was also the case for the correlations between use forms and reported impacts of climate change on the species (Figure 17).

Table X: Percentage of informants reporting impacts of climate change on the black plum

	RLF	GD	DFF	PD
Bioclimatic zone				
Guinean	20.62	3.09	45.36	30.93
Sudano-Guinean	0.00	15.63	12.50	71.88
Sudanian	1.35	10.81	16.22	71.62
Gender				
Female	11.25	10.00	35.00	43.75
Male	9.76	6.50	26.02	57.72
Age category				
Adult (<60)	10.34	8.62	29.31	51.72
Old (≥60)	10.34	6.90	29.89	52.87

RLF = reduction of fruiting period's length; GD = growth disturbance; DFF = delay in flowering/fruiting; PD = decrease of productivity

Table XI: Representation of climate change impacts on the black plum in the two dimensions (correspondence analysis)

	Dim1 (65.63%)		Dim2 (22.83%)	
	Contribution	**Cos^2**	**Contribution**	**Cos^2**
Reduction of length of fruiting	**39.18**	**0.80**	4.26	0.03
Growth disturbance	0.23	0.01	**79.00**	**0.92**
Delay in flowering/fruiting	**22.51**	0.67	14.45	0.15
Productivity decrease	**38.09**	**0.95**	2.29	0.02

Values in bold are the best representation of variables in the considered dimension (contribution > 100/4 = 25 % and squared cosine > 0.5)

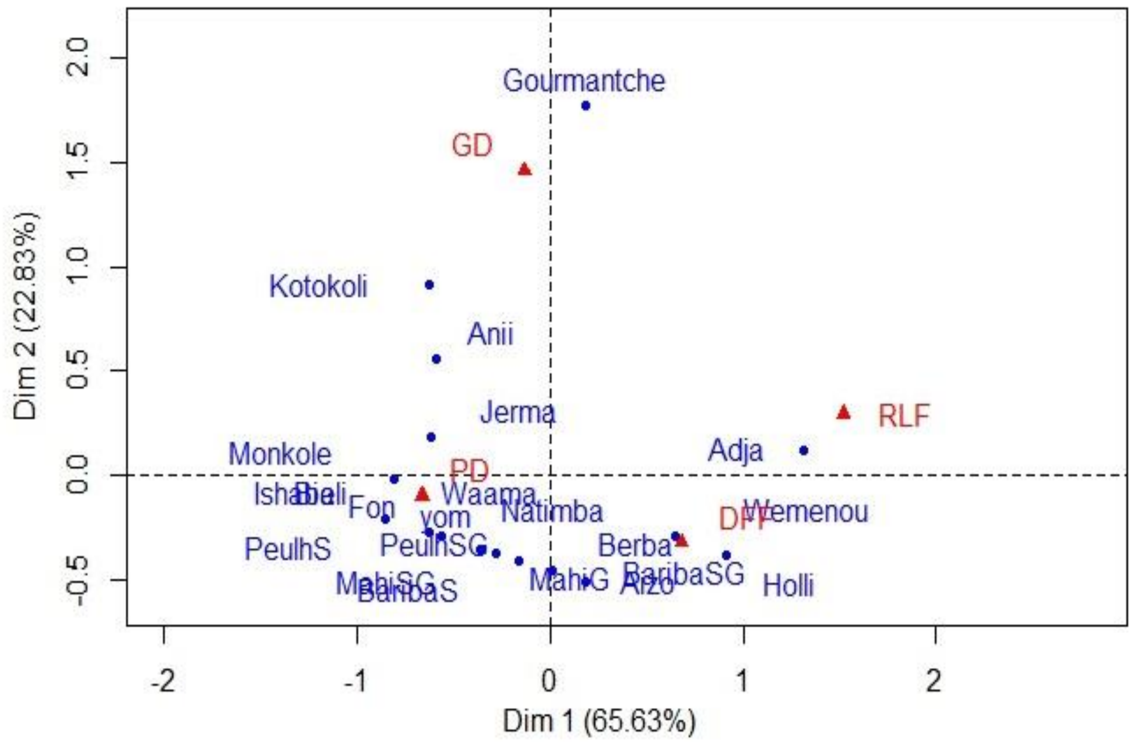


Figure 18: Projection of ethnic groups of Benin and impacts of climate change on the biology and productivity of the black plum according to local people

Ethnic groups in blue and reported impacts in red (GD = growth disturbance; PD = decrease of productivity; RLF = reduction of fruiting period's length; DFF = delay in flowering/fruiting)

4.2. Ecology and structural parameters of the black plum regarding climatic variability and local environment patterns

4.2.1. Ecology of the black plum

4.2.1.1. High occurrence habitat

The mean number of contacts as well as the mean number of adult individuals of the black plum per contact along transects were relatively low (0.65 – 0.91 contacts per transect in average, and 1.62 – 1.71 individuals in average per contact) and did not vary significantly between climatic zones (df = 2, p-value > 0.05, Table XII, Appendix 5). Significant effects of land cover types (df = 4, p-value < 0.001) and of classes of distance to the closest river (df = 3, p-value < 0.001) were observed on absolute frequencies of observation (mean number of contacts per transect), but not on abundance per contact (Table XII, Appendix 5). Moreover, significant interaction effects of climatic zone, and respectively land cover (df = 8, p-value < 0.001), and distance to the closest river (df = 6, p-value < 0.001) were observed on the absolute frequencies of contacts with *V. doniana* along transects. Within climatic zones, the black plum was more frequent in mosaics of croplands and fallow (MCF), with in average 4.10, 1.85, and 1.20 contacts per transect in the Guinean, Sudanian and Sudano-Guinean zones respectively (Figure 19a). Regarding distance to the closest river, the species was mostly observed in areas that were at less than 500 m to a river even though observation frequencies were relatively low (3.25, 2.15 and 1.75 in the Sudano-Guinean, Guinean and Sudanian zone respectively, see Figure 20a). Although significant interaction effects were noted on the frequency of observation, the species showed a relatively similar abundance in all habitats under consideration (Figures 19b & 20b). The findings revealed that the black plum occurred in variety of habitats, however, in the Sudano-Guinean zone the species was not observed beyond 1000 m to a river.

The black plum was observed in a variety of soils with the highest relative frequencies of observations on ferrallitic soil (30.53 %), mainly in the Guinean zone and on ferruginous soils with concretions (28.3 %). Soils under the species were acidic (pH < 6) and the acidity was more remarkable in the Guinean and Sudano-Guinean zones than in the Sudanian zone (Table XIII). In the Sudano-Guinean and Sudanian zones, soils under the species had higher proportions of organic carbon and coarse silt than in the Guinean zone (p-value < 0.05, Table XIII).

Table XII: Absolute frequencies of observation and abundance of the black plum along transects

	Mean number of contacts per transect		Mean number of individuals per contact	
	Mean ± SD	CV (%)	Mean ± SD	CV (%)
Climatic zone				
Guinean	0.91 ± 2.30	252.86	1.62 ± 1.10	68.29
Sudano-Guinean	0.70 ± 1.28	182.18	1.71 ± 1.08	62.92
Sudanian	0.65 ± 1.46	224.47	1.71 ± 1.06	61.87
p-value	0.567		0.861	
Land cover				
MCF	2.38 ± 2.86	120.20	1.69 ± 1.09	64.70
Plt	0.13 ± 0.43	322.86	1.50 ± 1.07	71.27
RF	0.18 ± 0.54	292.65	1.18 ± 0.60	51.03
TSS	0.92 ± 1.59	173.12	1.82 ± 1.16	63.59
Woodl	0.15 ± 0.48	320.66	1.33 ± 0.71	53.03
p-value	<0.001		0.513	
Distance class				
Class1	2.38 ± 2.42	101.63	1.67 ± 1.03	61.81
Class2	0.62 ± 1.32	213.41	1.51 ± 0.96	63.49
Class3	0.37 ± 1.19	325.29	1.59 ± 0.73	46.15
Class4	0.40 ± 1.83	458.44	2.00 ± 1.64	82.09
p-value	<0.001		0.549	

Land cover types: MCF = mosaics of croplands and fallows, Woodl = woodlands, Plt = plantation, RF = riparian forests, TSS = tree and shrub savannahs.
Classes of distance to the closest river: Class1= less than 500m; Class2 = between 500 and 1000m; Class3 = between 1000 and 1500m; Class4 = more than 1500m.

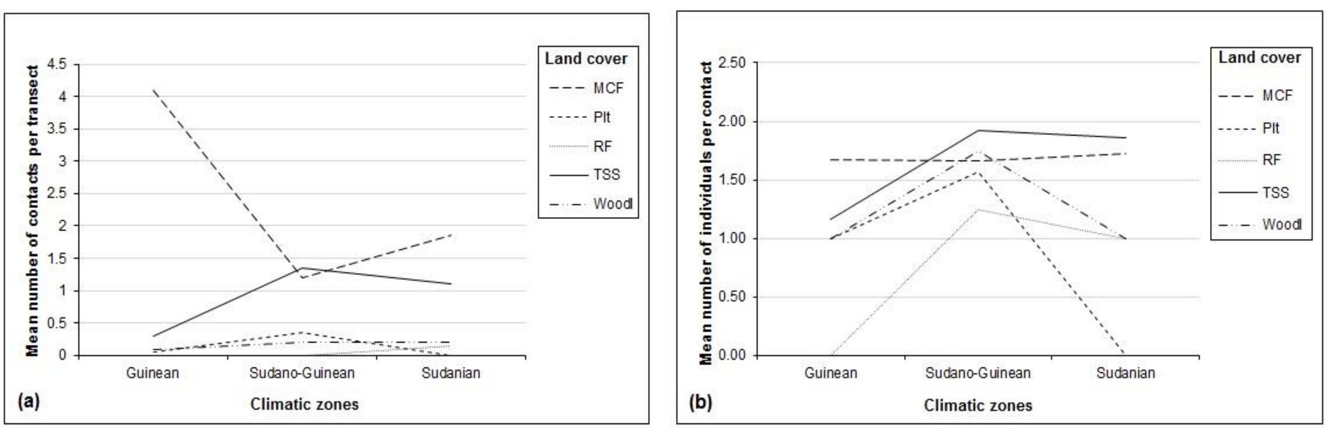


Figure 19: Interaction plot of climatic zone and land cover type on the occurrence of *Vitex doniana* in Benin (a) Frequency of observation; (b) Abundance per contact

MCF = mosaics of croplands and fallows, Plt = plantation, RF = riparian forests, TSS = tree and shrub savannah, Woodl = woodlands

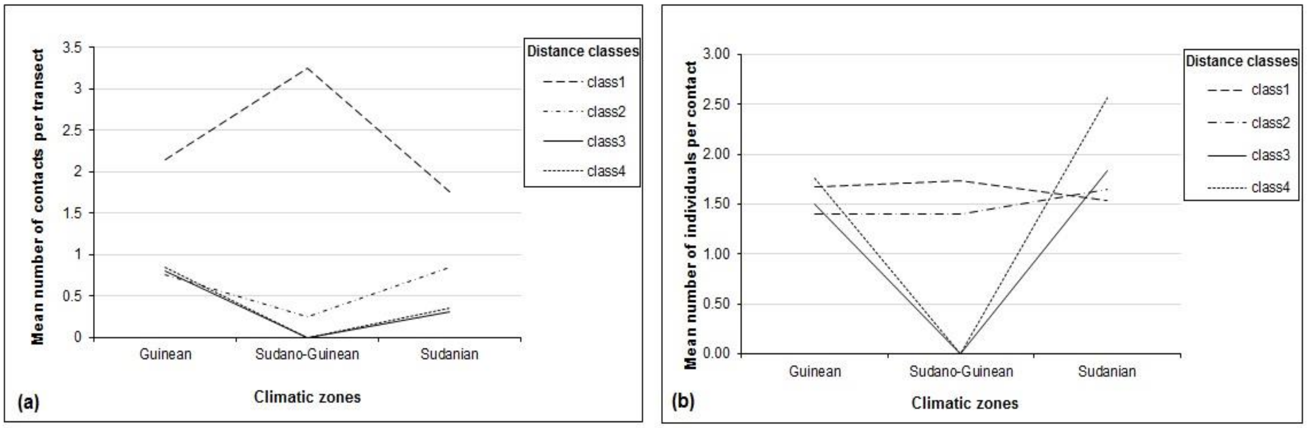


Figure 20: Interaction plot of climatic zone and distance to the closest river on the occurrence of *V. doniana* in Benin (a) Frequency of observation; (b) Abundance per contact

Class 1 = less than 500 m; Class 2 = between 500 and 1000 m; Class 3 = between 1000 and 1500 m; Class 4 = more than 1500 m

Table XIII: Soil parameters under the black plum according to climatic zones

	Guinean	Sudano-Guinean	Sudanian	p-value
pH	4.96a±0.5	5.10a±0.56	5.53b±0.52	0.006
OC (%)	0.85a±0.5	1.49b±0.91	1.41b±0.96	0.025
TN (%)	0.08a±0.03	0.10a±0.04	0.10a±0.03	0.298
CSilt (%)	6.77a±5.87	9.92ab±7.12	14.09b±9.08	0.007
FSilt (%)	7.22a±6.68	10.71a±7.39	9.27a±6.26	0.16
C (%)	13.55a±8.41	11.39a±5.91	9.98a±4.04	0.324
Fsand (%)	30.94a±9.62	26.00a±8.20	32.53a±9.74	0.091
Csand (%)	40.89a±18.19	41.15a±20.03	33.22a±11.88	0.323

OC = organic carbon; TN = total nitrogen; CSilt = coarse silt; FSilt = fine silt; C = clay; Fsand = fine sand; Csand = coarse sand. Values are mean ± standard deviation. P-values are from one-way anova on transformed data in some cases (square root transformation for OC, TN, C and Fsand; and log (x+1) for CSilt and FSilt. On lines, numbers followed by the same letters are not statistically different at 0.05.

4.2.1.2. Floristic composition of woody plant community around the species

The non-metric multidimensional scaling (NMDS) yielded a good ordination of the 226 plots with a stress of 0.061 and a R^2 value of 0.996. A clear discrimination of the plots according to climatic zones (Figure 21a), land cover types (Figure 21b) and distance to the closest river (Figure 21c), was not evidenced. However, a closer look at figure 21a revealed a discrimination-like pattern of plots along the first axis (NMDS1). Along this axis, plots of the Sudanian zone were projected at the left side, while Guinean plots were at the right side, with the Sudano-Guinean's in between them (Figure 21a). These results were emphasised by the pairwise Jaccard's index which showed that the black plum occurred in different woody floristic communities when considering either climatic zones (Table XIVa), land cover types (Table XIVb) or classes of distance to the closest river within climatic zones (Table XIVc). However regarding land cover types (Table XIVb), some similarities of woody communities (Jaccard > 0.5) around *V. doniana* were observed in the Sudanian zone between tree and shrub savannahs (TSS) and mosaic of croplands and fallows (MCF). In the Sudano-Guinean zone, woodland and plantation, and TSS and woodlands shared some common woody species around the black plum (Jaccard > 0.5). When considering the distance to the closest river, class1 (less than 500m) and class2 (500-1000m) in the Guinean zone also showed similar woody communities around the black plum (Table XIVc).

In addition, evidences were given by the indicator species analysis that the black plum was not followed by the same woody species regarding mainly climatic zones. For instance, in the Guinean zone, species such as *Albizia glaberrima*, *Morinda lucida*, *Antiaris toxicaria*, etc. were the most indicator species around the black plum. In the Sudano-Guinean in the counterpart, *Piliostigma thonningi*, *Daniellia oliveri*, *Terminalia glaucescens*, etc. were the most important indicator species surrounding the black plum while in the Sudanian zone, *Balanites aegyptiaca*, *Terminalia avicennoides*, *Tamarindus indica*, etc. were the most relevant woody species following the black plum (Table XV).

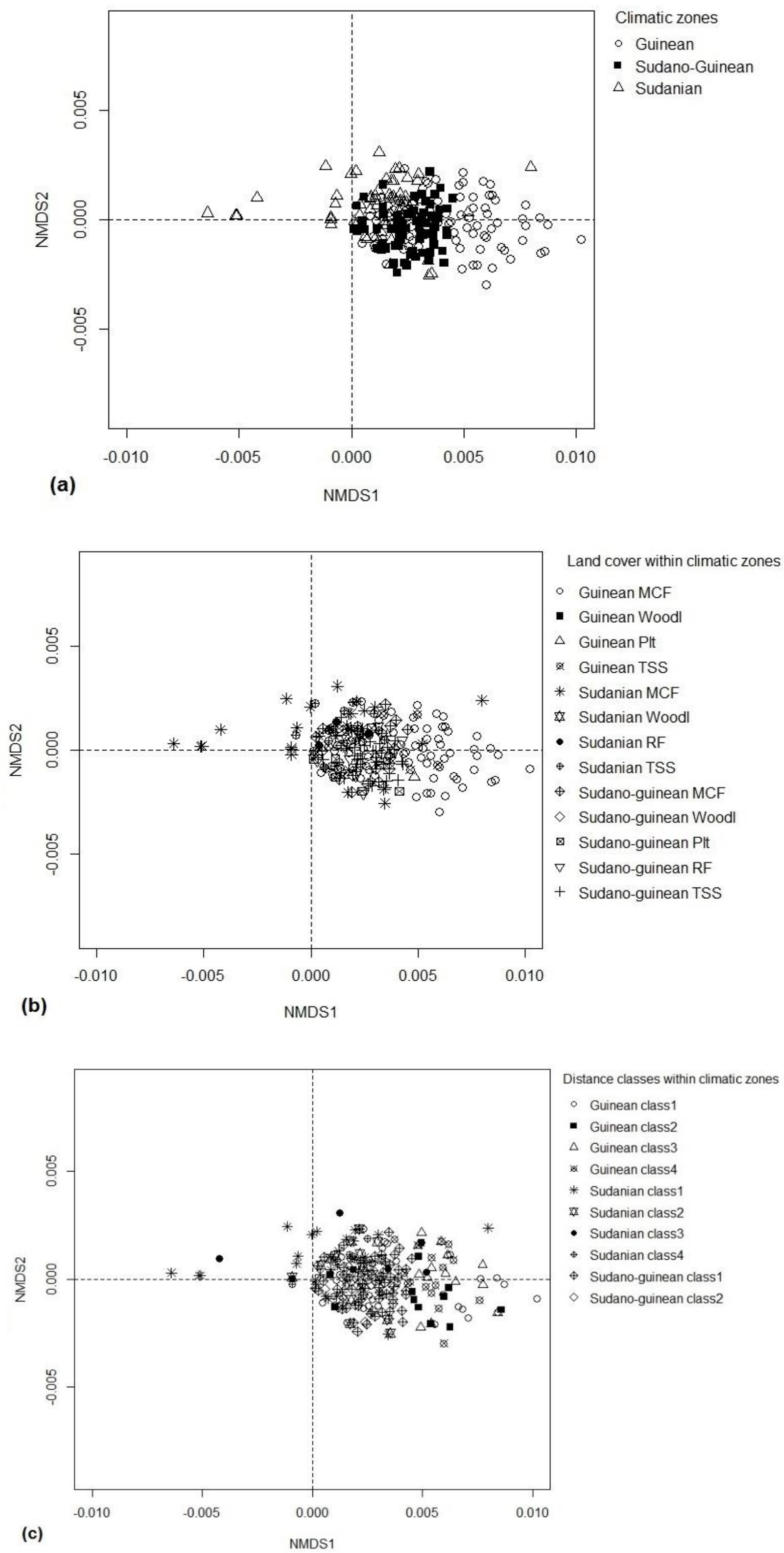


Figure 21: Projection of the 226 plots (50 x 20 m^2) in the NMDS1 and NMDS2 axes system

a. Projection regarding climatic zones; b. Projection regarding land cover types; c. Projection according to proximity to river

Table XIV: Pairwise Jaccard's similarity index

XIVa- According to climatic zones

	Guinean	**Sudano-Guinean**	**Sudanian**
Guinean	1		
Sudano-Guinean	0.41	1	
Sudanian	0.33	0.44	1

Note: Jaccard's similarity index < 0.5 indicates dissimilarity among the communities

XIVb- According to climatic zones and land cover types

	G-MCF	**G-Woodl**	**G-Plt**	**G-TSS**	**S-MCF**	**S-Woodl**	**S-RF**	**S-TSS**	**SG-MCF**	**SG-Woodl**	**SG-Plt**	**SG-RF**	**SG-TSS**
G-MCF	1												
G-Woodl	0.13	1											
G-Plt	0.05	0.00	1										
G-TSS	0.30	0.06	0.08	1									
S-MCF	0.27	0.09	0.05	0.25	1								
S-Woodl	0.16	0.20	0.00	0.31	0.25	1							
S-RF	0.13	0.08	0.00	0.27	0.13	0.17	1						
S-TSS	0.29	0.10	0.04	0.19	**0.55**	0.19	0.21	1					
SG-MCF	0.28	0.10	0.04	0.15	0.28	0.18	0.25	0.33	1				
SG-Woodl	0.30	0.14	0.00	0.30	0.36	0.32	0.35	0.45	0.48	1			
SG-Plt	0.24	0.13	0.00	0.15	0.3	0.24	0.22	0.39	0.42	**0.63**	1		
SG-RF	0.23	0.15	0.06	0.17	0.33	0.21	0.19	0.34	0.42	0.38	0.48	1	
SG-TSS	0.40	0.14	0.06	0.24	0.31	0.17	0.19	0.41	0.47	**0.53**	0.44	0.33	1

G- = Guinean; S- = Sudanian; SG- = Sudano-Guinean; MCF= Mosaics of croplands and fallows; Woodl = Woodlands; Plt = Plantation; RF = Riparian forests; TSS = Tree and shrub savannahs

XIVc- According to climatic zones and distance to the closest river

	G-class1	**G-class2**	**G-class3**	**G-class4**	**S-class1**	**S-class2**	**S-class3**	**S-class4**	**SG-class1**	**SG-class2**
G-class1	1									
G-class2	**0.61**	1								
G-class3	0.17	0.35	1							
G-class4	0.24	0.32	0.5	1						
S-class1	0.33	0.24	0.06	0.05	1					
S-class2	0.23	0.20	0.04	0.07	0.41	1				
S-class3	0.19	0.19	0.17	0.17	0.32	0.33	1			
S-class4	0.15	0.19	0.07	0.05	0.24	0.29	0.29	1		
SG-class1	0.38	0.37	0.15	0.18	0.43	0.20	0.21	0.13	1	
SG-class2	0.35	0.26	0.03	0.06	0.47	0.27	0.21	0.22	0.49	1

G- = Guinean; S- = Sudanian; SG- = Sudano-Guinean; Class1= less than 500m; Class2 = between 500 and 1000m; Class3 = between 1000 and 1500m; Class4 = more than 1500m

Table XV: Indicator species following the black plum regarding climatic zones

Climatic zones	Indicator species	A	B	IndVal	p-value
Guinean	*Albizia glaberrima*	1.000	0.209	0.457	0.001
	Morinda lucida	0.794	0.231	0.428	0.001
	Azadirachta indica	0.662	0.209	0.372	0.005
	Antiaris toxicaria	0.874	0.0989	0.294	0.006
Sudano-Guinean	*Daniellia oliveri*	0.693	0.600	0.645	0.001
	Terminalia glaucescens	0.814	0.486	0.629	0.001
	Piliostigma thonningii	0.782	0.357	0.528	0.001
	Ficus sur	0.593	0.357	0.46	0.001
	Prosopis africana	0.912	0.100	0.302	0.001
	Annona senegalensis	1.000	0.171	0.414	0.001
	Pericopsis laxiflora	1.000	0.129	0.359	0.001
	Sarcocephalus latifolius	0.699	0.186	0.36	0.001
	Anogeissus leiocarpa	0.623	0.271	0.411	0.002
	Khaya senegalensis	0.688	0.129	0.297	0.008
	Syzygium guineense	1.000	0.071	0.267	0.008
	Bridelia ferruginea	0.881	0.086	0.275	0.009
Sudanian	*Vitellaria paradoxa*	0.486	0.492	0.489	0.001
	Tamarindus indica	0.933	0.138	0.359	0.001
	Diospyros mespiliformis	0.737	0.154	0.337	0.001
	Balanites aegyptiaca	1.000	0.092	0.304	0.001
	Parkia biglobosa	0.522	0.338	0.42	0.010
	Terminalia avicennioides	1.000	0.062	0.248	0.006

A is the specificity (probability that the surveyed species belongs to the target site group given the fact that it has been found). B is the fidelity (probability of finding the species in sites belonging to the group). IndVal: Indicator Value Index. The significance of the test is given by p-value.

4.2.2. Structural parameters of the black plum

4.2.2.1. Dendrometric patterns

Tables XVI and XVII summarized dendrometric parameters of the black plum according to the considered environmental factors. In general, there were no significant effects of studied environmental factors on densities (adult and regeneration) of the species. Densities of adult individuals and densities of regeneration of the species were below 20 stems/ha and 10 plants/ha respectively (Tables XVI & XVII). Significant interaction effects of climatic zone and land cover type were observed on mean diameter (df = 6, F-value = 3.276, p-value = 0.004), basal area (df = 6, F-value = 2.863, p-value = 0.011), contribution of the species to stand basal area (df = 6, F-value = 3.024, p-value = 0.007) and mean height of Lorey (df = 6, F-value = 2.627, p-value = 0.018). Regarding the interactions of climatic zone and distance to the closest river, only contribution of the target species to stand basal (Cs) area was significantly affected (df = 4, F-value = 2.604, p-value = 0.037).

- ***Effects of land cover and climatic zones***

Within each of the three climatic zones, mean diameter (Dg) and basal area (Ba) varied significantly between land cover types. The highest values of these parameters were mostly recorded in mosaics of croplands and fallows in the Guinean and Sudanian zones, and in riparian forest in the Sudano-guinean zone (Table XVI). The contribution of *V. doniana* to the stand basal area (Cs) and mean height of Lorey (HL) varied significantly between land cover types only in the Sudanian and Guinean zone respectively, with the highest values (47.20 ± 30.18 % for Cs and 7.09 ± 3.10 m for HL) in mosaics of croplands and fallows (MCF).

When considering land cover types between climatic zones, mean diameter and basal area varied significantly only for MCF, and the highest values were noted in the Sudanian zone (46.11 ± 23.83 cm and 3.35 ± 3.07 m^2/ha respectively). The highest contribution of the species to stand basal area (Cs) was observed in the Guinean TSS (41.22 ± 26.80 %), whereas the highest mean height of Lorey was observed in the Sudanian woodlands (12.96 ± 2.44 m).

- ***Effects of distance to the closest river and climatic zone***

Within climatic zones, the dendrometric features of the black plum did not vary significantly between distance classes (Table XVII). However, in the Guinean zone, the contribution of the black plum to stand basal area varied significantly between classes of distance (Table XVII) with the highest value (61.46 ± 29.12%) in class3 (1000-1500 m).

Table XVI: Dendrometric parameters of the black plum according to climatic zones and land cover types in Benin

Parameters	Land cover	Guinean		Sudano-Guinean		Sudanian		p-value
		Mean	SD	Mean	SD	Mean	SD	
Density (N, stems/ha)	MCF	16.71a	11.45	16.67a	9.63	17.30a	10.71	0.945
	Woodl	-	-	17.50a	9.57	10.00a	0.00	0.072
	Plt	-	-	15.71	11.34	-	-	-
	RF	-	-	12.50a	7.07	10.00a	0.00	0.427
	TSS	11.67a	4.08	19.26a	12.69	18.64a	11.25	0.744
	p-value	0.25		0.40		0.13		
Density of regeneration (Nreg, plants/ha)	MCF	5.41a	6.95	4.17a	6.07	3.62a	6.75	0.549
	Woodl	-	-	9.50	11.24	0.00	na	-
	Plt	-	-	2.29	5.22	-	-	-
	RF	-	-	4.00a	7.41	15.33b	21.57	<0.001
	TSS	7.67a	7.94	8.44a	8.10	5.09a	5.75	0.157
	p-value	0.20		0.377		0.08		
Mean diameter (Dg, cm)	MCF	22.04a	10.96	25.67a	19.04	46.11b	23.83	<0.001
	Woodl	-	-	26.81a	23.53	32.83a	16.33	0.178
	Plt	-	-	7.44	2.46	-	-	-
	RF	-	-	41.54a	29.53	39.00a	39.36	0.881
	TSS	18.80a	16.33	18.73a	14.68	25.24a	14.34	0.169
	p-value	0.004		0.003		0.007		
Basal area (Ba, m^2/ha)	MCF	0.68a	0.62	1.36a	2.28	3.35b	3.07	<0.001
	Woodl	-	-	1.11a	1.22	1.00a	0.92	0.225
	Plt	-	-	0.11	0.18	-	-	-
	RF	-	-	2.04a	2.10	2.00a	3.03	0.791
	TSS	0.49a	0.8	0.98a	2.05	0.96a	0.92	0.149
	p-value	0.009		0.009		0.010		
Contribution to stand basal area (Cs, %)	MCF	41.08a	29.35	28.69b	24.66	47.20a	30.18	0.052
	Woodl	-	-	18.22a	3.83	20.24a	8.76	0.087
	Plt	-	-	6.56	3.45	-	-	-
	RF	-	-	26.83a	23.89	20.56a	25.97	0.713
	TSS	41.22a	26.80	20.67b	17.98	17.46b	13.03	0.015
	p-value	0.09		0.131		0.000		
Mean height of Lorey (HL, m)	MCF	7.09a	3.10	8.41a	5.07	8.31a	3.14	0.207
	Woodl	-	-	10.94a	7.26	12.69b	2.44	0.028
	Plt	-	-	4.73	1.31	-	-	-
	RF	-	-	13.00a	7.25	8.26a	3.38	0.684
	TSS	6.56a	5.97	6.57a	4.56	7.23a	3.39	0.508
	p-value	0.01		0.08		0.13		

SD = standard deviation. P-values computed from log-transformed data (y = log(x)) for Dg, Ba and HL for the comparison of the 3 climatic zones (last column) and land cover types (lines). On lines, mean values followed by the same letters are not statistically different at 0.05.

MCF= Mosaics of croplands and fallows; Woodl = Woodlands; Plt = Plantation; RF = Riparian forests; TSS = Tree and shrub savannahs

Table XVII: Dendrometric parameters of the black plum according to climatic zones and distance to the closest river in Benin

Parameters	Distance to the closest river	Guinean		Sudano-Guinean		Sudanian		p-value
		Mean	SD	Mean	SD	Mean	SD	
Density (N, stems/ha)	Class1	16.74a	10.40	17.38a	11.08	15.43a	8.86	0.575
	Class2	14.00a	8.28	14.00a	5.48	16.47a	11.69	0.641
	Class3	15.00a	7.30	-	-	18.33a	7.53	0.316
	Class4	17.65a	16.78	-	-	25.71a	15.12	0.195
	p-value	0.597		0.412		0.089		
Density of regeneration (Nreg, plants/ha)	Class1	3.86a	6.93	5.94a	7.63	4.06a	8.08	0.533
	Class2	6.53a	7.84	5.60a	6.54	4.12a	4.72	0.706
	Class3	8.00a	7.66	-	-	2.00b	3.10	0.048
	Class4	6.35a	4.54	-	-	9.71a	11.91	0.397
	p-value	0.40		0.946		0.561		
Mean diameter (Dg, cm)	Class1	21.63a	10.71	23.56a	20.22	39.77b	25.62	<0.001
	Class2	21.52a	14.90	16.44a	11.10	30.92a	19.03	0.108
	Class3	25.85a	11.18	-	-	57.36b	22.37	0.004
	Class4	19.39a	13.80	-	-	30.76b	7.16	0.014
	p-value	0.364		0.494		0.161		
Basal area (Ba, m^2/ha)	Class1	0.65a	0.57	1.20a	2.07	2.51b	2.88	0.002
	Class2	0.62a	0.77	0.47a	0.65	1.56a	2.42	0.085
	Class3	0.94a	0.78	-	-	4.47b	2.74	0.003
	Class4	0.57a	0.73	-	-	1.81b	1.09	0.004
	p-value	0.363		0.376		0.08		
Contribution to stand basal area (Cs, %)	Class1	30.94a	25.12	23.68a	21.00	33.54a	31.79	0.129
	Class2	51.90a	31.99	8.18b	6.84	27.10b	21.01	0.003
	Class3	61.46a	29.12	-	-	52.44a	30.73	0.531
	Class4	37.08a	27.88	-	-	43.37a	17.39	0.588
	p-value	0.001		0.107		0.234		
Mean height of Lorey (HL, m)	Class1	6.46a	3.42	8.07a	5.58	8.68a	3.60	0.080
	Class2	6.90a	3.07	7.09a	3.08	7.60a	3.79	0.944
	Class3	8.92a	3.06	-	-	7.66a	1.51	0.665
	Class4	6.71a	3.52	-	-	7.20a	1.01	0.364
	p-value	0.100		0.941		0.735		

SD = standard deviation. P-values computed from log-transformed data (y = log(x)) for Dg, Ba and HL for the comparison of the 3 climatic zones (last column) and classes of distance to the closest river (lines). On lines, mean values followed by the same letters are not statistically different at 0.05.

Class1= less than 500m; Class2 = between 500 and 1000m; Class3 = between 1000 and 1500m; Class4 = more than 1500m

There was a significant difference between climatic zones regarding mean diameter and basal area, for all distance classes, except for class 2 (500-1000 m). The highest values of these parameters were recorded in the Sudanian zone (Table XVII). However, regarding class 2 (500-1000 m), a significant difference was observed between climatic zones for the contribution of the species to stand basal area and, the Guinean zone showed the highest value (51.90 ± 31.99 %).

4.2.2.2. Diameter structure

The observed diameter distributions of the black plum were perfectly adjusted to the theoretical Weibull 3-parameter distribution for all stands regarding land cover types (df = 1, Chi-squared = 0.00 - 0.21, p-value = 0.993 - 0.647) and regarding distance to the closest river (df = 1, Chi-squared = 0.00 - 1.73, p-value = 0.974 - 0.188). The shape parameter varied from 0.850 to 1.551 for stands regarding land cover types and climatic zones (Figure 22). It ranged from 0.892 to 2.378 for stands regarding distance classes and climatic zones (Figure 23). The diameter structure of the species revealed, in general, a predominance of relatively young individuals (dbh < 25 cm). However, some particularities were noted in regard to the local environment.

Regarding land cover type, the diameter structure of the black plum presented a left-skewed distribution (1 < shape < 3.6) for MCF and TSS stands in the Guinean zone, and for MCF stand in the Sudanian zone (Figure 22). In these diameter structures, the 5-15 cm class was the most represented. For instance, in the Guinean MCF, 7 individuals were averagely observed per hectare for the 5-15 cm class, whereas the other classes had less than 5 individuals/ha each (df = 8, Chi-Squared = 17.42, p-value = 0.026). This trend was similar for the Guinean TSS stand, but some intermediate diameter classes were not observed (Figure 22). Stand of the Sudanian MCF showed a particular diameter distribution with no significant difference between diameter classes regarding the density (df = 8, Chi-squared = 4.03, p-value = 0.855). In this stand, approximately 2 individuals were observed per hectare for each diameter class. However, stands of MCF and TSS in the Sudano-Guinean zone exhibited a reversed-J structure (shape < 1) revealing then a high regeneration potential (Figure 22).

According to the distance to the closest river, left-skewed distribution of diameter structures (1 < shape < 3.6) were observed for the Guinean and Sudanian zones for all distance classes. A J-reversed distribution (shape < 1) was noted in the Sudano-Guinean zone for the two distance categories (Figure 23). In the Guinean zone, there was no significant difference between diameter classes for the stand located between 1000 and 1500 m to a river (df = 8, Chi-Squared = 9.69, p-value = 0.287). This was the case for all stands in the Sudanian zone.

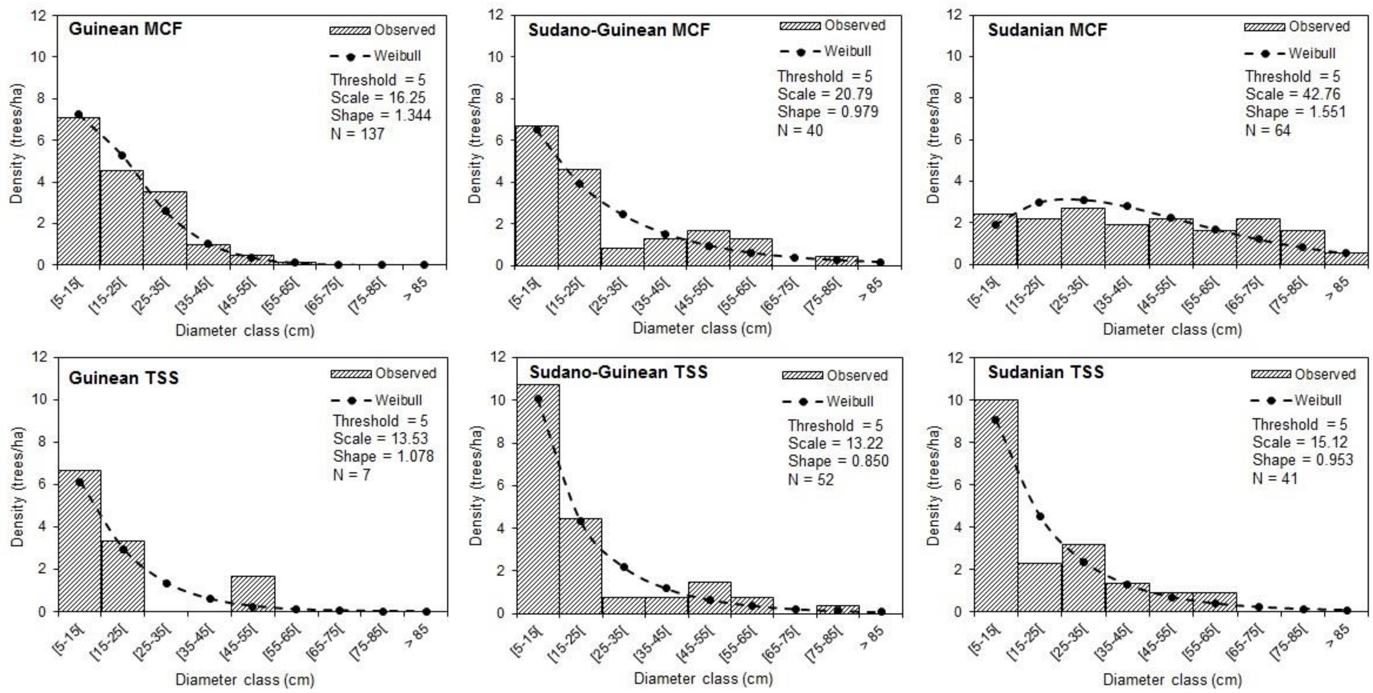


Figure 22: Diameter structures of the black plum according to climatic zones and land cover types in Benin

MCF= Mosaics of croplands and fallows; Woodl = Woodlands; Plt = Plantation; RF = Riparian forests; TSS = Tree and shrub savannahs

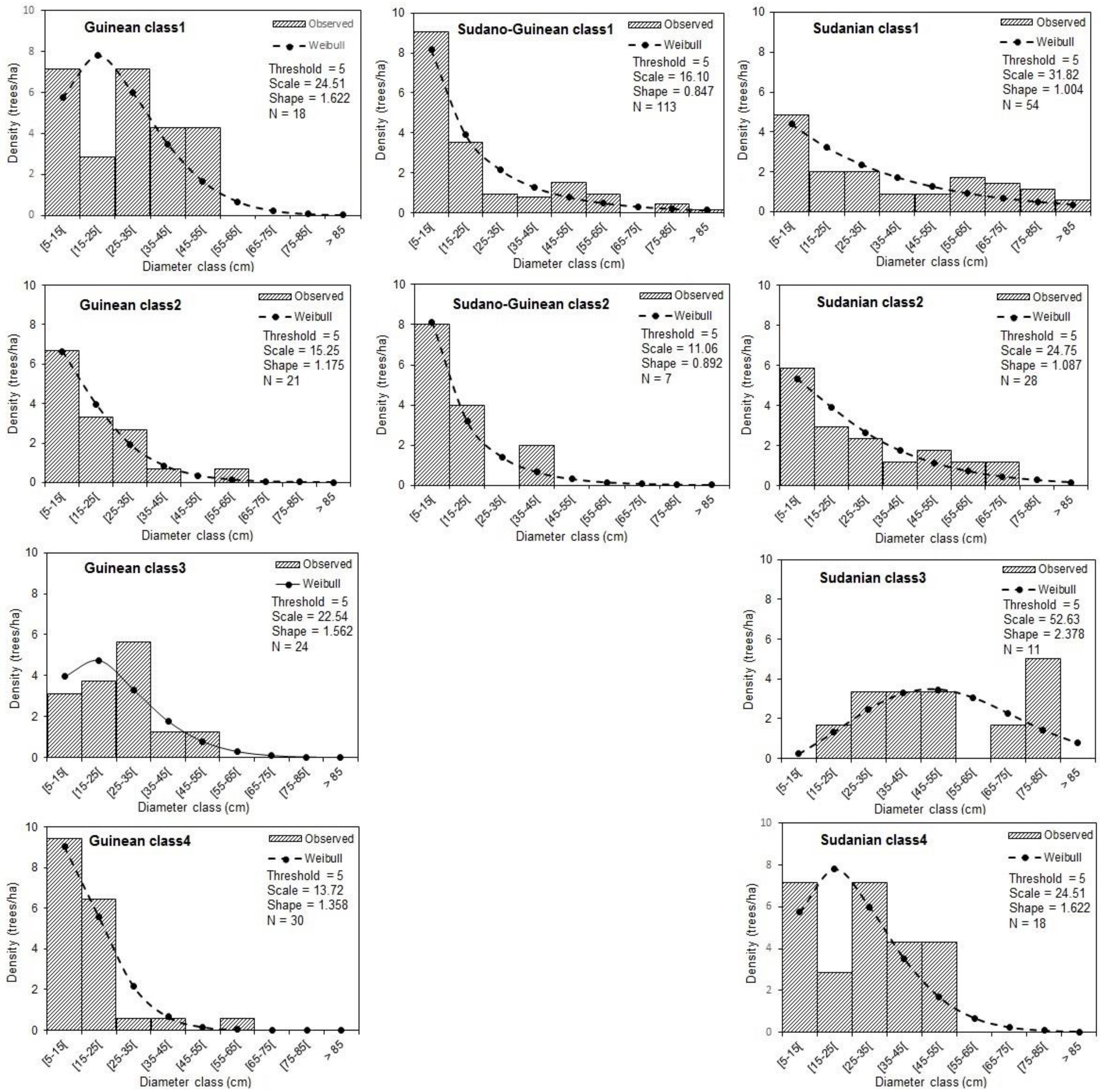


Figure 23: Diameter structures of the black plum according to climatic zones and classes of distance to the closest river in Benin

Class1= less than 500m; Class2 = between 500 and 1000m; Class3 = between 1000 and 1500m; Class4 = more than 1500m

4.3. Climate-induced morphological variability of the black plum

4.3.1. Morphological variability of the black plum

The morphological descriptors of trunk and canopy showed high amplitude of variation in all climatic zones (coefficients of variation > 25 %, Table XVIII). However, these morphological descriptors did not vary in the same way from one climatic zone to another. For instance, the circumference at 1.3 m and the crown diameter showed the greatest variability in the Guinean zone (CV = 48.37 %), while the bole height was the most fluctuating trait in the Sudano-Guinean zone (CV = 51.21 %). The other descriptors (tree height, crown height and crown shape) were most dispersed in the Sudanian zone than in the the other zones (Table XVIII). The Skewness coefficient of all these descriptors (except tree height in the Sudano-Guinean zone) was positive, suggesting a right asymmetrical distribution. Except the crown diameter, all the descriptors of trunk and canopy varied significantly between climatic zones (Table XVIII). Trees from the Sudanian zone were the thickest, while trees from the Sudano-Guinean zone were the tallest with a relatively rounded crown.

Most of the morphological descriptors of leaves and fruits were relatively less dispersed (CV < 15 %) around mean values in all climatic zones (Table XIX). Leaves and fruits descriptors showed the highest amplitude of variation in the Guinean and Sudanian zone respectively. The Skewness coefficient was close to zero for most of the leaves and fruits features in all climatic zones suggesting a normal distribution. All the leaves and fruits descriptors varied significantly between climatic zones and the lowest values were mostly recorded in the Sudanian zone. Trees in the Sudano-Guinean zone presented slightly higher leaves characteristics, while the greatest features for fruits were mostly recorded in the Guinean zone (Table XIX). In general, fruits were relatively oblong (length/width ratio was slightly above 1), but fruits from the Sudano-Guinean zone were longer than wide (fruit shape i.e. ratio fruit length/fruit width = 1.10 ± 0.01). It is also the case for endocarp shape where the ratio length/width is above 1, meaning that endocarp length is greater than endocarp’s width.

The variance components estimation revealed that the within-climatic zone effect represented the most important source of variability of leaves and fruits traits, with variation within tree being the highest (Table XX). The between climatic zones variability of leaves and fruits traits was relatively weak (< 30 % of total variation). Its lowest and highest values were recorded respectively for number of leaflets per leaf (2.19 %) and endocarp mass (26.93 %). Variability in morphological traits due to climatic zones was higher for fruits characteristics than for leaves (Table XX).

Table XVIII: Morphological descriptors of trunk and canopy of the black plum in Benin

	Guinean (35 trees)			**Sudano-Guinean (31 trees)**			**Sudanian (36 trees)**		
	Mean±SE	**CV**	**Skew.**	**Mean±SE**	**CV**	**Skew.**	**Mean±SE**	**CV**	**Skew.**
Circumference (cm)	115.77b±9.47	48.37	1.47	146.42a±10.84	41.21	0.42	156.14a±10.43	40.07	0.95
Tree height (m)	10.46b±0.50	28.25	0.20	15.68a±0.75	26.56	-0.68	9.40b±0.53	33.96	1.39
Bole height (m)	3.35b±0.19	34.08	0.46	5.98a±0.55	51.21	0.12	2.43c±0.16	39.70	1.29
Crown diameter (m)	8.50a±0.53	36.79	0.21	9.71a±0.54	30.71	0.07	8.49a±0.42	29.51	0.49
Crown height (m)	7.11b±0.43	36.06	0.53	9.70a±0.59	34.12	0.11	6.97b±0.48	41.62	1.58
Crown shape	0.87b±0.04	27.16	0.54	1.03a±0.05	28.64	0.64	0.85b±0.05	36.59	1.15

Crown shape = hcrown/dcrown; SE = standard error of mean; CV = coefficient of variation (%); Skew. = Skewness. On the lines, mean values followed by the same letters are not statistically different at 0.05 (Student-Newman-Keuls test)

Table XIX: Morphological descriptors of leaves and fruits of the black plum in Benin

	Guinean (350)			**Sudano-Guinean (310)**			**Sudanian (360)**		
	Mean±SE	CV	Skew	Mean±SE	CV	Skew	Mean±SE	CV	Skew
Leaf length (mm)	268.33b±11.85	13.96	-0.10	289.84a±7.77	8.50	0.09	244.02c±10.47	13.36	0.11
Petiole length (mm)	115.62b±6.09	16.72	-0.12	131.38a±4.09	10.11	-0.05	108.37c±5.48	15.91	0.11
Petiole diameter (mm)	7.50a±0.31	12.86	0.08	6.93b±0.23	10.35	0.07	6.94b±0.28	12.35	0.22
Leaflet length (mm)	152.71b±6.72	13.70	-0.01	158.46a±4.75	9.41	0.00	135.64c±6.09	13.84	0.04
Leaflet width (mm)	65.61a±3.11	14.97	0.05	65.43a±2.03	9.71	-0.01	60.68b±2.97	15.23	0.10
Number of leaflets	5.02ab±0.05	3.17	0.11	5.07a±0.09	5.82	0.66	4.98b±0.03	1.85	-1.11
Fruit length (mm)	24.81a±0.50	6.46	-0.20	24.87a±0.38	4.86	0.07	23.83b±0.43	5.67	-0.09
Fruit width (mm)	23.40a±0.46	6.21	-0.21	22.70b±0.33	4.66	-0.01	22.86b±0.44	6.03	-0.23
Fruit shape (length/width)	1.07b±0.01	3.81	0.09	1.10a±0.01	3.90	0.11	1.05b±0.01	4.10	0.21
Fruit fresh mass (g)	9.14a±0.43	15.19	-0.08	7.86b±0.26	11.20	0.04	7.50b±0.39	16.14	-0.11
Fruit dry mass (g)	3.73a±0.21	17.74	0.04	2.83b±0.11	13.56	0.22	2.46c±0.14	18.35	0.03
Endocarp length (mm)	17.07b±0.31	5.74	-0.24	17.30a±0.25	4.59	0.08	16.07c±0.32	6.31	0.03
Endocarp width (mm)	12.17a±0.81	6.52	0.03	12.15a±0.22	5.83	-0.11	11.58b±0.25	6.58	0.01
Endocarp shape (length/width)	1.43ab±0.02	5.52	-0.05	1.44a±0.03	5.94	0.10	1.40b±0.03	6.59	0.19
Endocarp mass (g)	1.76a±0.10	17.34	-0.10	1.47b±0.07	16.53	0.11	1.17c±0.06	16.80	-0.01
Pulp thickness (mm)	5.62a±0.16	9.08	0.04	5.28b±0.11	6.78	-0.30	5.64a±0.16	8.79	-0.08
Pulp mass (mm)	1.97a±0.15	22.72	0.12	1.37b±0.06	14.37	-0.07	1.29b±0.09	22.45	0.13

SE = standard error of mean; CV = coefficient of variation (%); Skew. = Skewness. On the lines, mean values followed by the same letters are not statistically different at 0.05 (Tukey's contrasts test for multiple comparisons of means)

Table XX: Variance components for leaves and fruits characteristics (%) from mixed effects model fit by restricted maximum likelihood (REML)

	Source of variation			
	Among climatic zones	Within-Climatic zone		
		Trees within climatic zone	Trees within transect	Within trees (error)
Leaf length	22.57	12.13	5.69	59.60
Petiole length	22.63	14.57	0.21	62.58
Petiole diameter	18.12	16.40	8.13	57.35
Leaflet length	21.11	11.81	13.49	53.59
Leaflet width	17.54	21.18	7.28	54.01
Number of leaflets	2.19	1.93	0.00	95.88
Fruit length	20.23	20.49	4.34	54.94
Fruit width	22.89	12.45	19.58	45.08
Fruit shape	23.61	15.03	20.31	41.06
Fruit fresh mass	25.46	19.84	7.66	47.04
Fruit dry mass	22.54	24.76	26.56	26.14
Pulp thickness	21.15	10.14	33.73	34.98
Pulp mass	18.37	20.28	39.27	22.08
Endocarp length	26.63	22.64	7.92	42.81
Endocarp width	20.73	19.25	14.79	45.23
Endocarp shape	19.67	22.22	6.79	51.32
Endocarp mass	26.93	25.95	7.09	40.03

4.3.2. Discriminant morphological descriptors of the black plum according to climatic zones

The stepwise discriminant analysis indicated that two significant discriminant functions were needed to separate *V. doniana* trees according to climatic zones (p-value < 0.001). The accuracy rate of the model revealed that 84.3 % of trees were perfectly assigned to their respective climatic zone. The Wilks'Lambda statistic ranged from 0.757 to 0.195 (first to last step) and p-value was very low (p-value < 0.001). Only 7 of the 23 descriptors were the most discriminant for climatic zone. These 7 discriminant morphological traits were: tree height, canopy height, leaf length, number of leaflets, circumference at 1.3 m, petiole diameter and pulp mass. The first function explaining 85.5 % of the total variance discriminated trees based on tree height, canopy height, leaf length and number of leaflets. This function separated Sudano-Guinean trees from the others. The second function accounting for 14.5 % of total variance performed trees discrimination based on circumference, petiole diameter and pulp mass. It discriminated Guinean trees from Sudanian trees (Figure 24).

Trees from the Sudano-Guinean zone were taller with higher canopy. They exhibited longer leaves with often more than 5 leaflets per leaf whereas those from the Sudanian zone were thicker (high circumference values) with relatively small petiole diameter for leaves and they produced fruits with reduced amount of pulp. Guinean trees thus diverged from the Sudanian counterparts.

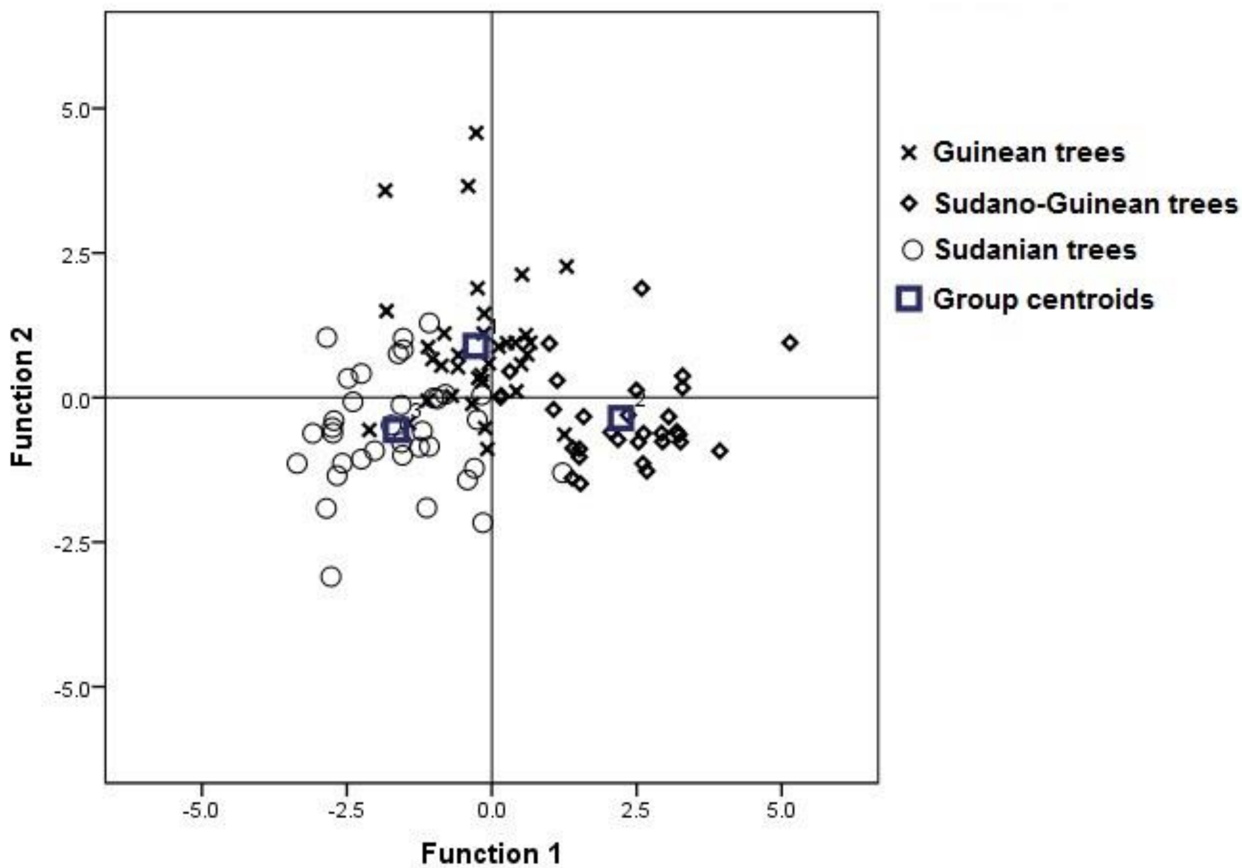


Figure 24: Projection of *V. doniana* trees regarding morphological traits in the system defined by the two canonical functions

Function 1 and 2 represent respectively 85.5 and 14.5 % of the total variance of 23 descriptors on 102 individuals. Symbols correspond to trees from each climatic zone of Benin (Circles: Sudanian trees; Lozenges: Sudano-Guinean trees; Crosses: Guinean trees; Squares: centroid of each group)

4.3.3. Relationships between discriminant morphological descriptors and bioclimatic variables

From the redundancy analysis, the best model explaining the relationships between the discriminant morphological descriptors of the black plum and bioclimatic variables took into account 8 of the 19 bioclimatic variables (F = 7.095, p-value = 0.001, AIC = 842.4, adjusted $R^2 = 0.326$). Only the first two axes were significant (p-value = 0.001) and they explained 37.9 % of the total variation in morphological traits due to the bioclimatic variables. The first axis (RDA1) explaining 32.05% of total variance, was a linear combination of annual mean diurnal range of temperature (bio2), isothermality (bio3), temperature seasonality (bio4), precipitation seasonality (bio15), and mean temperature of the coldest quarter (bio11). The second axis (RDA2, 0.06 % of total variation) on the other hand, was a linear combination of annual precipitation (bio12), precipitation of the warmest quarter (bio18) and mean temperature of the warmest quarter (bio10). However some of these bioclimatic variables such as annual precipitation and mean temperature of the coldest quarter were not statistically significant in the model (Table XXI).

Regarding the discriminant morphological variables, circumference at 1.3 m, tree height, crown height, leaf length, petiole diameter and pulp mass were loaded on RDA1, while number of leaflets was loaded on RDA2 (Table XXII). Based on scores of morphological traits and bioclimatic variables on RDA axes (Tables XXI & XXII), it was noted that circumference at 1.3 m, tree height, crown height, leaf length and petiole diameter were positively influenced by annual mean diurnal range of temperature (bio2), temperature seasonality (bio4) and precipitation seasonality (bio15). Meanwhile, pulp mass and number of leaflets were negatively affected respectively by isothermality (bio3) and mean temperature of the warmest quarter (bio10). The projection of *V. doniana* trees in the RDA axes system showed that Guinean trees were mainly located on the negative side of RDA1 and RDA2 while Sudanian trees were mainly in the positive side of RDA2 (Figure 25). The morphology of trees from these zones was likely affected by bioclimatic parameters in diverse ways.

There were no direct significant effects of the commonly used climatic parameters such as annual mean temperature and precipitation on morphological traits of the black plum. However, several bioclimatic variables based on their extremes such as temperature/precipitation of the warmest quarter and other related parameters showed significant influences on the morphological descriptors (Table XXI).

Table XXI: Significance of bioclimatic variables from permutation ANOVA test and scores on RDA axes

Bioclimatic variables	Permutation ANOVA				Scores on axes	
	Df	Variance	F	Pr(>F)	RDA1	RDA2
Annual mean diurnal range of temperature (bio2)	1	389.1	11.069	0.001	0.45	-0.42
Isothermality (bio3)	1	153.2	4.360	0.021	-0.51	0.48
Temperature seasonality (bio4)	1	145.3	4.133	0.029	0.42	-0.33
Mean temperature of warmest quarter (bio10)	1	576.2	16.391	0.001	-0.003	-0.14
Mean temperature of coldest quarter (bio11)	1	39.1	1.113	0.325	-0.52	0.16
Annual precipitation (bio12)	1	17.2	0.488	0.577	-0.13	0.32
Precipitation seasonality (bio15)	1	112.5	3.200	0.043	0.39	-0.27
Precipitation of warmest quarter (bio18)	1	562.5	16.003	0.001	-0.19	0.33
Residual	93	3268.9				

Table XXII: Scores of discriminant morphological traits on RDA axes

	RDA1 (32.05 %)	RDA2 (0.06 %)
Circumference at 1.3m	13.720	2.867
Tree height	0.846	-0.368
Crown height	0.594	-0.178
Leaf length	6.652	-5.851
Petiole diameter	0.089	0.013
Number of leaflets	0.002	-0.006
Pulp mass	-0.055	0.034

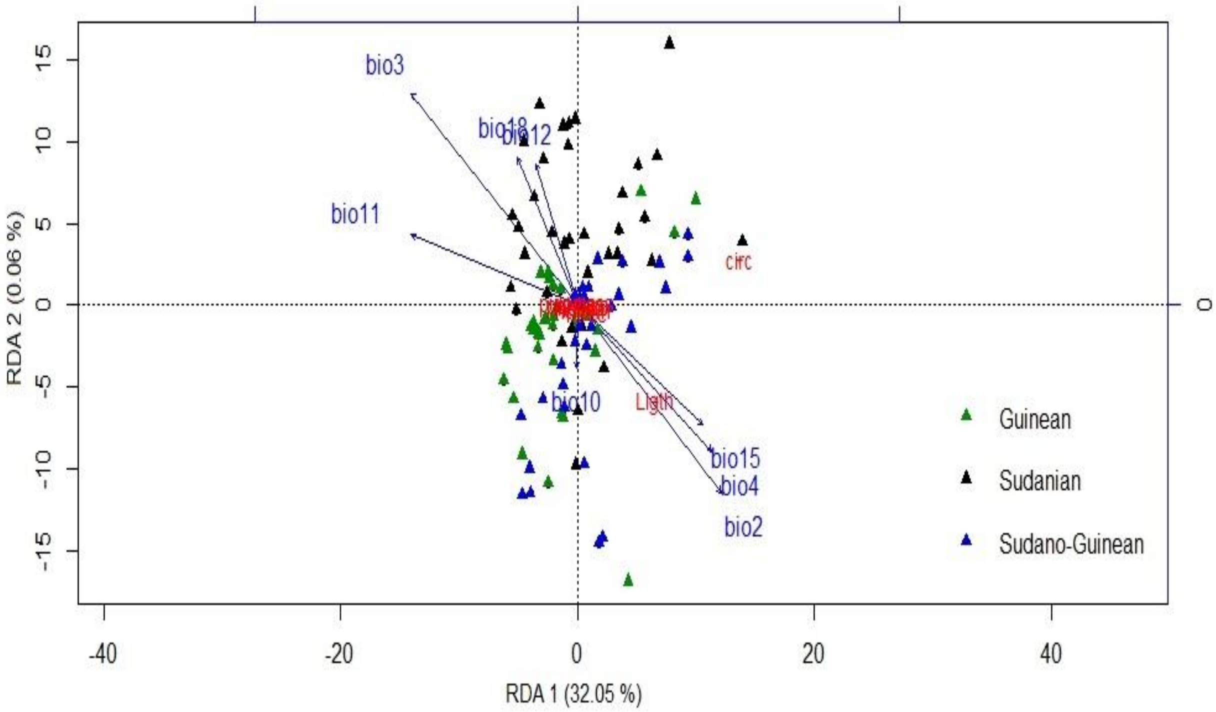


Figure 25: Projection of *V. doniana* trees in the RDA correlation triplot (scaling = 2) defined by the two first axes

Trees are represented by triangles (green, blue and black for respectively Guinean, Sudano-Guinean and Sudanian trees). Bioclimatic variables are represented by arrows (bio 2 = Annual mean diurnal range of temperature; bio 3 = Isothermality; bio 4 = Temperature seasonality; bio 10 = Mean temperature of the warmest quarter; bio 11 = mean temperature of the coldest quarter; bio 12 = Annual precipitation; bio 15 = Precipitation seasonality; bio 18 = Precipitation of the warmest quarter). Morphological variables (circ = circumference; htree = total height of tree; hcrown = crown height; Llgth = leaf length; petdiam = petiole diameter; lnumb = number of leaflets; pulpmass = pulp mass).

4.4. Radial growth and wood anatomical patterns of the black plum according to climatic zones

4.4.1. Radial growth of the black plum

Within discs, there was a good matching of the three radii along which TRW were measured with GLK values varying from 64 to 94 % in the Sudanian zone and from 64 to 98 % in the Guinean zone (see appendices 6 and 7). Between discs, there was not a perfect agreement of all radii within sites. Thus after cross dating quality checking with COFECHA programme, six of the seven discs per site presented some best matching radii with the rest of the site's dataset (see appendices 7 for detail on selected radii). Statistics of the cross-dated time-series are shown in table XXIII. Both stands exhibited a good agreement of time series among trees (mean GLK above 60 % and mean correlation between trees greater than 0.32). The mean sensitivity was higher for the two stands (0.33 and 0.34 for Guinean and Sudanian stand, respectively). The first order autocorrelation (AR1) was very low in both stands (0.002 and 0.076 for Guinean and Sudanian stand, respectively). The expressed population signal (EPS) was around 0.80 for both stands. The average annual radial growth was 0.89 and 0.79 cm/year for the Sudanian and Guinean stand respectively. It did not vary significantly between stands (df = 10, t = -1.036, p-value = 0.325).

In both stands, TRW increased with the age suggesting existence of an age trend (Figures 26 & 27). The removal of this age trend allowed the creation of a residual chronology for each stand, (Figure 28). The chronology index ranged from 0.401 to 1.679 in the Sudanian stand and from 0.505 to 1.476 in the Guinean stand. Stands chronologies were slightly in agreement (GLK = 52 % and Pearson's correlation = 0.39, p-value = 0.01).

Table XXIII: Statistics of cross-dated chronologies of TRW of the black plum in Sudanian and Guinean stands

	Tree provenance	
	Sudanian	**Guinean**
Number of trees	7	7
Number of dated trees	6	6
Covered period	1960-2014	1964-2014
Mean *Gleichläufigkeitk* (GLK, %)	70.16	65.13
Mean correlation between trees (R_{bt})	0.377	0.341
Mean sensitivity (MS)	0.33	0.34
Mean ring width (mm)	4.45	3.94
Standard deviation (Sd, mm)	1.97	1.70
Autocorrelation (AR1)	0.002	0.076
Expressed Population Signal	0.78	0.76

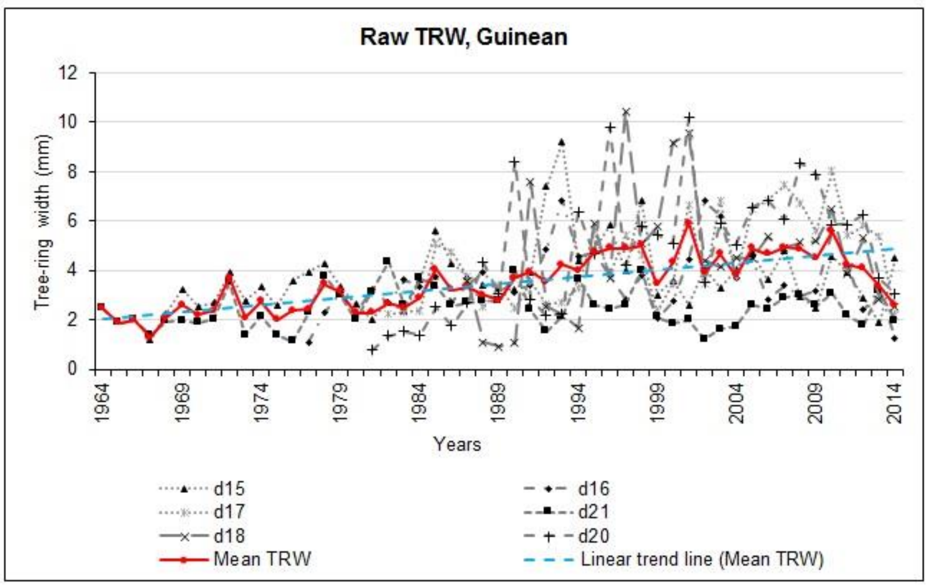


Figure 26: Cross-dated time series of TRW of *V. doniana* in the Guinean zone

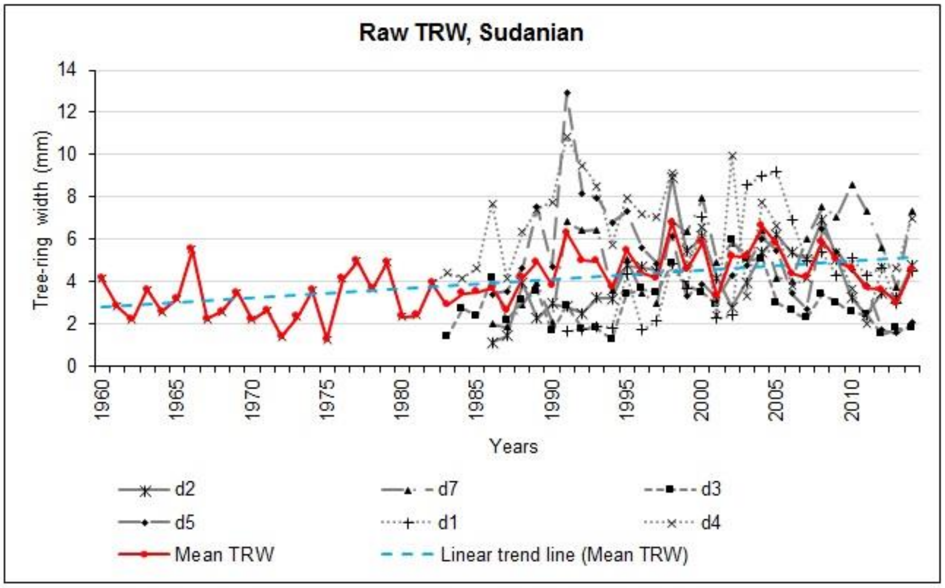


Figure 27: Cross-dated time series of TRW of *V. doniana* in the Sudanian zone

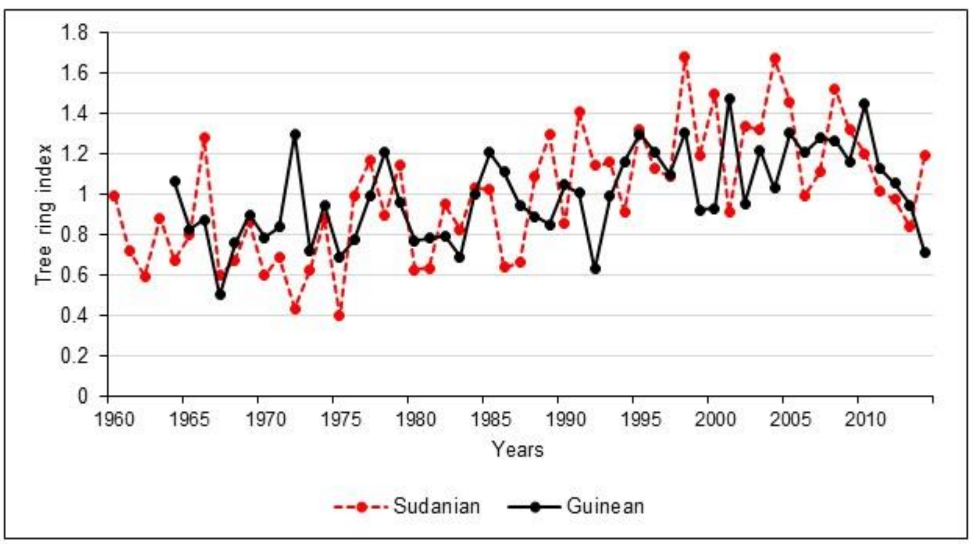


Figure 28: Mean residual chronologies of tree-ring index of *V. doniana* in the Sudanian and Guinean stands

4.4.2. Wood anatomical features of the black plum

There was no significant ring-to-ring variation for all vessel features of the black plum (p-value > 0.05, see appendix 8), but a significant tree-to-tree variation was observed within stands (Table XXIV, appendix 9). Between stands, significant differences (p-value < 0.05) were also found for all vessels features (Table XXV). Tree rings in the Guinean stand presented larger and more circular (circularity closer to 1) vessels resulting an important lumen fraction than the one from the Sudanian stand (Table XXV; Figures 29 a, b, c & 30a, b). However, vessels were more abundant in rings from Sudanian trees than in Guinean trees (Table XXV; Figure 30c).

4.4.3. Relationships between wood anatomical features and tree morphology

Correlations between tree morphology (dbh, bole height, tree total height and bark thickness) and wood anatomical features were in general greater than 0.5, but very few were significant (p-value < 0.05). For instance, only density of vessels was significantly correlated with the diameter at breast height (dbh) and the bark thickness respectively in the Sudanian and Guinean stand (Tables XXVI a & b).

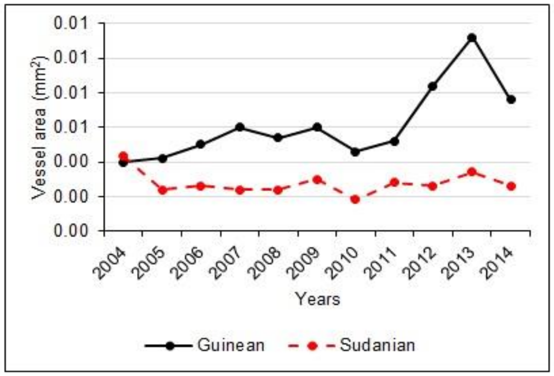
Table XXIV: Variation of wood anatomical parameters of the black plum between trees (rings from 2004 to 2014)

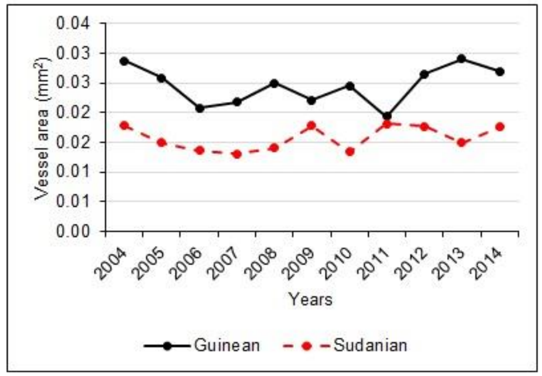
Climatic zones	Discs	mva (mm^2)	Mva (mm^2)	AvgVA (mm^2)	Circ	Density (ves/mm^2)	Lumen fraction (%)
Guinean	d16	0.006	0.052	0.028	0.811	4.882	13.604
	d18	0.003	0.023	0.013	0.803	9.869	11.525
	d19	0.006	0.050	0.025	0.808	6.662	16.003
	d20	0.006	0.048	0.025	0.792	5.370	13.073
	d21	0.009	0.058	0.033	0.783	6.774	21.301
	p-value	0.003	<0.001	<0.001	0.030	<0.001	<0.001
Sudanian	d1	0.003	0.039	0.018	0.705	6.937	11.993
	d2	0.003	0.031	0.015	0.760	7.291	10.374
	d3	0.004	0.039	0.019	0.739	6.869	13.160
	d5	0.001	0.024	0.012	0.752	21.522	21.689
	d7	0.003	0.028	0.015	0.797	9.188	10.834
	p-value	<0.001	0.006	0.015	<0.001	<0.001	<0.001

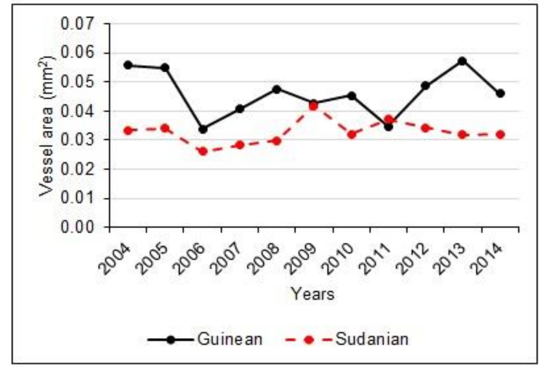
mva = minimal vessel area; Mva = maximum vessel area; AvgVA = average vessel area; Circ = vessel circularity; Density = density of vessels

Table XXV: Mean wood anatomical features of the black plum within climatic zones (rings from 2004 to 2014)

	Guinean	CV (%)	Sudanian	CV (%)	Kruskal-Wallis chi-squared	p-value
Minimum vessel area (mm^2)	0.006	71.10	0.003	52.71	32.108	<0.001
Mean vessel area (mm^2)	0.025	36.24	0.016	35.35	26.552	<0.001
Maximum vessel area (mm^2)	0.046	38.19	0.033	38.51	17.632	<0.001
Vessel circularity	0.800	2.87	0.75	5.59	42.566	<0.001
Vessel density ($vessels/mm^2$)	6.710	38.12	10.06	68.39	14.261	<0.001
Lumen fraction (%)	15.10	32.80	13.46	37.75	4.508	0.034





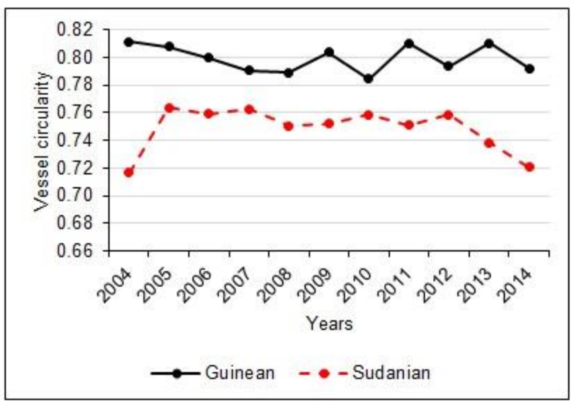


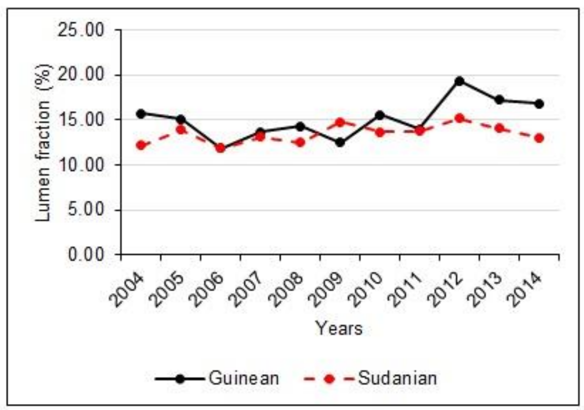
a. Minimum vessel area (mm^2)

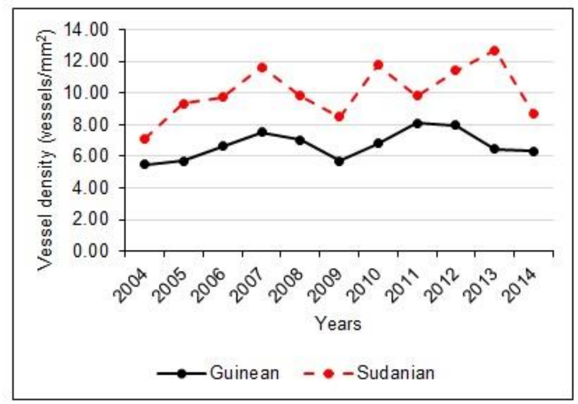
b. Mean vessel area (mm^2)

c. Maximum vessel area (mm^2)

Figure 29: Vessel size (mm^2) of the black plum according to climatic zones







a. Vessel shape (circularity)

b. Lumen fraction (%)

c. Density of vessels (vessels/mm^2)

Figure 30: Other vessel's features of the black plum

Table XXVI: Correlations between vessel features and tree morphology of the black plum

XXVIa. Sudanian stand

	dbh (cm)	Tree height (m)	Bole height (m)	Bark thickness (mm)
Minimum vessel area (mm^2)	-0.60	-0.01	0.43	0.60
Maximum vessel area (mm^2)	-0.81	-0.42	-0.05	0.47
Mean vessel area (mm^2)	-0.74	-0.36	0.23	0.69
Vessel circularity	0.58	0.56	0.68	0.12
Vessel density (vessels/mm^2)	0.89*	-0.22	-0.21	-0.61
Lumen fraction (%)	0.80	-0.52	-0.27	-0.58

dbh = diameter at breast height; *: Significant at 0.05

XXVIb. Guinean stand

	dbh (cm)	Tree height (m)	Bole height (m)	Bark thickness (mm)
Minimum vessel area (mm^2)	0.22	0.00	0.56	0.93
Maximum vessel area (mm^2)	0.07	0.00	0.58	0.80
Mean vessel area (mm^2)	-0.29	-0.43	0.87	0.81
Vessel circularity	-0.23	-0.63	0.26	0.12
Vessel density (vessels/mm^2)	-0.29	0.09	-0.54	-0.99*
Lumen fraction (%)	-0.35	-0.05	0.46	0.2

dbh = diameter at breast of height; *: Significant at 0.05

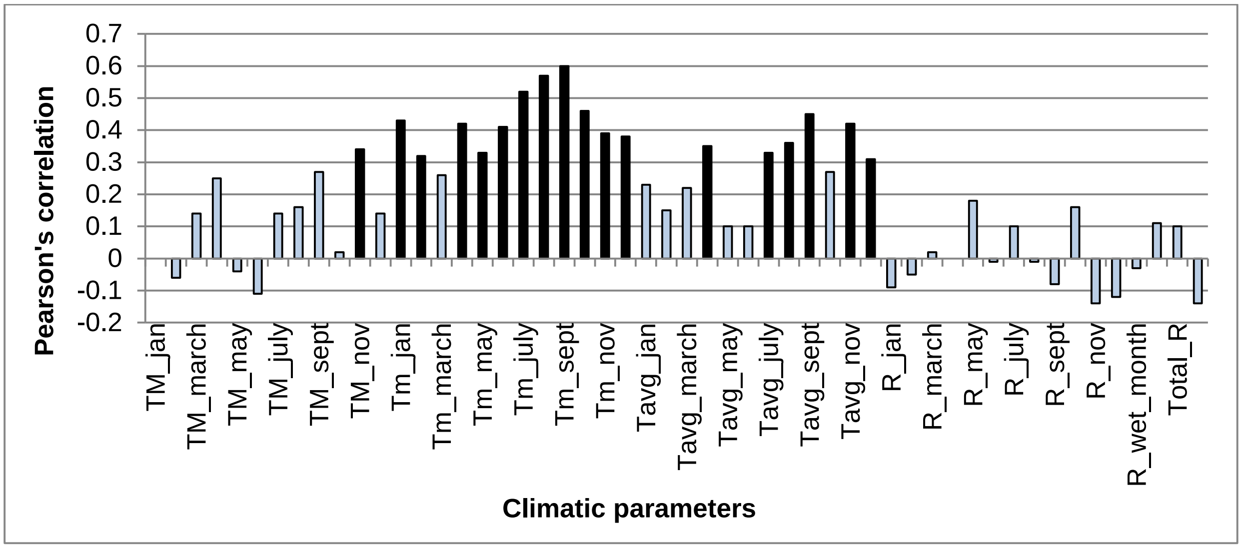
4.4.4. Effects of climatic factors on tree-ring index and on wood anatomical features

4.4.4.1. Climate and tree-ring index

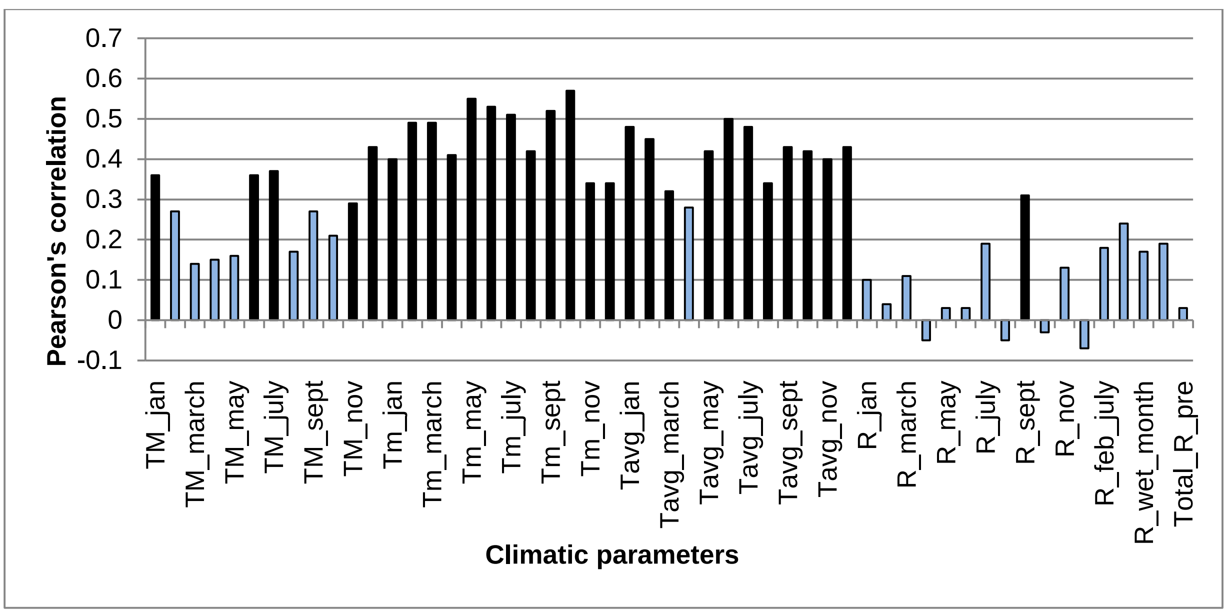
Residual chronologies of TRW were significantly correlated to 18 of the 51 tested climatic factors for Sudanian stand, and to 29 of those factors in the Guinean stand. Temperature parameters were the most important climatic factors affecting the tree-ring index in both stands. In the Sudanian stand, minimal temperature of July, August and September showed the highest correlations (above 0.5) with tree-ring index (Figure 31a). In this stand, none of the rainfall parameters had significant effect on the species' radial growth. In the Guinean stand, minimal temperature of May, June, July, September and October had the highest correlations with the tree-ring index (Figure 31b). In this stand, rainfall through September's precipitation had significant effect on tree-ring index (Pearson's correlation = 0.31).

4.4.4.2. Climate and wood anatomical features

Significant effects of climate on vessel features were recorded in both stands. In the Sudanian stand, maximum temperature of March negatively affected minimal vessel area and positively the vessel shape. Rainfall of April had a negative effect on lumen fraction, while rainfall of November was negatively correlated with density of vessels and vessel shape, and positively with minimum vessel area (Table XXVII). In the Guinean stand, minimum vessel area was positively correlated with rainfall of December. Maximum vessel area was under the positive effect of minimal temperature of November and December and under the negative effect of mean and maximal temperature of July. In the same stand, mean vessel area was positively influenced by minimal temperature of December and negatively by minimal and mean temperature of July. The vessel shape was negatively affected by total annual rainfall and minimal temperature of March, meanwhile, density of vessels was influenced by the mean temperature of December (Table XXVII).



a. Sudanian stand (Climatic data from Kandi's station, ASECNA Benin)



b. Guinean stand (Climatic data from Bohicon's station, ASECNA Benin)

Figure 31: Distribution of Pearson's correlations between tree-ring index of the black plum and climatic parameters of Benin

TM = maximum temperature; Tm = minimum temperature; Tavg = mean temperature; R = Rainfall. Significant correlations at 0.05 shown by black bars

Table XXVII: Correlations between vessel features of the black plum and climatic parameters of Benin

Climatic zones	Climatic parameters	mVA	MVA	VA	VC	LF	VD
Sudanian zone	Maximal temperature of March	-0.74*	0.19	-0.30	0.72*	0.30	0.34
	Rainfall of April	0.35	-0.49	-0.16	-0.47	-0.80*	-0.36
	Rainfall of November	0.88*	0.03	0.38	-0.94*	-0.42	-0.68*
Guinean zone	Maximal temperature of July	-0.25	-0.70*	-0.58	-0.19	-0.64	-0.04
	Maximal temperature of December	-0.15	-0.41	-0.45	0.34	-0.69*	-0.36
	Minimal temperature of March	0.00	0.20	0.18	-0.68*	0.20	-0.05
	Minimal temperature of July	-0.11	-0.77*	-0.72*	-0.38	-0.57	0.25
	Minimal temperature of November	-0.06	0.72*	0.65	0.06	0.72*	0.07
	Minimal temperature of December	-0.05	0.76*	0.67*	-0.15	0.18	-0.58
	Mean temperature of July	-0.20	-0.77*	-0.68*	-0.29	-0.65	0.08
	Mean temperature of December	-0.10	0.60	0.51	-0.02	-0.07	-0.71*
	Rainfall of April	0.65	0.11	0.22	0.03	0.79*	0.44
	Rainfall of December	0.80*	0.06	0.13	0.02	0.73*	0.53
	Total annual Rainfall	-0.30	-0.16	-0.06	-0.72*	-0.27	0.03

mVA = minimum vessel area; MVA = maximum vessel area; VA = average vessel area; VC = vessel circularity; LF = lumen fraction; VD = density of vessels; * = significant at 0.05
Climatic data used for the Sudanian zone were from Kandi's meteorological station, ASECNA-Benin
Climatic data used for the Guinean zone were from Bohicon's meteorological station, ASECNA-Benin

4.5. Habitat suitability for cultivation and *in situ* conservation of the black plum under current and future climates

4.5.1. Bioclimatic variables and model performance

Five of the 19 bioclimatic variables were selected as less-correlated ($r < 0.85$) and used for the species potential habitat modelling. These bioclimatic variables were: annual mean rainfall (bio12), annual mean diurnal range of temperature (bio2), mean temperature of the driest quarter (bio9), annual mean temperature (bio1) and precipitation of the driest month (bio14). Moreover, these bioclimatic variables showed significant variation (Wilcoxon signed-rank test, p-value < 0.05) between current climate and future projections with the most important changes reported in the Sudanian and Sudano-Guinean zones (Table XXVIII). For instance, annual mean rainfall, annual mean temperature and mean temperature of the driest quarter were projected to increase in all zones whatever the climatic scenario. Meanwhile, precipitation of the driest month is projected to significantly decrease in the Guinean zone and to remain stable in the other zones. Furthermore, in the Guinean zone, the annual rainfall is projected to vary slightly under both RCP (4.5 and 8.5) for HadGEM2-ES while significant increases were projected under MIROC5. In the same zone, annual mean temperature is projected to increase for about 2 °C. The projected increases mainly regarding temperature were more important in the two other zones (Table XXVIII).

Annual mean rainfall, annual mean diurnal range of temperature and mean temperature of the driest quarter were the most important predictors driving the species' distribution (Table XXIX). These variables have significant effects on the gain when used in isolation or removed from the modelling process (Figure 32). Annual mean precipitation was the most uniquely informative predictor because its presence/absence in the modelling process considerably affects the gain. Its contribution and permutation importance were around 50 % (Table XXIX).

The model had a high goodness-of-fit (cross-validated average AUC = 0.92 ± 0.02, Figure 33) and a very good predictive power (TSS = 0.72 ± 0.01). The 10^{th} percentile training presence logistic threshold for the habitat suitability discrimination was 0.22. Areas with occurrence probability above this threshold were then considered as suitable for the species, the remaining been considered as unsuitable areas.

Table XXVIII: Current and future projections of selected bioclimatic variables in Benin

Climatic zones	Climate	Bio12	Bio2	Bio9	Bio1	Bio14
Guinean	Current	1136.92a ± 59.56	82.95a ± 15.54	279.91a ± 1.96	273.82a ± 2.34	9.49a ± 3.84
	He4.5	1137.54a ± 59.24	79.11b ± 13.78	300.29b ± 3.00	293.11b ± 3.46	7.42b ± 2.49
	He8.5	1135.98b± 61.53	78.92b ± 13.80	306.60b ± 3.58	299.10b ± 3.63	6.41b ± 2.35
	Mi4.5	1231.52b ± 65.83	82.50b ± 14.89	297.10b ± 2.42	288.93b ± 2.46	7.08b ± 2.90
	Mi8.5	1214.40b ± 61.77	79.94b ± 13.49	298.92b ± 3.06	290.82b ± 2.11	7.15b ± 2.91
Sudano-Guinean	Current	1096.08a ± 51.52	121.36a ± 7.05	270.82a ± 4.22	269.80a ± 3.58	3.21a ± 1.24
	He4.5	1149.18b ± 70.28	114.45b ± 8.57	295.06b ± 4.29	292.35b ± 3.65	3.23b ± 1.26
	He8.5	1152.14b ± 75.71	113.31b ± 7.68	301.94b ± 3.99	299.01b ± 3.41	3.17b ± 1.17
	Mi4.5	1201.67b ± 63.17	120.40b ± 7.45	290.18b ± 4.14	286.30b ± 2.79	2.28b ± 1.01
	Mi8.5	1233.80b ± 73.76	115.69b ± 8.62	292.94b ± 2.78	289.03b ± 2.22	2.19b ± 0.96
Sudanian	Current	1054.32a ± 94.99	131.05a ± 1.97	268.49a ± 8.27	273.04a ± 6.64	0.20a ± 0.40
	He4.5	1167.59b ± 78.19	128.66b ± 1.94	294.00b ± 6.95	295.52b ± 7.06	0.20a ± 0.40
	He8.5	1190.36b ± 80.81	125.14b ± 1.78	301.27b ± 7.18	303.63b ± 7.26	0.20a ± 0.40
	Mi4.5	1173.18b ± 98.35	131.53b ± 2.10	287.37b ± 9.20	291.70b ± 6.70	0.20a ± 0.40
	Mi8.5	1206.60b ± 110.07	131.02a ± 2.44	294.92b ± 7.61	297.30b ± 6.89	0.20a ± 0.40

Values were extracted from Worldclim database Version 1.4 at 2.5-minute grid resolution (approximately 4.62 x 4.62 km^2 in West Africa) based on the occurrence points of the black plum in Benin. In each climatic zone, significant differences between current and each future scenario are shown by letters following mean values (Wilcoxon signed-rank test, p-value < 0.05). He4.5 & He8.5: HadGEM2-ES under respectively RCP 4.5 and 8.5. Mi4.5 & Mi8.5: MIROC5 under respectively RCP 4.5 and 8.5. Bio12 = Annual mean rainfall (mm); Bio2 = Annual mean diurnal range of temperature (10 x °C); Bio9 = Mean temperature of the driest quarter (10 x °C); Bio1 = Annual mean temperature (10 x °C); Bio14 = Precipitation of the driest month (mm).

Table XXIX: Variables contribution and permutation importance (%)

Variables	Definition	Contribution (%)	Permutation importance (%)
bio12	Annual mean rainfall (mm)	48.7	52.1
bio2	Annual mean diurnal range of temperature (10 x °C)	28.6	21.3
bio9	Mean temperature of the driest quarter (10 x °C)	15	17.8
bio1	Annual mean temperature (10 x °C)	5.4	6.8
bio14	Precipitation of the driest month (mm)	2.3	2.0

Figure 32: Jackknife of regularized training gain for the black plum

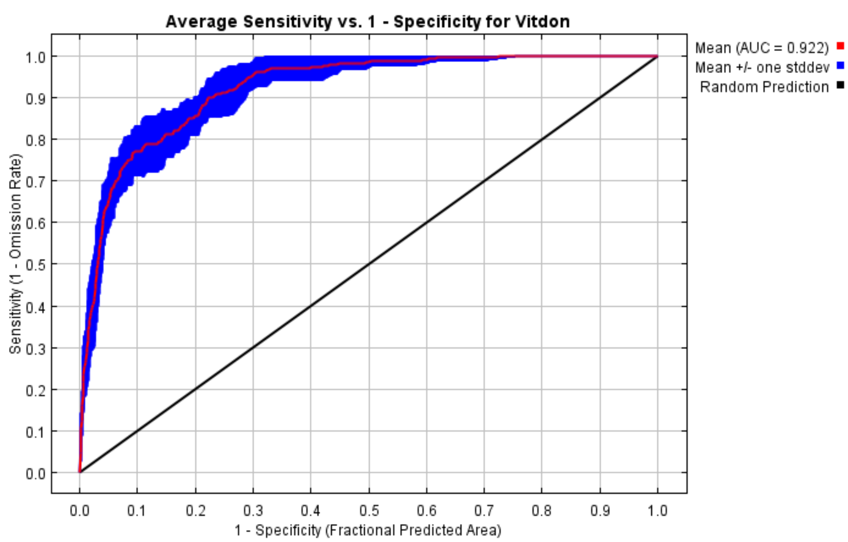


Figure 33: Cross-validated areas under the receiver operating characteristic curve (AUC)

4.5.2. Responses of the black plum to bioclimatic predictors

The black plum responded significantly to annual rainfall with a peak in its occurrence probability in areas with annual mean rainfall between 800 and 1200 mm (Figure 34a). According to annual mean diurnal range of temperature, occurrence probability of the species was at its highest level around 6 °C and decreased progressively when the amplitude range reached 12 °C. Areas with diurnal range of temperature between 12.5 and 15 °C were also suitable for the species (Figure 34b). Globally, habitat suitability of the species increased with the mean temperature of driest quarter (Figure 34c), but it decreased with the annual mean temperature (Figure 34d). Similarly, increases in the precipitation of the driest month reduced considerably the occurrence probability of the species (Figure 34e).

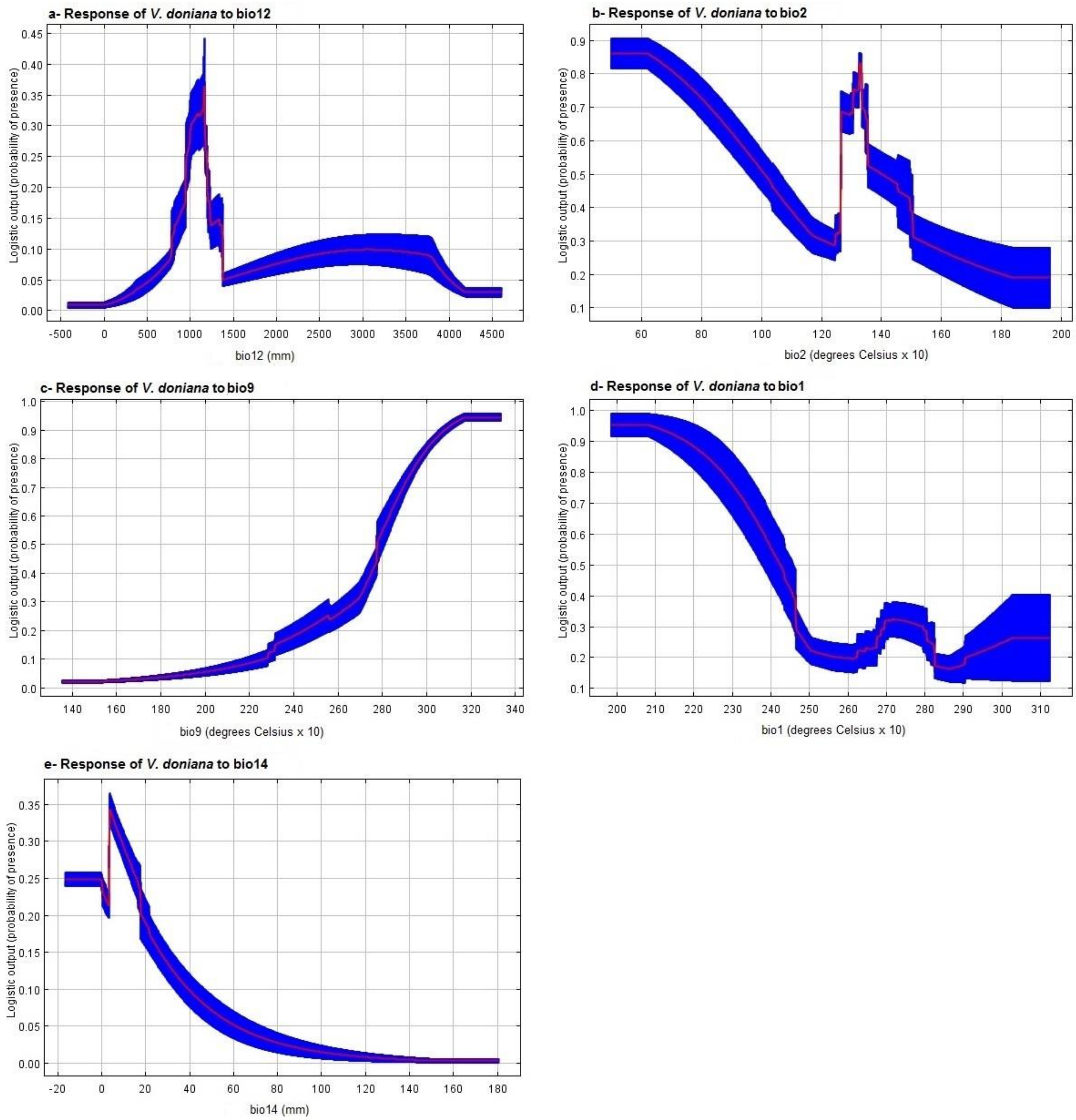


Figure 34: Response curves of the black plum to bioclimatic predictors in the habitat suitability modelling

Logistic output is the probability of presence. a- Annual mean rainfall (bio12, mm); b- Annual mean diurnal range of temperature (bio2, °C x 10); c- Mean temperature of driest quarter (bio9, °C x 10); d- Annual mean temperature (bio1, °C x 10); e- Precipitation of driest month (bio14, mm)

4.5.3. Suitable areas for the cultivation of the black plum in Benin under current and future climates

Under current climatic conditions, about 85 % (≈ 98,005 km^2) of Benin's area was modelled as potentially suitable for the cultivation of the black plum (Table XXX). This potential suitable habitat consisted of two blocks: a Southern block and a Northern block. The first block covered the Guinean zone and the lower part of the Sudano-Guinean zone. The second block included the upper part of the Sudano-Guinean zone and the Sudanian zone except its extreme Northern part, which is not actually suitable for the species (Figure 35a).

This habitat suitability was projected to increase by 3 to 12 % (about 3,512 to 14,278 km^2) under future climatic conditions for the year 2050 (Table XXX, Figures 35b, c, d & e). For instance, the extreme Northern part of the country will become suitable for the cultivation of the species under all the considered future climatic projections (Figures 35b, c, d & e). For the RCP 4.5 projections, the increase of the suitable habitat will be two times more important for MIROC5 than for HadGEM2-ES. Meanwhile, when considering RCP 8.5, the most important increase (+12.44 %) of the suitable area will be noted under HadGEM2-ES (Table XXX).

4.5.4. Suitable areas for the *in situ* conservation of the black plum within protected areas network under current and future climates

About 76 % (≈ 20,832 km^2) of the national PAN was suitable for the *in situ* conservation of the black plum under current climatic conditions (Table XXX). Regarding the two national parks, the major part of the W national park was not currently suitable for the conservation of the species (Figure 35a). Future climate will slightly ameliorate the *in situ* conservation of the species by the national PAN. Indeed, the proportion of the conserved suitable habitat will increase under the future climatic projections with HadGEM2-ES showing the greatest variation (thus, +20.71 and +23.27 % for RCP 4.5 and RCP 8.5 respectively). The most important change will likely occur in the W National Park in the Sudanian zone (Figures 35).

Table XXX: Variation of suitable areas for cultivation and *in situ* conservation of the black plum in Benin

Climate		Cultivation			Conservation by PAN		
		Area (Km^2)	Area (%)	Variation (%)	Area (Km^2)	Area (%)	Variation (%)
Current		98,005.21	85.40	-	20,832.46	76.28	-
RCP 4.5	HadGEM2-ES	103,522.26	90.21	+4.81	26,487.87	96.99	+20.71
	MIROC5	108,502.07	94.54	+9.15	25,603.57	93.75	+17.47
RCP 8.5	HadGEM2-ES	112,283.42	97.84	+12.44	27,187.08	99.55	+23.27
	MIROC5	101,517.94	88.46	+3.06	24,760.40	90.66	+14.38

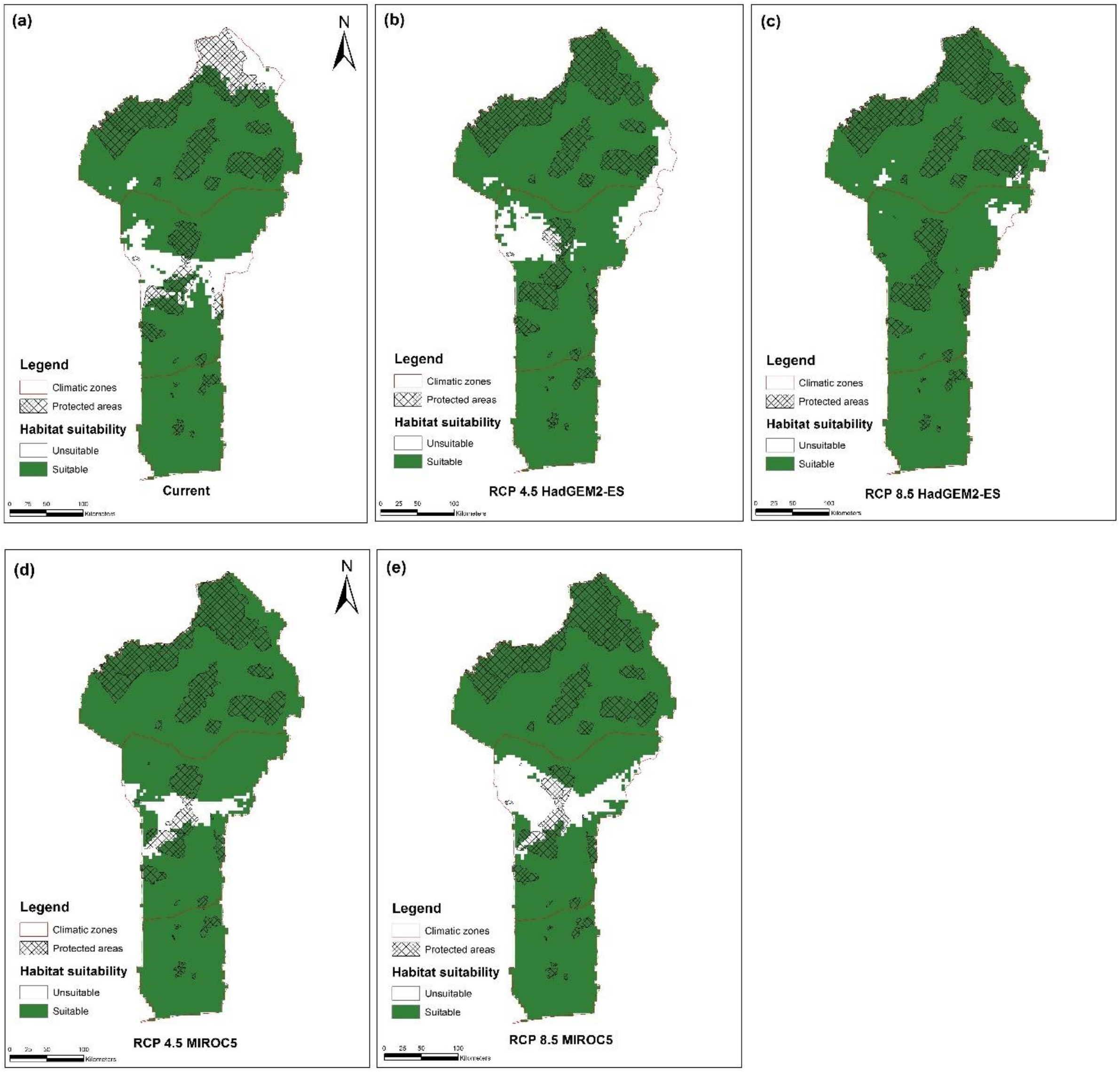


Figure 35: Maps of habitat suitability for cultivation and *in situ* conservation of the black plum under current and future climates in Benin

a. Current; b. HadGEM2-ES RCP 4.5; c. HadGEM2-ES RCP 8.5; d. MIROC5 RCP 4.5 and e. MIROC5 RCP 8.5

PART V: DISCUSSION

Through this work, we used the black plum, a key agroforestry species ranked among the top ten priority species for domestication programs in West Africa **(Akinnifesi *et al.*, 2008)**, to understand some of the mechanisms developed by the species to fit in various climatic environments. The main goal of the study was to improve knowledge on the ethnobotany of *Vitex doniana* and on the adaptive mechanisms used by the species to fit in various climatic zones of Benin in order to provide baseline information for the implementation of ecosystem-based adaptation approaches using *V. doniana* to face climate change. The study showed the ethnobotanical values of the species and the ecological, morphological, anatomical and spatial adjustments developed by the species in its occurrence zones. It provided useful information for the sustainable management and domestication schemes development for the species in the context of climate variability.

5.1. Use values and local perceptions on climate change and its impacts on the black plum

The assessment of the traditional ecological knowledge on the black plum confirmed that it is a well-known IATS diversely appreciated by local people. The significant differences observed between ethnic groups, as well as between age categories regarding the importance of the black plum (RUV, PPUV and UFV) suggested that the species is valued differently by local people in Benin. In fact, people showed interest in resources generally, and in plant particularly based on their knowledge and needs. This difference in use values of plant species was also induced by many other factors including culture, experiences, availability and accessibility of alternative resources **(Avouhou *et al.*, 2012)**. In this sense, the different ethnic groups surveyed showed particular interests in the black plum because traditional knowledge on the species has been kept through generations according to established customs. But the geographical location considered in this study through climatic zones, seemed to have some effects on the valuation of the species even if evidences were not significant. In fact, among the ethnic groups encountered in more than one climatic zone (*Bariba*, *Peulh* and *Mahi*), some showed specific interests in the use of the species depending on their location. For instance *Bariba* people living in the Sudanian zone were more interested in mature leaves, bark and flowers while, people from the same ethnic group but living in the Sudano-Guinean zone considered fruits and young leaves than the other parts of the species. Similarly, while *Peulh* people living in the Sudanian zone preferred mature leaves mainly for fodder and magical/cultural purposes, in the Sudano-Guinean zone they used mainly the trunk for fire and handicraft making more than the other parts of the species. These particularities might be attributed to cohabitation and intercultural exchanges that could have favored integration of uses learned from other sociocultural groups and subsequent changes in use habits **(Nesheim *et al.*, 2006; Gouwakinnou *et al.*,**

2011). Other factors such as the taste, the chemical composition, etc. of fruits/young leaves, which can slightly differ from one zone to another because of bioclimate and soil interactions, might also explain these specificities of use shown across ethnic groups.

The findings also showcased that fruits and young leaves were the most used parts and, that food (direct consumption of ripe fruits and sauce preparation with young leaves) and medicine were the most important use forms of *Vitex doniana* in Benin. These findings corroborate previous studies conducted in southern Benin **(Assogbadjo *et al.*, 2012; Dadjo *et al.*, 2012)**.

Ethnicity and geographic location (climatic zone) seemed to be important factors shaping opinions of local communities regarding climate change and its impacts on the biology and productivity of *V. doniana*. Overall, people gave their opinion based on their background and also on their immediate environment. The importance of ethnicity in people's opinion regarding issues like climate change may come from the fact that people belonging to a given sociolinguistic group shared some social experiences and cultural traditions and history **(Peoples and Bailey, 2010)**. In the same order, people living in the same area, experienced environment trends in the same way and since the climatic zones considered in this study present different features (wet versus dry), people's opinions are likely based on what they faced regarding the climate **(Teka *et al.*, 2013)**. For instance, the relatively important proportion of informants perceiving that the temperature was decreasing in the Sudanian zone known to be drier than the other zones can be linked to the normally hard climatic conditions offered by the environment in the zone.

In general, all interviewees noticed changes in climatic parameters. Although the perceptions depended on ethnicity and on climatic zone, most informants reported shortening of rainy season's length and temperature raising. These findings were in agreement with previous studies regarding perceptions of local people on climate change **(Hassan and Nhemachena, 2008; Gnanglè *et al.*, 2011; Gnanglè *et al.*, 2012; Teka *et al.*, 2013)**. Moreover, the perceived changes in the climate followed the empirical evidences given by previous studies for the three climatic zones of Benin **(Gnanglè *et al.*, 2011)**.

Informants have reported several potential impacts of these changes in climatic parameters on the biology and productivity of the species. Reduction of productivity and delay in flowering/fruiting were the most reported potential impacts. Here also, ethnicity and location were important factors affecting opinion of local people. All these opinions of local people regarding impacts of climate change on the biology and productivity of the species are plausible. However, empirical evidences should be provided to enhance these opinions. Perceived negative effects of changes in the climate on agroforestry species have previously been reported. For instance, decrease in fruit yield in tamarind trees was perceived by local people to result from rainfall decrease **(Fandohan and Cuni Sanchez, 2015)**. Several authors have also illustrated negative effects of water shortage (that could result from the combination of decrease in rainfall and temperature increase) on the growth rate of agroforestry species (e.g. baobab tree, *Adansonia digitata*, **(Wickens and Lowe, 2008)**). However, others factors that may also explain the perceived effects include fire, tree pruning and livestock grazing. The effects of changing rainfall patterns and temperature on fruit yield of African agroforestry species have not been sufficiently researched. However, trees faced with too dry environment could reduce fruit production as a response to water resources limitation (e.g. tamarind, **(Diallo *et al.*, 2007)**).

5.2. Ecology and structural patterns of the black plum

The study revealed some ecological particularities of the species in its occurrence range. The investigations confirmed that the black plum occurred in all climatic zones of Benin. Climatic variability influenced neither the frequency of observation (number of contacts) nor the abundance of the species (number of individuals per observation) along transects. This suggested that the species was fairly observed in all the three climatic zones of the country. Although the average frequency of observations and abundance of the species was low, in each climatic zone, the species was more frequent in mosaics of croplands and fallows and in areas relatively close to rivers (less than 500 m). The relatively high frequency of observation of the species in farmlands and fallows was likely due to its socio-economic importance which leaded to its conservation in agricultural lands. In addition, the proximity of rivers was a key factor for the establishment of the species. Regarding this factor, the Sudano-Guinean zone showed some particularities. In this zone, the species was not observed further than 1000 m from the closest river. This may indicate that in this climatic zone, the proximity of rivers, in general, and particularly the hygrometry is an important factor for the occurrence of the species. These findings confirmed the plasticity of the species regarding its habitat choice **(Arbonnier, 2004; Ky, 2008)**. In the same order, the findings followed the trend of decreasing abundance and frequency found out on the species at greater distance to river along gallery forest-savannah gradient **(Azihou *et al.*, 2013)**.

The study revealed that in terms of the local environment, the black plum occurred in different woody plant communities when considering the local environment. This suggested that within the different habitats colonized by the species, it was not followed by the same floristic cortege. Indeed, given that plant communities are governed by environmental conditions **(Adomou *et al.*, 2006)**, the occurrence of the black plum in a given area may suggest than that this area is suitable for the species but not necessary for the other plant species. Moreover, since local environmental stress was not uniform through the country, being followed by the same species in all conditions may negatively impact its fitness because in such conditions, competition for light and other resources will surely reduce its abilities to adapt to the stress **(Huston, 1979)**.

The study showed that the structural parameters mainly the mean diameter (Dg) and the basal area (Ba) of the black plum were influenced by studied factors. The combined effects of climatic zone and land cover type appeared the most important driving forces on the major structural parameters of the species in Benin. In the extremes climatic zones (Guinean and Sudanian), the species performed well in mosaics of croplands and fallows. This may be explained by the absence of relevant competitors for resources (light and water). For instance, in the Guinean zone, the black plum was one of the most common species that local people preserved when clearing land for agriculture. In the Sudanian zone, after *Vitellaria paradoxa* and *Parkia biglobosa*, the black plum had great values for local people. For that, it was among the most common species in agrosystems of the region **(Assogbadjo *et al.*, 2012)**. Moreover, in these farmlands and fallows, the species may indirectly benefit from the use of fertilizers and other agricultural inputs.

Densities for either adults (dbh $\geq$ 5 cm), or for juveniles (dbh < 5 cm) of the species were low. These low densities of the species, despite the research design, may suggest that the species did not have an aggregative distribution. This has already be documented in the Southern part of the country **(Dadjo, 2011)**. In fact, according to our research design, we were expecting higher values of densities since plots were set along transects around encountered adult individual of the species. In addition, the reported low densities may lead to a decline of the populations because such populations with low densities are more vulnerable to human pressures and other disturbance factors **(Cunningham and Mbenkum, 1993)**. **Oumorou *et al.* (2010)** have already documented low densities of the species in the district of Banikoara in the Sudanian zone.

As far as the diameter structure of the species is concerned, except stands of the Sudano-Guinean zone and, of the Sudanian tree and shrubs savannahs, all the diameter distributions were left-skewed ($1 < c < 3.6$), characteristic of single-species stands with predominance of young trees or small diameter trees, but a relatively low regeneration potential **(Husch *et al.*, 2003)**. These findings may suggest that the population of the species in those stands is relatively at risk of extinction. Indeed, when combining these findings regarding the diameter structure and the low densities observed for the regeneration of the species, one can assume that its survival is not guaranteed because of the human pressures and other hazards on the species **(Ramachandran *et al.*, 2014)**. Even in the Sudano-Guinean zone where the diameter structures followed a reversed-J trend in all stands ($c < 1$), with then a high regeneration potential, the low regeneration densities observed pose a threat for the survival of the species in the zone. In fact, densities of big individuals were low in all cases and this can be explained by the selective exploitation of the species by local people. Indeed, it was reported that its wood can be used for several purposes including building, charcoal production and carving **(Arbonnier, 2004; Ky, 2008; Dadjo *et al.*, 2012)**. Moreover, holes were often observed in the big trunks and, individuals were often highly pruned for forage and for young leaves collection (personal field observations). All these facts expose individuals of the species to death.

5.3. Climate and morphological variability of the black plum

The morphological characterisation of the black plum in relation to climate revealed some of the morphological adaptations developed by the species. It provided also some insights to the probable responses of the species to future climate change.

Indeed, the findings confirmed that there was an important variability of morphological traits in the species and climate contributed somehow to the expression of this variability. For instance, the relatively important dispersion of morphological descriptors around mean values gave evidences of the existence of heterogeneity in populations of the black plum as mentioned by **Ky (2008)**. This heterogeneity can be seen as a result of fitness of the species in various habitats and can increase its survival chance under climate change **(Visser, 2008)**. Moreover, the existence of this variability strengthened the potential of the species in cultivars selection for a domestication process **(Leakey *et al.*, 2008; Fandohan *et al.*, 2011a)**. In fact, genetic diversity improves fitness of populations by providing options to respond differently to environmental changes **(Whitham *et al.*, 2003; Hughes and Stachowicz, 2004)**.

Despite the significant differences observed between climatic zones regarding all the considered morphological traits, except crown diameter, part of variability due to climatic zone was relatively low. The most important variability was generally recorded at individual tree level. These findings are in agreement with previous studies on native plant species in Benin such as *Adansonia digitata* **(Assogbadjo *et al.*, 2011)**, *Sclerocarya birrea* **(Gouwakinnou *et al.*, 2011)** and on introduced plant species like *Jatropha curcas* **(Gbèmavo *et al.*, 2015)**. Since morphology is under the control of genotype, environment and their interactions, with genotype leading often the control for several morphological traits **(Schlichting and Pigliucci, 1998)**, these findings suggested that most of the variability in *V. doniana* was probably genetically-induced.

Although the projection of *V. doniana* trees in the axes system defined by the two canonical functions from the discriminant analysis did not show a clear separation of trees, the major differences between trees were revealed regarding position of group centroids. Based on the contrasting features presented by Guinean and Sudanian trees (heavy vs. light pulp mass for example), climate may be considered as playing an important role in the morphological variability of the species. Indeed, the Guinean zone known to be wetter and more forested than the Sudanian zone, hosted thinner and taller trees with globally larger leaves and higher fruiting parameters mainly regarding fruits and pulp masses. These results may suggest that the species undergoes adaptive strategies in regard to climatic factors. According to the Sudano-Guinean zone, the findings showed that trees from this zone presented ambiguous features for the trunk, canopy, leaves and fruits morphology. Although trees were generally taller with larger leaves in this zone than elsewhere, these findings may confirm the transitional climatic conditions of the zone. Previous studies have already highlighted the role of climate for the morphological variation of several useful species. This was the case for instance for *Anogeissus leiocarpa* in Burkina Faso, where the biggest trees (i.e. trees with high circumference and height) were found in the sahelian zone, whereas the smallest were often found in the sudanian zone **(Ouédraogo *et al.*, 2013)**.

Evidences of bioclimatic impacts were given by the redundancy analysis which revealed significant relationships between bioclimatic parameters and discriminant morphological descriptors of the black plum. Although the bioclimatic parameters explained a relatively low part of variation in morphological traits, impacts of climate on the species' morphology were obvious even if there might not be strong. This relatively weak influence of the bioclimatic variables on morphological descriptors emphasized findings on low variability due to climate. Also, this low influence of bioclimatic parameters might be due to the fact that climate was not surely the only factor affecting the morphology of the species. Indeed, environmental factors like topography, soil properties (type, moisture, nutrients content) have been reported as potential predictors for plant morphology **(Sankaran *et al.*, 2005)**. Since soil types and properties varied significantly across climatic zones of Benin **(Adomou *et al.*, 2006)**, soil may have contributed to the morphological variation of the species in Benin. The study revealed that mainly temperature and precipitation of the warmest quarter and other related parameters such as annual diurnal range of temperature, temperature and precipitation seasonality affected the species morphological diversity. This suggest that the species is relatively less sensitive to the commonly used climatic parameters such as mean annual temperature and mean annual rainfall in terms of morphological variability.

5.4. Radial growth and wood anatomical patterns of the black plum

Tree-ring analysis and wood anatomy assessment were used to evaluate the radial growth and vessels features of the black plum according to the climatic parameters of the two contrasting climatic zones of Benin.

Findings confirmed the existence of distinct rings in majority of the stems discs. Although, existence and annuality of rings in tropical plant species have been controversially discussed since early stages of dendrochronology application in the tropics **(Worbes, 2002)**, several studies using dendrochronology have been conducted in the region. For instance, some studies have proved that tree-rings can be used for tree growth estimations **(Worbes *et al.*, 2003; Krepkowski *et al.*, 2012)**, past climate impacts assessment **(Schöngart *et al.*, 2006)** and for understanding other ecological issues such as spatial and temporal fire distribution in savannah woodland and dry forest **(Sinsin *et al.*, 2015)** and carbon sequestration **(Mbow *et al.*, 2013)** in the tropical zone. The annuality of the observed rings in *V. doniana* trees was likely evident since the black plum is a deciduous species **(Ky, 2008)**. Indeed, formation and growth of ring is a function of cambial activity which is induced by physiological and environmental conditions mainly, growth limiting and periodically occurring factors. The quasi inexistence of those limiting factors in the tropics is one of the main reasons for doubting on growth rings formation in tropical wood species **(Worbes, 2002; Gebrekirstos *et al.*, 2014)**. However, deciduous species like *V. doniana*, by the mechanism of leaves releasing, experienced periodically growth interruption which can be linked to ring formation **(Détienne and Mariaux, 1976)**. Following this property of the species and findings regarding TRW series cross-dating, we assumed that rings in the black plum were annual.

Both Guinean and Sudanian TRW chronologies were well cross-dated for the majority of the stems discs, with GLK greater than 60 % and, between-trees correlation above 0.32. These values strengthens the annuality of the rings in the species. The high mean sensitivity and the very low first order autocorrelation observed in both stand suggests that there is a higher year-to-year variation in the tree ring width, but there is no significant effect of the previous year's growth on the following year's growth. The Expressed Population Signal (EPS) was around 0.80 in both stands revealing that there is likely a common environmental signal in trees within the two stands. Although the EPS was below the critical value of 0.85 **(Wigley *et al.*, 1984)**, the data set can still be used to assess the local variability of growth of the species. Indeed, most of the statistical parameters to assess TRW chronologies were developed from temperate species which responses to the environment are mostly driven by temperature **(Wigley *et al.*, 1984; Worbes, 2002)**. This common environmental signal in the two stands is also confirmed by similar annual radial growth, the good agreement and similarity of TRW chronologies between stands. These findings suggests therefore that there is the existence of common environmental driving forces on the radial growth of the black plum in Benin. Findings from the correlations analysis of the tree-ring index with climatic parameters, suggest that temperature is a key factor affecting the radial growth of the species in both stands. Indeed, residual chronologies of TRW were significantly correlated with several temperature parameters in both stands. Rainfall was significantly correlated with the tree-ring index in only the Guinean stand. And in this stand, only September's precipitation was targeted. These findings can be supported by the large water table of the species. Indeed, according to **Ky (2008)**, the species' annual rainfall range is from 750 to 2000 mm. With this large range, rainfall seemed not to be a factor with direct effects on the growth of the species.

Vessels in rings from the Guinean trees were wider and more circular (circularity closer to 1) resulting an important lumen fraction than the one from the Sudanian stand. However, vessels were more abundant in rings from Sudanian trees than in Guinean trees. These differences may be due to water availability which is higher in the Guinean zone **(Adomou *et al.*, 2006)**. In fact, when water is available, trees produce large vessels in order to increase the hydraulic conductivity following Hagen-Poisseuille's law **(Tyree *et al.*, 1994; von Arx *et al.*, 2012; Venegas-Gonzales *et al.*, 2015)**. In the counterpart, production of small vessels in the Sudanian zone was likely a response of the species to low turgor pressure since such vessels were reported to be more resistant to drought-induced embolism than wider vessels **(Domec and Gartner, 2002)**.

Significant effects of climate on vessel features were also recorded in both stands. Here for instance, the findings revealed significant correlations between rainfall variables and vessels features. The vessels features revealed therefore more climatic signal than TRW mainly regarding rainfall. Indeed, while only September's rainfall was significantly correlated with tree-ring indices in the Guinean zone, several significant correlations were observed between vessels features and rainfall parameters in both stands. In the Sudanian stand for instance, increases in April's precipitation (beginning of rainy season) will likely reduce lumen fraction and, increases in November's precipitation (starting of dry season) will reduce vessels density and favour production of elongate vessels i.e. vessel circularity will decrease. As far as Guinean stand is concerned, increases in April and December's precipitation will surely rise lumen fraction. In the same vein, increase of total annual rainfall will reduce vessel circularity enabling then production of less circular vessels. These findings are consistent with the idea that wood anatomical variables, mainly vessel features reveal more climatic information than TRW data **(Fonti *et al.*, 2010; Matisons *et al.*, 2012; Sreejith *et al.*, 2015; Venegas-Gonzales *et al.*, 2015)**.

These findings presents the black plum as a potential species for dendroecological studies in tropical Africa. Such studies, very relevant for climatic and ecological studies are very scare in the region because of the controversy regarding rings formation in tropical trees **(Worbes, 2002)**. Recent developments in the domain of dendrochronology, mainly use of stable-isotopes signatures have promoted its rapid expansion in the tropics because such techniques have given reliable proofs of ring annuality in several tropical species **(Gebrekirstos *et al.*, 2009; Wils *et al.*, 2011; Gebrekirstos *et al.*, 2014)**.

5.5. Impacts of current and future climate on habitat suitability for the cultivation and *in situ* conservation of the black plum

Capacities of the black plum to withstand climate change were also assessed using species distribution modelling tools mainly the Maximum Entropy algorithm.

Annual mean rainfall, annual mean diurnal range of temperature and mean temperature of the driest quarter were shown as the most important predictors driving the distribution of the black plum. Among these predictors, mean annual rainfall showed the greatest contribution confirming the importance of water availability in plants distribution **(Adomou *et al.*, 2006)**. The ecological optimum of the species regarding this climatic predictor is from 800 to 1200 mm (Figure 34a), and it is effectively within the range of 750-2000 mm indicated by the literature **(Arbonnier, 2004; Ky, 2008; Orwa *et al.*, 2009)**. As far as temperature is concerned, it was mainly annual mean diurnal range of temperature and mean temperature of the driest quarter that mostly controlled the distribution of the species.

Under current climate, about 85 % of Benin area was potentially suitable for the cultivation of the black plum and, about 76 % of the national PAN was actually suitable for the *in situ* conservation of the species. Significant increases were projected under future climatic (2050) scenarios with several currently unsuitable areas becoming suitable under all the climatic models mainly in the Sudanian and Sudano-Guinean zones. This increase in habitat suitability can be explained by the significant changes projected for the bioclimatic parameters in 2050. Indeed, according to the climatic models used in this study, the extreme northern part of the country (annual mean rainfall mostly below 700 mm) are projected to become wetter with annual rainfall reaching 900 mm **(Hijmans *et al.*, 2005)**. These changes in the rainfall will likely make the areas suitable for the black plum since its ecological optimum is between 750 and 2000 mm/year. These findings can be supported by the high plasticity of the species in habitat selection **(Arbonnier, 2004; Ky, 2008; Orwa *et al.*, 2009)**.

Although models in both RCP showed similar increasing trend of the habitat suitability for the cultivation and *in situ* conservation of the species, some particularities were noted. For instance, the most important variations were noted under the projection of the drastic scenario (i.e. RCP 8.5). This climatic scenario is more plausible than the second because, even though important mitigation actions are being undertaken, the Earth's climate system will still be facing the 'committed warming' **(Harris *et al.*, 2014)**. However, because of the important uncertainties regarding the climatic models **(Harris *et al.*, 2014)**, one should be cautious regarding these projections.

Even though habitat suitability for the cultivation and *in situ* conservation of the black plum were projected to significantly increase in the country, its productivity under future climate might be affected either positively or negatively. In fact, the species may have undergone several physiological adaptations as responses to past climates, but under the current rapid climate change, the expansion of the species in new areas will likely require important energy-dependant adjustments in morphological, physiological or behavioural traits and this could have negative impacts on its productivity **(Challinor *et al.*, 2006)**.

PART VI: CONCLUSION AND PERSPECTIVES

6.1. Conclusion: Implications of the study

This countrywide assessment on *Vitex doniana*, a key indigenous agroforestry tree species (IATS), with focus on its ethnobotany, ecology, morphology, radial growth, wood anatomy and geographic climatic range was carried out in order to capitalize information on its capacities to withstand climatic challenges. Such information is of high importance for future domestication and conservation programmes on the species in the context of climate change. The study showcased some of the important ecological, morphological, anatomical and geographical range adaptations developed by the species to fit in various climatic environments in Benin. This fitness of the species in various habitat is an opportunity for domestication policies and for its use in ecosystem-based adaptation approaches implementation.

The study demonstrated that the black plum is a well-known IATS and it is diversely valued by local people depending on their ethnicity and age category. Its fruits and young leaves are the most used parts. Moreover, food and medicine are the most widespread use forms. Local people are aware of climate change and according to their perceptions, these changes in climatic conditions are affecting the biology and productivity of the species. This importance of the species and the widespread traditional knowledge on the species can be seen as strengths for domestication policies development and for its integration in ecosystem-based approaches for adaptation to climate change. However, regarding the reported impacts, empirical evidences should be provided through long term studies in order to enhance these opinions.

At another side, the study highlighted the impacts of climate, land cover and proximity of river on the ecology and population structure of the black plum in Benin. From these findings, it can be asserted that irrespective of the climatic zone, the black plum is more frequent in mosaics of croplands and fallows (MCF) and, in areas relatively close to rivers. Furthermore, the black plum exhibits high values of mean diameter and basal area in MCF in the Guinean and Sudanian zones while in the Sudano-Guinean zone, the highest values of the same structural parameters were recorded in riparian forests. In addition, although the considered factors did not affect the adult and juvenile densities of the species, low density values were recorded for both adults and juveniles suggesting that the species is exposed to unpredictable decline. Therefore, biomonitoring actions are recommended to improve knowledge on the population dynamics of the species.

The study revealed also that the black plum exhibited an important morphological variability. This may imply that the species has an important survival chance in facing threats like climate change. Also, with this important morphological variability, the potential of the species for cultivars selection is strengthened. Furthermore, findings suggested that extreme parameters of a changing climate in the future could affect the morphology of the species. Conservation and domestication programs to be developed for the species should therefore take into account this climate-induced morphological variability.

Regarding the radial growth and anatomical patterns, the study suggests a similar growth trend of the species with an important year-to-year variation in ring width in the two extremes climatic zones of the country. Furthermore, it revealed that rings from the Guinean stand presented the lowest density of vessels and those vessels were wider than the one from the Sudanian stand. Climatic factors interacted significantly with tree-ring width and vessels features and, vessels parameters reveal more climatic signals than TRW. These findings imply that the black plum can be seen as a potential species for dendrochronological studies in tropical Africa. But, the new developed techniques for tree ring analysis such as use of stable-isotope should be recommended in order to have more reliable evidences for annuality of rings.

Finally, the study revealed that under current climatic conditions, the black plum can be cultivated in a wide range of areas in Benin. In addition, the national protected areas network offers a large extend of potentially favourable areas for the *in situ* conservation of the species and that future climate (2050) will increase this habitat suitability. With this apparently positive impact of future climate on its habitat suitability, the black plum can be considered as a good candidate for ecosystem-based adaptation approaches implementation to tackle climate change.

6.2. Perspectives for future research

Although, the study provided relevant information for the conservation and domestication policies development for the species in the context of climate change, some aspects deserve to be further investigated. Therefore, it will be interesting to carry out some complementary studies on the species in order to deepen the findings and also to cover other relevant conservation issues on the species.

Indeed, since fruits and young leaves were reported as the most important harvested organs, impacts of frequent harvesting of those organs on the viability of the species should be studied in order to provide additional information for its sustainable management. Moreover, evaluating nutritional values of those organs could be recommended in order to find out its importance in food security policies and also to foster domestication programmes.

Also, regarding the reported impacts of climate change on the species, empirical evidences should be provided. Therefore, long-term studies should be implemented on the phenology, physiology and productivity of the species in order to elucidate these opinions.

In the ecological point of view, since low densities of regeneration and adult individuals of the species were noted through the country, a biomonitoring of the population dynamics of the species is required in order to prevent it from unpredictable hazards. Moreover, an evaluation of human activities on the population dynamics of the species could reinforce sustainable management policies for the species.

As far as morphology of the species is concerned, based on the important part of variability noted within-tree, population genetic studies are recommended on the species. Such studies improve knowledge on the genotype of the species in relation to climate and help in developing selection and domestication schemes for the species.

Moreover, as the species is seen as a potential candidate for dendroecological studies in tropics, more investigations are needed to deepen the findings. For that, studies based on the use of stable-isotopes might be helpful in understanding impacts of past climate on the species and in predicting its future.

Finally, following results on geographic range dynamics of the species, performances of the species in the potentially news suitable areas should be evaluated. Long-term studies are then required on the physiology, phenology and productivity of the species through its climatic range in order to build a consistent database for the conservation and domestication.

Beside all these recommended complementary studies, it will be very interesting to assess (i) the germination capacities, (ii) the early growth and leaves productivity of the species with regard to climatic zone; and (iii) the carbon sequestration potentialities of the species. These additional studies will surely be useful for the use of the species in ecosystem-based approaches for adaptation to climate change.

REFERENCES

Abràmoff M.D., Magalhães P.J. & Ram S.J., 2004. Image Processing with ImageJ. *Biophotonics International*, 11:36-42.

Achigan-Dako E.G., N'Danikou S., Tchokponhoué D.A., Komlan F.A., Larwanou M., Vodouhè R.S. & Ahanchédé A., 2014. Sustainable use and conservation of *Vitex doniana* Sweet: Unlocking the propagation ability using stem cuttings. *Journal of Agriculture and Environment for International Development*, 108(1):43-62.

Achigan-Dako E.G., N'Danikou S., Assogba-Komlan F., Ambrose-Oji B., Ahanchédé A. & Pasquini M.W., 2011. Diversity, geographical, and consumption patterns of traditional vegetables in sociolinguistic communities in Benin: Implications for domestication and utilization. *Economic Botany*, 65(2):129-145.

Adam K.S. & Boko M., 1993. *Le Benin.* Cotonou, Benin: Les Editions du Flamboyant, 97p.

Adjanohoun E.J., Adjakidje V., Ahyi M.R.A., Ake Assi L., Akoegninou A., D'Almeida J., Apovo F., Boukef K., Chadare M., Cusset G., Dramane K., Eyme J., Gassita J.-N., Gbaguidi N., Goudote E., Guinko S., Houngnon P., Issa L., Keita A., Kiniffo H.V., Kone-Bamba D., Musampa Nseyya A., Saadou M., Sodogandji T., De Souza S., Tchabi A., Zinsou Dossa C. & Zohoun T., 1989. *Contribution aux études ethnobotaniques et floristiques en République populaire du Bénin.* Paris, France: ACCT, 895p.

Adomou A.C., 2005. Vegetation patterns and environmental gradients in Benin: Implications for biogeography and conservation. PhD. Wageningen University, Wageningen, the Netherlands, 150p.

Adomou A.C., Sinsin B. & Van der Maesen L.J.G., 2006. Phytosociological and Chorological Approaches to Phytogeography: A Meso-Scale Study in Benin. *Systematics and Geography of Plants*, 76(2):155-178.

Agresti A., 2002. *Categorical Data Analysis, 2nd.* New Jersey, USA: John Wiley & Sons, Inc., Hoboken, 721p.

Ahoton L.E., Adjakpa J.B., Gouda M., Daînou O. & Akpo E., 2011. Effet des traitements de semences du prunier des savanes (*Vitex doniana* Sweet) sur la régénération et la croissance des plantules. *Annales des Sciences Agronomiques*, 15:21-35.

Akinnifesi F.K., Sileshi G., Ajayi O.C., Chirwa P.W., Kwesiga F.R. & Harawa R., 2008. Contributions of agroforestry research and development to livelihood of smallholder farmers in Southern Africa: 2. Fruit, medicinal, fuel wood and fodder tree Systems. *Agricultural Journal*, 3(1):76-88.

Akoegninou A., van der Burg W.J. & van der Maesen L.J.G., 2006. *Flore Analytique du Bénin.* Cotonou & Wageningen: Backhuys Publishers, 1063p.

Allouche O., Tsoar A. & Kadmon R., 2006. Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). *Journal of Applied Ecology*, 43:1223-1232.

American Meteorology Society. 2015. Rainfall intensity. *Glossary of meteorology.* 2 ed. Cambridge, Massachusetts American Meteorology Society.

Angiosperm Phylogeny Group. 2009. An update of the Angiosperm Phylogeny Group classification for the orders and families of flowering plants: APG III. *Botanical Journal of the Linnean Society*, 161(2):105–121.

Anyomi K.A., Raulier F., Mailly D., Girardin M. & Bergeron Y., 2012. Using height growth to model local and regional response of trembling aspen (*Populus tremuloides* Michx.) to climate within the boreal forest of western Québec. *Ecological Modelling*, 243:123-132.

Arbonnier M., 2004. *Trees, shrubs and lianas of West African dry zones.* France: Editions Quae, 574p.

Aregheore E.M., 2009. Country pasture/forage resource profile: The Republic of Benin. FAO, Rome, Italy, 35p.

Assogbadjo A.E., Glèlè Kakaï R., Edon S., Kyndt T. & Sinsin B., 2011. Natural variation in fruit characteristics, seed germination and seedling growth of *Adansonia digitata* L. in Benin. *New Forests,* 41(1):113-125.

Assogbadjo A.E., Glèlè Kakaï R., Vodouhê F.G., Djagoun C.A.M.S., Codjia J.T.C. & Sinsin B., 2012. Biodiversity and socioeconomic factors supporting farmers' choice of wild edible trees in the agroforestry systems of Benin (West Africa). *Forest Policy and Economics,* 14:41-49.

Avouhou H.T., Vodouhe R.S., Dansi A., Bellon M. & Kpeki B., 2012. Ethnobotanical factors influencing the use and management of wild edible plants in agricultural environments in Benin. *Ethnobotany Research & Applications,* 10:571-592.

Awoyé O.H.R., 2015. Implications of future climate change on agricultural production in tropical West Africa: Evidence from the Republic of Benin. PhD. Bayerischen Julius-Maximilians-Universitat Wursburg, Wursburg, Germany, 219p.

Axelson J.N., Bast A., Alfaro R., Smith D.J. & H. G., 2014. Variation in wood anatomical structure of Douglas-fir defoliated by the western spruce budworm: a case study in the coastal-transitional zone of British Columbia, Canada. *Trees,* 28:1837-1846.

Ayantunde A.A., Briejer M., Hiernaux P., Udo H.M.J. & Tabo R., 2008. Botanical knowledge and its differentiation by age, gender and ethnicity in southwestern Niger. *Human Ecology,* 36(6):881-889.

Azihou A.F., Glèlè Kakaï R., Bellefontaine R. & Sinsin B., 2013. Distribution of tree species along a gallery forest–savanna gradient: patterns, overlaps and ecological thresholds. *Journal of Tropical Ecology,* 29(1):25-37.

Bates D., Maechler M., Bolker B. & Walker S., 2015. Fitting linear mixed-effects models using lme4. *Journal of Statistical Software,* 67(1):1-48.

Bayala J., Sanou J., Teklehaimanot Z., Kalinganire A. & Ouédraogo S.J., 2014. Parklands for buffering climate risk and sustaining agricultural production in the Sahel of West Africa. *Current Opinion in Environmental Sustainability,* 6:28-34.

Bellard C., Bertelsmeier C., Leadley P., Thuiller W. & Courchamp F., 2012. Impacts of climate change on the future of biodiversity. *Ecology Letters,* 15:365-377.

Beltrán-Rodríguez L., Ortiz-Sánchez A., Mariano N.A., Maldonado-Almanza B. & Reyes-García V., 2014. Factors affecting ethnobotanical knowledge in a mestizo community of the Sierra de Huautla Biosphere Reserve, Mexico. *Journal of Ethnobiology and Ethnomedicine,* 10:1-18.

Bray J.R. & Curtis J.T., 1957. An ordination of the upland forest communities in southern Wisconsin. *Ecological Monographs,* 27:325-349.

Brou Y.T., Akindès F. & Bigot S., 2005. La variabilité climatique en Côte d'Ivoire: entre perceptions sociales et réponses agricoles. *Cahiers Agricultures,* 14(6):533-540.

Brown M.B., 1977. Algorithm AS 116: The tetrachoric correlation and its asymptotic standard error. *Applied Statistics,* 26:343-351.

Burnham K.P. & Anderson D.R., 2003. *Model selection and multimodel inference : a practical information-theoretic approach.* New York, USA: Springer, 488p.

Busby J.W., Smith T.G., White K.L. & Strange S.M., 2012. Locating climate insecurity: Where are the most vulnerable places in Africa? In: Scheffran J., Brzoska M., Brauch H.G., Link P.M. & Schilling J. (eds.). *Climate Change, Human Security and Violent Conflict.* Berlin Heidelberg, Germany: Springer 463-511.

Cabral C., 2013. *Multidisciplinary taxonomic revision in the genus Vitex L. in Africa.* Saarbrücken, Germany: Lambert Academic Publishing (LAP), 304p.

Camou-Guerrero A., Reyes-García V., Martínez-Ramos M. & Casas A., 2008. Knowledge and use value of plant species in a Rarámuri community: A gender perspective for conservation. *Human Ecology,* 36:259-272.

Campbell A., Kapos V., Scharlemann J.P.W., Bubb P., Chenery A., Coad L., Dickson B., Doswald N., Khan M.S.I., Kershaw F. & Rashid M., 2009. Review of the literature on the links between biodiversity and climate change: Impacts, adaptation and mitigation. Secretariat of the Convention on Biological Diversity, Montreal, Canada, 124p.

Challinor A.J., Wheeler T.R., Osborne T.M. & Slingo J.M., 2006. Assessing the vulnerability of crop productivity to climate change thresholds using an integrated crop-climate model. In: Schellnhuber J.e.a. (ed.). *Avoiding dangerous climate change.* Cambridge, UK: Cambridge University Press, 187-194.

Chao A., Chazdon R.L., Colwell R.K. & Shen T.J., 2005. A new statistical approach for assessing similarity of species composition with incidence and abundance data. *Ecology Letters*, 8:148-159.

Charmantier A., McCleery R.H., Cole L.R., Perrins C., Kruuk L.E.B. & Sheldon B.C., 2008. Adaptive phenotypic plasticity in response to climate change in a wild bird population. *Science*, 320:800-803.

Chevin L.-M., Lande R. & Mace G.M., 2010. Adaptation, plasticity and extinction in a changing environment: towards a predictive theory. *PLoS Biology*, 8(4):e1000357.

Cochran W.G., 1977. *Sampling techniques.* 3rd ed. New York, USA: John Wiley & Sons, 448p.

Convention on Biological Diversity. 2009. Connecting biodiversity and climate change mitigation and adaptation. CBD, Montreal, 126p.

Cook E.R. & Holmes R.L., 1986. Guide for computer program ARSTAN. In: Holmes R.L., Adams R.K. & Fritts H.C. (eds.). *Tree-ring chronologies of western North America: California, eastern Oregon and northern Great Basin.* Tucson, Arizona: University of Arizona Press, 50-65.

Cornelissen J.H.C., Lavorel S., Garnier E., Diaz S., Buchmann N., Gurvich D.E., Reich P.B., Ter Steege H., Morgan H.D., Van Der Heijden M.G.A. & others. 2003. A handbook of protocols for standardised and easy measurement of plant functional traits worldwide. *Australian Journal of Botany*, 51(4):335-380.

Cunningham A.B. & Mbenkum F.T., 1993. Sustainability of harvesting *Prunus africana* bark in Cameroun: A medicinal plant in international trade. In: Division of Ecological Science U. (ed.). *People Plants Working Paper* Paris, France, 11-46.

Dadjo C., Assogbadjo A.E., Fandohan B., Glèlè Kakaï R., Chakeredza S., Houehanou T.D., Damme P.V. & Sinsin B., 2012. Uses and management of black plum (*Vitex doniana* Sweet) in Southern Benin. *Fruits*, 67(4):239-248.

Dadjo C.P.A.F., 2011. Caractérisation ethnobotanique, morphologique et distribution de *Vitex doniana* Sweet (Verbenaceae) au Sud-Bénin. Thèse pour l'obtention du Diplôme d'Ingénieur Agronome. Université d'Abomey-Calavi, Abomey-Calavi, Bénin, 86p.

Dagnelie P., 1998. *Statistiques théoriques et appliquées.* 2nd ed. Bruxelles, Belgique: De Boeck et Larcier, 659p.

De Cáceres M. & Legendre P., 2009. Associations between species and groups of sites: indices and statistical inference. *Ecology*, 90(12):3566-3574.

De Caceres M., Legendre P., Wiser S.K. & Brotons L., 2012. Using species combinations in indicator value analyses. *Methods in Ecology and Evolution*, 3:973-982.

de Chazal J. & Rounsevell M.D.A., 2009. Land-use and climate change within assessments of biodiversity change: A review. *Global Environmental Change*, 19:306-315.

Détienne P. & Mariaux A., 1976. Nature et périodicité des cernes de bois dans le Samba. *Bois et Forêts des Tropiques*, 169:29-35.

Diallo B.O., Joly H.I., Mckey D., Hossaertmckey M. & Chevallier M.H., 2007. Genetic diversity of *Tamarindus indica* populations: Any clues on the origin from its current distribution? *African Journal of Biotechnology*, 6(7):853-860.

Djégo J.G.M., 2006. Phytosociologie de la végétation de sous-bois et impact écologique des plantations forestières sur la diversité floristique au sud et au centre du Bénin. Thèse Unique. Université d'Abomey-Calavi, 369p.

Domec J.C. & Gartner B.L., 2002. How do water transport and water storage differ in coniferous earlywood and latewood? *Journal of Experimental Botany,* 53:2369-2379.

Doswald N. & Osti M., 2011. Ecosystem-based approaches to adaptation and mitigation – good practice examples and lessons learned in Europe. Bundesamt für Naturschutz (BfN), Bonn, Germany, 48p.

Elith J., Graham C.H., Anderson R.P., Dudik M., Ferrier S., Guisan A., Hijmans R.J., Huettmann F., Leathwick J.R., Lehmann A., Li J., Lohmann L.G., Loiselle B.A., Manion G., Moritz C., Nakamura M., Nakazawa Y., Overton J.M., Peterson A.T., Phillips S.J., Richardson K., Scachetti-Pereira R., Schapire R.E., Soberon J., Williams S., Wisz M.S. & Zimmermann N.E., 2006. Novel methods improve prediction of species' distributions from occurrence data. *Ecography,* 29:129-151.

Elith J., Kearney M. & Philips S., 2011a. The art of modeling range-shifting species. *Methods in Ecology and Evolution,* 1:330-342.

Elith J., Philips S.J., Hastie T., Dudik M., En Chee Y. & Yates C.J., 2011b. A statistical explanation of MaxEnt for ecologists. *Diversity and Distribution,* 17:43-57.

ESRI, 2014. ArcGIS Desktop. Version 10.3. World Shaded Relief, ESRI: USA.

Fandohan A.B., Gouwakinnou N.G., Déléké-Koko K.I.E., Glèlè Kakaï R. & Assogbadjo A.E., 2015a. Domesticating and conserving indigenous trees species: An ecosystem based approach for adaptation to climate change in sub-Sahara Africa. *Revue CAMES,* 3(1):55-60.

Fandohan A.B., Oduor A.M.O., Sode A.I., Wu L., Cuni-Sanchez A., Assede E. & Gouwakinnou G.N., 2015b. Modeling vulnerability of protected areas to invasion by *Chromolaena odorata* under current and future climates. *Ecosystem Health and Sustainability,* 1(6).

Fandohan B., Assogbadjo A.E., Glèlè Kakaï R., Kyndt T. & Sinsin B., 2011a. Quantitative morphological descriptors confirm traditionally classified morphotypes of *Tamarindus indica* L. fruits. *Genetic Resources and Crop Evolution,* 58(2):299-309.

Fandohan B., Assogbadjo A.E., Glèlè Kakaï R.L. & Sinsin B., 2011b. Effectiveness of a protected areas network in the conservation of *Tamarindus indica* (Leguminosea–Caesalpinioideae) in Benin. *African Journal of Ecology,* 49:40-50.

Fandohan B., Assogbadjo A.E., Kakaï R.G. & Sinsin B., 2011c. Geographical distribution, tree density and fruit production of *Tamarindus indica* L. (Fabaceae) across three ecological regions in Benin. *Fruits,* 66(2):65-78.

Fandohan B. & Cuni Sanchez A., 2015. Local perceptions of climate change and its impacts on indigenous fruit trees, Water, adaptation and sustainability in Benin. In: D Stucker D. & Lopez-Gunn E. (eds.). *Adaptation to climate change through water resources management capacity, equity and sustainability.* London and New York: Taylor and Francis, 180-196.

Fandohan B., Gouwakinnou G.N., Fonton N.H., Sinsin B. & Liu J., 2013. Impact des changements climatiques sur la répartition géographique des aires favorables à la culture et à la conservation des fruitiers sous-utilisés : cas du tamarinier au Bénin. *Biotechnology, Agronomy, Society and Environment,* 17(3).

FAO. 2012. Forest Management and Climate Change: a literature review. FAO, Rome, Italy, 55p.

Fernandez M.E., Gyenge J.E., de Urquiza M.M. & Varela S., 2012. Adaptability to climate change in forestry species: drought effects on growth and wood anatomy of ponderosa pines growing at different competition levels. *Forest Systems,* 21(1):162-173.

Fonti P., von Arx G., García-González I., Elimann B., Sass-Klaassen U., Gärtner H. & Eckstein D., 2010. Studying global changes through investigation on the plastic responses of xylem anatomy in tree-rings. *New Phytologist,* 185:42-63.

Fritts H.C., 2001. *Tree-rings and climate.* Caldwell: The Blackburn Press, 567p.

Garrity D.P., Akinnifesi F.K., Ajayi O.C., Weldesemayat S.G., Mowo J.G., Kalinganire A., Larwanou M. & Bayala J., 2010. Evergreen Agriculture: a robust approach to sustainable food security in Africa. *Food Security,* 2:197-214.

Gärtner H., Cherubini P., Fonti P., von Arx G., Schneider L., Nievergelt D., Verstege A., Bast A., Schweingruber F.H. & Büntgen U., 2015. A technical perspective in modern tree-ring research - How to overcome dendroecological and wood anatomical challenges. *Journal of Visualized Experiments,* 97.

Gbèmavo C.J., Gandji K., Gnanglè C.P., Assogbadjo A.E. & Glèlè Kakaï R.L., 2015. Variabilité morphologiques et conservation des morphotypes de Jatropha curcas Linn. (Euphoriaceae) au Benin. *Journal of Agriculture and Environment for International Development,* 109(1) 55-69.

GBIF. 2015. *GBIF Occurrence Download.* [Online]. Available at: www.gbif.org/occurrence/download/0004919-150922153815467 [Accessed, 7th October 2015].

Gebrekirstos A., Brauning A., Sass-Klassen U. & Mbow C., 2014. Opportunities and applications of dendrochronology in Africa. *Current Opinion in Environmental Sustainability,* 6:48-53.

Gebrekirstos A., Worbes M., Teketay D., Fetene M. & Mitlohner R., 2009. Stable carbon isotope ratios in tree rings of co-occuring species from semi-arid tropics in Africa: Patterns and climatic signals. *Global Planet Change,* 66:253-260.

Glèlè Kakaï R., Akpona T.J.D., Assogbadjo A.E., Gaoué O.G., Chakeredza S., Gnanglè P.C., Mensah G.A. & Sinsin B., 2011. Ecological adaptation of the shea butter tree (*Vitellaria paradox*a C.F. Gaertn.) along climatic gradient in Benin, West Africa. *African Journal of Ecology,* 49:440-449.

Glèlè Kakaï R., Bonou W. & Lykke A.M., 2016. Approche méthodologique de construction et d'interprétation des structures en diamètre des arbres. *Annales des Sciences Agronomiques,* 20:99-112.

Glèlè Kakaï R., Sodjinou E. & Fonton N., 2006. *Conditions d'application des méthodes statistiques paramétriques: Applications sur ordinateur.* Cotonou, Benin: INRAB, 96p.

Gnanglè C.P., Glèlè Kakaï R., Assogbadjo A.E., Vodounnon S., Yabi J.A. & Sokpon N., 2011. Tendances climatiques passées, modélisation, perceptions et adaptations locales au Bénin. *Climatologie,* 8:27-40.

Gnanglè P.C., Egah J., Baco M.N., Gbèmavo C.D.S.J., Glèlè Kakaï R. & Sokpon N., 2012. Perceptions locales du Changement Climatique et mesures d'adaptation dans la Gestion Des Parcs À Karité Au Nord-Bénin. *International Journal of Biological and Chemical Sciences,* 6(1):136-149.

Gomez-Beloz A., 2002. Plant use knowledge of the Winikina Warao: The case for questionnaires in ethnobotany. *Economy Botany,* 56:231-241.

Gonzalez P., 2001. Desertification and a shift of forest species in the West African Sahel. *Climate Research,* 17:217-228.

Gouwakinnou G.N., Assogbadjo A.E., Lykke A.M. & Sinsin B., 2011. Phenotypic variations in fruits and selection potential in *Sclerocarya birrea* subsp. *birrea*. *Scientia Horticulturae,* 129(4):777-783.

Grissino-Mayer H.D., 2001. Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. *Tree-Ring Research,* 57:205-221.

Hannah L., Midgley G.F. & Millar D., 2002. Climate change-integrated conservation strategies. *Global Ecology and Biogeography,* 11:485-495.

Harley R.M., Atkins S., Budntsev P.D., Cantino P.D., Conn B.J., Grayer R., Harley M.M., De Kok R., Kresstovskaja T., Morales R., Paton A.J., Ryding O. & Upson T., 2004. Labiatae. In: Kubitzki K. (ed.). *The Families and Genera of Vascular Plants: Flowering Plant-Dicotyledons.* Germany: Springer-Verlag, 267-268.

Harris R.M.B., Grose M.R., Lee G., Bindoff N.L., Porfiri L.L. & Fox-Hughes P., 2014. Climate projections for ecologists. *Wiley Interdisciplinary Reviews: Climate Change,* 5:621-637.

Hassan R. & Nhemachena C., 2008. Determinants of African farmers' strategies for adapting to climate change: Multinomial choice analysis. *African Journal of Agricultural and Resource Economics,* 2(1):83-104.

Hijmans R.J., Cameron S.E., Parra J.L., Jones P.G., Jarvis A. & others. 2005. Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology,* 25(15):1965-1978.

Hoffmann A.A. & Sgro C.M., 2011. Climate change and evolutionary adaptation. *Nature,* 470:479-485.

Holmes R.L., 1986. Quality control of crossdating and measuring: a user's manual for program COFECHA. In: Holmes R.L., Adams, R.K., Fritts, H.C. (ed.). *Tree-ring chronologies of western North America: California, eastern Oregon and northern Great Basin.* Tucson, Arizona, 41-49.

Hothorn T., Bretz F. & Westfall P., 2008. Simultaneous inference in general parametric models. *Biometrical Journal,* 50(3):346-363.

Hughes A.R. & Stachowicz J.J., 2004. Genetic diversity enhances the resistance of a seagrass ecosystem to disturbance. *Proceedings of the National Academy of Sciences of the United States of America,* 101(24):8998-9002.

Husch B., Beers T. & Kershaw J., 2003. *Forest Mensuration, 4th Edition.* London: Ronald Press Company, 410p.

Huston M., 1979. A general hypothesis of species diversity. *The American Naturalist,* 113:81-101.

INSAE. 2003. Troisième recensement général de la population et de l'habitation de Février 2002. INSAE, Cotonou, Benin, 15p.

INSAE. 2013. Résultats provisoires du quatrième Recensement Général de la Population et de l'Habitat (RGPH4). Institut National de la Statistique Appliquée et de l'Economie (INSAE), Cotonou, Benin, 8p.

IPCC. 2013. *Climate change 2013: The physical science basis.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 1535p.

IPCC. 2014. Climate Change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132p.

Ishaya S. & Abaje I.B., 2008. Indigenous people's perception on climate change and adaptation strategies in Jema's local government area of Kaduna state, Nigeria. *Journal of Geography and Regional Planning,* 1(8):138-143.

IUCN & UNEP-WCMC. 2015. *The World Database on Protected Areas (WDPA).* [Online]. Available at: www.protectedplanet.net [Accessed, 27th November 2015].

Johnson N.L. & Kotz S., 1970. *Distributions in statistics: Continuous univariate distributions.* New York, USA: John Wiley & Sons, 752p.

Judex M., Röhrig J., Schulz O. & Thamm H., 2009. *IMPETUS Atlas du Bénin. Résultats de recherche 2000-2007, 3rd ed.* Boon, Germany: Département de Géographie, Université de Boon, 128p.

Kalame F.B., Nkem J., Idinoba M. & Kanninen M., 2009. Matching national forest policies and management practices for climate change adaptation in Burkina Faso and Ghana. *Mitigation and Adaptation Strategies to Global Change,* 14:135-151.

Kilani A.M., 2006. Antibacterial assessment of whole stem bark of *Vitex doniana* against some enterobactriaceae. *African Journal of Biotechnology,* 5(10):958-959.

Krepkowski J., Brauning A. & Gebrekirstos A., 2012. Growth dynamics and potential for cross-dating and multi-century climate reconstruction of *Podocarpus falcatus* in Ethiopia. *Dendrochronologia,* 30:257-265.

Kuznetsova A., Brockhoff P.B. & Christensen R.H.B., 2014. lmerTest: tests in linear mixed effects models. R package Version 2.0-20. [Available at: https://cran.r-project.org/web/package/lmerTest/index.html].

Ky K.J.M., 2008. *Vitex doniana* Sweet. In: Louppe D., Oteng-Amoako A.A. & Brink M. (eds.). *Prota: Timbers/Bois d'oeuvre.* Wageningen, Pays Bas: Backhuys Publishers, Leiden/CTA, Wageningen, PROTA Foundation, 578-581.

Le Barbé L., Alé G., Millet B., Texier H., Borel Y. & Gualde R., 1993. *Les ressources en eaux superficielles de la République du Bénin.* Paris, France: ORSTOM Editions, 540p.

Leakey R., Fuller S., Treloar T., Stevenson L., Hunter D., Nevenimo T., Binifa J. & Moxon J., 2008. Characterization of tree-to-tree variation in morphological, nutritional and medicinal properties of *Canarium indicum* nuts. *Agroforestry Systems,* 73(1):77-87.

Lucier A., Ayres M., Karnosky D., Thompson I., Loehle C., Percy K. & Sohngen B., 2009. Forest responses and vulnerabilities to recent climate change. In: Seppala R., Buck, A. and Katila, P. (ed.). *Adaptation of forests and people to climate change.* IUFRO, 29-52.

Madsen H. & Thyregod P., 2011. *Introduction to General and Generalized Linear Models.* London: Chapman & Hall/CRC, 291p.

Mangiafico S.S., 2015. *An R Companion for the Handbook of Biological Statistics, version 1.09i.* New Brunswick, NJ, USA: Rutgers Cooperative Extension, 269p.

Mapongmetsem P.M., Djoumessi M.C., Yemele M.T., Fawa G., Doumara D.G., Noubissie J.B.T., Tientcheu A., Louise M. & Bellefontaine R., 2012. Domestication de *Vitex doniana* Sweet. (Verbenaceae): influence du type de substrat, de la stimulation hormonale, de la surface foliaire et de la position du nœud sur l'enracinement des boutures uninodales. *Journal of Agriculture and Environment for International Development,* 106(1):23-45.

Mason R.L., Gunst R.F. & Hess J.L., 2003. *Statistical design and analysis of experiments: With applications to engineering and science, 2nd Edition.* Hoboken, New Jersey: John Wiley & Sons, 729p.

Matisons R., Elferts D. & Brūmelis G., 2012. Changes in climatic signals of English oak tree-ring width and cross-section area of earlywood vessels in Latvia during the period 1900-2009. *Forest Ecology and Management,* 279:34-44.

Mbow C., Chhin S., Sambou B. & Skole D., 2013. Potential of dendrochronology to assess annual rates of biomass productivity in savanna trees of West Africa. *Dendrochronologia,* 31:41-51.

Mensah S., Houehanou T.D., Sogbohossou E.A., Assogbadjo A.E. & Glèlè Kakaï R., 2014. Effect of human disturbance and climatic variability on the population structure of *Afzelia africana* Sm. ex pers. (Fabaceae–Caesalpinioideae) at country broad-scale (Benin,West Africa). *South African Journal of Botany,* 95(2014):165–173.

Minitab Inc., 2010. Statistical Software. Version 17. Minitab, Inc.: State College, PA.

Munang R., Thiaw I., Alverson K., Mumba M., Liu J. & Rivington M., 2013. Climate change and Ecosystem-based Adaptation: a new pragmatic approach to buffering climate change impacts. *Current Opinion in Environmental Sustainability,* 5(1):67-71.

N'Danikou S., Achigan-Dako E.G., Tchokponhoué D.A., Assogba K.F., Vodouhè R.S. & Ahanchédé A., 2015. Improving seedling production for *Vitex doniana*. *Seed Science and Technology,* 43:10-19.

N'Danikou S., Achigan-Dako E.G., Tchokponhoué D.A., Assogba Komlan F., Gebauer J., Vodouhè R.S. & Ahanchédé A., 2014. Enhancing germination and seedling growth in *Vitex doniana* Sweet for horticultural prospects and conservation of genetic resources. *Fruits,* 69(4):279-291.

Nacoulma B.M.I., Traoré S., Hahn K. & Thiombiano A., 2011. Impact of land use types on population structure and extent of bark and foliage harvest of *Afzelia africana* and *Pterocarpus erinaceus* in Eastern Burkina Faso. *International Journal of Biodiversity and Conservation*, 3(3):62-72.

Nesheim I., Dhillion S.S. & Stølen K.A., 2006. What happens to traditional knowledge and use of natural resources when people migrate? *Human Ecology,* 34(1):99-131.

Oksanen J., Blanchet F.G., Kindt R., Legendre P., Minchin P.R., O'Hara R.B., Simpson G.L., Solymos P., Stevens M.H.H. & Wagner H., 2013. Vegan: Community Ecology Package. R package version 2.0-10. [Available at: https://cran.r-project.org, https://github.com/vegandevs/vegan].

Orekan V.O.A., 2007. Exécution d'un inventaire forestier national (IFN) : Traitement et analyse des données Landsat 7 ETM + Elaboration de la carte forestière. Projet Bois de Feu - Phase II. Direction des Forêts et des Ressources Naturelles, Ministère de l'Environnement et de la Protection de la Nature, République du Bénin, Cotonou, Bénin, 61p.

Orwa C., Mutua A., Kindt R., Jamnadass R. & Simons A., 2009. *Agroforestree Database: a tree reference and selection guide version 4.0.* [Online]. Available at: http://www.worldagroforestry.org/af/treedb/ [Accessed, 25th October 2013].

Ouédraogo A., Glèlè Kakaï R. & Thiombiano A., 2013. Population structure of the widespread species, *Anogeissus leiocarpa* (DC.) Guill. & Perr. across the climatic gradient in West Africa semi-arid area. *South African Journal of Botany,* 88 (2013):286-295.

Oumorou M., Sinadouwirou T., Kiki M., Glèlè Kakaï R., Mensah G.A. & Sinsin B., 2010. Disturbance and population structure of *Vitex doniana* Sw. in northern Benin, West Africa. *International Journal of Biological and Chemical Sciences,* 4(3):624-632.

Padmalatha K., Jayaram K., Raju N.L., Prasad M.N.V. & Arora R., 2009. Ethnopharmacological and biotechnological significance of *Vitex*. *Bioremediation, Biodiversity and Bioavailability,* 3(1):6-14.

Parmesan C., 2006. Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution and Systematics,* 37:637-669.

Pearson R.G., Christopher J., Raxworthy M.N. & Peterson A.T., 2007. Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. *Journal of Biogeography,* 34:102-117.

Peoples J. & Bailey G., 2010. *Humanity: An Introduction to Cultural Anthropology, 9th ed.* Belmont, USA: Wadsworth, 389p.

Phillips S.J., Anderson R.P. & Schapire R.E., 2006. Maximum entropy modelling of species geographic distributions. *Ecological Modelling,* 190:231-259.

R Core Team, 2016. R: A language and environment for statistical computing. Version 3.3.1. R Foundation for Statistical Computing: Vienna, Austria.

Ramachandran V.S., Swarupanandan K. & Sanjappa M., 2014. Status and distribution of *Humboldtia bourdillonii* (Leguminosae), an endangered tree species of the Western Ghats, India. *Tropical Ecology,* 55(1):85-91.

Revelle W., 2016. psych: Procedures for personality and psychological research. 1.6.6. Northwestern University: Evanston, Illinois, USA. [Available at: https://CRAN.R-project.org/package=psych].

Rondeux J., 1999. *La mesure des peuplements forestiers, 2nd.* Gembloux, Belgique: Presses Agronomiques de Gembloux, 521p.

Salamin N., Wuest R.O., Lavergne S., Thuiller W. & Pearman P.B., 2010. Assessing rapid evolution in a changing environment. *Trends in Ecology and Evolution,* 25:692-698.

Sankaran M., Hanan N.P., Scholes R.J., Ratnam J., Augustine D.J., Cade B.S., Gignoux J., Higgins S.I., Le Roux X., Ludwig F. & others. 2005. Determinants of woody cover in African savannas. *Nature,* 438(7069):846-849.

Sanoussi A., Ahoton L.E. & Odjo T., 2012. Propagation of black plum (*Vitex donania* Sweet) using stem and root cuttings in the ecological conditions of South Benin. *Tropicultura,* 30(2):107-112.

SAS Institute Inc., 2003. SAS. Version 9.1. SAS institute Cary: North Carolina, USA.

Scheldeman X. & van Zonneveld M., 2010. *Training manual on spatial analysis of plant diversity and distribution.* Rome, Italy: Bioversity International, 179p.

Schlichting C. & Pigliucci M., 1998. *Phenotypic evolution: a reaction norm perspective.* Sunderland, USA: Sinauer Associates Incorporated, 387p.

Schöngart J., Orthmann B., Hennenberg K.J., Porembski S. & Worbes M., 2006. Climate-growth relationships of tropical tree species in West Africa and their potential for climate reconstruction. *Global Change Biology,* 12:1139-1150.

Schwartz M.W., 2012. Using niche models with climate projections to inform conservation management decisions. *Biological Conservation,* 155:149-156.

Šēnhofa S., Zeps M., Matisons R., Smilga J., Lazdiņa D. & Ā. J., 2016. Effect of climatic factors on tree-ring width of *Populus* hybrids in Latvia. *Silva Fennica,* 50(1):1-12.

Sinsin F., Glèlè Kakaï R., Orthmann B. & Sinsin B., 2015. Tree-ring: a suitable implement for spatial and temporal fire distribution analysis in savanna woodland and dry forest. *Journal of Forestry Research,* 26(2):435-446.

Sommer J.H., Kreft H., Kier G., Jetz W., Mutke J. & Barthlott W., 2010. Projected impacts of climate change on regional capacities for global plant species richness. *Proceedings of the Royal Society of London B: Biological Sciences,* 277:2271-2280.

SPSS IBM, 2011. Statistical Package for Social Science. Version 20. SPSS IBM, Inc.: Chicago, USA.

Sreejith B., Anoop E.V., Anoob P., Vishnu R., Anish M., Adarsh M. & Vikas K., 2015. Responses of short period ring width and mean vessel area chronologies of plantation grown teak (*Tectona grandis* L. F.) to climate in Thrissur, Kerala, India. *Research Journal of Agriculture and Forestry Sciences,* 3(4):11-18.

Tantipisanuh N., Savini T., Cutter P. & Gale G.A., 2016. Biodiversity gap analysis of the protected area system of the Indo-Burma Hotspot and priorities for increasing biodiversity representation. *Biological Conservation,* 195:203-213.

Teka O., Houessou G.L., Oumorou M., Vogt J. & Sinsin B., 2013. An assessment of climate variation risks on agricultural production. *International Journal of Climate Change Strategies and Management,* 5(2):166-180.

The Plant List. 2013. *The Plant List.* [Online]. Available at: http://www.theplantlist.org [Accessed, 07th April 2016].

Tyree M.T., Davis S.D. & Cochard H., 1994. Biophysical perspectives of xylem evolution: is there a tradeoff of hydraulic efficiency for vulnerability to dysfunction? *IAWA Journal,* 15(4):335-360.

Vavrek M.J., 2011. Fossil: palaeoecological and palaeogeographical analysis tools. *Palaeontologia Electronica,* 14(1):1-16.

Venables W.N. & Ripley B.D., 2002. *Modern Applied Statistics with S (MASS), 4th Edition.* New York, USA: Springer-Verlag 498p.

Venegas-Gonzales A., von Arx G., Chagas M.P. & Filho M.T., 2015. Plasticity in xylem anatomical traits of two tropical species in response to intra-seasonal climate variability. *Trees,* 29:423-435.

Visser M.E., 2008. Keeping up with a warming world; assessing the rate of adaptation to climate change. *Proceedings of the Royal Society of London B: Biological Sciences,* 275(2008):649-659.

von Arx G., Archer S.A. & Hughes M.K., 2012. Long-term functional plasticity in plant hydraulic architecture in response to supplemental moisture. *Annal of Botany,* 109:1091-1100.

Walther G.-R., 2003. Plants in a warmer world. *Perspectives in Plant Ecology, Evolution and Systematics,* 6(2003):169-185.

Walther G.-R., Post E., Convey P., Menzel A., Parmesan C., Beebee T.J.C., Fromentin J.-M., Guldberg O.H. & Bairlein F., 2002. Ecological responses to recent climate change. *Nature,* 416:389-395.

Whitham T.G., Young W.P., Martinsen G.D., Gehring C.A., Schweitzer J.A., Shuster S.M., Wimp G.M., Fischer D.G., Bailey J.K., Lindroth R.L. & others. 2003. Community and ecosystem genetics: a consequence of the extended phenotype. *Ecology,* 84(3):559-573.

Wickens G.E. & Lowe P., 2008. *The baobabs, pachycauls of Africa, Madagascar and Australia.* Dordrecht, The Netherlands: Kluwer Academic Publishers Group, 498p.

Wigley T.M.L., Briffa K.R. & Jones D., 1984. On the average value of correlated time series with application in dendroclimatology and hydrometereology. *Journal of Climate and Applied Meteorology,* 23:201-221.

Willaime M.M.P. & Volkoff B., 1967. *Carte pédologique du Dahomey à l'échelle de 1/1000 000.ORSTOM* Paris, France.

Wils T.H., Sass-Klaassen U., Eshetu Z., Brauning A., Gebrekirstos A., Couralet C., Robertson I., Touchan R., Koprowski M., Conway D., Briffa K.R. & Beeckman H., 2011. Dendrochronology in the dry tropics: the Ethiopian case. *Trees Structure and Function,* 25:345-354.

Worbes M., 2002. One hundred years of tree-ring research in the tropics - a brief history and an outlook to future challenges. *Dendrochronologia,* 20(2002):217-231.

Worbes M., Staschel R., Roloff A. & Junk W.J., 2003. Tree ring analysis reveals age structure, dynamyc and wood production of a natural forest stand in Cameroon. *Forest Ecology and Management,* 173:105-123.

APPENDICES

Appendix 1: Contributions of ethnic groups on PC1 and PC2 (PCA on plant parts use values)

Ethnic groups	PC1 (30.17%)	PC2 (24.48%)
Adja	0.49	**3.69**
Aïzo	**-1.84**	0.47
Anii	**-2.73**	0.54
BaribaSG	**-1.89**	-0.92
BaribaS	-0.39	**0.63**
Berba	-0.28	**-1.01**
Biali	**-0.80**	0.41
Fon	-0.59	**-0.80**
Gourmantché	**2.49**	-0.54
Holli	**-0.95**	0.92
Ishabè	**-2.20**	-0.08
Jerma	**2.20**	0.48
Kotokoli	-0.08	**-1.82**
MahiG	1.14	**1.97**
MahiSG	**0.58**	0.37
Monkolé	-0.26	**-0.40**
Natimba	0.32	**0.39**
PeulhSG	1.66	**-2.09**
PeulhS	**2.16**	-0.44
Waama	-0.88	**-1.49**
Wémènou	0.99	**1.07**
Yom	0.86	**-1.37**

Values in bold represented highest contributions

Appendix 2: Contributions of ethnic groups on PC1, PC2 and PC3 (PCA on use form values)

Ethnic groups	PC1 (29.60%)	PC2 (21.44%)	PC3 (17.40%)
Adja	**-0.92**	0.77	0.91
Aïzo	-0.56	0.59	**-0.66**
Anii	-0.83	1.28	**-0.94**
BaribaSG	-0.74	-0.71	**-2.11**
BaribaS	**-0.70**	0.48	0.52
Berba	0.01	**-1.23**	0.33
Biali	**-0.99**	0.52	0.20
Fon	0.75	**-1.01**	0.18
Gourmantché	**1.52**	-0.87	1.30
Holli	**-1.08**	0.74	-0.24
Ishabè	**-1.09**	0.62	-0.73
Jerma	0.61	-0.81	**1.89**
Kotokoli	1.17	0.24	**-1.29**
MahiG	-1.13	1.16	**1.69**
MahiSG	-0.67	-0.16	**1.11**
Monkolé	**1.93**	-1.11	0.33
Natimba	-0.53	**1.08**	0.40
PeulhSG	0.55	**-0.84**	-0.35
PeulhS	**4.35**	2.03	-0.48
Waama	0.02	1.05	**-1.28**
Wémènou	**-1.01**	-0.38	0.20
Yom	-0.66	**-2.95**	-0.97

Values in bold represented highest contributions

Appendix 3: Contributions of ethnic groups on Dimensions 1 and 2 (Correspondence analysis on perceptions of local people on climate change)

Ethnic groups	**Dim1 (40.30%)**	**Dim 2 (29.84%)**
Adja	**2.83**	0.36
Aïzo	**81.73**	0.70
Anii	0.76	**50.90**
BaribaS	**0.43**	0.04
BaribaSG	2.53	**11.66**
Berba	1.35	**6.12**
Biali	**1.26**	0.74
Fon	**1.05**	0.01
Gourmantché	**0.13**	0.06
Holli	0.54	**1.08**
Ishabè	0.43	**1.17**
Jerma	**3.56**	1.59
Kotokoli	0.23	**17.59**
MahiG	0.57	**0.63**
MahiSG	0.02	**1.34**
Monkolé	0.02	**1.57**
Natimba	**0.82**	0.01
Wémènou	0.71	**1.98**
PeulhS	0.04	**0.18**
PeulhSG	0.40	**0.58**
Waama	**0.52**	0.08
Yom	0.06	**1.60**

Values in bold represented highest contributions

Appendix 4: Contributions of ethnic groups on Dimensions 1 and 2 (Correspondence analysis potential impacts of climate change on biology and productivity of *V. doniana*)

Ethnic groups	Dim1 (65.63%)	Dim2 (22.83%)
Adja	**51.27**	1.36
Aïzo	0.13	**2.94**
Anii	4.80	**12.21**
BaribaS	0.22	**3.81**
BaribaSG	0.00	**0.96**
Berba	0.00	**3.83**
Biali	**0.59**	0.10
Fon	**7.35**	3.98
Gourmantché	0.19	**50.99**
Holli	**6.76**	3.39
Ishabè	**2.36**	0.41
Jerma	**7.02**	1.90
Kotokoli	0.95	**5.84**
MahiG	0.74	**1.98**
MahiSG	0.19	**0.97**
Monkolé	**9.09**	0.00
Natimba	**1.55**	1.18
Wémènou	**5.03**	2.87
PeulhS	**0.59**	0.10
PeulhSG	0.00	**0.96**
Waama	**0.59**	0.10
Yom	**0.59**	0.10

Values in bold represented highest contributions

Appendix 5: Negative binomial regression estimates for frequency and abundance of the black plum

	Number of contacts per transect			Abundance per contact		
Factors	**Estimates**	**t-value**	**p-value**	**Estimates**	**t-value**	**p-value**
Climatic zones (Ref= Guinean)						
Sudanian	-0.336	-1.073	0.284	0.056	0.528	0.598
Sudano-Guinean	-0.262	-0.841	0.401	0.059	0.577	0.565
Land cover types (Ref=MCF)						
Woodl	-2.766	-6.400	<0.001	-0.234	-0.957	0.339
Plt	-2.883	-6.413	<0.001	-0.116	-0.476	0.635
RF	-2.565	-6.326	<0.001	-0.355	-1.506	0.133
TSS	-0.956	-3.299	0.001	0.076	0.771	0.442
Classes of distance (Ref=Class1)						
Class2	-1.352	-2.864	0.005	-0.099	-0.811	0.418
Class3	-1.872	-3.675	<0.001	-0.049	-0.331	0.741
Class4	-1.785	-3.556	<0.001	0.180	1.377	0.170

Land cover types: MCF = mosaics of croplands and fallows, Woodl = woodlands, Plt = plantation, RF = riparian forests, TSS = tree and shrub savannahs.

Classes of distance to the closest river: Class1= less than 500m; Class2 = between 500 and 1000m; Class3 = between 1000 and 1500m; Class4 = more than 1500m.

Appendix 6: Cross-dated radii of *V. doniana* stem discs from the Sudanian zone

	Sample	Ref.	OVL	GLK	TV	TVBP	TVH	CDI	DateL	DateR
Disc 1	r1	r2	23	68	9.70	6.40	3.30	33	1992	2014
	r1	r3	23	77	5.10	7.40	6.20	53	1992	2014
	r2	r3	23	64	7.00	10.60	6.10	53	1992	2014
Disc 2	r1	r2	29	79	5.30	5.20	5.20	41	1986	2014
	r1	r3	29	71	0.10	2.80	1.90	17	1986	2014
	r2	r3	29	71	2.20	5.30	3.10	30	1986	2014
Disc 3	r1	r2	32	81	4.00	3.20	3.90	29	1983	2014
	r1	r3	32	87	2.70	2.30	3.00	23	1983	2014
	r2	r3	32	94	1.50	5.90	5.90	55	1983	2014
Disc 4	r1	r2	55	76	2.20	2.80	3.10	23	1960	2014
	r1	r3	55	65	2.20	1.90	2.00	13	1960	2014
	r2	r3	55	70	5.20	3.00	2.70	20	1960	2014
Disc 5	r1	r2	29	82	7.20	4.30	3.90	34	1986	2014
	r1	r3	29	68	8.00	6.00	6.10	41	1986	2014
	r2	r3	29	79	9.80	6.90	7.40	56	1986	2014
Disc 6	r1	r2	41	89	6.70	6.90	6.50	59	1974	2014
	r1	r3	41	76	5.70	4.70	3.80	32	1974	2014
	r2	r3	41	70	4.90	3.50	2.60	22	1974	2014
Disc 7	r1	r2	29	75	4.20	6.30	4.20	39	1986	2014
	r1	r3	29	79	3.90	5.20	3.80	35	1986	2014
	r2	r3	29	75	2.80	4.70	5.00	37	1986	2014

Appendix 7: Cross-dated radii of *V. doniana* stem discs from Guinean zone

	Sample	Ref.	OVL	GLK	TV	TVBP	TVH	CDI	DateL	DateR
	r1	r2	48	96	2.70	5.80	5.50	54	1967	2014
Disc 15	r1	r3	48	94	3.20	7.90	7.30	71	1967	2014
	r2	r3	48	98	3.70	5.50	4.70	50	1967	2014
	r1	r2	38	88	2.80	3.60	3.30	30	1977	2014
Disc 16	r1	r3	38	72	3.10	3.40	3.30	24	1977	2014
	r2	r3	38	76	3.20	3.50	4.20	29	1977	2014
	r1	r2	33	81	1.20	2.10	3.10	21	1982	2014
Disc 17	r1	r3	33	91	2.80	3.20	4.40	34	1982	2014
	r2	r3	33	78	4.10	2.10	2.70	19	1982	2014
	r1	r2	28	70	5.40	4.10	5.20	33	1987	2014
Disc 18	r1	r3	28	67	4.10	2.90	4.50	24	1987	2014
	r2	r3	28	89	8.00	5.90	6.40	55	1987	2014
	r1	r2	41	84	3.80	6.30	5.80	51	1974	2014
Disc 19	r1	r3	41	84	3.70	6.30	6.40	53	1974	2014
	r2	r3	41	90	6.80	6.10	5.60	52	1974	2014
	r1	r2	34	85	9.90	5.70	6.20	51	1981	2014
Disc 20	r1	r3	34	88	6.00	5.00	5.30	45	1981	2014
	r2	r3	34	85	6.80	3.80	4.20	34	1981	2014
	r1	r2	51	64	1.50	2.50	2.30	15	1964	2014
Disc 21	r1	r3	51	84	4.20	5.30	5.00	43	1964	2014
	r2	r3	51	68	2.10	2.70	2.30	17	1964	2014

Appendix 8: Between discs cross-dating of *V. doniana* trees

a. Guinean zone

Sample	Ref.	OVL	GLK	TV	TVBP	TVH	CDI	DateL	DateR
vdon-d15-r2	vdon-d16-r1	38	68	1.6	2.1	1.3	11	1967	2014
vdon-d15-r3	vdon-d16-r1	38	65	1.3	2.5	0.1	8	1967	2014
vdon-d15-r3	vdon-d16-r2	38	64	1.9	2.3	1.2	11	1967	2014
vdon-d16-r1	vdon-d17-r2	33	69	1.8	1.1	3	14	1977	2014
vdon-d16-r1	vdon-d17-r1	33	63	1.3	1.8	2.8	14	1977	2014
vdon-d17-r1	vdon-d21-r1	33	66	0.6	1.2	1.7	10	1982	2014
vdon-d17-r1	vdon-d18-r3	28	63	0.2	0.5	1.4	6	1982	2014
vdon-d17-r2	vdon-d21-r1	33	72	0.6	2.4	2.7	18	1982	2014
vdon-d17-r2	vdon-d18-r2	28	63	0.1	1.3	1.6	9	1982	2014
vdon-d17-r3	vdon-d18-r1	28	67	2.8	1.5	1.7	11	1982	2014
vdon-d20-r1	vdon-d21-r2	34	61	2.1	1.5	2.1	11	1981	2014
vdon-d20-r2	vdon-d21-r2	34	70	1.1	2	2.4	15	1981	2014
vdon-d20-r2	vdon-d21-r1	34	64	0.4	1.6	1.9	11	1981	2014
vdon-d20-r2	vdon-d21-r3	34	61	1.9	3.1	2.2	16	1981	2014
vdon-d20-r3	vdon-d21-r2	34	61	2.5	1.5	2.3	12	1981	2014

b. Sudanian zone

Sample	Ref.	OVL	GLK	TV	TVBP	TVH	CDI	DateL	DateR
vdon-d1-r1	vdon-d2-r3	23	73	3.6	1	0.8	7	1992	2014
vdon-d1-r3	vdon-d2-r3	23	77	2.8	1.2	0.6	7	1992	2014
vdon-d2-r3	vdon-d7-r2	29	68	2.3	1.7	1.4	11	1986	2014
vdon-d3-r3	vdon-d1-r1	23	64	4.4	2.7	1.7	14	1983	2014
vdon-d4-r2	vdon-d7-r3	29	68	1.7	0.6	0.9	5	1960	2014
vdon-d5-r2	vdon-d2-r1	29	71	0.5	2.1	0.7	10	1986	2014

Appendix 9: Results of Kruskal-Wallis test on ring-to-ring variation of vessel features of the black plum

	Sudanian			Guinean		
Wood anatomical features	**Kruskal-Wallis chi-squared**	**Degree of freedom**	**p-value**	**Kruskal-Wallis chi-squared**	**Degree of freedom**	**p-value**
Minimum vessel area (mm^2)	4.889	10	0.898	8.618	10	0.569
Maximum vessel area (mm^2)	4.365	10	0.929	10.567	10	0.392
Mean vessel area (mm^2)	7.036	10	0.722	6.4	10	0.781
Vessel circularity	5.824	10	0.83	9.117	10	0.521
Vessel density (vessels/mm^2)	9.29	10	0.505	6.704	10	0.753
Lumen fraction (%)	2.717	10	0.987	9.337	10	0.501

Appendix 10: Results of Kruskal-Wallis test on tree-to-tree variation of vessel features of the black plum

	Sudanian			Guinean		
Wood anatomical features	**Kruskal-Wallis chi-squared**	**Degree of freedom**	**p-value**	**Kruskal-Wallis chi-squared**	**Degree of freedom**	**p-value**
Minimum vessel area (mm^2)	20.94	4	<0.001	16.16	4	0.003
Maximum vessel area (mm^2)	14.57	4	0.006	25.75	4	<0.001
Mean vessel area (mm^2)	12.40	4	0.015	30.41	4	<0.001
Vessel circularity	27.56	4	<0.001	10.75	4	0.030
Vessel density (vessels/mm^2)	22.54	4	<0.001	22.59	4	<0.001
Lumen fraction (%)	29.93	4	<0.001	24.36	4	<0.001

Appendix 11: List of plant species cited in the thesis

Plant species	**Family**	**Life form**
Adansonia digitata L.	Bombacaceae	mPh
Afzelia africana Smith ex Pers.	Leguminosae-Caesalpinioideae	mPh
Albizia glaberrima (Schum. & Thonn.) Benth.	Leguminosae-Mimosoideae	mph
Annona senegalensis Pers.	Annonaceae	nph
Anogeissus leiocarpa (DC.) Guill. & Perr.	Combretaceae	mPh
Antiaris toxicaria Lesch.	Moraceae	MPh
Azadirachta indica A. Juss.	Meliaceae	mPh
Balanites aegyptiaca (L.) Delile	Zygophyllaceae	mph
Bridelia ferruginea Benth.	Euphorbiaceae	mph
Ceiba pentandra (L.) Gaertn.	Bombacaceae	MPh
Celtis zenkeri Engl.	Celtidaceae	MPh
Cola gigantea A. CHEV.	Sterculiaceae	mPh
Daniellia oliveri (Rolfe) Hutch. & Dalziel	Leguminosae-Caesalpinioideae	mPh
Diospyros mespiliformis Hochst. ex A. DC.	Ebenaceae	mPh
Ficus sur Forssk.	Moraceae	mph
Jatropha curcas L.	Euphorbiaceae	nph
Khaya senegalensis (Desr.) A. Juss.	Meliaceae	mPh
Milicia excelsa (Welw.) C.C. Berg	Moraceae	MPh
Monotes kerstingii Gilg.	Dipterocarpaceae	mph
Morinda lucida Benth.	Rubiaceae	mph
Parkia biglobosa (Jacq.) R.Br. ex G. Don f.	Leguminosae-Mimosoideae	mPh
Pericopsis laxiflora (Benth.) van. Meeuwen	Leguminosae-Papilionoideae	mph
Piliostigma thonningii (Schumach.) Milne-Redh.	Leguminosae-Caesalpinioideae	mph
Prosopis africana (Guill. & Perr.) Taub.	Leguminosae-Mimosoideae	mPh
Pterocarpus erinaceus Poir.	Leguminosae-Papilionoideae	mPh
Sarcocephalus latifolius (Sm.) E. A. Bruce	Rubiaceae	mph
Sclerocarya birrea (A. Rich.) Hochst.	Anacardiaceae	mph
Syzygium guineense (Willd.) DC. var. *guineense*	Myrtaceae	mph
Tamarindus indica L.	Leguminosae-Mimosoideae	mPh
Terminalia avicennioides Guill. & Perr.	Combretaceae	mph
Terminalia glaucescens Planch. ex Benth.	Combretaceae	mPh
Triplochiton scleroxylon K. Schum.	Sterculiaceae	mPh
Uapaca togoensis Pax.	Flacourtiaceae	mPh
Vitellaria paradoxa C.F. Gaertn.	Sapotaceae	mPh
Vitex doniana Sweet	Lamiaceae	mph

MPh: megaphanerophyte (> 30 m tall); mPh: mesophanerophyte (8-30 m); mph: microphanerophyte (2-8 m); nph: nanophanerophyte (0.5-2 m)
Source: **(Adomou, 2005; Akoegninou *et al.*, 2006)**

Appendix 12: Curriculum Vitae

Achille Hounkpèvi was born in Porto-Novo (Republic of Benin), on 12 May 1982, from Pierre Assogba Hounkpèvi and Agnès Ahoudji Yazin. After a primary studies certificate (Certificat d'Etudes Primaires) in 1995 and a College Certificate (Brevet d'Etudes du Premier Cycle) in 1999, he obtained a Scientific Baccalaureate (Baccalauréat, Serie D) at *Lycée Béhanzin* (Porto-Novo, Benin) in 2002. Thereafter, he studied Geography for one year (2002-2003) at *Faculté des Lettres, Arts et Sciences Humaines (FLASH)* of University of Abomey-Calavi, Campus of Porto-Novo before joining *Faculté des Sciences Agronomiques* in the main campus of the same university in 2003 for agricultural studies. In this school, he obtained successively a Bachelor of Science degree in Agronomy (Diplôme d'Agronomie Générale) in 2007, an Agronomist Engineer Degree (Diplôme d'Ingénieur Agronome) with focus on natural resources management in 2008 and a Master of Science (Diplôme d'Etudes Approfondies) in the same subject in 2010.

After graduation, he worked from February 2010 to July 2012 with the company *Denrées et Fournitures Agricoles* in Cotonou as Responsible of technical framing with frequent activities in the northern part of the country. In July 2012, he got a scholarship from the West African Service Centre on Climate Change and adapted Land use (WASCAL) to conduct the current PhD research activity within the Graduate Research Programme Climate Change and Biodiversity, University Félix Houphouët-Boigny, Côte d'Ivoire. His ambition is to contribute to the understanding of mechanisms developed by plant species to adapt to threats like climate variability and change, and also to foster conservation and domestication strategies of indigenous agroforestry species.

His institutional address in Benin is: Laboratoire de Biomathématiques et d'Estimations Forestières (LABEF), Faculté des Sciences Agronomiques, Université d'Abomey-Calavi, 04 BP 1525 Cotonou, Bénin. E-mail: achille.hounkpevi@labef-uac.org ; hounkpeviachille@gmail.com.

Appendix 13: List of published manuscripts and oral communications

Manuscripts from the thesis

1. **Hounkpèvi, A**., Azihou, A. F., Kouassi, K. E., Porembski, S. & Glèlè Kakaï, R. (2016) Climate-induced morphological variation of black plum (*Vitex doniana* Sw.) in Benin, West Africa. ***Genetic Resources and Crop Evolution*** 63(6): 1073-1084. DOI: 10.1007/s10722-016-0409-9.
2. **Hounkpèvi, A.**, Tosso, F., Gbèmavo, D. S. J. C., Kouassi, E. K., Koné, D. & Glèlè Kakaï, R. (2016). Climate and potential habitat suitability for cultivation and in situ conservation of the black plum (*Vitex doniana* Sweet) in Benin, West Africa. ***International Journal of Agronomy and Agricultural Research*** 8(4): 67-80.

Communications

Hounkpèvi, A., Kouassi, E. K., Koné, D. & Glèlè Kakaï R. 2016. Impacts of climate change on the potential habitat suitability for cultivation and conservation of the black plum (*Vitex doniana* Sweet) in Benin. Abstracts book of the first edition of the International congress of *Association Ivoirienne des Sciences Agronomiques (AISA)*, Yamoussoukro-Côte d'Ivoire, 16-20 February 2016.

Other manuscripts

1. **Hounkpèvi, A**., Yèvidé, A. S. I., Ganglo, C. J., Devineau, J.-L., Azontondé, A. H., Adjakidjè, V., Agbossou, E. K. & De Foucault, B., 2011. Structure et écologie de la forêt à *Diospyros mespiliformis* Hochst. ex A. DC. et à *Dialium guineense* Willd. de la réserve de Massi (La Lama), Bénin. *Bois et Forêts des Tropiques* n°308 (2): 33 – 46.

MANUSCRIPT 1

Hounkpèvi, A., Azihou, A. F., Kouassi, K. E., Porembski, S. & Glèlè Kakaï, R. (2016) Climate-induced morphological variation of black plum (*Vitex doniana* Sw.) in Benin, West Africa. **Genetic Resources and Crop Evolution 63(6):1073-1084.** DOI: 10.1007/s10722-016-0409-9.

Genet Resour Crop Evol (2016) 63:1073–1084
DOI 10.1007/s10722-016-0409-9

NOTES ON NEGLECTED AND UNDERUTILIZED CROPS

Climate-induced morphological variation of black plum (*Vitex doniana* Sw.) in Benin, West Africa

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Abstract There are evidences that plant morphology is shaped by genotype, but local environment mainly climate influences morphology as well. In this study the morphological variability of *Vitex doniana*, a multipurpose tree species was characterised in relation with climatic parameters in order to provide insights to the species possible responses to future climate change. Morphological data were collected on 102 trees randomly selected along unfixed transects in the three climatic zones of Benin. Data were collected on fruiting trees at three levels: tree (trunk and canopy), leaves and fruits. Variance components were estimated for identification of variability sources regarding leaves and fruits characteristics. The most important discriminant descriptors regarding climatic zones were selected through a stepwise discriminant analysis. Relationship between those discriminant morphological traits and bioclimatic variables were assessed through a redundancy analysis. Our findings confirmed that there is an important variability of morphological traits of the species and climate, mainly some of its extremes parameters plays a non-negligible role. Trees in the Sudanian region are the biggest with fruits producing little pulp while individuals in the more humid Guinean region present a higher amount of pulp whereas Sudano-Guinean trees are the tallest with larger leaves. Although the climate-induced variability of the species is relatively low, the study gives insights in probable effects of climate

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variability on its morphology. Population genetic studies are required for a better understanding of climatic impacts on *V. doniana* in order to develop selection and domestication schemes which could contribute to its conservation.

Keywords Agroforestry species · Benin · Bioclimatic variables · Plant morphology · Savannah · *Vitex doniana*

Introduction

Morphological variability reflecting general intraspecific genetic variability occurs in most plant species as response to local environmental fluctuations (Ellison et al. 2004; Miner et al. 2005). This variability is an essential component of plant fitness and a precondition to adapt to various environments and is also the basis for selection by humans for domestication purposes (Cornelius 1994; Ellison et al. 2004; Ewédjè et al. 2012). There are evidences that plant morphology is shaped by genotype, but local environment mainly climate can play an important role too (Schlichting and Pigliucci 1998; Ellison et al. 2004; Guerin et al. 2012). It is therefore important to evaluate this variability in order to sustainably manage useful plant species and give insights into probable effects of unpredictable hazards like climate change.

Our study focused on *Vitex doniana* Sweet, an important agroforestry tree species widespread in tropical Africa. Different parts of the plant are widely used for several purposes among which are young leaves for sauces preparation and ripened fruits for direct consumption being most common among people in its geographical range (Ky 2008). The mature leaves, the bark and the roots are also used to treat several diseases (Kilani 2006; Padmalatha et al. 2009; Dadjo et al. 2012). Moreover, it presents some agronomic potentialities regarding soil fertility improvement through litter production (Mapongmetsem et al. 2005). In Benin, *V. doniana* is known as a particular agroforestry tree with high socio-economic values (Oumorou et al. 2010; Achigan-Dako et al. 2011; Dadjo et al. 2012).

Some studies have addressed its uses in pharmacology (Kilani 2006; Padmalatha et al. 2009) and in food processing (Okigbo 2003; Agbédé and Ibitoyé 2007), its ethnobotanical values (Dadjo et al. 2012), domestication status and germinative abilities (Sanoussi et al. 2012; Achigan-Dako et al. 2014; N'Danikou et al. 2014). However, little is known on its morphological variability and the relationship between this variability and climatic conditions.

Following the concept of phenotypic plasticity—capacity of a given genotype to produce physiological or morphological phenotypes in response to variations of environmental conditions (Pigliucci 2006)—we expect that *V. doniana* develops specific morphological traits according to climatic zones in Benin. More specifically, since the three climatic zones of Benin reflect a south-north climate drying gradient (wet–dry) coupled with an opening of the vegetation (forest–savannah), we hypothesize that (1) due to the availability of water and competition for light, trees of the Guinean zone are higher, thinner, with the best fruiting performance and larger leaves (lower evapotranspiration); (2) in contrast, trees of the Sudanian zone are shorter, thicker, with wider canopy, smaller leaves (adaptation to higher evapotranspiration) and lower fruiting performance; (3) trees in the Sudano-Guinean zone are assumed to have intermediate characteristics.

Therefore, we characterized the morphological variability of the species in relation with climatic conditions in order to provide relevant information on its probable responses to future climate change.

Materials and methods

Target species and study area

The black plum (*Vitex doniana* Sweet, Lamiaceae formerly Verbenaceae) is a deciduous plant species widespread in tropical Africa, from Senegal to Somalia and to South Africa, and also in Comoros and Seychelles (Ky 2008; Orwa et al. 2009). It is occasionally cultivated in Mauritius. The species occurs in various habitats from forests to savannahs, often in wet localities and along rivers, and on termite mounds, up to 2000 m altitude. Regions with mean annual rainfall between 750–2000 mm and temperatures ranging from 10 to 30 °C are suitable for the species (Ky 2008). The variability of *V. doniana* is remarkable regarding its morphology as well as its habitat choice. It is a deciduous small to medium sized tree species up to 25 m, bole branchless for up to 11 m with a diameter which can reach 160 cm. It has opposite and digitate compound leaves. The flowers are bisexual and zygomorphic and the fruits obovoid to oblong-ellipsoid drupes (2–3 cm long), purplish black, fleshy, with woody 4-celled stone, up to 4-seeded (Arbonnier 2002; Ky 2008) .

The study was carried out in the three climatic zones of Benin Republic in West Africa (Fig. 1). The Guinean zone located between 6°25′ and 7°30′N is characterised by a subequatorial climate with four seasons (two rainy and two dry). The rainfall is bimodal (averagely 1200 mm per year), the temperature varies between 25 and 29 °C, and relative humidity is between 69 and 97 %. The Sudano-Guinean zone, from 7°30′ to 9°45′N, is a transitional zone with two rainy seasons merging in a unimodal regime. The annual rainfall varies between 900 and 1110 mm, the temperature is between 25 and 29 °C and relative humidity ranges from 31 to 98 %. The Sudanian zone, between 9°45′ to 12°25′N, has a tropical dry climate with two equally long seasons (rainy and dry). The mean annual rainfall in this zone is often <1000 mm; the relative humidity varies from 18 to 99 % and temperature from 24 to 31 °C (Adomou et al. 2006; Assogbadjo et al. 2012; Gnanglè et al. 2012).

Data collection

Morphological data were collected from July to October 2014 in the three climatic zones following unfixed transects (length varying from 1 to 6 km). Seven, six and nine transects were followed respectively in the Guinean, Sudano-Guinean and Sudanian zone. A distance of at least 20 m was left between fruiting trees in order to avoid genetically close individuals. A total of 102 fruiting individuals of *V. doniana* were assessed (35, 31, and 36 respectively in the Guinean, Sudano-Guinean and Sudanian zone). Ten leaves and ten fruits were randomly selected per tree (Cornelissen et al. 2003) for morphological description. Moreover, data were collected on the trunk, the canopy, the leaves and the fruits in the field (Fig. 2). On the trunk, circumference at 1.3 m (*circ*, cm), total height (*htree*, m) and bole height (*hbole*, m) i.e. height from ground to the first big branch were measured. Concerning the canopy, four radii (r_i) were measured from the projection of the crown on the ground (Fig. 2a). For the leaves, leaf length (*Llgth*, mm), length and width of the main leaflet (*llgth* and *lwdth*, mm), petiole length and diameter (*petlgth* and *petdiam*, mm) and number of leaflets (*lnumb*) were noted (Fig. 2b). For the fruits, length and width of fruit (*flgth* and *fwdth*, mm) and fruit fresh mass (*ffmass*, g) were measured (Fig. 2c).

These parameters were measured with an electronic digital calliper (0.01 mm resolution) for length and width and a 0.01 g-precision scale for weight.

After measuring the above described parameters, fruits were oven dried at 65 °C for 48 h for determination of their dry mass (*fdmass*, g) following Fandohan et al. (2011). The pulp and fibres have been removed from the dry fruits in order to have the endocarp for which length (*endolgth*, mm), width (*endowdth*, mm) and mass (*endomass*, g) were measured.

Finally, the GPS coordinates of each tree were recorded and used in QGIS 1.8.0 (Quantum Development Team 2016) to extract bioclimatic data for each tree from WorldClim 2.5′ × 2.5′ database (Hijmans et al. 2005).

Data processing and analysis

From the measured parameters, the following variables were computed:

- Mean diameter of canopy (*dcrown*, m): It was computed from the four measured radii (r_i, i from 1 to 4) using the following formula (Glèlè Kakaï et al. 2011):

$$dcrown = 2\sqrt{\sum \frac{r_i^2}{4}} \quad (1)$$

- Height of canopy (*hcrown*, m): It is the difference between total height and bole height

$$hcrown = htree - hbole \quad (2)$$

- Canopy shape (*shcrown*): It is the ratio of height of canopy over mean diameter of canopy

$$shcrown = \frac{hcrown}{dcrown} \quad (3)$$

- Pulp Thickness (*pulpthick*, mm): It is the difference between fruit width and endocarp width divided by 2.

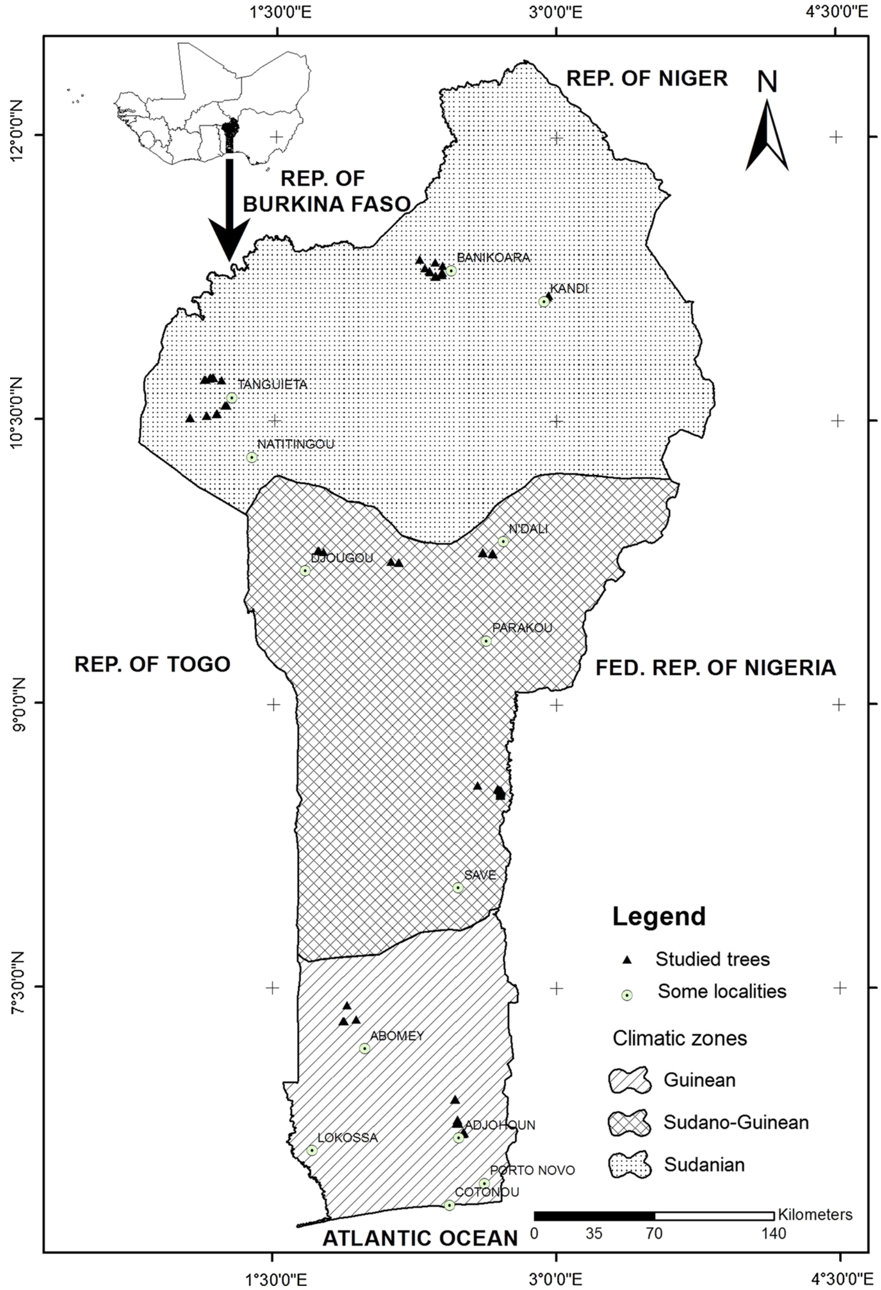

Fig. 1 Location of sampled trees in Benin Republic. Climatic zones (from South to North: Guinean, Sudano-Guinean and Sudanian zone) are adapted from Adomou et al. (2006)

$$pulpthick = \frac{(fwdth - endowdth)}{2} \quad (4)$$

- Pulp mass (*pulpmass*, g): It is the difference between dry mass of fruit and endocarp mass

$$pulpmass = fdwght - endowght \quad (5)$$

- Fruit shape (*fshape*): It is the ratio of fruit length over fruit width

$$fshape = \frac{flgth}{fwdth} \quad (6)$$

- Endocarp shape (*endshape*): It is the ratio of endocarp length over endocarp width

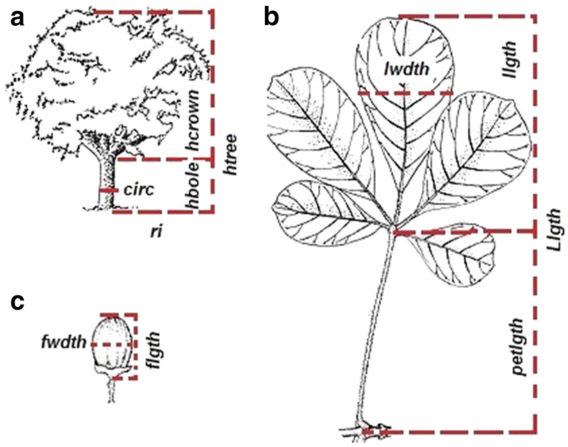

Fig. 2 Morphological descriptors measured on *V. doniana* (adapted from Ky (2008)). **a** Tree: circumference at 1.3 m (*circ*, cm); total height (*htree*, m); bole height (*hbole*, m) and crown height (*hcrown*, m) and crown radii (r_i, m). **b** Leaf: leaf length (*Llgth*, mm), length and width of the main leaflet (*llgth* and *lwdth*, mm), petiole length (*petlgth*, mm). **c** Fruit: length and width of fruit (*flgth* and *fwdth*, mm)

$$endshape = \frac{endolgth}{endowdth} \quad (7)$$

Mean values, standard error of mean and coefficient of variation were computed for trunk and canopy traits per climatic zone. The same descriptive statistics were calculated for each morphological parameter of leaves and fruits per climatic zone taking into account variation in fruits/leaves by using the two-stage sampling formulas of Cochran (1977). The skewness was also calculated for each morphological trait to appreciate normality of its distribution within climatic zone. One way-ANOVA was used to test for differences in trunk/canopy morphological traits between climatic zones. The analysis was performed on log transformed data except for crown diameter in order to meet normality and homogeneity of variance assumptions. Student-Newman-Keuls' posthoc test was used to classify mean values of those morphological traits. Meanwhile, linear mixed effects models using the restricted maximum likelihood (REML) from lme4 (Bates et al. 2015) and lmerTest packages (Kuznetsova et al. 2014) were performed on leaves and fruits morphological traits for the same comparison purpose and to estimate the part of their variability explained by between-climatic zone effect and within-climatic zone effect (tree-within climatic zone, tree-within transect and within-tree effects). Since sample sizes (number of transects per climatic zone, number of trees considered per climatic zone and per transect) were unequal, Satterthwaite approximation was used as correction formula for the degrees of freedom in order to have accurate *P* values (Mason et al. 2003). Tukey's contrasts for multiple comparisons of means from multcomp package (Hothorn et al. 2008) was used for means classification (Mangiafico 2015). For these linear mixed effects models, climatic zone with its three modalities (Guinean, Sudano-Guinean and Sudanian) was considered as fixed factor while transect (7, 6 and 9 respectively in the Guinean, Sudano-Guinean and Sudanian zones) and fruiting tree (from which ten leaves/fruits were measured) were considered as nested factors.

A stepwise linear discriminant analysis was performed in order to find out the most important morphological traits that discriminate trees regarding climatic zones. For this analysis, morphological traits at trunk and canopy levels and mean values per tree for leaves and fruits characteristics were used.

Finally, a redundancy analysis (RDA) was performed to assess relationships between morphological descriptors and bioclimatic variables. The analysis was run on the standardized means values of the previously selected discriminant morphological traits and all the 19 bioclimatic variables extracted from WorldClim database. The best model was selected by removing sequentially bioclimatic variables with the step function in Vegan package (Oksanen et al. 2013). The model selection was based on the Akaike's Information Criterion (AIC) which measures the goodness of fit, with the best model showing the small AIC (Burnham and Anderson 2003). For the selected model, significance of canonical axes was tested using the marginal permutation test from Vegan package. Moreover, the significance of each bioclimatic variables in the model was tested using the permutation ANOVA test. All these analyses were run with the vegan package (Oksanen et al. 2013).

R 3.2.2 software (R Core Team 2015) was used for the one-way ANOVA, linear mixed effects models and RDA while SPSS 20 (SPSS IBM. 2011) was used for the stepwise discriminant analysis.

Results

Morphological variability of *Vitex doniana*

Morphological descriptors of trunk and canopy show high amplitude of variation in all climatic zones with coefficients of variation above 25 % (Table 1). However, these morphological descriptors do not vary in the same way from one climatic zone to another. For instance, circumference at 1.3 m and crown diameter showed the greatest variability in the Guinean zone (CV = 48.37 %), while bole height was the most fluctuating trait in the Sudano-Guinean zone (CV = 51.21 %). The other descriptors (tree height, crown height and crown shape) were most dispersed in the Sudanian zone (Table 1). The Skewness coefficient of all these descriptors (except tree height in the Sudano-Guinean zone) was positive suggesting right asymmetrical distribution. Apart from the crown diameter, all the descriptors of trunk and canopy varied significantly between climatic zones. Trees from the Sudanian zone were the thickest while trees from the Sudano-Guinean zone were the tallest with relatively rounded crown (crown shape i.e. ratio hcrown/dcrown = 1, Table 1).

Most of the morphological descriptors of leaves and fruits were relatively less dispersed (CV <15 %) around mean values in all climatic zones (Table 2). Leaves and fruits descriptors showed the highest amplitude of variation in respectively the Guinean and Sudanian climatic zone. The Skewness coefficient was close to zero for most of the leaves and fruits features in all climatic zones suggesting a normal distribution. All the leaves and fruits descriptors varied significantly between climatic zones and the lowest values were mostly recorded in the Sudanian zone. Trees in the Sudano-Guinean zone presented slightly higher leaves characteristics, while the greatest features for fruits were mostly recorded in the Guinean zone (Table 2). In general, fruits were relatively oblong (length/width ratio was slightly above 1), but fruits from the Sudano-Guinean zone were longer than wide.

The variance components estimation revealed that the within-climatic zone effect represented the most important source of variability of leaves and fruits traits, with variation within tree being the highest (Table 3). The between climatic zones variability of leaves and fruits traits was relatively weak (<30 % of total variation). Its lowest and highest values were recorded respectively for number of leaflets per leaf (2.19 %) and endocarp mass (26.93 %). Variability in morphological traits due to climatic zone was higher for fruits characteristics than for leaves (Table 3).

Discriminant morphologic descriptors of *Vitex doniana* according to climatic zones

The stepwise discriminant analysis indicated that two significant discriminant axes were needed to separate *V. doniana* trees according to climatic zones ($P = 0.000$). The model accuracy rate revealed that 84.3 % of trees were perfectly assigned to their respective climatic zone. The Wilks'Lambda statistic ranged from 0.757 to 0.195 (first to last step) and P value was 0.000. Only 7 of the 23 descriptors were the most discriminant for climatic zone. The first axis

Table 1 Morphological descriptors of trunk and canopy of *V. doniana*

	Guinean (35 trees)			Sudano-Guinean (31 trees)			Sudanian (36 trees)		
	Mean ± SE	CV	Skew.	Mean ± SE	CV	Skew.	Mean ± SE	CV	Skew.
Circumference (cm)	115.77b ± 9.47	48.37	1.47	146.42a ± 10.84	41.21	0.42	156.14a ± 10.43	40.07	0.95
Tree height (m)	10.46b ± 0.50	28.25	0.2	15.68a ± 0.75	26.56	−0.68	9.40b ± 0.53	33.96	1.39
Bole height (m)	3.35b ± 0.19	34.08	0.46	5.98a ± 0.55	51.21	0.12	2.43c ± 0.16	39.70	1.29
Crown diameter (m)	8.50a ± 0.53	36.79	0.21	9.71a ± 0.54	30.71	0.07	8.49a ± 0.42	29.51	0.49
Crown height (m)	7.11b ± 0.43	36.06	0.53	9.70a ± 0.59	34.12	0.11	6.97b ± 0.48	41.62	1.58
Crown shape	0.87b ± 0.04	27.16	0.54	1.03a ± 0.05	28.64	0.64	0.85b ± 0.05	36.59	1.15

On the lines, values followed by the same letters are not statistically different at 0.05 (Student-Newman-Keuls test)

SE, standard error of mean; CV, coefficient of variation (%); Skew., Skewness

Table 2 Morphological descriptors of leaves and fruits of *V. doniana*

	Guinean (350)			Sudano-Guinean (310)			Sudanian (360)		
	Mean ± SE	CV	Skew	Mean ± SE	CV	Skew	Mean ± SE	CV	Skew
Leaf length (mm)	268.33b ± 11.85	13.96	−0.10	289.84a ± 7.77	8.50	0.09	244.02c ± 10.47	13.36	0.11
Petiole length (mm)	115.62b ± 6.09	16.72	−0.12	131.38a ± 4.09	10.11	−0.05	108.37c ± 5.48	15.91	0.11
Petiole diameter (mm)	7.50a ± 0.31	12.86	0.08	6.93b ± 0.23	10.35	0.07	6.94b ± 0.28	12.35	0.22
Leaflet length (mm)	152.71b ± 6.72	13.70	−0.01	158.46a ± 4.75	9.41	0.00	135.64c ± 6.09	13.84	0.04
Leaflet width (mm)	65.61a ± 3.11	14.97	0.05	65.43a ± 2.03	9.71	−0.01	60.68b ± 2.97	15.23	0.10
Number of leaflets	5.02ab ± 0.05	3.17	0.11	5.07a ± 0.09	5.82	0.66	4.98b ± 0.03	1.85	−1.11
Fruit length (mm)	24.81a ± 0.50	6.46	−0.20	24.87a ± 0.38	4.86	0.07	23.83b ± 0.43	5.67	−0.09
Fruit width (mm)	23.40a ± 0.46	6.21	−0.21	22.70b ± 0.33	4.66	−0.01	22.86b ± 0.44	6.03	−0.23
Fruit shape (length/width)	1.07b ± 0.01	3.81	0.09	1.10a ± 0.01	3.90	0.11	1.05b ± 0.01	4.10	0.21
Fruit fresh mass (g)	9.14a ± 0.43	15.19	−0.08	7.86b ± 0.26	11.20	0.04	7.50b ± 0.39	16.14	−0.11
Fruit dry mass (g)	3.73a ± 0.21	17.74	0.04	2.83b ± 0.11	13.56	0.22	2.46c ± 0.14	18.35	0.03
Endocarp length (mm)	17.07b ± 0.31	5.74	−0.24	17.30a ± 0.25	4.59	0.08	16.07c ± 0.32	6.31	0.03
Endocarp width (mm)	12.17a ± 0.81	6.52	0.03	12.15a ± 0.22	5.83	−0.11	11.58b ± 0.25	6.58	0.01
Endocarp shape (length/width)	1.43ab ± 0.02	5.52	−0.05	1.44a ± 0.03	5.94	0.10	1.40b ± 0.03	6.59	0.19
Endocarp mass (g)	1.76a ± 0.10	17.34	−0.10	1.47b ± 0.07	16.53	0.11	1.17c ± 0.06	16.80	−0.01
Pulp thickness (mm)	5.62a ± 0.16	9.08	0.04	5.28b ± 0.11	6.78	−0.30	5.64a ± 0.16	8.79	−0.08
Pulp mass (mm)	1.97a ± 0.15	22.72	0.12	1.37b ± 0.06	14.37	−0.07	1.29b ± 0.09	22.45	0.13

On the lines, values followed by the same letters are not statistically different at 0.05 (Tukey's contrasts test for multiple comparisons of means)

SE, standard error of mean; CV, coefficient of variation (%); Skew, Skewness

explaining 85.5 % of the total variance discriminated trees based on tree height, canopy height, leaf length and number of leaflets. This axis separated Sudano-Guinean trees from the others. The second axis accounting for 14.5 % of total variance performed trees discrimination based on circumference, petiole diameter and pulp mass. It discriminated Guinean trees from Sudanian trees (Fig. 3).

Trees from the Sudano-Guinean zone were taller with higher canopy. They exhibited longer leaves with often more than 5 leaflets per leaf whereas those from the Sudanian zone were thicker (high circumference values) with relatively small petiole diameter for leaves and produced fruits with reduced pulp mass. Guinean trees thus diverged from the Sudanian counterparts.

Relationships between discriminant morphological descriptors and bioclimatic variables

From the redundancy analysis, the best model explaining the relationships between the discriminant morphological descriptors of *V. doniana* and bioclimatic variables took into account 8 of the 19 bioclimatic variables ($F = 7.095$, P value $= 0.001$, $AIC = 842.4$, adjusted $R^2 = 0.326$). Only the first two axes were significant (P value $= 0.001$) and they explained 37.9 % of the total variation in morphological traits due to the bioclimatic variables. The first axis (RDA1) explaining 32.05 % of total variance, was a linear combination of annual mean diurnal range of temperature (bio2), isothermality (bio3), temperature seasonality (bio4), precipitation seasonality (bio15), and mean temperature of the coldest quarter (bio11). The second axis (RDA2, 0.06 % of total variation) on the other hand, was a linear combination of annual precipitation (bio12), precipitation of the warmest quarter (bio18) and mean temperature of the warmest quarter (bio10). However some of these bioclimatic variables such as annual precipitation and mean temperature of the coldest quarter were not statistically significant in the model (Table 4).

Regarding the discriminant morphological variables, circumference at 1.3 m, tree height, crown

Table 3 Variance components for leaves and fruits characteristics (percentage) from mixed effects model fit by restricted maximum likelihood (REML)

	Source of variation				
	Among climatic zones	Within-Climatic zone			Total
		Trees within climatic zone	Trees within transect	Within trees (error)	
Leaf length (cm)	22.57	12.13	5.69	59.60	100
Petiole length (mm)	22.63	14.57	0.21	62.58	100
Petiole diameter (mm)	18.12	16.40	8.13	57.35	100
Leaflet length (mm)	21.11	11.81	13.49	53.59	100
Leaflet width (mm)	17.54	21.18	7.28	54.01	100
Number of leaflets	2.19	1.93	0.00	95.88	100
Fruit length (mm)	20.23	20.49	4.34	54.94	100
Fruit width (mm)	22.89	12.45	19.58	45.08	100
Fruit shape	23.61	15.03	20.31	41.06	100
Fruit fresh mass (g)	25.46	19.84	7.66	47.04	100
Fruit dry mass (g)	22.54	24.76	26.56	26.14	100
Pulp thickness (mm)	21.15	10.14	33.73	34.98	100
Pulp mass (g)	18.37	20.28	39.27	22.08	100
Endocarp length (mm)	26.63	22.64	7.92	42.81	100
Endocarp width (mm)	20.73	19.25	14.79	45.23	100
Endocarp shape	19.67	22.22	6.79	51.32	100
Endocarp mass (g)	26.93	25.95	7.09	40.03	100

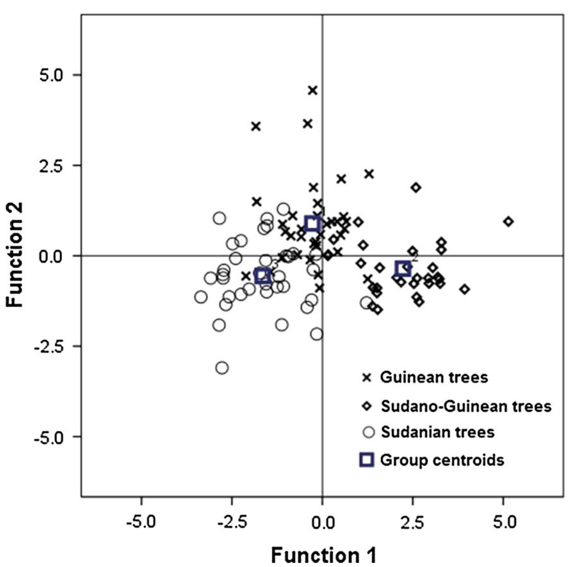

Fig. 3 Projection of *V. doniana* trees regarding morphological traits in the system defined by the two canonical functions. Function 1 and 2 represent respectively 85.5 and 14.5 % of the total variance of 23 descriptors on 102 individuals. Symbols correspond to trees from each climatic zone of Benin (*Circles* Sudanian trees, *Lozenges* Sudano-Guinean trees, *Crosses* Guinean trees, *Squares* centroid of each group)

height, leaf length, petiole diameter and pulp mass were loaded on RDA1, while number of leaflets was loaded on RDA2 (Table 5).

Based on scores of morphological traits and bioclimatic variables on RDA axes (Tables 4, 5), it was noted that circumference at 1.3 m, tree height, crown height, leaf length and petiole diameter were positively influenced by annual mean diurnal range of temperature (bio2), temperature seasonality (bio4) and precipitation seasonality (bio15). Meanwhile, pulp mass and number of leaflets were negatively affected respectively by isothermality (bio3) and mean temperature of the warmest quarter (bio10). The projection of *V. doniana* trees in the RDA axes system showed that Guinean trees were mainly located on the negative side of RDA1 and RDA2 while Sudanian trees were mainly in the positive side of RDA2 (Fig. 4). The morphology of trees from these zones was likely affected by bioclimatic parameters in diverse way.

There were no direct significant effects of the commonly used climatic parameters such as annual mean temperature and precipitation on morphological

Table 4 Significance of bioclimatic variables from permutation ANOVA test and scores on RDA axes

Bioclimatic variables	Permutation ANOVA				Scores on axes	
	Df	Variance	F	Pr (>F)	RDA1	RDA2
Annual mean diurnal range of temperature (bio2)	1	389.1	11.069	0.001***	0.45	−0.42
Isothermality (bio3)	1	153.2	4.360	0.021*	−0.51	0.48
Temperature seasonality (bio4)	1	145.3	4.133	0.029*	0.42	−0.33
Mean temperature of warmest quarter (bio10)	1	576.2	16.391	0.001***	−0.003	−0.14
Mean temperature of coldest quarter (bio11)	1	39.1	1.113	0.325 ns	−0.52	0.16
Annual precipitation (bio12)	1	17.2	0.488	0.577 ns	-0.13	0.32
Precipitation seasonality (bio15)	1	112.5	3.200	0.043*	0.39	−0.27
Precipitation of warmest quarter (bio18)	1	562.5	16.003	0.001***	−0.19	0.33
Residual	93	3268.9				

ns non-significant

* *P* value <0.05; *** *P* value <0.001

Table 5 Scores of discriminant morphological traits on RDA axes

	RDA1 (32.05 %)	RDA2 (0.06 %)
Circumference at 1.3 m	13.720	2.867
Tree height	0.846	−0.368
Crown height	0.594	−0.178
Leaf length	6.652	−5.851
Petiole diameter	0.089	0.013
Number of leaflets	0.002	−0.006
Pulp mass	−0.055	0.034

traits of *V. doniana*. However, several bioclimatic variables based on their extremes such as temperature/precipitation of the warmest quarter and other related parameters showed significant influences on the morphological descriptors (Table 4).

Discussion

In the present study, we investigated the morphological diversity of *V. doniana* in relation to climate in order to highlight probable effects of climate change on the species. The morphological description was performed at three levels: tree (trunk and canopy), leaf and fruit. Findings from the study confirmed that there is an important variability of morphological traits in the species and climate plays a non-negligible role.

The relatively important dispersion of morphological descriptors around mean values (Tables 1, 2) gives evidences of the existence of heterogeneity in *V. doniana* populations as mentioned by Ky (2008). This heterogeneity can be seen as a result of fitness of the species in various habitats and can increase its survival chance under climate change (Visser 2008). Moreover, the existence of this variability strengthens the potential of the species in cultivars selection for a domestication process (Leakey et al. 2008; Fandohan et al. 2011). Indeed, genetic diversity improves fitness of populations by providing options to respond differently to environmental changes (Whitham et al. 2003; Hughes and Stachowicz 2004).

Significant differences were observed between climatic zones regarding the considered morphological traits, but part of variability due to climatic zone was relatively low and the most important variability was generally recorded at individual tree level (Table 3). These findings are in agreement with previous studies on native and introduced plant species in Benin such as *Adansonia digitata* L. (Assogbadjo et al. 2011), *Jatropha curcas* L. (Gbèmavo et al. 2015), *Sclerocarya birrea* subsp. *birrea* (A. Rich) Hochst. (Gouwakinnou et al. 2011). Since morphology is under the control of genotype, environment and their interactions, with genotype leading the control (Schlichting and Pigliucci 1998), our findings show that most of the variability in *V. doniana* was probably genetically-induced. Therefore, population genetic studies about this species are required to deepen knowledge on its gene pool in relation with climatic parameters.

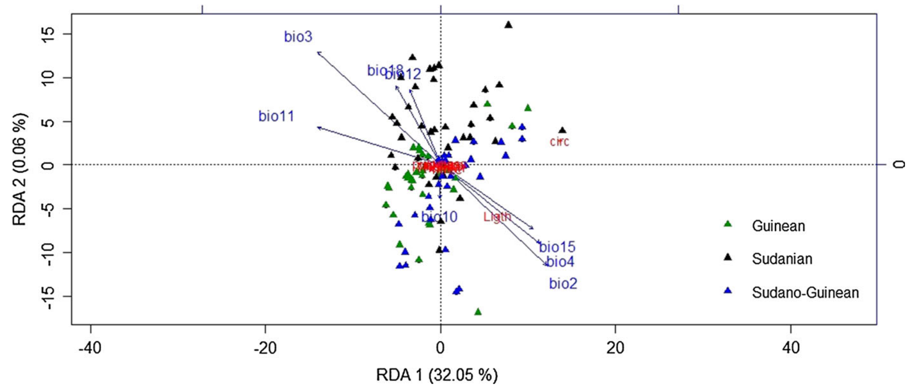

Fig. 4 Projection of *V. doniana* trees in the RDA correlation triplot (scaling = 2) defined by the two first axes. Trees are represented by triangles (green, blue and black for respectively Guinean, Sudano-Guinean and Sudanian trees). Bioclimatic variables are represented by arrows (bio 2 = Annual mean diurnal range of temperature; bio 3 = Isothermality; bio 4 = Temperature seasonality; bio 10 = Mean temperature of the warmest quarter; bio 11 = mean temperature of the coldest quarter; bio 12 = Annual precipitation; bio 15 = Precipitation seasonality; bio 18 = Precipitation of the warmest quarter). Morphological variables (*circ* circumference, *htree* total height of tree, *hcrown* crown height, *Llgth* leaf length, *petdiam* petiole diameter, *lnumb* number of leaflets, *pulpmass* pulp mass)

Although the projection of *V. doniana* trees in the axes system defined by the two canonical functions from the discriminant analysis did not show a clear separation of trees (Fig. 3), the major differences between trees were revealed regarding position of group centroids. Based on contrasting features of Guinean and Sudanian trees (heavy vs. light pulp mass for example), climate may be considered as playing an important role in the morphological variability of the species. Indeed, the Guinean zone known to be wetter and more forested than the Sudanian zone, hosted thinner and taller trees with globally larger leaves and higher fruiting parameters mainly regarding fruits and pulp masses. These results confirmed our expectations and may suggest that the species undergoes adaptive strategies in regard to climatic factors. According to trees in the Sudano-Guinean zone, our findings showed some deviation from the expected trends. Trees are generally taller with larger leaves in this zone than elsewhere. These trends might suggest that this climatic zone is very close to the humid climatic conditions. Previous studies have already highlighted the role of climate for the morphological variation of several useful species. This was the case for instance for *Anogeissus leiocarpa* (DC.) Guill. et Perr. in Burkina Faso (Ouédraogo et al. 2013).

The redundancy analysis revealed significant relationships between bioclimatic parameters and discriminant morphological descriptors of *V. doniana*. Although the bioclimatic parameters explained a relatively low part of variation in morphological traits, impacts of climate on the species' morphology are obvious even if there might not be strong. This relatively weak influence of the bioclimatic variables on morphological descriptors emphasized findings on low variability due to climate. Also, the low influence of bioclimatic parameters might be due to the fact that climate is not the only factor affecting the morphology of the species. Indeed, environmental factors like topography, soil properties (type, moisture, nutrients content) have been reported as potential predictors (Sankaran et al. 2005). Since soil types and properties varied significantly across climatic zones of Benin (Adomou et al. 2006), soil may have contributed to the morphological variation of *V. doniana* in Benin. The study also revealed that mean annual temperature and rainfall do not have direct impacts on the discriminant descriptors, but rather their extremes (temperature and precipitation of the warmest quarter) and other related parameters such as annual diurnal range of temperature, temperature and precipitation seasonality that drive the plant's morphological diversity.

Conclusion

In the present study, we investigated the morphological diversity of *V. doniana* in relation with climate in order to highlight probable effects of climate change on the species. The morphological description was performed at three levels: tree (trunk and canopy), leaves and fruits. The study revealed that *V. doniana* shows an important morphological variability and that climate contributes somehow to its morphological diversity in Benin. Moreover, our findings suggest that extreme parameters of a changing climate in the future could affect the morphology of the species. However, population genetic studies should be undertaken on the species in order to improve knowledge on its variability in relation with climate and help in developing selection and domestication schemes for the species. Finally, conservation programs should be envisaged for the species by taking into account this morphological variability.

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Compliance with ethical standards

Conflict of interest We declare that there is no conflict of interest.

References

Achigan-Dako EG, N'Danikou S, Assogba-Komlan F, Ambrose-Oji B, Ahanchédé A, Pasquini MW (2011) Diversity, geographical, and consumption patterns of traditional vegetables in sociolinguistic communities in Benin: implications for domestication and utilization. Econ Bot 65(2):129–145

Achigan-Dako EG, N'Danikou S, Tchokponhoué DA, Komlan FA, Larwanou M, Vodouhè RS, Ahanchédé A (2014) Sustainable use and conservation of *Vitex doniana* Sweet: unlocking the propagation ability using stem cuttings. J Agric Environ Int Dev 108(1):43–62

Adomou AC, Sinsin B, Van der Maesen LJG (2006) Phytosociological and chorological approaches to phytogeography: a meso-scale study in Benin. Syst Geogr Plants 76(2):155–178

Agbédé JO, Ibitoyé AA (2007) Chemical composition of black plum (*Vitex doniana*): an under-utilized fruit. J Food Agric Environ 5(2):95–96

Arbonnier M (2002) Arbres, arbustes et lianes des zones sèches d'Afrique de l'Ouest, 2nd edn. Editions Quae, France

Assogbadjo AE, Glèlè Kakaï R, Edon S, Kyndt T, Sinsin B (2011) Natural variation in fruit characteristics, seed germination and seedling growth of *Adansonia digitata* L. Benin. New For 41(1):113–125. doi:10.1007/s11056-010-9214-z

Assogbadjo AE, Chadaré FJ, Glèlè Kakaï R, Fandohan B, Baidu-Forson JJ (2012) Variation in biochemical composition of baobab (*Adansonia digitata*) pulp, leaves and seeds in relation to soil types and tree provenances. Agric Ecosyst Environ 157:94–99. doi:10.1016/j.agee.2012.01.021

Bates D, Maechler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models using lme4. J Stat Softw 67(1):1–48. doi:10.18637/jss.v067.i01

Burnham KP, Anderson DR (2003) Model selection and multimodel inference: a practical information-theoretic approach. Springer, New York

Cochran WG (1977) Sampling techniques, 3rd edn. Wiley, New York

Cornelissen JHC, Lavorel S, Garnier E, Diaz S, Buchmann N, Gurvich DE, Reich PB, Ter Steege H, Morgan HD, Van Der Heijden MGA et al (2003) A handbook of protocols for standardised and easy measurement of plant functional traits worldwide. Aust J Bot 51(4):335–380

Cornelius J (1994) The effectiveness of plus-tree selection for yield. For Ecol Manag 67(1):23–34

Dadjo C, Assogbadjo AE, Fandohan B, Glèlè Kakaï R, Chakeredza S, Houehanou TD, Damme PV, Sinsin B (2012) Uses and management of black plum (*Vitex doniana* Sweet) in Southern Benin. Fruits 67(4):239–248. doi:10.1051/fruits/2012017

Ellison AM, Buckley HL, Miller TE, Gotelli NJ (2004) Morphological variation in *Sarracenia purpurea* (Sarraceniaceae): geographic, environmental and taxonomic correlates. Am J Bot 91(11):1930–1935

Ewédjè E-EBK, Parmentier I, Natta A, Ahanchédé A, Hardy OJ (2012) Morphological variability of the tallow tree, *Pentadesma butyracea* Sabine (Clusiaceae), in Benin. Genet Resour Crop Evol 59:625–633. doi:10.1007/s10722-012-9802-1

Fandohan B, Assogbadjo AE, Glèlè Kakaï R, Kyndt T, Sinsin B (2011) Quantitative morphological descriptors confirm traditionally classified morphotypes of *Tamarindus indica* L. fruits. Genet Resour Crop Evol 58(2):299–309. doi:10.1007/s10722-010-9575-3

Gbèmavo CJ, Gandji K, Gnanglè CP, Assogbadjo AE, Glèlè Kakaï RL (2015) Variabilité morphologiques et conservation des morphotypes de *Jatropha curcas* Linn. (Euphoriaceae) au Benin. J Agric Environ Int Dev 109(1):55–69. doi:10.12895/jaeid.20151.234

Glèlè Kakaï R, Akpona T, Assogbadjo AE, Gaoué OG, Chakeredza S, Gnanglè PC, Mensah GA, Sinsin B (2011) Ecological adaptation of the shea butter tree (*Vitellaria paradoxa* CF Gaertn.) along climatic gradient in Bénin, West Africa. Afr J Ecol 49(4):440–449

Gnanglè PC, Egah J, Baco MN, Gbèmavo CDSJ, Glèlè Kakaï R, Sokpon N (2012) Perceptions locales du changement climatique et mesures d'adaptation dans la gestion des parcs à karité au Nord-Bénin. Int J Biol Chem Sci. doi:10.4314/ijbcs.v6i1.13

Gouwakinnou GN, Assogbadjo AE, Lykke AM, Sinsin B (2011) Phenotypic variations in fruits and selection potential in *Sclerocarya birrea* subsp. *birrea*. Sci Hortic 129(4):777–783. doi:10.1016/j.scienta.2011.05.041

Guerin GR, Wen H, Lowe AJ (2012) Leaf morphology shift linked to climate change. Biol Lett 8(5):882–886. doi:10.1098/rsbl.2012.0458

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A et al (2005) Very high resolution interpolated climate surfaces for global land areas. Int J Climatol 25(15):1965–1978

Hothorn T, Bretz F, Westfall P (2008) Simultaneous inference in general parametric models. Biom J 50(3):346–363. doi:10.1002/bimj.200810425

Hughes AR, Stachowicz JJ (2004) Genetic diversity enhances the resistance of a seagrass ecosystem to disturbance. Proc Natl Acad Sci USA 101(24):8998–9002

Kilani AM (2006) Antibacterial assessment of whole stem bark of *Vitex doniana* against some enterobactriaceae. Afr J Biotechnol 5(10):958–959

Kuznetsova A, Brockhoff PB, Christensen RHB (2014) lmerTest: tests in linear mixed effects models. R package Version 2.0-20. https://cran.r-project.org/web/packages/lmertest/lmertest.pdf

Ky KJM (2008) *Vitex doniana* sweet. In: Louppe D, Oteng-Amoako AA, Brink M (eds) Prota: Timbers/Bois d'oeuvre, vol 7(1). Backhuys Publishers, Leiden, pp 578–581

Leakey R, Fuller S, Treloar T, Stevenson L, Hunter D, Nevenimo T, Binifa J, Moxon J (2008) Characterization of tree-to-tree variation in morphological, nutritional and medicinal properties of *Canarium indicum* nuts. Agrofor Syst 73(1):77–87

Mangiafico SS (2015) An R companion for the handbook of biological statistics, version 1.09i. Rutgers Cooperative Extension, New Brunswick

Mapongmetsem PM, Benoit LB, Nkongmeneck BA, Ngassoum MB, Gübbük H, Baye-Niwah C, Longmou J (2005) Litterfall, decomposition and nutrients release in *Vitex doniana* Sweet. and *Vitex madiensis* Oliv. in the Sudano–Guinea Savannah. Akdeniz Üniv Ziraat Fak Derg 18(1):63–75

Mason RL, Gunst RF, Hess JL (2003) Statistical design and analysis of experiments: with applications to engineering and science, vol 474, 2nd edn. Wiley, Hoboken

Miner BG, Sultan SE, Morgan SG, Padilla DK, Relyea RA (2005) Ecological consequences of phenotypic plasticity. Trends Ecol Evol 20(12):685–692. doi:10.1016/j.tree.2005.08.002

N'Danikou S, Achigan-Dako EG, Tchokponhoué DA, Assogba Komlan F, Gebauer J, Vodouhè RS, Ahanchédé A (2014) Enhancing germination and seedling growth in *Vitex doniana* Sweet for horticultural prospects and conservation of genetic resources. Fruits 69(4):279–291. doi:10.1051/fruits/2014017

Okigbo RN (2003) Fermentation of black plum (*Vitex doniana* Sweet) juice for production of wine. Fruits 58(06):363–369

Oksanen J, Blanchet FG, Kindt R, Legendre P, Minchin PR, O'Hara RB, Simpson GL, Solymos P, Stevens MHH, Wagner H (2013) Vegan: community ecology package. R package version 2.0-10. http://CRAN.R-project.org/package=vegan

Orwa C, Mutua A, Kindt R, Jamnadass R, Simons A (2009) Agroforestree Database: a tree reference and selection guide version 4.0. http://www.worldagroforestry.org/af/treedb/

Ouédraogo A, Glèlè Kakaï R, Thiombiano A (2013) Population structure of the widespread species, Anogeissus leiocarpa (DC.) Guill. & Perr. across the climatic gradient in West Africa semi-arid area. S Afr J Bot 88:286–295. doi:10.1016/j.sajb.2013.07.029

Oumorou M, Sinadouwirou T, Kiki M, Glèlè Kakaï R, Mensah GA, Sinsin B (2010) Disturbance and population structure of *Vitex doniana* Sw. in northern Benin, West Africa. Int J Biol Chem Sci 4(3):624–632

Padmalatha K, Jayaram K, Raju NL, Prasad MNV, Arora R (2009) Ethnopharmacological and biotechnological significance of *Vitex*. Bioremediat Biodivers Bioavailab 3(1):6–14

Pigliucci M (2006) Phenotypic plasticity and evolution by genetic assimilation. J Exp Biol 209(12):2362–2367. doi:10.1242/jeb.02070

Quantum Development Team (2016) Quantum GIS geographic information system. 2.12.3-Lyon. Free Software Foundation, India

R Core Team (2015) R: a language and environment for statistical computing. Version 3.2.2. R Foundation for Statistical Computing, Vienna

Sankaran M, Hanan NP, Scholes RJ, Ratnam J, Augustine DJ, Cade BS, Gignoux J, Higgins SI, Le Roux X, Ludwig F et al (2005) Determinants of woody cover in African savannas. Nature 438(7069):846–849

Sanoussi A, Ahoton LE, Odjo T (2012) Propagation of black plum (*Vitex donania* Sweet) using stem and root cuttings in the ecological conditions of South Benin. Tropicultura 30(2):107–112

Schlichting C, Pigliucci M (1998) Phenotypic evolution: a reaction norm perspective. Sinauer Associates Incorporated, Sunderland

SPSS IBM (2011) Statistical package for social science. Version 20. SPSS IBM, Inc., Chicago

Visser ME (2008) Keeping up with a warming world; assessing the rate of adaptation to climate change. Proc R Soc B 275:649–659. doi:10.1098/rspb.2007.0997

Whitham TG, Young WP, Martinsen GD, Gehring CA, Schweitzer JA, Shuster SM, Wimp GM, Fischer DG, Bailey JK, Lindroth RL et al (2003) Community and ecosystem genetics: a consequence of the extended phenotype. Ecology 84(3):559–573

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Climate and potential habitat suitability for cultivation and in situ conservation of the black plum (*Vitex doniana* Sweet) in Benin, West Africa

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Key words: Climatic envelope, MaxEnt, Species distribution modelling, Representation gap analysis, *Vitex doniana*.

Abstract

Sustainable management actions are needed for several indigenous agro forestry plant species like the black plum (*Vitex doniana* Sweet) because they are facing increasing pressures due to the rapid human growth and threats such as climate change. By combining species distribution modelling using the Maximum Entropy Algorithm (Max Ent) and representation gap analysis, this study accessed the impacts of current and future (2050) climates on the potential distribution of *Vitex doniana* in Benin with insight on the protected areas network (PAN). The model showed a high goodness-of-fit (AUC = 0.92 ± 0.02) and a very good predictive power (TSS = 0.72 ± 0.01). Our findings indicated annual mean rainfall, annual mean diurnal range of temperature and mean temperature of the driest quarter as the most important predictors driving the distribution of *V. doniana*. Under current climate, about 85 % of Benin area is potentially suitable for its cultivation. This potential suitable area is projected to increase by 3 to 12 % under future climatic conditions. A large proportion (76.28 %) of the national PAN was reported as potentially suitable for the conservation of the species under current climate with increase projections of 14 to 23 % under future climate. The study showed that *V. doniana* can be cultivated in several areas of Benin and that the PAN is potentially suitable for its conservation. These findings highlighted some of the opportunities of integrating *V. doniana* in the formal production systems of Benin and also its potentialities in ecosystems restoration under the changing climate.

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Introduction

Indigenous agro forestry species, formerly considered as less useful and underutilized products are becoming nowadays important resources for many food security policies mainly in developing countries (Garrity, 2004, Oladélé, 2011). These species provide several goods to local communities enhancing then their capacity to face food shortage (Atato *et al.*, 2011) and to alleviate poverty (Akinnifesi *et al.*, 2008, Oladélé, 2011). Moreover, they provide several ecosystem services and contribute to biodiversity conservation (Vodouhè *et al.*, 2011). Unfortunately, most of these agroforestry species are overexploited and threatened in their natural biotopes (Maundu *et al.*, 2006). In fact, habitat and population of these species are facing increasing pressures due to the rapid human population growth (Maundu *et al.*, 2006, Nacoulma *et al.*, 2011, Haarmeyer *et al.*, 2013, Mensah *et al.*, 2014) and this combined with climate change add several uncertainties to their fitness and survival (IPCC, 2007, FAO, 2012). This situation has enhanced the need of developing sustainable management, domestication and conservation strategies for those species with a focus on climate change.

Climate change, one of the biggest challenges for this century, occurs mainly as alterations over time in weather parameters such as temperature, precipitation and wind, and changes in temperature are the most considered facts (de Chazal and Rounsevell, 2009). The implications of these change are significant for the long-term stability of natural ecosystems and for the many benefits and services that humans take from them (Lucier *et al.*, 2009). Several impacts have been reported on biological systems, with species extinction being the most extreme and irreversible negative impact (Bellard *et al.*, 2012). In Africa for instance, more than 5,000 species might lose their natural habitat before 2080 (McClean *et al.*, 2005). To avoid or reduce the amplitude of those effects, biodiversity components must produce adaptive responses which can be of several time-dependent types (Parmesan, 2006, Bellard *et al.*, 2012). Whatever the adaptation mechanism used, species responses to climate change have been observed along three non-exclusive axes: time (e.g. phenology), space (e.g. range) and self (e.g. physiology), with the first two axes being the most easily observable (Parmesan, 2006). In the spatial point of view, through seed dispersal, plant species track appropriate conditions and follow them by shifting their geographical range in order to stay in quasi-equilibrium with the climatic conditions they are adapted to (Bellard *et al.*, 2012). Evidences of such geographical range shifting have been given by several modelling studies and experimental trials on species tolerance. These studies revealed significant changes in the distribution of some species and ecosystems, principally due to increasing temperature and alteration of precipitation regimes (Walther *et al.*, 2002, Campbell *et al.*, 2009).

In this context of a changing climate, assessing spatial dynamics of suitable habitat of useful species is an important steps towards their domestication and integration into formal agricultural production systems especially in developing countries where rural population are still dependent on such resources (Oladélé, 2011). Furthermore, this assessment is relevant for in situ conservation planning strategies taking into account the existing extensive protected areas network. Despite the increasing literature on climate change impacts on plant species distribution and effectiveness of protected areas network in conserving suitable habitat of native plant species (Fandohan *et al.*, 2013), little is known on how climate could affect habitat suitability for cultivation and conservation of several useful indigenous agroforestry species such as the black plum.

The black plum (*Vitex doniana* Sweet) is one of these very important indigenous agroforestry species valued by local communities in many parts of Africa and for which sustainable management and domestication programs are required (Maundu *et al.*, 2009, Achigan-Dako *et al.*, 2011, Mapongmetsem *et al.*, 2012). Beside its potential role in soil fertility improvement by litter production (Mapongmetsem *et al.*, 2005), several parts of the species are used for food, medicine and other purposes (Dadjo *et al.*, 2012). It is known that its leaves are used as fodder for livestock and the young leaves as leafy vegetables in sauces preparation. The blackish pulp of its ripened fruits is edible and used in preparation of some sweet drinks. The wood is suitable for construction and fire (Arbonnier, 2004, Ky, 2008, Orwa *et al.*, 2009, Dadjo *et al.*, 2012). The mature leaves, the bark and the roots have phytotherapeutic properties and are used to heal several diseases (Iwueke *et al.*, 2006, Kilani, 2006, Padmalatha *et al.*, 2009). Given its socio-economic importance, its integration into the formal production systems could foster domestication strategies and reduce anthropogenic pressures on its natural populations. In addition, knowledge on its conservation by protected areas is relevant for designing strategies for plant genetic resources management. It is therefore crucial to assess impacts of climate on the species habitat in order to identify suitable areas for its cultivation and conservation.

Thus, through species distribution modelling using the Maximum Entropy Algorithm "MaxEnt" (Phillips *et al.*, 2006) and representation gap analysis, this study aimed at assessing impacts of current and future (2050) climates on *V. doniana*'s habitat suitability for its cultivation and in situ conservation in Benin. Specifically, it addressed the following research questions: i) what are the bioclimatic variables controlling *V. doniana*'s potential distribution? ii) How will the species' habitat suitability change with climate? iii) How far the national protected areas network might conserve the species' suitable habitat under current and future climates?

Material and methods

Target species and study area

The black plum (*Vitex doniana* Sweet) is a deciduous plant species occurring in tropical Africa from Senegal to Somalia and to South Africa, also in Comoros and Seychelles (Arbonnier, 2004, Ky, 2008). It was formerly classified in the Verbenaceae family but based upon several phylogenetic studies, it has been transferred to the Lamiaceae family (Cantino *et al.*, 1992, Harley *et al.*, 2004). It colonises various habitats from forests to savannahs, often in wet localities and along rivers, and on termite mounds, up to 2000 m altitude. It occurs in regions with a mean annual rainfall between 750-2000 mm and temperature ranging from 10 to 30°C (Arbonnier, 2004, Ky, 2008, Orwa *et al.*, 2009). It has been mentioned as naturally occurring in all the three climatic zones of Benin (Assogbadjo *et al.*, 2012).

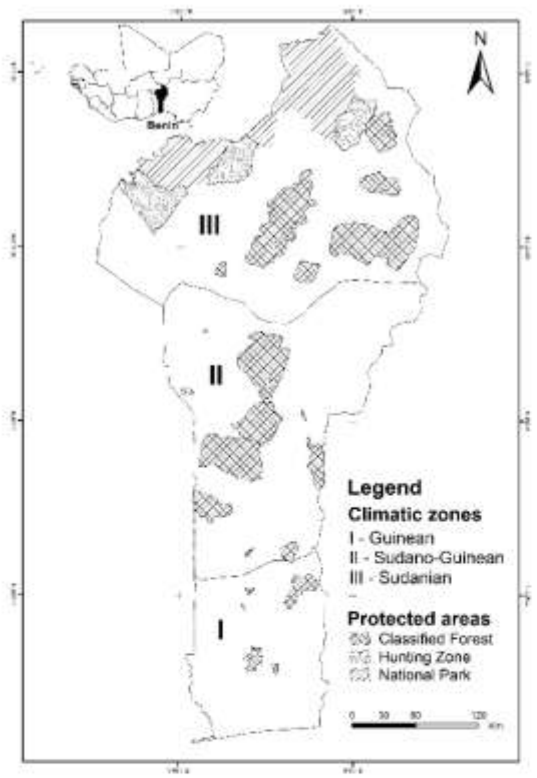

Fig. 1. Climatic zones and protected areas network of Benin.

The study was carried out in Benin republic (114,763 km^2), located between 6°10' and 12°50' N and 1° and 3°40' E in West Africa (Fig. 1). The country's climatic profile shows two contrasting climatic zones (Guinean vs. Sudanian) and a transitional zone (Sudano-Guinean). The Guinean zone (between 6°25' and 7°30' N) is characterised by a subequatorial climate with four seasons (two rainy and two dry). The rainfall of about 1200 mm per year is bimodal mostly from March to July and September to November. The temperature varies between 25 and 29 °C, and the relative humidity varies between 69 % and 97 %. The

Sudanian zone (9°45' - 12°25' N) has a tropical dry climate with two equal length seasons (rainy and dry). The mean annual rainfall in this zone is often less than 1000 mm and occurs mainly from May to September. The relative humidity varies from 18% to 99% and temperature from 24 to 31°C. The Sudano-Guinean (from 7°30' to 9°45' N) is a transitional zone with two rainy seasons merging in a unimodal regime. The annual rainfall fluctuate between 900 and 1110 mm, the temperature is between 25 and 29°C and relative humidity from 31 % to 98 % (Fandohan *et al.*, 2011, Gnanglè *et al.*, 2011, Assogbadjo *et al.*, 2012).

About 24 % of the country (approximately 27,310.47 km²) is legally protected by the national protected areas network constituted of two parks (Pendjari in the North-western part and W in the extreme Northern part of the country, Fig. 1) and several classified forests (IUCN and UNEP-WCMC, 2015).

Data collection

A total of 227 occurrence points (longitude and latitude) were obtained from fieldwork in Benin and from the Global Biodiversity Information Facility portal (GBIF, 2015) for the West African region (Fig. 2).

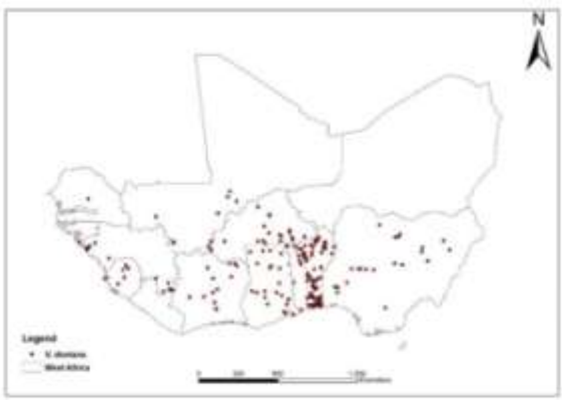

Fig. 2. Occurrence of *V. doniana* in West Africa (Data source: GBIF and fieldwork).

Bioclimatic data for current (1950-2000) and projections for 2050 were extracted from World Clim (available at www.worldclim.org/bioclim), Version 1.4 database (Hijmans *et al.*, 2005) at 2.5-minute grid resolution (approximately 4.62 x 4.62 km² in West Africa). This database includes 19 bioclimatic variables (Bio1 to Bio19) which are derived from average minimum and maximum temperature and rainfall data (Hijmans *et al.*, 2005).

According to the future climate (2050), projections from two models of the Coupled Model Intercomparison Project phase 5 (CMIP5) were preferred because of their commonness use and satisfactory features for simulating the global climate response to increasing greenhouse gas concentration (Fandohan *et al.*, 2015, McSweeney *et al.*, 2015). These models were the Met Office climate model (HadGEM2-ES) and the Model for Interdisciplinary Research on Climate Change (MIROC5). They were considered under two of the four Representative Concentration Pathway (RCP) developed by the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report: RCP 4.5 and RCP 8.5. These RCP were preferred because they projected the most divergent trends for the West African region compared to the others (IPCC, 2013). With this divergent trend (low vs. high emissions scenario), the range of emissions uncertainty is well captured (Harris *et al.*, 2014). For instance, temperature is projected to rise above industrial level by at least 1.4°C under RC 4.5 in West Africa by mid-21st century, with atmospheric CO_2 reaching 500 ppm and by 2°C with atmospheric CO_2 over 550 ppm under the more drastic RCP 8.5 (IPCC, 2013).

The Protected Area Network (PAN) map of Benin was obtained from the World Database on Protected Areas (IUCN and UNEP-WCMC, 2015) and used to assess the in situ conservation of the species in the country under current and future climates.

Data analysis

The Maximum Entropy species distribution model algorithm (MaxEnt, version 3.3.3k" Princeton University, Princeton, New Jersey, USA) was used for the habitat suitability modelling. This modelling tool requiring presence-only data is one of the best-performing algorithm among those using climate modelling approaches (Phillips *et al.*, 2006) and is relatively robust for small sample sizes (Pearson *et* *al*., 2007). It is a machine learning method that estimates species' distribution across a study area by calculating the probability distribution of maximum entropy subject to the constraint that the expected value of each feature under this estimated distribution should match its empirical average (Phillips *et al*., 2006). Although there are several conceptual ambiguities and uncertainties about bioclimatic envelope modelling (Schwartz, 2012), MaxEnt remains an important modelling tool in assessing potential impacts of climate change on species distribution (Elith *et al*., 2011a).

During the modelling process, presence data were cleaned up by removing duplicate records in grids in order to reduce sampling bias which may result from the over sampling of some sites in the study area (Elith *et al*., 2006). Only the less-correlated ($r < 0.85$) bioclimatic variables were selected with the environmental niche modelling tools (ENMTs) and used for the modelling (Elith *et al*., 2011b). During these bioclimatic variables selection process, priority was given to those reflecting water availability since plants distribution in the study area is known to be under the influence of mainly soil moisture, total rainfall, air humidity and the length of the dry season (Adomou *et al*., 2006). MaxEnt's internal Jackknife test was performed to assess the contribution of the selected variables in the distribution of the species (Pearson *et al*., 2007).

Twenty five percent (25%) of the occurrence points was used for model testing and 75% for model calibration in five replicates. The five replicates were averaged through cross-validation. Two criteria were used to evaluate the performance i.e. goodness-of-fit and predictive power of the model: (i) the area under the receiver operating characteristic curve (AUC) and the true skill statistic (TSS) (Allouche *et al*., 2006, Elith *et al*., 2006, Pearson *et al*., 2007). The AUC is the probability that a randomly chosen presence point of the species will be ranked as more suitable than a randomly chosen absence point (Elith *et al*., 2006). A model is considered as having a good fit when its AUC is close to one ($AUC \geq 0.75$) (Elith *et al*., 2006). The TSS is the capacity of the model to accurately detect true presences (sensitivity) and true absences (specificity). A model with $TSS \leq 0$ indicates a random prediction, while a model with a TSS close to 1 ($TSS > 0.5$) has a good predictive power (Allouche *et al*., 2006).

To capture the correct range of each bioclimatic factor, we performed the modelling process using occurrence and climatic data for the whole West Africa. The outputs of MaxEnt were then clipped on Benin, to mark out the study area. The potential habitat suitability across the study area was assessed based on the logistic probability distributions generated by Ma x Ent using the 10 percentile training presence logistic threshold. Thus, areas with occurrence probability above the threshold value were considered as suitable for the species and areas with occurrence probability below the threshold value were taken as unsuitable habitats (Scheldeman and van Zonneveld, 2010, Fandohan *et al*., 2015). Suitable/unsuitable habitats of the species under current and future climates were mapped in ArcGIS 10.3 (ESRI, 2014).

Representation gap analysis was used to assess how far the national protected areas network conserve the species (Fandohan *et al*., 2013, Tantipisanuh *et al*., 2016). For that, PAN of Benin was overlain on the present and future habitat suitability maps and proportions of suitable and unsuitable areas within the PAN were estimated in ArcGIS 10.3 (ESRI, 2014).

Results

Bioclimatic variables importance and model performance

Five of the 19 bioclimatic variables were selected as less-correlated ($r < 0.85$) and used for the species potential habitat modelling. Annual mean rainfall, annual mean diurnal range of temperature and mean temperature of the driest quarter were the most important predictors driving the species' distribution (Table 1). These variables have significant effect on the gain when used in isolation or removed from the modelling process (Fig. 3). Annual mean rainfall was the most uniquely informative predictor because its presence/absence in the model considerably affects the gain; its contribution and permutation importance were around 50 % (Table 1). The five bioclimatic variables used for the modelling showed significant variation (Wilcoxon signed-rank test, p-value < 0.05) between current climate and future projections with the most important changes reported in the Sudanian and Sudano-Guinean zones (Table 2). Annual mean rainfall, annual mean temperature and mean temperature of the driest quarter were projected to increase in all zones whatever the climatic scenario. Meanwhile, precipitation of the driest month is projected to significantly decrease in the Guinean zone and to remain stable in the other zones.

Table 1. Variables contribution and permutation importance (%).

Varia-bles	Definition	Contri-bution (%)	Permutation importance (%)
bio12	Annual mean rainfall	48.7	52.1
bio2	Annual mean diurnal range of temperature	28.6	21.3
bio9	Mean temperature of the driest quarter	15	17.8
bio1	Annual mean temperature	5.4	6.8
bio14	Precipitation of the driest month	2.3	2.0

Fig. 3. Jackknife of regularized training gain for V. doniana.

Table 2. Current and future projections of selected bioclimatic variables in Benin (mean ± standard deviation).

Climatic zones	Climate	Bio12	Bio2	Bio9	Bio1	Bio14
Guinean	Current	1136.92a ± 59.56	82.95a ± 15.54	279.91a ± 1.96	273.82a ± 2.34	9.49a ± 3.84
	He4.5	1137.54a ± 59.24	79.11b ± 13.78	300.29b ± 3.00	293.11b ± 3.46	7.42b ± 2.49
	He8.5	1135.98b± 61.53	78.92b ± 13.80	306.60b ± 3.58	299.10b ± 3.63	6.41b ± 2.35
	Mi4.5	1231.52b ± 65.83	82.50b ± 14.89	297.10b ± 2.42	288.93b ± 2.46	7.08b ± 2.90
	Mi8.5	1214.40b ± 61.77	79.94b ± 13.49	298.92b ± 3.06	290.82b ± 2.11	7.15b ± 2.91
Sudano-Guinean	Current	1096.08a ± 51.52	121.36a ± 7.05	270.82a ± 4.22	269.80a ± 3.58	3.21a ± 1.24
	He4.5	1149.18b ± 70.28	114.45b ± 8.57	295.06b ± 4.29	292.35b ± 3.65	3.23b ± 1.26
	He8.5	1152.14b ± 75.71	113.31b ± 7.68	301.94b ± 3.99	299.01b ± 3.41	3.17b ± 1.17
	Mi4.5	1201.67b ± 63.17	120.40b ± 7.45	290.18b ± 4.14	286.30b ± 2.79	2.28b ± 1.01
	Mi8.5	1233.80b ± 73.76	115.69b ± 8.62	292.94b ± 2.78	289.03b ± 2.22	2.19b ± 0.96
Sudanian	Current	1054.32a ± 94.99	131.05a ± 1.97	268.49a ± 8.27	273.04a ± 6.64	0.20a ± 0.40
	He4.5	1167.59b ± 78.19	128.66b ± 1.94	294.00b ± 6.95	295.52b ± 7.06	0.20a ± 0.40
	He8.5	1190.36b ± 80.81	125.14b ± 1.78	301.27b ± 7.18	303.63b ± 7.26	0.20a ± 0.40
	Mi4.5	1173.18b ± 98.35	131.53b ± 2.10	287.37b ± 9.20	291.70b ± 6.70	0.20a ± 0.40
	Mi8.5	1206.60b ± 110.07	131.02a ± 2.44	294.92b ± 7.61	297.30b ± 6.89	0.20a ± 0.40

Values were extracted from Worldclim database Version 1.4 at 2.5-minute grid resolution (approximately 4.62 x 4.62 km^2 in West Africa) based on the occurrence points of *V. doniana* in Benin. In each climatic zone, significant differences between current and each future scenario are shown by letters following mean values (Wilcoxon signed-rank test, p-value < 0.05). He4.5 & He8.5: HadGEM2-ES under respectively RCP 4.5 and 8.5. Mi4.5 & Mi8.5: MIROC5 under respectively RCP 4.5 and 8.5. Bio12 =

Annual mean rainfall (mm); Bio2 = Annual mean diurnal range of temperature (10 x °C); Bio9 = Mean temperature of the driest quarter (10 x °C); Bio1 = Annual mean temperature (10 x °C); Bio14 = Precipitation of the driest month (mm).

The model had a very goodness-of-fit (cross-validated average AUC = 0.92 ± 0.02) and a very good predictive power (TSS = 0.72 ± 0.01). The 10th percentile training presence logistic threshold for the habitat suitability discrimination was 0.22. Areas with occurrence probability above this threshold were then considered as suitable for the species, the remaining been considered as unsuitable areas.

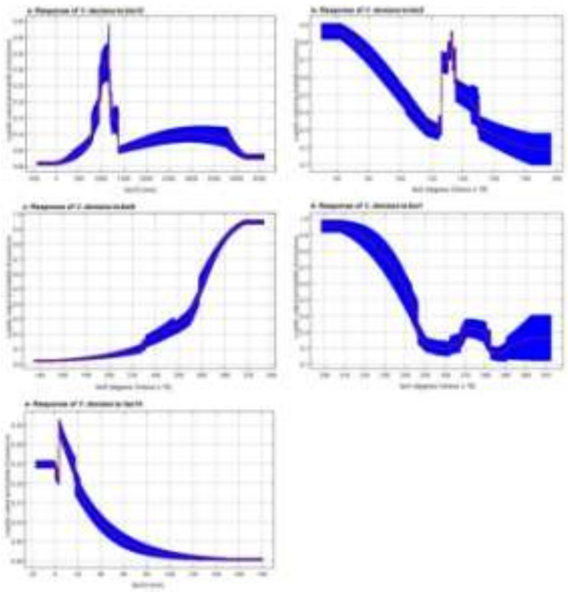

Fig. 4. Response curves of V. doniana to bioclimatic predictors in the habitat suitability modelling.

Responses of V. doniana to the selected bioclimatic predictors

Vitex doniana preferred areas with the annual mean rainfall between 800 and 1200 mm (Fig. 4a). Occurrence probability of the species was at its highest level for annual mean diurnal range of temperature around 6°C and decreased progressively when the range increased up to 12°C. Areas with diurnal range of temperature between 12.5 and 15°C were also suitable for the species (Fig. 4b). Globally, habitat suitability of the species increased with the mean temperature of the driest quarter (Fig. 4c), but it decreased with the annual mean temperature (Fig. 4d). Similarly, increases in the precipitation of the driest month reduced the habitat suitability of *V. doniana* (Fig. 4e).

Logistic output is the occurrence probability of *V. doniana*. a- Annual mean rainfall (bio12, mm); b- Annual mean diurnal range of temperature (bi o2,°C x 10); c- Mean temperature of driest quarter (bi o9,°C x 10); d- Annual mean temperature (bio1, °C x 10); e- Precipitation of driest month (bio14, mm).

Suitable areas for cultivation of V. doniana in Benin

Under current climatic conditions, about 85 % (≈ 98,005 km^2) of Benin's area was potentially suitable for the cultivation of *V. doniana* (Table 3). This suitable habitat consisted of two blocks: a southern block and a northern block. The first block covered the Guinean zone and the lower part of the Sudano-Guinean zone; the second block included the upper part of the Sudano-Guinean zone and the Sudanian zone except its extreme northern part which is not actually suitable for the species (Fig. 5a). The habitat suitability was projected to increase by 3 to 12 % (about 3,512 to 14,278 km^2) under future climatic conditions for the year 2050 (Table 3; Fig. 5b, c, d & e). For instance, the extreme northern part of the country will become suitable for the cultivation of the species under all the considered future climatic projections. For the RCP 4.5 projections, the increase of the suitable habitat will be two times more important for MIROC5 than for HadGEM2-ES. Meanwhile, when considering RCP 8.5, the most important increase of the suitable area will be noted under Had GEM2-ES (Table 3).

Conservation of V. doniana by protected areas network under current and future climate

Under current climate, about 76 % (≈ 20,832 km^2) of the national PAN was suitable for the conservation of *V. doniana* (Table 3). Regarding the two national parks, the major part of the W national park was not currently suitable for the conservation of the species (Fig. 5a). Future climate will slightly ameliorate the in situ conservation of the species by the national PAN. Indeed, the proportion of the conserved suitable habitat will increase under the future climatic projections with HadGEM2-ES showing the greatest variation (thus, +20.71 and +23.27 % for RCP 4.5 and RCP 8.5 respectively). The most important change will likely occur in the W National Park in the Sudanian zone (Fig. 5).

Table 3. Dynamic of suitable areas for cultivation and conservation of V. doniana

Climate		Cultivation			Conservation by PAN		
		Area (Km²)	Area (%)	Variation (%)	Area (Km²)	Area (%)	Variation (%)
Current		98,005.21	85.40	-	20,832.46	76.28	-
RCP 4.5	HadGEM2-ES	103,522.26	90.21	+4.81	26,487.87	96.99	+20.71
	MIROC5	108,502.07	94.54	+9.15	25,603.57	93.75	+17.47
RCP 8.5	HadGEM2-ES	112,283.42	97.84	+12.44	27,187.08	99.55	+23.27
	MIROC5	101,517.94	88.46	+3.06	24,760.40	90.66	+14.38

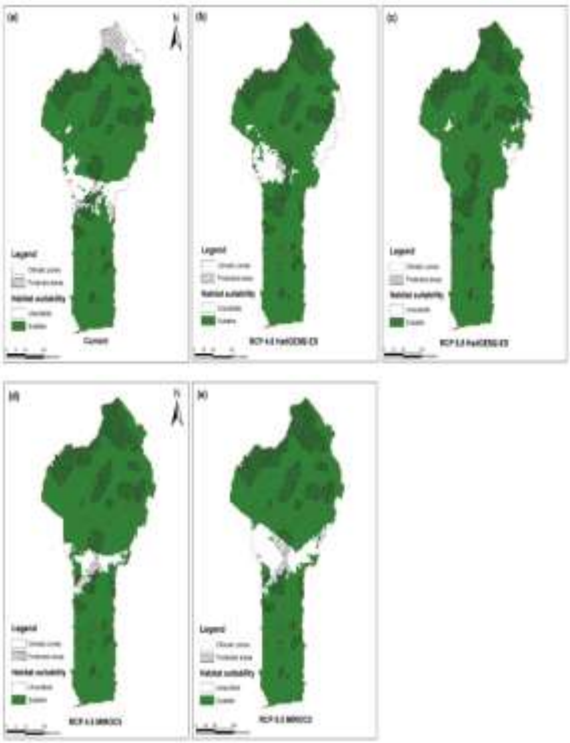

Fig. 5. Potential suitability maps for cultivation and conservation of V. doniana under current and future climate in Benin.

a. Current climatic conditions; b. Future projection according to HadGEM2-ES under RCP 4.5; c. Future projections HadGEM2-ES under RCP 8.5; d. Future projections with MIROC5 under RCP 4.5 and e. Future projections according to MIROC5 under RCP 8.5.

Discussion

Species potential distribution is driven by biotic and abiotic factors with climate playing a determinant role (Walther, 2003, Adomou *et al.*, 2006, Sommer *et al.*, 2010). There are evidences that change in climate will affect distribution of several species (IPCC, 2007, Busby *et al.*, 2010). Species distribution modelling (SDM) are widely used to determine habitat suitability patterns at large spatial scales and to produce spatially explicit and comprehensive maps that are particularly useful for identifying areas where conservation efforts are most needed or effective. Generally, these SDM techniques taking into account information on habitat requirements derived from known occurrence sites are widely used to predict potential habitat of species under current or possible future conditions. Even if these models can not indicate the realised niche, they provide relevant habitat suitability information for a given species and can guide sustainable management plans (Phillips *et al.*, 2006, Sommer *et al.*, 2010, Schwartz, 2012). This information on the derived distribution map are useful in identifying suitable areas for cultivation and assessing conservation status of target species by protected areas network (Schwartz, 2012, Fandohan *et al.*, 2013, Tantipisanuh *et al.*, 2016).

Here, Maximum entropy algorithm (Ma x Ent), one of the most used SDM techniques, was used to assess habitat suitability for cultivation and in situ conservation of *V. doniana* by PAN under current and future (2050) climatic conditions. The future climatic conditions considered were the projections of the Met Office climate model (Had GEM2-ES) and the Model for Interdisciplinary Research on Climate Change (MIROC5) under RCP 4.5 and RCP 8.5. These climatic models projected significant changes in the study area (Table 2). by mid-21st century (Hijmans *et al.*, 2005, IPCC, 2013).

Findings indicated annual mean rainfall, annual mean diurnal range of temperature and mean temperature of the driest quarter as the most important predictors driving the distribution of *V. doniana* (Table 1). Among these predictors, mean annual rainfall showed the greatest contribution confirming the importance of water availability in plants distribution (Adomou *et al.*, 2006). The ecological optimum of the species regarding this climatic predictor is from 800 to 1200 mm (Fig. 4a), and it is effectively within the range of 750-2000 mm indicated by the literature (Arbonnier, 2004, Ky, 2008, Orwa *et al.*, 2009). Regarding temperature factor, it is mainly annual mean diurnal range of temperature and mean temperature of the driest quarter that mostly controlled the species distribution (Table 1).

Following our findings, approximately 85% of Benin's area is potentially suitable for the cultivation of *V. doniana* and about 76% of the national PAN is suitable for its conservation. Significant increases were projected under future climatic (2050) scenarios with several currently unsuitable areas becoming suitable under all the climatic models mainly in the Sudanian and Sudano-Guinean zones. This increase in habitat suitability can be explained by the significant changes projected for the bioclimatic parameters in 2050 (Table 2). Indeed, according to the climatic models used in this study, the extreme northern part of the country (annual mean rainfall mostly below 700 mm) are projected to become wetter with annual rainfall reaching 900 mm (Hijmans *et al.*, 2005). These changes in the rainfall will likely make the areas suitable for *V. doniana* since its ecological optimum is between 750 and 2000 mm/year (Arbonnier, 2004, Ky, 2008, Orwa *et al.*, 2009). The high plasticity of the species in habitat selection also support our findings (Arbonnier, 2004, Ky, 2008, Orwa *et al.*, 2009).

Although models in both RCP showed similar increasing trend of the habitat suitability for cultivation and conservation of the species, some particularities were noted. For instance, the most important variations were noted under the projection of the drastic scenario i.e. RCP 8.5 (Table 3). This climatic scenario is more likely than the second because even though important mitigation actions are being undertaken, the Earth's climate system will still be facing the 'committed warming' (Harris *et al.*, 2014). However, because of the important uncertainties regarding the climatic models (Harris *et al.*, 2014), one should be cautious regarding these projections.

Even though habitat suitability for cultivation and conservation of *V. doniana* are projected to have significant increases in the country, its productivity under future climate might be affected either positively or negatively. In fact, the species may have undergone several physiological adaptations in response to past climates, but under the current rapid climate change, the expansion of the species in new areas will likely require important energy-dependant adjustments in morphological, physiological or behavioural traits of the species and this could have negative impacts on its productivity (Challinor *et al.*, 2006). Long term studies are then required on the physiology, phenology and productivity of the species through its climatic range in order to build a consistent database for the sustainable management of the species under the changing climate.

Conclusion and implications of the study

Findings of this study suggested that *Vitex doniana*, a key agroforestry species for local communities in tropical Africa can be cultivated in a wide range of areas in Benin. Moreover, the national protected areas network offered a large extent of favourable areas for its in situ conservation. With the apparently positive impact of future climate on its habitat suitability, *V. doniana* can be considered as a good candidate for ecological restoration of degraded ecosystems with regard to challenges like climate change.

Conflict of interest
No conflicts of interest to declare.

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Abbreviations
AUC: Area under the receiver operating characteristic curve
CMIP5: Coupled Model Intercomparison Project phase 5
ENMTs: Environmental niche modelling tools
GBIF: Global Biodiversity Information Facility
HadGEM2-ES: Met Office climate model
IPCC: Intergovernmental Panel on Climate Change
MaxEnt: Maximum Entropy
MIROC5: Model for Interdisciplinary Research on Climate Change
PAN: Protected Area Network
RCP: Representative Concentration Pathway
SDM: Species distribution modelling
TSS: True skill statistic

References
Achigan-Dako EG, N'Danikou S, Assogba-Komlan F, Ambrose-Oji B, Ahanchédé A, Pasquini MW. 2011. Diversity, geographical, and consumption patterns of traditional vegetables in sociolinguistic communities in Benin: Implications for domestication and utilization. Economic Botany **65(2),** 129-145. http://dx.doi.org/10.1007/s12231-011-9153-4

Adomou AC, Sinsin B, Van der Maesen LJG. 2006. Phytosociological and Chorological Approaches to Phytogeography: A Meso-Scale Study in Benin. Systematics and geography of plants **76(2),** 155-178.

Akinnifesi FK, Sileshi G, Ajayi OC, Chirwa PW, Kwesiga FR, Harawa R. 2008. Contributions of agroforestry research and development to livelihood of smallholder farmers in Southern Africa: 2. Fruit, medicinal, fuel wood and fodder tree Systems. Agricultural Journal **3(1),** 76-88.

Allouche O, Tsoar A, Kadmon R. 2006. Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). Journal of Applied Ecology **43,** 1223-1232. http://dx.doi.org/10.1111/j.1365-2664.2006.01214.x

Arbonnier M. 2004. Trees, shrubs and lianas of West African dry zones. France: Editions Quae.

Assogbadjo AE, Glèlè Kakaï R, Vodouhê FG, Djagoun CAMS, Codjia JTC, Sinsin B. 2012. Biodiversity and socioeconomic factors supporting farmers' choice of wild edible trees in the agroforestry systems of Benin (West Africa). Forest Policy and Economics **14,** 41-49. http://dx.doi.org/10.1016/j.forpol.2011.07.013

Atato A, Wala K, Batawila K, Lamien N, Akpagana K. 2011. Edible wild fruit highly consumed during food shortage period in togo: State of knowledge and conservation status. Journal of Life Sciences **5,** 1046-1057.

Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F. 2012. Impacts of climate change on the future of biodiversity. Ecology Letters **15,** 365-377. http://dx.doi.org/10.1111/j.1461-0248.2011.01736.x

Busby JW, Smith TG, White KL, Strange SM. 2010. Locating climate insecurity: where are the most vulnerable places in Africa? Austin, TX, USA: University of Texas, The Robert Strauss Center for International Security and Law, Climate Change and African Political Stability (CCAPS) Programme.

Campbell A, Kapos V, Scharlemann JPW, Bubb P, Chenery A, Coad L, Dickson B, Doswald N, Khan MSI, Kershaw F, Rashid M. 2009. Review of the literature on the links between biodiversity and climate change: Impacts, adaptation and mitigation. Montreal, Canada: Secretariat of the Convention on Biological Diversity.

Cantino PD, Harley RM, Wagstaff SJ. 1992. Genera of Labiatae: Status and Classification. In: Harley RM, Reynolds T, Ed. Advances in Labiate Science. Kew: Royal Botanic Gardens.

Challinor AJ, Wheeler TR, Osborne TM, Slingo JM. 2006. Assessing the vulnerability of crop productivity to climate change thresholds using an integrated crop-climate model. In: Schellnhuber JEA, Ed. Avoiding dangerous climate change. Cambridge, UK: Cambridge University Press.

Dadjo C, Assogbadjo AE, Fandohan B, Glèlè Kakaï R, Chakeredza S, Houehanou TD, Damme PV, Sinsin B. 2012. Uses and management of black plum (*Vitex doniana* Sweet) in Southern Benin. Fruits **67(4),** 239-248. http://dx.doi.org/10.1051/fruits/2012017

de Chazal J, Rounsevell MDA. 2009. Land-use and climate change within assessments of biodiversity change: A review. Global Environmental Change **19,** 306-315.http://dx.doi.org/10.1016/j.gloenvcha.2008.09.007

Elith J, Graham CH, Anderson RP, Dudik M, Ferrier S, Guisan A, Hijmans RJ, Huettmann F, Leathwick JR, Lehmann A, Li J, Lohmann LG, Loiselle BA, Manion G, Moritz C, Nakamura M, Nakazawa Y, Overton JM, Peterson AT, Phillips SJ, Richardson K, Scachetti-Pereira R, Schapire RE, Soberon J, Williams S, Wisz MS, Zimmermann NE. 2006. Novel methods improve prediction of species' distributions from occurrence data. Ecography **29,** 129-151. http://dx.doi.org/10.1111/j.2006.0906-7590.04596.x

Elith J, Kearney M, Philips S. 2011a. The art of modeling range-shifting species. Methods Ecology and Evolution **1,** 330-342. http://dx.doi.org/10.1111/j.2041-210X.2010.00036.x

Elith J, Philips SJ, Hastie T, Dudik M, En Chee Y, Yates CJ. 2011b. A statistical explanation of MaxEnt for ecologists. Diversity and Distribution **17,** 43-57. http://dx.doi.org/10.1111/j.1472-4642.2010.00725.x

ESRI. 2014. ArcGIS Desktop. Version 10.3 ed. USA: World Shaded Relief, ESRI.

Fandohan AB, Oduor AMO, Sode AI, Wu L, Cuni-Sanchez A, Assede E, Gouwakinnou GN. 2015. Modeling vulnerability of protected areas to invasion by *Chromolaena odorata* under current and future climates. Ecosystem Health and Sustainability **1(6)**. http://dx.doi.org/10.1890/EHS15-0003.1

Fandohan B, Assogbadjo AE, Glèlè Kakaï RL, Sinsin B. 2011. Effectiveness of a protected areas network in the conservation of *Tamarindus indica* (Leguminosea–Caesalpinioideae) in Benin. African Journal of Ecology **49,** 40-50. http://dx.doi.org/10.1111/j.1365-2028.2010.01228.x

Fandohan B, Gouwakinnou GN, Fonton NH, Sinsin B, Liu J. 2013. Impact des changements climatiques sur la répartition géographique des aires favorables à la culture et à la conservation des fruitiers sous-utilisés : cas du tamarinier au Bénin. Biotechnology, Agronomy, Society and Environment **17(3)**.

FAO. 2012. Forest Management and Climate Change: a literature review. In: Fao (ed.) Forests and Climate Change. Rome, Italy: FAO.

Garrity DP. 2004. Agroforestry and the achievement of the Millennium Development Goals. Agroforestry systems **61,** 5-17. http://dx.doi.org/10.1023/B:AGFO.0000028986.37502.7c

GBIF. 2015. GBIF Occurrence Download. Denmark: Global Biodiversity Information Facility.

www.gbif.org/occurrence/download/0004919-150922153815467

Gnanglè CP, Glèlè Kakaï R, Assogbadjo AE, Vodounnon S, Yabi JA, Sokpon N. 2011. Tendances climatiques passées, modélisation, perceptions et adaptations locales au Bénin. Climatologie **8,** 27-40. http://dx.doi.org/10.4267/climatologie.259

Haarmeyer DH, Schumann K, Bernhardt-Romermann M, Wittig R, Thiombiano A, Hahn K. 2013. Human impact on population structure and fruit production of the socio-economically important tree *Lannea microcarpa* in Burkina Faso. Agroforestery Systems **87,** 1363-1375. http://dx.doi.org/10.1007/s10457-013-9644-7

Harley RM, Atkins S, Budntsev PD, Cantino PD, Conn BJ, Grayer R, Harley MM, De Kok R, Kresstovskaja T, Morales R, Paton AJ, Ryding O, Upson T. 2004. Labiatae. In: Kubitzki K, Ed. The Families and Genera of Vascular Plants: Flowering Plant-Dicotyledons. Germany: Springer-Verlag.

Harris RMB, Grose MR, Lee G, Bindoff NL, Porfiri LL, Fox-Hughes P. 2014. Climate projections for ecologists. Wiley Interdisciplinary Reviews: Climate Change **5,** 621-637. http://dx.doi.org/10.1002/wcc.291

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A, others. 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology **25(15),** 1965-1978. http://dx.doi.org/10.1002/joc.1276

IPCC. 2007. Climate change: synthesis report. New York, USA: Intergovernmental Panel on Climate Change (IPCC).

IPCC. 2013. Climate change 2013: the physical science basis. Contribution of Working Group I to the fifth assessment report of the intergovernmental panel on climate change. New York, USA: Intergovernmental Panel on Climate Change.

IUCN, UNEP-WCMC. 2015. The World Database on Protected Areas (WDPA). Cambridge, UK. www.protectedplanet.net

Iwueke AV, Nwodo OFC, Okoli CO. 2006. Evaluation of the anti-inflammatory and analgesic activities of *Vitex doniana* leaves. African journal of biotechnology **5(20),** 1929-1935. http://dx.doi.org/10.5897/AJB2006.000-5086

Kilani AM. 2006. Antibacterial assessment of whole stem bark of *Vitex doniana* against some enterobactriaceae. African journal of biotechnology **5(10),** 958-959. http://dx.doi.org/10.5897/AJB06.085

Ky KJM. 2008. *Vitex doniana* Sweet. In: Louppe D, Oteng-Amoako AA, Brink M, Ed. Prota: Timbers/Bois d'oeuvre. Wageningen, Pays Bas: Backhuys Publishers, Leiden/CTA, Wageningen, PROTA Foundation.

Lucier A, Ayres M, Karnosky D, Thompson I, Loehle C, Percy K, Sohngen B. 2009. Forest responses and vulnerabilities to recent climate change. In*:* Seppala R, Buck, A. And Katila, P. (ed.) Adaptation of forests and people to climate change. IUFRO.

Mapongmetsem PM, Benoit LB, Nkongmeneck BA, Ngassoum MB, Gübbük H, Baye–Niwah C, Longmou J. 2005. Litterfall, Decomposition and Nutrients Release in *Vitex doniana* Sweet. and *Vitex madiensis* Oliv. in the Sudano–Guinea Savannah. Akdeniz Üniversitesi Ziraat Fakültesi Dergisi **18(1),** 63-75.

Mapongmetsem PM, Djoumessi MC, Yemele MT, Fawa G, Doumara DG, Noubissie JBT, Tientcheu A, Louise M, Bellefontaine R. 2012. Domestication de *Vitex doniana* Sweet. (Verbenaceae): influence du type de substrat, de la stimulation hormonale, de la surface foliaire et de la position du nœud sur l'enracinement des boutures uninodales. Journal of Agriculture and Environment for International Development **106(1),** 23-45. http://dx.doi.org/10.12895/jaeid.20121.50

Maundu P, Achigan-Dako EG, Morimoto Y. 2009. Biodiversity of African vegetables. In: Shackleton CM, Pasquini MW, Drescher AW, Ed. African Indigenous Vegetables in Urban Agriculture. Earthscan, London, UK.

Maundu P, Kariuki P, Eyog-Matig O. 2006. Threats to medicinal plant species-an African perspective. In: Miththapala S, Ed. Conserving medicinal species: Securing a healthy future. Asia: Ecosystems and Livelihoods Group (IUCN).

McClean CJ, Lovett JC, Kuper W, Hannah L, Sommer JH, Barthlott W, Termansen M, Smith GE, Tokamine S, Taplin JRD. 2005. African plant diversity and climate change. Annals of the Missouri Botanical Garden **92,** 139-152.

McSweeney CF, Jones RG, Lee RW, Rowell DP. 2015. Selecting CMIP5 GCMs for downscaling over multiple regions. Climate Dynamics **44,** 3237-3260. http://dx.doi.org/10.1007/s00382-014-2418-8

Mensah S, Houehanou TD, Sogbohossou EA, Assogbadjo AE, Glèlè Kakaï R. 2014. Effect of human disturbance and climatic variability on the population structure of *Afzelia africana* Sm. ex pers. (Fabaceae–Caesalpinioideae) at country broad-scale (Benin,West Africa). South African Journal of Botany **95,** 165-173. http://dx.doi.org/10.1016/j.sajb.2014.09.008

Nacoulma BMI, Traoré S, Hahn K, Thiombiano A. 2011. Impact of land use types on population structure and extent of bark and foliage harvest of *Afzelia africana* and *Pterocarpus erinaceus* in Eastern Burkina Faso. International Journal of Biodiversity and Conservation **3(3),** 62-72.

Oladélé OI. 2011. Contribution of indigenous vegetables and fruits to poverty alleviation in Oyo State, Nigeria. Journal of Human and Ecology **34(1),** 1-6.

Orwa C, Mutua A, Kindt R, Jamnadass R, Simons A. 2009. Agroforestree Database: a tree reference and selection guide version 4.0. http://www.worldagroforestry.org/af/treedb/

Padmalatha K, Jayaram K, Raju NL, Prasad MNV, Arora R. 2009. Ethnopharmacological and biotechnological significance of *Vitex*. Bioremediation, Biodiversity and Bioavailability **3(1),** 6-14.

Parmesan C. 2006. Ecological and evolutionary responses to recent climate change. Annual Review of Ecology, Evolution and Systematics **37,** 637-669. http://dx.doi.org/10.1146/annurev.ecolsys.37.091305.110100

Pearson RG, Christopher J, Raxworthy MN, Peterson AT. 2007. Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. Journal Biogeography **34,** 102-117. http://dx.doi.org/10.1111/j.1365-2699.2006.01594.x

Phillips SJ, Anderson RP, Schapire RE. 2006. Maximum entropy modelling of species geographic distributions. Ecological Modelling **190,** 231-259. http://dx.doi.org/10.1016/j.ecolmodel.2005.03.026

Scheldeman X, van Zonneveld M. 2010. Training manual on spatial analysis of plant diversity and distribution. Rome, Italy: Bioversity International.

Schwartz MW. 2012. Using niche models with climate projections to inform conservation management decisions. Biological Conservation **155,** 149-156. http://dx.doi.org/10.1016/j.biocon.2012.06.011

Sommer JH, Kreft H, Kier G, Jetz W, Mutke J, Barthlott W. 2010. Projected impacts of climate change on regional capacities for global plant species richness. Proceedings of the Royal Society of London B: Biological Sciences **277,** 2271-2280. http://dx.doi.org/10.1098/rspb.2010.0120

Tantipisanuh N, Savini T, Cutter P, Gale GA. 2016. Biodiversity gap analysis of the protected area system of the Indo-Burma Hotspot and priorities for increasing biodiversity representation. Biological Conservation **195,** 203-213. http://dx.doi.org/10.1016/j.biocon.2015.12.043

Vodouhè R, Dansi A, Avohou HT, Kpèki B, Azihou F. 2011. Plant domestication and its contributions to in situ conservation of genetic resources in Benin. International Journal of Biodiversity and Conservation **3(2),** 40-56.

Walther G-R. 2003. Plants in a warmer world. Perspectives in Plant Ecology, Evolution and Systematics **6,** 169-185. http://dx.doi.org/10.1078/1433-8319-00076

Walther G-R, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin J-M, Guldberg OH, Bairlein F. 2002. Ecological responses to recent climate change. Nature **416,** 389-395. http://dx.doi.org/10.1038/416389a.

Appendix 16: Synthesis in French (synthèse en Français)

ETHNOBOTANIQUE ET ADAPTATION ECOLOGIQUE DU PRUNIER NOIR (*VITEX DONIANA* SWEET) AUX CONDITIONS CLIMATIQUES DU BENIN, AFRIQUE DE L'OUEST: IMPLICATIONS POUR LA CONSERVATION ET LA DOMESTICATION

Introduction

Le changement climatique constitue un des plus grands défis de notre planète depuis des décennies. Il est principalement vu comme une modification dans le temps des paramètres météorologiques tels que la température, la pluviométrie et le vent. Cependant, l'augmentation de la température est considérée le plus souvent comme l'indicateur le plus illustratif. Ces changements sont dus en grande partie aux fortes concentrations des gaz à effets de serre, notamment le dioxyde de carbone dans l'atmosphère. Bien que la contribution des pays sous-développés, en particulier ceux de l'Afrique sub-saharienne, aux émissions de ces gaz soit faible, cette région est non seulement la plus affectée, mais aussi la moins apte à faire face aux potentiels impacts négatifs liés à ces changements. De ce fait, les secteurs clés à effets adoucissant sur le climat, tel que l'agroforesterie devraient être fortement promus dans cette région.

Plusieurs approches prometteuses ont été envisagées pour assurer l'adaptation locale au changement climatique, y compris les approches basées sur les écosystèmes pour l'adaptation (EBA) au changement climatique. Dans le cadre de ces approches basées sur les écosystèmes, les espèces agroforestières locales pourraient être considérées comme des composantes clés en raison de leur rôle potentiel dans l'atténuation des impacts socioculturels et économiques du changement climatique et de leur forte capacité de stabilisation de l'environnement et de restauration écologique. Par exemple, le maintien de ces espèces dans les espaces agricoles est une stratégie adoptée par les paysans pour satisfaire leurs besoins en matière de ressources essentielles comme la nourriture, les produits médicinaux, le fourrage, les combustibles et autres produits marchands. Dans le même temps, cela constitue une source d'importants services écosystémiques tels que l'amélioration de la fertilité des sols, la protection des bassins versants, la séquestration du carbone, la conservation de la biodiversité et la restauration des écosystèmes. Cependant, bien que l'on ne sache toujours pas laquelle de ces espèces est plus susceptible de résister au changement climatique, leur intégration dans les systèmes de production formels pourrait jouer un rôle clé dans la mise en œuvre des approches basées sur les écosystèmes pour l'adaptation au changement climatique. Par conséquent, il est crucial d'évaluer les connaissances écologiques traditionnelles sur ces espèces en ce qui concerne le changement climatique et d'évaluer les mécanismes d'adaptation qu'elles développent face à des menaces comme les changements dans l'utilisation des terres et les changements climatiques afin de promouvoir leur intégration dans les approches EBA.

En effet, plusieurs mécanismes sont développés par les espèces végétales pour survivre aux changements climatiques et ceci dépendant de l'espèce et de sa localisation géographique. Ces mécanismes impliquent des ajustements phénotypiques et / ou génétiques, les processus phénotypiques étant les plus rapides et les plus importants. En ce qui concerne ces processus phénotypiques, la variation des caractéristiques morphologiques, physiologiques ou comportementales est la plus pertinente. Ainsi, il a été noté que le développement des morphotypes favorisait l'aptitude des espèces dans un environnement en pleine évolution. Aussi, l'ajustement de l'anatomie du bois, notamment la taille et la distribution des vaisseaux, est reconnu comme pertinent pour le transport et l'utilisation de l'eau. De plus, l'expansion ou la contraction des aires de distribution aideraient les espèces dans leur quête de conditions climatiques favorables. Mais est-ce que toutes les espèces utilisent les mêmes mécanismes? Il est donc important d'évaluer l'écologie, la morphologie, l'anatomie du bois et la répartition géographique d'espèces présentes dans diverses zones climatiques afin de prédire certaines de leurs réponses au changement climatique et de favoriser leur domestication et conservation qui peuvent être valorisées dans la mise en œuvre des approches EBA.

A travers ce travail, nous avons étudié le prunier noir (*Vitex doniana* Sweet), une des dix espèces agroforestières prioritaires pour les programmes de domestication en Afrique occidentale, pour comprendre certains des mécanismes développés cette plante pour suivre dans différents environnements climatiques afin de prédire ses réponses potentielles aux changements climatiques. L'objectif global de cette étude est d'améliorer les connaissances sur l'ethnobotanique de *V. doniana* et sur les mécanismes adaptatifs utilisés par l'espèce pour survivre dans différentes zones climatiques du Bénin afin de fournir des informations de base pour la mise en œuvre des approches d'adaptation basées sur les écosystèmes en utilisant *V. doniana* pour faire face au changement climatique. Pour cela, les connaissances traditionnelles sur les valeurs d'usages de l'espèce ainsi que les perceptions locales des populations sur les changements climatiques et ses impacts potentiels sur la biologie et la productivité de l'espèce ont d'abord été inventoriées. Ensuite l'écologie, les paramètres structuraux, la variabilité morphologique, la croissance radiale et l'anatomie du bois (densité, forme et taille des vaisseaux) de l'espèce ont été étudiés en relation avec les conditions climatiques afin d'identifier les stratégies d'adaptations développées par l'espèce pour sa survie dans les différents habitats. Finalement, les impacts des climats présent et futur sur les habitats favorables à la culture et la conservation de l'espèce ont été évalués afin d'identifier ses potentialités à faire face aux changements climatiques et à être utilisée dans les programmes de restauration d'écosystèmes dégradés.

Méthodologie

L'étude a été réalisée dans les trois zones climatiques de la République du Bénin, située en Afrique de l'Ouest entre 6°25' et 12°50' latitude Nord, et 0°45' et 3°50' longitude Est. Le pays couvre une superficie de 114,763 km^2 et est subdivisé en trois zones climatiques. Ces zones climatiques sont du Sud au Nord : la zone guinéenne caractérisée par un climat de type subéquatorial (deux saisons pluvieuses alternées par deux saisons sèches), la zone soudano-guinéenne qui est une zone de transition et la zone soudanienne présentant un climat de type tropical sec (une saison sèche et une saison pluvieuse).

Les valeurs d'usages ainsi que les perceptions locales sur les changements climatiques et leurs impacts sur la biologie et la productivité de l'espèce ont été étudiées à travers des enquêtes ethnobotaniques dans cinq localités choisies au hasard dans chacune des zones climatiques. L'approximation normale de la distribution binomiale a été utilisée pour déterminer le nombre d'enquêtés à considérer par localité. Les données ont été collectées durant des entretiens semi-structurés individuels sur un total de 441 personnes appartenant à 19 groupes ethniques. Trois paramètres ethnobotaniques d'utilisation des plantes (nombre d'utilisations mentionnées, les organes utilisés et les formes d'utilisation de la plante) ont été retenus pour évaluer l'importance de l'espèce. En ce qui concerne les perceptions locales sur les changements climatiques, les modifications observées sur la température, la longueur des saisons pluvieuses et l'intensité des pluies ont été notées ainsi que leurs impacts potentiels sur la biologie et la productivité de l'espèce. L'ethnie, le genre, l'âge et la localisation des enquêtés sont les facteurs considérés dans l'évaluation des connaissances endogènes sur l'espèce. Le test de Kruskal-Wallis a été utilisé pour comparer les différents groupes d'enquêtés en considérant le nombre d'utilisations mentionnées tandis que le test de Chi-2 ou son alternatif test exact de Fisher a été utilisé pour évaluer l'influence des facteurs sociolinguistiques sur les perceptions locales et les impacts potentiels des changements climatiques sur l'espèce.

L'écologie et les paramètres structuraux de l'espèce ont été étudiés le long de soixante transects de 3 km chacun, à raison de quatre dans chacune des cinq localités considérées lors des enquêtes ethnobotaniques. Dans chacune de ces localités, les transects ont été arrangés suivant les quatre directions (Nord, Sud, Est, Ouest). Des bandes d'investigations de 100 m ont été considérées le long de chaque transect. Au sein desdites bandes, des placettes de 50 x 20 m^2 ont été installées autour de chaque individu de *V. doniana* rencontré (diamètre à 1.3 m ≥ 5 cm). Au sein de chacune de ces placettes, cinq placeaux (10 x 10 m^2) ont été installés pour l'étude de la régénération (dbh < 5 cm) de l'espèce. A l'intérieur de chaque placette, le diamètre à hauteur de poitrine (dbh) de tous les arbres ayant un diamètre supérieur ou égal à 5 cm et la hauteur des individus adultes du prunier noir ont été mesurés. Aussi, les facteurs abiotiques tels que les types de couvert végétal et de sol ont été relevés sur le terrain et mis à jour en projetant les coordonnées (longitude et latitude) des centres de placettes sur la carte d'occupation des terres d'une part et celle des sols du Benin d'autre part. Le même processus a été utilisé sur la carte hydrographique du pays pour la détermination de la distance entre les centres de placettes et le plus proche cours d'eau. Le nombre de contacts avec les pieds de *V. doniana* (dbh ≥ 5 cm) le long des transects ainsi que les nombres d'arbres par contact ont été utilisés pour identifier les habitats de fortes fréquences d'observation et d'abondance du prunier noir au regard de l'environnement local (zone climatique, couvert végétal et proximité de cours d'eau). Les communautés floristiques dans lesquelles l'espèce apparait ont été étudiées à travers un positionnement multidimensionnel des placettes. L'indice de similarité de Jaccard a été calculé et utilisé pour analyser les similarités entre ces communautés végétales abritant l'espèce en fonction des paramètres de son environnement local. Les paramètres structuraux de *V. doniana* tels que la densité d'arbres (N, arbres/ha), la surface terrière (Ba, m^2/ha), le diamètre quadratique moyen (Dg, cm), la hauteur moyenne de Lorey (HL, m), la contribution de *V. doniana* à la surface terrière du peuplement arborescent, et la densité de régénération (Nreg, tiges/ha) ont été calculés par placette. Leurs valeurs moyennes et coefficients de variation ont été déterminés et utilisés pour comparer les populations de l'espèce suivant les caractéristiques de son environnement local. La structure en diamètre de l'espèce a été établie et ajustée à la distribution théorique à 3 paramètres de Weibull. Ces structures ont été établies pour chaque type de couvert végétal et chaque classe de distance au cours d'eau le plus proche au sein de chaque zone climatique.

Les données morphologiques de l'espèce ont été collectées dans les trois zones climatiques le long de transects de direction et longueur variables (1 à 6 km). Au total, 102 arbres portant des fruits ont été étudiés (35, 31 et 36 respectivement dans la zone guinéenne, soudano-guinéenne et soudanienne). Au niveau de chaque arbre, les données ont été collectées sur le tronc, le houppier et sur 10 feuilles et 10 fruits aléatoirement sélectionnés pour la description morphologique. Les coordonnées GPS de chaque arbre ont été enregistrées et utilisées pour extraire les données bioclimatiques de la base de données de WorldClim. La valeur moyenne, l'erreur-type et le coefficient de variation ont été calculée pour chacun des traits morphologiques par zone climatique. L'analyse de la variance à un critère a été utilisée pour comparer les zones climatiques en fonction des traits morphologiques du tronc et du houppier. Les modèles linéaires mixtes ont été utilisés sur les traits morphologiques des feuilles et des fruits pour la comparaison des zones climatiques et pour l'estimation des composantes de la variance afin d'identifier les sources de variabilité de ces traits. Afin d'identifier les traits morphologiques caractéristiques des zones climatiques, une analyse discriminante pas à pas a été réalisée sur les valeurs moyennes des paramètres morphologiques. Les relations entre ces paramètres morphologiques discriminants et les variables bioclimatiques ont été évaluées à l'aide d'une analyse canonique de redondance sur les valeurs moyennes de ces traits et les variables bioclimatiques extraites pour chaque arbre.

La croissance radiale et l'anatomie du bois notamment la section, la forme et la densité des vaisseaux ont été évaluées à travers l'analyse des cernes de bois collectées dans les deux zones climatiques extrêmes (guinéenne et soudanienne) du pays. Sept disques ont été collectés dans chacune de ces zones et leurs surfaces ont été traitées suivant le protocole décrit par Gärtner et al. (2015). Ainsi, après avoir poli la surface des disques de bois, les cernes ont été marquées le long de trois rayons sur chaque disque. La largeur des cernes a été mesurée avec une précision de 0,01 mm en utilisant le logiciel *Time Series Analysis and Presentation* (TSAPWin) combiné au dispositif de mesure numérique LINTAB 5 (RinnTECH, Heidelberg, Germany) relié à un stéréomicroscope (Wild M3Z, Leica, Germany). Les chronologies issues de la mesure des largeurs de cernes ont été datées en utilisant le logiciel TSAPWin à travers un processus de synchronisation deux à deux des rayons le long desquels les mesures ont été effectuées en utilisant l'un comme référence et vice-versa. La qualité des datations a été évaluée dans le programme COFECHA. Les chronologies résiduelles des largeurs de cernes ont été établies en utilisant la procédure de normalisation des données brutes à l'aide de la courbe exponentielle négative dans le programme ARSTAN afin d'éliminer les effets de la croissance biologique. Les chronologies moyennes ont été ensuite établies pour chaque zone climatique et utilisée pour évaluer la tendance de la croissance radiale à travers une analyse de corrélations et un test t de Student. En ce qui concerne l'acquisition des données de l'anatomie du bois (section, forme et densité des vaisseaux au sein des cernes), des sections fines (15 µm) de bois ont été coupées à l'aide d'un microtome à partir de la surface du disque le long d'un des trois rayons utilisés lors de la mesure des largeurs de cernes. Ces micro-sections de bois ont été traitées suivant le processus décrit par Gärtner et al. (2015) pour la mise au point d'échantillons permanents de tissu de bois fixés entre lames et lamelles. Des images microscopiques de ces échantillons ont été prises au grossissement de 40X à l'aide d'une caméra (LEICA DFC 420 C) montée sur un microscope (LEICA DM 1000). Le logiciel ImageJ a été utilisé pour l'acquisition des données anatomiques à partir des images couvrant les derniers cernes (2004-2014). Au sein de chacun de ces cernes, la section de chaque vaisseau (mm^2) et leur forme c'est-à-dire leur circularité ont été mesurées. Les valeurs minimales, maximales et moyennes de la section des vaisseaux ainsi que celles de leur circularité, la proportion de pores, et la densité de vaisseaux ont été déterminées par cerne et utilisées pour la comparaison des zones climatiques à l'aide du test non paramétrique de Kruskal-Wallis. Une analyse des corrélations de Pearson a été utilisée pour évaluer les relations entre les variables morphologiques des arbres (diamètre, hauteur du fut, la hauteur totale et l'épaisseur de l'écorce) et les paramètres anatomiques du bois d'une part, et entre les paramètres climatiques et l'anatomie du bois d'autre part. La même analyse a été utilisée pour voir les relations entre les chronologies résiduelles des largeurs de cernes et les paramètres climatiques. Les dits paramètres ont été obtenus à partir des stations météorologiques proches des sites de collecte des disques.

Finalement, les impacts des climats présent et futur sur les habitats favorables à la culture et à la conservation du prunier noir ont été évalués à partir de la modélisation de la niche climatique de l'espèce à l'aide de l'algorithme du maximum d'entropie (MaxEnt). Deux cent vingt-sept (227) points de présence de l'espèce ont été obtenus à partir des explorations à travers le Bénin et aussi à partir de la base de données du *Global Biodiversity Facility* sur toute la zone de l'Afrique de l'Ouest. Les données bioclimatiques du présent (1950-2000) ainsi que leurs projections pour l'année 2050 ont été extraites de la base de données de WorldClim, version 1.4 à la résolution spatiale approximative de 4,62 x 4,62 Km^2. En ce qui concerne le climat du futur, les projections de deux modèles climatiques (HadGEM2-ES et MIROC5) du Projet d'Inter comparaison de modèles couplés, phase 5 (*Coupled Model Intercomparison Project phase 5*, CMIP5) ont été utilisées. Ces deux modèles ont été considérés sous deux des scénarios climatiques (RCP 4.5 et RCP 8.5) développés par le Groupe Intergouvernemental d'Experts sur l'Evolution du climat (GIEC) dans son cinquième rapport. La carte du réseau d'aires protégées du Bénin obtenue de la base mondiale de données sur les aires protégées a été utilisée pour évaluer leurs potentialités à conserver l'espèce sous les climats présent et futur. Seules les variables bioclimatiques les moins corrélées (r < 0.85) ont été sélectionnées et utilisées dans le processus de modélisation. Le test de Jackknife a été utilisé pour déterminer l'importance des variables dans la distribution de l'espèce. Pour l'évaluation du modèle, 25 % des points de présence de l'espèce ont été utilisés pour l'entrainement et les 75 % restants pour la calibration du modèle. La validation croisée du modèle a été répétée cinq fois afin d'obtenir des estimations performantes. Les statistiques AUC (*Area Under the Curve*) et TSS (*True skill statistic*) ont été utilisées pour évaluer les performances du modèle. La qualité des habitats pour l'espèce a été évaluée à partir de la distribution de la probabilité logistique d'occurrence de l'espèce générée par le modèle en utilisant la valeur du dixième percentile de présence (*10th percentile training presence logistic threshold*) comme seuil. Ainsi, un habitat est considéré comme favorable lorsque la probabilité de présence de l'espèce à cet endroit est supérieure au seuil. Dans le cas contraire, l'habitat est considéré comme non favorable. Une analyse des lacunes de représentation (*gap representation analysis*) des habitats favorables à l'espèce dans les aires protégées a été effectuée en superposant les résultats de la modélisation à la carte du réseau d'aires protégées du pays. Les proportions d'habitats favorables et non favorables ont été estimées pour chacun des modèles climatiques.

Résultats et discussion

Les résultats confirment que le prunier noir est une espèce agroforestière à usages multiples et diversement appréciée par les populations. Le nombre d'utilisations mentionnées par enquêté varie faiblement d'une zone climatique à une autre (df = 2, p-value = 0,045), avec les valeurs les plus élevées dans les zones soudanienne (3,16 ± 1,41) et guinéenne (3,15 ± 1,28). Par contre, des variations très significatives du nombre d'utilisations ont été observées entre groupes ethniques (df = 21, p-value < 0,001) et entre catégories d'âge (df = 1, p-value = 0,003). Ces différences dans les valeurs d'usage de l'espèce peuvent être dues à de nombreux facteurs notamment les us et coutumes, les expériences acquises et la disponibilité de ressources alternatives. Les fruits et les jeunes feuilles de l'espèce sont les organes les plus utilisés. L'alimentation (consommation directe des fruits murs et préparation de sauces à partir des jeunes feuilles) et la phytothérapie (utilisation des organes de la plante pour le traitement des maladies) sont les formes d'utilisation les plus importantes. En général, tous les interviewés ont perçu que les paramètres climatiques changent. Bien que ces perceptions dépendent des ethnies et de la location des enquêtés, la réduction de la longueur des saisons pluvieuses (27,46 %) et l'augmentation de la température (26,1 %) sont les perceptions les plus mentionnées. Selon les populations locales, ces changements ont des impacts sur la biologie et la productivité de l'espèce. Ainsi, les impacts potentiels mentionnés sont : (i) réduction de la productivité, (ii) retard dans la floraison et la fructification, (iii) réduction de la longueur de la période de fructification, et (iv) les perturbations de la croissance. Ces impacts mentionnés dépendent aussi de l'ethnie et de la location des enquêtés. Ces résultats corroborent les études antérieures sur les perceptions locales sur les changements climatiques et suivent aussi les tendances climatiques observées dans les trois zones climatiques du pays. Néanmoins, en ce qui concerne les impacts potentiels de ces changements sur l'espèce, les données d'observations sur de longues périodes sont indispensables pour renforcer l'opinion des populations locales.

L'étude de l'écologie et des paramètres structuraux de l'espèce montrent que la fréquence d'observation et l'abondance du prunier noir le long des transects sont relativement faibles (0,65 – 0,91 contact en moyenne par transect, et 1,62 – 1,71 individus en moyenne par contact) et ne varient pas significativement d'une zone climatique à une autre (df = 2, p-value > 0,05). Mais le type de couvert végétal ainsi que la proximité des cours d'eau ont des effets significatifs sur la fréquence d'observation de l'espèce. Quelle que soit la zone climatique, *V. doniana* est plus observée dans les champs et jachères d'une part, et dans les zones situées à moins de 500 m d'un cours d'eau d'autre part. Le fait que l'espèce est préservée dans les espaces agricoles compte tenu de sa grande importance socio-économique pourrait expliquer ces fortes fréquences d'observation dans les champs et jachères. Aussi, la proximité des cours d'eau serait un facteur clé pour son établissement. En considérant l'environnement local du prunier noir, l'étude révèle que l'espèce n'est pas suivie par le même cortège floristique. Les paramètres structuraux notamment le diamètre moyen (Dg) et la surface terrière (Ba) de l'espèce sont sous l'influence des facteurs en considération et leurs interactions. Les effets combinés de la zone climatique et du couvert végétal apparaissent les plus importants sur ces paramètres structuraux. Dans les zones climatiques extrêmes (guinéenne et soudanienne) par exemple, les fortes performances de l'espèce sont observées dans les champs et jachères. L'absence de compétiteurs de taille autour de l'espèce dans ces milieux et aussi les effets indirects des intrants agricoles et d'autres pratiques culturales peuvent avoir favorisé cette situation. Néanmoins, les densités d'individus adultes ainsi que de la régénération sont faibles et ceci pourrait constituer une menace pour la survie de l'espèce. Les structures en diamètre de l'espèce montrent la prédominance des juvéniles (dbh entre 5 et 30 cm). Ceci pourrait suggérer que la population de l'espèce est très jeune. Mais compte tenu des densités faibles observées pour sa régénération, si des mesures de gestion durable ne sont pas mises en œuvre pour favoriser et suivre cette régénération, la survie de l'espèce pourrait être affectée par de rapides déclins de sa population à cause des fortes pressions anthropiques.

La caractérisation morphologique révèle aussi que des adaptations ont été développées par l'espèce en relation avec les conditions climatiques. Les résultats confirment qu'il existe une importante variabilité des traits morphologiques de l'espèce et que le climat a une contribution non négligeable dans l'expression de cette variabilité. En effet, la plupart des traits morphologiques présentent des coefficients de variation élevés et cela suggère l'existence d'une hétérogénéité dans les populations de l'espèce. Cette forte hétérogénéité au sein des populations peut être vue comme un résultat de l'adaptation de l'espèce aux divers habitats et contribue de ce fait à l'augmentation des chances de l'espèce à survivre aux menaces comme le changement climatique. Malgré les différences significatives observées entre les zones climatiques pour tous les traits morphologiques exceptés le diamètre moyen du houppier, la part de variabilité due aux zones climatiques est relativement faible. C'est plutôt au niveau des individus que la part de la variabilité des traits morphologiques est importante. C'est résultats suggèrent que la variabilité morphologique du prunier noir est probablement due au génotype. Toutefois, des spécificités morphologiques ont été notées sur l'espèce selon les zones climatiques. Par exemple, les résultats de l'analyse discriminante ont montré que sept des variables morphologiques permettent de caractériser les populations de l'espèce selon les zones climatiques. Les arbres de la zone soudano-guinéenne par exemple sont les plus hauts, avec de grand houppier et des feuilles plus grandes ayant souvent plus de cinq folioles. Les arbres de la zone soudanienne sont par contre les plus gros; leurs feuilles présentent des pétioles de petit diamètre à la base; ils produisent des fruits avec très peu de pulpe. Par contre, les arbres de la zone guinéenne présentent des caractéristiques divergentes par rapport à ceux de la zone soudanienne. Ces résultats ont été renforcés par l'analyse canonique de redondance qui a montré qu'il existe une relation entre les traits morphologiques discriminants et les variables bioclimatiques. Même si l'influence de ces variables bioclimatiques sur la morphologie de l'espèce est relativement faible, les impacts du climat, notamment ceux des paramètres climatiques extrêmes (température et pluviométrie du trimestre le plus chaud, l'amplitude thermique annuelle, la saisonnalité de la température et de la pluviométrie) sur la morphologie de l'espèce sont évidents. De ces résultats, nous pouvons dire que l'espèce a développé des stratégies d'adaptations au climat et que des changements dans les facteurs climatiques pourront induire encore d'autres adaptations morphologiques importantes.

L'analyse des caractéristiques des cernes de bois a aussi révélé des ajustements dans l'anatomie du bois de l'espèce suivant les zones climatiques. Tout d'abord, l'étude a montré l'existence de cernes distincts dans la majorité de disques. En se basant sur le fait que le prunier noir renouvelle ses feuilles une fois l'an, la formation des cernes a été considérée comme intervenant également de façon annuelle. Ainsi six disques sur les sept collectés par zone climatiques ont été bien datés avec des valeurs du coefficient de coïncidence (*Gleichläufigkeitk*, GLK) et celle de la corrélation inter-série au-dessus de 60 % et 0,32 respectivement. Les deux zones climatiques ont montré l'existence de signaux communs à cause des valeurs de corrélations inter-séries et de signal exprimé par la population (*Expressed Population Signal*, EPS) élevées. La croissance radiale annuelle est identique dans les deux zones climatiques (0,89 et 0,79 cm/an pour la zone soudanienne et guinéenne respectivement), avec une grande variation interannuelle de la largeur des cernes (sensitivité moyenne élevée). L'autocorrélation de premier ordre (AR1) est faible dans les deux zones climatiques, ce qui révèle que la croissance de l'année écoulée n'a pas d'effets significatifs sur celle de l'année à venir. Les deux zones climatiques présentent ainsi des chronologies similaires (GLK = 52 % ; corrélation de Pearson = 0,39 ; p-value = 0,01). Au sein des zones climatiques, il n'y a pas de variations significatives des caractéristiques des vaisseaux d'un cerne à un autre, mais des variations importantes ont été plutôt observées sur ces paramètres entre arbres. Entre zones climatiques, toutes les variables des vaisseaux varient significativement (p-value < 0,05). Les vaisseaux des arbres de la zone guinéenne sont plus grands et plus circulaires, engendrant ainsi une plus grande porosité par cerne. Néanmoins, dans les cernes des arbres de la zone soudanienne, les vaisseaux de taille réduite sont plus abondants (10,06 vaisseaux/mm^2 contre 6,71 vaisseaux/mm^2 dans la zone guinéenne). Ces différences peuvent être dues à la disponibilité de l'eau qui est apparemment plus élevée dans la zone guinéenne. Ainsi, la production de grands vaisseaux en nombre réduit dans les cernes des arbres de la zone guinéenne est probablement une réponse des arbres à la forte disponibilité de l'eau par l'augmentation de la conductivité hydraulique. Par contre, la production de nombreux petits vaisseaux dans la zone soudanienne est due à la faible pression de turgescence étant donné que les petits vaisseaux sont plus résistants à l'embolisme dû au manque d'eau que les larges vaisseaux. En ce qui concerne les corrélations entre les variables morphologiques et les caractéristiques de l'anatomie du bois, seule la densité des vaisseaux est significativement corrélée au diamètre des arbres et à l'épaisseur de l'écorce dans la zone soudanienne et guinéenne respectivement. Les chronologies résiduelles des largeurs de cernes sont corrélées avec de nombreux paramètres climatiques notamment ceux de la température. C'est seulement au niveau des arbres de la zone guinéenne que la pluviométrie du mois de Septembre a un effet significatif sur la chronologie des largeurs de cernes. Par contre, de nombreux paramètres de la pluviométrie sont significativement corrélés aux variables des vaisseaux. Ceci suggère que les caractéristiques des vaisseaux révèlent plus d'informations climatiques que les chronologies des largeurs de cernes. Ces résultats montrent que le prunier noir a des potentialités pour les études dendrochronologies en Afrique tropicale. Néanmoins des techniques plus performantes d'analyse des cernes peuvent être envisagées afin de mieux approfondir ces résultats.

Le modèle de distribution des habitats potentiellement favorables à la culture et à la conservation de l'espèce sous les climats présent et futur a montré de très bonnes performances (AUC = 0,92 ± 0,02 ; TSS = 0,72 ± 0,01). Les paramètres bioclimatiques tels que la pluviométrie moyenne annuelle, l'amplitude thermique diurne moyenne annuelle et la température moyenne du trimestre le plus chaud sont les prédicteurs contribuant le plus à la distribution de l'espèce. Sous le climat actuel, environ 85 % de la superficie du Bénin est potentiellement favorable à la culture de l'espèce. Cette proportion d'habitats potentiellement favorables à la culture de l'espèce va augmenter sous les projections climatiques à l'horizon 2050 (sous HadGEMS-ES : + 4,81% et + 12,44 % respectivement pour RCP 4,5 et RCP 8,5; sous MIROC5 : + 9,15 % et 3,06 % pour RCP 4,5 et RCP 8,5 respectivement). En ce qui concerne la conservation de l'espèce, environ 76 % de la superficie du réseau national d'aires protégées est potentiellement favorable à sa conservation. Le climat à l'horizon 2050 fera augmenter cette proportion d'aires favorables à la conservation de l'espèce par les aires protégées avec le modèle HadGEM2-ES présentant les fortes tendances (+ 20,71 % et + 23,27 % pour RCP 4,5 et RCP 8,5 respectivement). Les changements les plus importants se feront dans le parc national du W, dans la zone soudanienne où les pluviométries actuellement souvent en dessous de 700 mm par an vont augmenter jusqu'à 900 mm/an. Néanmoins, malgré les impacts potentiellement positifs des projections climatiques sur la répartition des aires favorables à la culture et à la conservation de l'espèce dans le pays, sa productivité pourrait ne pas suivre la même tendance. En effet, s'il est probable que l'espèce ait eu à faire des adaptations physiologiques pendant dans millénaires pour survivre dans divers habitats, son expansion dans de nouvelles aires sous le changement climatique brusque de ce centenaire pourrait engendrer d'importants ajustements plus consommateurs en terme d'énergie et ceci pourrait affecter la productivité de l'espèce. Pour cela, des études sur le long terme sont recommandées sur la physiologie, la phénologie et la productivité de l'espèce dans l'aire climatique afin de disposer d'une base consistante de données pour les politiques de domestication et de gestion durable de l'espèce.

Conclusion et perspectives de recherche

Cette étude sur *Vitex doniana*, une espèce agroforestière clé, avec un accent particulier sur son ethnobotanique, son écologie, sa morphologie, sa croissance radiale, l'anatomie de son bois et la distribution des habitats favorable à sa culture et à sa conservation a été effectuée au Benin afin de capitaliser les informations sur ses capacités à résister aux défis climatiques. Ces informations sont d'une importance capitale pour les programmes de domestication et de conservation de l'espèce dans le contexte des changements climatiques. Ainsi, l'étude nous a permis de capitaliser les connaissances traditionnelles sur les utilisations de l'espèce, les perceptions locales sur les changements climatiques et leurs impacts potentiels sur la biologie et la productivité de l'espèce. Elle a surtout permis de comprendre certains des mécanismes écologiques, morphologiques, anatomiques et biogéographiques d'adaptation développés par le prunier noir pour suivre dans divers environnements climatiques. A cause de ces mécanismes d'adaptations développés par l'espèce pour survivre dans diverses zones climatiques, l'espèce peut être considérée comme une opportunité pour les programmes de domestication et aussi pour son intégration dans les approches d'adaptation basées sur les écosystèmes.

Bien que l'étude ait fourni des informations utiles pour le développement des systèmes de gestion durable et de domestication de l'espèce dans le contexte de la variabilité du climat, il sera très intéressant d'envisager des études complémentaires afin d'approfondir les résultats obtenus.

En effet, étant donné que les fruits et les jeunes feuilles ont été signalés comme les organes les plus utilisés, les impacts de la fréquence de récolte de ces organes sur la viabilité de l'espèce devraient être étudiés afin de fournir des informations supplémentaires pour sa gestion durable.

En outre, en ce qui concerne les impacts du changement climatique sur les espèces, des preuves empiriques devraient être fournies au moyen d'études à long terme sur la phénologie, la physiologie et la productivité de l'espèce afin d'élucider ces opinions.

Du point de vue écologique, étant donné que de faibles densités de régénération et des individus adultes de l'espèce ont été notés à travers le pays, une surveillance biologique de la dynamique de la population de l'espèce est nécessaire afin de prévenir les risques imprévisibles.

En ce qui concerne la morphologie de l'espèce, compte tenu de la forte part de la variabilité observée au sein de l'arbre, des études génétiques sont recommandées afin d'améliorer les connaissances sur le génotype de l'espèce en rapport avec le climat et aussi d'aider à développer des schémas de sélection et de domestication en rapport avec le climat.

De plus, un approfondissement des études des cernes de bois de l'espèce avec l'utilisation d'isotopes pourrait être utile pour comprendre les impacts du climat passé sur l'espèce et pour prédire son avenir.

Enfin, au regard des résultats sur la dynamique de l'aire de répartition géographique de l'espèce, les performances de l'espèce dans les nouvelles aires potentielles devraient être évaluées à travers des études de long terme sur sa productivité dans ces zones.

En dehors de toutes ces études complémentaires recommandées, il sera très intéressant d'évaluer (i) les capacités de germination, (ii) la croissance juvénile et la productivité foliaire de l'espèce en relation avec les zones climatiques; et (iii) les potentialités de séquestration du carbone par l'espèce. Ces études supplémentaires seront sûrement utiles pour l'utilisation de cette espèce dans les approches écosystémiques d'adaptation au changement climatique.

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Présentée par **Achille HOUNKPEVI**

Theme : **ETHNOBOTANY AND ECOLOGICAL ADAPTATION OF THE BLACK PLUM (*VITEX DONIANA* SWEET) TO CLIMATIC CONDITIONS IN BENIN, WEST AFRICA : IMPLICATIONS FOR CONSERVATION AND DOMESTICATION**

Vu et approuvé
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Directeur GRP WASCAL
Coordonnateur CEA-CCBAD

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Félix HOUPHOUËT-BOIGNY

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ABSTRACT

Climate change is projected to highly impact biodiversity components such as ecosystems and organisms. Through this work, *Vitex doniana* Sweet, one of the top ten priority species for domestication programs in West Africa was used to understand some of the mechanisms developed by plants to fit in various climatic environments. Uses values and perceptions of local people on climate change and its impacts on the biology and productivity of species were assessed through ethnobotanical survey. Ecology, structural parameters and the morphological variability of the species were assessed along transects within climatic zones of Benin. Radial growth and wood anatomical patterns of the species were studied in the two extreme (wet vs. dry) climatic zones using tree rings. Finally, impacts of current and future climates on the habitat suitability for cultivation and *in situ* conservation of the species were assessed through species distribution modelling using the Maximum Entropy algorithm (MaxEnt). The findings confirmed that *V. doniana* is an important agroforestry species diversely appreciated by local people depending on their ethnicity and age category. Shortening of rainy season's length and temperature raising are the most reported perceptions on climate change. According to local people, these changes affect negatively the biology and productivity of the species. Regarding the ecology of the species, whatever the climatic zone, the species is more frequent in mosaics of croplands and fallows, and in areas close to river (less than 500 m). Structural parameters, mainly mean diameter (Dg) and basal area (Ba) of the species are under combined effects of climatic zone and land cover. The study revealed a relatively low climate-induced variability of morphological traits. Trees from the Sudanian region are the biggest, with fruits producing little pulp while individuals from the Guinean zone present a higher amount of pulp. Sudano-Guinean trees are the tallest with larger leaves. As far as the tree-ring analysis is concerned, trees from both climatic zones show common signal with a similar annual radial growth rate (0.8 cm/year). Vessels features vary significantly between stands with larger and more circular vessels in the Guinean zone. However, vessels are more abundant in rings from Sudanian trees. Finally, under current climatic conditions, about 85 % of Benin area is potentially suitable for the cultivation of *V. doniana* and, increase of 3 to 12 % of this habitat is projected under future climatic conditions for the year 2050. Moreover, a large proportion (76.28 %) of the national PAN was reported as potentially suitable for the *in situ* conservation of the species under current climate. This proportion is also projected to increase by 14 to 23 % under future climate. These findings highlighted some of the opportunities of integrating the black plum in the formal production systems of Benin and also its potentialities for ecosystem-based adaptation approaches implementation.
Keywords: Benin, climate change, neglected and underutilized species, plant ecology, plant morphology, species distribution, *Vitex doniana*, wood anatomy

RESUME

Les changements climatiques ont d'importants impacts sur les composantes de la biodiversité tels que les écosystèmes et les organismes. A travers ce travail, *Vitex doniana* Sweet, une des dix espèces agroforestières prioritaires pour les programmes de domestication en Afrique occidentale, a été utilisée pour comprendre certains des mécanismes développés par les plantes pour s'adapter à différents environnements climatiques. Les valeurs d'usage et les perceptions des populations locales sur les changements climatiques et ses impacts sur la biologie et la productivité de l'espèce ont été évaluées à travers des enquêtes ethnobotaniques. L'écologie, les paramètres structuraux et la variabilité morphologique de l'espèce ont été évalués le long de transects au sein des zones climatiques du Benin. La croissance radiale et l'anatomie du bois de l'espèce ont été étudiées dans les deux zones climatiques extrêmes (humide vs. sèche) du pays en utilisant les cernes de bois. Enfin, les impacts des climats actuel et futur sur les habitats favorables à la culture et la conservation de l'espèce ont été évalués à travers la modélisation de sa niche climatique en utilisant l'algorithme du maximum d'entropie (MaxEnt). Les résultats confirment que *V. doniana* est une importante espèce agroforestière diversement appréciée par les populations locales selon leur ethnie et âge. Le raccourcissement de la longueur de la saison pluvieuse et l'élévation de la température sont les perceptions locales les plus signalées en ce qui concerne les changements climatiques. Selon la population locale, ces changements affectent négativement la biologie et la productivité de l'espèce. En ce qui concerne l'écologie de l'espèce, quelle que soit la zone climatique, l'espèce est plus fréquente dans les champs et jachères, et à proximité des rivières (moins de 500 m). Ses paramètres structuraux, notamment le diamètre moyen (Dg) et la surface terrière (Ba) sont sous les effets combinés de la zone climatique et du couvert végétal. L'étude a révélé que le climat induit une variabilité relativement faible des traits morphologiques. Les arbres de la zone soudanienne sont les plus gros, avec des fruits produisant peu de pulpe, alors que ceux de la zone guinéenne présentent une plus grande quantité de pulpe. Ceux de la zone soudano-guinéenne sont les plus grands avec de plus large feuilles. En ce qui concerne l'analyse des cernes, les arbres des deux zones climatiques présentent des signaux communs avec une croissance radiale annuelle similaire (0,8 cm/an). Les caractéristiques des vaisseaux varient significativement entre les zones avec les plus larges et circulaires vaisseaux dans la zone Guinéenne. Toutefois, les vaisseaux sont plus abondants dans les cernes des arbres du Soudanien. Enfin, sous les conditions climatiques actuelles, environ 85% de la superficie du Bénin est potentiellement favorable à la culture de *V. doniana* et, une augmentation de 3 à 12% de cet habitat est projetée sous les conditions climatiques de l'année 2050. De plus, une grande proportion (76,28%) du réseau national d'aires protégées du pays est potentiellement favorable à la conservation de l'espèce sous le climat actuel. Cette proportion aussi augmentera de 14 à 23% sous le futur climat. Ces résultats mettent en évidence quelques-unes des possibilités d'intégration du prunier noir dans les systèmes formels de production au Bénin et aussi ses potentialités pour la mise en œuvre des approches basées sur les écosystèmes pour l'adaptation aux changements climatiques.
Mots clés: Anatomie du bois, Bénin, changements climatiques, espèces négligées et sous-utilisées, écologie des plantes, morphologie des plantes, distribution des espèces, *Vitex doniana*