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Speciality: Climate Change and Biodiversity

CASHEW (*Anacardium occidentale* L.) CULTIVATION IN TOGO (WEST AFRICA): CURRENT AND FUTURE DISTRIBUTION, POTENTIAL OF CARBON SEQUESTRATION, AND ANALYSIS OF THE INTERANNUAL VARIATION OF CARBON ISOTOPE RATIO REGARDING THE CLIMATIC GRADIENT.

AGBOKA Kossi-Messan Jacques

Public defense on Saturday, 28th June 2025

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PROGRAMME DE RECHERCHE DE TROISIÈME CYCLE CHANGEMENT CLIMATIQUE ET BIODIVERSITÉ

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Spécialité : Changement Climatique et Biodiversité

CULTURE DE L'ANACARDE (*Anacardium occidentale* L.) AU TOGO (AFRIQUE DE L'OUEST) : DISTRIBUTION ACTUELLE ET FUTURE, POTENTIEL DE SEQUESTRATION DU CARBONE, ET ANALYSE DE LA VARIATION INTERANNUELLE DU RAPPORT ISOTOPIQUE DU CARBONE EN FONCTION DU GRADIENT CLIMATIQUE.

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DEDICATION

First and foremost, I dedicate this thesis to the Almighty GOD for His goodness throughout my life. Second, I dedicate this work to my mother, Odette A. KOUGBLENOU, and my late father, Komlan AGBOKA, from wherever you are, know that your wisdom has led me through my everyday life, and I am now a full-grown man.

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LIST OF ABBREVIATION

C Carbon

CNSL cashew nut shell extracts

DOC Dissolved Organic Carbon

GHG Greenhouse gases

IPCC Intergovernmental Panel on Climate Change

PBZ Paclobutrazol

POM Particulate Organic Matter

SCP Single Cell Protein

SDM: Species Distribution Modelling

SOC Soil Organic Carbon

SOM Soil Organic Matter

SORAD Société régionale d'aménagement development

TOGOFRUIT Office National de promotion et de développement des cultures

UNFCCC United Nations Framework Convention on Climate Change

USDA United States Department of Agriculture

WRB World Reference Base

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ABSTRACT

Cashew cultivation is gaining importance in Togo, as it has throughout Sub-Saharan Africa, due to recent trade developments in the two primary products: cashew kernels and cashew balm. The species' cost-effectiveness encourages producers to create new plantations in places that are not always conducive to its growth. Therefore, this study aimed to investigate (1) the assessment of the current distribution of cashew trees in Togo, (2) the prediction of the potential effect of climate change on the distribution of the habitat of *Anacardium occidentale* L. in Togo, (3) the evaluation of the organic carbon stock in the cashew plantations, in Togo regarding the climate gradient; (4) the examination inter-annual variability of carbon isotope ratios of cashew tree in the humid and dry cashew nut production zones with climatic parameters. The study used 2538 occurrence data and 17 soil and environmental parameters, HadGEM3-GC3.1-L and MIROC6 models to predict current and future appropriate habitats under two Shared Socioeconomic Pathways (SSP245 and SSP585) by 2050 and 2070. To measure carbon stock in the biomass, allometric equations were utilized and soil carbon stock was assessed using laboratory analysis**.** The climatic parameters were used to correlate with the $\delta^{13}C$ values to be measured in the stem disks over a period of eight (08) years. According to the present model, 78.92% of Togo's topography is very favourable to sustainable cashew-growing practices. According to the MOROC6 Model, very favourable cashew nut production areas will be decreased to 5.24% in the SSP 245 scenario and altogether disappear with the SSP585 scenario by 2050. The Guinean zone has a higher soil carbon stock (86.89 ± 4.06 t C/ha) compared to the Sudanian zone (80.23 ± 3.78 t). The same trend can be observed in the various cashew tree components (trunk, branches and leaves), the tree trunk had 79% of the carbon stock, compared to 19% and 2% in the branches and leaves, respectively. One particular individual of cashew (BI) located in the dry cashew production zone (Soudanian climate) in Togo shows a positive and significative correlation between $\delta^{13}C$ and temperature ($r = 0.722$; $p<0.05$), making it a useful proxy for temperature reconstruction

Keywords : Suitable habitat, *Anacardium occidentale* L., carbon sequestration, carbon isotope, Togo

RÉSUMÉ

La culture de l'anacarde prend de l'importance au Togo, comme dans toute l'Afrique subsaharienne, en raison de l'évolution récente du commerce des deux principaux produits : les amandes de cajou et le baume de cajou. La rentabilité de l'espèce incite les producteurs à créer de nouvelles plantations dans des endroits qui ne sont pas toujours propices à sa croissance. Cette étude a donc été menée pour(1) évaluer de la distribution actuelle des anacardiers au Togo, (2) prédire l'effet potentiel du changement climatique sur la distribution de l'habitat d'*Anacardium occidentale* L. au Togo, (3) évaluer le stock de carbone organique dans les plantations d'anacardiers, au Togo en fonction du gradient climatique, (4) examiner la variabilité interannuelle des ratios isotopiques de carbone de l'anacardier dans les zones humides et sèches de production d'anacardiers avec des paramètres climatiques. Deux milles cinq cent trente-huit (2538) données d'occurrence et 17 paramètres pédologiques et environnementaux, ainsi que les modèles HadGEM3-GC3.1-L et MIROC6 ont été utilisés pour prédire les habitats appropriés actuels et futurs en utilisant deux Shared Socioeconomic Pathways (SSP245 et SSP585) d'ici 2050 et 2070. Pour mesurer le stock de carbone dans la biomasse, des équations allométriques ont été utilisées et le stock de carbone du sol a été évalué à l'aide d'analyses au laboratoire. Les paramètres climatiques ont été utilisés pour corréler les valeurs de $\delta^{13}C$ à mesurer dans les rondelles de tige sur une période de huit (08) ans. Selon le présent modèle, 78,92% de la topographie du Togo est très favorable aux pratiques de culture durable de l'anacarde. Selon le modèle MOROC6, les zones de production d'anacarde très favorables seront réduites à 5,24% dans le scénario SSP 245 et disparaîtront complètement avec le scénario SSP585 à l'horizon 2050. La zone guinéenne a un stock de carbone du sol plus élevé (86,89 ± 4,06 t C/ha) par rapport à la zone soudanienne (80,23 ± 3,78 t). La même tendance peut être observée dans les différents composants de l'anacardier (tronc, branches et feuilles), le tronc de l'anacardier contient 79% du stock de carbone, contre 19% et 2% dans les branches et les feuilles, respectivement. Un individu particulier d'anacardier (BI), situé dans la zone sèche de production d'anacarde (climat soudanien) au Togo, montre une corrélation positive et significative entre $\delta^{13}C$ et la température ($r= 0,722$; $p<0,05$), ce qui en fait un proxy utile pour la reconstruction de la température.

Mots clés : Habitat propice, *Anacardium occidentale* L., séquestration du carbone, isotope du carbone, Togo.

INTRODUCTION

People's high quality of life is based on a healthy natural ecosystem and a livable climate **(IPCC and IPBES, 2021)**. The goals of a number of international initiatives, including the United Nations Sustainable Development Goals (SDGs), the Paris Agreement to the United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity's Strategic Plan for Biodiversity 2011-2020 **(IPCC and IPBES, 2021),** are to protect biodiversity, prevent dangerous climate change and promote an acceptable and equitable quality of life for all. Even though each of these organisations has distinct objectives, they all make it abundantly evident that the problems of biodiversity loss, climate change, and human welfare are intertwined, and that people's high quality of life may be jeopardized if the two crises are not addressed together **(IPBES, 2019)**. Sadly, there has been a significant shift in the world, particularly in the past few decades **(Oguntunde *et al*., 2014).** The Intergovernmental Panel on Climate Change (IPCC) specialists agree on the influence of this phenomenon, which is currently noticeable in every part of the world, despite the fact that the nature and scope of the alterations cannot be precisely measured **(Tidjani and Akponikpè, 2012).** Global climate change is manifested locally through a variety of changes that alter production conditions, according to **Dugué (2012)**. These include: firstly, a change in climate calendars (specifically, a delay in the onset of rains); secondly, variations in the amount of rainfall received annually in many regions, along with longer and more frequent drought spells; and thirdly, an increase in the frequency of extreme phenomena and abnormal events (such as hurricanes, frosts, and abnormally high temperatures). The same author claims that a high degree of temporal and spatial variability at the local level can also be used to explain this phenomenon. It is evident from the IPCC's Assessment Report 6 (AR6) **(IPCC,2022)** that, in addition to natural climate variability, human-induced climate change has resulted in widespread negative consequences and associated losses and damages to people and wildlife, including more frequent and intense extreme events. People, ecosystems and a large percentage of species become vulnerable as a result of this phenomenon of climate variability **(IPCC, 2022)**. Trees in general, and cashew trees in particular, are among the species that are at risk of climate change.

With 5.35 million hectares of plantations in 2011, cashew (*Anacardium occidentale* L.) was one of the first nut crops sold worldwide **(FAO, 2014).** Global economic, social and environmental issues can be resolved by its manufacturing **(Balogoun *et al*., 2014).** According to Food and Agricultural Organisation **(FAO, 2014),** around 950.375 tons of cashew nuts were exported in

2011, valued at 1.12 billion US dollars. Because of its nuts, cashew nut shell juice and balm, cashew is a significant cash crop. Originally from the Caribbean and northeast Brazil, the cashew tree (*Anacardium occidentale* L.) was brought in Africa as a reforestation species and is currently grown in orchards to produce nuts **(Totjssaint-norlet and Giffard, 1961)**. Products made from cashews are frequently utilized. Similar to peanuts, the nut is primarily eaten as an "appetizer". However, it can also be used to make confections (chocolate, honey, etc.) or items for the chocolate business. Nuts can be utilized as powder, granules, or whole nuts in the food sector for cookies, pastries and yoghurts **(Ricau, 2013).** In order to use them as sandwich dough, they can also be processed into butter. Caribbean oil, a caustic oil that is taken from the fruit's shell, is produced by the cashew tree (Contribution of cashew nut production to the second objective of Togo's national development plan: Developing agricultural processing centers). This oil is used as an insulating substance in aviation.

As carbon (C) sinks, cashews serve two essentially distinct purposes, which helps them achieve SDG 13. Cashews store a significant amount of organic carbon (C) in both aboveground and belowground biomass by using photosynthesis to absorb atmospheric CO_2. This is especially important for herbaceous plants with large root systems and perennial trees (cashews). According to **Jansson *et al.* (2010),** sequestering carbon in live biomass is a very short-term (decades to centuries) process; as the plants decompose, the carbon is released back into the atmosphere. Nonetheless, cashew trees can continue to absorb carbon for several centuries, in an ecosystem provided in which they are kept healthy and unaltered. Although cashew biomass can also be gathered and used into long-lasting materials like fiber-cement and composites, its capacity to store carbon is again limited. When carbon from aboveground biomass moves to the roots and into the pool of SOC (Soil Organic Carbon), it can be sequestered for a long time (millennia). It can also be added to the soil in various ways, such as phytoliths or biochar. In addition to their ability to absorb CO_2, cashews can also operate as bioenergy crops, which will reduce greenhouse gas emissions from fossil fuels **(Jansson *et al.*, 2010).**

Traditional medicine uses the cashew tree's bark and apple to cure a variety of illnesses, including bronchitis, cough, diabetes, diuretics, dyspepsia, eczema, fever, intestinal colic, psoriasis, syphilis, ulcers, and urinary tract conditions **(Tuo, 2007).** It demonstrates how cashew nut production contributes to SDG 3, which aims to guarantee healthy lives and advance wellbeing for people of all ages. Many regional recipes are made with the flour that is taken out of the nut. Alcoholic beverages made from its juice bring in a sizable sum of money for its makers. The production of cashew nuts contributes to SDGs 1 and 2, as well as the third goal of Togo's national development plan, which is to consolidate social development and strengthen inclusion mechanisms **(Martin, 2003; Bezerra *et al*., 2007)**. Because of all these uses, cashew cultivation is an activity that helps many countries in the world achieve socio-economic development. Global economic, social, and environmental issues can be resolved by its manufacturing **(Balogoun *et al*., 2014).** Because cashew trees are crucial to the production of nuts, it is important to identify ways to adapt cashew nut production to climate change in order to boost nut productivity. This is because cashew trees are also susceptible to climate change. This vulnerability due to climate change led to the reduction of cashew nut productivity as cause abortion or drying of the flowers, fallen of the leaves and the immature fruits **(Balogoun *et al.*, 2014).** For this reason, **Bello *et al*. (2017)** have analyzed the perceptions of cashew producers, about climate change effect on cashew productivity, to identify the adaptation strategies developed to mitigate them. **Balogoun *et al*. (2016)** also work on the effect of climatic factors on cashew (*Anacardium occidentale* L.) productivity in Benin. In Togo the cashew sector is still young, very few data are available. Very few scientific studies have been carried out on the impact of climate change on cashew tree habitats, studies on the assessment of organic carbon stock in cashew plantations are almost non-existent.

In addition, the IPCC warns in its Assessment Report 6 (AR6) that if global warming continues to climb by 1.5°C in the near future, it would inevitably exacerbate a number of climatic hazards and pose a number of threats to ecosystems and people. Finding strategies for climate mitigation is crucial if we want to keep global warming from approaching 1.5°C in the foreseeable future. We, therefore, decided to conduct this study to identify adaptation strategies to mitigate climate change effect on cashew nut production in Togo (contribution of our study to points 13 and 17 of the first aspiration of the African Union's Agenda 2063 and SDG 13).

From this general problematic arise the following research questions:

- What is the current distribution of cashews trees in Togo?
- What will be the impact of climate change on cashew trees habitat in Togo?
- What is the organic carbon stock in cashew tree plantations according to Togo's climatic gradient?
- Are there climatic signals in the carbon isotope ratios of cashews in humid and dry production zones of the species in Togo?

The first possible answers to these questions, which constitute the study's hypotheses, need to be verified in order to arrive at precise conclusions in this work, are:

- ❖ The favourable areas for sustainable cashew trees-growing practices are concentrated in the north of Togo;
- ❖ The change in the climate will induce an increase of favourable cashew nut production areas;
- ❖ The organic carbon in the cashew trees plantations is the same in the humid and dry zones;
- ❖ There are no climatic signals in the carbon isotope ratios of cashews in humid and dry production zones of the species in Togo.

The main objective of this study is to identify adaptation strategies to mitigate climate change effects on cashew nut production in Togo.

To verify the study hypotheses, this research work has set itself the following specific objectives:

- ❖ To assess the current distribution of cashew tree (*Anacardium occidentale* L.) in Togo;
- ❖ To predict the potential effect of climate change on the distribution of the habitat of cashew (*Anacardium occidentale* L.) in Togo;
- ❖ To evaluate the organic carbon stock in the cashew plantations, in Togo regarding the climate gradient;
- ❖ To examine inter-annual variability of carbon isotope ratios of cashew trees in the humid and dry cashew nuts production zones with climatic parameters.

Achieving these specific objectives will enable us to verify the above hypotheses and answer the research questions raised above.

PART I: LITERATURE REVIEW

I.1 ORIGIN AND DISTRIBUTION OF CASHEW TREE

Figure 1 below shows the worldwide distribution of cashew nut producers. The farmed cashew is said to have started in the restinga (low vegetation found along the sandy coast) in northeastern Brazil. *Anacardium occidentale* is also likely native to the savannas of Colombia, Venezuela, and the Guianas **(Mitchell and Mori, 1987).** It is also a dominating native in central and Amazonian Brazil's cerrados. Early travellers introduced the plant to South America west of the Andes, Central America, the West Indies and finally to the East. **Lautié *et al.* (2001)** claim that the cashew tree expanded spontaneously and naturally in South America, but that its expansion to other continents is the result of human interference. The Portuguese brought it to Mozambique and India between 1563 and 1578 **(Andrighetti, 1994**), before spreading it to South-East Asia. It spread throughout Africa in the second half of the 16th century, beginning on the east coast and progressing westward. The tree then spread to Australia and portions of North America. Cashew tree cultivation in Togo began in 1960 through collective fields managed by the Togolese Ministry of Agriculture's Société Régionale d'Aménagement Development (SORAD) to supply the company TOGOFRUIT (Office National de Promotion et de Développement des Cultures). Production began in colonial times. When TOGOFRUIT closed in 1982, the industry came to an end; it resumed in 2000 **(MAEH, 2015).** Cashew tree is currently farmed in four of the six agricultural zones (Savanes, Kara, Centrale and Plateaux).

I.2 AGROECOLOGY OF CASHEW TREE

Figure 2 below shows an illustration of the cashew tree in its ecosystem. Cashew grows from 0 to 1,000 meters above sea level. It enjoys high temperatures, with an annual average of 17-38°C, and is particularly frost-sensitive. Low temperatures have been linked to delayed blooming. It is drought resilient because of its deep and broad root system and can flourish in places with just 762-1,275 mm of rainfall per year **(Lim, 2012)**. It thrives in places with uniformly distributed 500-3,500 mm rainfall, a dry spell during the blooming and fruiting season, and relative humidity levels ranging from 65 to 80%. High rainfall and humidity promote illnesses that kill blooms and fruits while reducing fruit set. According to **Lim (2012)** cashew tree can grow in a variety of soils with a pH of 4.3-6.5, ranging from poor sandy soils like bris soils in Terengganu, Malaysia, and slightly saline soils to sterile, very shallow and impervious savanna soils with few other trees or crops, as well as lateritic soils like Cochin and Kerala in India. However, cashew trees are sensitive to poor soil drainage, therefore calcareous or very saline soils, pure clays, and waterlogged soils should be avoided. It grows in deep, rich, friable sandy soils with a pH of 4.5-6.5. Cultivation should take place on almost level sections of red-yellow podzols, quartziferous sands and red-yellow latosol. Bees, wasps, ants, flies, and hummingbirds help pollinate the blooms. The fruits are spread mostly by frugivorous bats and secondly by water.

I.3 BOTANY OF CASHEW TREE

A small, evergreen perennial tree with a low spreading crown (6-12 m), grows to a height of 2-10(−15) m. It has brown or grey bark, smooth to rough, with longitudinal cracks and a deep root system. The leaves are simple, alternate, coriaceous, glabrous, narrowly to broadly obovate, sometimes broadly oblong or elliptic, 10-18 × 8-15 cm, apically rounded or shallowly emarginate or shortly acuminate, entire, cuneate or obtuse at base attenuate or auriculate, prominently veined with 9-14 pairs of widely spreading lateral veins, short petiolate, reddish bronze when young and dark green when mature **(Lim, 2012).** The inflorescence is a subcorymbose, terminal panicle that is 10-25 cm long, branched, and sparsely to densely puberulous near the apices of rachises. It commonly bears male, female and hermaphroditic flowers that are white or pale green with red or pink lines at anthesis and turn dark red after fertilization (figure 3). Male flowers are the most frequent, with five in number. They normally have one exserted stamen and nine little inserted ones, as well as a small pistillode about 0.3-1 mm in length. Bisexual flowers include 5 lanceolate to broadly oblong sepals, a cylindric corolla of 5 petals and 6-10 (−12) stamens with one long exserted stamen, all with normal anthers. The ovary is glabrous, one-locular, and one-ovulate, with a central awl-shaped style and punctiform stigma. In contrast, female blooms have staminodes. The fruit is a reniform achene (nut) approximately 3 cm long and 2.5 cm wide, connected to the distal end of an expanded receptacle and hypocarp, known as the cashew-apple, which is lustrous, orangey, red, or yellowish, pear-shaped or rhomboid-to-ovate, soft, juicy, 10-20 cm long and 4-8 cm wide **(Lim, 2012).** The nut is green when young and dark brown when mature, with an edible yellowish white reniform, hard kernel with two large white cotyledons and a small embryo, surrounded by a hard pericarp made of a double wall separated by honey-combed cellular fibrous tissues filled with a caustic resiny oil.

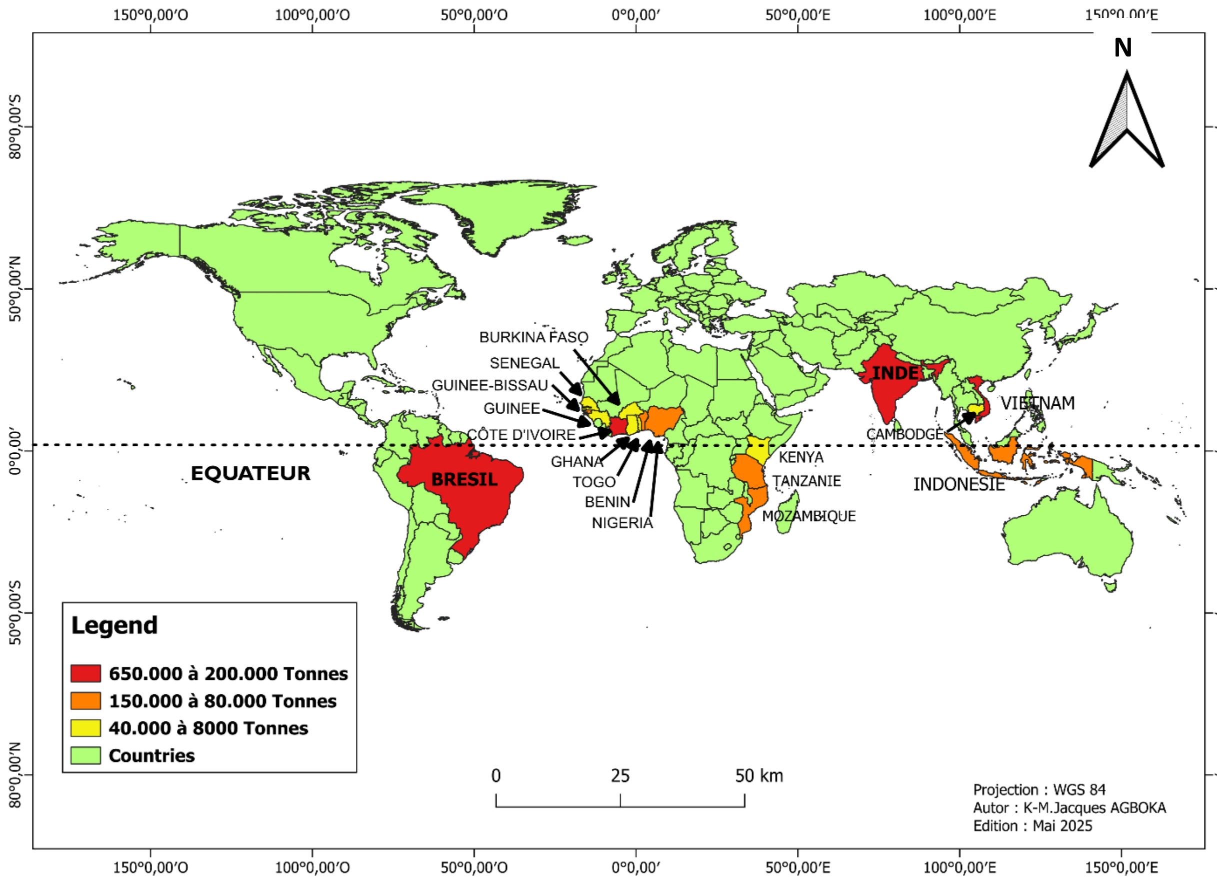

Figure 1: Global geographical representation of cashew nut producers

(Source: **Tall, 2013)**

Figure 2: Photo of a cashew tree in the Tchamba prefecture, Togo
(Source: **Assih and Nenonene, 2022**)

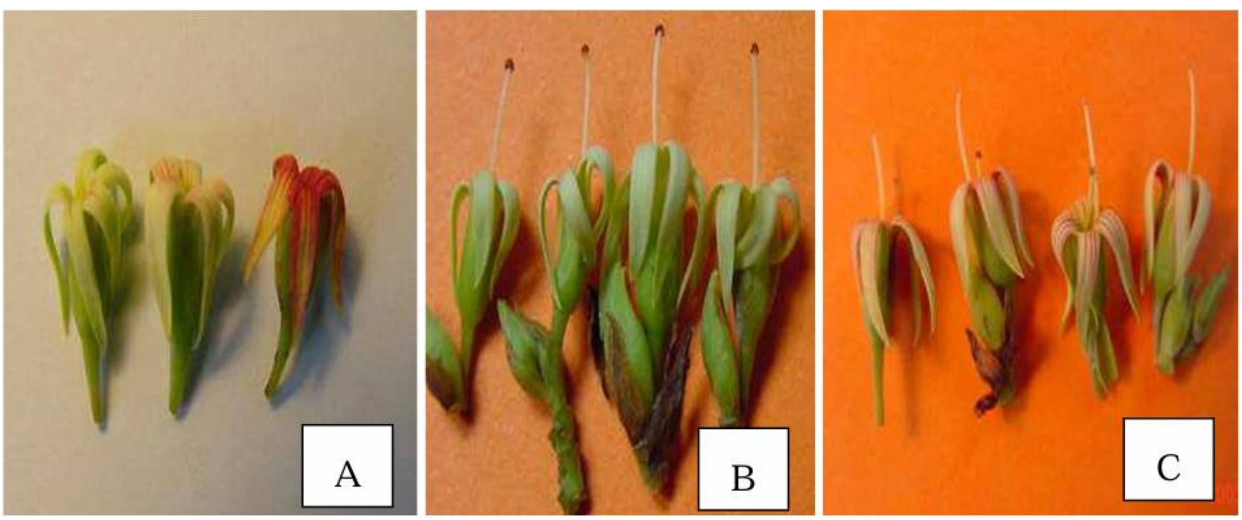

Figure 3: The different types of flowers of cashew tree (A: sterile, B: male and C: hermaphrodite)
(Source: **Semporé *et al.*, 2021**)

I.4 NUTRITIVE AND MEDICINAL PROPERTIES OF CASHEW TREE

I.4.1 Nutritive properties of Cashew tree

Raw cashew nuts (without the pericarp) were found to contain the following proximate composition (per 100 g edible part) in US analyses **(USDA 2010):** Water 5.20 g, energy 553 kcal (2,314 kJ), protein 18.22 g, total lipid 43.85 g, ash 2.54 g, carbohydrates 30.19 g, total dietary fiber 3.3 g, total sugars 5.91 g, Ca 37 mg, Fe 6.68 mg, Mg 292 mg, P 593 mg, K 660 mg, Na 12 mg, Zn 5.78 mg, Cu 2.195 mg, Mn 1.655 mg, Se 19.9 mg, vitamin C 0.5 mg, thiamine 0.423 mg, riboflavin 0.058 mg, niacin 1.062 mg,vitamin E (a-tocopherol) 0.090 mg, b-tocopherol 0.03 mg, g-tocopherol 5.31 mg, d-tocopherol 0.36 mg, vitamin K (phylloquinone) 34.1 mg, total saturated fatty acids 7.783 g, 8:0 (caprylic acid) 0.015 g, 10:0 (capric acid) 0.015 g, 12:0 (lauric acid) 0.015 g, 14:0 (myristic acid) 0.015 g, 16:0 (palmitic acid) 3.916 g, 17:0 (margaric acid) threonine 0.688 g, isoleucine 0.789 g, leucine 1.427 g, lysine 0.928 g, methionine 0.362 g, cystine 0.393 g, phenylalanine 0.951 g, tyrosine 0.508 g, valine 1.094 g, arginine 2.213 g, histidine 0.456 g, ala nine 0.837 g, aspartic acid 1.795 g, glutamic acid 4.506 g, glycine 0.937 g, proline 0.812 g, serine 1.079 g, lutein + zeaxanthin 22 mg. According to the above, cashew nuts are healthy, high in calories, lipids (mostly unsaturated fatty acids) - oleic and linoleic acids, vitamin E (tocopherols), protein, amino acids, vitamin K, and minerals such as Fe, Mg, Zn, Cu, and Selenium. It also contains vitamins B and B6, pantothenic acid, lutein, and zeaxanthin. Nuts such as cashew, Brazil nut, pecan, pinenut, and pistachio include phytosterols, tocopherols, and squalene, all of which have cardioprotective properties.

According to studies conducted in Ireland, the total oil content of cashew nuts ranged from 40.4% to 60.8% (w/w), with peroxide values ranging from 0.14 to 0.22 mEq O2/kg oil. Oleic acid (C18:1) is the most abundant monounsaturated fatty acid, with linoleic acid (C18:2) being the most prevalent polyunsaturated fatty acid **(Ryan *et al.,* 2006).** Total tocopherol levels varied between 60.8 and 291.0 mg/g. Squalene levels varied from 39.5 mg/g oil in the pine nut to 1377.8 mg/g oil in the Brazil nut. B-sites tool was the most common phytosterol, with concentrations ranging from 1325.4 to 4685.9 mg/g oil. The research showed that cashew nuts are an excellent source of unsaturated fatty acids, tocopherols, squalene, and phytosterols. Raw cashew nut kernels were found to possess appreciable levels of certain bioactive compounds such as b-carotene (9.57 mg/100 g of DM), lutein (30.29 mg/100 g of DM), zeaxanthin (0.56 mg/100 g of DM), a-tocopherol (0.29 mg/100 g of DM), g-tocopherol (1.10 mg/100 g of DM), thiamin (1.08 mg/100 g of DM), stearic acid (4.96 g/100 g of DM), oleic acid (21.87 g/100 g of DM), and linoleic acid (5.55 g/100 g of DM) **(Trox *et al.* 2010)**. All conventional shelling methods, including oil-bath roasting, steam roasting, drying, and open pan roasting, significantly reduced these bioactive compounds, whereas the Flores hand-cracking method produced comparable levels of carotenoids, thiamin, and unsaturated fatty acids in cashew nuts to raw unprocessed samples. Cashew apples were discovered to have 87.9% water, 0.2% protein, 0.1% fat, 11.6% carbohydrate, 0.2% ash, 0.01% Ca, 0.01% P, 0.002% Fe, 0.26% vitamin C, and 0.09% b-carotene **(Nair *et al*., 1979; Duke 1983)**. The test was discovered to contain a-catechin, a-sitosterol, 1-epicatechin proanthocyanadins, leucocyanadine and leucopelargodonidine. The nut's dark hue was due to an iron-polyphenol combination. The shell oil included approximately 90% anacardic acid (C_{22} H_{32} O_3) and 10% cardol (C_{32} H_{27} O_4). It produced glycerides, linoleic, palmitic, stearic, and lignoceric acids, as well as sitosterol. Gum exudates were shown to include arabinose, galactose, rhamnose, and xylose **(Moorton, 1987).** The carotenoid content differed between red and yellow cashew apples, as well as two commercial brands of pasteurized cashew juice **(Cecchi and Rodriguez-Amaya, 1981)**. a-carotene, b-carotene, z-carotene, cis-b-carotene, cryptoxanthin, aurochrome, cryptochrome, and auroxanthin, with b-carotene being the most common pigment.

The colour differences indicated the overall quantity, not the type of carotenoid present. Processed juice exhibited reduced total carotenoid and vitamin A levels, but increased epoxide. There were no quantifiable variations between samples from the same brand or across brands of pasteurized juice. Cashew apples are also rich in flavonoids **(de Brito *et al.,* 2007; Michodjehoun-Mestres *et al.,* 2009a)** and tannins **(Michodjehoun-Mestres *et al.,* 2009b)**. The methanol-water extract of cashew apple contained one anthocyanin, 3-O-hexoside of methyl-cyanidin, and thirteen glycosylated flavonols, including 3-O-galactoside, 3-O-glucoside, 3-O-rhamnoside, 3-O-xylopyranoside, 3-O-arabinose pyranose, and 3-O-arabinofuranoside of quercetin, kaempferol 3-O-glucoside, and myricetin **(de Brito *et al.* 2007).** The hydrolyzed extract contained trace quantities of both delphinidin and rhamnetin. Monomeric phenols were recovered from the peel and flesh of four cashew apple genotypes from Brazil and Benin (West Africa) using a 60:40 acetone/water mixture **(Michodjehoun-Mestres *et al.* 2009a).**

Assunção and Mercadante (2003a, b) discovered that cashew apples and their derivatives contain carotenoids and ascorbic acid. **Assunção and Mercadante (2003b)** found b-carotene (16.6-67.9 mg/100 g), b-cryptoxan thin (7.7-64.4 mg/100 g), a-carotene (5.9-51.9 mg/100 g), and 9-cis- + 13-

cis-b-carotene (3.3-15.6 mg/100 g) in fruits from several locations in Brazil. In general, the amounts of carotenoids were higher in the red than in the yellow cashew apples from both areas; for example, the levels of a- and b-carotene were around 1.8 and 1.3 times higher in the red than in the yellow fruits from the Southeast and Northeast. In comparison, the yellow type contained somewhat more ascorbic acid. Elongated red and yellow fruits also had somewhat more ascorbic acid than globose red fruits. The overall carotenoid concentration of the globose red fruits was 1.5 and 1.7 times lower than that of the yellow and red cultivars, all of which originated in the Northeast. Yellow fruits from the Northeast had 1.7 times more provitamin A than those from the Southeast, but red varieties had equal amounts. The yellow and red types from the Northeast had non-significantly greater ascorbic acid levels than those from the Southeast.

According to **Assunção and Mercadante (2003a),** concentrated juice, frozen pulp, nectar, ready-to-drink, and sweetened concentrated juice had ascorbic acid concentrations ranging from 13.7 to 121.7 mg/100 g and total carotenoid levels ranging from 8.2 to 197.8 mg/100 g. The bulk of the goods included b-carotene as the leading carotenoid, followed by a-carotene, b-cryptoxanthin, and 9-cis- +13-cis b-carotene in almost equal quantities. However, in 10 of the 60 samples examined, another carotenoid profile was discovered, containing auroxanthin, 5,8-epoxy-cryptoxanthin, 5,8-epoxy-lutein, z-carotene, and two unidentified carotenoids. Cashew apple products have been shown to be excellent sources of vitamin C but not particularly good sources of carotenoids in the human diet. When compared to other tropical fruits such as pineapple, orange, grapes, mango, and lemon, cashew apple juice contains the most vitamin C (203.5 mg/100 ml) per edible portion **(Akinwale, 2000)**. Orange, grape, pineapple, mango, and lemon juices had average vitamin C levels of 54.7 mg, 45.0 mg, 14.70 mg, 30.9 mg, and 33.7 mg per 100 ml, respectively. It was discovered to have about four times the amount of vitamin C found in popular citrus fruits, as well as more than four times that of other fruits. As a result, blending cashew apples with other tropical fruits increased their nutritional value. In contrast, these fruits increased the acceptability of cashew juice in terms of taste and flavor. Consumers found the mixes satisfactory, despite their major differences in flavor, color, and texture. Cashew apple nectar, a byproduct of cashew nut processing, was discovered to have an unusual tropical scent. The aroma volatiles in pasteurized and reconstituted (from concentrate) Brazilian cashew apple nectars were identified as methional, (Z)-1,5-octadien-3-one, (Z)-2-nominal, (E, Z)-2,4-decadienal, (E, E)-2,4-decadienal, b-damascenone, and d-decalactone **(Valim *et al.*, 2003).** These molecules, along with butyric acid, ethyl 3-methylbutyrate, 2-methylbutyric acid, acetic acid, benzaldehyde, homo furaneol, (E)-2-nonenal, g-dodecalactone, and an unknown, were the most potent aroma volatiles. In the reconstituted sample, 36 fragrance volatiles were discovered, whereas 41 were found in the pasteurized sample. Both samples shared thirty-four fragrance active components. Cashew apples were characterized by ethyl 3-methyl butyrate and 2-methylbutyric acid. The first detection of 2-methyl-3-furanthiol and bis(2-methyl-3-furyl) disulfide in cashew apples. Both were aromatic (meaty). Young tender cashew leafy shoots had the following proximate composition per 100 g edible portion **(Tee *and* Khan., 1988):** moisture 89.1%, energy 35 kcal, carbohydrates 4.5 g, fat 0.2 g, protein 3.8 g, fiber 1.5 g, Ash 0.9 g, Ca 53 mg, P 29 mg, Fe 3.5 mg, carotene 2,076 mg, vitamin A 653 mg RE, vitamin B2 1.19 mg, niacin 0.5 mg, vitamin C 91 mg. Cashew leaves also contained 773 mg lutein and 1,324 mg b-carotene **(Tee and Khan, 1988).** The soft green branches of cashew were also high in protein, vitamins A, and C. Anacardic acids were discovered to be the most abundant alkylphenols in both cold-pressed raw and roasted cashew nut oils, followed by cardol, cardanol, and 2-methyl cardol compounds **(Gómez-Caravaca *et al.,* 2010).** With the exception of cardanols, raw and roasted oils had identical compositions. The oil made from roasted cashew nuts has a greater proportion of cardanols. Tocopherol level in raw and roasted cashew nut oil ranged from 171.48 to 29.56 mg/100 g, with b-tocopherol decreasing the most (93.68%). In addition, minor polar molecules in cashew oil dropped after roasting, from 346.52 to 262.83 mg/kg.

I.4.2 Medical properties of Cashew tree

I.4.2.1 Antihypertensive activity of Cashew tree

Tannins in cashew apple (hypocarp) were shown to have antihypertensive properties, supporting the plant's usage in folkloric medicine for the treatment of diabetic mellitus, diarrhea, and hypertension in south Cameroon and other African nations **(Paris *et al.,* 1977).**

I.4.2.2 Larvicidal activity of Cashew tree

Sodium salts of Cashew Nut Shell Extracts (CNSL) and anacardic acids derived from *Anacardium occidentale* also shown strong anti-vectorial action against *Aedes aegypti* larvae **(Laurens *et al.*, 1997).** *Aedes aegypti* larvae and pupae were found to be very sensitive to 12 ppm CNSL, but

Anopheles subpictus larvae and pupae were found to be susceptible to 38 ppm of Cardanol/CNSL solution in laboratory and field settings in Andhra Pradesh **(Mukhopadhyay *et al*., 2011)**.

I.4.2.3 Antiophidian activity of Cashew

Anacardium occidentale bark extract was discovered to inhibit *Vipera russelii* venom hydrolytic enzymes such as phospholipase, protease, and hyaluronidase in a dose-dependent manner **(Ushanandini *et al.,* 2009).** These enzymes are responsible for both local consequences of envenomation, such as tissue damage, inflammation and myonecrosis, as well as systemic effects, such as organ failure and coagulation component alterations. Furthermore, the extract inhibited snake venom-induced pharmacological effects such as oedema, haemorrhage, and myotoxic effects, including mortality. The bark extract inhibited both hydrolytic enzymes and pharmacological effects, the researchers concluded that it could be used as an alternative treatment to serum therapy, as well as a rich source of potential inhibitors of hydrolytic enzymes involved in a variety of physiopathological disorders.

I.4.2.4 Tyrosinase Inhibition activity of Cashew tree

Anacardic acids, 2-methylcardols, and cardols isolated from different portions of the cashew fruit have been shown to suppress tyrosinase activity **(Kubo *et al.,* 1994).** Kinetic studies with the two main active compounds, 6-[8(Z), 11(Z),14-pentadecatrienylsalicylic acid and 5-[8(Z),11(Z),14-pentadecatrienylresorcinol, revealed that both of these phenolic compounds exhibited characteristic competitive inhibition of the oxidation of L-3,4-dihydroxyphenylalanine (L-DOPA) by mushroom tyrosinase. Separate investigations have shown that cashew leaf extract (CLE) has the potential to be utilized as a tyrosinase inhibitor to treat pigmentation disorders **(Sreenivasan and Abdul Gaffar, 2008).** The extract inhibited tyrosinase and decreased melanin in human epidermal melanocytes exposed to the leaf extract for more than 24 hours. The CLE extract also showed strong antioxidant activity. **Kubo *et al*. (2011)** discovered that, while anacardic acids and cardols block tyrosinase, a critical enzyme in melanin formation, melanogenesis in melanocytes was not inhibited but rather accelerated in cultured murine B16-F10 melanoma cells. Both anacardic acids and cardols had considerable cytotoxicity. Cardol triene, isolated from cashew nut shell liquid, was discovered to be a powerful irreversible competitive tyrosinase inhibitor with a complicated mechanism of tyrosinase inactivation **(Zhuang *et al.,* 2010).** Two molecules of cardol triene may attach to one molecule of tyrosinase, resulting in the full loss of catalytic activity.

I.4.2.5 Antiviral activity of Cashew tree

Extracts of *Anacardium occidentale* leaves (4 mg/ml) and Psidium guajava leaves (8 mg/ml) were exclusively effective against simian rotavirus (82.2% and 93.8% inhibition, respectively) **(Gonçalves *et al.,* 2005).** Rotaviruses are well known as the leading cause of diarrhea in newborns and young children in both developed and developing nations. In Brazil, diarrhea is a leading cause of mortality, particularly among infants.

I.5 OTHER TRADITIONAL USES OF CASHEW TREES

Cashew apples, kernels, leaves, bark, wood, and roots have all been used in traditional folk medicine. The leaves, bark, and roots are used to manage and/or control arthritis, diabetes and other inflammatory conditions among Yoruba-speaking people in western Nigeria, as well as to treat diabetes mellitus, diarrhoea and hypertension in Cameroon's south and other African countries. Buds and young leaves are used to treat skin disorders. In Java, aged leaves are used as a paste to treat skin irritations and burns. Pulped leaves are applied to the skin of babies to treat pemphigus neonatorum **(Lim, 2012).** Cashew leaf tea (also known as casho) is a popular diarrhea cure in Peruvian herbal medicine. Cashew leaf teas are used to treat mouth ulcers, tonsillitis and throat disorders, as well as to clean wounds. To cure diarrhea, the Tikuna tribe in northwest Amazonia makes a drink from cashew leaves. Tribals in India utilize leaves and branches as an antibacterial in their postpartum baths. Cashew apples are anti-scorbutic, astringent and diuretic, and are used to treat cholera and renal problems. **Lim (2012)** mentioned that In Java, cashew apple juice is used to treat vomiting, thrush, and catarrh. Cashew syrup is said to be an effective cure for coughs and colds. Cashew apple juice is reported to be useful for treating syphilis and is used to cure sore throats and chronic diarrhea in Cuba and Brazil. In Brazilian herbal medicine, cashew apples are used to treat syphilis as well as a diuretic, stimulant, and aphrodisiac. Fresh or distilled, it is a strong diuretic with sudorific qualities. Brandy is used as a liniment to treat rheumatism and neuralgia. Small dosages of old cashew liquor are effective in treating stomachaches. The kernel serves as a demulcent, emollient and diarrhea remedy **(Lim, 2012).**

The resinous juice of the seeds is used to treat mental disorders, heart palpitations, and rheumatism, as well as memory loss caused by smallpox. Snake bites are treated with powdered seeds to counteract the poison. Cashew nut shell oil has antihypertensive and purgative properties; it is used to treat blood sugar issues, renal difficulties, hookworms, and cholera. on India, the oil is used to treat fissures on the soles of the feet, as well as corns, leprous sores, and warts in Johore, Malaysia. The kernel oil acts as a chemical antidote to irritating toxins and serves as an excellent medium for liniments and other exterior applications. Cashew bark is astringent, counterirritant, rubefacient, and vesicant, and it is used to treat ulcers. The native Sakais of Peninsular Malaysia utilize a bark infusion to treat acute diarrhea and constipation. Root infusion is a great purgative. The Wayãpi tribe in Guyana uses cashew bark tea to treat diarrhea and colic in newborns. In Brazil, cashew bark tea is used as a douche for vaginal discharge, an astringent to halt bleeding after tooth extraction and a diarrhea remedy. Cashew bark is used to treat eczema, psoriasis, scrofula, dyspepsia, genital issues, venereal illnesses, impotence, bronchitis, cough, intestinal colic, leishmaniasis and syphilis-related cashew skin conditions **(Lim, 2012).** Diabetes, weakness, muscle debility, urinary problems and asthma can all be treated with a cashew bark infusion or maceration. A gargle made from bark and leaves is used to treat toothaches, aching gums, and sore throats.

I.6 OTHER USES OF CASHEW TREE

Cashew nut shell oil or liquid (CNSL) is mostly composed of cardanol (decarboxylated anacardic acid), anacardic acids, cardol, and 2-methyl cardol **(Tamura and Kumar, 2002; De Lima *et al.,* 2008)**. It is usually obtained as a byproduct during the kernel extraction process. CNSL has wide industrial applications and is a valuable raw material for a number of polymer-based industries such as paints and varnishes, resins, industrial and decorative laminates, brake linings, lubricants, rubber compounding resins and other synthetic resins (epoxy resins), adhesives, gums, impregnations, sealants for cracks and joints in buildings **(Nair *et al.,* 1979; Ohler, 1979; Murthy and Sivasamban, 1979).** CNLS can be used as a floor covering, preservative to treat, for example, wooden structures and fishing nets, and other technical products **(Nair *et al.,* 1979; Ohler, 1979; Murthy and Sivasamban, 1979)**. CNSL and its derivatives are also employed as bactericides, fungicides, herbicides, insecticides, and in the production of antioxidants and medicines. Rice husk boards with CNSL reside-based resin as a binder are used for artificial ceilings, insulation panels, and acoustic reasons. Several derivatives of 3-penta decyl phenol have been synthesized and utilized to develop effective pesticides and medicinal substances. Cardanol, the primary component of CNSL, is light in colour and is used in lacquers, coatings, insulating varnishes, furniture coatings, and as a medium for quick-drying enamels. CNSL's dark hue makes it unsuitable for use with light-colored finishes. CNSL distillation waste and alky blends are used to make air-drying varnishes, cycle enamels, and primers. The films made from cardanol-based resins and vinyl resins have good characteristics. Cardanolformaldehye resin was reacted with epichlorohydrin to produce pale-colored adhesives. Chemical alteration of cardanol's alkyl side chain can result in the development of polyfunctional compounds, which are then employed to make water-soluble binders and modified alkyd resins **(Madhusudhan and Murthy 1992)**. The qualities of the coatings created from these binders, such as flexibility, hardness, and resistance To water and chemicals, were discovered to be superior to those of coatings based on traditional cardanol media. In Tanzania, CNSL has been used to create tribal markings and scars on the face and body, as well as to preserve fishing lines, books, and chicken eggs. It is also good against termites.

The cake that remains after extracting oil from the kernel is fed to animals. Shell waste is commonly utilized as fuel in cashew nut shell liquid extraction operations. Seed coatings are used for chicken feed. Anacardic acids have been used to treat dental abscesses because they are deadly to Gram-positive bacteria. **Oddoye *et al.* (2009)** discovered that dried cashew pulp, the sun-dried waste left after extracting juice from the cashew apple, may be utilized in developing pig diets at a level of 200 g/kg with no detrimental effects. **Pacheco *et al.* (2010)** discovered that cashew apple bagasse provides an effective support for *Saccharomyces cere visiae* cell immobilization in the generation of ethanol.

Ten sequential fermentations of cashew apple juice for ethanol generation were performed using immobilized Saccharomyces cerevisiae. High ethanol productivity was achieved from the third to the eleventh fermentation test. Ethanol concentrations (approximately 19.82 37.83 g/l, mean value) and productivities (around 3.30-6.31 g/l) were both high and consistent. Residual sugar concentrations were low in virtually all fermentations (approximately 3.00 g/l), with conversions ranging from 44.80% to 96.50%, indicating an efficiency of 85.30-98.52% and operational stability of the biocatalyst for ethanol fermentation. **Araújo *et al.* (2011)** used two yeast strains, SCP and SCT, to ferment cashew apple juice and generate alcohol. The fermented products from both yeast strains included ethanol concentrations greater than 6% v/v and total acidity less than 90 mEq/l, indicating a pH of 3.8-3.9. Methanol was not found. The presence of aldehydes (butyl aldehyde diethyl acetal, 2,4-dime thyl-hepta-2,4-dienal, and 2-methyl-2-pentenal) and esters (ethyl a-methylbutyrate) expressing fruity scent distinguished the volatile chemicals. The SCT strain proved to be more efficient, generating 10% more alcohol than the SCP strain **(Siong *et al.,* 1988)** Wood pulp is used to make corrugated cardboard boxes. The wood known as 'white mahogany' in Latin America is rather durable and utilized in a variety of industrial applications, including wheel hubs, yokes, fishing boats, furniture, false ceilings, and interior design. timber boxes are foldable and robust enough to compete with traditional timber packing containers. Corrugated and hardboard boxes are made from wood pulp. The wood is often used for firewood and charcoal. Wood ash is high in potassium and is thus used as a fertilizer for agricultural plants. The bark produces an unpleasant sap of thick brown resin that is used as indelible ink to mark and print linens and cotton. The resin is also used as a varnish, fishnet preservative, and soldering flux. The stem also produces an amber-coloured gum that is partially soluble in water, with the majority expanding into a jelly-like mass. This gum is employed as an adhesive (for woodwork panels, plywood, and bookbinding), in part due to its insecticidal characteristics. The caustic sap from the bark contains 3-5% tannin and is used in the tanning industry.

I.7 AGRICULTURAL PRACTICES AND CASHEW NUT PRODUCTION

The agricultural techniques used by farmers influence the yield and quality of cashew nuts **(Olubode *et al.,* 2018**). These writers argue that optimizing cashew management strategies can increase cashew's economic, nutritional and industrial performance. Among agroforestry approaches in cashew nut production, fruiting size, stocking density modification and the use of cropping systems to manage weeds demand special attention **(Adiga *et al.,* 2020; Nayak *et al.,* 2020; Olubode *et al.,* 2018)**. Fruiting size increases the number of new buds that produce virtually solely flowers in the cashew tree **(Adiga *et al.,* 2020).** Pruning is also known to increase light interception and photosynthesis. Improving light interception has been shown to increase the production of hermaphroditic blooms in cashew trees **(Murali *et al.,* 2015; Waghmare and Joshi, 2008)**. It should be noted that among the three types of blooms on the cashew tree, hermaphroditic flowers produce the most fruit.

The cashew nut is a multi-year crop, with economic production beginning at eight years old. Tighter cropping patterns can help farmers make their investments more lucrative in a shorter period of time. Unlike other tree crops, cashew canopy development is gradual during the initial years of planting and continues until the 12th year **(Mog *et al.,* 2019)**. A looser cropping plan does not allow for optimal use of space, nutrients, water, or solar radiation, as well as weed management in the early years of orchard establishment **(Mangalassery *et al.,* 2019)**, which is associated with low profitability. However, as the plants grow, the absence of silvicultural techniques such as pruning and thinning leads to a considerable loss in output. To improve plant density, growers can prune plants on a yearly basis or employ plant growth regulators such as paclobutrazol (PBZ) **(Adiga *et al.,* 2020),** which inhibits gibberellin synthesis. If properly maintained, cultural associations can benefit the cashew tree **(Balogoun *et al.,* 2014).** Indeed, cultural associations make orchard upkeep easier, which improves yields. Furthermore, linked crops can boost soil fertility by introducing organic matter into the soil. However, while selecting crops to mix with the cashew tree, consider the host plants of the cashew tree pests, which may contribute to restricting cashew nut production and quality.

I.8 CLIMATIC FACTORS AFFECTING CASHEW NUT PRODUCTION

Cashew farming, which was formerly done only for ecological reasons, has recently become economically important **(Diomandé *et al.,* 2021; Math *et al.,* 2018).** However, most growers still see cashew trees as a marginal crop **(Adejumo *et al.,* 2010)**, therefore they receive little attention. Although resilient, cashew production is influenced by climate variations **(Balogoun *et al.,* 2016; Bello *et al.,* 2016; Datta, 2013; Rupa *et al.,* 2013)**. **Datta (2013)**, discovered that rainfed cashew farming is extremely vulnerable to climate change and weather risks, especially during the reproduction period. Indeed, this author believes that unseasonal rainfall and heavy dew during blooming and fruiting have a detrimental impact on cashew nut productivity and quality. Similarly, droughts drastically diminish cashew output **(Rupa *et al.,* 2013)**. High humidity results in the proliferation of harmful insects and diseases.

Not all climatic factors have the same degree of impact on cashew production. Among these factors, those which have a preponderant effect on the behavior of the cashew tree are four in number: rainfall and the distribution of rainfall over the course of the year, temperature, and sunshine during the flowering and growth period. fruiting and relative humidity **(Goujon *et al.,* 1973; Haldankar *et al.,* 2003).** High humidity promotes the spread of dangerous insects and illnesses. Not all climate elements have the same effect on cashew output. Four of these characteristics have a significant impact on the cashew tree's behavior: rainfall and its distribution throughout the year, temperature, and sunlight during the flowering and growth period. Fruiting and relative humidity **(Goujon *et al.,* 1973; Haldankar *et al.,* 2003)**. Wind speed has a significant impact on cashew tree production. Rainfall and rainfall distribution throughout the year, the cashew tree is a savannah plant whose ecological circumstances in general, and the lengthy dry season in particular, support its development **(Bassett *et al*., 2018)** and strong output. To produce successfully, the cashew tree requires consistent and reliable precipitation throughout the year **(Abdul Salam and Peter, 2010).**

Precipitation has varying effects on plants depending on their developmental stage. Cashew nut germination requires adequate moisture; in the case of rainfed cultivation, seeding must occur when the rains restart **(Azam-Ali and Judge 2001).** Irregular rainfall and an early end to the rainy season, as is becoming more common in Togo **(Adewi *et al.,* 2010),** raise the danger of sprouted seedlings drying out. To avoid the loss of young seedlings at the conclusion of the rainy season, deeper seeding (5 to 10 cm) and mulching are frequently advised **(Azam-Ali and Judge, 2001).** Soaking nuts in water before planting can also help to speed up germination **(Lakshmana and Maruthi, 2018)**. Water shortage at the seedling stage (13 months) has been shown to have a considerable effect on height, number of primary branches, number of secondary branches, and canopy **diameter (Lubis *et al.,*1999)**. Once established, cashew plants can survive for several months without irrigation (**Joker and Jepsen**, 2003) and adapt to very diverse rainfall regimes with no significant differences in their behavior, with average annual rainfall ranging from weak (300-600 mm) to strong (2700-3500 mm) as said by **Rejani *et al.* (2013).**

According to **Lacroix (2003)**, the cashew tree likes 800 to 1800 mm of rainfall each year in a single season spanning 5 to 7 months. The dry season coincides with cashew tree blossom and nut growth when the crop's water requirements are at their peak **(Oliveira *et al.,* 2006).** Thus, the final rains right before blooming boost yields by ensuring an adequate water reserve for fruiting **(Balogoun *et al.,* 2016; Bello *et al.,* 2016)**. **Lubis *et al.* (1999)** found that water deficiency has a negative and substantial impact on blooming. According to **Balogoun *et al.* (2016),** a lack of sufficient rain before the start of the dry season would result in a decrease in the number of hermaphroditic flowers, which are the most likely to bear fruit among the varieties of blooms produced by cashew trees. According to **Abdul Salam and Peter (2010)**, rains during flowering are detrimental to cashew tree productivity because they cause coulure, the emergence of fungal diseases such as anthracnose, and the proliferation of biting-sucking insects such as Helopeltis theivora.

I.8.1 Temperature

Cashew trees are sun-loving plants that can survive a broad variety of temperatures **(Abdul Salam and Peter, 2010; Dendena and Corsi, 2014; Joker and Jepsen, 2003; Kapinga and Montero, 2017)**. This tolerance is especially essential when all other environmental conditions are favorable **(Abdul Salam and Peter, 2010)**. The cashew tree requires a generally dry environment and warm weather (15-20°C), as well as moderate dew at night, to blossom properly **(Datta, 2013)**. The author suggests that high temperatures (>34.4 °C) and low relative humidity (<20%) in the afternoon lead flowers to dry out. During the fruiting period, high temperatures (>35°C) impact nut size and kernel weight **(Prasada Rao *et al.,* 2010).** Monthly temperatures necessary for excellent production range from 15°C to 35°C, with a 25°C ideal **(Abdul Salam and Peter, 2010; Dendena and Corsi, 2014; Joker and Jepsen, 2003)**.

I.8.2 Sunshine

The cashew tree is a stringent sun-loving plant that requires ample light for growth **(Trekpo, 2003)**. The cashew tree produces more fruit on the periphery branches that receive more sunshine **(Abdul Salam and Peter, 2010)**. The cashew tree's reaction to sunshine is quick and favorable. Flowering requires high sunshine (more than 9 hours each day). However, excessive sun radiation can burn and kill leaves and even plants **(Yao *et al.,* 2013)**.

I.8.3 Relative humidity

The relative humidity requirements of the cashew tree vary according to its developmental stage. They are more during the vegetative phase than in the reproductive phase **(Yao *et al.,* 2007)**. According to **Haldankar *et al.* (2003),** research conducted in India on a cashew tree variety (Vengurala-1), relative humidity is positively and substantially associated (r=0.89) with cashew nut yield. Its fluctuation throughout the pre-flowering season (September–November) has a significant impact on cashew output. For optimal productivity, relative humidity should range between 60 and 80%. High relative humidity (over 80%) during the harvest time degrades nut quality.

I.8.4 Wind speed

Wind has an impact on agricultural productivity by influencing crop evapotranspiration and mechanical activity on crops **(d'Orgeval, 2006).** Cashew trees are less vulnerable to wind than other fruit trees, such as citrus fruits. However, with speeds of 7 m/s or higher, **Aguiar and Costa (2002)** observed significant flower and fruit losses, as well as windthrow losses. In Togo, the onset of cashew tree blossoming corresponds with the entrance of the harmattan, a dry and powerful wind that sweeps from the northeast to the southwest. This has a significant effect on cashew nut productivity **(Balogoun *et al.,* 2016; Bello *et al.,* 2017).** Beyond impacting the plants in production, the wind has an impact on the young grafted plants. Strong winds can shatter the welding points of scions and rootstocks. Several strategies exist for protecting grafts against wind damage in young plants, including staking or covering the plants with high-density polyethylene bags **(Abdul Salam and Peter, 2010).** Windbreaks are installed in manufacturing plants to minimize the fall of flowers and fruits. Flowering and the beginning of fruiting are the times when the cashew tree's climatic conditions are most important. During this time, extremely high temperatures, dry or forceful winds, storms, and hail can all cause significant damage to blooms or young immature fruits, reducing the amount of fruits per plant **(Ricau, 2013).**

I.9 EDAPHIC FACTORS AND CASHEW NUT PRODUCTION

Cashew is a crop that can endure a broad range of soil conditions **(Mangalassery *et al.,* 2019)**. It is grown on degraded (eroded) soils that are not particularly productive and may be extremely poorly irrigated, making successful production with other crops impossible **(Bezerra *et al.,* 2007; Mangalassery *et al.,* 2019)**. However, it is well recognized that the type and quality of soil have a significant impact on the growth and development of cashew trees **(Dendena and Corsi, 2014).** This quality considers both physical quality (depth of topsoil, texture, etc.) and chemical quality (availability of mineral elements).

I.9.1 Physical quality of the soil and cashew nut production

The most significant physical features of the soil to consider for optimum cashew production are depth, aeration and adequate drainage capacity **(Joker and Jepsen, 2003; Ngatunga *et al.,* 2001)**. The cashew tree's taproot system is sensitive to the soil's physical restrictions. According to **Dodzoe *et al.* (2001)**, luvisoils, lixisoils and acrisoils are ideal soils for cashew development due to their adequate depth (>100-150 cm) and average texture (rich in silt).

I.9.2 Soil chemical quality and cashew production

Low soil fertility is one of the most significant factors affecting cashew nut yield **(Mangalassery and Nayak, 2020)**. However, the availability of nutrients in soils suitable for cashew growth appears to be of little importance to growers **(Adejumo *et al.,* 2010).** Studies on cashew-growing soils in India have shown a cumulative depletion of nutrients due to non-restitution of nutrients consumed, resulting in a gradual drop in yields **(Mangalassery *and* Nayak, 2020).** According to **Ngatunga *et al.* (2001)**, there is a favorable link between cashew nut yields and soil exchangeable base and organic matter concentration. **Widiatmaka *et al.* (2014)** published similar findings, demonstrating the effect of soil factors on cashew output in Indonesia.

I.10 WATER DEFICIT

Plants are likely to be subjected to a variety of biotic and abiotic factors that affect their development, growth and production **(Beniken *et al.,*2011). Serrano *et al.* (1999),** argue that water deficiency and salinity are the fundamental reasons for low agricultural yield. According to **Zhu (2002),** water stress is the first abiotic element that affects plant evolution. Drought causes water stress (water deficit), which can lead to an increase in salt content in the **soil (Gueta-Dahan *et al.,* 1997)**. Drought and salinity are characterized by a decrease in the basic water potential due to partial dehydration of tissues, which causes osmotic stress, a change in homeostasis and a change in the distribution of ions in cells **(Serrano *et al.,* 1999)**. In agriculture, drought results in insufficient soil water availability to meet crop needs **(Passioura, 1996; Pereira *et al.,* 2007)**. According to **Chaves and Oliveira (2004),** a water shortage occurs when plants' water supply decreases temporarily. Water scarcity continues to be an issue affecting tree growth and development in arid and semi-arid regions **(Kagambèga *et al.,* 2019).** The soils in these places are frequently nutrient deficient, which further limits production **(El fakhri *et al.,* 2011**). According to the same authors, under water stress, the buildup of Na+ and Cl- ions in the plant, reduces the uptake of important cations like K^+ and Ca^{2+}.

I.10.1 Effects of water deficit on the cashew tree

Water deficiency symptoms differ per crop and depend on the duration and severity of the stress. The water shortage is divided into three phases, according to **Sinclair and Ludlow (1986)**. During the first phase, transpiration and photosynthesis are maintained as if the plants were watered at field capacity until the water content is lowered to the point where water absorption no longer meets evapotranspiration requirements. Then, after reaching a threshold (about 50% of available water), transpiration and photosynthesis are decreased below the potential amount. Finally, plants reach the third phase when their stomata are entirely closed. Water stress has an impact on cashew production. According to scientists, water scarcity has a negative and considerable impact on vegetative development, inflorescence formation, and yield. They also discovered an increase in protein content in almonds with increasing water stress. Due to a lack of water, nuts are left unfilled or incomplete. Contrary to popular belief, irrigation has been found to increase production in cashew trees, albeit the results vary by variety **(Gawankar *et al.,* 2020; Oliveira *et al.,* 2006)**.

I.10.2 Plant adaptation mechanisms to water stress

When faced with a water shortage, plants evolve a variety of solutions (Figure 4). Their survival rate changes according to their level of tolerance and the rate at which accessible water is reduced **(Svoboda *et al.,* 2010)**. Two types of techniques may be distinguished: avoidance and tolerance **(Svoboda *et al.,* 2016).** The initial goal is to prevent dehydration by keeping plant tissues as water-rich as possible. The second technique includes adapting to reduced water potentials. Responses vary depending on the technique. The first method, known as evasion, allows plants to modify and/or abbreviate their vegetative cycle over time. The second method, avoidance, allows plants to reduce water loss while increasing water intake. Water losses are reduced by shutting stomata and/or decreasing transpiring leaf surface area by inhibiting leaf development or yellowing. Water absorption is enhanced by allocating more resources to the growth of the root system **(Jackson *et al.,* 2000)**. Plants respond to water deficiency by accumulating osmoregulatory metabolites, which assist in maintaining turgor. This is the case for certain free amino acids, including proline. Plants exposed to water scarcity, respond first by accumulating proline. It also helps to preserve membrane protein structure, reduce lipid peroxidation, and maintain membrane integrity **(Verslues**

and Sharma, 2010). This buildup reduces the osmotic potential **(Chaves *et al.,* 2003)**. Too much turgor loss causes membranes and enzymatic systems to break down **(Mahajan and Tuteja, 2005)**.

I.11 THE GLOBAL CARBON CYCLE

Figure 5 depicts a simplified global carbon cycle. The soil carbon pool is the world's fourth biggest stock, almost five times larger than the carbon stored in terrestrial plants and three times greater than the carbon stored in the atmosphere. At a depth of 3m, SOC accounts for 69% of the soil carbon pool, with soil inorganic carbon accounting for the remaining 721 Pg C **(Batjes, 1996).**

I.12 TOPSOIL ORGANIC CARBON

Most SOC statistics, however, pertain to the topsoil or A horizon, which is typically the top 10-30 cm **(Sanchez,2019**). While the fall in SOC concentration with depth is substantial (Figure 6), the quantities involved are also enormous, resulting in large subsurface carbon stocks when adjusted for bulk density. SOC diminishes when natural systems are converted to agricultural production, particularly in the topsoil **(Dedzoe *et al.,* 2001).**

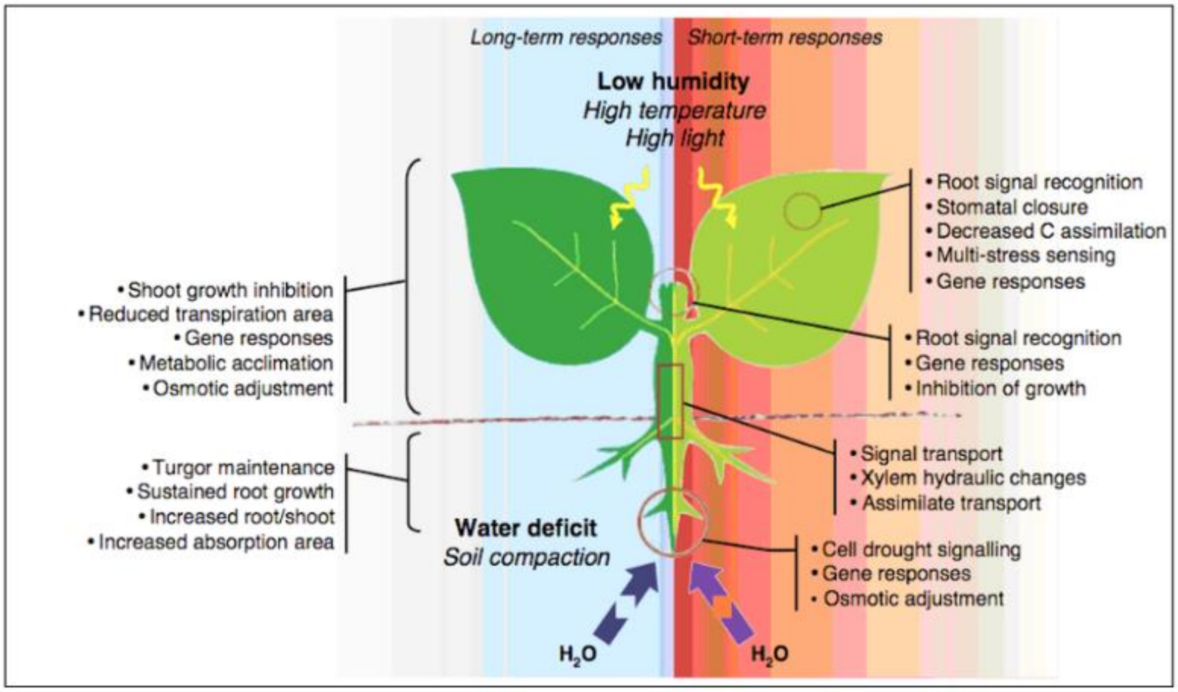

Figure 4: Plant responses to short-term (right) and long-term (left) water stress.

(Source: **Chaves *et al.*, 2003)**

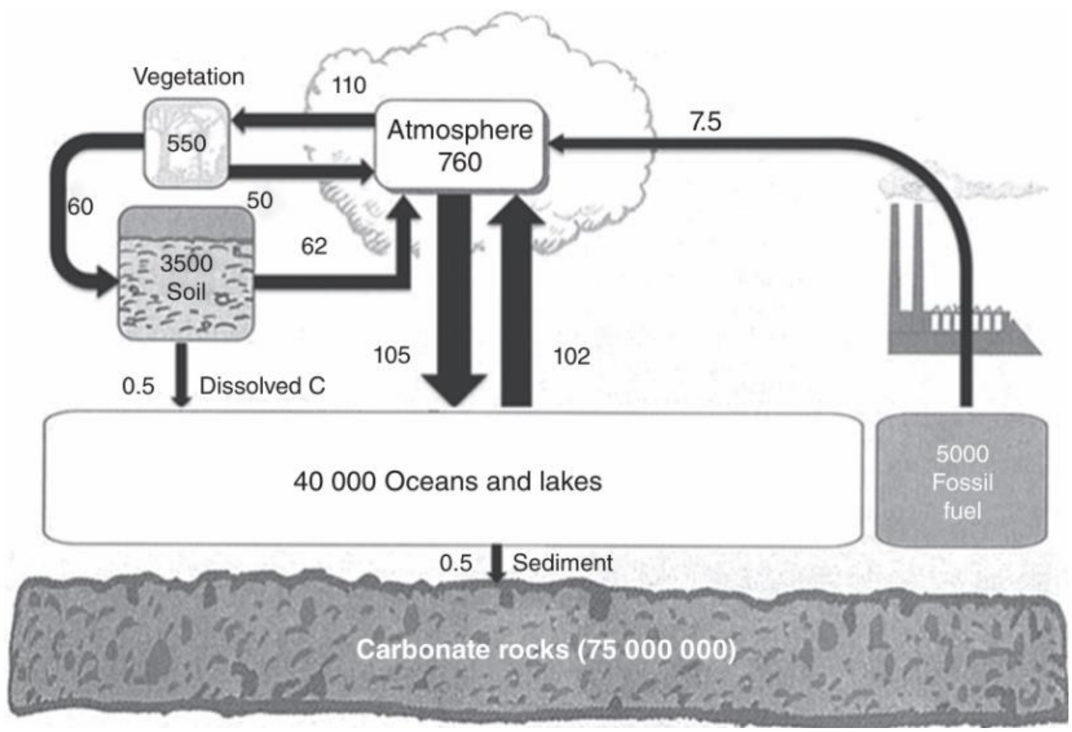

Figure 5: Simplified carbon cycle of the Earth. Adapted from **Brady *et al.* (2008)** and **Pan *et al.* (2011)**. Stocks (boxes) are in petagrams (Pg C) and fluxes (arrows) are in Pg C per year. Calculation of the soil carbon pool is the author's own

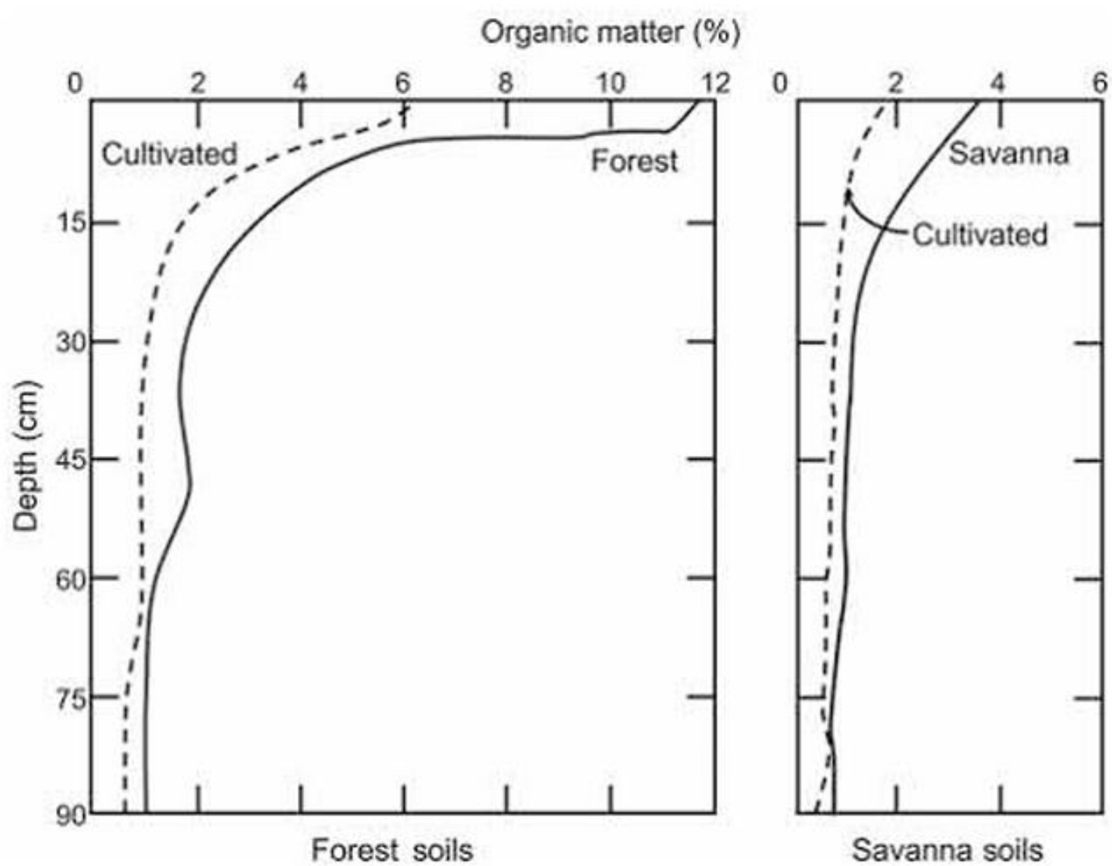

Figure 6: SOM concentrations decrease rapidly with depth. This figure shows data from West African forest and savanna soils in their natural state and after cultivation. Source: **Brams (1971)**.

I.13 SUBSOIL ORGANIC CARBON

Most SOC models do not reach deeper than 1 m, despite the fact that most tropical soils (save in mountain regions) are deeper, sometimes surpassing 2 m and sometimes exceeding 15 m**. Batjes (1996)** discovered the following ranges in SOC at various depth intervals, which he used to distinguish tropical soils from the rest of the globe. Batjes identified 72 of 105 World Reference Base (WRB) system soil units had carbon stores at the 0-200 cm depth interval, showing that for the majority of the soil units, the 0-100 cm limit underestimates soil carbon levels. As a result, models (not just for the tropics) should reach deeper than the standard 1m depth stated, such as by **Eswaran *et al*. (1993).** In the tropics, the 100-200-cm depth interval provides 60% more SOC (an average of 232 Pg C). **Jackson *et al.* (2000),** went further, to 3 m, utilizing a global database of around 1500 soil profiles. They discovered that, on a global scale, the 2-3m depth gap added 351 Pg of SOC to the total. They did not separate the tropics, but estimated three tropical biomes, which resulted in the following additional SOC stocks for the 2-3m depth interval: tropical evergreen forests (66 Pg C), tropical savannas (63 Pg C), and tropical deciduous forests (44 Pg C), which together accounted for half of the total increase in global SOC stocks when calculated down to 3 m. The revised total SOC stock in the tropics at 0-3m is 801 Pg C, which is an underestimate because it excludes tropical semiarid, arid, and other biomes, and many soils are deeper than 3m **Sanchez (2019).** This doubles SOC stocks in the tropics and across the world compared **to Eswaran *et al*. (1993)** estimations of the top one million. In the tropics and throughout the world, the subsoil (30-300 cm) contains approximately three-quarters of the SOC.

I.14 SOIL CARBON SEQUESTRATION

Lal (2008), described soil carbon sequestration as the process of transferring and securely storing atmospheric CO_2 into long-lived SOC pools. Carbon sequestration is measured as a rate (kg C/ha per year), not as a stock. The majority of carbon sequestration data is confined to the topsoil or to a maximum depth of 1m, and it is seldom documented at the full depth of plant roots. Figure 7 depicts various essential points. First, this graph depicts carbon inventories, not rates. This U shape can be divided into four parts from which rates can be calculated: (1) the initial carbon loss rate, from 1907 to about 1947, where approximately 47 percent of the topsoil carbon was lost; (2) a zero rate from 1947 to 1970, reaching the bottom and a new equilibrium, remaining relatively flat for 18 years; (3) a slightly increased carbon sequestration rate from 1970 to 1990; and finally (4) projected carbon sequestration rates to 2030 depending on crop yield rates. The carbon release rate throughout the 40 years following land use transition (prairie to farming) was 81 g C/m^2 per year. From 1970 to 1990, the carbon sequestration rate was 28 g C/m^2 year. From 1990 to 2030, the estimated carbon sequestration rate was 50 g C/m^2 per year (assuming that 70% of the region's agriculture was conventionally tilled, 27% reduced tillage, and 3% no-till). Second, it took ten years for the favorable impact of no-till to absorb carbon following land use intensification caused by its implementation. Third, after 50 years of intensified land usage, the original SOC content was not met. Fourth, the carbon sequestration rate may eventually approach zero in a few decades when the soil achieves its initial SOC, although it is unclear whether this will be a progressive drop or a sudden rate shift **(Lahoz-Monfort *et al.,* 2014; Tisdall and Oades, 1982).**

I.15 SOIL CARBON SEQUESTRATION PROCESS

Carbon sequestration occurs in soil microaggregates seen in slow or passive SOC pools. Until the 1990s, soil structure was not thought to be crucial in the formation and stabilization of carbon in recalcitrant SOC pools**. Elliott *et al*. (1996), Six *et al*. (2000) and Six *et al*. (2004)** in Colorado identified soil aggregation as the primary mechanism for carbon sequestration. What follows is heavily dependent on these significant reviews, which in turn build on the pioneering work of **Tisdal and Oades (1982)** and **Oades *et al*. (1989)** in Australia. Soil aggregates are the primary source of physical protection for soil. Aggregates are classified into macroaggregates (250-2000 µm), which are sand-sized, and microaggregates (53-250 µm). There are enormous macroaggregates of above 2000 µm, bigger than sand and nearing gravel-sized particles (**Townsend Peterson *et al.,* 2007)**. Microaggregates arise initially as a result of solid phase interactions involving silt particles, clay minerals, iron and aluminium oxides, polyvalent cations, active SOC pool fractions such as POM and DOC, microbial mucilage, and polysaccharides that consolidate around a litter fragment in the center. These aggregates have strong linkages, particularly when polysaccharides enter the microaggregates' pores. Microaggregates are often resistant to tillage. Their pores are smaller than those of most decomposing bacteria, therefore they cannot access organic carbon molecules. When exposed, such SOC molecules can be chemically labile or chemically resistant, but their chemical structure makes no difference when they form microaggregates. **Denef *et al*. (2004)** demonstrated this quite effectively, with microaggregates inside macroaggregates accounting for more than 90% of the carbon growth under no-till across a wide range of soils. Therefore, microaggregates rather than macroaggregates sequester and protect SOC in the long term. Microaggregates in the slow and passive SOC pools are also largely responsible for improving soil physical properties. Microaggregates inside macroaggregates are the ideal location for carbon sequestration. Macroaggregates form after microaggregates. They are sand-sized and consist of microaggregates, sand and binding agents, such as new POM, bacterial cells, polysaccharides and, especially, fungal hypha strands including mycorrhizae. Their pores are big enough for bacteria to enter and squeeze through. Macroaggregates have a quicker turnover period than microaggregates, and they contribute to nutrient release when they degrade and short-term carbon sequestration when they develop. The SOM that holds macroaggregates together frequently decomposes when disturbed by tillage or other physical processes. Macroaggregates are lacking in fields under long-term cultivation. They might be the first aggregates created after transitioning from conventional to no-till farming. Macroaggregates contain a larger proportion of SOC than microaggregates **(Krull *et al.*, 2003)**, except in oxide-dominated variable-charge soils **(Elliott and Gaffen, 1991; Six *et al.*, 2000)**. Larger aggregates, those larger than 2 mm, are mostly bound by roots and mycorrhizae, although their turnover period is extremely short. They are irrelevant to carbon sequestration **(Elliott *et al.*, 1996).**

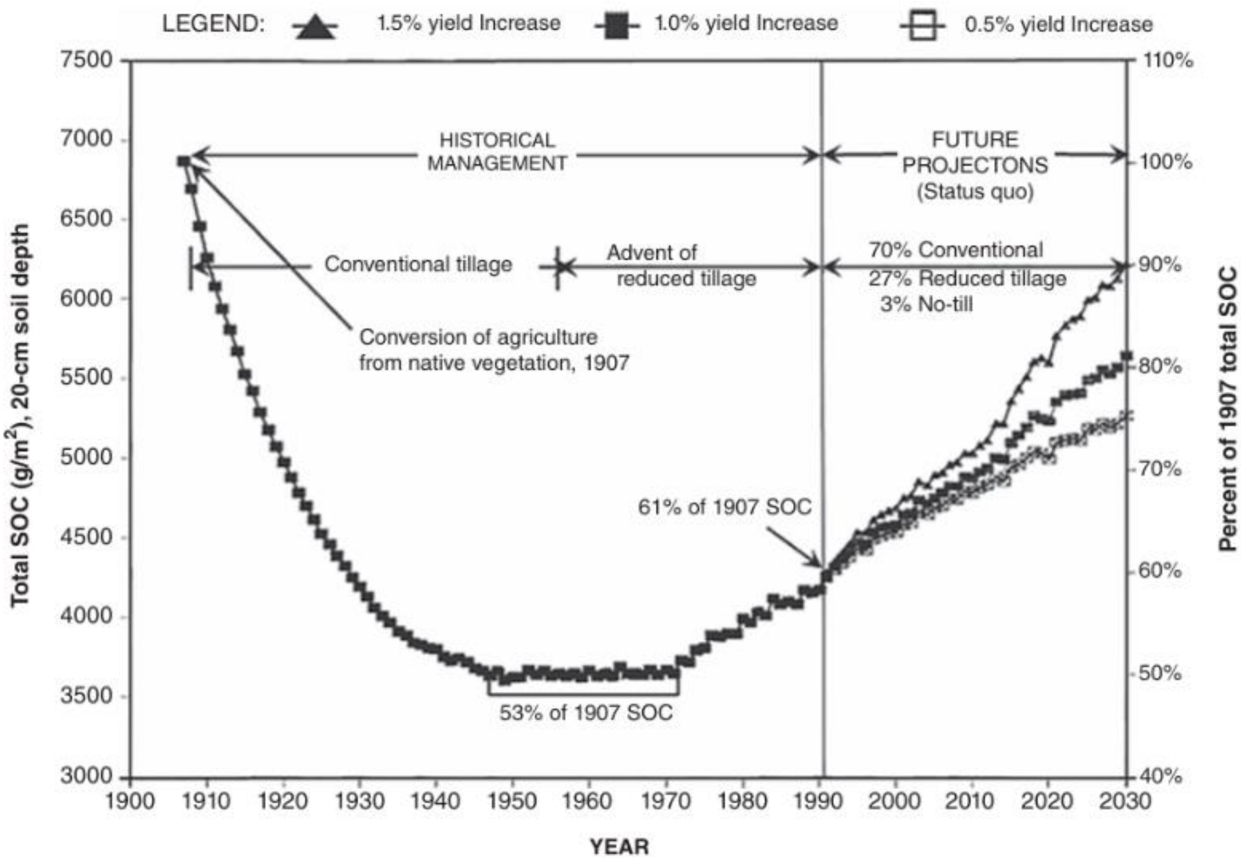

Figure 7: A century of modeled SOC changes in the top 20 cm of a generic US Midwest soil using the Century model. Source: **(Donigan, 1994).**

I.16. CLIMATE CHANGE

Climate change is undoubtedly a reality in the early twenty-first century, putting an end to decades of scepticism thanks to mounting scientific data. It is also obvious that most changes are anthropogenic, meaning they are produced by humans rather than natural variations **(Hansen, 2004).** Given the overwhelming evidence, catastrophic catastrophes such as "tropical" Hurricane Sandy, which devastated the shores of temperate New York and New Jersey in the United States, and high heat waves in France have caused sceptics to reconsider (**Carpenter *et al.*, 1993)**. Trace amounts of heat-trapping gases capture infrared radiation in our atmosphere, which causes global warming. The "greenhouse effect," caused by increased trace concentrations of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other gases that trap outgoing radiation in the atmosphere, causes higher air temperatures (**Chytrý and Rafajová, 2003)**. The respiration of plants, animals, and aerobic microbes, as well as the mineralization of soil organic carbon and the burning of tropical forests, all emit carbon dioxide, the primary greenhouse gas. Methane is primarily created by the anaerobic breakdown of carbon under flooded soil conditions and enteric fermentation by ruminants. Soils and manures produce nitrogen oxides (mostly N_2O, but also NO) as intermediate products of nitrification and denitrification. The global warming potential of CH4 is 20 times greater than that of CO_2, whereas N_2O is 298 times more. When combined, they are referred to as CO_2-equivalents (CO_2-eq). These gases are mixed together in the atmosphere, regardless of where they came from **Sanchez (2019).** Estimates from Antarctic ice cores and direct observations at Mauna Loa, Hawaii, show a CO_2 level of 280 ppm in pre-industrial times (about 1750), which gradually increased to roughly 330 ppm in the 1950s, 200 years later. Concentrations subsequently began to rapidly climb, reaching 400 ppm CO_2 in January 2015 and 405 ppm CO_2 in March 2016 **(Sin, 2016).**

At the end of the twentieth century, the global mean annual temperature at the Earth's surface had risen by 0.8 ^{o}C compared to pre-industrial levels. Temperatures are presently rising by an average of 0.2^{o}C every decade **(Hansen *et al*., 2016),** and by the end of 2010, the global mean annual temperature had risen by 1^{o}C. Projections for the remainder of the twenty-first century range from a 2^{o}C to a 5^{o}C increase above pre-industrial levels. Sea level rose by 6-9 meters when the Earth was less than 1 degree Celsius warmer than now, 120,000 years ago **(Hansen *et al*., 2016),** indicating that we are in trouble. The melting of snow and glaciers on tropical Mount Kilimanjaro, 5895 meters high and south of the equator, is devastating evidence for those living in the tropics **(Thompson *et al*., 2009; Thompson, 2010)**.

The United Nations Paris Agreement, signed in December 2015, is the first comprehensive agreement among countries above current or pre-industrial levels. The language of the Paris Agreement states "above pre-industrial levels". This implies that any subsequent temperature rises will be limited to 1ºC. The wording also begs for "efforts" to restrict the increase to 1.5ºC, which translates to simply an additional 0.5ºC being exceedingly tough. The 2ºC rise in global warming will occur when atmospheric CO_2 levels hit 450 ppm, which is close to the current level of 405 ppm. The United Nations pronouncements are not famed for their correctness, but in this situation, ambiguity will not help **Sanchez (2019)**. The Paris Agreement also asks for net-zero emissions with a balance of sources and sinks by the second part of this century. These are beautiful goals, but they would need remarkable efforts in climate mitigation. Without such measures, CO_2levels would climb to 550-700 ppm CO_2-eq by 2050, raising global temperatures by 3 to 5 degrees Celsius, a disastrous scenario **(Stern and Taylor, 2007).**

Climate change research is often classified into three categories: effects, adaptation, and mitigation. Impacts are the effects of expected climate change on humans and ecosystems. Adaptation is the ability of individuals and ecosystems to cope, which is typically characterized in terms of vulnerability. Mitigation refers to the steps that individuals can take to reduce global warming. Avoiding deforestation is considered mitigation. The subsections that follow describe the results of useful references pertinent to the tropics. Many more may be found in the IPCC's Fifth Assessment Report **(Stocker *et al*., 2014)**, as well as prior assessment reports.

I.17 DENDROCHRONOLOGY

Dendrochronology is the study of dating tree rings to the year they formed and utilizing precisely dated tree rings to find environmental signals common to a population of trees **(Fichtler *et al*., 2004; Gebrekirstos *et al*., 2014)**. The rings are generated by the occasional stoppage of development induced by severe environmental variations **(Schongart *et al*., 2006; Gebrekirstos *et al*., 2008)**. Trees have an advantage over other natural archives for climatic and environmental studies **(Schweingruber *et al*., 1988; McCarroll and Loader, 2004; Gebrekirstos *et al*., 2011a)** because they are widespread, allowing for the examination of geographical variations in environmental conditions. It is also feasible to construct chronologies of trees with overlapping life spans and examine the variability in the measurements **(McCarroll and Loader, 2004; Gebrekirstos *et al.*, 2008; Schoengart *et al.,* 2006)**. Annual rings have been discovered in tree species ranging from desert **(Fichtler *et al.*, 2004; Gebrekirstos *et al.*, 2008; Gebrekirstos *et al.*, 2014)** to humid zones **(Trouet *et al.*, 2010)** and riparian habitats **(Schongart *et al.*, 2006)**. Such research has revealed that many tree species from tropical regions with one severe dry season per year form annual rings with anatomical structures similar to temperate tree growth rings.

Unlike temperate zones, few research has been done in tropical locations **(Worbes, 2002; Schongart *et al.*, 2006),** despite numerous publications on the potential of tropical trees for climatic and environmental studies. This is mostly due to tropical nations' inadequate technological and financial resources. Furthermore, tree ring research has been impeded by the difficulties of accessing forest stands and the poor sampling reproducibility caused by the large species variety that comes with low abundances of individuals of any one species in most tropical forests. In recent years, isotope ratios in tree rings cellulose have opened another avenue for examining the physiology of riparian trees. Carbon, hydrogen, nitrogen, and oxygen are the chemical elements in wood that have many stable (non-radioactive) isotopes. Carbon (C) contains two stable isotopes, ^{12C} and ^{13}C, each with six protons and either six or seven neutrons **(McCarroll and Loader, 2004).** Physical, chemical, and biological processes can distinguish between these isotopes due to their different masses, which causes the carbon isotopes to fractionate even though they have the same chemical characteristics **(McCarroll and Loader, 2004; Krepkowski *et al.*, 2013).** When external air is converted to leaf sugars, carbon isotopic fractionation takes place in two primary stages **(McCarroll and Loader, 2004)**: The carbon dioxide (CO_2) molecules containing the lighter isotope of carbon (^{12}C) bounce off one another the furthest during air diffusion through the stomata, making them more easily diffused than those containing the heavier isotope (^{13}C). In comparison to the surrounding air, the interior air of plant leaves is reduced at ^{13}C. The second stage of fractionation is when the photosynthetic enzyme ribulose-1-5-bisphosphat-carboxylase, a major CO_2acceptor in plants, uses internal CO_2. ^{12}C is typically preferred over ^{13}C for this biological process **(Krepkowski *et al.*, 2013)**.

Plants' leaf phenology, or seasonal changes in leaf area, affects how well they absorb carbon **(Caldararu *et al.*, 2014).** Climate has a major impact on phenological cycles, and variations in climate can have a substantial impact on the timing and spatial patterns of phenological dates **(Krepkowski *et al.*, 2013).** Accordingly, tree-ring cellulose's $^{13}C/^{12}C$ ratios can occasionally exhibit strong relationships with climatic variables **(Fichtler *et al*., 2010; Brienen *et al*., 2011)**. A number of studies have successfully applied stable isotope approaches in climate studies **(Gebrekirstos *et al*., 2009; Fichtler *et al*., 2010; Brienen *et al*., 2011; Gebrekirstos *et al*., 2012)**. For example, a number of broadleaved tree species in different tropical climates showed a substantial negative association between yearly precipitation and ^{13}C time series of tree rings **(Fichtler *et al*., 2010**). In West African Sahel woodland species, **Gebrekirstos *et al*. (2011b and 2012)** discovered that yearly ^{13}C changes were significantly correlated negatively with precipitation and humidity and positively with temperature. Delta notation (δ) is typically used to indicate the isotope composition of a substance or compound as deviations from the internationally recognized standard material (Pee Dee Bee), for which the isotopic ratio is known. The mass spectrometer is used to measure the isotope ratio.

I.18 GENERALITY ON THE STUDY AREA

I.18.1 Localisation

The Atlantic Ocean, Benin, Ghana, and Burkina-Faso are Togo's neighbors to the south, east, west, and north, respectively (Figure 8). Togo is a West African nation that occupies 56,600 km². It is situated on the Guinean Gulf coast between latitudes 6°06'N and 11°08'N and longitudes 0°09 W and 1°49 W.

I.18.2 Climate of the study area

There are two main climatic zones in Togo: There is a wet season from May to October and a dry season from November to April in the northern (eighth parallel) tropical Sudanian climate. The temperature in this zone ranges from 29 to 32°C (Figure 9), while the yearly rainfall ranges from 850 to 1400 mm. It takes fewer than 175 days for plants to grow. Two dry seasons and two rainy seasons of varying lengths define the tropical climate of Guinea in the south (south of the 7th parallel). Rainfall ranges from 1000 to 1600 mm every year. In general, the temperature is high. According to **Badameli and Dubreuil (2015),** temperatures can rise to 27°C along the coast and 28°C in the north. Additionally, the southern parts have high average relative humidity (73 to 90%), whereas the northern regions have low average relative humidity (53 to 67%). The average daily daylight duration is 6 hours 37 minutes, while the average wind speed is 1.93 meters per second. According to **Badameli and Dubreuil (2015),** the average annual evapotranspiration is 1.540 mm.

I.18.3 Vegetation of the study area

Apart from a few rare works actually devoted to the distribution of plant formations in Togo, most of the studies carried out on the ecosystems of Togo are spatially very localized, limited to a type of vegetation; sacred forests of South Togo, mangroves, etc., or to a phytogeographic facies, or even to a particular type of environment (Lake Togo, Nangbéto dam). According to the work of **Ern (1979),** it can be noted that Togo has five main phytogeographic domains called ecological zones which are:

I.18.3.1 Zone I: northern plains zone

Zone I or Northern Plains Zone extends over the peneplain north of Dapaong to the southern limit of the Volta Basin, almost following the Bandjeli–Kpessidè axis. The main plant formations in this area are Sudanese savannas dominated by Mimosoidae Leguminous (*Acacia* spp.), or Combretaceae (*Terminalia* spp., *Combretum* spp.), dry *Anogeissus* forests, gallery forests and in places, meadows around temporary or permanent ponds containing *Nymphaea lotus* L., *Nymphaea guineensis* Schumach. and Thonn, *Hygrophila* spp., *Oryza longistaminata* A. Chev. and Roehrich etc. In several localities, there are vast agroforestry areas in the form of parks with *Vitellaria paradoxa* C.F. Gaertn (shea) or *Parkia biglobosa* Benth and *Parkia biglobosa* (Jacq) *Adansonia digitata* L.(baobab) or *Borassus aethiopum* Mart (palm tree).

I.18.3.2 Zone II: Northern Mountains Zone

This encompasses the Northern Mountains range, which extends roughly from the latitude of Sokodé to that of Défalé-Kanté under a two-season Sudanese climate. This is the domain of excellence of the dense dry forest of *Anogeissus leiocarpus* Guill. and Perr or *Monotes kertingii* Gilg and *Uapaca togoensis* Pax and open forests of *Isoberlinia doka* Craib and Stapf and *Isoberlinia tomentosa* Hutch. There are savannas of Combretaceae but also agroforestry parks as previously. Gallery forests are well represented there.

I.18.3.3 Zone III: Central Plains Zone

Zone with a Guinean lowland climate, it occupies the Benin-Togolese plain to the east of the Atakora range. The dominant vegetation of this zone is the savanna crossed by vast expanses of dry forests of *Anogeissus leiocarpus* Guill. and Perr. These Guinean savannas have a relatively varied flora, dominated by Combretaceae and Andropogonae. There are also islands of semi-deciduous forests scattered here and there as well as gallery forests whose main species are: *Cynometra megalophylla* Harms, *Parinari congensis* Didr, *Pterocarpus santalinoides* L'Hér. The savannas of the zone have a relatively varied flora, dominated by Combretaceae and Andropogonae.

I.18.3.4 Zone IV: southern zone of the Togo Mountains

This zone corresponds to the southern part of the Togo Mountains. The climate there is a subequatorial climate with a rainy season. It is a Guinean mountain climate. It constitutes the current domain of real dense semi-deciduous forests. The main species of these forests are *Milicia excelsa* Welw, *Khaya grandifoliola* C.DC, *Erythrophleum suaveolens* Guill. and Perr., *Antiaris africana* Engl., *Terminalia superba* Engl. and Diels, and *Parinari glabra* Oliv. These forests are interspersed with Guinean savannas in which the following woody plants are found: *Lophira lanceolata* Tiegh, *Terminalia glaucescens* Planch, *Pterocarpus erinaceus* Poir, *Hymenocardia acida* Tul, *Crossopteryx febrifuga* Benth, *Faurea speciosa* Welw., *Vitex doniana* Sweet. etc.

I.18.3.5 Zone V : southern coastal zone

Zone V, which corresponds to the coastline, has very degraded plant formations. It is a mosaic of disparate forest islands, with species such as *Milicia excelsa* Welw., *Antiaris africana* Engl, relict gallery forests with *Cynometa megalophylla* Harms, *Pterocarpus santalinoides* L'Hér., *Cola gigantea* A. Chev., etc., highly anthropized savannas, coastal thickets, halophilic or marshy meadows, mangroves, fallow land and crops.

I.18.4 Population of the study area

According to the final results of the fifth General Population and Housing Census (RGPH-5), the resident population of Togo in November 2022 stands at 8,095,498 inhabitants, including 3,944,510 men and 4,150,988 women. The latter represent 51.3% of the population, confirming the predominance of women in Togo. The density of Togo's population is 143/km^2 **(DGSCN, 2022)**. Togo is separated into five economic and administrative regions: Maritime, Central, Savannahs, Kara, and Plateaux.

The population lives mainly in rural areas with 4,621,706 inhabitants compared to 3,473,792 in urban areas, representing an urbanization rate of 42.9%. Excluding Greater Lomé, the urbanization rate in the rest of the country is 21.8% **(DGSCN, 2022)**. This rate varies greatly from one region to another, ranging from 13.8% in the Maritime without Greater Lomé to 28.9% in the Kara region. Togo's urban population is concentrated in Greater Lomé, which is home to just over six out of ten city dwellers (63.0%). The rest of the urban population is unevenly distributed across the five regions, with percentages ranging from 5.3% in the Maritime region (excluding Greater Lomé) to

10.6% in the Plateaux region. The spatial distribution of the population shows strong regional disparity. Indeed, depending on the region, the Togolese population is distributed as follows: Greater Lomé 2,188,376 inhabitants (27.0%), Plateaux 1,635,946 inhabitants (20.2%), Maritime without Greater Lomé 1,346,615 inhabitants (16.6%), Savanes 1,143,520 inhabitants (14.1%), Kara 985,512 inhabitants (12.2%) and Centrale 795,529 inhabitants (9.8%).

Togo has thirty-nine (39) cities corresponding to the prefecture capitals. Grand Lomé remains the most populated city and Tanjore the least populated. The ten most populated cities in Togo excluding Lomé are, in descending order: Kara, Dapaong, Sokodé, Atakpamé, Kpalimé, Tsévié, Anié, Cinkassé, Notsé and Tabligbo **(DGSCN, 2022)**. As for housing, a total of 1,768,367 dwellings are counted throughout the territory. The results reveal that housing in Togo is dominated by the "traditional" type (745,221 or 42%), followed by the semi-modern type (541,190 or 31%) and the modern type (481,976 or 27%). Furthermore, a total of 7,629 socio-collective infrastructures were geolocated across the country **(DGSCN, 2022)**.

I.19 GENERALITY ON THE STUDY SPECIES

The Anacardiaceae family includes the cashew tree as a perennial. It belongs to the dicotyledonous class of angiosperms. There are 400–600 species and 60–74 genera in this family, depending on the classification or authors **(Kapinga and Montero, 2017).** Only the cashew tree (*Anacardium occidentale* L.), out of the eight species in the genus Anacardium, has commercial significance due to its highly valued nuts and apples on the global market **(Dendena and Corsi, 2014).**. Its height can range from 7 to 14 meters, depending on the situation. Its canopy varies in size as well, with a maximum diameter of 20 meters **(Dendena and Corsi, 2014).** The cashew tree canopy has a spherical form in its natural state The taproot system of the cashew tree is still delicate and vulnerable to too much water. Cashew root system dispersion is dependent on soil type, plant material, planting technique, age, and soil water and nutrient availability **(Dendena and Corsi, 2014).** Cashew roots can grow up to 300 cm laterally around the tree and 100 cm vertically in shallow lateritic soils, which are typical of tropical regions where cashews are endemic **(Abdul Salam and Peter, 2010)**. The first 15 to 45 cm of soil contains more than 90% of the lateral roots, which spread laterally to more than twice the diameter of the canopy **(Kapinga and Montero, 2017).** The petals are white or yellow, sometimes streaked of pink, free, linear to lance-shaped, alternated, and with imbricate pre-flowering. As **Lefèbvre mentioned in 1969**, the stamens, generally to the number of 10, are welded by the base of the nets in a tube of 2 mm length.

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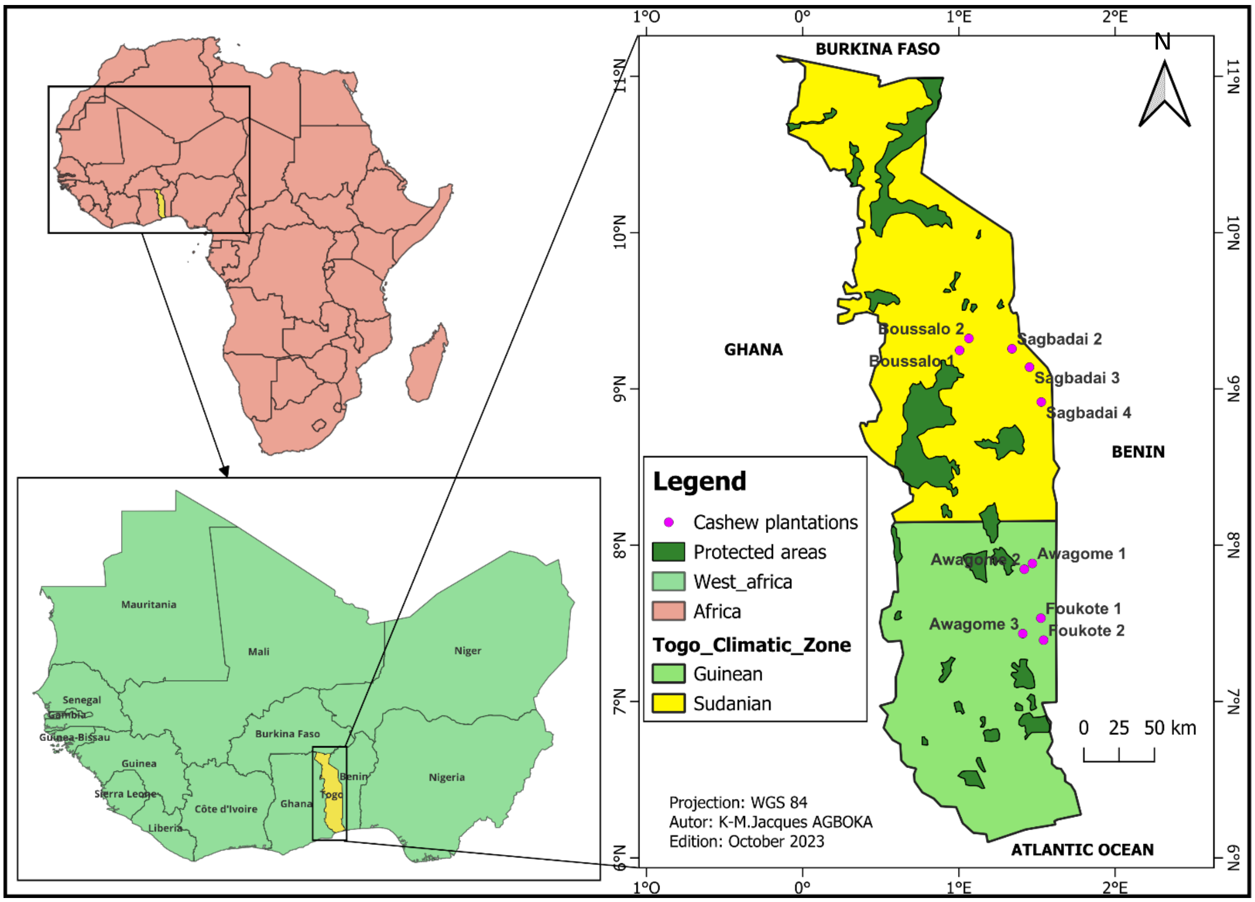


Figure 8: Location of the study area Togo in West Africa.

The circle indicates the location of the study sites (collection of the stem disc).

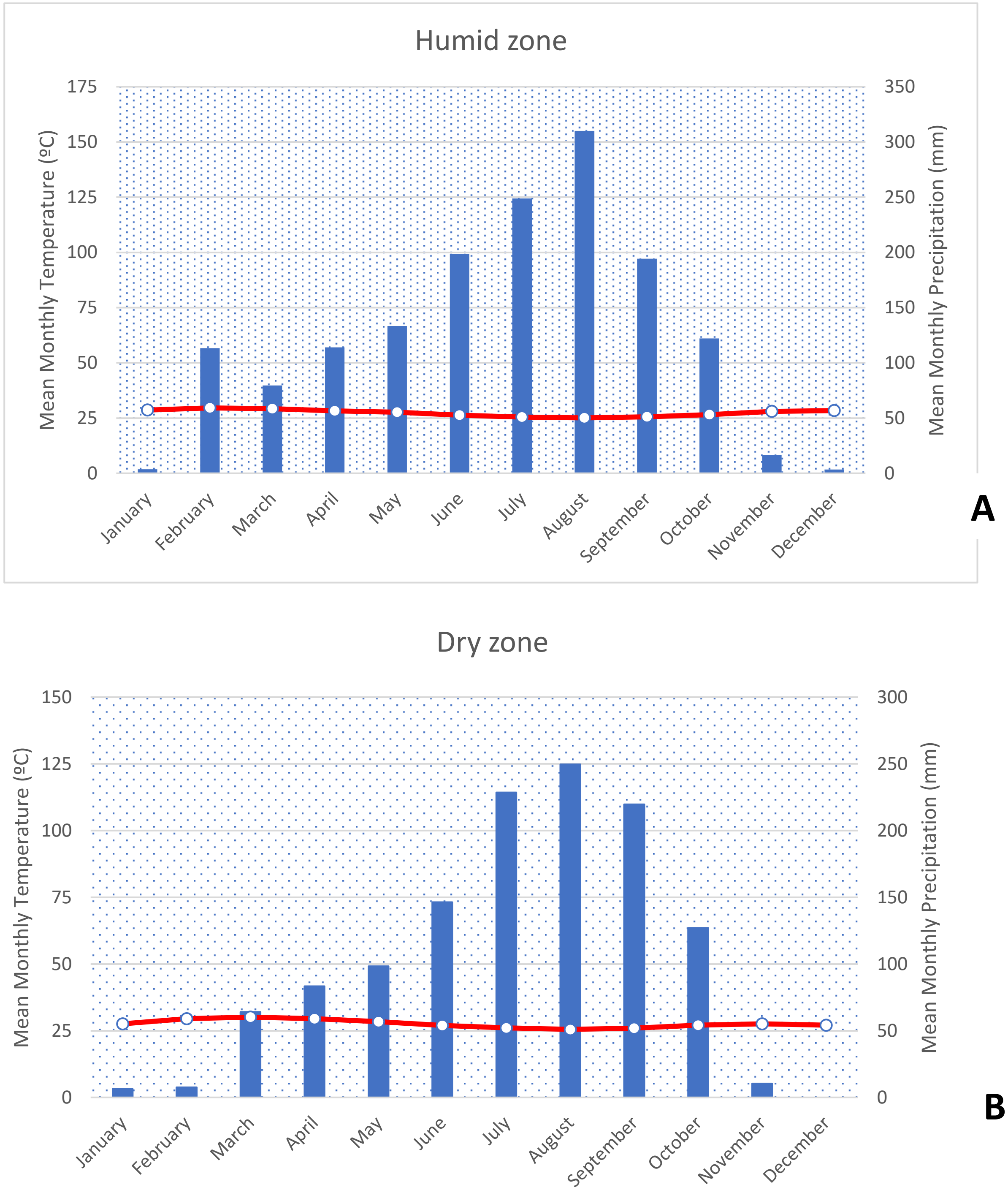


Figure 9: Climatic diagram of the study area (A: Guinean climate; B: Soudanian climate). Rainfall (mm) and temperature (ºC) data (2014–2023) were obtained from Togo Meteorological Agency.

PART II: MATERIALS AND METHODS

II.1. DATA COLLECTED

II.1.1. Occurrence data collection

Between August and December 2023, occurrence data for cashew trees in Togo were gathered using a GPS (Global Positioning System). The research conducted by **Atakpama *et al.* (2023)** allowed us to collect occurrence points from Benin and Ghana. These cashew tree occurrence sites were recorded using GPS. To increase the model's accuracy, it was suggested that occurrence data include as much of the area as feasible where the species is influenced by similar climatic conditions. As a result, new cashew tree occurrence data in West Africa from the Global Biodiversity Information Facility platform (https://www.gbif.org/) were acquired using the "gbif" plugin in the QGIS 3.24 software1 (Figure 10**).** These are the updated data from 1950 to 2021. After crosschecking and suppressing incorrect and duplicated occurrences, a total of 2,538 points of occurrence were included in the modeling. Table 1 shows information on the places of occurrence and their sources.

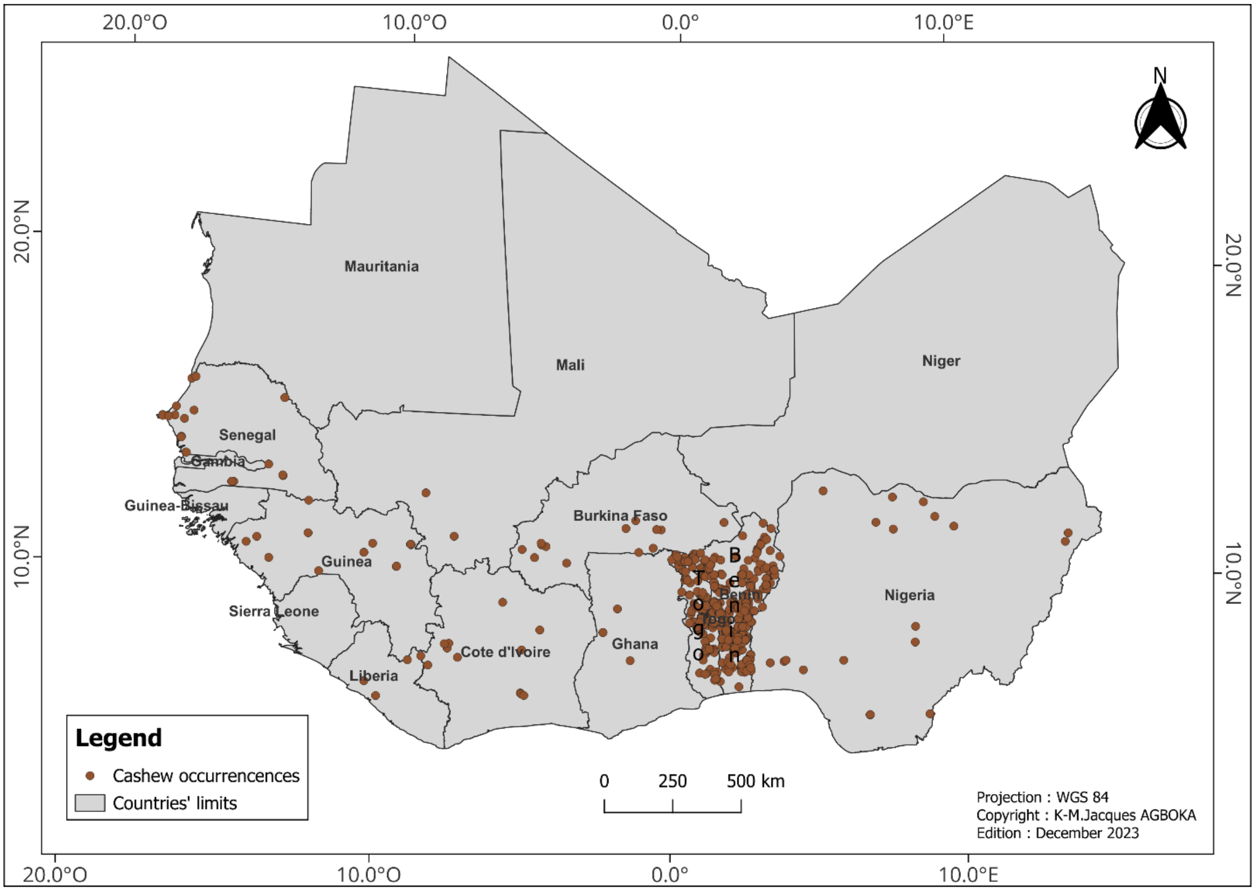


Figure 10**:** Spatial distribution of cashew tree in West Africa.

The occurrence points observed on the map are the result of the occurrence points taken by the GPS in the field, the GBIF data and the occurrence points taken by **Atakpama *et al.* (2023).** It is therefore not an exhaustive list of cashew trees in West Africa.

Table 1: Sources and number of occurrence points used for modelling.

Source of occurrence points	Number of occurrence points
Atakpama *et al.* (2023)	705
Fieldwork	833
GBIF	1000

II.1.2. Environmental data collection

Table 2 below shows environmental data including climate, elevation and soil. The soil data was collected from the Harmonized Soil database of FAO https://www.fao.org/soils-portal/data-hub/soil-maps-anddatabases/harmonized-world-soil-database-v12/en/ (accessed on 12 December 2023). The climate and elevation data were obtained from the WorldClim version 2.1 database http://www.worldclim.org (accessed on 15 December 2023) and included the 19 bioclimatic variables. Data on the bioclimatic variables were downloaded for both the current (1970–2000), future (2050; 2041–2060) and (2070; 2061-2080) climate at the resolution of 30 arc-seconds (~1 km^2). Previous studies reported some discontinuities in the bioclimatic variables, namely the mean temperature of the wettest quarter (Bio 8), mean temperature of the driest quarter (Bio 9), precipitation of the warmest quarter (Bio 18), and precipitation of the coldest quarter (Bio 19) in sub-Saharan Africa **(Booth, 2022),** which were attributed to sudden changes in the quarterly periods used to calculate these variables **(Booth, 2022).** Therefore, we omitted the four variables in further analysis. These variable layers were cropped along the West African boundaries and then converted to ASCII files compatible with the MaxEnt algorithm (version 3.4). The models were performed using all environmental variables **(Moukrim *et al*.,2020; Feng *et al*., 2019)** instead of correlative analysis and choice of variables as done in several previous studies by **Dimobe *et al.* (2020)** and **Atakpama *et al.* (2023**). The potential future distributions of *Anacardium occidentale* under climate change were predicted using two Global Circulation Models (GCMs): "HadGEM3-GC3.1-LL" (Third Hadley Centre Global Environment Model in the Global Coupled Configuration 3.1) developed by the Hadley Center, United Kingdom **(Andrews *et al*., 2020);** and MIROC6 (Model for Interdisciplinary Research on Climate) developed by the Japanese modelling community, **Tatebe *et al.* (2019).** The future climate conditions were projected at the 2050 horizon (average for 2041–2060) and 2070 horizon (average for 2061-2080) under two IPCC-CMIP6 Shared Socioeconomic Pathways (ssp) scenarios, ssp245 and ssp585 were used to reduce the climate uncertainty, **Koo *et al.* (2017).** Of these, the ssp245 is the medium forcing scenario with intermediate climate change challenges and the ssp585 would be the most chaotic scenario if we assume no measures are taken to avoid the climate effects **(Ames-Martínez *et al.,* 2022)**.

Table 2**:** Environmental variables used for modelling.

Environmental variables	Description of the variable
Soil	Soil
Elevation	Altitude
Temperature Variables	
bio1	Annual Mean Temperature
bio2	Mean Diurnal Range
bio3	Isothermality (BIO2/BIO7) (* 100)
bio4	Temperature Seasonality (standard deviation *100)
bio5	Max. Temperature of Warmest Month
bio6	Min. Temperature of Coldest Month
bio7	Temperature Annual Range (BIO5-BIO6)
bio10	Mean Temperature of Warmest Quarter
bio11	Mean Temperature of Coldest Quarter
Pluviometry variable	
bio12	Annual Precipitation
bio13	Precipitation of Wettest Month
bio14	Precipitation of Driest Month
bio15	Precipitation Seasonality (Coefficient of Variation)
bio16	Precipitation of Wettest Quarter
bio17	Precipitation of Driest Quarter

II.2. MATERIALS

II.2.1. Biological material

The basic biological material of this study consists of ten (10) years old cashew tree (Anacardium occidentale L.) plantations.

II.2.2. Other materials

During our research, we used: Smart Zoom to obtain the macroscopic structure from the thin sections of the stem disks (Figure 12), the material of the powded wood sample collection (Figure 13), and cashew stem disks (Figure 14). The occurrence data for cashew trees in Togo were gathered using a GPS (Global Positioning System).

II.3. SOFTWARE AND MODELS USED

Cashew tree occurrence data in West Africa from the Global Biodiversity Information Facility platform (https://www.gbif.org/) were acquired using the "gbif" plugin in the QGIS 3.24 software1 (Figure 10**).** The QGIS 3.24 software 1 was also used to map the cashew potential current and future growing areas. The potential future distributions of *Anacardium occidentale* under climate change were predicted using two Global Circulation Models (GCMs): "HadGEM3-GC3.1-LL" (Third Hadley Centre Global Environment Model in the Global Coupled Configuration 3.1) developed by the Hadley Center, United Kingdom **(Andrews *et al*., 2020);** and MIROC6 (Model for Interdisciplinary Research on Climate) developed by the Japanese modelling community, **Tatebe *et al.* (2019).** The future climate conditions were projected at the 2050 horizon (average for 2041–2060) and 2070 horizon (average for 2061-2080) under two IPCC-CMIP6 Shared Socioeconomic Pathways (ssp) scenarios, ssp245 and ssp585 were used to reduce the climate uncertainty, **Koo *et al.* (2017).** The MaxEnt (Maximum Entropy) model was used to estimate the potential distribution of cashew trees based on their presence data and environmental factors. The R software version 4.3.3 was used for the dendrometric data analysis (t-test) and the correlation of the $\delta^{13}C$ to climatic parameters.

II.4. METHODS

II.4.1. Assessment of the current distribution and prediction of the potential effect of climate change on the distribution of the habitat of cashew trees in Togo

II.4.1.1. Modelling and validation of the Maxent model

The Excel file of cashew tree occurrence points has been converted into a CSV file, for compatibility with the MaxEnt model. To make the model more accurate, it has been run ten times. A total of 25% of the points of presence were used to test the model and the remaining 75% of the data were used to train the model **(Nneji *et al.*, 2020).**

To analyze model accuracy, the area under the receiver operating curve (AUC) was calculated using receiver operating characteristics (ROC) analysis. **Swets (1988),** classified the AUC values into three categories: 0.5–0.7, 0.7–0.9 and AUC values >0.9, which indicate poor, moderate, and high model performance, respectively. The AUC value close to 0.5 indicates that the model is no better than a randomly generated model, while the AUC values >0.9, indicate the SDM strength of the model **(Wei *et al.,* 2018).** Jackknife analysis was used to determine which climatic variables were important for the distribution of *Anacardium occidentale* **(Saha *et al.,* 2021).** The True Skill Statistics (TSS) is the capacity of the model to accurately detect true presences (sensitivity) and true absences (specificity). TSS ≤ 0 indicates a random prediction, while values close to 1 (TSS > 0.5) characterize a model with good predictive power **(Allouche and Kadmon,2006)**.

The calculation of the TSS was as follows (**Allouche and Kadmon, 2006):**

True skill statistic (TSS) = Sensitivity + Specificity-1

The QGIS 3.24 software 1 was used to map the cashew potential current and future growing areas. Two habitats were first defined based on the 10-percentile threshold: unfavourable habitat (habitats with a probability below the threshold) and favourable habitat (habitats with a probability above the threshold) as noted by **Atakpama *et al.* (2023).** Then the favourable habitat was subdivided into less favourable, moderately favourable, and highly favourable. The area of each habitat and its dynamics under each scenario were calculated.

II.4.2. Assessment of the organic carbon stock in the cashew plantations in Togo regarding the climate gradient.

II.4.2.1. Experimental design

The trees on which data were collected, were in a delimited plot of 400 m² in each plantation, to assess the trees' density. A total of ten (10) cashew plantations were selected as part of our study, with five plantations selected for each climatic zone.

II.4.2.2 Methods of dendrometric and soil data collection and statistical analysis

The synoptic stations of Atakpame and Sokode were used to gather meteorological data, including mean temperatures (°C) and precipitation (mm). As a result, these data were gathered during a ten-year period (2014–2023).
Measurements of biomass were made on each 400 m^2 plot. Rectangular plots are thought to be more reflective of the stand and more heterogeneous **(Hairiah *et al.*, 2011)**. As a transect, the plot offers a typical perspective of the plantations. We take into account four DBH classes (0–5,5–10, 10-15 and > 15) in each plot. A SUUNTO clinometer was then used to measure each tree's height. The Ruban pi was used to estimate the diameter at breast height (DBH). Two sightings were used to calculate the trees' height (H). First at the shaft's top (V1) and second at the shaft's base (V2). The proportion of the distance (L) between the operator and the tree is represented by these two observations. The relationship established by **Rondeux (1999)** is used to determine the measured tree's total height (H):

$$H= [(V2-V1) * L]/100 \quad (1)$$

The cylinder method was used to calculate the bulk density of the soil. A hollow metal cylinder with a volume of 100 cm^3 is used to collect a sample of soil. At the end, the clod that was removed from the cylinder is shaved. The amount of soil removed is equivalent to the cylinder's volume. After that, the soil is taken out and dried at the Institut Togolais de Recherche Agronomiques' (ITRA) Soil and Plant Laboratory at 105°C. The approach used to estimate sequestered carbon is based on the suggestions made by **MacDiken (1997), Valentini (2007) and the IPCC (2003)** in the "Good Practice Guidance for Land Use, Land-use Change and Forestry" (LULUCF). It involved calculating the amount of organic matter in the soil and assessing the biomass of the tree's various subsurface and aerial sections. Estimating the total organic carbon at various soil depths or globally for one or more horizons and transforming the data while accounting for soil bulk density, allowed for the determination of soil carbon. Using Equation 2, the organic carbon stock was calculated. The total amount of carbon at the designated depths, represented in tons of carbon per hectare, was the outcome **(FAO, 2002)** Equation (2).

$$SOC= C/100 \times \rho \times D \times (1-Frag) \times 100 \quad \text{(Equation 2)}$$

Where:

SOC = soil organic carbon stock (t C ha-1)
C = soil organic carbon concentration of soil fines (fraction < 2 mm) determined in the laboratory (%, g kg-1)
ρ = soil bulk density (g cm-3)
D = depth of the sampled soil layer (cm)
frag = % volume of coarse fragments/100
Hundred (100) is used to convert the unit to t C ha-1
Note: SOC is determined on the fine soil fraction (< 2 mm) and the bulk density should be corrected for the proportion of the soil volume occupied by coarse fragments (> 2 mm). To create composite samples, soil samples were taken at four separate locations in the 400 m² corner of each plot at depths of 0–25 cm and 25–50 cm. Forty soil samples in all were gathered. To separate the fine and coarse components, the soil samples were first allowed to dry at ambient temperature before being sieved through a 2 mm screen. The chemical analysis was conducted using these small soil samples.
Three quadrats with a surface area of one meter square were used to measure the quantity of carbon in the litter and herbaceous vegetation at each main plot. The amount per hectare was then calculated. After all of the vegetation in each quadrat was removed, the litter was gathered and weighed on-site. After that, samples of the vegetation and litter were collected and sent to the lab for chemical analysis. By oxidizing soil organic matter with potassium dichromate ($K_2Cr_2O_7$ 1N) in an acidic medium with a sol/$K_2Cr_2O_7$ ratio of 0.25/10, the **Walkley and Black (1934)** method was used to quantify the amount of organic carbon in the soil. After adding the diphenylamine indicator, the carbon content is ascertained by titrating with a 0.5 N iron sulphate solution. To increase the trustworthiness of the results, several publications suggested using certain regression equations for the most common species for the evaluation of carbon stock in the above and root biomass **(MacDiken, 1997; IPCC, 2003). The FAO (1997)** created equations 3 and 4 for arid zones (less than 1500 mm annually), and cashew was regarded as a large tree (height > 7 m). The determination of areal biomass and root biomass stock has been done using equations 3 and 4.
Equation (3): AB = $exp^{(-1{,}996+2{,}32 lnD)}$; With AB = Aerial Biomass, D = Diameter of the tree (D in cm). Equation (4) = RB = $exp^{(-1{,}0587+0{,}8836 * \ln(AB))}$ With RB = Root Biomass.
Table 3 below gives a description of the type of climate prevailing in the localities we used as study sites, and figure 11 shows the system for collecting dendrometric and soil data. The

allometric equations created by **FAO (1997)** and modified by **Boulmane *et al*. (2013)** based on the carbon stock models for the various tree components were used to determine the amount of carbon in the various tree sections in each plantation (Table 4).
After being dried for 72 hours at 65 °C in an oven, the samples of herbaceous plants and litter were crushed, and the dry ashing method was used to measure the amount of organic carbon. Equation 5 was used to calculate the herbaceous vegetation's proportion of dry matter and Equation 6 was used to calculate the biomass **(Valentini, 2007)**. The average herbaceous biomass was then converted to ton per hectare. Equation (5): DM = (PSE/PHE)*100 where DM = percentage of dry matter (%); PSE = dry weight of the sample after three days in the oven at 65 ° C (g); PHE = wet weight of the sample measured in the field (g). Equation (6): B = (PHT*DM)/100; where: B = biomass (g); PHT = total wet weight in measured in the field (g); DM = percentage of dry matter (%).
Cashew stand structure analysis consisted of the determination of keys structure parameters as tree density, mean diameter, mean heigh and basal area **(Curtis and McIntosh, 1951).** Diameter size class distribution was established for each site and in order to determine the variation of different parameters according to tree classes. For each parameter determined, Students T-test was performed to compare mean values of each zone. All analysis was done using R software version 4.3.3. The following Table 5 presents main parameter determined.

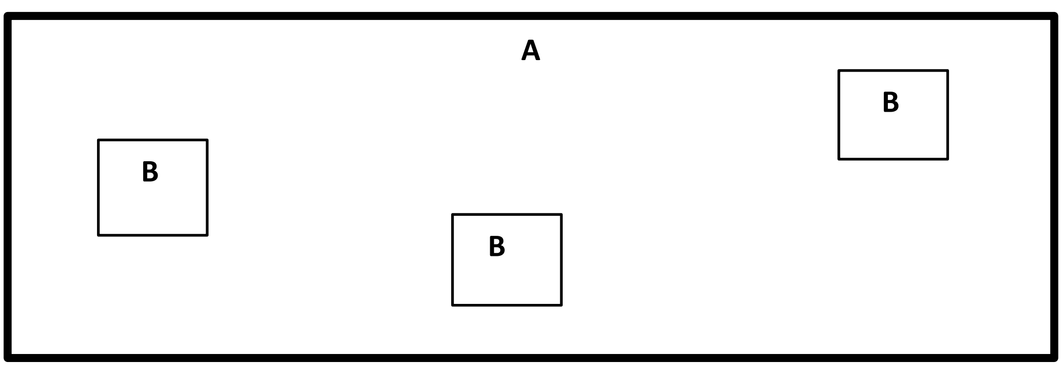


Figure 11: Experimental system for collecting soil and dendrometric data.
A: 400 m² plot used to collect dendrometric and soil data; B: Quadrat of 1 m² used to collect litter and grasses.

Table 3: Characteristics of the study area

Area	Season. Rainfall and Temperature	Climate	Bulk density g/cm^3	
	(Badameli and Dubreuil, 2015)		0-25 cm	25-50 cm
Foukotè 1	Two dry seasons and two rainy seasons Temperature: 27 to 28°C Rainfall: 1000 to 1600 mm	Guinean (A)	0.985	0.985
Foukotè 2			0.983	0.995
Awagomé 1			0.989	0.99
Awagomé 2			0.988	0.993
Awagomé 3			0.982	0.972
Sagbadaï 2	One dry season and one rainy season Temperature: 29 to 32°C Rainfall: 850 to 1400	Soudanian (B)	0.981	0.974
Sagbadaï 3			0.975	0.978
Sagbadaï 4			0.963	0.926
Boussalo 1			0.95	0.963
Boussalo 2			0.974	0.952

Table 4: Allometric equations to assess carbon stocks in the various components of the trees

Component of the tree	Adjusted model of carbon stock Estimation (Kg/tree)	R^2
Trunk	$SCTr = 191 \times (D^2H)$	0.97
Branches	$SCBr = 46 \times (D^2H)$	0.95
Leaves	$SCL = 5.4 \times (D^2H)$	0.96

Note: D = diameter at 1.30 m, H = height of the tree (in meter), D and H are in meter (m). SCTr = carbon stock in the trunk, SCBr = carbon stock in the branches, SCL = carbon stock in the leaves.

Table 5**:** Diversity and structure metrics to be computed for the structural analysis

Parameters	**Formula**	**Formula details**	**Interpretation**	**References**
Density, *D*	$RD = \frac{N}{TN}$	N is the number of individuals of a species and TN is the total number of individuals considering all species	Measures abundance of a species relative to abundance of all species	**Cintron and Schaeffer-Novelli (1984)**
Basal area, *G* ($m^2.ha^{-1}$)	$G=\frac{10000\pi}{4s}\sum_{i=1}^{n_g} d_i^2$	d_i is the diameter of the tree i^{th} of the plot	Dendrometric parameter which inform to basal area distribution	**Cintron and Schaeffer-Novelli (1984)**
Mean diameter, *D* (cm)	$D=\sqrt{\frac{1}{n}\sum_{i=1}^{n} d_i^2}$	d_i is the diameter (in cm) of the tree i^{th} of the plot	Measures horizontal growth of a species	**Cintron and Schaeffer-Novelli (1984)**

II.4.3. Examination of the inter-annual variability of carbon isotope ratios of cashews in the humid and dry cashew production zones of Togo with climatic parameters

II.4.3.1. Design and macroscopic picture of the stem disk

The stem disks were collected on ten (10) year old cashew trees. Five (05) stem disks per climatic zone (humid and dry cashew production zones). The stem disks in each production zone have been identified; dry cashew production zones (BIII, BII, BV, BI and BVIII) and wet cashew production zone (AII, AVI, AVIII, AI and AIII). Three (03) stem disks were randomly selected per climatic zone (humid and dry cashew production zones) for isotopic analysis. The three stem disks selected in each cashew production area were: AII, AVI and AVIII for the humid cashew production zone and BI, BIII and BV for the dry cashew production zone. The stem disks selected randomly were observed with the smartzomm 5 (Figure 12). After the realization of the thin section of each sample (randomly selected stem disk), according to the method of **Amparado *et al.* (1990)**, we moved on to the observation of the different samples using the zoom smart 5.

II.4.3.2. Bulk (whole) wood method

For every cashew disc that was chosen, the carbon-13 ($\delta^{13}C$) tests were performed using bulk wood. Recent studies comparing the isotopic composition of various wood components (cellulose, lignin, and bulk wood) have found a high correlation between cellulose and bulk wood as well as between cellulose and lignin, despite previous research showing that different wood components have different isotopic signatures **(Gebrekirstos *et al.*, 2012).** Bulk wood has occasionally been found to be a better climate proxy than cellulose, sometimes much better **(Krepkowski *et al.*, 2013).** Using a tiny drill with a 0.5 mm diameter (Figure 13), powdered samples were created along the line (false rings) of each cashew disc (Figure 14) in order to use the bulk wood method. To prevent cross-contamination, compressed air was used to clean the disk after each sample was collected. To symbolize the entire ring, the powders were combined into tin capsules and beaten with a metal rod. Each year's subsamples were weighed and placed in 0.4–0.5 mg tin capsules. A mass spectrometer (Delta V Advantage, Thermo Electron, Bremen, Germany) connected to a HekaTech Elemental Analyzer was used to analyze the composition of carbon isotopes (separation of carbon isotopes based on masses). The results are given in δ-notation, which is the relative deviation from the PDB (Pee Dee Belemnite) standards: $\delta^{13}C= [(^{13}C/12C)\ sample/\ (^{13}C/12C)\ PDB) -1] \times 1000‰$.

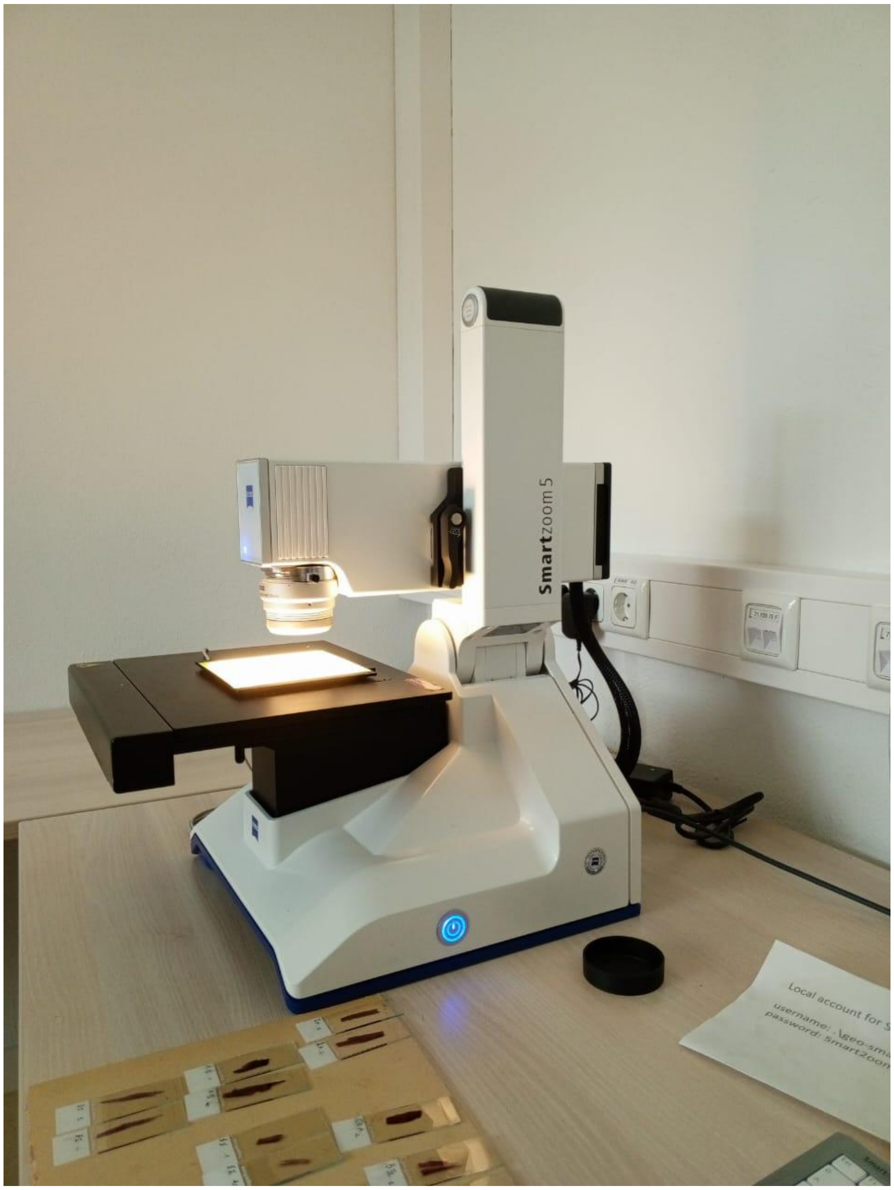


Figure 12: Smart zoom, used to obtain the macroscopic structure from the thin sections of the stem disks.

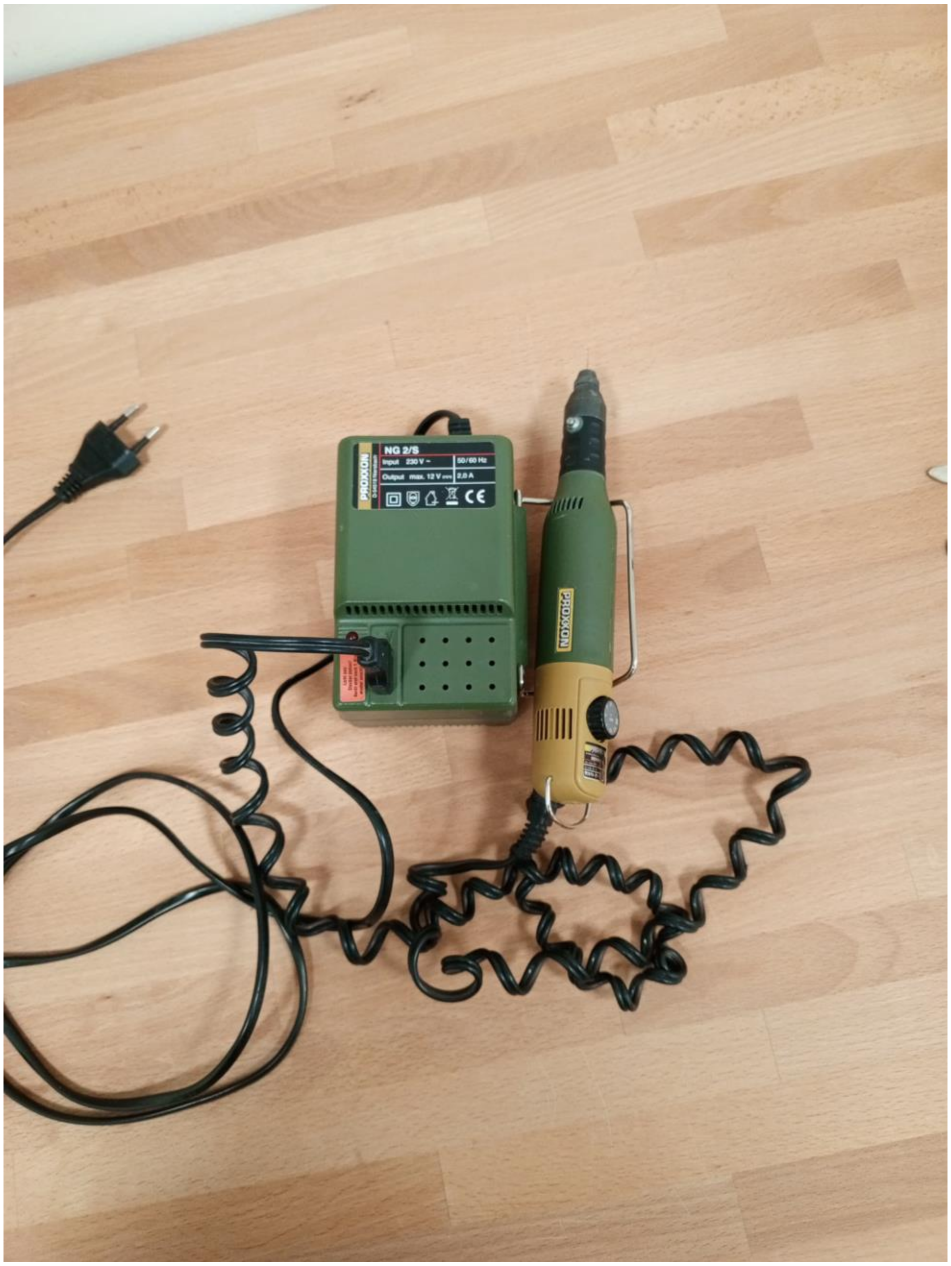


Figure 13: Material of powded wood sample collection

Figure14: Illustration of the collection of wood powders from cashew stem disks

II.4.3.3. Statistical analysis

Trends and variability found in tree ring isotopic data are unrelated to historical climate. The decrease in atmospheric $\delta^{13}C$ values brought on by the burning of ^{13}C-depleted fossil fuels is one non-climatic trend that can be eliminated from the $\delta^{13}C$ dataset. **McCarroll and Loader (2004),** showed that this tendency was eliminated by adding published annual values of the $\delta^{13}C$ reduction in atmospheric CO_2. The correlation of the $\delta^{13}C$ to climatic parameters, such as mean annual precipitation and temperature, was assessed using Pearson correlation analysis for the chosen cashew trees in both the wet and dry cashew production zones. The Meteorological Stations of Togo provided the climate data. From 2016 to 2023, meteorological data were gathered for the dry and humid cashew production zones. In using R software version 4.3.3, the correlation analyses were carried out.

PART III: RESULTS

III.1. CURRENT DISTRIBUTION AND PREDICTION OF THE POTENTIAL EFFECT OF CLIMATE CHANGE ON THE DISTRIBUTION OF THE HABITAT OF CASHEW TREES IN TOGO

III.1.1. CONTRIBUTION OF VARIABLES AND MODEL PERFORMANCE

The variable that contributed mostly to the models was the soil variable (hwsd), followed respectively by the annual precipitation (bio12), and the temperature seasonality (bio4). The least contributing variable was the altitude (elev) as indicated on Figure 15. The average AUC and the True skill statistic (TSS) values were respectively 0.949 (Figure 16) and 0.88, showing a good prediction of habitat.

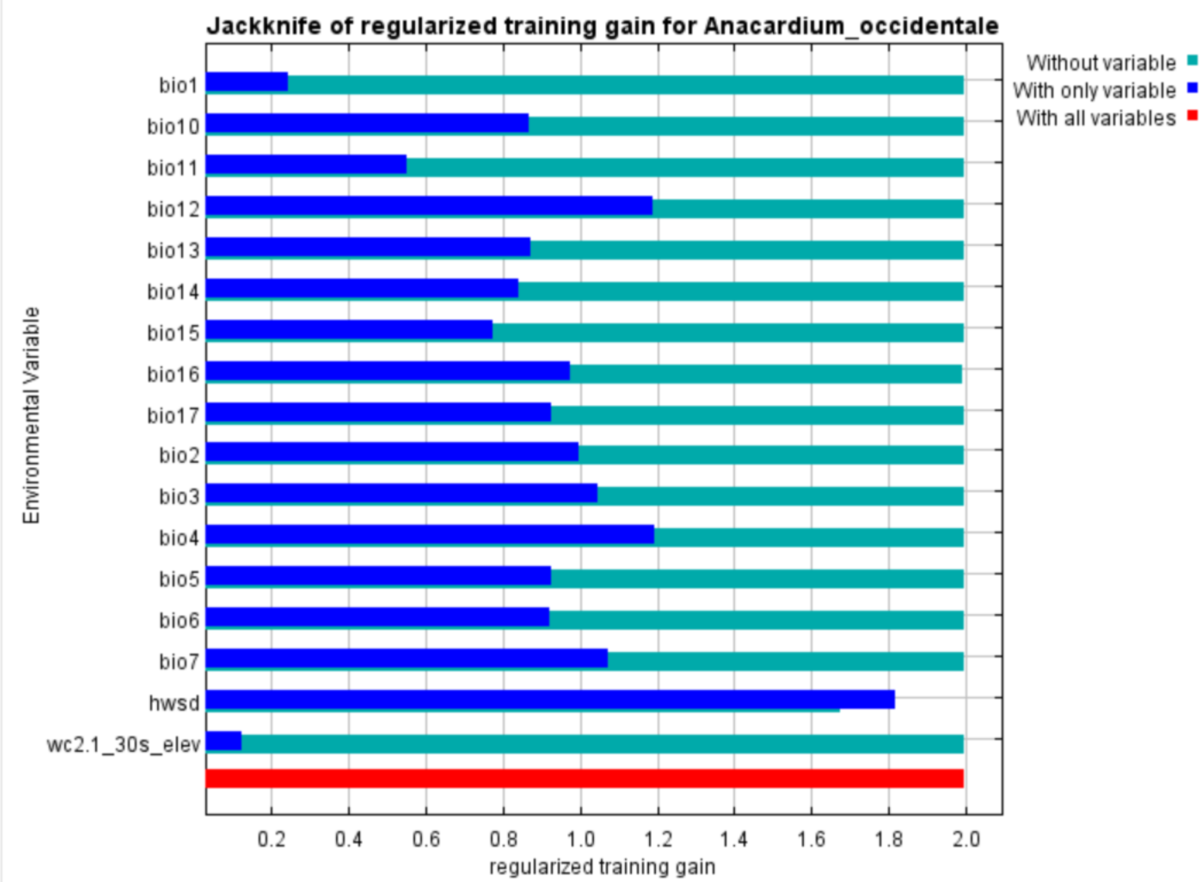


Figure15: Contribution of variables in the modelling according to the Jackknife test

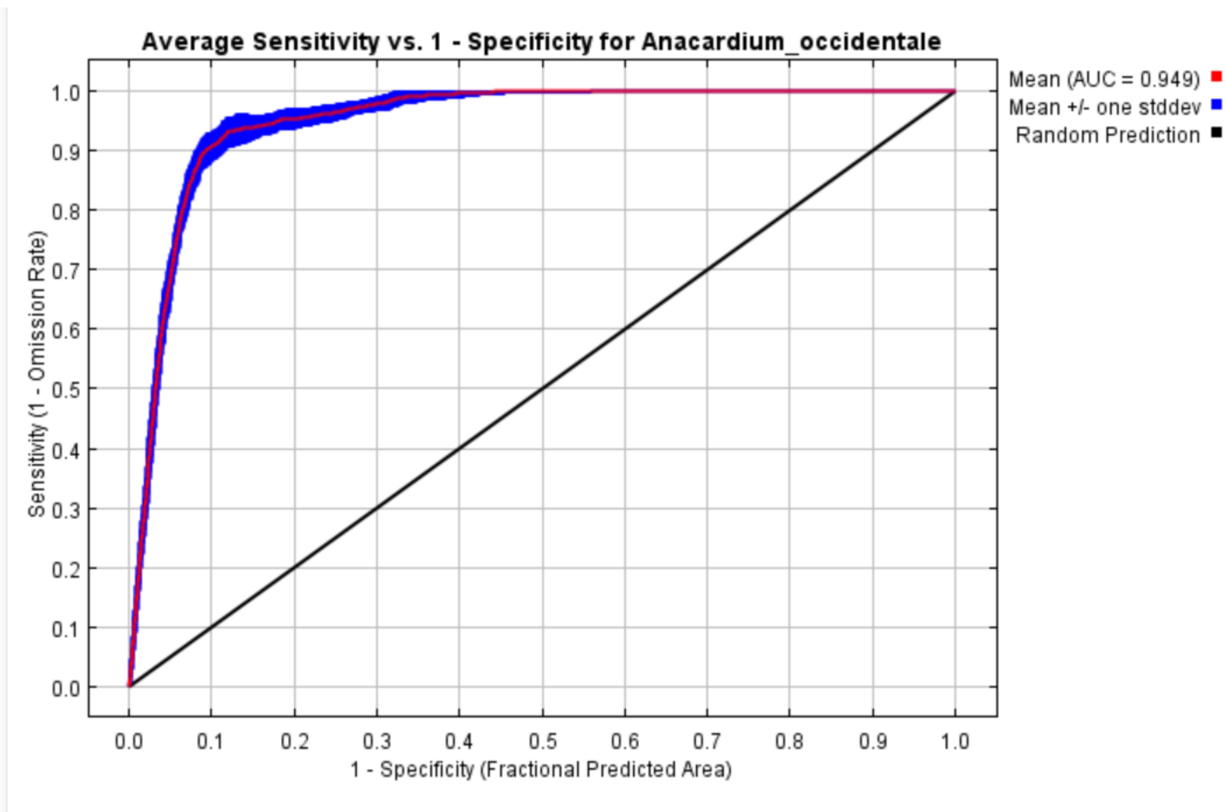


Figure 16: The Cross-validated areas under the receiver operating characteristic curve (AUC)

III.1. 2. CURRENT AND FUTURE POTENTIAL CROPPING AREA OF *A. occidentale* IN 2050 AND 2070.

The current predictions for potential suitability (less favourable, moderately favourable and highly favourable) regions identified 89.14% of Togo's national territory, while the potentially unfavourable areas account for 10.86% of the territory (Figures 17 and 18). The current scenario shows that *A. occidentale* is potentially distributed in the Eastern part of the Plateaux region, most of the part of the Central region, the whole of the Kara region and most of the areas of the Savanes region (Figure 19).

The future climate change impacts on the potential distribution of *A. occidentale* in Togo using the HadGEM3-GC3.1-LL and MIROC6 models under ssp245 and ssp585 (ssp: shared socio-economic pathways) scenarios are shown in Figure 18. Based on the AUC and TSS values for the 2050 period, models using ssp245 (Middle of the road: Moderate greenhouse gas emissions) and ssp585 (Fossil-fueled development: Highest emission of greenhouse gases) data had high predictive performance (AUC> 0.90; TSS = 0.88). With the HadGEM model using ssp245 and ssp585 scenarios, the regions defined as having high suitability will decrease (Figure 18). These Global Circulation Models indicated that there was a significant spatial extension of the suitable (less favourable, moderately favourable and unfavourable) regions when compared with the current values, while the highly favourable suitable regions were decreased (Figure 19). The results from the MIROC6 model using the ssp245 and ssp585 scenarios are shown in Figure 16**.** The MIROC6 model has predicted that the high potential areas of cashew cultivation will be reduced to 5.24% for the scenario ssp245, but the ssp585 scenario predicted the complete disappearance of areas with high potential cashew nut production. The HadGEM model predicted that potential areas of high cashew cultivation will be 3.71% and 0.26% of Togolese territory, under the ssp245 and ssp585 scenarios, respectively. The HadGEM model predicted a large expansion (from the Maritime region to the Savanes region) of potentially moderately favourable areas for *A. occidentale* under both scenarios (Figure 19). But for the MIROC6 model the potential moderately favourable area for *A. occidentale* under ssp245 has changed to less favourable under ssp585, these changes are observable from the Maritime region to the Savanes region (Figure 19)

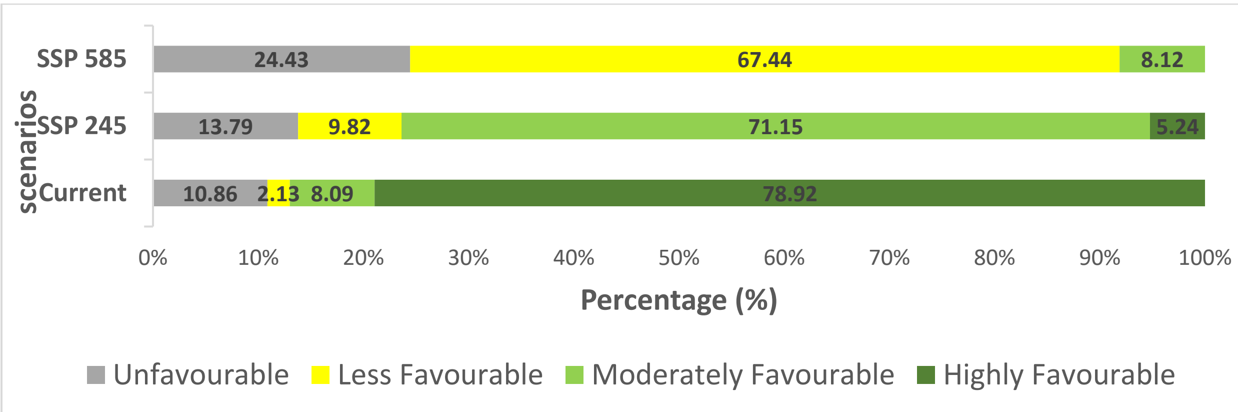


Figure17: Proportion of current and potential future habitats according to MIROC6 under ssp245 and ssp585 scenarios of the cashew tree in Togo. ssp245 (Middle of the road: Moderate greenhouse gas emissions) and ssp585 (Fossil-fueled development: Highest emission of greenhouse gases)

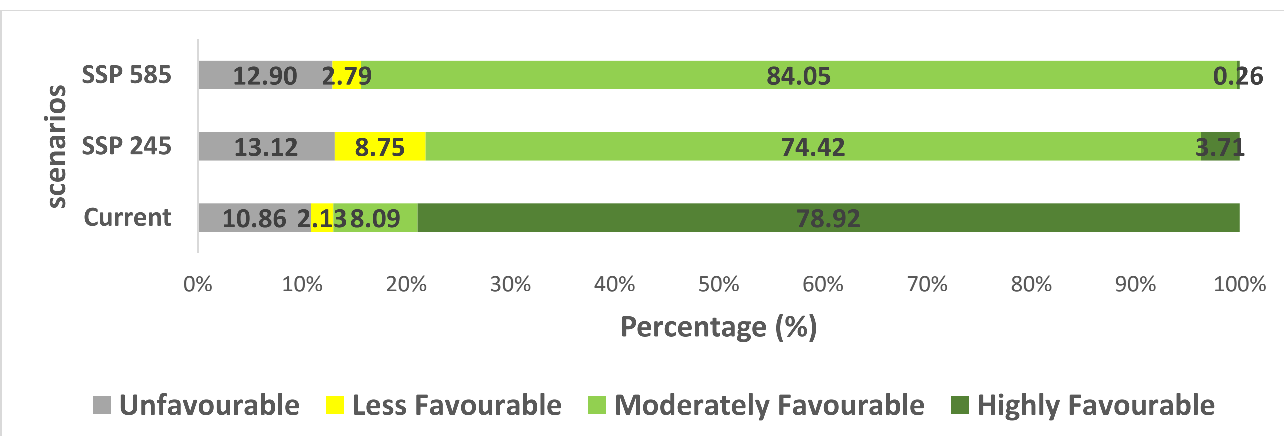


Figure 18: Proportion of current and potential future habitats according to HadGEM under ssp245 and ssp585 scenarios of the cashew tree in Togo. ssp245 (Middle of the road: Moderate greenhouse gas emissions) and ssp585 (Fossil-fueled development: Highest emission of greenhouse gases)

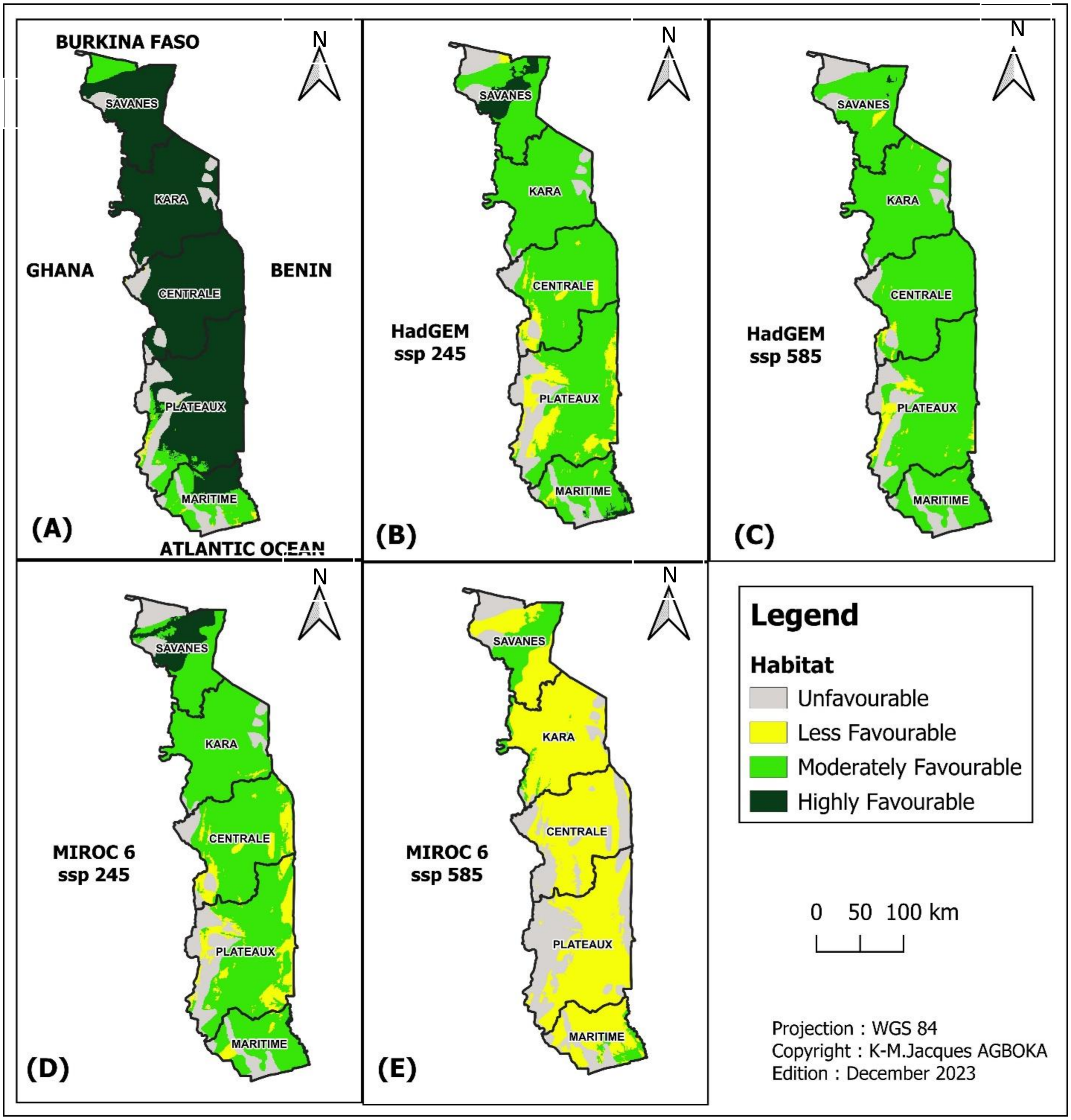


Figure19**:** Current habitat suitability according to economic regions; and future potential distribution in 2050 for *Anacardium occidentale* in Togo, according to GCM-HadGEM A, scenarios; B, ssp 245; C, ssp585 GCM-MIROC6, scenarios; D, ssp 245; E, ssp 585. ssp245 (Middle of the road: Moderate greenhouse gas emissions) and ssp585 (Fossil-fueled development: Highest emission of greenhouse gases)

Figure 20 displays the findings of the MIROC6 model for the ssp245 and ssp585 scenarios. The HadGEM model utilizing the ssp245 and ssp585 scenarios will dramatically reduce the number of locations designated as having high suitability (Figure 21). Figure 22 depicts the projected climate change consequences on the possible distribution of *A. occidentale* in Togo using the HadGEM3-GC3.1-LL and MIROC6 models for ssp245 and ssp585 scenarios. Models employing ssp245 and ssp585 data demonstrated strong prediction performance for the 2070 era, with AUC and TSS values of 0.949 and 0.88, respectively. These Global Circulation Models revealed a large geographical extension of the suitable (less favourable, moderately favourable, and unfavourable) areas when compared to existing values, but the extremely advantageous appropriate regions were reduced (Figure 22). The MIROC6 model predicts that high-potential cashew agriculture regions would vanish entirely under scenarios ssp245 and ssp585. According to the HadGEM model, possible regions of high cashew cultivation would be 15.06% and 0.02% of Togolese territory under the ssp245 and ssp585 scenarios, respectively. Under the scenario ssp245, the HadGEM model anticipated a considerable extension (from the Maritime region to the Savanes region) of possibly moderately good places for *A. occidentale*; however, in the ssp585 scenario, the same broad expansion is shown for less favourable habitats (Figure 22). For the MIROC6 model, the potential unfavorable area for *A. occidentale* expands significantly under ssp245 and ssp585, with changes seen from the Maritime to the Savanes regions (Figure 22).

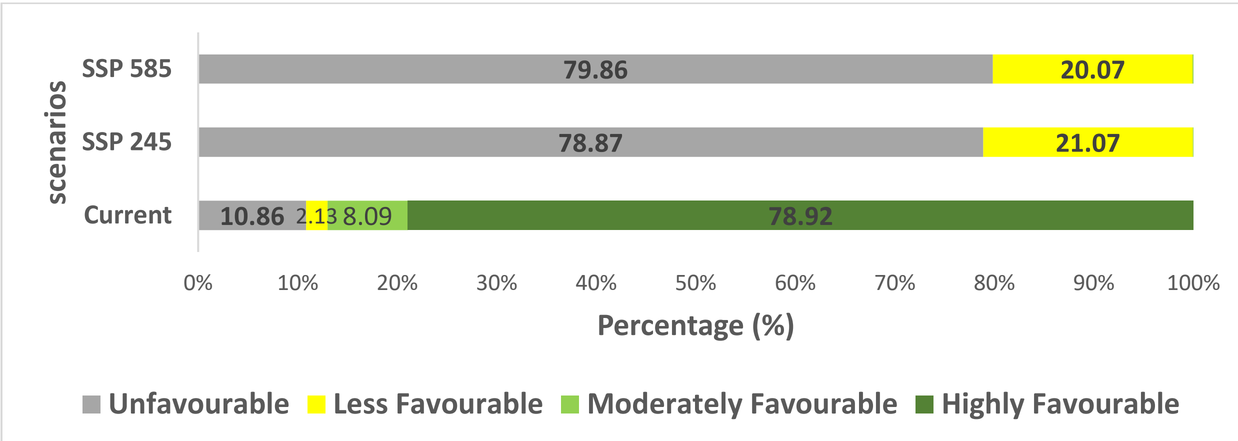


Figure 20: Proportion of current and potential future habitats according to MIROC6 under ssp245 and ssp585 scenarios of the cashew tree in Togo. ssp245 (Middle of the road: Moderate greenhouse gas emissions) and ssp585 (Fossil-fueled development: Highest emission of greenhouse gases)

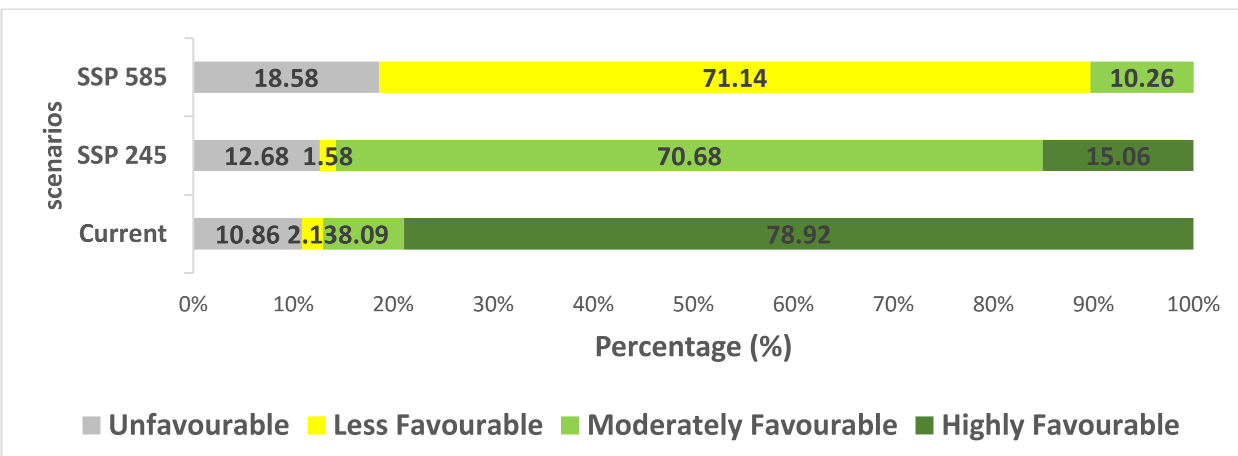


Figure 21: Proportion of current and potential future habitats according to HadGEM under ssp245 and ssp585 scenarios of the cashew tree in Togo. ssp245 (Middle of the road: Moderate greenhouse gas emissions) and ssp585 (Fossil-fueled development: Highest emission of greenhouse gases)

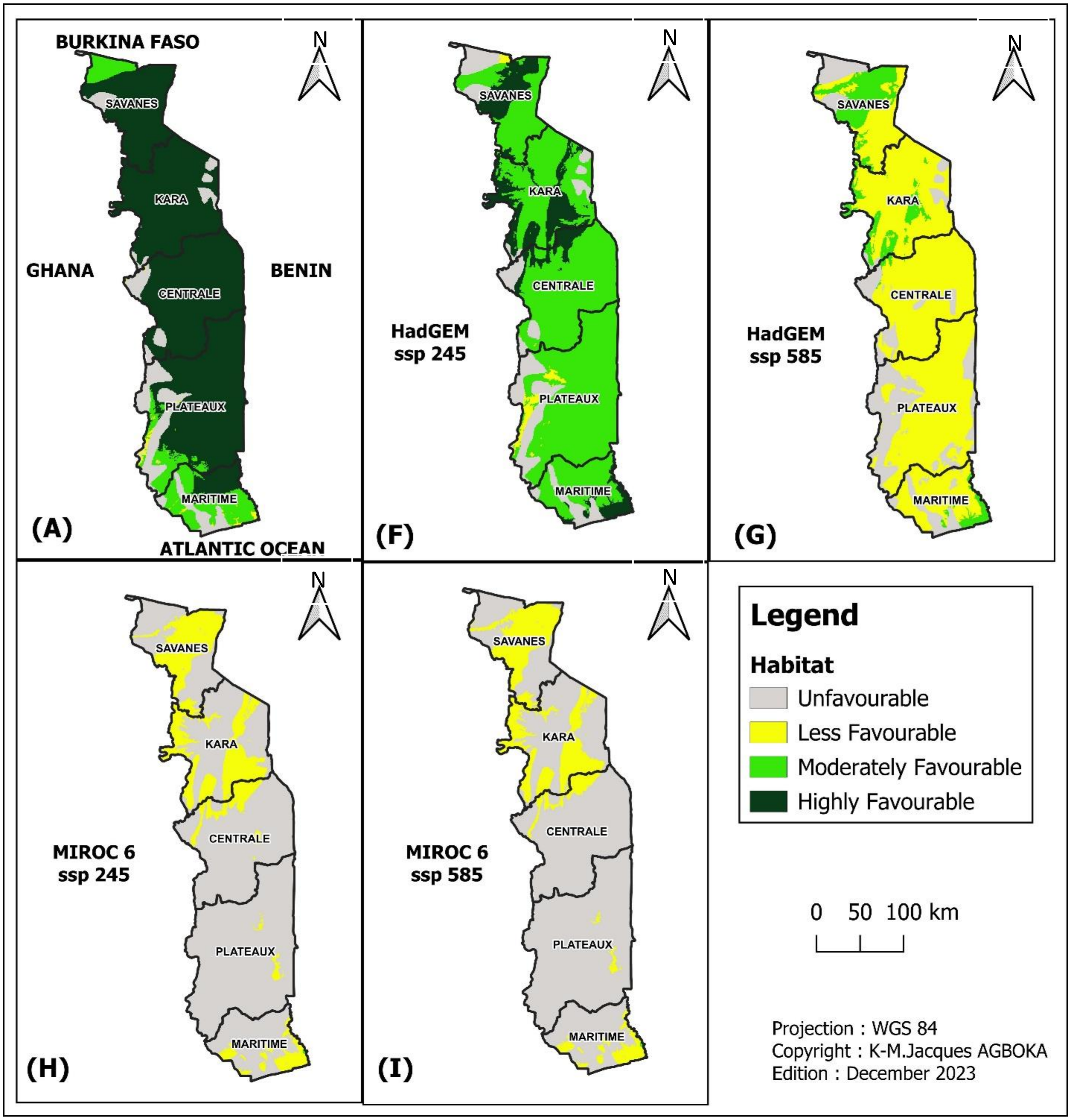


Figure 22: Current habitat suitability according to economic regions; and future potential distribution in 2070 for *Anacardium occidentale* in Togo, according to GCM-HadGEM A, scenarios; F, ssp 245; G, ssp585 GCM-MIROC6, scenarios; H, ssp 245; I, ssp 585. ssp245 (Middle of the road: Moderate greenhouse gas emissions) and ssp585 (Fossil-fueled development: Highest emission of greenhouse gases)

III.2. STRUCTURAL CHARACTERIZATION OF CASHEW TREE STANDS

The tables 6, 7, 8, 9 and Figure 23 below present the structural parameters of cashew tree stands based on main parameters such as density of individuals, diameter, height and basal area.

The density of individuals (Table 6), at the scale of the two climatic zones, a high value was observed for the Guinean climate (255±73.06 individuals/ha) and then the Soudanian climate (155±65.38 individuals/ha). A comparison of the density of the two climate zones shows that the lowest density value was observed in the Soudanian climate zone (37.5±12.5 individuals/ha), while the highest value was observed in the Guinean climate zone (445±178.96/ha).

As for the diameter of individuals (Table 7), considering the two climatic zones, the highest average value is observed for the Guinean climate (5.37±0.56 cm), followed by the Soudanian climate (4.82±0.44 cm). The lowest mean diameter value is 3.48±0.76 cm and is obtained in cashew trees stands located in the Guinean climate zones. Considering the cashew stands located in the Soudanian climate zones, the high mean diameter value was 17.60±1.04 cm while the low value was 4, 38±0.13 cm. In the Guinean climate zone, the highest mean value was (19.37±1.48 cm), followed by (12.42±0.54 cm). The lowest mean diameter value was 3.48±0.76 cm.

For the height, at the scale of the two climatic zones, we observe that the average height of cashew tree stands increases with the cashew tree classes. The highest mean height was 6.67±0.52 m for the cashew stand located in the Guinean climatic zone, whereas the lowest height is observed in the Sudanian climatic zone and was 3.88±0.88 m (Table 8).

The basal areas of the cashew tree populations increase when the tree classes increase. An average of fifteen-point twenty-two square metres per hectare (15.22±2.25 m^2/ha) was the mean basal area for the Guinean climate zones, while 10.51±1.99 m^2/ha was the mean basal area for the cashew tree stands located in the Soudanian climate zones (Table 9)

Table 6: Structural characteristics of the cashew tree population: the case of density

Structural parameters	Cashew tree population	Density (individuals/Ha)		P
		Zone A	Zone B	
[0-5[	142.86±77.4816	185±105.06	37.5±12.5	0.245
[5-10[	435±100.014	445±178.96	425±113.74	0.225
[10-15[	375±70.71	335±129.08	415±70.98	0.624
>15	205±49.13	255±73.06	155±65.38	0.104
Overall	205±49.13	255±73.06	155±65.38	0.174

Zone A: Guinean climate; Zone B : Soudanian climate

Table 7: Structural characteristics of the cashew tree population: the case of diameter (DBH)

Structural parameters	Cashew tree population	Average diameter (Cm)		P
		Zone A	Zone B	
[0-5[	3.74±0.55	3.48±0.76	4. 38±0.13	0.058
[5-10[	6.86±0.22	6.80±0.40	6.91±0.022	0.522
[10-15[	12.22±0.29	12.42±0.54	12.02±0.24	0.522
>15	18.49±0.90	19.37±1.48	17.60±1.04	0.357
Overall	5.09±0.35	5.37±0.56	4.82±0.44	0.508

Zone A: Guinean climate; Zone B : Soudanian climate

Table 8: Structural characteristics of the cashew tree population: the case of the height

Structural parameters	Cashew tree population	Average Height (Cm)		P
		Zone A	Zone B	
[0-5[	4.48±0.69	4.72±0.93	3.88±0.88	0.224
[5-10[	4.35±0.24	4.66±0.33	4.03±0.31	0.197
[10-15[	5.3±0.35	5.53±0.58	5.06±0.44	0.544
>15	6.15±0.42	6.67±0.52	5.63±0.62	0.241
Overall	11.52±0.82	12.12±1.52	10.94±0.77	0.463

Zone A: Guinean climate; Zone B : Soudanian climate

Table 9: Structural characteristics of the cashew tree population: the case of the basal area

Structural parameters	Cashew tree population	Basal area (m^2/ha)		P
		Zone A	Zone B	
[0-5[	0.17±0.08	0.22±0.11	0.06±0.01	0.122
[5-10[	1.76±0.41	1.76±0.69	1.76±0.52	0.255
[10-15[	4.25±0.75	3.81±1.39	4.69±0.71	0.477
>15	6.73±2.08	9.42±3.63	9.42±3.63	0.221
Overall	12.86±1.62	15.22±2.25	10.51±1.99	0.156

Zone A: Guinean climate; Zone B : Soudanian climate

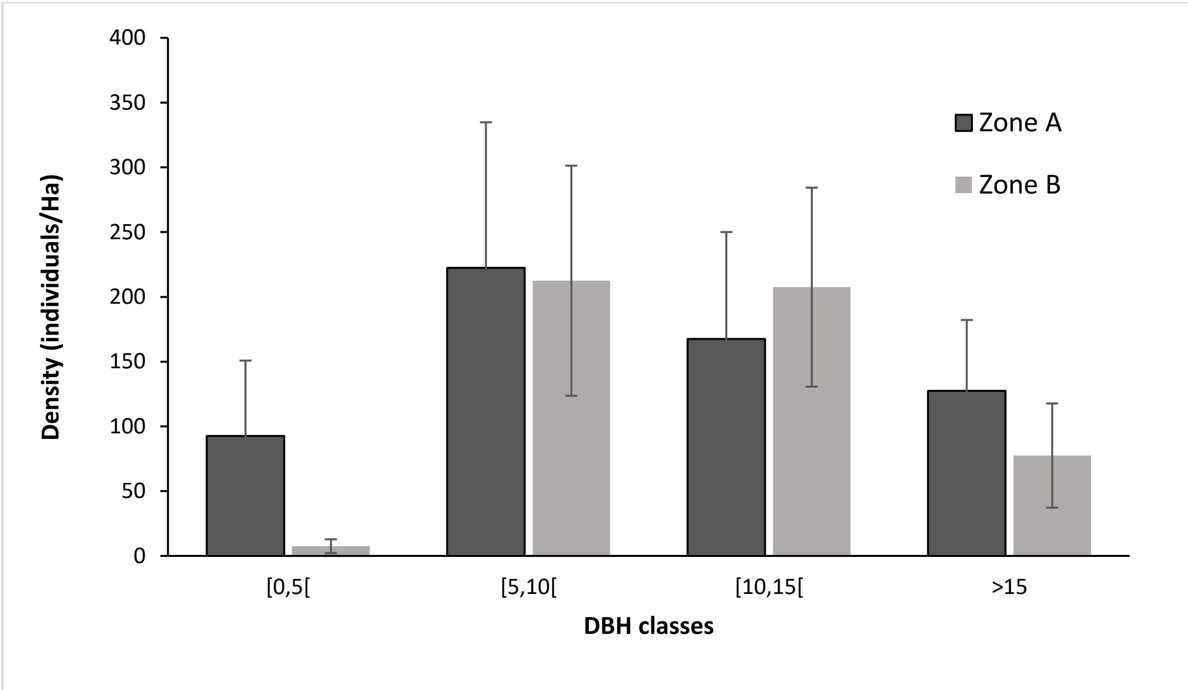


Figure 23: Density of cashew trees as a function of DBH classes and climatic gradient. (Zone A: Guinean climate; Zone B: Soudanian climate)

III.3. AERIAL AND UNDERGROUND BIOMASS OF CASHEW TREES

The variation of aerial and underground biomass according to the two climatic zones (Guinean and Soudaninan climate zones) was assessed and the observed averages are recorded in the tables 10 and 11 below. The analysis of these results shows that the biomass (aerial and underground) varies from one climatic zone to another. Considering the two climatic zones, the highest aerial and root biomass was observed in the Guinean climate zone: 30.93±5.89 kg/individual for the aerial biomass (Table 10) and 0.82±0.15 kg/individual for the root biomass (Table 11). An analysis of Tables 10 and 11 below shows that biomass (aerial and root) increases slightly on average as a function of changes in tree classes, for both climatic zones (Guinean and Sudanian).

Table 10: Aerial biomass of cashew tree

Structural parameters	Cashew tree population	Aboveground biomass (kg/individual)		P
		Zone A	Zone B	
[0-5[	0.22±0.10	0.28±0.14	0.07±0.02	0.160
[5-10[	2.73±0.63	2.72±1.07	2.74±0.82	0.774
[10-15[	7.7±1.35	6.91±2.50	8.42±3.39	0.590
>15	14.72±4.77	21.04±8.42	8.42±3.39	0.203
Overall	25.30±4.77	30.93±5.89	19.68±3.90	0.139

Zone A: Guinean climate; Zone B : Soudanian climate

Table 11: Underground biomass of cashew tree

Structural parameters	Cashew tree population	Underground biomass (kg/individual)		P
		Zone A	Zone B	
[0-5[	0.07±0.03	0.09±0.04	0.02±0.01	0.117
[5-10[	0.25±0.05	0.27±0.09	0.23±0.06	0.987
[10-15[	0.27±0.06	0.25±0.11	0.276±0.05	0.878
>15	0.17±0.04	0.21±0.07	0.12±0.05	0.307
Overall	0.73±0.04	0.82±0.15	0.64±0.11	0.139

Zone A: Guinean climate; Zone B : Soudanian climate

III.4. STOCK OF ORGANIC CARBON IN THE DIFFERENT COMPARTMENTS OF CASHEW TREES IN LITTER AND SOIL

Tables 12, 13, 14, 15 and 16 below show the amount of carbon stored in the cashew tree's different compartments (trunks, branches, and leaves) as a function of climatic zone and tree classes, as well as the carbon stored in the soil and the litter as a function of the climatic zone. Generally, trunks store more carbon (79%) than other compartments (branches (19%) and leaves (2%)). On the other hand, the cashew tree compartment that stores on average less tonnes of carbon per hectare is the leaf (Figure 25), and this is observed in the case of the two climatic zones (Guinean and Sudanian climate). Furthermore, the average carbon stored in the trunk by cashew trees in the Guinean zone (23.17±4.80 kg C/individual) is greater than that stored by cashew trees's trunk in the Sudanian zone 13.69±3.20 kg C/individual. The trend remains the same if we compare the average carbon stored in the two climatic zones' other compartments (branches and leaves). The Soil in the Guinean climate zone sequesters more carbon per hectare than the soil in the Soudanian climate zone (Table 15), the opposite trend is observed for the average amount of carbon stored in litter per hectare. What's more, the amount of carbon sequestered increases with the depth (from 0-25 cm to 25-50 cm).

Figure 24 shows the cumulative carbon stock as a function of DBH classes and the climate zones. In the Guinean climatic zone, cashew trees with a DBH greater than 15 cm, store 68% of organic carbon. On the other hand, in the Sudanian climatic zone, cashew trees with a DBH greater than 15 and those with a DBH between 10 and 15 cm store almost the same amount of carbon, 46% and 42%, respectively. Figure 24 shows that whatever the climatic zone (Guinean or Sudanian) and the cashew tree compartment (stems, branches and leaves), the cumulative percentage of organic carbon stored remains the same.

Table 12: Stock of organic carbon stored in the trunks of the cashew trees.

Structural parameters	Cashew tree population	Carbon stock in the Trunk (kg C/individual)		P
		Zone A	Zone B	
[0-5[	0.14±0.05	0.18±0.07	0.05±0.025	0.100
[5-10[	1.84±0.4	1.93±0.68	1.74±0.50	0.953
[10-15[	5.55±1.18	5.41±2.33	5.70±0.90	0.910
>15	10.94±3.69	15.65±6.56	6.23±2.65	0.220
Overall	18.43±3.14	23.17±4.80	13.69±3.20	0.149

Zone A: Guinean climate; Zone B : Soudanian climate

Table 13 : Stock of organic carbon stored in the branches of the cashew trees

Structural parameters	Cashew tree population	Carbon stock in the Branch (kg C/individual)		P
		Zone A	Zone B	
[0-5[	0.03±0.01	0.04±0.01688	0.01±0.006	0.100
[5-10[	0.44±0.096	0.47±0.16	1.37±0.22	0.953
[10-15[	1.34±0.28	1.30±0.56	1.37±0.22	0.910
>15	2.63±0.89	3.77±1.58	1.50±0.64	0.220
Overall	4.43±0.76	5.58±1.15	1±0.77	0.384

Zone A: Guinean climate; Zone B : Soudanian climate

Table 14 : Stock of organic carbon stored in the leaves of the cashew trees

Structural parameters	Cashew tree population	Carbon stock in the Leaf (Kg C/individual)		P
		Zone A	Zone B	
[0-5[	0.004±0.002	0.01±0.001	0.001±0.00	0.100
[5-10[	0.05±0.01	0.05±0.02	0.05±0.01	0.953
[10-15[	0.16±0.033	0.15±0.07	0.16±0.03	0.220
>15	0.31±0.10	0.44±0.19	0.18±0.07	0.220
Overall	0.52±0.09	0.93±0.14	0.38±0.09	0.156

Zone A: Guinean climate; Zone B : Soudanian climate

Table 15: Stock of organic carbon stored in the soil of the cashew plantations.

Depth	Carbon stock in the Soil (t C/ha)		P
	Zone A	Zone B	
0 – 25 cm	18.49±1.13	20.97±1.56	2.445
25 – 50 cm	38.72±2.43	43.92±3.17	1.251
Total	86.89± 4.06	80.23 ± 3.78	1.02

Zone A: Guinean climate ; Zone B : Soudanian climate

Table 16 : Stock of organic carbon stored in the litter of the cashew plantations.

Carbon stock in the Litter (t C/ha)		P
Zone A	Zone B	
0.47±0.02	0.50±01	2.11

Zone A: Guinean climate; Zone B : Soudanian climate

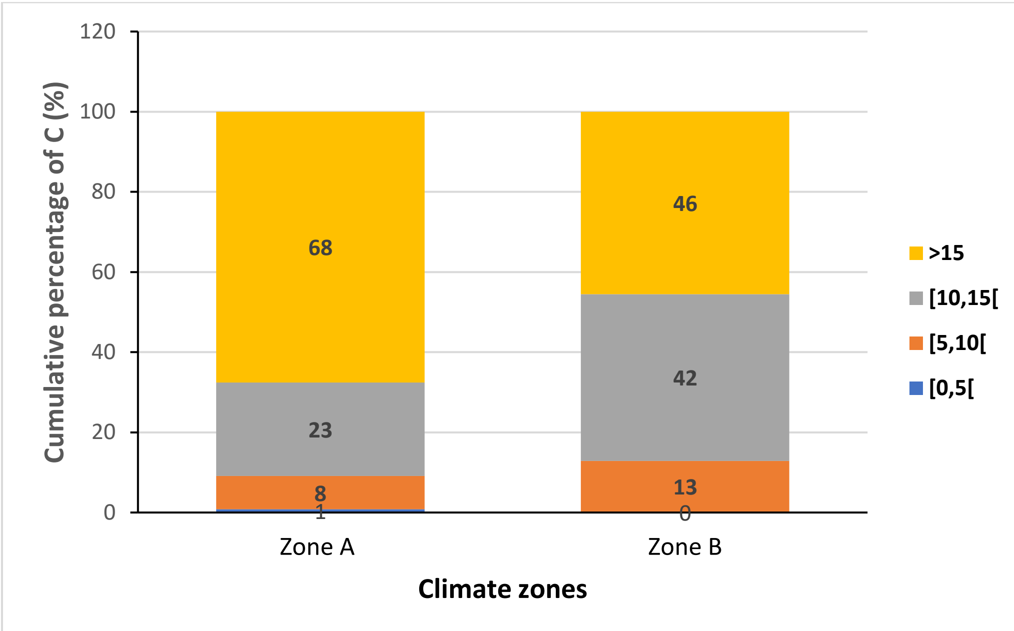


Figure 24: Cumulative carbon stock as a function of DBH classes and climatic gradient. (Zone A: Guinean climate ; Zone B : Soudanian climate)

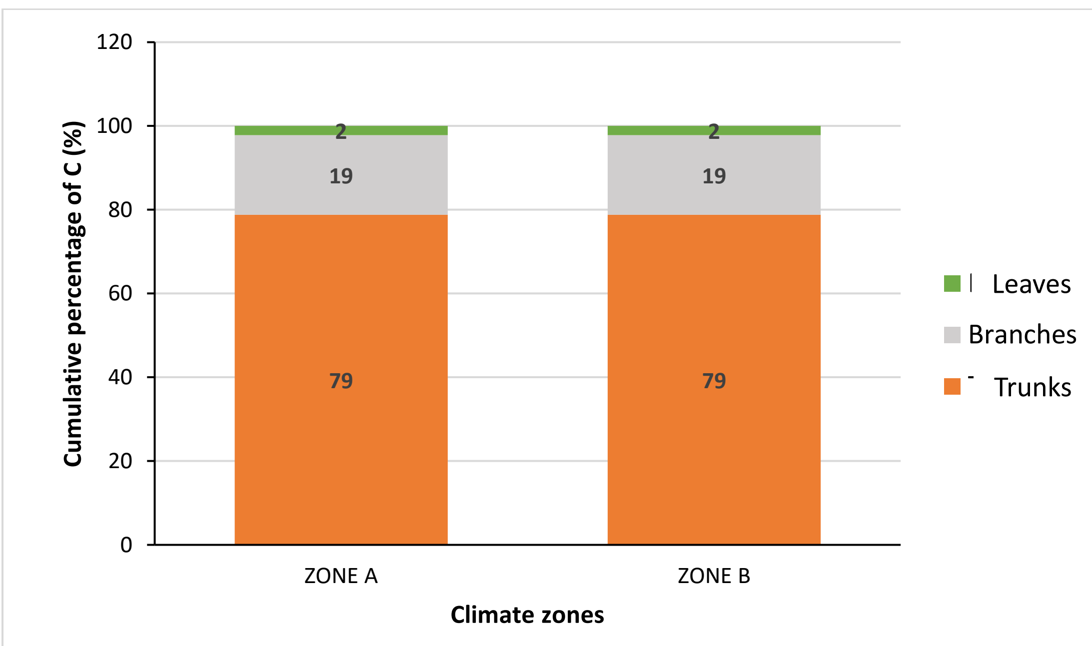


Figure 25: Cumulative organic carbon stock in the different compartments (leaves, branches and trunks) of cashew trees regarding the climatic gradient. (Zone A: Guinean climate; Zone B: Soudanian climate)

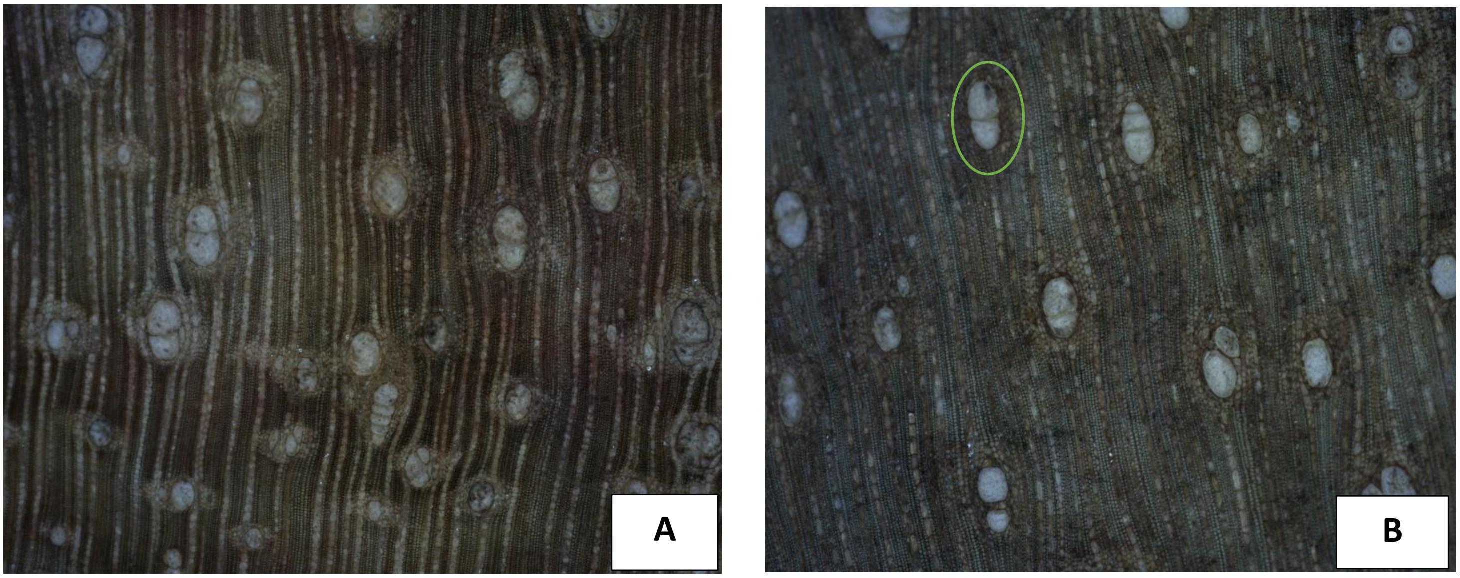
III.5. INTER-ANNUAL VARIABILITY OF CARBON ISOTOP RATIOS OF CASHEW IN THE HUMID AND DRY CASHEW PRODUCTION ZONES OF TOGO WITH CLIMATIC PARAMETERS

III.5.1 MACROSCOPIC STRUCTURE OF CASHEW DISK STEMS COLLECTED IN WET AND DRY CASHEW PRODUCTION ZONES.

Figures 26 and 27 show the macroscopic structure of cashew disk stems collected in the two cashew production zones (wet and dry) in Togo. Figure 27 clearly shows that there is no apparent ring in the cashew stem discs in the two production zones. The stem discs of cashew trees have vessels whose organisation and size differ from one production zone to another (figure 27). The stem disks collected in the wet zone have wider vessel sizes than those collected in the dry zone, and the stem disks collected in the dry zone are grouped in clusters of two or three (2-3), whereas those collected in the wet zone have solitary vessels. Figure 27 below shows us that cashew disk stems collected in humid and dry areas have vessels that are surrounded by parenchyma and these vessels are filled by thailosis.

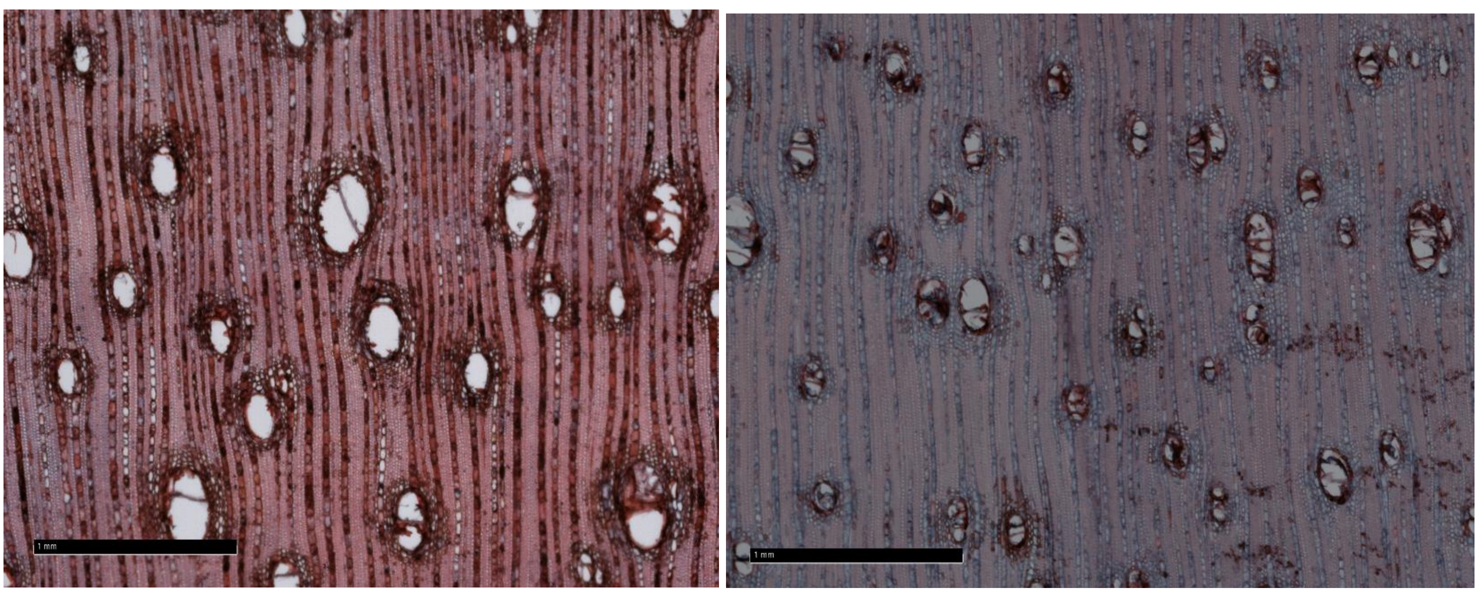
III.5.2. VARIATION OF THE CARBON ISOTOPE RATIO AS A FUNCTION OF TIME (YEAR)

Tables 18 and 19 show the variation of carbon isotope ratios of cashew tree individuals and climatic parameters (temperature and precipitation) as a function of the year. Table 17 shows the statistical values of carbon isotopes measured in cashew stem disks over the period 2016 to 2023. The highest average carbon isotope value was obtained in the AVI individual (-27.03 ± 0.11), for the wet cashew production zone and (-26.15± 0.11) for the BV individual which was collected in the dry cashew production zone. It can therefore be deduced that of the two cashew tree production zones (wet and dry) BV has the higher average carbon isotope values. On the other hand, the lowest carbon isotope value was observed in individual BIII (-28.14 ± 0.08).



Anacardium occidentale L.

Figure26: Macroscopic picture of the stem disk (A: collected in the humid zone and B in the dry zone). The encircled structure is a vessel filled with thailosis.



Humid production zone

Dry production zone

Anacardium occidentale L.

Figure 27: Transverse sections of *Anacardium occidentale* L. in the humid and dry production zones of Togo

Table 17: Statistical characterisation of Carbon-13 ($\delta\ ^{13}C$) series

Humid cashew production zone			
	AII	AVI	AVIII
Mean	-27.43	-27.03	-27.43
SE	0.12	0.11	0.09
Minimum	-27.81	-27.55	-27.83
Minimum	-26.92	-26.47	-27.13
Dry cashew production zone			
	BIII	BI	BV
Mean	-28.14	-27.16	-26.1525
SE	0.08	0.10	0.11
Minimum	-28.56	-27.62	-26.48
Minimum	-27.86	-26.75	-25.57

III.5.3. PATTERNS OF CARBON-13 IN TREE STEM DISKS USING WHOLE WOOD

Inter-annual changes in $\delta^{13}C$ recording followed almost a similar trend in AVI and AVIII throughout the recording period 2016-2023 (Fig 28 a), with the exception of AII. Tables 18 and 19 show the variation of the annual $\delta^{13}C$ values from 2016 to 2023.

The figure 28b shows that the inter-annual patterns of $\delta^{13}C$ ratios in the tree stem disk of A. *occidentale* are uniform between the three individual cashews. This indicates that marked changes in stable isotope ratios are synchronized amongst cashew individuals in the dry cashew production zone (Fig 28 b). This is verified by cross-correlation analysis of the individual mean $\delta^{13}C$ series ($r = 0.41$, $p<0.05$).

III.5.4. RELATIONSHIP BETWEEN CARBON-13 IN WHOLE WOOD OF TREES AND CLIMATIC PARAMETERS

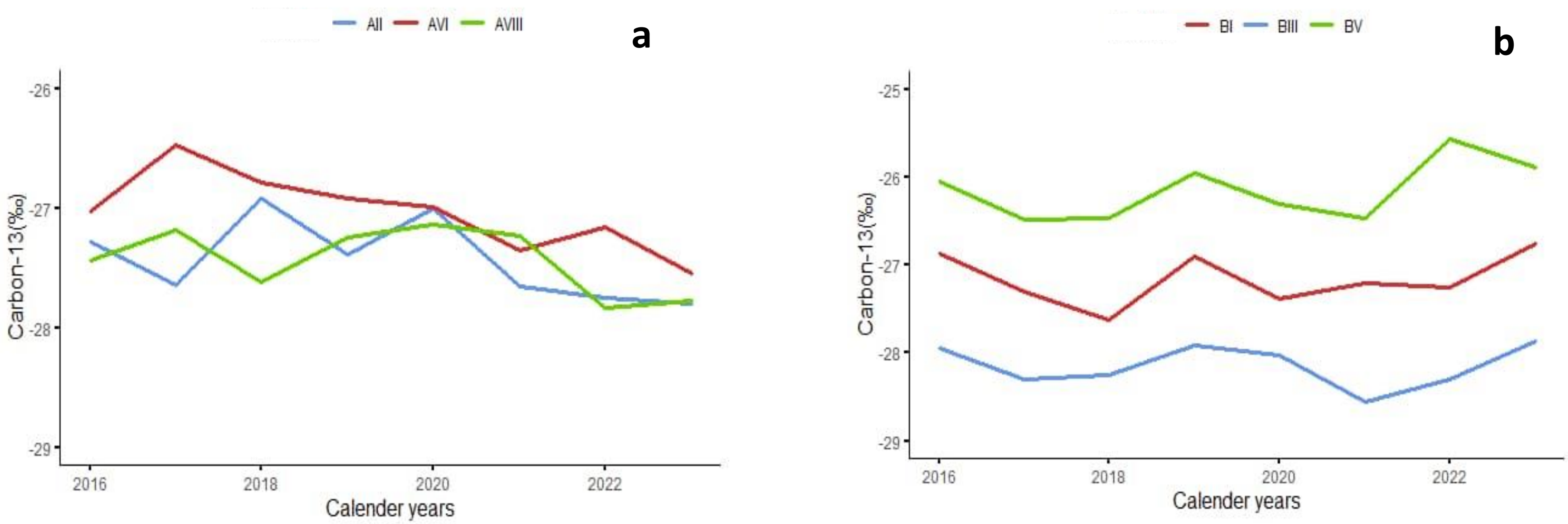
The annual temperature and rainfall averages over the past 8 years have been linked to Carbon-13 ($\delta^{13}C$) of *Anacardium occidentale* L. collected in the humid and dry cashew production zones of Togo. From these results, there was a positive and significant correlation ($r = 0.722$; $P <0.05$), between the Carbon-13 ($\delta^{13}C$) of the individual BI and the temperature (Figure 29 b). However, there was no correlation between the Carbon-13 ($\delta^{13}C$) of the individuals (AII; AVI; AVIII; BI; BIII and BV) and the mean of the rainfall over the last 8 years ($P > 0.05$),as showed Figure 30a and b

Table 18: $\delta^{13}C$ values of *Anacardium occidentale* L. collected from humid and dry cashew production zone and the mean annual precipitation of the humid and dry cashew production zone from 2016 to 2023.

Years	*Anacardium occidentale* L. $\delta^{13}C$ (‰)						Annual precipitation (mm) Humid production zone	Annual precipitation (mm) Dry production zone
	Humid production zone			Dry production zone				
	A II	A VI	A VIII	B III	B I	B V		
2016	-27.29	-27.02	-27.44	-27.94	-26.87	-26.06	1508.2	1110.7
2017	-27.64	-26.47	-27.19	-28.31	-27.30	-26.48	1532.8	1112.1
2018	-26.92	-26.79	-27.62	-28.25	-27.62	-26.47	1603.7	1386.6
2019	-27.40	-26.92	-27.25	-27.92	-26.90	-25.96	1846.5	1033.8
2020	-27.00	-26.99	-27.13	-28.03	-27.38	-26.31	980.4	1483.1
2021	-27.65	-27.35	-27.23	-28.56	-27.21	-26.47	1224.3	1311.2
2022	-27.76	-27.16	-27.83	-28.30	-27.25	-25.57	1220.6	1389.1
2023	-27.81	-27.55	-27.78	-27.86	-26.75	-25.90	2334.4	1264

Table 19: $\delta^{13}C$ values of *Anacardium occidentale* L. collected from humid and dry cashew production zone and the mean annual temperature of the humid and dry cashew production zone from 2016 to 2023.

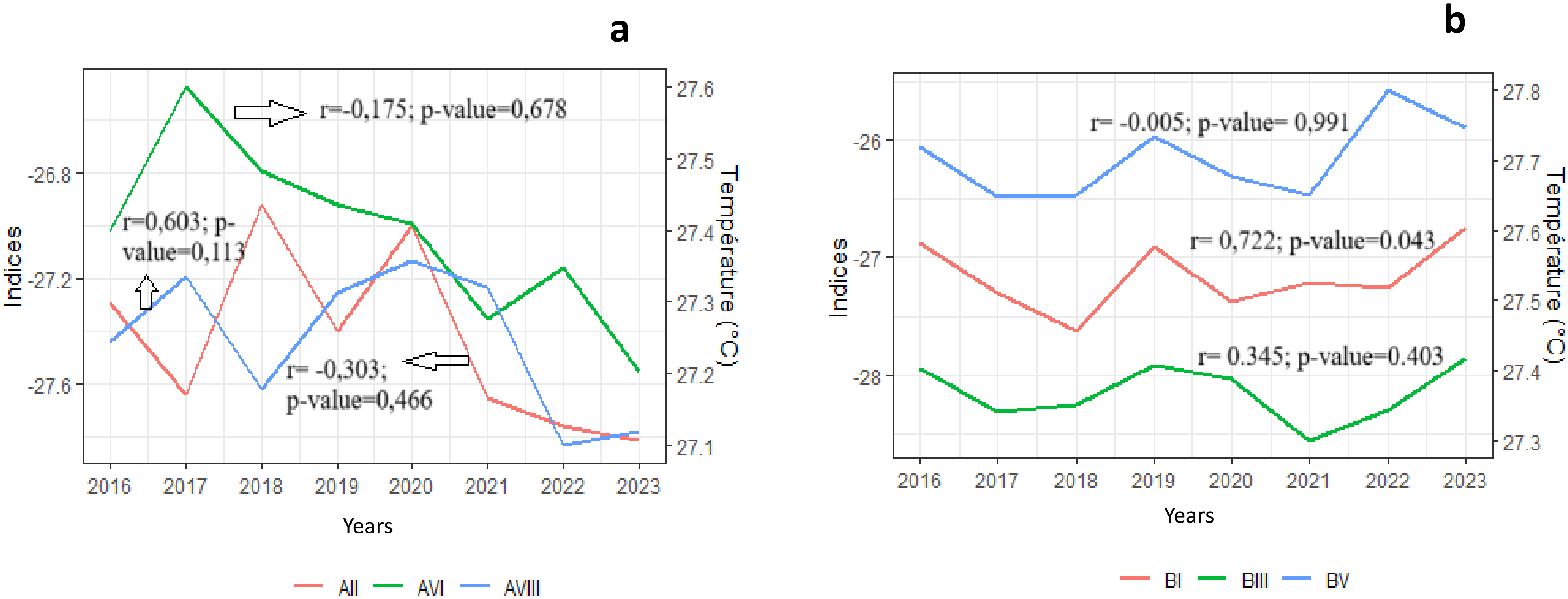
Years	*Anacardium occidentale* L. $\delta^{13}C$ (‰)						Mean annual temperature (%) Humid production zone	Mean annual temperature (%) Dry production zone
	Humid production zone			Dry production zone				
	A II	A VI	A VIII	B III	B I	B V		
2016	-27.29	-27.02	-27.44	-27.94	-26.87	-26.06	27.5	27.7
2017	-27.64	-26.47	-27.19	-28.31	-27.30	-26.48	27.6	27.6
2018	-26.92	-26.79	-27.62	-28.25	-27.62	-26.47	27.1	27.3
2019	-27.40	-26.92	-27.25	-27.92	-26.90	-25.96	27.5	27.8
2020	-27.00	-26.99	-27.13	-28.03	-27.38	-26.31	27.6	27.7
2021	-27.65	-27.35	-27.23	-28.56	-27.21	-26.47	27.6	27.8
2022	-27.76	-27.16	-27.83	-28.30	-27.25	-25.57	27.2	27.4
2023	-27.81	-27.55	-27.78	-27.86	-26.75	-25.90	27.6	27.8



Humid cashew production zone

Dry cashew production zone

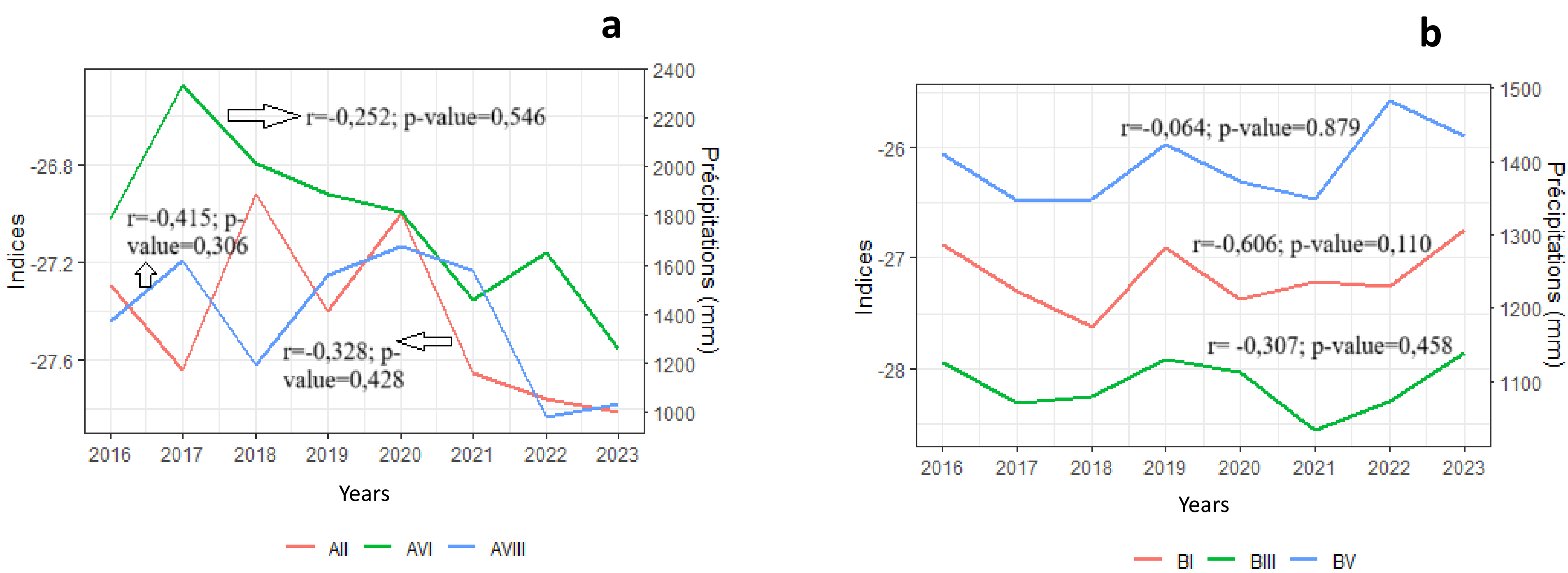
Figure 28: Inter-annual pattern of Carbon-13 ($\delta^{13}C$) of *Anacardium occidentale L*. in the humid and dry cashew production zones of Togo. (Each curve on each graph corresponds to one individual of *Anacardium occidentale* L.)



Humid cashew production zone

Dry cashew production zone

Figure 29: Correlation *of Anacardium occidentale* L. individual chronologies from the humid and dry cashew production zone to the temperature. Variable is yearly average temperature. Significance level (p≤0.05).



Humid cashew production zone

Dry cashew production zone

Figure 30: Correlation of *Anacardium occidentale* L. individual chronologies from the humid and dry cashew production zone to the precipitation. Variable is yearly average precipitation. Significance level ($p \leq 0.05$).

PART IV: DISCUSSION

As for any scientific document, after the results have been presented, the presented results need to be discussed. This fourth part of our document will be devoted to the discussion of the results presented in the third part of this document.

The strength and validity of species distribution models are dependent on the input data. This work employed the maximum entropy (MaxEnt) technique, which has been used by various authors in species distribution **(Abdou *et al.,* 2016; Lyam *et al*., 2012),** to map probable cashew-producing sites in Togo. This approach's strength is its capacity to incorporate occurrence data and environmental factors across the research region **(Lahoz-Monfort *et al.,* 2014).** It also has the ability to run both quantitative and qualitative data **(Atakpama *et al.,* 2023).** The value of the Area Under the Curve accurately predicted the geographic distribution of cashew trees in Togo. Currently, the less favourable environment for cashew cultivation is located in locations with significant rainfall, notably in the southern hilly highlands and Togo's coastline zone. The Kara and Central areas are quite favourable. This finding is consistent with the species' present cultivation regions as well as the cashew tree's rainfall needs **(Ricau, 2013).**

Future forecasts (2050 and 2070) from both models and scenarios indicate a decline in the appropriate habitat (very favourable) relative to the present area (current> 2050; current > 2070). Edaphic variables are among the environmental factors that can predict and influence species distribution, particularly plant species **(Austin and Van Niel, 2011; Mod, 2016).** The findings of this study revealed that soil is a key determinant in the regional distribution of cashew trees, followed by annual precipitation (bio12) and temperature seasonality (bio4). Soil influences plant physiological status, hence its impact on the model is significant, as **Gnahoua and Louppe (2003)** interpreted the implications of the cashew tree edaphic needs. The plant does not survive on clayey, waterlogged lowland soils like those found in Togo's Maritime area. This scenario might be connected to soil pH which has been demonstrated to have a significant impact on plant species distribution **(Chytry and Rafajová, 2003).** The pH of the soil can alter the availability of resources and plant nutrient absorption. In addition, **FAO (1994),** indicates that the optimum pH for cashew growth is between 4.5 and 6.5, with the lower limit as low as 3.8. Seasonal temperature and precipitation determine soil moisture content **(Mod, 2016)**. The influence of seasonality, temperature and annual precipitation confirms **Lyam *et al.* (2012)** findings. **Lyam *et al.* (2012)** have demonstrated that temperature and precipitation have important roles in plant species and vegetation distribution. Both of these factors added to the soil have a direct impact on the geographical distribution of cashews and might be the key environmental characteristics in the species' ecology **(Atakpama *et al.,* 2023).**

The first part of the discussion focused on the environmental factors affecting the distribution of cashew tree habitats in Togo. In the following section, we discussed the impact of climate change on the potential cashew production areas in Togo.

Predicting how species will adapt to climate change is a critical component in developing biodiversity conservation and management strategies, as well as making cashew nut production climate resilient. Climate forecasts show that the extent of habitat now suitable for cashew farming in Togo would alter under both HadGEM and MIROC6 scenarios (ssp245 and ssp585) by 2050 and 2070. This might be because the cashew tree lacks the ability to adjust to climate change. Furthermore, climate change is expected to limit the geographical range of cashew plants. These findings contradict those of **Atakpama *et al.* (2023),** who discovered that climate change will not diminish the geographical spread of cashew trees in Togo. This distinction stems from the fact that our study employed the Shared Socioeconomic Pathways (SSPs) scenarios, whereas **Atakpama *et al*. (2023)** used the Representative Concentration Pathways (RCPs) scenarios.

The forecast models employed for the 2050 and 2070 horizons revealed that ecosystems conducive to cashew development will decline. Given the development of habitats using HadGEM, MIROC6 and both scenarios ssp245 and ssp585, it is obvious that climate change will pose a danger to cashew farming in Togo. It is thus a crop that is not resistant to climate change. **Mod (2016)** also suggests that biotic and human disturbances might influence the distribution of species niches. Natural disturbances such as herbivory, human settlements and density in SDMs should be effective predictors of climate change's effects on species niches **(Atakpama *et al.,* 2023).** This can help us understand how temperature and rainfall patterns may impact vegetation dispersal. According to HadGEM's predictions under ssp245 and ssp585 scenarios, and MIROC6's projection under ssp245, more than 50% of cashew trees will be conserved/cultivated sustainably by 2050. According to the MIROC6 model, under the ssp585 scenario, Togo's habitats that are now highly beneficial to species would be increasingly influenced by climate change as they become less suitable. In addition to that, according to HadGEM's forecasts under ssp245 and ssp585 scenarios, as well as MIROC6's projections under ssp245 and ssp585 scenarios, Togo's ecosystems, which are currently very advantageous to cashew sustainable cultivation, would be more altered by climate change, becoming unsuitable by 2070.

The first two parts of this discussion focused on assessing the impact of climate change on potential cashew habitats in Togo. The results presented in the third part clearly show that cashew plantations contribute to carbon sequestration. In the following section, we discussed the results obtained concerning carbon sequestration in cashew plantations in Togo according to climatic zones.

The carbon storage in each compartment varies by location (cashew production areas) and tree DBH in the different climatic zones. Of course, trees with a high DBH. store more carbon. This conclusion supports (**Deisingh and Thompson, 2004)**'s prior findings that the longer a tree grows, the more carbon it sequesters. Soil organic carbon reserves vary by location, ranging from 18.49±1.13 t C/ha to 43.92±3.17 t C/ha, which do not fall within the 11 to 33 t C/ha range determined by **Volkoff *et al*. (1999),** in Benin. The fluctuations in soil carbon stock are determined by soil depth and climate gradient. Soil carbon reserves are higher than the estimation of 31t C/ha by **IPCC (2003),** for the dry tropics and close to the 42 t C/ha obtained **by Tinlot (2010)** and **Sonwa (2004)** in a cocoa-based agroforestry system. The low carbon content of the soil in cashew farms could be attributed to increased organic matter decomposition caused by greater temperatures in the research location, which is located in the Sudanian climate zone. Our investigation found that carbon stock in litter ranged from 0.47±0.02 t C/ha to 0.50±01 t C/ha. This finding differs from the 2.8 t C/ha determined by the **IPCC (2003).** The low carbon rate could be attributed to the poor quality of litter. In India, **Rupa *et al*. (2013),** found that 7-year-old cashew farms with 156 to 600 trees per hectare, stored between 32.25 and 59.22 t C/ha. According to (**Albrecht and Kandji, 2003)**, the carbon storage capacity of an agroforestry system ranges from 12 to 228 t C/ha, with an average of 95 t C/ha. Our study's computed values fall within this range. The difference in C stock between zones might thus be attributed to variations in planting density. The quantity of carbon trapped by the agroforestry system varies according to the tree species and plantation density. **Montagnini and Nair (2004),** found that the quantity of carbon sequestered varies by tree species, geographic region (climate, soil), planting density and system management. **Lawal and Adekunle (2010),** found that a 20-year agroforest yielded less than 60 and 90 t C/ha. The plantation soil's carbon stock exceeds the agricultural system's expected worth. This allows us to argue that the agroforestry system is a carbon sink in comparison to the agricultural system. As a result of the quick regeneration and abundance of litter, natural forests have a higher carbon stock than agroforestry systems. **Montagnini and Nair (2004)** observed that agroforestry systems had an indirect influence on carbon capture by lessening strain on wild forests.

The previous section enabled us to discuss how carbon sequestration in cashew plantations in Togo varies according to the climatic zone. But it would be very interesting to discuss how climatic gradients in Togo influence carbon sequestration. This is the object of the following section.

Rainfall, temperature and wind are the most essential climatic characteristics of agricultural production, with a specific climatic gradient **(Yabi *et al.*, 2013)**. The effect of climatic conditions on carbon stock reveals that temperature has a negative and substantial association with carbon stock in cashew plantations **(Bello *et al.*, 2017)**. **Reichstein (2007)** and **Jayathilaka *et al.* (2012)**, explain that high temperatures resulted in a high CO_2 content, which contributed to low carbon sequestration. According to our findings, the Sudanian climatic zone is more exposed to high mean temperatures (29 to 32°C), which explains why cashew farms in this zone store less carbon than those in the Guinean zone. Carbon storage or release is determined by both organic matter degradation processes and biomass behavior in response to climatic change. The high temperature stimulates microbe activity **(Fissore *et al.*, 2008),** resulting in the oxidation of organic matter, which influences atmospheric CO_2 levels. Furthermore, high rainfall promotes high primary productivity, both aerial and root, resulting in large CO_2 emissions **(Reichstein, 2007).** This explains why cashew plants in the Guinean zone (with annual rainfall ranging from 1000 to 1600 mm) have more aerial and root biomass than cashew trees in the Sudanian climatic zone. In general, stimulating plant growth with higher temperatures would increase carbon in litter **(Reichstein, 2007),** which has an influence on the environment because of a greater release of CO_2 into the atmosphere **(Lawal and Adekunle, 2010).** As a result, in our study, litter from the Sudanian zone (high average temperature) retains more carbon than litter from plantations in the Guinean climate zone. Rising temperatures and variable precipitation can lead to a rise in water deficit. Litter breakdown would consequently be minimized and retarded, allowing for large carbon storage in forest soils **(Kurz-Besson *et al.*, 2006).** The investigation of carbon stock variation along the climatic gradient found that cashew plants in the Guinean climate zone sequestered more carbon. This finding could be explained by the fact that the temperature in this zone promotes canopy growth, which can trap CO_2 in the atmosphere while simultaneously slowing the mineralization of organic materials for carbon storage in soils. The low carbon stock found in the Sudanese zone could be linked to the reported high temperatures. According to **Jayathilaka *et al*. (2012)**, an increase in temperature causes a release of carbon stock in soil.

The following section discussed, the inter-annual variation in carbon isotopes measured in cashew stem disks collected in Togo's wet and dry cashew-growing areas.

The great similarity of the pattern of carbon-13 ($\delta^{13}C$) of individuals of cashew at the dry cashew production zone confirmed that tree growth happened every year and that the climate of the dry cashew production zone may influence the stable carbon discrimination. On one hand, the strong similarity between $\delta^{13}C$ of individual cashews in the dry cashew production zone agrees with numerous studies suggesting that species growing in the same environment respond similarly to climate changes (**Schongart *et al*., 2006; Fichtler *et al*., 2010; Gebrekirstos *et al*., 2012**). However, there is a limited resemblance between the pattern of $\delta^{13}C$ of individual of cashew in the humid cashew production zone This can be explained by the fact that the humid cashew zone is not a very suitable area for cashew cultivation. It is important to note that the humid cashew-growing zone is characterised by high rainfall. **Balogoun *et al* (2017)**, state that high rainfall hinders cashew development.

Wood rings have always been used as proxy data when reconstructing the climate in an area where there is no meteorological station. Using carbon isotopes in this research we have interpreted the existence of climatic signals in cashew tree stem disk and then discussed the relationship between carbon isotope ratios and climatic parameters in the following section.

Temperature showed a positive and significant correlation with BI's $\delta^{13}C$. This is because $\delta^{13}C$ rises with increasing temperature. In the dry cashew producing zone, leaf stomata may close, making $\delta^{13}C$ indistinguishable. This increases the richness of the ^{13}C isotope in tree rings **(Fichtler *et al*. 2010).**

At the level of the correlation between precipitation and carbon-13 ($\delta^{13}C$) of individual of cashew. There was no significant correlation between the precipitation and the carbon-13 ($\delta^{13}C$) of individual of cashew in both dry and humid cashew production zones. It may be that the eight-year duration of our study is not long enough to obtain a statistically significant correlation between precipitation and carbon-13 ($\delta^{13}C$) of individual of cashew. Studies by **Gebrekirstos *et al*. (2009)** have shown that tree ring $\delta^{13}C$ values of species (which have at least 40 years old) revealed a significant negative correlation with precipitation.

CONCLUSION, RECOMMENDATIONS AND PERSPECTIVES

CONCLUSION

This work aimed to contribute to the development of appropriate strategies to ensure sustainable cashew production in Togo, under changing climatic conditions. We firstly evaluated how climate change affects the spatial distribution of possible production areas for cashew trees in Togo, by 2050 and 2070. The findings indicate that soil is the most important predictor of the geographical distribution of cashew trees in Togo. Current climatic conditions suggest that 78.92% of the country's land area is ideal for cashew nut farming. The fraction of highly favourable habitats would drop considerably by 2050 in both models (HadGEM and MIROC6) under two climatic scenarios (ssp245 and ssp585). Climate change will gradually reduce *A. occidentale*'s appropriate habitat by 2070. Under two climate scenarios (ssp245 and ssp585), the share of highly favorable habitats in both models (HadGEM and MIROC6) will decrease significantly by 2070. A. *occidentale* productivity is projected to drop as appropriate habitat area decreases. Secondly, we assess the potential of carbon sequestration of cashew plantation in Togo, according to the climatic gradient. The results demonstrated that cashew plantations are agroforestry systems that store differing amounts of carbon, based on climate zones (Guinean and Soudanian), soil depth and the various compartments (trunks, branches, and leaves) of the cashew tree. Climate-related variables influence this fluctuation. In terms of climatic zones, the trees located in the Guinean climate has the most biomass, whereas the Soudanian climate has the least. According to the several compartments to be considered in the cashew plantation, the soil and trunk biomass store a significant quantity of carbon. Herbaceous biomass contains little carbon, yet it contributes to soil carbon sequestration capacity. We have finally examined the inter-annual variability of carbon isotope ratios of cashews in the humid and dry cashew production zones with climatic parameters in Togo. The findings of this study demonstrate that cashew individuals in the dry cashew production zone exhibit a similar pattern of carbon stable isotope curve. One particular individual of cashew located in the dry cashew production zone (Soudanian climate) in Togo, shows a positive and significant correlation between $\delta^{13}C$ and temperature, making it a useful proxy for temperature reconstruction.

RECOMMENDATIONS

Preventive actions such as preserving/cultivating A. *occidentale* may be required to adapt to climate change. Cashew producers and the Ministry of Agriculture, Livestock, and Rural Development of Togo need to establish effective strategies to increase the population's resilience to future climatic events.

Policies must be developed to promote sustainable agroforestry systems through the implementation of climate change-related carbon sequestration initiatives on cashew in Togo. In this regard, investigations on greenhouse gas (GHG) emissions on cashew plantations should be considered in order to compare emission and sequestration rates.

The $\delta^{13}C$ values could be utilized to understand the ecophysiology of cashews (e.g., their endurance to heat waves) and so select the suitable individual of cashew for reforestation of locations with little precipitation and high temperatures. Togo's environment ministry must therefore implement a reforestation policy using cashew trees.

PERSPECTIVES

1. Further studies on cashew Species Distribution Modelling (SDM) need to be conducted using the production data (yield) and also the surface area of land devoted to cashew cultivation in the different production zones.
2. It would be interesting to carry out a study to examine changes in total organic carbon stored in cashew tree plantations as a function of the climatic gradient in Togo.
3. Further studies need to be carried out on cashew trees using carbon and oxygen isotopes over a longer period.

REFERENCES

Abdou, L., Diouf, A., Inoussa, M. M., Mamoudou, B. M., Illiassou, S. A., & Mahamane, A. (2016). Modelling the geographic distribution of Prosopis africana (G. and Perr.) Taub. in Niger. Environment and Natural Resources Research, 6(2), 136-144.

Abdul Salam, M. A., & Peter, K. (2010). Cashew-a monograph, p 257.

Adejumo, T. A., Olaniyi, J. O., Akanbi, W. B., & Akande, O. G. (2010). Growth, fruit yield and nutritional quality of tomato varieties. *African journal of food science*, *4*(6), 398-402.

Adewi, E., Badameli, K. M., & Dubreuil, V. (2010). Evolution des saisons des pluies potentiellement utiles au Togo de 1950 à 2000. *Climatologie*, *7*, 89-107.

Adiga, D. J., Veena, G. L., Thondaiman, V., & Babli, M. (2020). An overview of canopy management in cashew (Anacardium occidentale L.). *Journal of Horticultural Sciences*, *15*(2), 127-135.

Aguiar, M de J.N., and C.A.R. Costa. (2002). Exigências Climáticas. p. 21-23. In: L. de M. Barros (ed.) Caju. Produção: Aspectos técnicos. Embrapa Agroindústria Tropical. Fortaleza. (Frutas do Brasil, 30).

Akinwale, T. O. (2000). Cashew apple juice: its use in fortifying the nutritional quality of some tropical fruits. European Food Research and Technology, 211, 205-207.

Albrecht, A., & Kandji, S. T. (2003). Carbon sequestration in tropical agroforestry systems. *Agriculture, ecosystems & environment*, *99*(1-3), 15-27.

Allouche, O., Tsoar, A., and Kadmon, R. (2006). Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). *Journal of Applied Ecology*, *43*(6), 1223-1232.

Ames-Martínez, F. N., Luna-Vega, I., Dieringer, G., & Rodríguez-Ramírez, E. C. (2022). The effect of climate change on Arcto-Tertiary Mexican beech forests: Exploring their past, present, and future distribution. Ecology and Evolution, 12(8), e9228.

Amparado, R. F., Beeckman, H., & Lemeur, R. (1990). Thin section preparation of poplar tree-rings for computer-aided image analysis in dendrochronological investigations. Silva Gandavensis, 55.

Andrews, T., Andrews, M. B., Bodas-Salcedo, A., Jones, G. S., Kuhlbrodt, T., Manners, J., ... & Tang, Y. (2020). Forcings, feedbacks, and climate sensitivity in HadGEM3-GC3. 1 and UKESM1. *Journal of Advances in Modeling Earth Systems*, *11*(12), 4377-4394.

Andrighetti, R. (1994). FACING THE LAND. *Canadian Architect*, *39*(8), 13-19.

Araújo, S. M., Silva, C. F., Moreira, J. J. S., Narain, N., & Souza, R. R. (2011). Biotechnological process for obtaining new fermented products from cashew apple fruit by Saccharomyces cerevisiae strains. Journal of Industrial Microbiology and Biotechnology, 38(9), 1161-1169.

Assih, A., & Nenonene, A. Y. (2022). Soil fertility status of cashew (Anacardium occidentale L.) orchards and its effects on cashew nut productivity in Togo.

Assunção, R. B., & Mercadante, A. Z. (2003a). Carotenoids and ascorbic acid composition from commercial products of cashew apple (Anacardium occidentale L.). Journal of food composition and analysis, 16(6), 647-657.

Assunção, R. B., & Mercadante, A. Z. (2003b). Carotenoids and ascorbic acid from cashew apple (Anacardium occidentale L.): variety and geographic effects. Food Chemistry, 81(4), 495-502.

Atakpama, W., Assang, M. D., Ahouandjinou, E. B. O., Dimobe, K., Gouwakinnou, G. N., & Akpagana, K. (2023). Priority area for sustainable Cashew (Anacardium occidentale L.) growing in Togo: Economic implications and conservation areas. Revue Nature et Technologie, 15(1), 29-40.

Austin, M. P., and Van Niel, K. P. (2011). Improving species distribution models for climate change studies: variable selection and scale. Journal of Biogeography, 38(1), 1-8.. https://doi.org/10.1111/j.1365-2699.2010.02416.x

Azam-Ali, S. H., & Judge, E. C. (2001). Small-scale cashew nut processing. *Coventry (UK): ITDG Schumacher Centre for Technology and Development Bourton on Dunsmore*, 1-70.

Badameli, A., and Dubreuil, V. (2015, July). Diagnostic du changement climatique au Togo à travers l'évolution de la température entre 1961 et 2010. In *XXVIIIe Colloque de l'association internationale de Climatologie* (pp. 421-426).

Balogoun, I., Saïdou, A., Ahoton E.L., Amadji, G.L., Ahohuendo, C.B., Adebo, I.B., Babatoundé, S., Chougourou, D., Adoukonou, S.H., Ahanchédé, A. (2014). Caractérisation des systèmes de production à base d'anacardier dans les principales zones de culture au Bénin. Agronomie africaine, 26, 9-22.

Balogoun, I., Ahoton, L. E., Saïdou, A., Bello, D. O., Ezin, V., Amadji, G. L., ... & Ahanchede, A. (2016). Effect of climatic factors on cashew (*Anacardium occidentale* L.) productivity in Benin (West Africa).

Bassett, T. J., Koné, M., & Pavlovic, N. R. (2018). Power Relations and Upgrading in the Cashew Value Chain of Côte d'Ivoire. *Development and Change*, *49*(5), 1223-1247.

Batjes, N. H. (1996). Total carbon and nitrogen in the soils of the world. *European journal of soil science*, *47*(2), 151-163.

Bello, O. D., Akponikpè, P. B. I., Ahoton, E. L., Saidou, A., Ezin, A. V., Kpadonou, G. E., ... & Aho, N. (2016). Trend Analysis Of Climate Change And Its Impacts On Cashew Nut Production (Anacardiumoccidentalel.) In Benin. *Octa Journal of Environmental Research*, *4*(3).

Bello, D. O., Ahoton, L. E., Saidu, A., Akponikpè, I. P. B., Ezin, V. A., Balogoun, I., & Aho, N. (2017). Climate change and cashew (Anacardium occidentale L.) productivity in Benin (West Africa): perceptions and endogenous measures of adaptation. *International Journal of Biological and Chemical Sciences*, *11*(3), 924-946.

Beniken, L., Beqqali, M., Dahan, R., Benkirane, R., Omari, F. E., Benazouz, A., ... & Gaboun, F. (2011). Évaluation de la résistance de dix porte-greffes d'agrumes résistants à la tristeza vis-à-vis du déficit hydrique. *Fruits*, *66*(6), 373-384.

Bezerra, M. A., Lacerda, C. F. D., Gomes Filho, E., de Abreu, C. E., & Prisco, J. T. (2007). Physiology of cashew plants grown under adverse conditions. Brazilian Journal of Plant Physiology, 19, 449-461.. https://doi.org/10.1590/S1677-04202007000400012

Booth, T. H. (2022). Checking bioclimatic variables that combine temperature and precipitation data before their use in species distribution models. *Austral Ecology*, *47*(7), 1506-1514.

Boulmane, M., Regina, I.S., Khia, A., Oubrahim, H. (2013). Estimation du stock de carbone dans les iliçaies du Haut Atlas Marocain. Ann. Rech. For. Maroc, 20, 275 – 286.

Brady, N. C., Weil, R. R., & Weil, R. R. (2008). *The nature and properties of soils* (Vol. 13, pp. 662-710). Upper Saddle River, NJ: Prentice Hall.

Brams, E. A. (1971). Continuous cultivation of West African soils: Organic matter diminution and effects of applied lime and phosphorus. *Plant and Soil*, *35*, 401-414.

Brienen, R. J., Wanek, W., & Hietz, P. (2011). Stable carbon isotopes in tree rings indicate improved water use efficiency and drought responses of a tropical dry forest tree species. *Trees*, *25*, 103-113.

Caldararu, S., Purves, D. W., & Palmer, P. I. (2014). Phenology as a strategy for carbon optimality: a global model. *Biogeosciences*, *11*(3), 763-778.

Carpenter, G., Gillison, A. N., & Winter, J. (1993). DOMAIN: a flexible modelling procedure for mapping potential distributions of plants and animals. *Biodiversity & Conservation*, *2*, 667-680.

Cecchi, H. M., & Rodriguez-amaya, D. B. (1981). Carotenoid composition and vitamin A value of fresh and pasteurized cashew-apple (Anacardium occidentale L.) juice. Journal of Food Science, 46(1), 147-149.

Chaves, M. M., Maroco, J. P., & Pereira, J. S. (2003). Understanding plant responses to drought—from genes to the whole plant. *Functional plant biology*, *30*(3), 239-264.

Chaves, M. M., & Oliveira, M. M. (2004). Mechanisms underlying plant resilience to water deficits: prospects for water-saving agriculture. *Journal of experimental botany*, *55*(407), 2365-2384.

Chytrý, M., & Rafajová, M. (2003). Czech National Phytosociological Database: basic statistics of the available vegetation-plot data.

Curtis, J.T., & McIntosh, R. P. (1951). An Upland Forest Continuum in the Prairie-Forest Border Region of Wisconsin. Ecology, 31, 476-496. http://dx.doi.org/10.2307/1931725

Datta, S. (2013). Impact of climate change in Indian horticulture-a review. *International Journal of Science, Environment and Technology*, *2*(4), 661-671.

de Brito, E. S., de Araújo, M. C. P., Lin, L. Z., & Harnly, J. (2007). Determination of the flavonoid components of cashew apple *(Anacardium occidentale)* by LC-DAD-ESI/MS. *Food chemistry*, *105*(3), 1112-1118.

De Lima, S. G., Feitosa, C. M., Citó, A. M. G. L., Moita Neto, J. M., Lopes, J. A. D., Leite, A. S., ... & Cavalcante, A. A. C. M. (2008). Effects of immature cashew nut-shell liquid (Anacardium occidentale) against oxidative damage in Saccharomyces cerevisiae and inhibition of acetylcholinesterase activity. Genet Mol Res, 7(3), 806-818.

Dedzoe, C. D., Senayah, J. K., & Asiamah, R. D. (2001). Suitable agro-ecologies for cashew (Anacardium occidetale L) production in Ghana. *West African Journal of Applied Ecology*, *2*(1).

Deisingh, A. K., & Thompson, M. (2004). Biosensors for the detection of bacteria. *Canadian journal of microbiology*, *50*(2), 69-77.

Dendena, B., & Corsi, S. (2014). Cashew, from seed to market: a review. *Agronomy for sustainable development*, *34*, 753-772.

Denef, K., Six, J., Merckx, R., & Paustian, K. (2004). Carbon sequestration in microaggregates of no-tillage soils with different clay mineralogy. *Soil Science Society of America Journal*, *68*(6), 1935-1944.

DGSCN. (2022). General Census of Population and Housing final results. Togo: Togolese Republic / Ministry to the President of the Republic, Head of Planning, Development and Regional Planning. French. 24.

Dimobe, K., Ouédraogo, A., Ouédraogo, K., Goetze, D., Stein, K., Schmidt, M., ... & Thiombiano, A. (2020). Climate change reduces the distribution area of the shea tree (Vitellaria paradoxa CF Gaertn.) in Burkina Faso. Journal of Arid Environments, 181, 104237.. https://doi.org/10.1016/j.jaridenv.2020.104237

Diomandé, S., Amba, G. J. A., Gnahoré, É., & BAKAYOKO, A. (2021). Diversité floristique et structurale de la forêt classée de la Mabi au Sud-Est de la Côte d'Ivoire. *Afrique Science*, *18*(1), 159-171.

Donigan, H. J. (1994). Peleliu: The Forgotten Battle. Marine Corps Gazette, 96-103.

d'Orgeval, T. (2006). *Impact du changement climatique sur le cycle de l'eau en Afrique de l'Ouest: modélisation et incertitudes* (Doctoral dissertation, Paris 6).

Dugué, M. J. (2012). Caractérisation des stratégies d'adaptation au changement climatique en agriculture paysanne. Etude de capitalisation réalisée sur les terrains de coopération d'AVSF. Agronomie et vétérinaire sans frontière. 50p.

Duke, J. A. (1983). Anacardium occidentale L. Handbook of energy crops. http://www. hort. purdue. edu/newcrop/duke_energy/Anacardium_occidentale. html.

El Fakhri, G., Surti, S., Trott, C. M., Scheuermann, J., & Karp, J. S. (2011). Improvement in lesion detection with whole-body oncologic time-of-flight PET. *Journal of Nuclear Medicine*, *52*(3), 347-353.

Elliott, R., Sahakian, B. J., McKay, A. P., Herrod, J. J., Robbins, T. W., & Paykel, E. S. (1996). Neuropsychological impairments in unipolar depression: the influence of perceived failure on subsequent performance. *Psychological medicine*, *26*(5), 975-989.

Elliott, W. P., & Gaffen, D. J. (1991). On the utility of radiosonde humidity archives for climate studies. *Bulletin of the American Meteorological Society*, *72*(10), 1507-1520.

Ern, H. (1979). Die vegetation togos. gliederung, gefährdung, erhaltung. *Willdenowia*, 295-312.

Eswaran, H., Van Den Berg, E., & Reich, P. (1993). Organic carbon in soils of the world. *Soil Science Society of America Journal*, *57*(1), 192-194.

FAO .(1994). Ecocrop 1. The adaptability level of the FAO crop environmental requirements database. Version 1.0. Land Resources Management and Conservation Service, FAO, Rome.

FAO, (1997). Agriculture et le changement climatique : le rôle de la FAO. L'Actualité, 3p.

FAO, (2002). La séquestration du carbone dans le sol pour une meilleure gestion des terres.

FAO. (2014). Base des données de la FAO 2011. http://faostat3.fao.org.

Feng, X., Park, D. S., Liang, Y., Pandey, R., & Papeş, M. (2019). Collinearity in ecological niche modelling: Confusions and challenges. Ecology and evolution, 9(18), 10365-10376. https://doi.org/10.1002/ece3.5555

Fichtler, E., Trouet, V., Beeckman, H., Coppin, P., Worbes, M. (2004). Climatic signals in tree rings of Burkea africana and Pterocarpus angolensis from semiarid forests in Namibia. Trees - Structure and Function 18: 442-451.

Fichtler, E., Helle, G., & Worbes, M. (2010). Stable-carbon isotope time series from tropical tree rings indicate a precipitation signal. *Tree-ring research*, *66*(1), 35-49.

Fissore, C., Giardina, C. P., Kolka, R. K., Trettin, C. C., King, G. M., Jurgensen, M. F., Barton, C. D., McDowell, S. D. (2008). Temperature and vegetation effects on soil organic carbon quality along a forested mean annual temperature gradient in North America. Global Change Biology, 14, 193-205.

Gawankar, M. S., Kulkarni, M. M., Haldankar, P. M., & Salvi, B. R. (2020). Technologies for Cashew productivity enhancement in Maharashtra. *Emergent Life Sciences Research*, *6*, 5-12.

Gebrekirstos, A., Mitlöhner, R., Teketay, D., & Worbes, M. (2008). Climate–growth relationships of the dominant tree species from semi-arid savanna woodland in Ethiopia. *Trees*, *22*, 631-641.

Gebrekirstos, A., Worbes, M., Teketay, D., Fetene, M., Mitlöhner, R. (2009). Stable carbon isotope ratios in tree rings of co-occurring species from semi-arid tropics in Africa: patterns and climatic signals. Global and Planetary Change 66: 253-260.

Gebrekirstos, A., Van Noordwijk, M., Neufeldt, H., Mitlöhner, R. (2011a): Relationships of stable carbon isotopes, plant water potential and growth: an approach to asses water use efficiency and growth strategies of dry land agroforestry species. Trees - Structure and Function 25: 95 102.

Gebrekirstos, A., Bräuning, A., Van Noordwijk, M., & Mitlöhner, R. (2011b). Keynote paper: understanding past, present and future climate changes from East to West Africa. *Agric. Innov. Sustainable Develop*, *3*, 77-86.

Gebrekirstos, A., Mitlöhner, R., Van Noordwijk, M., & Bräuning, A. (2012). Tracing responses to climate variability from stable isotopes in tree rings of Anogeissus leiocarpus and Sclerocarya birrea from the Sahel zone, Burkina Faso. *Trace*, *10*, 6-12.

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

Global Biodiversity Information Facility (GBIF). Angelica gigas Nakai. (2022). Available online: https://www.gbif.org/species/5537749 (accessed on 15 December 2023)

Gnahoua, G.M. & Louppe D., (2003). Anacardier, HAL-Archives ouvertes. http://hal.cirad.fr/cirad-00429280 (accessed on: 19/12/2023)

Gómez-Caravaca, A. M., Verardo, V., & Caboni, M. F. (2010). Chromatographic techniques for the determination of alkyl-phenols, tocopherols and other minor polar compounds in raw and roasted cold pressed cashew nut oils. Journal of Chromatography A, 1217(47), 7411-7417.

Gonçalves, J. L. S., Lopes, R. C., Oliveira, D. B., Costa, S. S., Miranda, M. M. F. S., Romanos, M. T. V., ... & Wigg, M. D. (2005). In vitro anti-rotavirus activity of some medicinal plants used in Brazil against diarrhea. Journal of ethnopharmacology, 99(3), 403-407.

Goujon, P., Lefebvre, A., Leturcq, P. H., Marcellesi, A. P., & Praloran, J. C. (1973). Etudes sur l'Anacardier. *Bois & Forets des Tropiques*, *151*, 27-53.

Gueta-Dahan, Y., Yaniv, Z., Zilinskas, B. A., & Ben-Hayyim, G. (1997). Salt and oxidative stress: similar and specific responses and their relation to salt tolerance in citrus. *Planta*, *203*, 460-469.

Hairiah, K., Dewi, S., Agus, F., Velarde, S. J., Ekadinata, A., Rahayu, S., Van Noordwijk, M. (2011). Measuring carbon stocks across land use system. A manual. Bogor: World Agroforestry Centre - ICRAF, SEA Regional Office. 154p.

Haldankar, P. M., Deshpande, S. B., Chavan, V. G., Dalvi, M. B., Patil, B. P., Joshi, G. D., & RAO, E. B. (2003). Weather associated yield variability in Cashewnut. *Journal of Agrometeorology*, *5*(2), 73-76.

Hansen, J. (2004). Defusing the global warming time bomb. Scientific American, 290(3), 68-77.

Hansen, M. C., Krylov, A., Tyukavina, A., Potapov, P. V., Turubanova, S., Zutta, B., ... & Moore, R. (2016). Humid tropical forest disturbance alerts using Landsat data. *Environmental Research Letters*, *11*(3), 034008.

IPBES. (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science- Policy Platform on Biodiversity and Ecosystem Services. IPBES secretariat. IPBES.

IPCC. (2003). Good Practice Guidance for Land Use, Land-use Change and Forestry (LULUCF). Institute for Global Environmental Strategies, Hayama, Japan.

IPCC and IPBES. (2021). Scientific outcome of the IPCC-IPBES co-sponsored workshop on biodiversity and climate change.

IPCC. (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability-Summary for Policymakers released. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Geneva, p 52

Jackson, R. B., Schenk, H. J., Jobbagy, E. G., Canadell, J., Colello, G. D., Dickinson, R. E., ... & Sykes, M. T. (2000). Belowground consequences of vegetation change and their treatment in models. *Ecological applications*, *10*(2), 470-483.

Jansson, C., Wullschleger, S. D., Kalluri, U. C., & Tuskan, G. A. (2010). Phytosequestration: carbon biosequestration by plants and the prospects of genetic engineering. *Bioscience*, *60*(9), 685-696.

Jayathilaka, P.M.S., Soni, P., Perret, S., Jayasuriya, H.P.W., Salokhe, V.M. (2012). Spatial assessment of climate change effects on crop suitability for major plantation crops in Sri Lanka. Regional environmental change 1, 55-68.

Joker, D., & Jepsen, J. (2003). Jatropha curcas L. *Seed leaflet*, *83*, 1-2.

Kagambèga, F. W., Nana, R., Bayen, P., Thiombiano, A., & Boussim, J. I. (2019). Tolérance au déficit hydrique de cinq espèces prioritaires pour le reboisement au Burkina Faso. *BASE*.

Kapinga, A. F., & Montero, C. S. (2017). Exploring the socio-cultural challenges of food processing women entrepreneurs in Iringa, Tanzania and strategies used to tackle them. *Journal of Global Entrepreneurship Research*, *7*(1), 17.

Koo, K.A.; Park, S.U.; Kong, W.S.; Hong, S.; Jang, I.; Seo, C.(2017). Potential climate change effects on tree distributions in the Korean peninsula: Understanding model & climate uncertainties. Ecol. Model. 2017, 353, 17–27.

Krepkowski, J., Gebrekirstos, A., Shibistova, O., & Bräuning, A. (2013). Stable carbon isotope labeling reveals different carry-over effects between functional types of tropical trees in an Ethiopian mountain forest. *New Phytologist*, *199*(2), 431-440.

Krull, E. S., Baldock, J. A., & Skjemstad, J. O. (2003). Importance of mechanisms and processes of the stabilisation of soil organic matter for modelling carbon turnover. *Functional plant biology*, *30*(2), 207-222.

Kubo, I., Kinst-Hori, I., & Yokokawa, Y. (1994). Tyrosinase inhibitors from Anacardium occidentale fruits. Journal of Natural Products, 57(4), 545-551.

Kubo, I., Nitoda, T., Tocoli, F. E., & Green, I. R. (2011). Multifunctional cytotoxic agents from Anacardium occidentale. Phytotherapy Research, 25(1), 38-45.

Kurz-Besson, C., Coûteaux, M.M., Berg, B., Remacle, J., Ribeiro C., Romanyà J., Thiéry J.M. (2006). A climate response function explaining most of the forest floor needle mass and the needle decomposition in pine forests across Europe. Plant and Soil. 285, 97-114.

Lacroix, T. (2003). *Espace transnational et territoires. Les réseaux marocains du développement* (Doctoral dissertation, Université de Poitiers).

Lahoz-Monfort, J. J., Guillera-Arroita, G., & Wintle, B. A. (2014). Imperfect detection impacts the performance of species distribution models. Global ecology and biogeography, 23(4), 504-515. https://doi.org/10.1111/geb.12138

Lakshmana, C. M., & Maruthi, I. (2018). THE DISABLED POPULATION ANDTHEIR EDUCATIONAL STATUS IN INDIA. *Periferia*, *10*(2), 135-157.

Laurens, A., Fourneau, C., Hocquemiller, R., Cavé, A., Bories, C., & Loiseau, P. M. (1997). Antivectorial Activities of Cashew Nut Shell Extracts from Anacardium occidentaleL. Phytotherapy Research: An International Journal Devoted to Medical and Scientific Research on Plants and Plant Products, 11(2), 145-146.

Lautié, E., Dornier, M., de Souza Filho, M., & Reynes, M. (2001). Les produits de l'anacardier: caractéristiques, voies de valorisation et marchés. *Fruits*, *56*(4), 235-248.

Lawal, A., & Adekunle, V. A. J. (2010). A silvicultural approach to volume yield, biodiversity and soil fertility restoration of degraded natural forest in South-West Nigeria. *International Journal of Biodiversity Science, Ecosystem Services & Management*, *9*(3), 201-214.

Lefèbvre, A.(1969). L'anacardier, une richesse de Madagascar, Fruits, 24 (1) (1969): 43-61. Available online: https://revues.cirad.fr/index.php/fruits/article/view/33606 (accessed on: 11/03/2022)

Lim, T. K. (2012). *Anacardium occidentale*. In Springer eBooks (p. 45-68). https://doi.org/10.1007/978-90-481-8661-7_6

Lubis, A. H., Hecht, N. L., Jr Graves, G. A., & Ruh, R. (1999). Microstructure-Property Relations of Hot-Pressed Silicon Carbide-Aluminum Nitride Compositions at Room and Elevated Temperatures. *Journal of the American Ceramic Society*, *82*(9), 2481-2489.

Lyam, P.T., Adeyemi T.O. & Ogundipe O.T.(2012). Distribution modelling of Chrysophyllum albidum G. Don. in South-WestNigeria, Journal of Natural & Environmental Sciences, 3 (2) (2012): 7-14.

Available on: https://www.researchgate.net/publication/259569958_Distribution_Modeling_of_Chrysophyllum_albidum_GDon_in_South West_Nigeria (accessed on: 15/12/2023)

MacDiken, K.G. (1997). A guide to monitoring carbon storage in forestry and agroforestry projects. Forest Carbon Monitoring Program. Winrock International Institute for Agricultural Development, Arlington, USA, 91p.

Madhusudhan, V., & Murthy, B. G. K. (1992). Polyfunctional compounds from cardanol. Progress in organic coatings, 20(1), 63-71.

MAEH. (2015). d'investissement Programme agricole, national de sécurité alimentaire et nutritionnelle (PNIASAN). MAEP.

Mahajan, S., & Tuteja, N. (2005). Cold, salinity and drought stresses: an overview. *Archives of biochemistry and biophysics*, *444*(2), 139-158.

Mangalassery, S., & Nayak, M. G. (2020). Strategies for soil and water conservation, and irrigation management in cashew. *Training manual on Cashew Production and Post Harvest Technologies. ICAR-Directorate of Cashew Research, Puttur, Karnataka, India. 143p*, 51.

Mangalassery, S., Rejani, R., Singh, V., Adiga, J. D., Kalaivanan, D., Rupa, T. R., & Philip, P. S. (2019). Impact of different irrigation regimes under varied planting density on growth, yield and economic return of cashew (Anacardium occidentale L.). *Irrigation Science*, *37*, 483-494.

Martin, K.P. (2003). Plant regeneration through direct somatic embryogenesis on seed coat explants of cashew (Anacardium occidentale L.). Scientia Horticulturae, 98: 299–304.

Math, M. C., Hebbar, H. H., & Yatish, K. V. (2018). Optimization and kinetic study of CaO nano-particles catalyzed biodiesel production from Bombax ceiba oil. *Energy*, *143*, 25-34.

McCarroll, D., & Loader, N.J., (2004). Stable isotopes in tree rings. Quaternary Sci. Rev. 23, 771–801. https://doi.org/10.1016/j.quascirev.2003.06.017.

Michodjehoun-Mestres L, Souquet J-M, Fulcrand H, Meudec E, Reynes M, Brillouet J-M (2009a) Characterisation of highly polymerised prodelphini dins from skin and flesh of four cashew apple (Anacardium occidentale L.) genotypes. Food Chem 114(3):989–995

Michodjehoun-Mestres, L., Souquet, J. M., Fulcrand, H., Bouchut, C., Reynes, M., & Brillouet, J. M. (2009b). Monomeric phenols of cashew apple (Anacardium occidentale L.). Food Chemistry, 112(4), 851-857.

Mitchell, J.D, Mori, S.A. (1987). The A. occidentale and its relatives (*Anacardium*: Anacardiaceae). Mem N Y Bot Gard 42:1–76

Mod, H. K., Scherrer, D., Luoto, M., & Guisan, A. (2016). What we use is not what we know: environmental predictors in plant distribution models. Journal of Vegetation Science, 27(6), 1308-1322.https://onlinelibrary.wiley.com/doi/epdf/10.1111/jvs.12444 (accessed on: 19/12/203)

Mog, B. J., Wang, Q., Douglass, J., Hwang, M. S., Hsiue, E. H. C., Zhang, M., ... & Vogelstein, B. (2019). Direct detection and quantification of neoantigens. *Cancer immunology research*, *7*(11), 1748-1754.

Montagnini, F., Nair, P. (2004). Carbon sequestration: An underexploited environmental benefit of agroforestry systems. Agroforestry Systems, 61, 281-295.

Moorton, R. (1987). Euripides' Andromeda in Aristophanes' Frogs. The American Journal of Philology, 108(3), 434-436

Moukrim, S., Lahssini S., Rifai N., Menzou K., Mharzi-Alaoui H., Labbaci A., Rhazi M., Wahby I., El Madihi M. & Rhazi L. (2020). Modélisation de la distribution potentielle de Cedrus atlantica

Manetti au Maroc et impacts du changement climatique, Bois & Forets des Tropiques, 344 (2020): 3-16. https://doi.org/10.19182/bft2020.344.a31888

Mukhopadhyay, S. K., Chattopadhyay, A., Chakraborty, I., & Bhattacharya, I. (2011). Crops that feed the world 5. Sweetpotato. Sweetpotatoes for income and food security. *Food security*, *3*, 283-305.

Murali, K., Kumar, P. P., & Rani, M. A. (2015). Effect of tertiary shoot pruning and foliar spray of nutrients on flowering and yield of cashew (Anacardium occidentale L.) under high density planting system. *The Bioscan*, *10*(1), 411-415.

Murthy, B. G. K., & Sivasamban, M. A. (1979, March). Recent trends in CNSL utilization. In *International Cashew Symposium 108* (pp. 200-206).

Nair, M. K., Rao, E. B., Nambiar, K. K. N., & Nambiar, M. C. (1979). Mono-graph on Plantation Crops-1: Cashew (Ana-cardium occidentale L.). Central Plantation Crops Research Institute, Kerala India, 43-65.

Nayak, M. G., Muralidhara, B. M., Janani, P., & Savadi, S. (2020). Performance of cashew (Anacardium occidentale) varieties under different planting density for growth and yield traits. *Indian Journal of Agricultural Sciences*, *90*(8), 1453-9.

Ngatunga, E. L., Cools, N., Dondeyne, S., & Deckers, J. A. (2001). Soil suitability for cashew in South Eastern Tanzania. *The Land*, *5*(1), 3-16.

Nneji, L. M., Salako, G., Oladipo, S. O., Ayoola, A. O., Onadeko, A. B., Adedeji, B. E., ... & Adeola, A. C. (2020). Species Distribution Modelling predicts habitat suitability and reduction of suitable habitat under future climatic scenarios for Sclerophrys perreti: A critically endangered Nigerian endemic toad. African Journal of Ecology, 58(3), 481-491.

Oades, J. M., Gillman, G. P., Uehara, G., Hue, N. V., Van Noordwijk, M., Robertson, G. P., & Wada, K. (1989). Interactions of soil organic matter and variable-charge clays. *Dynamics of soil organic matter in tropical ecosystems*, *3*, 69-96.

Oddoye, E. O. K., Takrama, J. F., Anchirina, V., & Agyente-Badu, K. (2009). Effects on performance of growing pigs fed diets containing different levels of dried cashew pulp. Tropical animal health and production, 41, 1577-1581.

Oguntunde, O. S., Ajibefun, I.A., Oguntunde, P.G., and Anugwo, S.C. (2014). Analysis of trend and association between climatic variables and cocoa yield in Ondo State 1976-2009. Journal of Meteorology and Climate Science, 12(1):42-50.

Ohler, J. G. (1979). Cashew. Department of Agricultural Research. Koninklijk Instituut voor de Tropen.

Oliveira, N. N., Mothé, C. G., Mothé, M. G., & de Oliveira, L. G. (2006). Cashew nut and cashew apple: a scientific and technological monitoring worldwide review. *Journal of Food Science and Technology*, *57*, 12-21.

Olubode, O. O., Joseph-Adekunle, T. T., Hammed, L. A., & Olaiya, A. O. (2018). Evaluation of production practices and yield enhancing techniques on productivity of cashew (Anacardium occidentale L.). *Fruits*, *73*(2), 75-100.

Pacheco, A. M., Gondim, D. R., & Gonçalves, L. R. B. (2010). Ethanol production by fermentation using immobilized cells of Saccharomyces cerevisiae in cashew apple bagasse. Applied biochemistry and biotechnology, 161, 209-217.

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., ... & Hayes, D. (2011). A large and persistent carbon sink in the world's forests. *science*, *333*(6045), 988-993.

Paris, R., Plat, M., Linhard, J., & Laurens, A. (1977). Recherche chimique et pharmacologique sur les feuilles d'Anacardium occidentale L.(Anacardiacées).

Passioura, J. B. (1996). Drought and drought tolerance. *Plant growth regulation*, *20*, 79-83.

Pereira, V. J., Linden, K. G., & Weinberg, H. S. (2007). Evaluation of UV irradiation for photolytic and oxidative degradation of pharmaceutical compounds in water. *Water Research*, *41*(19), 4413-4423.

Prasada, G. S. L. H. V., Rao, V. U. M., & Rao, G. G. S. N. (2010). *Climate change and agriculture over India*. PHI Learning Pvt. Ltd..

Reichstein, M. (2007). Impacts of climate change on forest soil carbon: principles, factors, models, uncertainties. Forestry and climate change. 10, 127-135.

Rejani, R., Rupa, T. R., & Bhat, M. G. (2013). Impact of climate change on cashew and adaptation strategies. In *Climate-resilient horticulture: adaptation and mitigation strategies* (pp. 189-198). India: Springer India.

Ricau, P., (2013). Connaître et comprendre le marché international de l'anacarde. 48 p. Available online:https://www.inter-reseaux.org/wp content/uploads/Guide_RONGEAD___Le_Marche_Internation al_de_l_Anacarde_v-light.pdf (accessed on: 15/12/2023)

Rondeux, J. (1999). Les mesures des arbres et des peuplements forestiers. Gembloux, Belgique: Les presses agronomiques de gembloux, 522p. Rupa, T. R., Rejani, R., Bhat, G. M. (2013). Impact of Climate Change on Cashew and Adaptation Strategies. Climate-Resilient Horticulture: Adaptation and Mitigation Strategies. 9, 78-91, Springer India.

Rupa, T. R., Rejani, R., & Bhat, M. G. (2013). Impact of climate change on cashew and adaptation strategies. In *Climate-resilient horticulture: adaptation and mitigation strategies* (pp. 189-198). India: Springer India.

Ryan, E., Galvin, K., O'connor, T. P., Maguire, A. R., & O'brien, N. M. (2006). Fatty acid profile, tocopherol, squalene and phytosterol content of brazil, pecan, pine, pistachio and cashew nuts. International journal of food sciences and nutrition, 57(3-4), 219-228.

Saha, A., Rahman, S., & Alam, S. (2021). Modelling current and future potential distributions of desert locust Schistocerca gregaria (Forskål) under climate change scenarios using MaxEnt. Journal of Asia-Pacific Biodiversity, 14(3), 399-409.

Sanchez, P. A. (2019). *Properties and Management of Soils in the Tropics*. Cambridge University Press.

Schoengart, 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*(7), 1139-1150.

Schweingruber, F. H., Bartholin, T., Schaur, E., & Briffa, K. R. (1988). Radiodensitometric-dendroclimatological conifer chronologies from Lapland (Scandinavia) and the Alps (Switzerland). *Boreas*, *17*(4), 559-566.

Semporé, J. N., Songré-Ouattara, L. T., Tarpaga, W. V., Bationo, F., & Dicko, M. H. (2021). Morphological characterization and quality assessment of cashew (Anacardium occidentale L.) nuts from 53 accessions of Burkina Faso. *Journal of agriculture and food research*, *6*, 100219.

Serrano, R., Mulet, J. M., Rios, G., Marquez, J. A., De Larrinoa, I. F., Leube, M. P., ... & Montesinos, C. (1999). A glimpse of the mechanisms of ion homeostasis during salt stress. *Journal of experimental botany*, 1023-1036.

Sinclair, T. R., & Ludlow, M. M. (1986). Influence of soil water supply on the plant water balance of four tropical grain legumes. *Functional Plant Biology*, *13*(3), 329-341.

Siong, T. E., Noor, M. I., Azudin, M. N., & Idris, K. (1988). Nutrient composition of Malaysian foods.

Sin, M. H. (2016). *Homo Oikos Sacralis: Redefining Human Being in the Face of the Environmental Crisis* (Doctoral dissertation, Graduate Theological Union).

Six, J. A. E. T., Elliott, E. T., & Paustian, K. (2000). Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry*, *32*(14), 2099-2103.

Six, J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil and tillage research*, *79*(1), 7-31.

Sonwa, D. (2004). Biomass management and diversification within cocoa agroforests in the humid forest zone of southern Cameroon. PhD Thesis. Institüt für Gartenbauwissenschaft der Rheinischen Friedrich-Wilhelms-Universität Bonn. 112 p.

Sreenivasan, P. K., & Gaffar, A. (2008). Antibacterials as anti-inflammatory agents: Dual action agents for oral health. *Antonie van Leeuwenhoek*, *93*, 227-239.

Stern, N., & Taylor, C. (2007). Climate change: Risk, ethics, and the Stern review. *Science*, *317*(5835), 203-204.

Stocker, T., Qin, D., Plattner, G. K., Tignor, M., Allen, S., Boschung, J., ... & Midgley, P. (2014). Summary for policymakers.

Svoboda, K., O'Connor, D. H., Peron, S. P., & Huber, D. (2010). Neural activity in barrel cortex underlying vibrissa-based object localization in mice. *Neuron*, *67*(6), 1048-1061.

Svoboda, P., Janská, A., Spiwok, V., Prášil, I. T., Kosová, K., Vítámvás, P., & Ovesná, J. (2016). Global scale transcriptional profiling of two contrasting barley genotypes exposed to moderate drought conditions: contribution of leaves and crowns to water shortage coping strategies. *Frontiers in Plant Science*, *7*, 1958.

Swets, J. A. (1988). Measuring the accuracy of diagnostic systems. Science, 240(4857), 1285-1293.

Tall, D. (2013). *How humans learn to think mathematically: Exploring the three worlds of mathematics*. Cambridge University Press.

Tamura, K., & Kumar, S. (2002). Evolutionary distance estimation under heterogeneous substitution pattern among lineages. *Molecular biology and evolution*, *19*(10), 1727-1736.

Tatebe, H., Ogura, T., Nitta, T., Komuro, Y., Ogochi, K., Takemura, T., ... & Kimoto, M. (2019). Description and basic evaluation of simulated mean state, internal variability, and climate sensitivity in MIROC6. Geoscientific Model Development, 12(7), 2727-2765.

Tee, T. W., & Khan, A. R. M. (1988). Removal of lead, cadmium and zinc by waste tea leaves. *Environmental Technology*, *9*(11), 1223-1232.

Thompson, R. C., Swan, S. H., Moore, C. J., & Vom Saal, F. S. (2009). Our plastic age. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 1973-1976.

Thompson, L. G.(2010). Ice Cores, High-Mountain Glaciers, and Climate.

Tidjani, M. A., and Akponikpe, P. B. I. (2012). Évaluation des stratégies paysannes d'adaptation aux changements climatiques: cas de la production du maïs au Nord-Bénin. African Crop Science Journal. 20(2): 425 – 441

Tinlot, M. (2010). Evaluation ex ante du bilan carbone des dynamiques de développement agricole et forestier: Application sur la filière anacarde au Burkina Faso. Mémoire de Fin d'Etudes d'ingénieur de l'Institut Supérieur d'Agriculture de LILLE, 89P.

Tisdall, J. M., & OADES, J. M. (1982). Organic matter and water-stable aggregates in soils. *Journal of soil science*, *33*(2), 141-163.

Totjssaint-norlet, P. and Giffard,P.(1961). Les plantations de Darcassou (Anacardium occidentale L.) au Sénégal. ISRA, rapport n°1082/232/663, 35p.

Townsend Peterson, A., Papeş, M., & Eaton, M. (2007). Transferability and model evaluation in ecological niche modeling: a comparison of GARP and Maxent. *Ecography*, *30*(4), 550-560.

Trekpo, P. (2003). Projet Restauration des Ressources Forestières de Bassila. *La Culture de l'Anacardier dans la Région de Bassila au Nord Bénin*.

Trouet, V., Esper, J., & Beeckman, H. (2010). Climate/growth relationships of Brachystegia spiciformis from the miombo woodland in south central Africa. *Dendrochronologia*, *28*(3), 161-171.

Trox, J., Vadivel, V., Vetter, W., Stuetz, W., Scherbaum, V., Gola, U., ... & Biesalski, H. K. (2010). Bioactive compounds in cashew nut (Anacardium occidentale L.) kernels: effect of different shelling methods. Journal of agricultural and food chemistry, 58(9), 5341-5346.

Tuo, G. (2007). Analyse de la filière anacarde en Côte d'Ivoire : stratégie de développement et lutte contre la pauvreté. Mémoire de DEA, Université de Bouaké, 80p.

U.S. Department of Agriculture (USDA), Research Service .(2010). USDA National Nutrient Database for Standard Reference, Release 23. Nutrient Data Laboratory Home Page. http://www.ars.usda.gov/ba/ bhnrc/nd

Ushanandini, S., Nagaraju, S., Nayaka, S. C., Kumar, K. H., Kemparaju, K., & Girish, K. S. (2009). The anti-ophidian properties of *Anacardium occidentale* bark extract. Immunopharmacology and immunotoxicology, 31(4), 607-615.

Valentini. (2007). Evaluation de la séquestration de carbone dans des plantations agroforestières et des jachères issues d'une agriculture migratoire dans les territoires autochtones de Talamanca au Costa. Mémoire présenté pour l'obtention du grade de Maître es sciences (M.Sc). Faculté des Sciences de l'Agriculture et de l'alimentation, Université Laval Québec.140p.

Valim, M. F., Rouseff, R. L., & Lin, J. (2003). Gas chromatographic− olfactometric characterization of aroma compounds in two types of cashew apple nectar. Journal of Agricultural and Food Chemistry, 51(4), 1010-1015.

Verslues, P. E., & Sharma, S. (2010). Proline metabolism and its implications for plant-environment interaction. *The Arabidopsis Book/American Society of Plant Biologists*, *8*.

Volkoff, B., Faure, P., Dubroeucq, D., Viennot, M. (1999). Estimation des stocks de carbone des sols du Bénin, étude de gestion des sols. Rapport d'étude, Institut Nationale des Recherches Agricoles du Bénin, Cotonou, Bénin. 115-130.

Waghmare, G. M., & Joshi, G. D. (2008). Response of mango (Magifera indica) to light pruning for vegetative and flowering flushes. *The Indian Journal of Agricultural Sciences*, *78*(8).

Walkley, A., Black, I.A. (1934). An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci., 37, 29-38.

Wei, B., Wang, R., Hou, K., Wang, X., & Wu, W. (2018). Predicting the current and future cultivation regions of Carthamus tinctorius L. using MaxEnt model under climate change in China. Global Ecology and Conservation, 16, e00477.

Widiatmaka, Sutandi, A., Iswandi, A., Daras, U., Hikmat, M., & Krisnohadi, A. (2014). Establishing land suitability criteria for cashew (Anacardium occidentale L.) in Indonesia. *Applied and Environmental Soil Science*, *2014*(1), 743194.

Yabi, I., Yabi, B. F., Dadegnon S. (2013). Diversité des espèces végétales au sein des agro-forêts à base d'anacardier dans la commune de Savalou au Benin. International Journal of Biological and Chemical Sciences, 7, 696-706.

Yao, Y., Gaither, A., Porter, D., Borawski, J., Yang, G., Donovan, J., ... & Zawel, L. (2007). A Smac mimetic rescue screen reveals roles for inhibitor of apoptosis proteins in tumor necrosis factor-α signaling. *Cancer research*, *67*(24), 11493-11498.

Yao, S., Ni, J., Ma, T., & Li, C. (2013). Heterotrophic nitrification and aerobic denitrification at low temperature by a newly isolated bacterium, Acinetobacter sp. HA2. *Bioresource technology*, *139*, 80-86.

Zhu, J. K. (2002). Salt and drought stress signal transduction in plants. *Annual review of plant biology*, *53*(1), 247-273.

Zhuang, J. X., Hu, Y. H., Yang, M. H., Liu, F. J., Qiu, L., Zhou, X. W., & Chen, Q. X. (2010). Irreversible competitive inhibitory kinetics of cardol triene on mushroom tyrosinase. Journal of agricultural and food chemistry, 58(24), 12993-12998.

PUBLICATIONS