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Climate Change, Agriculture and Food Security in Sahel

Thèse dirigée par Julie LE GALLO

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“Notre génération peut être la première à mettre fin à la pauvreté et la dernière génération à lutter contre le changement climatique avant qu’il ne soit trop tard."

— Ban Ki-moon, Décembre, 2014

“Le changement climatique est l’un des plus grands défis de notre temps. Il change déjà nos vies quotidiennes, à l‘échelle mondiale. Chacun d’entre nous est impacté. Et si nous ne faisons rien, nos enfants vont connaître un monde de migrations, de guerres, et de pénuries. Peu importe où nous vivons, nous partageons la même responsabilité : Make our planet great again ! "

— Emmanuel Macron, Septempre, 2017

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Résumé de la thèse

Changement Climatique, Agriculture et Sécurité Alimentaire dans le Sahel

Cette thèse traite de l'impact du changement climatique sur l'agriculture et la sécurité alimentaire dans la zone du Sahel que nous définissons comme une région comportant 12 pays et 52 zones agroécologiques à l'intérieur de ces pays. La zone d'étude couvre le Burkina Faso, la Djibouti, l'Érythrée, l'Éthiopie, le Mali, la Mauritanie, le Niger, Nigéria, Sénégal, la Somalie, le Soudan et le Tchad. La situation de cette partie du monde est fortement impactée par le changement climatique car l'agriculture, largement pluviale, y joue un rôle économique important. Il est alors attendu que le changement climatique aura un impact sur la production alimentaire, ce qui rendra encore plus difficile la disponibilité et l'accès aux aliments.

D'un point de vue théorique, cette thèse vise à alimenter la littérature sur le changement climatique et ses effets sur les secteurs agricoles dans le monde, particulièrement dans le Sahel, en mettant un accent sur les zones agroécologiques. D'un point de vue empirique et en mobilisant notamment les techniques statistiques et économétriques, cette thèse prend en compte les caractéristiques agricoles et climatiques de chaque pays et zones agroécologiques du Sahel.

Dans le premier chapitre, nous traitons la question du changement et de la variabilité climatiques en se basant sur les précipitations et la température durant les différentes saisons des pays et zones agroécologiques du Sahel. En s'appuyant sur un modèle de régression linéaire et un modèle de changement structurel endogène, nous montrons que les pays et les zones agroécologiques sont effectivement affectés par le changement climatique et que l'année 1980 est un point essentiel dans l'explication de ce phénomène aux deux échelles. Nous montrons également que les zones désertiques et arides ont subi un grand nombre de chocs de 1901 à 2016, à l'exception du Nigéria, où les zones humides et les zones non désertiques ont subi plusieurs chocs.

Dans le deuxième chapitre, nous étudions la relation entre le changement et la variabilité climatiques, mesurés par les conditions de température et de précipitations pendant les saisons des pluies, et la production agricole au niveau des pays et au niveau des zones agroécologiques du Sahel. En se concentrant sur un indice de production agricole et cinq céréales (maïs, mil, sorgho, blé et riz), nous étudions cette relation à l'aide d'une base de données originale avec des variables socio-économiques et climatiques. Sur la base d'une fonction de production agricole estimée pour la période 1961-2016, nous montrons que les précipitations et les températures moyennes pendant la saison de croissance ont des effets très hétérogènes sur la production agricole selon la zone céréalière et agricole, en fonction des besoins spécifiques et du stress liés aux conditions céréalières et agronomiques et climatiques de chaque zone.

Dans le troisième chapitre, nous analysons le lien entre changement climatique et la sécurité alimentaire dans les pays du Sahel. En se basant sur une analyse multidimensionnelle de la sécurité alimentaire et un modèle de données de panel avec les variables climatiques d'intérêt rétardées, nous montrons que la sécheresse et les inondations affectent négativement la sécurité alimentaire. En présence de ces catastrophes climatiques, les inondations causent davantage de dommages à la sécurité alimentaire. Les facteurs socioéconomiques jouent également un rôle important dans la sécurité alimentaire. Nos résultats montrent ainsi que le faible niveau de développement économique, la croissance démographique et l'inflation des prix des denrées alimentaires ne permettent pas d'assurer la sécurité alimentaire. En outre, l'absence des conflits et la stabilité politique sont des leviers importants d'amélioration de la situation de sécurité alimentaire des populations.

Mots clés: Changement climatique, Production agricole, Sécurité Alimentaire, Sahel, Zones Agroécologiques, Économétrie.

Climate Change, Agriculture and Food Security in the Sahel

This thesis deals with the impact of climate change on agriculture and food security in the Sahel zone that we define as a region comprising 12 countries and 52 agroecological zones within these countries. The study area covers Burkina Faso, Djibouti, Eritrea, Ethiopia, Mali, Mauritania, Niger, Nigeria, Senegal, Somalia, Sudan and Chad. The situation in this part of the world is strongly impacted by climate change because agriculture, largely rainfed, plays an important economic role there. Climate change is then expected to have an impact on food production, which will make food availability and access even more difficult.
From a theoretical point of view, this thesis aims to feed the literature on climate change and its effects on agricultural sectors in the world, particularly in the Sahel, by focusing on agroecological zones. From an empirical point of view and by using a range of statistical and econometric techniques, this thesis takes into account the agricultural and climatic characteristics of each country and agroecological zones of the Sahel.

In the first chapter, we deal with the issue of climate change and variability based on precipitation and temperature during the different seasons of the countries and agroecological zones of the Sahel. Using a linear regression model and an endogenous structural change model, we show that countries and agroecological zones are indeed affected by climate change and that the year 1980 is an essential point in explaining this phenomenon for both scales. We also show that desert and arid areas suffered a large number of shocks from 1901 to 2016, with the exception of Nigeria, where wetlands and non-desert areas suffered several shocks.

In the second chapter, we study the relationship between climate change and variability, measured by temperature and precipitation conditions in the rainy seasons, and agricultural production at country level and at the level of agroecological zones in the Sahel. Focusing on an agricultural production index and five cereals (corn, millet, sorghum, wheat and rice), we study this relationship using an original database with socio-economic and climate

variables. On the basis of an estimated agricultural production function for the 1961-2016 period, we show that precipitation and average temperatures during the growing season have very heterogeneous effects on agricultural production according to the cereal and agricultural zone, depending specific needs and stress linked to the cereal and agronomic and climatic conditions of each zone.

In the third chapter, we analyze the link between climate change and food security in the Sahel countries. Based on a multidimensional analysis of food security and a panel data model with delayed climate variables of interest, we show that drought and floods negatively affect food security. In the presence of these climatic disasters, floods cause more damage to food security. Socioeconomic factors also play an important role in food security. Our results show that the low level of economic development, population growth and inflation of food prices do not guarantee food security. In addition, the absence of conflicts and political stability are important levers for improving the food security situation of the populations.

Keywords: Climate Change; Agricultural Production; Food Security; Sahel; Agroecological zones; Econometrics.

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Introduction générale

Le changement climatique se manifeste sous de nombreuses formes : la hausse des températures moyennes mondiales, une plus grande variabilité des températures et des précipitations et la plus grande occurrence des événements extrêmes tels que la sécheresse, les inondations et les vents violents. La liste des chocs climatiques s'allonge au fil des années (Masih et al., 2014; Yobom, 2020).

Même si les causes naturelles ne sont pas négligeables (Caminade and Terray, 2010; Dai, 2011, 2013), les différents types d'activités humaines génèrent des émissions de gaz à effet de serre provoquant le changement climatique, avec des implications négatives importantes pour l'économie, le bien-être des populations et l'environnement (Stern, 2008; Desboeufs et al., 2010; Touchan et al., 2011). Pour Stern (2008), les émissions de gaz à effet de serre (GES) sont des externalités dont les impacts sont catastrophiques pour le globe. Par conséquent, le changement climatique peut être appréhendé économiquement comme étant la conséquence d'une externalité négative mondiale indissociable au mode et rythme de la croissance et du développement économique actuel mettant en danger un bien public global qui est le « climat » (Nordhaus, 1999; Grasso, 2004).

Cependant, les responsables de ces émissions ne sont pas appelés à supporter les coûts économiques, permettant ainsi de considérer le changement climatique comme étant la plus grande défaillance de marché que le monde n'ait jamais connu (Stern, 2008). Le climat est un bien accessible à tous les États du monde qui n'ont pas nécessairement intérêt à le produire. Autrement dit, le climat est un bien dont le coût marginal de fourniture à un agent économique supplémentaire est nul, et dont il est impossible ou coûteux d'interdire l'accès à un agent économique (Nordhaus, 1999). Du fait de ses caractéristiques, aucun État n'a ainsi intérêt à financer la protection du climat, en attendant que d'autres le fassent pour en bénéficier sans frais. Face à la double défaillance des marchés et des États, il est nécessaire de recourir à la coopération internationale.

Le mode idéal de gestion des biens publics globaux est un régime coopératif, où les nations négocient des accords contraignants permettant d'assurer un niveau de fourniture efficace de bien public (Nordhaus, 1999). Dans cette optique, la volonté des États a conduit à la mise en place de la Convention cadre des Nations Unies sur les changements climatiques (CCNUCC) qui est une institution de coordination (Rhodes, 2016) permettant aux États de disposer d'une réponse internationale. Ainsi, la conférence des Parties de la Convention cadre des Nations Unies sur les changements climatiques fournit annuellement des bilans et propose des mesures dans la lutte contre le changement à l'échelle mondiale en se basant également sur des directives et stratégies nationales.
La dernière en date est la COP25 qui s'est tenue à Madrid et dont l'objectif était

l'accomplissement de l'accord de Paris (COP21), elle succède la COP24 en Pologne qui a permis l'adoption et la validation des directives de mise en oeuvre de l'accord de Paris. La COP21 de Paris a été l'une des plus importantes rencontres dans la lutte contre le réchauffement climatique : 195 nations se sont réunies pour la définition des mesures permettant de lutter contre le changement climatique. Les signataires de ce traité ont convenu de limiter le réchauffement climatique en contenant la hausse de température en dessous de 2°C par rapport à l'ère préindustrielle avec une volonté de continuer les efforts afin de la limiter en dessous de 1,5 °C dans le long terme (Rhodes, 2016). Au final, l'accord historique de Paris a été ratifié par 183 sur 195 pays ayant adopté le dit accord.

Bien que la COP25 n'ait pas permis aux participants d'aboutir à un consensus sur les règles des marchés carbone internationaux, elle a permis aux États de faire une annonce importante qui devrait ouvrir la voie pour la COP26 à Glasgow où les États signataires de l'accord de Paris doivent annoncer leurs contributions nationales à l'atténuation du réchauffement climatique, plus ambitieuses selon les parties prenantes que celles présentées en 2015. Cette rencontre de Madrid a également permis aux scientifiques de réflechir sur la manière dont les pays peuvent conduire l'agriculture dans un monde de changement climatique et ce programme s'achèvera à la prochaine COP26 de 2020 prévue à Glasgow.

Si la lutte contre les changements climatiques représente le cas parfait d'un bien public global, l'élaboration et la mise en place d'une action internationale concertée demeure extrêmement complexe et ardue. Cette première tentative souffre en effet de lacunes structurelles et d'un contexte conjoncturel qui vont jusqu'à remettre en cause son entrée en fonction. Par exemple, la sortie des États-Unis de l'Accord de Paris, le pays responsable des plus grandes émissions de gaz à effet de serre, représente d'ailleurs le plus grand obstacle auquel fait face la lutte aux changements climatiques à l'heure actuelle. L'incertitude plane ainsi sur la réalisation de ces accords et le respect de ces mesures compte tenu des coûts financiers des mécanismes d'atténuation. En outre, il y a des fortes incitations au comportement de "passager clandestin" susceptible d'être adopté par certains États signataires pouvant mettre en échec la réalisation des différents accords (Rhodes, 2016; Nordhaus, 1999).

Le réchauffement climatique cause d'énormes dommages économiques sur les populations humaines, l'écosystème et les différents secteurs économiques. L'évaluation et l'estimation de ces coûts ont fait l'objet de plusieurs études catégorisées en deux approches : globale et partielle. La première s'intéresse à l'évaluation globale du changement climatique, tandis que la seconde ne s'intéresse qu'à un seul secteur.
Les approches globales ont été menées par Nordhaus (1994) et Stern (2008) dans leurs différents travaux sur l'évaluation des coûts liés aux politiques d'atténuation et les coûts de l'inaction. La plupart des approches actuelles globales de modélisation utilisent des fonctions de dommages pour paramétrer une relation simplifiée entre les variables climatiques, telles que les changements de température et les pertes économiques (Diaz and Moore, 2017). Par exemple, Nordhaus (1994) introduit une fonction de dommage climatique qui perturbe l'économie. Cette fonction de dommage lie la hausse de la température au PIB, la température étant elle-même fonction du niveau de concentration en gaz à effet de serre.
D'autres auteurs (Hanemann and Dale, 2006; Ali, 2012; Diaz and Moore, 2017; Auffhammer,

2018) ont également évalué les dommages économiques causés par le changement climatique en se penchant sur le montant des coûts, et donc le potentiel économique de l'atténénuation, en s'opposant dans une certaine mesure aux travaux de Nordhaus (1994) et Stern (2008). Par exemple, Diaz and Moore (2017) estiment que ces modèles sont incomplets et que l'adaptation, la vulnérabilité et les résultats empiriques pourraient améliorer considérablement la modélisation des dommages et la robustesse du coût social des valeurs de carbone produites. De plus, Hanemann and Dale (2006) estiment que la moyenne excessive des changements dans les variables climatiques, que la moyenne soit temporelle, spatiale ou sectorielle, tend à sous-estimer les dommages causés par le réchauffement climatique.

Dans la littérature, on trouve également une multitude d'approches partielles complétant l'approche globale tantôt sur l'agriculture (You et al., 2009; Rowhani et al., 2011; Chen et al., 2016; Brown et al., 2017), tantôt sur la sécurité alimentaire (Celia Reyes and Calubayan, 2014; Furuya et al., 2015; Eric and Kinda, 2016).
Parmi ces secteurs, l'agriculture est le secteur le plus étudié en raison de son importance économique et de sa forte dépendance aux conditions climatiques avec un effet mitigé car certaines régions du monde bénéficieront du réchauffement climatique. Néanmoins, la production alimentaire mondiale devrait être signitivement affectée par le changement climatique (Lobell et al., 2011).

Cette thèse se situe dans une approche partielle, contribuant ainsi à cette littérature existante, en évaluant l'impact du changement climatique sur l'agriculture et la sécurité alimentaire au Sahel. Elle n'a pas pour objectif d'évaluer les coûts économiques du changement climatique mais se base sur un modèle statistique et met également en exergue l'existence du changement climatique en apportant des preuves suppplémentaires quant à la situation climatique du Sahel. Elle s' intéresse à la zone du Sahel qui est une partie du monde où les problèmes climatiques constituent un enjeu majeur pour la population et spécialement la population agricole pauvre.

Dans ce contexte, nous adoptons une nouvelle définition du Sahel que nous appelons "Sahel élargi" qui est composé des 12 pays du Sénégal à la Corne de l'Afrique (Burkina Faso, Tchad, Djibouti, Ethiopie, Erytrée, Mali, Mauritanie, Niger, Nigeria, Sénégal, Somalie et le Soudan). À partir des informations de la FAO, nous avons également identifié 52 zones agroécologiques au niveau de ces pays dont la répartition varie d'un pays à autre. Ici, nous adoptons la définition de la FAO qui définit une zone agroécologique comme étant "une unité cartographique de ressources en terres, définie en termes de climat, de géomorphologie et de sols, et/ou du couvert végétal et possédant un éventail spécifique de potentiels et de contraintes pour l'utilisation des terres".

Après la définition de la zone d'étude et l'identification des zones agroécologiques, nous avons mené plusieurs travaux pour la construction du volet empirique de cette thèse. D'un point de vue géographique, nous les avons cartographié afin d'obtenir leurs coordonnées grâce aux techniques de la géomatique. D'un point de vue agronomique et climatique, nous avons effectué un travail de collecte d'information permettant de décrire les caractérisques agricoles et climatiques des zones agroécologiques tout en établissant des calendriers agricoles de chaque zone agroécologique en fonction de chaque céréale. Nous avons également fait un travail pour décrire le stress et les besoins des principales céréales étudiées (maïs, mil, sorgo, riz et blé) dans cette thèse. Toutes ces informations ont permis de construire des variables climatiques utilisées dans les analyses empiriques de la thèse.

Alors que la plupart des études scientifiques (Nicholson, 2005; Nyong et al., 2007; Giannini et al., 2008; Lebel et al., 2009; Mahe and Paturel, 2009; Ozer et al., 2010; Sissoko et al., 2011; Bayala et al., 2015; Nicholson, 2013) se sont intéressées au Sahel Ouest africain (du Sénégal au Tchad), nous intégrons tous les pays de l'Afrique de l'Est car ces pays ont des confirgurations climatiques similaires à ceux de l'Afrique de l'Ouest. Les pays de ce "Sahel" élargi ont les mêmes caractéristiques et sont confrontés aux problèmes de variabilité des précipitations et de la hausse de la température (Yobom, 2020). Tous ces pays font face à une variation de leur production agricole, à une croissance démographique et sont confrontés de manière cyclique aux situations d'insécurité alimentaire. En plus des problèmes socioéconomiques, ces pays sont affectés de manière régulière aux conflits liés aux guerres civiles et au terrorisme. Notre étude porte à la fois sur les zones agroécologiques et les pays du Sahel.

Cette thèse fournit des élements de réponse visant à alimenter le débat scientifique sur l'existence du changement et de la variabilité climatique et ses conséquences sur les secteurs agricoles, notamment l'agriculture et la sécurité alimentaire, en plaçant le Sahel au milieu des débats. Actuellement, le Sahel est la zone la plus sensible dans le monde en raison de sa forte vulnérabilité climatique, ses problèmes économiques et les guerres (migrations, conflits civils et terrorisme). Plus précisement, cette thèse a un triple objectif.

Premièrement, elle définit un nouveau Sahel et montre l'existence du changement climatique au niveau des pays et des zones agroécologiques. Autrement dit, elle cherche à répondre aux questions suivantes : le changement climatique existe-t-il au niveau de ces deux échelles d'analyse ? Si oui, à partir de quelle période ce phénomène séculaire a t-il débuté ? En outre, y a-t-il une hétérogénéité entre les zones agroécologiques et entre les pays du Sahel ?
Deuxièmement, elle évalue l'impact du changement climatique sur la production agricole. En d'autres termes, le changement climatique à travers les précipitations et la température a-t-il eu des effets sur la production agricole des pays et des zones agroécologiques du Sahel ? Cet impact est-il similaire entre les différentes régions ?
Troisièmement, elle étudie le lien entre changement climatique et sécurité alimentaire dans les pays du Sahel. Elle cherche à répondre aux questions suivantes : le changement climatique, notamment à travers l'occurence des sécheresses et des inondations, affecte-t-il la sécurité alimentaire ? En outre, les déterminants socioéconomiques jouent-ils un rôle dans l'amélioration de la sécurité alimentaire ?

Afin de répondre à ces questions et en se basant sur des méthodes économétriques et statistiques, la thèse est organisée en trois chapitres couvrant différentes études et échelles géographiques, pays et les zones agroécologiques identifiées à l'échelle des pays. Globalement, toutes les analyses et les choix de période sont effectuées en raison de la disponibilté des données. Une annexe générale fournit également un point détaillé de la situation économique et agronomique des pays de l'échantillon.

Le reste de l'introduction propose un état de lieux sur les principales thématiques de cette thèse. Une analyse des enjeux du changement climatique est présentée dans la section 0.1, avec un focus mondial et sahélien. La section 0.2 présente de manière succincte les liens du climat avec l'agriculture (0.2.1) et propose un bref aperçu avec la situation alimentaire (0.2.2). Enfin, la section 0.3 décrit la structure de la thèse.

0.1 Mise en évidence du changement climatique

Selon le Groupe d'Experts Intergouvernemental sur l'Évolution du Climat (GIEC), le taux actuel d'émissions de gaz à effet de serre devrait entraîner une hausse des températures moyennes de 0,2°C par décennie, atteignant d'ici 2050 le seuil de 2°C au-dessus des niveaux préindustriels. Ces résultats sont également partagés par Stern (2008) qui estime que le stock de gaz dans l'atmosphère actuel est de 430 ppm, contre un niveau de 280 ppm avant l'époque industrielle. Cette augmentation a entrainé une hausse de température de 0,5°C, en présence d'un scenario d'action d'atténuation elle augmentera de 0,5°C supplémentaire. Dans le même contexte, le stock pourra atteindre le double de la période préindustrielle soit (550 ppm) d'ici 2035, et le réchauffement pourrait atteindre 2°C avec un seuil de risque de 99%.

Le changement climatique est un fait patent et historique dont les impacts sont incertains et susceptibles de ne devenir de réels enjeux que dans un avenir lointain (Nordhaus, 1999). Bien que différentes régions et pays sont déjà affectés, les effets tardent à apparaître dans certains endroits et régions du monde. Dans son rapport, Stern (2008) estime qu'une action forte et précoce sur le changement climatique l'emportera sur les coûts. Une action collective permettra d'éviter les pires effets susceptibles du changement climatique et espérer avoir une bonne croissance. En outre, il faut dès à présent investir dans la maîtrise des effets du changement climatique en adoptant un accord global avec toutes les parties prenantes. En revanche, tout retard exigera des efforts supplémentaires et réduit le risque de résorber la concentration des gaz à effet de serre dans l'atmosphère.

Aujourd'hui, les effets sont visibles. Le Centre de recherche sur l'épidémologie des désatres (Kihl and CRED, 2020) indique qu'en 2019, le monde a connu plusieurs catastrophes naturelles et la plupart d'entres elles étaient dévastatrices. Tous ces événements sont liés au changement climatique, causant d'énormes dégâts matériels et humains. Par exemple, la dernière catastrophe liée aux effets du changement climatique est l'incendie de la saison 2019-2020 en Australie (March et al., 2020). Ces feux de brousse se sont distingués par leur intensité et durée. Elle est due à la sécheresse, à la chaleur et les vents violents. Selon l'ONU, cette catastrophe a causé l'endommagement d'environ 18 millions d'hectares, 5900 bâtiments et la perte humaine d'au moins 34 personnes (March et al., 2020; Colvin et al., 2020).
Au Sahel, l'ONU estime qu'environ 80% des terres agricoles sont dégradées et que les températures augmentent 1,5 fois plus rapide que la moyenne mondiale. Par ailleurs, les sécheresses et les inondations sont de plus en plus longues et fréquentes.

Bien que le changement climatique soit mondial, ses impacts négatifs ne sont pas uniformément repartis (Stern, 2008). Par ailleurs, les pays pauvres souffriront plus tôt et plus sévèrement que les pays développés. De fait, ils sont plus vulnérables en raison de leur forte dépendance à l'égard des secteurs agricoles et de leur faible capacité et moyen à faire face à la variabilité et aux événements climatiques extrêmes (Haile, 2005; Sissoko et al., 2011).

La plupart des études sur le changement climatique au Sahel (Hôte et al., 2002; Hastenrath and Polzin, 2011; Adeniyi, 2016; Rajaud and de Noblet, 2017; Frankignoul and Hasselmann, 1977; Pascual et al., 2006; Nicholson et al., 2012) se font uniquement à l'échelle des pays et sont limités au Sahel ouest africain. En plus de prendre en compte les pays de l'Afrique de l'est, cette thèse fournit des preuves sur l'existence du changement climatique à l'échelle des zones agroécologiques car ces terres sont utilisées pour les activités agricoles. L'essentiel des productions agricoles proviennent des zones agroécologiques cultivables et connaître leur potentiel climatique et montrer l'existence du changement climatique à cette échelle est important.

Dans la littérature, les travaux utilisent différentes variables et approches pour montrer l'existence du changement climatique, explication du changement climatique avec la sécheresse (Brooks, 2004; Ozer et al., 2010; Masih et al., 2014; Giannini et al., 2008), inondations (Dittrich et al., 2016; Di Baldassarre et al., 2010), avec la précipitation ou température (Hôte et al., 2002; Hastenrath and Polzin, 2011; Adeniyi, 2016; Rajaud and de Noblet, 2017; Frankignoul and Hasselmann, 1977; Pascual et al., 2006; Nicholson et al., 2012).

Contrairement aux travaux de (Adeniyi, 2016; Frigg et al., 2015; Hulme et al., 2009; Paturel et al., 1997; Sylla et al., 2018) qui ont utilisé des méthodes de calibration pour expliquer l'existence du changement climatique, cette thèse contribue à la littérature empirique en montrant l'existence du changement et la variabilité climatique en utilisant des variables climatiques (précipitations et température) saisonnières et un modèle de régression linéaire (Fahrmeir et al., 2013; Bingham and Fry, 2010) couplé à un modèle à changement structurel (Bai and Perron, 1998, 2003).

Dans ce contexte, notre chapitre vise à contribuer à la littérature en s'appuyant sur une base originale construite en prenant en compte les configurations climatiques de chaque pays. Pour connaître la dispersion en termes de dispersion tendance, nous utilisons la moyenne, la médiane et le maximum de la température et précipitation durant la saison sèche et pluvieuse. Le modèle linéaire estimé par la méthode des Moindres Carrés Ordinaires (MCO) a permis d'évaluer l'évolution de nos variables climatiques en niveau et en termes de tendance sur la période de 1901 à 2016. L'utilisation du modèle à changement structurel a permis de détecter des ruptures endogènes dans l'évolution des variables climatiques, montrant ainsi la période des chocs climatiques dans les pays et zones agroécologiques.

L'intérêt de cette analyse est de mettre en exergue l'existence du changement et variabilité à la fois à l'échelle des pays et zones agroécologiques. Les résultats montrent également qu'au même moment où les pays de l'Afrique de l'Ouest faisaient face au changement climatique, les pays de l'Afrique de l'est du Soudan à la Somalie, subissaient les mêmes effets néfastes du réchauffement climatique. Les résultats de ces deux modèles sont unanimes. Le changement climatique a bien commencé au niveau des pays et zones agroécologiques du Sahel, l'année 1980 reste une année importante dans l'explication du changement climatique dans le Sahel. Cependant, les résultats indiquent également une forte hétéorgéneité entre les pays, et entre les zones agroécologiques.

0.2 Changement climatique et secteurs agricoles

0.2.1 Effets du changement climatique sur l'agriculture

Les précipitations et la température sont les principaux inputs dans un système agricole pluvial, induisant une forte dépendance au climat de l'agriculture. De part leurs effets, les changements climatiques ont des incidences de plus en plus marquées sur les conditions climatiques et la production alimentaire des différentes régions (Sissoko et al., 2011; Muller, 2013; Ward et al., 2014), bien que certaines régions disposent des conditions climatiques propices aux activités agricoles.

Les céréales et les différents végétaux dépendent fortement du climat et leur cycle de croissance dépend des conditions climatiques appropriées. Chaque céréale nécessite une température optimale et des exigences propres en eau (Agu and Palmer, 1997; Porter and Gawith, 1999; Sánchez et al., 2014). Dans certaines régions, la hausse des températures peut entraîner le développement de certaines cultures. Toutefois, si les températures dépassent le niveau optimal pour la croissance d'une culture donnée ou si les quantités en eau et en nutriments sont insuffisantes, les rendements vont baisser (Karim et al., 2000; Schlenker and Roberts, 2009; Lobell et al., 2011; Mendelsohn, 2014).

En outre, les rendements des cultures peuvent baisser avec l'accroissement des sécheresses et inondations qui ont des effets néfastes sur les cultures et réduit leurs rendements. La sécheresse peut brûler les feuilles des cultures et les inondations risquent d'endommager les cultures et les champs (Abaje et al., 2013; Zhang et al., 2015; Winkler et al., 2017). Les pays et régions arides ont des difficultés à gérer la sécheresse car ils font déjà face à la fois à une baisse prononcée des précipitations et la hausse des températures moyennes. Un grand nombre d'insectes nuisibles et de maladies se développeront dans des climats plus chauds et plus humides et avec une plus grande concentration de gaz carbonique dans l'atmosphère (Stange and Ayres, 2001; Ward and Masters, 2007) pouvant affecter les productions céréalières.

L'effet cumulé des températures plus extrêmes et d'une pluviométrie plus faible peut rendre la croissance de certaines cultures totalement impossible. En d'autres termes, la culture de certaines variétés céréalières va disparaître dans les prochaines décennies. Cette situation conduit les scientifiques à développer d'autres variétés, comme le cas actuellement avec les tentatives d'une nouvelle variété de blé au Sénégal.

Bien qu'il soit difficile d'évaluer et de prévoir les effets précis du changement climatique sur l'agriculture, Chen et al., 2016; Mendelsohn et al., 1994; Liu et al., 2004; Cui et al., 2019; Antle and Stockle, 2017 ont évalué ce lien en se basant sur différentes approches, en montrant de manière globale que les effets du climat varient en fonction des régions et des cultures.

Pour Mendelsohn and Dinar (2009), il existe plusieurs approches utilisées dans la littérature empirique pour évaluer le lien changement climatique et agriculture. Par exemple, le modèle ricardien est developpé par Mendelsohn et al. (1994), qui se base sur la valeur de terre. D'autres approches telles que les modèles de simulation des cultures (Rosenzweig and Parry, 1994) et fonctions de production agricole ou de rendement (Lobell et al., 2011; Chen et al., 2016) sont également utilisées dans cette partie de la littérature.

En utilisant une fonction de production agricole, Ward et al. (2014) montrent que les rendements céréaliers en Afrique subsaharienne diminuent avec l'augmentation de la température et augmentent avec des précipitations totales élevées tandis que Liu et al. (2004) indiquent qu'une température plus élevée et davantage de précipitations auront un impact global positif sur l'agriculture chinoise. Rowhani et al. (2011) et You et al. (2009) indiquent que la variabilité des précipitations et des températures augmente pendant la saison de croissance et a un effet négatif sur les céréales.

Contrairement aux travaux de Muller, 2013; Bayala et al., 2015; Sissoko et al., 2011; Wood and Mendelsohn, 2015a; Ward et al., 2014; Kotir, 2011, qui se sont focalisés à l'échelle des pays, cette thèse évalue l'impact du changement climatique sur la production des cinq principales céréales (maïs, mil, sorgo, blé et riz) du Sahel et l'indice net de production agricole à la fois au niveau des pays et zones agroécologiques du Sahel en explorant une fonction de production agricole de 1961 à 2016.
Ainsi, elle contribue à la littérature empirique en adoptant également la version statistique de l'approche de la production agricole car ce cadre suppose que les conditions climatiques (précipitations et température) sont des facteurs incontrôlables et donc des variables exogènes nécessaires dans le cadre des activités agricoles. En outre, le modèle est estimé avec un modèle à effet fixe avec robustesse, permettant de mesurer l'effet de l'utilisation de chaque input dans les productions agricoles dans les pays et dans les zones agroécologiques du Sahel.

Au niveau des zones agroécologiques, la stratégie empirique prend uniquement en compte celles dans lesquelles où la céréale est cultivée, ce qui permet de connaître le potentiel agricole de chaque zone agroécologique et d'évaluer l'hétéorogénéité entre les zones agroécologiques.
Nos résultats montrent que les précipitations et la température ont des effets hétérogènes sur la production des différentes céréales entre les pays et les zones agroécologiques du Sahel et confortent bien la plupart des travaux dont ceux de Rowhani et al. (2011) et You et al. (2009) qui indiquent l'effet differencié du changement climatique sur les céréales et les régions.

0.2.2 Répercussions sur la sécurité alimentaire

La sécurité alimentaire et l'agriculture entretiennent des liens étroits. Bien que les événements météorologiques extrêmes réduisent les revenus des populations et leur accès à la nourriture, l'agriculture, en raison de son importance économique, apparaît comme le secteur principal par lequel le changement climatique affecte toutes les dimensions de la sécurité alimentaire (Kotir, 2011).

Les effets du changement climatique sur les moyens d'existence s'intensifient et varient selon les pays et régions. Le changement climatique influence la disponibilité d'aliments. Ses effets néfastes affectent considérablement les rendements des cultures et les stocks alimentaires. Cette situation sévit principalement en Afrique subsaharienne et en Asie du Sud, où on trouve le plus grand nombre des personnes souffrant de malnutrition et d'insécurité alimentaire. Globalement, une baisse de la productivité agricole aurait de lourdes conséquences pour la sécurité alimentaire (Wheeler and Von Braun, 2013).

Les effets du changement climatique sont plus prononcés chez les populations vulnérables, donc tout accroissement des chocs climatiques aura des impacts plus intenses chez les ménages pauvres agricoles dont les principales activités se focalisent essentiellement sur l'agriculture. Autrement dit, les pertes de revenus provoquées par la sécheresse et les inondations affaiblissent cette catégorie de population tout en limitant leur capacité future à disposer des revenus et des conditions financières pour des nouvelles activités agricoles (Ashley, 2016; Haile, 2005).

La baisse de la disponibilité alimentaire crée de la rareté donc une augmentation des prix des denrées alimentaires. L'inflation touche toutes les populations pauvres n'ayant pas des revenus importants, car les ménages pauvres ont tendance à consacrer la plus grande partie de leurs revenus aux dépenses de consommation (Lovendal et al., 2007).

L'évolution de l'utilisation de la nourriture affectera la situation des populations pauvres et vulnérables en matière de nutrition. La hausse des températures favorise le développement d'agents pathogénes et la pénurie d'eau affecte la qualité de l'eau et les habitudes d'hygiène. Par exemple, les diarrhées provoquées par la mauvaise qualité de l'eau affectent les populations les plus démunies qui seraient les plus gravement touchées, à commencer par les enfants pauvres (OMS, 2003; FAO, 2016).

Le changement climatique à travers ses différents effets néfastes nuira à la stabilité des disponibilités alimentaires, de l'accès aux aliments et de leur utilisation en raison des changements de saisonnalité, des fluctuations plus marquées de la productivité des écosystèmes, et d'une augmentation des risques doublée d'une baisse de la prévisibilité en matière d'approvisionnement.

Le changement climatique ne sera qu'un facteur parmi d'autres dans les tendances futures qui se dessinent en matière de pauvreté et de sécurité alimentaire. Ces tendances, et la mesure dans laquelle elles seront influencées par le changement climatique, dépendront essentiellement du développement socioéconomique des années à venir.

Pour évaluer les impacts du changement climatique sur la sécurité alimentaire, nous utilisons un modèle multidimensionnel qui se focalise sur les quatre dimensions de la sécurité alimentaire, contrairement aux études de Eric and Kinda, 2016; Ringler et al., 2010; Masipa, 2017; Ahmad Munir and Iqbal, 2015; Karfakis et al., 2011. Dans le cadre de cette thèse et en se basant sur des données climatiques et socioéconomiques allant de 2000 à 2016, nous utilisons un modèle en données de panel avec effets fixes pour estimer cette relation.

Les résultats montrent que l'insécurité alimentaire dans les pays du Sahel ne peut pas être expliquée uniquement par l'occurence des chocs climatiques tels que la sécheresse et les inondations. Les bonnes conditions socioéconomiques des États sahéliens peuvent contribuer à améliorer la situation de sécurité alimentaire des populations. Par exemple, la stabilité politique et l'absence des violences et un niveau de PIB par tête élevé jouent un rôle important dans la définition des quatre dimensions de la sécurité alimentaire dans le Sahel.

0.3 Plan de la thèse

Cette thèse vise ainsi à alimenter le débat existant sur le changement climatique, la production agricole et la sécurité alimentaire. Elle est organisée en trois chapitres.

Le premier chapitre intitulé **"Climate change and variability in Sahel"** présente une revue de littérature sur le changement climatique et son impact économique et propose un examen de l'existence du changement climatique à la fois au niveau des pays et des zones agroécologiques du Sahel.

Le chapitre 2 intitulé **"Climate change and agriculture : empirical evidence for agroecological zones and countries of the Sahel"** utilise les résultats du chapitre 1 comme un point de départ: des effets hétérogènes du changement et variabilité climatique entre les zones agroécologiques et les pays pour évaluer le lien climat et agriculture dans le Sahel.

Le chapitre 3 intitulé **"Climate change and food security: a multidimensional analysis in the Sahel for the period 2000-2016"** propose une revue de littérature de ce lien et l'analyse en se basant sur les quatre dimensions de la sécurité alimentaire : disponibilité, accessibilité, utilisation et stabilité.

Chapter 1

Climate change and variability in countries and agroeological zones of the Sahel

This article statistically evaluates the extent of climate change and variability in the Sahel countries since 1901. We perform a statistical analysis based on a linear regression model estimated by Ordinary Least Squares (OLS) and on a structural change model using two databases at different scales (countries and agroecological zones) that provide information on temperature and precipitation. The first database from the World Bank provides temperature and precipitation data from 1901 to 2012 and pertains to a country level. The analysis of agroecological zones is based an original database from 1901 to 2016 constructed with data provided by the Royal Netherlands Meteorological Institute. The results suggest that climate change has indeed started in all the countries of the Sahel with 1980 being a turning point of global warming. They also suggest that agroecological zones are experiencing climate change and variability, with turning points in 1940 and 1980. Thermal shocks in agroecological zones are more numerous than those caused by rainfall. Desert and arid areas have experienced a large number of shocks from 1901 to 2016, with the exception of Nigeria, where wetlands and non-desert areas experienced several shocks. Several extreme events (natural or anthropogenic) causing enormous damage have occurred around this year. The results also indicate that weak countries enormously suffer in consequence of extreme events such as drought and floods.

Note: A short version of this chapter has been published:
Yobom O. (2020) Climate change and variability: empirical evidence for countries and agroecological zones of the Sahel, *Climatic Change*, forthcoming.

It was also the subject of a presentation "Change and variability in the Sahel" during the PhD students day of the Dynamics and Regional Planning axis, CESAER (2017).

1.1 Introduction

Projection by the Intergovernmental Panel on Climate Change (Smith et al., 2014; Pachauri et al., 2014) based on all proposed emission scenarios indicate an increase in surface temperature during the 21st century. Changes will be observed in air temperature, water cycle and sea level. The average global increase in surface temperature for the period 2016-2035 will be between 0.3 and 0.7°C. Changes in precipitation will not be uniform in the world with decreasing average precipitation in arid subtropical regions and in most mid-latitude regions, while an increase will be observed in Wetlands following sea-level rise at the end of the 21st century. Climate change is a threat to the development of the entire planet, although in some countries the effects seem slow to appear.

The political response to climate change has evolved over time. Prior to the Paris 2015 (COP21) and Marrakech 2016 (COP22) meetings, several international climate summits and conferences have been organized, but COP21 is considered to be the only agreement of a universal and global nature. It is also historical because of its content, as this agreement recognizes climate justice through the principle of differentiation between countries (developed countries, emerging and polluting countries, developing countries and Island states). On the other hand, COP22 is an action conference whose aim is to contribute to the implementation of the results of COP21 by increasing the mobilization of state and non-state actors. All parties pledged to respect the Paris agreement, but the exit of Donald Trump announcing the withdrawal of the USA constitutes an important turning point in the fight against global warming. For the current US president, the Paris agreement, the key of which is to limit global warming to 2°C by 2100 (COP21), is a brake for economic growth (decline in employment and US economic recovery). For the World Meteorological Organization, 2016 was the warmest year ever and the years ahead will be warmer if there is no quick reaction. In response, European countries, other economic powers and other signatory countries are organizing and remain united for the implementation of the Paris Agreement, under the slogan advocated by French President Emmanuel Macron, "Make Our Planet Great Again". For instance, the United Nations Framework Convention on Climate Change (UNFCCC) is an institution characterized by a balance of power between States, but observers and actors struggling to implement the Paris agreement hope that a consensus will be reached and that the United States will return in the game as they represent the second largest CO2 emitter in the world. COP24 was held from 2 to 15 December 2018 in Katowice, just after Brazil refused to organize COP25 because of President Bolsonaro's position in the fight against global warming. One of the most important achievements of COP24 is the finalization of the text on the full implementation of the Paris Agreement, in accordance with the decisions adopted in Paris and Marrakech. In addition, the specificity of COP24 is to have included the "facilitation dialogue" whose purpose is to facilitate the implementation of national commitments. Overall, this COP24 helped to endow the Paris agreement with tools, especially a clarity on financing, but the limit is that the international community has not committed to do more and faster against global warming. To general surprise, the COP25 held in 2019 in Madrid is a total failure compared to the previous ones. During this conference, the stakeholders failed to reach a consensus on the rules of international carbon markets, the last part of the user manual of the Paris Agreement of 2015 (COP21). The ambition thus turns to COP26 which will be held at the end of 2020 in Glasgow.

In this context, this chapter addresses the issue of climate change and variability in the economies of the Sahelian belt. Like other African countries, the countries that form the Sahelian belt are confronted with an extremely variable and uncertain climate (Lumbroso et al., 2015). The Sahel is known for its fragility due to climatic variability (CILSS, 2010). The Sahel is a strip located between the isohyet 200 *mm* and the isoshyet 600 *mm*, sometimes 150 *mm* and 500 *mm* (CILSS, 2010) and a small difference with the Midlands of Sudan which were between the isohyet 200 mm and the 800 *mm* isohyet (Kassas, 2008b). Thus, we have adopted the following definition of the Sahel: it is composed of the countries of Burkina Faso, Chad, Djibouti, Eritrea, Ethiopia, Mali, Mauritania, Niger, Nigeria, Senegal, Somalia, and Sudan. The Sahelian population is mainly rural, its agriculture depends heavily on weather conditions. Then, any climatic variation affects the agricultural and financial performances of this segment of the population. The lack of water is the main problem of the Sahel countries.

Earlier work has already been done in West Africa specifically in the West African Sahel (Ozer et al., 2003, 2010; Mahe et al., 2001; Hôte et al., 2002; Adeniyi, 2016) but is now dated and confined to the West African Sahel: ten years ago, it was thought that climate change would only affect these countries. It was even thought that droughts were statistically over at the level of these countries, but that the rainfall deficit would remain persistent until the end of the 2000s (Ozer et al., 2010). However, the frequency of droughts has increased in some East African countries that are part of our current definition of the Sahel. Their effects in the 1970s and 1980s were catastrophic for the West African Sahelian population. All other things being equal, these effects are also valid for the countries of East Africa. Mahe et al. (2001) analyzed the rainfall of 23 countries of Central and West Africa over the period 1910 to 1989. The results showed that a first rupture appeared in the 1950s in several units of West Africa. The main break-up period is between 1968 and 1970, followed by a second in the early 1980s. Hôte et al. (2002) also analyzed the annual rainfall index in the West African Sahel from 1896 to 2000 using data provided by the Agrhymet Regional Center of Niamey. They find that the drought began in the 1970s and was not over until the late 2000s, although the years 1994 and 1999 brought some humidity. Failing to stop, climate change through its effects is spreading and affects the entire Sahelian band. Based on IPCC scenarios, Adeniyi (2016) shows that the projected rainfall increase over West Africa is based on average rainfall as he estimates that extreme precipitation is expected to decrease significantly.

Accordingly, it is important to focus today on the extended Sahel. To the best of our knowledge, such a study has never been done and it is important to know whether the changes detected in West Africa 10 years ago are starting to be seen in East Africa today, thus justifying this new definition of the Sahelian band as part of this work. Our analysis is also unique because it is the first to be interested in climate change and variability at a more disaggregated level, that of agroecological zones. Although the West African Sahel has been the subject of several studies, its agroecological zones have not been explored in details yet. This disaggregated analysis is important as agroecological zones represent consistent areas from an agronomic point of view, where the agricultural practice of these countries is determined by the characteristics of these areas. To do so, we have constructed an original database including temperature and precipitation at the agroecological zone level.

This chapter presents the phenomenon of climate change and all the elements that enable us to understand the problem of climate variability in the world in general and in the Sahel in particular. We undertake a general theoretical examination and an empirical examination based on data from the Sahel countries and their respective agroecological zones. In the theoretical part, we present a recent literature review to describe and explain climate change at global level. Next, we address the causes of climate change and the impacts of global warming on economies. In the empirical part, we carry out a statistical analysis on the Sahel countries and the agroecological zones while presenting the variables and the study area, the framework of the analysis and the results obtained.

1.2 Climate change: definitions, measures and models

In this first section, we discuss and define the climate and global warming, their measures and the models used to measure climate and climate change.

1.2.1 Definitions

Climate

In order to link climate change to the economy, we first need to understand climate and the phenomenon of climate change Stern (2008). In the scientific literature and public discourses, there is no single definition of climate and global warming. Climate experts are not unanimous on the definition of climate, global warming, climate trends or other fluctuation (Werndl, 2016). However, the issue at stake is important as a poor definition of these terms leads to confusion and incomprehension of the climate system. We therefore provide here some key aspects that can provide a conceptual definition of climate and climate change.

Pachauri et al. (2014) define the climate, climate change and the various phenomena that can result. The intergovernmental body provides a definition in the strict sense of the climate, according to which "climate generally refers to average time or more precisely to a statistical description based on averages and variability of relevant quantities over periods ranging from a few months to thousands, the standard period, as defined by the World Meteorological Organization, is 30 years. These quantities are usually surface variables such as temperature, precipitation height and wind. In a broader sense, climate refers to the state of the climate system, including its statistical description". According to this definition, we argue that the global climate is a "statistical distribution" of all terrestrial atmospheric conditions in the world over a period of time.

The traditional definition of climate is that of the statistical properties of the meteorological conditions observed at the time and at the place of the year, and these statistical properties are determined from observations made over a certain reference period (Stone et al., 2009). Indeed, the climate varies from one place to another, depending on latitude, distance to the sea, vegetation, presence or absence of mountains or other geographical factors. The climate also varies over time; from one season to another, from one year to another, from one decade to another or from a much longer time scale, such as Ice Age (Lead, 2000).

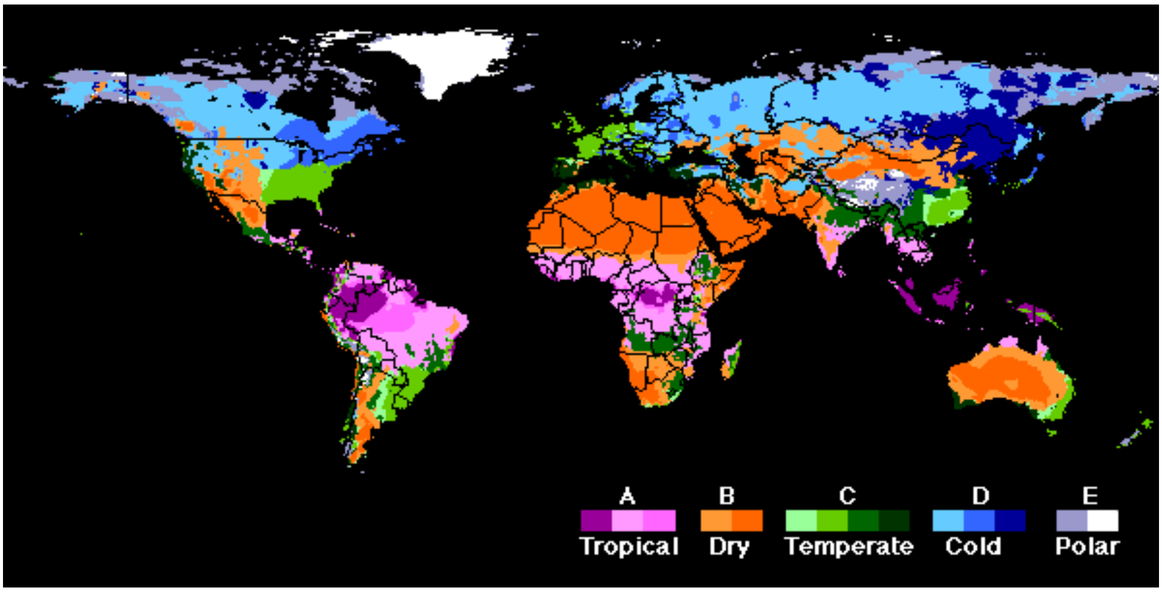
To these definitions of climate, we must also add that of the weather which is defined by Lead (2000) as "the fluctuating state of the atmosphere that surrounds us, characterized by temperature, wind, precipitation, clouds and other meteorological elements". Thus, the knowledge of the weather makes it possible to have an idea on the distribution of the climate in which we live.
The Köppen climate classification system lists five types of climate based on monthly and annual averages of precipitation and temperature. Each type of climate is indicated by a capital letter: wet humid climates (A), dry climates (B), mid-latitude climate with mild winters (C), wet climates in mid-Latitude with cold winters (D) and polar climates (E) with very cold winters and summers (Pidwirny and Jones, 2006).

The spatial and temporal aspects must be taken into account Stone et al. (2009) in the definition of climate. When discussing the climate of a country or region, we need to consider climate variables or factors on the same scale. In general, they are dynamic meteorological variables such as surface air temperature or surface pressure describing the state of the atmosphere at a given time (Werndl, 2016). In other words, climate is a set of weather conditions, a distribution of climatic variables that can appear for a certain configuration of the climate system (Bradley et al., 2017).

A distinction must be made between weather and climate. Allen (2003) quotes Edward Lorenz (indefinite) who states that "climate is what you expect, time is what you get". Allen (2003) argues that climate is "time" and that statistics are defined by the statistician as the "expected time" and its variability for a given time, taking into account all the properties of the oceanic atmospheric system, emissions Current greenhouse gas emissions, solar activity, etc.
Based on these definitions, variables of interest are dynamic climatic variables (Stone et al., 2009). On the other hand, in the literature, several variables can explain climate, for example the temperature of the ocean (Werndl, 2016). The list of climatic variables is long, it can group the variables describing flora and fauna, but they are not often taken into account in the literature. Furthermore, temperature and precipitation are also relevant variables that may explain the climatic situation of a given geographic or geographic area.

Figure 1.1 displays Köppen's climate classification. The climatic conditions can be different at the level of a continent, a country and even at the level of a country. They vary temporarily and spatially. Thus, the climate system is the sum of all climates in each geographical area. For example, the tropical climate is characterized by high and constrasted temperatures, which vary according to the season, the temperature in summer is around 23°C and the winter temperature is around 35°C (Paturel et al., 1997). Climatic conditions may be unfavorable for desert areas (African and Arab countries) with temperatures up to 46°C and rainfall often low and abnormal (Al-Mebayedh, 2013). Being a long-term phenomenon, climate can vary according to regions, countries and continents. It is important to see how it can change over a period so we define climate change in the next section.

Figure 1.1Köppen's climate classification



Source: FAO-SDRN-Agrometeorology Group 1997

Climate change

Being a global phenomenon, global warming is generally characterized by an increase in the average temperature of the oceans and the atmosphere. In other words, this would result from a sharp increase in the concentration of greenhouse gases (NAZA, 1998), such as carbon dioxide, methane and nitrogen dioxide. Indeed, these gases are responsible for climate change (Muller, 2013).

Climate change is also considered as the variation in the state of the climate, which is detectable by statistical tests (Pachauri et al., 2014; Werndl, 2016). This variation translates into changes in the mean and / or variability of climatic properties over a long period of time, decades or more. In other words, climate change can be assimilated to the variation over time of meteorological factors (Stone et al., 2009).

In its first article, the UNFCCC defines climate change as "climate change that is directly or indirectly attributed to human activity that changes the composition of the global atmosphere and adds to the natural climatic variability observed under comparable conditions". According to this definition, the UNFCCC distinguishes between climate change caused by human activities on the atmosphere and those caused by natural problems.

Indeed, the natural greenhouse effect creates habitable climatic conditions in which humankind can aspire to live in relatively benign conditions, otherwise the earth would be a very icy and unbearable place. An increased greenhouse effect, however, refers to the possible rise in the average temperature of the earth's surface that is greater than that due to the natural greenhouse effect due to an increase in greenhouse gas concentrations caused by human activities (NAZA, 1998).

Such global warming as a result of an increase in the greenhouse effect would likely lead to other, sometimes harmful changes in the climate for example, changes in precipitation, thunderstorms and the level of the oceans (NAZA, 1998).

For Stone et al. (2009), climate change refers to any change in climate whether it is forced

naturally or anthropologically.
Werndl (2016) lists five criteria for a rigorous definition of climate change. The first criterion suggests that the definition of climate must be empirically applicable, i.e. the definition must allow an estimation of the past and future climate. The second criterion indicates that the definition of climate must correctly classify the different climate over different periods. The third criterion stresses that the climate must not depend on our knowledge, i.e. it does not take into account the speculations made on the climate. The fourth criterion indicates that the definition of climate must apply to the past, present and future. Finally, the fifth criterion emphasizes that a definition of climate must be mathematically well defined. In general, the criteria defined must lead to a definition that must be empirically applicable and that takes account of past and future climate. This definition should also make it possible to classify the different types of climate over time. Thus, Werndl (2016) defines climate as a finite distribution over time resulting from the regime of variable external conditions. In other words, actual external conditions over a period of time are subject to a certain regime of varying external conditions. This definition is new and is not yet shared in the climate literature. With this in mind, Werndl (2016) speaks of climate change when there are different climates for two successive periods of time, and that there may be external and internal climate change due to different initial values. For Werndl (2016), this definition is specific because it is empirically applicable, the actual climate system is subject to a certain regime of variable external conditions over a sufficiently long period, so the climate of this period coincides with the distribution in time of the actual evolution of climate variables. This definition is also unique because it makes it possible to make an immediate link with the observations.
Focusing on Africa and the Sahel, climate change is perceived differently. For Ouédraogo et al. (2010), climate change leads to environmental degradation. Thus, Sahelian peasants perceive changes in precipitation through its direct effects on soils and vegetation cover. For instance, according to Ouédraogo et al. (2010), climate change in Burkina Faso is perceived by farmers through rainfall changes as agricultural activities depend on precipitation. Climate change results in decreased and increasing irregularities in rainfall, a deregulation of the winter season, and a high frequency of drought (Ouédraogo et al., 2010).
Summarizing, climate change measures depend on the climate variables used, the perception of farmers and people with activities dependent on climate change. If climate change can be observed over a long period of time, the local population aged in a given region is better placed to testify. The climate is variable over time, it can be explained by several indicators that can translate this variation on the different systems that are linked to the climate to a certain extent.

1.2.2 Measures

Climate change is a disruption of the climate system and climate measurement involves comparing the results of the climate variable to its equilibrium value. It is measured by the standard deviation or the average absolute deviation of the distribution of a variable from its mean or long-term trend. Moreover, it should be noted that the standard deviation weighs and evaluates better the extreme events (Badolo and Kinda, 2014). Climate change indicators may vary according to geographic and climatic zones. At the global level, IPCC observations are made through land temperature, ocean heat content, sea level, and atmospheric water value. Recent observations have shown that these indicators are high, and are considered by scientists to be evidence of climate change (Smith et al., 2014). The high frequency of droughts over the last 50 years can explain and also measure the effects of climate change on the economies of the five continents. Based on the Center for Research on the Epidemioligy of Disasters database, Masih et al. (2014) report that the world experienced 642 droughts worldwide during the period from 1900 to 2013. These events killed over 11 million people, affected more than two billion and estimated economic damage to more than 100 million for the whole world.

Klos et al. (2015) conducted surveys of natural resource professionals to list biophysical indicators to obtain indicators or local factors to assess climate change in Idaho and provide relevant information to decision makers to measure climate change. They argue that changes in water resources and risk of forest fires are the most important issues for the professionals interviewed. They listed indicators that included direct climate measurements (air temperature, rainfall, stream temperature, snowpack, streamflow, drought, plant phenology) and indicators partially influenced by climate (fire disturbance, human activities, species viability and productivity, biotic disturbance, animal phenology). These indicators are classified into two dimensions according to their relationship with the climate and their involvement in the triggering of the climate change process. Other variables that are partially influenced by climate can be strongly controlled by other mechanisms such as land management, ecological stressors (Klos et al., 2015).

Climate change measures may also vary from one area to another depending on climatic characteristics. In the Sahel, agricultural practices are mostly rainfed and climatic variables such as precipitation and temperature can determine climatic variability. Farmers perceive climate change as rainfall decreases because the quantity and distribution of annual and decadal rainfall is highly variable (Branca et al., 2013) and are the main constraints to agricultural development (Sissoko et al., 2011). For example, Eric and Kinda (2016) argue that climate change translates into rainfall variability, drought, floods and extreme temperatures. According to these authors, climate change is measured by the standard deviation of the rate of growth of the water balance (the difference between precipitation and evaporation) and extreme events (drought, floods and extreme temperatures). It should also be noted that, in the Sahel, environmental variables such as desertification and dwindling water supplies are pointed out as threats and it should be added that lack of resources and soil depletion are due to climate change (Heinrigs, 2010). Consequently, changes in rainfall patterns, temperature and / or frequency or severity of extreme events will have direct impacts on crop yields (Sissoko et al., 2011).

1.2.3 Models

Definitions of climate and climate change cover statistical aspects, suggesting the existence of climate models to measure these climatic variations (Stone et al., 2009). Thus, scientists use mathematical and statistical models to analyze the distribution of climate variables. The call to mathematics solves the complex equations derived from these laws. For **?**, the characteristics and the particularity of climate processes leave no room for laboratory experiments, the only way is mathematical modeling, hence the complexity of the definition of climate change. This approach is also shared by Hulme et al. (2009) who argue that the climate can not be measured by our senses or by our instruments such as wind and water. They also support that the climate has several interpretations because it contains a physical definition (the Amazonian climate is more humid than that of the Sahara) and cultural (the

meaning of the climate of the Sahara is totally different for a bedouin than a berliner).
Before enumerating the climatic models developed in the climate literature, we define and describe a climate model. The aim of the section is not to detail climate models in general but we provide a theoretical analysis while evoking the debates built around the modeling of the climate. The IPCC defines a climate model as a numerical representation of the climate system based on the physical, chemical and biological properties of its components, interactions and feedback processes, and the recognition of some of its known properties Pachauri et al. (2014). Currently, there are about 20 climate models that are continually being developed by national modeling centers such as NASA, the UK Met Office and the Beijing Climate Center Bradley et al. (2017). Old climate models were based on moisture and cloud processes, whereas the new models take into account the role of vegetation, forests, grasslands and crops in measuring and controlling the amount of dioxide Carbon in the atmosphere (NAZA, 1998). According to Parker (2006), these models may be competing or compatible, while emphasizing that pluralism in climate modeling combines an ontic competitive pluralism with an integrative pragmatic pluralism. In other words, the ontic dimension concerns the compatibility of hypotheses on what is "the world", whereas the pragmatic dimension concerns the compatibility of models in practice.
Climate models are used as a research tool to study and simulate climate for operational purposes, including monthly, seasonal and interannual climate forecasts (Pachauri et al., 2014). In addition, models can also describe the state of the climate system. For example, the empirical study of climate requires observations and models that provide such data. While the data show that the hottest temperatures have been observed since the 20th century, the models also allow scientists to prove the existence of climate change and to detect the causes of this temperature rise Bradley et al. (2017). In other words, models are relevant tools for characterizing and evoking the causes of climate change.
The models also seek to identify the origin and factors responsible for climate change. Human activities have long been indexed and are considered the main sources of climate change. For that reason, questions about the existence of climate change and its attribution raise problems Bradley et al. (2017), known as the detection problem (Pachauri et al., 2014). Thus, the detection of climate change is defined by the IPCC as a process by which scientists demonstrate that the climate or a climate system has changed, without giving the reason for this change. Moreover, the identified change is detected in the observations if it is established that its probability of occurrence by chance arising only from internal variability is low (Pachauri et al., 2014).
According to Bradley et al. (2017), this definition is inadequate with that of Werndl (2016) which defined climate as a finite distribution over a relatively short period of time. However, this definition is reported by climatologists and scientists to set up statistical tests and hypotheses to detect climatic variation. Climate change is detected when observed values fall outside a predefined range of internal variability (Pachauri et al., 2014). Thus, the tests carried out allow scientists to know whether the detected climate change is due to human activities or other causes. Climate change attribution is a mechanism to assess the contribution of different factors to climate change detected with a statistical confidence level (Pachauri et al., 2014). However, the representation of the climate system can be made differently and by models of different complexity, i.e. they can use a single component or a combination of several components (Pachauri et al., 2014).
For Goosse (2015), climate models should use at least the physical behavior of the atmosphere, ocean and sea ice. In addition, terrestrial carbon cycles, vegetation and Ice

cap are also taken into account, thus giving models of the terrestrial system. This analysis is also shared by Parker (2006) who argue that climate scientists use an approach based on a multitude of models to represent the climate system.

According to Pachauri et al. (2014), climate models are differentiated by the number of spatial dimensions, how physical, chemical or biological processes are considered and their empirical parameterizations. For Rial et al. (2004), the Earth's climate system is non-linear because of the disproportion of inputs and outputs. To this end, climate change corresponds to a sequential process or to episodes where multiple equilibria are the norm. They also consider that the climate system is not really a stationary process, but is subjected to natural and anthropogenic variations in forcing. For Parker (2006), climate models are opposed to one another because of the assumptions made and scientists are unable to announce that one model is better than the other models in a study of future climate change. This difficulty can be explained by the uncertainty that conditions the climate and the difficulties encountered during the assessment of climate models.

To understand and predict climate change, NAZA (1998) proposes the following models. First, socio-economic models that predict the future use of fossil fuels and the use of alternative fuels. These models depend on technology, public policy and social attitudes, economic development, standard of living and the habit of people to resort to energy and chemicals. Then, the psycho-chemical models of the terrestrial system that give an idea of the amount of gas released into the atmosphere. The chemicals and natural processes on the surface of the earth affect the release. Finally, coupled ocean atmosphere models provide information on how the climate system (temperature, humidity, clouds and precipitation) responds to climate change in the composition of the atmosphere (NAZA, 1998; Stone et al., 2009). In addition to these models, others are proposed in the climate literature. We mention here the main ones. Energy balance models (EBMs) or simple models (Stone et al., 2009) were introduced by Budyko (1969) whose objective is to estimate climate change from the energy balance of the earth, considering that the earth as a flat surface with a layer at the top (Bradley et al., 2017). In addition to their simplicity, these models only provide average global values for the calculated variables and provide a good qualitative understanding of the greenhouse effect (Bradley et al., 2017).

Among the models, there are also models of intermediate complexity (EMICs), which are called models of reduced complexity (Stone et al., 2009). They complete the niche between the EBMs and the GCMs. They are simple (Stone et al., 2009) but they always include a geographical representation of the earth (Goosse, 2015; Stone et al., 2009). In other words, these models provide more than averages over the entire land or more vague areas. Furthermore, they include much more degrees of freedom than EMB models (Goosse, 2015) and are used in paleo-climatic applications because of their effectiveness (Stone et al., 2009). On the other hand, EMICs have parameters that are difficult to adjust to reproduce the observed characteristics of the climate system, for example some simpler models, for which reason the level of approximation is chosen considerably between the different EMICs (Stone et al., 2009).

In addition, there are also general circulation models (GCMs) that provide a more accurate and complex description of the climate system (Goosse, 2015). Currently, they are the most commonly used for projections reported in IPCC assessment reports (Stone et al., 2009).

In previous years, the GCMs models only consisted of a representation of the atmosphere, the land surface, sometimes ocean circulation, and a more simplified version of sea ice (Stone et al., 2009). Currently, they take into account several components, and many

newly developed models include sea ice, carbon cycle, ice sheet dynamics and atmospheric chemistry (Stone et al., 2009).
All climate models require several components, and consideration of these components depends on the modeler's goal (Stone et al., 2009). The main components of global studies can be the atmosphere, ocean, sea ice, land surface, marine biogeochemistry, ice sheet and possible coupling between components and Models of terrestrial systems. The effects of climate change are diverse and affect all of humanity. Human, animal and plant species are the main victims of climate problems. They also affect economies and threaten human activities. After elucidating the models assessing climate change, we must identify the main causes and consequences of global warming.

1.3 Climate change and economic activities

In this section, we explain the link between climate change and human activities. First, we explain how human activities and nature affect the climate. Next, we address the effects of this change on human economic activities. Climate change has a significant impact on human health, economic activity and the environment. Finally, we address the channels through which climate change affects a country's economy by delaying economic activity in countries whose agriculture represents an important economic resource.

1.3.1 Causes of climate change

The causes of climate change can be natural (the presence of greenhouse gases in the atmosphere) and / or anthropic (land-use change, the combustion of fossil fuels, sulfate aerosols and black carbon). The discussion will focus on Africa and the Sahel, because according to our research, Africa is the only continent with a high number of droughts and heavy human consequences.

Natural Causes of Climate Change

Climate change can be caused by natural factors such as the El Niño phenomenon, droughts, floods, volcanic eruptions and other natural factors that could alter the climate system. The natural causes of climate change are often caused by water. Scientists are certain of the link between climate change and rainfall variability (Stern, 2008). For example, the majority of the disastrous effects of climate change are manifested through water: glacier melt and floods, droughts, storms, rising ocean levels. Since the 1950s, many changes have been unprecedented for millennia. The atmosphere and ocean have warmed, snow and ice cover has decreased, and sea levels have risen (Pachauri et al., 2014). However, the causes may vary from one geographical area to another.
Natural causes causing drought in Africa have been studied in several studies (Caminade and Terray, 2010; Dai, 2011, 2013; Giannini et al., 2008; Manatsa et al., 2008; Nicholson et al., 2000). These authors have focused on anthropogenic factors to try to explain the causes of drought in Africa. For them, climate change, aerosol emissions, land-use practices, and land-atmosphere interactions are mechanisms for drought induction (Desboeufs et al., 2010; Hwang et al., 2013; Masih et al., 2014). There are also other factors that can lead to drought conditions such as El Niño-Southern Oscillation (ENSO) and SST due to their strong influence on the continent as a whole. These two factors and land-atmospheric feed-back

are the main factors that determine and explain rainfall variability in Africa (Nicholson et al., 2000). The atmosphere is a determining factor in explaining the situation of the terrestrial climate system. For Nicholson et al. (2000), these factors alone or in combination can change atmospheric dynamics and patterns of circulation. For example, they cause changes in Hadley and Walker flows or higher-level stream flows. The results coincide with the work of Rouault and Richard (2005) who have done similar studies but using data on the Normalized Precipitation Index from 1900 to 2004 in South Africa. The results obtained show a strong correlation between droughts and El Niño mechanisms. This is reinforced by the fact that 8 of the 12 droughts that occurred in Southern Africa coincide with the years of the El Niño phenomenon.

By studying the correlation between precipitation and ENSO Nicholson and Kim (1997) asserted that the ENSO mechanism is causing precipitation and on the continent. Moreover, it is at the origin of numerous anomalies in Equatorial and Southern Africa. They also indicate that precipitation is negatively correlated with El Niño in the southern part of Africa. This correlation study was confirmed by Phillips et al. (1998), which showed that during the El Niño Southern Oscillation passage precipitation decreased, thus affecting agricultural production in Zimbabwe.

In southern Africa, droughts occur mostly during the warm El Niño Southern Oscillation Phillips et al. (1998). However, the El Niño mechanism is not the only factor causing drought in Southern Africa, as was the case in the 1970-88 period, there are other explanatory factors (Manatsa et al., 2008; Collier et al., 2008a). For example, droughts from 1950 to 1969 originate in the oceanic and atmospheric anomalies registered in the region.

In analyzing droughts from 1950 to 1988, Richard et al. (2001) argued that the droughts of 1970-1988 were severe and differed from those of 1950 to 1969 and that El Niño was not responsible for the 1925-1926 and 1997-1998 droughts in Southern Africa. As previously discussed, El Niño Southern Oscillation has two phases, one cold and the other warm. In the preceding paragraphs, it is clear that the hot phase that tends to affect Southern Africa. The main cause of drought (2010-2011) in East Africa was the Niña Dutra et al. (2013), which is the cold phase of the mechanism.

In trying to identify the cause of drought, Lott et al. (2013) found that human activities had no effect on short rains and that this drought was exclusively the work of the Niña in the Pacific (Haile, 2005; Tierney et al., 2013). The deficit in precipitation in West Africa is due to the warming of the Indian Ocean and the rise in greenhouse gas and aerosol emissions after the Second World War (Desboeufs et al., 2010; Funk et al., 2008; Williams and Funk, 2011).

Human causes of climate change

Climate change can also be caused by human activities related to logging, agriculture, industrial activities and all other activities that have an impact on the environment.

For Stern (2008), human activities generate greenhouse gas emissions and an increase in the stock of these gases causes global warming, and consequently a change in climate, itself causing serious effects on the economy, human life and the environment. Since the pre-industrial period, population and economic growth have been the two factors that have favored the growth of anthropogenic greenhouse gas emissions reaching a very high level, leading to atmospheric concentrations of carbon dioxide, methane and nitrous oxide for at least 800,000 years. For IPCC, increases in atmospheric concentrations associated with other

anthropogenic factors have been detected throughout the climate system and are highly likely to have been the main cause of warming since the mid-20th century (Pachauri et al., 2014).
Since the 1950s, many changes have been unprecedented for millennia. The atmosphere and ocean have warmed, snow and ice cover has decreased, and sea levels have risen (Pachauri et al., 2014).
From the perspective of economic theory, Stern (2008) argues that greenhouse gas emissions are the cause of climate change and represent "externalities" whose costs are not being paid today and in the future. In other words, climate change is a major market failure, the biggest known to date, and a unique challenge for the global economy.
In addition to greenhouse gas emissions, human activities may also cause a change in precipitation by forcing by aerosol which tends to modulate regional precipitation (Sarojini et al., 2016). Indeed, humans through their various activities, emit greenhouse gases, increasing the stock of gas in the atmosphere and thus causing a rise in temperature (Stern, 2008).
According to Funk et al. (2008) the anthropogenic warming of the Indian Ocean in the late twentieth century has probably already produced extremely dangerous climatic changes by causing droughts and social disruption in some of the world's most fragile food economies. Interactions may be complex. For instance, sahelian precipitation drops when the Atlantic Ocean north of the equator is cold and the south of the equator is hot (Caminade and Terray, 2010).
Many studies (Caminade and Terray, 2010; Lebel and Ali, 2009a) noted that the most recent and severe droughts in the Sahel have been caused by warming of the ocean (Atlantic Ocean and Indian Ocean) and a southward shift of inter-tropical convergence zone. Furthemore, Zheng and Eltahir (1997) have shown that there is a particular link between vegetation and climate in the Sahel. They claim that land and atmospheric fallout through natural vegetation and land cover change are also important factors.
Monsoon simulations of West Africa with a simple zonally-symmetric model, Zheng and Eltahir (1997) have argued that "that the potential impact of human induced change of land cover on regional climate depends critically on the location of the change in vegetation cover". The authors also obtained results on the impact of deforestation depending on the geographic location. They argue that desertification at border with the Sahara leaves a relatively minor impact on monsoon circulation and regional rainfall and this situation concerns Chad, Niger, Mali and Mauritania. However, deforestation along the southern coast of West Africa is likely to result in a complete collapse of moonsoon circulation and a significant reduction in regional rainfall, and includes Nigeria, Ghana and Côte d'Ivoire (Zheng and Eltahir, 1997) .
The relationship between climate and vegetation explains why atmospheric circulation, and therefore precipitation, on West Africa may be sensitive to changes in vegetation cover near the desert border (Zheng and Eltahir, 1997). Furthemore, human activities inducing greenhouse gas emissions are considered a contributing factor to global warming Dai (2013) and also cause drought in Africa (Touchan et al., 2011). Haile (2005) argue that the precipitation model in sub-Saharan Africa is influenced by the high variability of the intra-seasonal and inter-annual climate, including occasional El Niño events in the tropical Pacific, often resulting in extreme weather events such as droughts and floods.
In an attempt to identify the chemical composition of rainfall in Niger, Desboeufs et al. (2010) indicated that biogenic emissions have a strong influence on the composition of

rainfall on the Sahel during the rainy season. They also indicate that there is a strong influence of dust and a limited marine or anthropogenic contribution. The anthropogenic cooling of aerosols in the northern hemisphere is the main cause of change in the atmosphere (Hwang et al., 2013).
The climatic changes induced by natural and anthropological causes that we have mentioned have multiple and difficult consequences. Climate change is causing considerable changes to the environment, the economy and human life, and other climate variables. The economic consequences are variable at the regional and global levels. We provide some details on this issue in the following paragraph.

1.3.2 The economic consequences of climate change

This section aims to explain how climate change can affect the economy of a country or region. The consequences of climate change may vary depending on the situation and level of development of a country. For example, the number of drought listed by Masih et al. (2014) had negative effects but the severity is different on the five continents.

In this section, we focus on the impact of droughts and floods, which have the most catastrophic climatic consequences (human losses, material and economic damage). On the one hand, flooding is defined by the IPCC (2012) as the overflow of normal boundaries of a watercourse, or the accumulation of water over areas that are not normally submerged. On the other hand, two types of drought are to be distinguished, a meteorological drought that is considered a period with an abnormal precipitation deficit while a megadrought is a very long and pervasive drought that lasts much longer than normal, usually a decade or more. Then, we will link climate change, human health and economic activity. There is a strong link between the three aspects. Human activity is conditioned by good health and a enabling environment.

Impact of floods and droughts on the economy

Floods and droughts are the consequences of climate change (water-related), which have significant effects on economies, agricultural production (Haile, 2005), infrastructure and on the population of a country. While it is difficult to quantify the damage caused by climatic shocks, the typical shock in a developing country reduces annual GDP by about 0.4 percent (Collier et al., 2008a; Pachauri et al., 2014).

Flooding has serious repercussions on infrastructure, particularly on the road network, which is currently unpaved and therefore particularly vulnerable to flooding erosion (Collier et al., 2008a). Consequently, the poor state of the road infrastructure hinders the movement of goods and people within a country. With sea-level rise, IPCC forecasts indicate that most coastal and low-lying areas will be highly vulnerable to flooding and erosion in the 21st century and beyond (Pachauri et al., 2014). In addition, the IPCC (2012) defines drought as an abnormally dry period of time leading to severe hydrological imbalance. It is also defined by Masih et al. (2014) as a repetitive climatic phenomenon affecting the world by causing loss of life, crops, food shortages. These effects can lead to famine in many regions and countries, malnutrition, human mortality, health problems and mass migration.

The available scientific studies do not provide sufficient geospatial and long-term temporal coverage of past drought events at the global and continental levels. Drought impacts are observable at different geographical scales and the damage depends on the initial situation of the region or country concerned (Masih et al., 2014) .

In examining droughts and aridity around the world, Dai (2011) reported that large-scale droughts occurred during the last century worldwide, causing considerable human and economic damage. North America and China also experienced severe and multi-year droughts from 1900 to 2013, causing enormous damage, affecting families or individual communities, resulting in loss of life 12 million people died and 2 billion (Masih et al., 2014). Africa has also experienced many severe long-term droughts, such as the drought of 1999-2002 in northwest Africa, droughts of the 1970s and 1980s in West Africa (Sahel), the drought of 2010-2011 in East Africa (Horn of Africa) and 2001-2003 in drought in the south and south-east of Africa, and many other droughts (Masih et al., 2014). Drought losses include livelihoods and water sources, and cause enormous damage to water resources (acute food shortage) and, during these periods, the health status of the population deteriorates due to lack of nutrition (Masih et al., 2014; Muller, 2013). Many regions of Africa will suffer from droughts and floods as global warming is likely to increase their frequency and intensity. For example, the Sahel countries may be more humid or dry (Collier et al., 2008a) and the Sahel has recorded several droughts several decades since the last glaciation (Brooks, 2004).

Droughts are one of the main causes of migration in developing countries and the Sahel in particular. The severe droughts of the Sahel in the 1910s, 1940s, 1960s, 1970s and 1980s caused enormous socio-economic and environmental impacts in this semi-arid region, resulting in massive migration, famine and desertification (Masih et al., 2014).

Touchan et al. (2011) argue that changes in precipitation and the frequency and duration of drought may be characteristic of anthropogenic climate change that directly affects human populations. This idea is shared by Funk et al. (2008) who argue that rural development in Africa has stalled and African rural poverty has developed in the 1990s. Over the past decades, Africa has experienced significant population growth and the population is unable to addressing climate change issues. Africa's progress towards the Millennium Development Goals is limited (Haile, 2005). For example, water demand is increasing, water sources are limited and climate change and climate models exacerbate the effects of drought around the world (Masih et al., 2014; Pachauri et al., 2014). It is also considered by the IPCC (2012) as a period marked by a rise in temperature and a decrease in precipitation. Many crops in Africa are grown near their thermal tolerance limits. A rise in temperature at the approach of flowering may affect crop yields such as wheat, fruit trees, peanuts and soybeans (Challinor et al., 2007).

Such extreme weather risks becoming more frequent with global warming, creating a high annual variability in crop production. However, higher temperatures and prolonged periods of drought will force large areas of marginal agriculture out of their production. Corn harvesting over most of southern Africa is already experiencing drought stress every year Collier et al. (2008a). Precipitation plays a major role in determining agricultural production and thus the economic and social well-being of rural communities (Haile, 2005) and the poor distribution of precipitation has considerable economic effects.

Being an indicator of climate change, drought can be explained by the number of human losses, crop failures, manulification, health problems and migration (Masih et al., 2014).

Climate change, human health and economic activities

While the effects of droughts and floods seem to predominate, there are also other significant effects of climate change. Climate change has significant economic costs and economic impacts on vulnerable countries and economic sectors, slowing economic growth, impeding poverty reduction efforts and increasing food insecurity (Pachauri et al., 2014). Haile (2005) estimates that extreme events can have long-term adverse effects on households ability to have sustainable access to food and the environment.

For example, agriculture is the most important activity in Africa. The sector employs more than 60% of the population and can account for more than 50% of GDP in some regions. Although agriculture accounts for a small share of GDP in the United States, the United States continues to be the largest producer and exporter of agricultural products in the world (Schlenker and Roberts, 2009). The difference between these two continents lies in the level of economic fundamentals and the degree of economic diversification. Indeed, the consequences of climate change on agriculture result in lower agricultural incomes, unemployment of the agricultural population and economic loss at the country level. All these consequences are linked to the decline in agricultural production (Sissoko et al., 2011). For example, over the last decade, anthropogenic climate change has led to rising temperatures and some rainfall irregularities with increases in precipitation in northern Europe and decreases in parts of southern and eastern Europe (Olesen et al., 2011).

The economic impacts of climate change are enormous because African economies are not diversified and a large part of the population is active in agriculture. This trend is not favorable when the agricultural sector is affected by climate change. At the macroeconomic level, the reallocation of factors across sectors has been more limited than in other regions of the world. Africa remains heavily dependent on the same narrow range of commodity exports as other sectors do not offer opportunities (Collier et al., 2008a). At the microeconomic level, technical progress has been slower than in other regions, both on farms and in manufacturing (Collier et al., 2008a). The intersectoral issue is that climate change will detract Africa's comparative advantage from agriculture (Collier et al., 2008a). Agriculture remains rainfed and traditional in most African countries and to address climate change (Collier et al., 2008a; Haile, 2005), transferring agricultural resources from sectors or activities that are less vulnerable to climate change. Menawhile, the industry sector is weakly developed with less developed domestic markets. Collier et al. (2008a) finds that African economies have not shown a high degree of adaptability even though households have considerable experience in tackling temporary shocks, this defensive flexibility has not been combined with sustained capacity at adapt to new circumstances or adopt new technologies. Higher temperatures and higher maximum temperatures will also affect health (Collier et al., 2008a; Haile, 2005). High peak temperatures (above 30°C) will increase mortality, especially in large agglomerations, although the effect is modest in the general context of African mortality (Collier et al., 2008a).

For Pascual et al. (2006), the effects by the disease are likely to be higher due to the strong correlation between climatic variables and the mosquito population. For example, geographic distribution and rates of mosquito development are strongly influenced by temperature, precipitation and humidity. There has been a resurgence of malaria in the highlands of East Africa in recent years as the temperature in the highlands of East Africa has increased by 0.5 ° C since 1980, rapidly than the world average. Many factors are likely to be involved: poor implementation of drug treatment, drug resistance, land-use

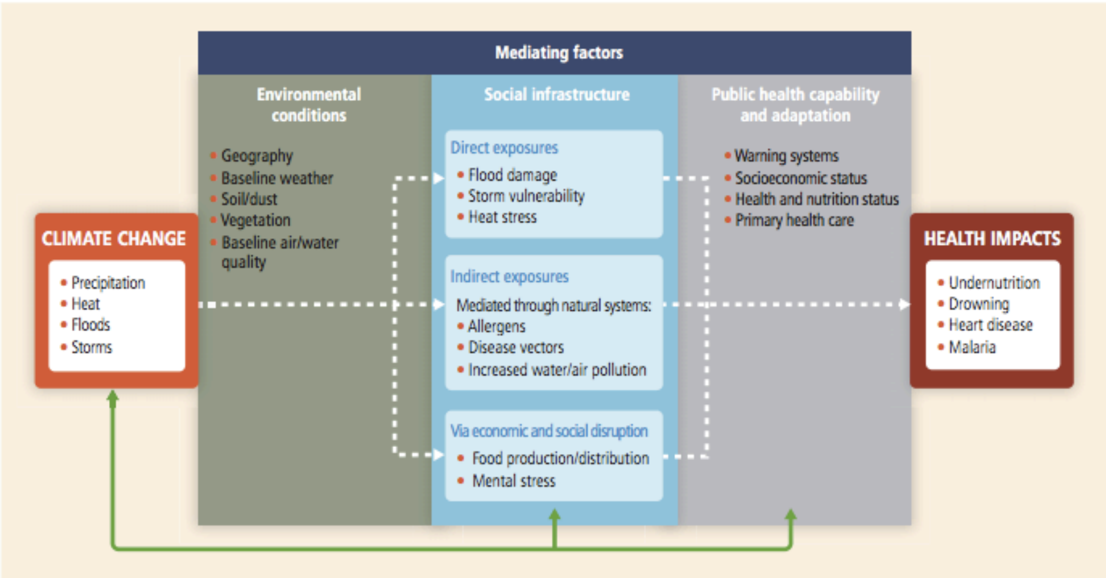
change and various sociodemographic factors, including poverty, but there is also a strong correlation with climate change. Malaria already has an enormous impact on Africa, in addition to the direct health effects Collier et al. (2008a), it reduces incomes by two thirds and a 10% reduction is associated with a 0.3% (Gallup et al., 1999). For Collier et al. (2008a), the rise in global temperatures will in turn lead to an increase in sea level, one meter or more by the end of the century. Such an increase would affect some 6 million people in the Nile delta. In addition, IPCC forecasts indicate that human pressure on ecosystems is expected to increase in the coming decades due to population growth, economic development and urbanization, and costs will represent several percentage points of their gross domestic product (Pachauri et al., 2014). Agricultural activities will be limited due to the poor health of the agricultural population. In addition to affecting climatic conditions, climate change increases disease and reduces the size of the inactive agricultural population.
After citing the causes and consequences of climate change, it is necessary to identify the factors or indicators through which global warming affects the economy and economic activities of a given country or region.

1.3.3 The channels of transmission of climate change

In this section, we establish and develop the link between climate change and a country's economy. In other words, we are trying to identify the means by which global warming affects a given economy directly or indirectly. This link can be explained at the macroeconomic and microeconomic level.
At the aggregate level, variables can affect the level of production in a country or region by lowering agricultural yields and limiting economic growth (Abidoye and Odusola, 2015; Dell et al., 2008). At the micro level, these effects can be explained by the level of physical productivity, conflict and health of the workforce (Abidoye and Odusola, 2015).
For its part, the IPCC identifies three ways in which climate change can affect human health. If humans are sick, the economy is also indirectly affected because they are unable to carry out activities to boost the economy. For instance, Gallup et al. (1999) points out that malaria reduces labor productivity in some countries and slows economic growth by about 1% per year in sub-Saharan Africa. Beyond a certain level, climate change can increase malaria by 10% (McMichael et al., 1996).
Thus, the level of a nation's agricultural production can be explained by the health of farmers and animals (social welfare). Traditional agriculture and mechanism require better health of farmers. This vision is supported by Fankhauser and Tol (2005), the fact that the economic effects of climate change are generally measured to the extent that the climate of a given period affects social welfare during this period. Climate change can affect human health in three ways.
First, climate change (thunderstorms, floods, air pollution, etc.) can directly affect human health. Exposure of humans to extreme events leads to serious health problems that can lead to death. Lack of adaptation means that human losses in some areas are high. Second, climate change can affect human health through the ecosystem. The presence of mosquitoes carrying diseases in some countries results from the effects of climate change. We can also cite the rise in temperature and the pollution of the water resources (river, sea and lake) used by the population. Third, climate change can affect human health through changes and activities by humans on the environment. To satisfy their needs, humans develop actions such as agriculture, animal husbandry and construction. Conflicts and wars between men

lead to massive displacements, leading to the exhaustion of labor in conflict zones (Bouley and Rabie, 2017).
Exposure pathways by which climate change affects human health are plotted by Smith et al. (2014) in the following 1.2. The green column of the figure 1.2 shows the effects of environmental conditions on how a given population may be exposed to the effects of climate change. The gray columnn indicates how provisions such as basic public health and socioeconomic conditions can play a role in real health produced by the three types of exposure. The green arrows at the bottom of the figure 1.2 show the existence of feedback

Figure 1.2Three primary exposure pathways by which climate change affects health



Source: Smith et al. (2014)

mechanisms (positive or negative) between societal infrastructure, public health, adaptation measures and climate change itself. Establishing adaptation mechanisms can increase the resilience of populations, limit human and economic losses (Smith et al., 2014).
In the literature, several studies have been made at different scales (continent, region and country) to explain the link between climate change and economic growth. In general, climate change affects economic growth considerably. Based on a standard neoclassical growth theory, Fankhauser and Tol (2005) identified the channels of transmission through which climate change can affect economic growth. For the authors, capital accumulation and saving are the two dynamic channels through which climate change is likely to affect a country's long-term economic growth. Indeed, the prospect of future damage (or benefits) also affects the accumulation of capital and the propensity of economic agents to save, and thus the rate of economic growth. This conception refers to the idea that economic agents are risk-averse, because in the presence of risks they change their behavior. In addition to these two channels, they cite another potential channel of transmission that is the rate of accumulation of human capital. Therefore, climate change affects social welfare i.e. the rise in temperature does not promote learning and negatively impacts the workforce (degradation of health). Dell et al. (2008) used the annual variation in temperature and precipitation over the last 50 years to assess the impact of climate change around the world. They obtain three main results, which differ according to the level of development of each country. First, the rise in temperature has a different impact on countries. It causes a decline

in economic growth, but it has no effect on the developed countries. Secondly, a high level of temperature rather decreases the rate of growth than the level of production. Finally, rising temperatures affect poor countries by reducing agricultural production, industrial production and overall investment, and increasing political instability in poor countries. The precipitation analysis gives the opposite result to temperature, Dell et al. (2008) estimates that rainfall does not adversely affect a country's economic growth despite its level of economic development. This result is similar to that obtained by the same authors, analyzing the relationship between temperature and income in 12 countries in America, Dell et al. (2009) argue that there is a negative relationship between temperature and income in these states.

Using an economic simulation model, Fankhauser and Tol (2005) conclude that, in the long term, climate change can effectively reverse the trend of economic growth and reduce per capita income. For example, for a global warming of 3°C, direct damage to the economy is estimated at least 15% of GDP.

Based on annual data for 34 countries over the period 1961 to 2009, Abidoye and Odusola (2015) analyzed econometrically the impact of climate change in Africa. They argue that the economic landscape of most African countries depends crucially on the dynamics of climate change because of the role of climate on the economic growth of countries. Any rise in temperature will decrease economic growth in African countries.

Using data on temperature and precipitation from 1970 to 2009 for a sample of 18 countries in sub-Saharan Africa, and using the econometric technique of cointegration of panels of long-term and short-term effects of climate change on growth, **?** argue that temperatures above 24.9°C would significantly reduce economic performance in these countries. These effects are also observable at the individual country level. Using a cointegration analysis on Ethiopia, Ali (2012) finds a negative effect on growth, while changes in rainfall magnitude and rainfall variability have long-term drag effects (long-term Drag effects) on the production level. **?** analyzed econometrically the effect of climate change on agricultural productivity over the period 1980 to 2005 in Nigeria, based on a cointegration model approach. The results show that the change in temperature generates a negative effect whereas the change in rainfall has a positive effect on agricultural productivity.

After this review of the literature on climate change and its link with the economy sphere, in the following sections, we precede statistical modeling that focuses on both countries and agroecological zones. This modeling makes it possible to answer empirically on the existence of the phenomenon of climate change in the countries of the Sahel.

1.4 Study area and data

1.4.1 Study area

This section presents the countries and the agroecological zones of the Sahelian band.

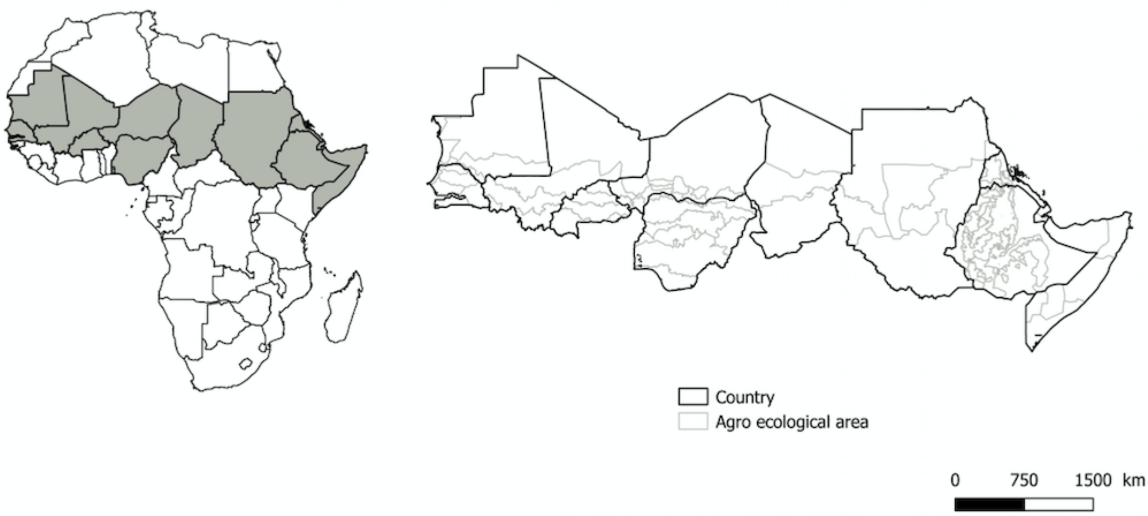
Definition and construction of the Sahelian band

The Sahel, as defined by Permanent Interstate Committee for drought control in the Sahel (CILSS), covers nine countries: Mauritania, Senegal, Gambia, Guinea-Bissau, Mali, Burkina Faso, Niger, Chad and Cape Verde, with a total area of 5,400,000 square kilometers and a population of nearly 60 million (Sissoko et al., 2011). However, the Sahel is difficult to delimit because it is composed of several sub-Saharan African countries bordered by a similar climatic zone. The West African Sahel is defined as a semi-arid range of grasslands, shrubs and small thorny trees located just south of the Sahara desert (Nicholson, 2013; Sissoko et al., 2011). According to Nicholson (2013), the Sahel extends about 5,000 kilometers from the east-west extent of Africa and the Sahara to the wet savanna at about 10 ° North. It includes Mauritania, Senegal, Mali, Niger, Chad, Sudan and the northern parts of Burkina Faso and Nigeria.

Our definition of the Sahel is different from that of the CILSS, and consists of the sum of the two definitions given by Nicholson (2013) and Sissoko et al. (2011). More precisely, we have selected countries with the same climatic characteristics (variation of weather conditions, variable and hot climate, uncertain rainy seasons, famine, food insecurity, regular occurrence of floods and droughts) and countries bordered by the desert and those whose sensitivity to climatic shocks are similar.

Thus, our Sahel (see figure 1.3) includes 6 countries in West Africa (Burkina Faso, Mali, Mauritania, Niger, Nigeria and Senegal), 5 East African countries (Djibouti, Eritrea, Ethiopia, Somalia and Sudan) and 1 country in Central Africa (Chad). In these countries, agriculture and livestock are the main sources of economic wealth and agricultural activity remains the main source of subsistence for the majority of people living in the region (Sissoko et al., 2011). The 12 countries forming the Sahelian band are the most vulnerable

Figure 1.3 Perimeter of study



Source: Calculations and achievements by the author

in the world. In addition to the great climatic variability, they face civil wars, mass migration (internal or external), and terrorism that create lasting instability. Faced with all these difficulties, the fields are deserted, the farmers take flight and take refuge far from their field. As in recent decades, these countries have seen unprecedented population growth, their economic inconsistency accentuates the problem of food self-sufficiency. The population is increasing, agricultural production stagnates or is trending downward.

Presentation of agroecological zones

The analysis of climate change and variability is also interesting at a smaller scale: the agroecological zone. Since 30 years, FAO has put in place a global system of agroecological zones which is defined as a method to measure the potential of agricultural land productivity. In other words, it characterizes climate, soil and land conditions relevant to agricultural production. This method has led to the design and identification of agroecological zones. We share FAO's definition of agroecological zones as country-specific land resource mapping units in the world. They are built on the basis of country-specific climate, soil and vegetation cover characteristics. This characterization is specific because it also looks at the potentials and constraints for land use. Within each country, there are agroecological zones, the number and characteristics of which vary from one country to another. Table 2.2 gives the names and number of agroecological zones for each country. Despite their belonging to the Sahelian belt, the 52 agroecological zones

Table 1.1Presentation of agroecological zones

Country	Number	Name
Burkina Faso	4	North Sahel, North Soudania, South Sahelian, South Soudania.
Chad	3	Desert area, Sahelian zone, Soudanian zone.
Djibouti	3	Coastal plains, Interior plains and low altitude, Mountain and Valleys zones.
Ethiopia	7	Arid agroecology, Humid agroecology, Moist agroecology, Per humid agroecology, Semi-arid agroecology, Sub-humid agroecology, Sub-moist agroecology.
Mali	4	Saharan zone, Sahelian zone, Soudanian zone, Sudano guinean zone.
Mauritania	4	Arid zone, Maritime zone, River zone, Sahelian zone.
Niger	5	Saharan zone, Saharo-sahelian zone, Sahelian zone, Sahelo-Sudanian zone, Soudanian zone.
Nigeria	6	Derived savanna, Humid forest, Northern guinea savanna, Sahel savanna, Southern Guinea Savanna, Sudan Savanna.
Senegal	6	Bassin arrachidier, Casamance, Centre East and South East, Niayes, Sylvopastoral zone, Valley of the reiver.
Somalia	5	Bari, Bay and Bakool, Coastal central and southern Somalia, Shabelle and Juba Valleys, Somaliland.
Sudan	5	Dense Savannah and Equatorial Zone, Desert and Semi-arid desert zone, Flood and Basin irrigated zones, Jebel Marra zone, Poor and Dense savannah zone.

Source: Identification and construction of agroecological zones by the author using data and information.

have specific individual characteristics. As we will see, they are distinguished by their area, the temperature recorded and the seasonal precipitation or the quantities of water received annually. They can also be distinguished by the start and end dates of the rainy seasons

and by their agricultural practices, the cropping system (irrigated or rainy) and the types of crops used. The period of sowing and harvesting can be heterogeneous.
The analysis of rainfall and temperature at the level of the 52 agroecological zones makes it possible to study, on the one hand, climate change and variability in the 12 countries. On the other hand, it is also a question of establishing a ranking of the countries, that is to say to esatablish a distinction between the countries in which there are no marked differences between the zones and those which present remarkable differences.

1.4.2 Data

To uncover the phenomenon of climate change and variability in the Sahel, we use two main climate variables: temperature and precipitation. The analysis concerns two different scales distinguished by the study period and the sources of the data.
The first analysis covers 12 countries (Burkina Faso, Chad, Djibouti, Eritrea, Ethiopia, Mali, Mauritania, Niger, Nigeria, Senegal, Somalia and Sudan) for the period 1901-2012 and the second one covers the 52 agroecological zones of the countries selected (except Eritrea, see below) for the period 1901-2016. Our climate data sources come from the Climate Research Unit (2016). At the country level, we extracted monthly average data from the World Bank Climate Change Knowledge Portal. The monthly data are extracted from the database of the Royal Netherlands Meteorological Institute (KNMI) which explores data on climate and climate change.
The temperature and precipitation data available from these two databases are data expressed as monthly averages. Regarding the analysis of agroecological zones and in the absence of data at this level, we used R and QGIS to process, construct and map the agroecological zones of each country in the Sahel based on the information provided by the Food and Agriculture Organization of the United Nations. After the construction, we obtained the masks of the geographical coordinates of each agroecological zone of each country which allowed to reconstruct the temperature and precipitation data at the level of the agroecological zones. However, we were not able to produce agroecological maps of the Eritrea due to the lack of data and information on the shapes and perimeters of agroecological zones for this country.
Given the scope of this thesis, we constructed climatic variables that can be linked to agriculture because this sector is dominant in these countries[1]. In particular, we focus on temperatures and precipitations during the dry and the rainy seasons. In the Sahel, the dry season is variable but is between September and May in most countries. It is characterized by the absence or the weakness of rains. On the other hand, the rainy season is the growing season which is the period when agriculture is practiced in the Sahel because the soil is wet because of the high rainfall. Seasonal rainfall therefore plays a crucial role (Maharana et al., 2018).
Specifically, from the average monthly temperature, we computed 6 temperature variables built according to the seasons: minimum annual temperature (i.e. the average monthly temperature of the coldest month of the season), annual median temperature (i.e. the average monthly temperature of the season), maximum annual temperature (i.e. the average monthly temperature of the hottest month of the season) for both the dry and rainy season.

[1]The agricultural sector employs about 80% of the Sahelian population and is the main source of consumption and income of Sahelian households. Agricultural activities account for between 60% and 100% of the income of the poorest African households (Davis et al., 2010)

The computation and analysis of the annual median, the annual minimum and the annual maximum temperature provides a good idea of the distribution of this variable both in terms of central tendency and dispersion. From the average monthly precipitations, we computed total annual precipitation and seasonal mean precipitation.
In total, at the country level, we have 112 annual observations for precipitation and temperature variables and 116 annual observations for agroecological zones. Table 1.2 describes the variables used in this analysis of climate change in the Sahel. It provides an overview of precipitation and temperature indicating the source, period and frequency of these variables. Table 1.3 presents the descriptive statistics of our 8 climates variables.

Table 1.2Description of variables used

Variables	Description and source	Period	Frequency
Temperature	Temperature values are measured at the level of countries and agroecological zones. We compute minimum temperature, median temperature and maximum temperature for both the dry and rainy seasons. Country-level data were produced by the University of East Anglia (UEA) Climate Research Unit (CRU) and are available on the World Bank Climate Change Knowledge Portal. Data at the level of agroecological zones were constructed based on data from the Royal Meteorological Institute of the Netherlands.	1901 to 2012 / 1901 to 2016	Temperature is provided for each month, we use this data to compute and transform the values of these quantities into data at an annual frequency for the dry and rainy seasons.
Precipitation	Rainfall values are measured at the level of countries and agroecological zones. We compute total annual precipitation and mean seasonal precipitation (vegetative period). Precipitation is obtained from the same databases as temperature.	1901 to 2012 / 1901 to 2016	Rainfall is also provided in monthly data. We use these values to compute total annual precipitation and seasonal precipitation.

Table 1.3Descriptive statistics of climate data.

Climate variables	Country level		Agroecological level	
	Mean	Std. Dev.	Mean	Std. Dev.
Precipitation				
Total precipitation	468.09	320.38	619.37	444.52
Seasonnal Precipitation	80.73	51.69	103.08	70.11
Temperature				
Minimum temperature of rainy season	27.63	2.90	26.66	3.65
Median temperature of rainy season	29.01	2.55	27.84	3.68
Maximum temperature of rainy season	30.42	2.42	29.68	3.79
Minimum temperature of dry season	22.29	2.12	22.73	2.84
Median temperature of dry season	26.18	1.64	26.05	3.01
Maximum temperature of dry season	30.01	2.54	29.87	4.00
Countries	12			
Agroecological zones	52			

1.5 Methodology

Our aim is to see whether countries have experienced this phenomenon of climate change and the period from which these countries began to register these climatic variations. The aim is not to predict future precipitations and temperatures but to observe the evolution of the temperatures and precipitation during the period (1901 to 2012, for countries and 1901 to 2016 for agroecological zones) and to find potential structures or subperiods using econometric (statistical) techniques to find endogenous ruptures. To that purpose, we present in this section the methodology of linear models with fixed effects and structural change models.

1.5.1 Pooled model with country effects

In order to detect climate change, we first use a simple pooled panel linear statistical model with a measure of climate change as the dependent variable and time as the main dependent variable with heterogeneous coefficients. The implementation of this model is done on two spatial scales: 12 countries with annual observations ranging from 1901 to 2012 and 52 agroecological zones with annual observations ranging from 1901 to 2016. The specification is as follows:

$$y_{it} = \sum_{i=1}^{N} \alpha_{1i} + \sum_{i=1}^{N} \alpha_{2i} year_t + \epsilon_{it} \tag{1.1}$$

where y_{it} is the dependent variable (annual median temperature, annual minimum temperature, annual maximum temperature of the dry and rainy seasons, total annual precipitation and seasonal annual precipitation) for area (country or agroecological zone) i at time t; $year_t$ is the variable representing the year of observation. We then have $N = 112\ observations \cdot 12\ countries = 1344\ global\ observation$) at the country level and $N = 116\ observations \cdot 52\ zones = 6032\ global\ observations$ at the agroecological zones level. ϵ_t represents the error term. The effect of climate change is assessed by the marginal effect of y_{it} over $year_t$, ie α_{2i} . This marginal effect varies over areas if the estimates of α_{2i} are significantly different from each other, which can be test for by a simple F-test. Furthermore, if the area fixed effects α_{1i} are significantly different from each other, then the intercept significantly differ between areas.

1.5.2 Structural change model

The structural change model allows endogenous detection of structural breaks in the coefficients in time series. We base our analysis on (Bai and Perron, 1998, 2003) who developed procedures for detecting ruptures in the longitudinal data and the necessary associated statistical tests. Generally, the structural change test is defined naturally for longitudinal data (Bai and Perron, 1998), the principle is to estimate the relationship between the dependent and the independent variables and to verify whether the nature of the relationship changes over the period. Wald-type tests are used to test models with multiple structural changes by formulating the null structural non-change hypothesis ℓ versus the alternative hypothesis containing an arbitrary number of changes denoted $\ell + 1$. This procedure then corresponds to a specific general modeling strategy that allows to endogenously determine the appropriate number of changes in the data. One drawback of this procedure is the problem associated with hypothesis testing under multiple changes Bai and Perron (2003) as is the case with the present empiric application.
Formally, consider the regression for a single area (country or agroecological zone, therefore omitting the index i) over the period. We then consider the following linear regression with m breaks ($m + 1$ regimes):

$$y_t = z_t^{'} \delta_j + \epsilon_t \qquad t = T_{j-1} + 1, ..., T_j \tag{1.2}$$

for $j = 1, ..., m + 1$. In this model, y_t is the observed dependent variable at time t; $z_t(q \times 1)$ is the vector of covariates (corresponding to the constant term and the coefficient associated

to the trend in our case) and δ_j ($j = 1,...,m+1$) is the corresponding vector of unknown coefficients to be estimated including α_1 and α_2; ϵ_{it} is the disturbance for area i and at time t. The indices ($T_1,...,T_m$), or the break points, are explicitly treated as unknown (we use the convention that T_0 and $T_{m+1} = T$). The purpose of this econometric approach is then to estimate the unknown regression coefficients with the break points when the T observations on (y_t, x_t, z_t) are available. Moreover, the variance of u_t needs not be constant: breaks in variance are possible provided that they occur on the same dates as the breaks in the regression parameters. For each possible partition of the data, the model is then estimated using OLS and the best model is selected *via* a cross-validation procedure. This procedure then allows to detect both changes in the intercept and in the trend.
From a practical point of view, the implementation of this model can be summarized by the following ideas: i) the objective of this second model on structural change is to strengthen the previous econometric analysis, ii) the idea behind this model is to detect the sub-periods using econometric techniques to find the breaks endogenously, iii) then, one must appreciate the evolution of the temperature and precipitations and visually mark the obvious and flagrant breaks and iv) finally, the graphical observation must correspond to the theoretical analysis relating to the evolution of the two variables used: search for the historical explanation of the breaks.

1.6 Application on different countries

In this section, we first estimate the models as in equation 2.2 to see if intercepts and trends are significantly different across countries. We also produce graphs for each climatic variables (temperature and precipitation) and each country to show their evolution over time and empirically verify the existence of climate change in the Sahel countries using a simple linear model and a structural change model. Climate change often results in higher temperature and lower rainfall. In addition, we discuss the results obtained with the structural change model proposed by Bai and Perron (2003) in order to identify breaks or sub-periods in the countries of East Africa, which to the best of our knowledge is the first analysis of this type.

1.6.1 Pooled model with heterogeneous coefficients

The estimation results are presented in table 1.4. For each indicator, we provide at the bottom of the table the results of the homogeneity tests : homogeneity of intercept across countries ($H_0 : \alpha_{1i} = \alpha_1$) and homogeneity of slopes across countries ($H_0 : \alpha_{2i} = \alpha_2$). The null hypothesis is rejected for all climate variables meaning that both the intercepts and the slopes differ. This can be explained by the fact that although we have grouped countries that have a similar climatic situation, forming the Sahelian bloc, these countries still have different configurations and differ from each other in their geographical position and the size of their national territory. For example, some countries are landlocked without access to the sea and some countries have large or small inland water areas and openings to the sea. Furthermore, as we show later, within a country, the climate is very variable and the composition of the landscape is also different. This can be explained by the varying number of agroecological zones (see table 2.2) within a country.
The extent of a country can also be the source of heterogeneity because the climate seems to be contrasted in countries with a large territorial area. For example, Nigeria receives

a significant amount of rain because the country has four rainy seasons spread all over its territory. Indeed, the temperature varies within the agroecological zones. In Niger, the desert represents a large part of the national territory, which explains the fact that the country records high temperatures and low annual rainfall. This characteristic is also observable in Mauritania, the national rainfall is very low accompanied by intense heat. It should also be noted that the presence of forests or savannas has a significant impact on the average temperature at the country level.
All these elements justifies a country-by-country analysis that we carry out in the following sections.

1.6.2 Temperature

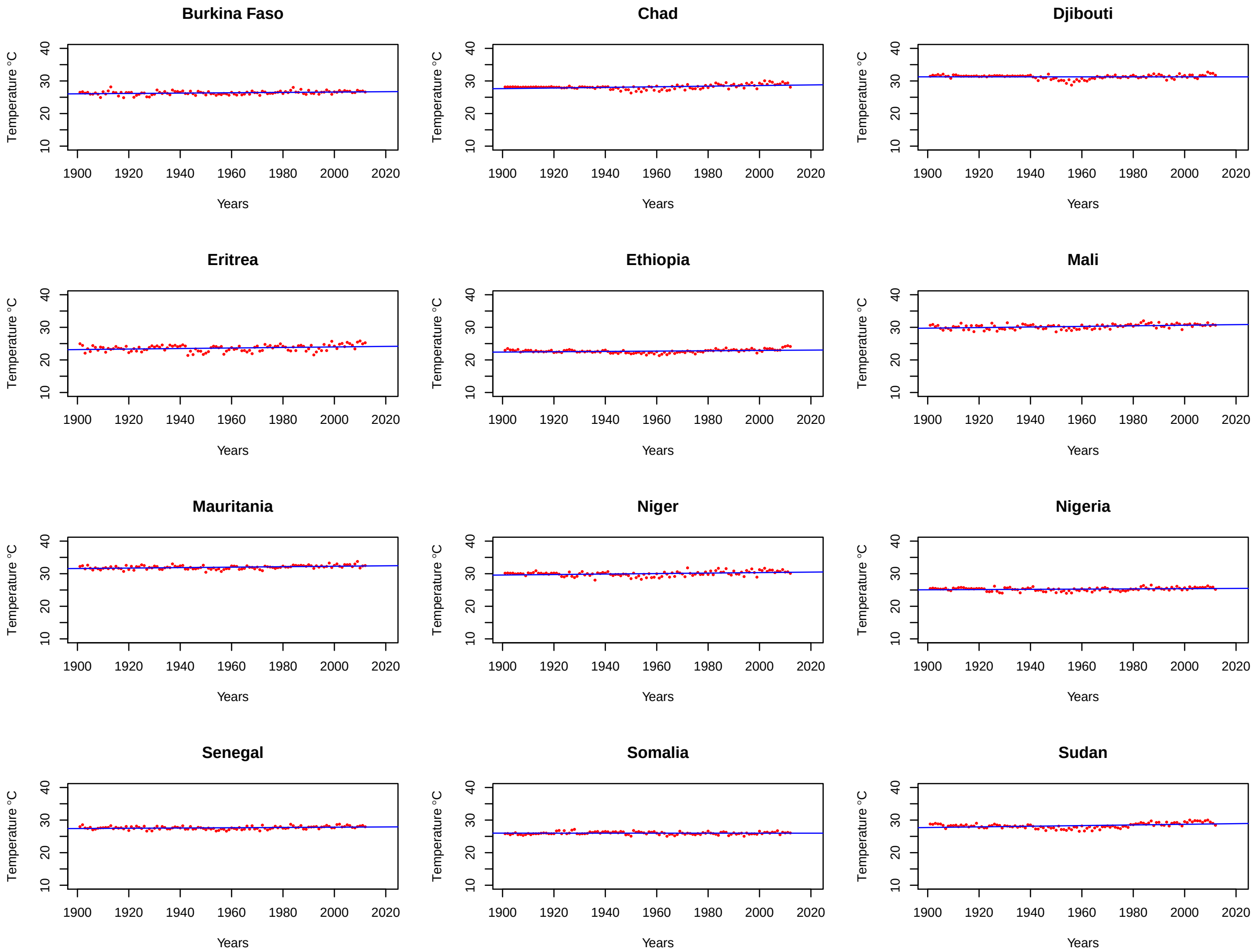
Figures 1.4, 1.5, 1.6, 1.7, 1.8 and 1.9 provide a graphical overview of the evolution of the temperature over the period 1901 and 2016 in the Sahel countries. These graphical representations concern the median, minimum and maximum temperatures, respectively, during the dry and rainy seasons. We comment on the graphs by grouping countries according to the trend of the temperature variables, which makes it possible to make a comparison between the countries.
Looking first at temperature in the rainy season, the series of graphical trends illustrated in figures 1.4, 1.5 and 1.6 show the evolution and interannual variability of the minimum, median and maximum temperature during the rainy season from 1901 to 2016 in the Sahel countries. The representations in figure 1.4 show that countries have experienced a distinct increase in the trend of annual minimum temperature during the rainy season. In addition, this increase is accompanied by a small annual variability but remarkable in some countries over the entire period. Three groups of countries emerge from the analysis of figure 1.4 and estimation results in table 1.4. First, eight countries (Burkina Faso, Chad, Eritrea, Ethiopia, Mali, Mauritania, Niger, Senegal and Sudan) experienced a significant increase in temperature minimum during the rainy season over the entire period. There is a gradual increase in the minimum temperature during the rainy season at the beginning of the period, but it increased from the 1980s for both groups of countries. Second, for Nigeria, the slope coefficient indicating change in minimum temperature during the rainy season is only significant at 10% . Finally, Djibouti and Somalia did not experience a significant rise in minimum temperature during the rainy season. Most these countries have a minimum annual temperature during the rainy season of between 30 and 40 over the entire period.
Figure 1.5 shows the annual median temperature during the rainy season in the 12 Sahelian countries. We see that there is an interannual evolution and variability of the median temperature during the rainy season. The latter has gradually increased but the year 1980 constitutes an important turning point. Three groups of countries also stand out with respect to their trend and interannual variability.
The first group made up of Chad, Djibouti, Eritrea, Ethiopia, Mauritania, Niger and Sudan, experienced a very remarkable and significant uptrend of the median temperature throughout the period. Then Mali experienced a significant but less important increase in median temperature over the period. Finally, the slopes for Burkina, Nigeria, Senegal and Somalia are not significant, showing there was no change during the period for these countries with respect to median temperature in the rainy saison.
In comparison with the two previous climatic variables, the analysis of the graphical series in figure 1.6 and estimation results in table 1.4 shows that the maximum temperature has

Table 1.4Regressions results with country fixed effects

	Dependent variable: Climate variables							
	TempminRain	TempmedRain	TempmaxRain	TempminDry	TempmedDry	TempmaxDry	RainSum	RainSeason
Burkina	15.693***	23.992***	20.227***	15.222***	11.258***	18.567***	2,138.647***	420.053***
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Chad	9.728***	10.386***	11.909***	22.721***	15.335***	10.859***	443.341	89.890
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Djibouti	31.401***	22.148***	23.516***	17.810***	18.353***	17.431***	−16.364	117.699*
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Eritrea	7.775**	11.788***	16.410***	14.739***	12.302***	4.723	855.250**	11.912
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Ethiopia	12.822***	14.340***	6.643**	11.035**	12.371***	9.543***	1,607.414***	247.479***
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Mali	12.547***	25.599***	13.446***	4.447	−2.703	10.375***	1,284.374***	314.934***
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Mauritania	18.336***	21.196***	16.286***	3.719	−9.030**	8.505**	393.009	100.260
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Niger	15.455***	20.209***	19.740***	20.551***	16.174***	21.987***	368.249	106.570
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Nigeria	18.449***	22.285***	22.563***	25.639***	16.862***	17.379***	2,445.411***	260.903***
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Senegal	19.772***	23.784***	20.510***	7.900*	13.782***	7.905**	4,398.572***	1,134.395***
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Somalia	26.161***	24.097***	20.957***	20.018***	27.699***	21.485***	−11.388	0.729
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Sudan	8.902**	11.943***	13.011***	9.120**	−0.112	2.721	729.066**	165.253**
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
year.Burkina	0.005***	0.002	0.005***	0.005**	0.009***	0.007***	−0.682***	−0.129***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.176)	(0.036)
year.Chad	0.009***	0.010***	0.010***	−0.001	0.006***	0.010***	−0.049	−0.004
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.176)	(0.036)
year.Djibouti	−0.0001	0.005***	0.005***	0.003	0.004**	0.007***	0.108	−0.046
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.176)	(0.036)
year.Eritrea	0.008***	0.008***	0.007***	0.004*	0.007***	0.012***	−0.310*	0.008
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.176)	(0.036)
year.Ethiopia	0.005***	0.005***	0.009***	0.005**	0.005**	0.008***	−0.445**	−0.081**
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.176)	(0.036)
year.Mali	0.009***	0.003**	0.010***	0.008***	0.015***	0.012***	−0.480***	−0.120***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.176)	(0.036)
year.Mauritania	0.007***	0.006***	0.009***	0.008***	0.018***	0.012***	−0.148	−0.040
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.176)	(0.036)
year.Niger	0.007***	0.006***	0.007***	−0.001	0.005**	0.005***	−0.093	−0.029
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.176)	(0.036)
year.Nigeria	0.003*	0.002	0.004**	−0.001	0.004**	0.005***	−0.656***	−0.068*
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.176)	(0.036)
year.Senegal	0.004**	0.002	0.005***	0.008***	0.007***	0.012***	−1.842***	−0.492***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.176)	(0.036)
year.Somalia	−0.0001	0.002	0.004**	0.003	−0.0004	0.004*	0.136	0.019
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.176)	(0.036)
year.Sudan	0.010***	0.009***	0.009***	0.006***	0.014***	0.14***	−0.147	−0.041
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.176)	(0.036)
Observations	1,344	1,344	1,344	1,344	1,344	1,344	1,344	1,344
R^2	1.000	1.000	1.000	0.999	0.999	1.000	0.989	0.984
Model	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS
Global Test of homogeneity								
Fisher-test	1656.7***	1009.8***	1281.7***	1286.2***	1063.4***	403.41***	275.16***	861.07***
P-value	(<0.001)	(<0.001)	(<0.001)	(<0.001)	(<0.001)	(<0.001)	(<0.001)	(<0.001)
Test of homogeneity of intercept								
Fischer-test	3.9661***	3.2159***	2.4829***	2.7014**	6.641***	3.1578***	13.755***	18.787***
P-value	(<0.001)	(<0.001)	(0.0044)	(0.0019)	(<0.001)	(<0.001)	(<0.001)	(<0.001)
Test of homogeneity of slope								
Fischer-test	3.5839***	3.0556***	2.1068***	2.4968***	6.7388***	3.3793***	9.134***	14.253***
P-value	(<0.001)	(<0.001)	(0.0174)	(0.00418)	(<0.001)	(<0.001)	(<0.001)	(<0.001)

Note: *p<0.1; **p<0.05; ***p<0.01

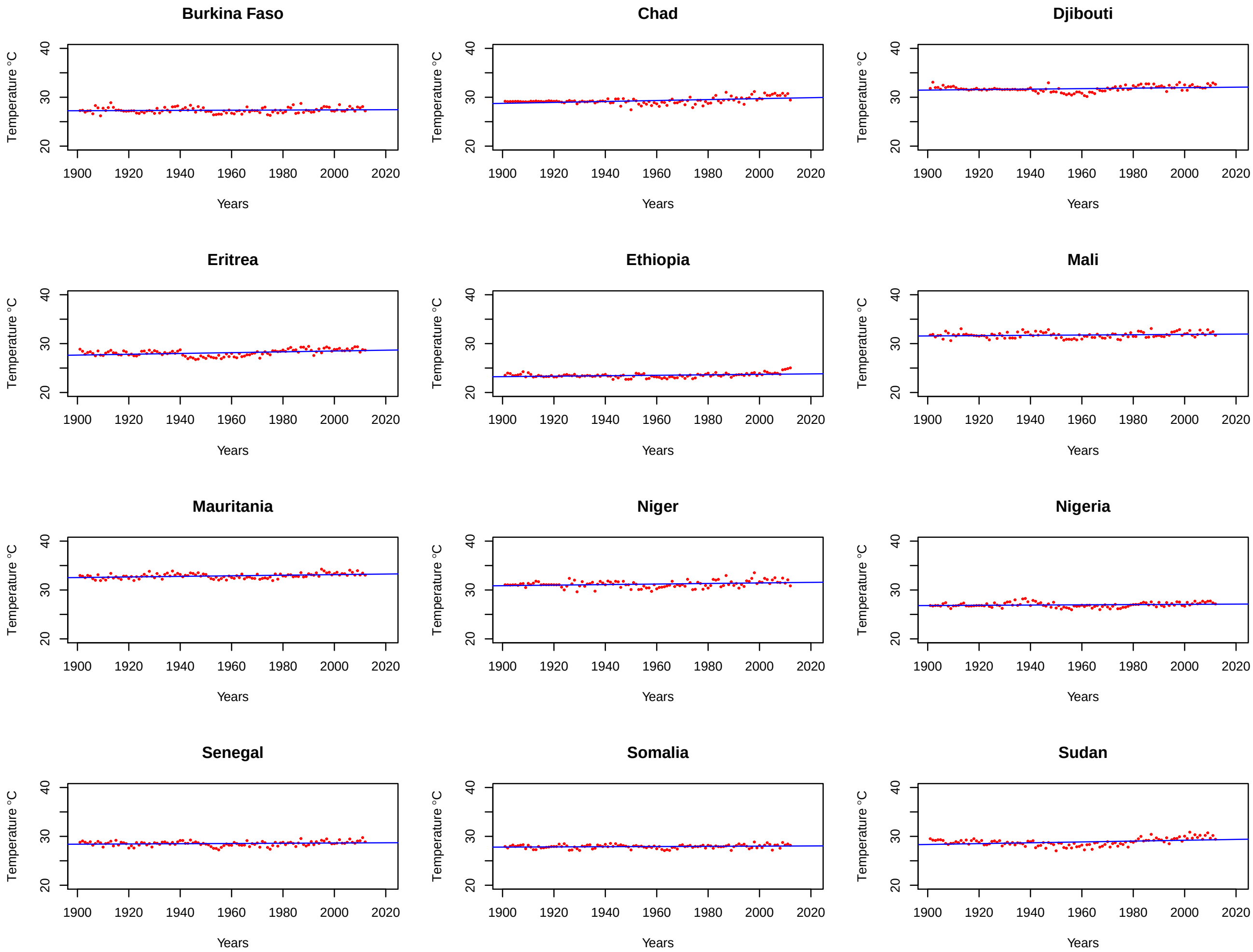
Figure 1.4Minimum annual temperature during the rainy season in the Sahel countries from 1901 to 2016



Source: Calculations and achievements by the author.

risen sharply and has had an significant upward trend over the entire period and for all countries. Graphically, the year 1980 also seems as a turning point of the evolution of the maximum temperature during the rainy season in the countries forming the Sahelian band. Figures 1.7, 1.8 and 1.9 show the evolution of the 3 variables related to temperature during the dry season. The corresponding estimation results appear in the last three columns of table 1.4. Figure 1.7 shows the graphical representation of the annual minimum temperature during the dry season in the Sahel countries. Three groups of countries appear. The first group of countries consists of the countries (Burkina, Ethiopia, Mali, Mauritania, Senegal and Sudan) which experienced a sharp increase and year-to-year variability in the minimum temperature of the dry season over the period. The second group is formed by the countries (Eritrea and Sudan) which also experienced an increase of the same variable but less than that of the countries of the first group. Finally, the last group consists of Chad, Djibouti, Niger, Nigeria and Somalia. Unlike the countries of the first two groups, these countries did not experience a significant increase in the minimum annual temperature during the dry season over the entire period. In general, the minimum annual temperature

Figure 1.5Annual median temperature during the rainy season in the Sahel countries from 1901 to 2016



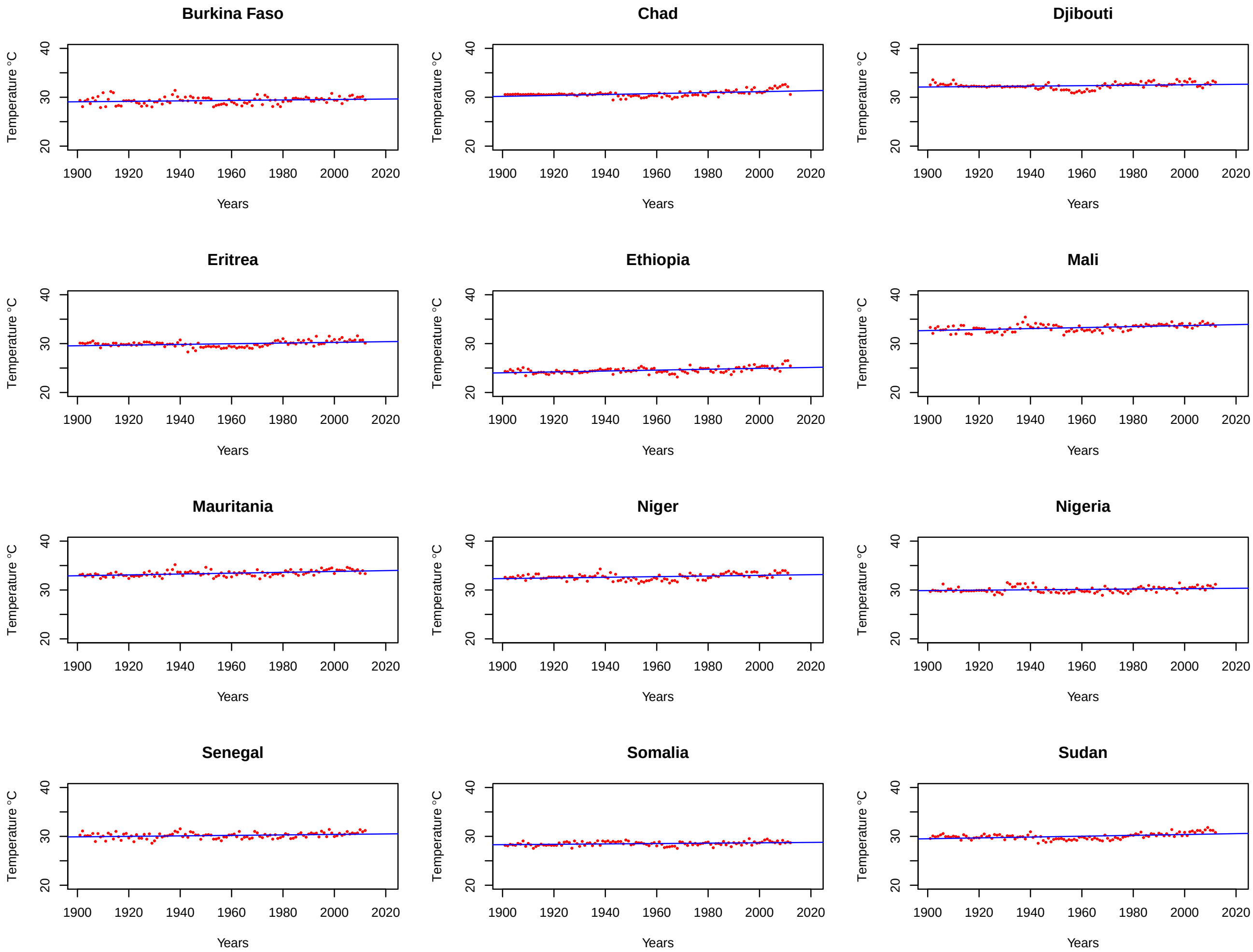
Source: Calculations and achievements by the author.

is very variable during the dry season compared with the rainy season. This distinction can be explained by the length of the season and the fact that during the dry season the Sahel countries record higher temperatures.

In contrast to the median temperature of the rainy season, that of the dry season (see figure 1.8) significantly increased in all countries but distinctively, except in Somalia where it is not significant. It has also increased, but less so in Niger and Nigeria, but with greater interannual variability than in the other 9 countries. The graphical analysis shows the period of change is around the year 1980 as it was the case for the other variables above. Figure 1.9 shows the graphical representation of the maximum annual temperature during the dry season in the Sahel countries. The graphical analysis clearly shows that all countries experienced a strong and significant increase in maximum temperature during the dry season in all countries, slightly in Nigeria and not remarkable in Somalia. This increase is accompanied by remarkable year-to-year variability over the entire analysis period.

Overall, the results do not allow to reject the hypothesis of a significant increase in temperature during the vegetative and dry season for all countries over the entire period.

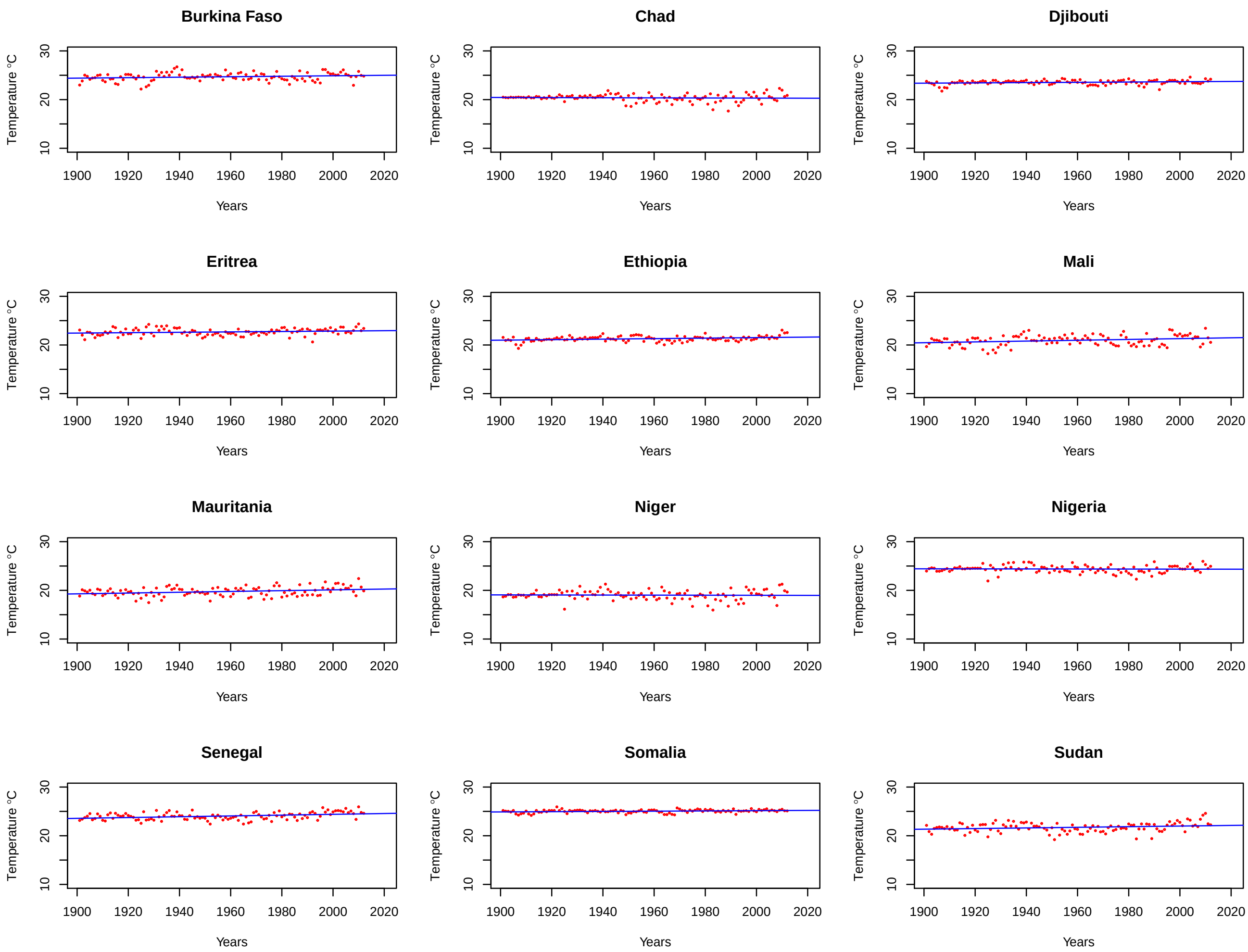
Figure 1.6Maximum annual temperature during the rainy season in Sahel countries from 1901 to 2016



Source: Calculations and achievements by the author.

Globally also, the maximum annual temperature during the rainy season is higher than that of the dry season over the entire period and for all countries in the Sahel. As a result, the hypothesis that the Sahel countries are experiencing global warming is valid.
We now turn to the analysis of structural change using the six variables we have constructed. The results of our structural analysis are graphically represented in figures 1.10, 1.11, 1.12, 1.13, 1.14 and 1.15. For the change in minimum temperature during the rainy season of table 1.10, all countries experienced at least one break over the entire period. Chad and Djibouti experienced individually three shocks related to this variable but at different times with a periodically similar shock around the 1980s. Next, Ethiopia, Nigeria, Niger and Somalia each experienced two shocks at different times but with the year 1980 is an important turning point in the explanation of these breaks. Finally, Burkina Faso, Mauritania, Senegal and Sudan experienced only one shock but at the same time ie in 1980. For most countries, the year 1980 marks a turning point in the rise of temperatures and thus appears as a period of rupture and change. The results therefore confirm those obtained by (Nicholson, 2013) that the West African Sahel is well known for the severe droughts that

Figure 1.7Minimum annual temperature during the dry season in Sahel countries from 1901 to 2016



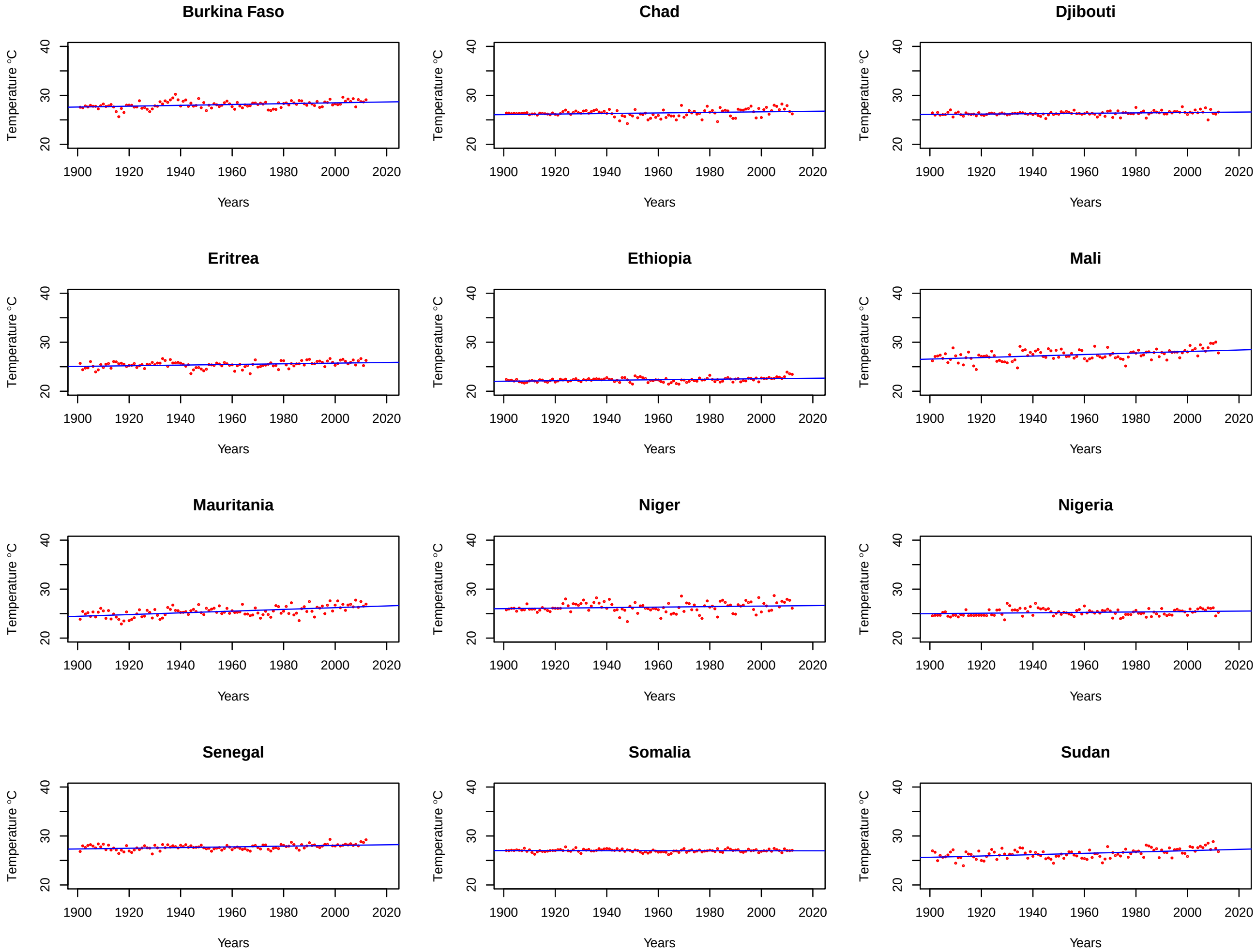
Source: Calculations and achievements by the author.

ravaged the region in the 1970s and 1980s. We find that the countries of West Africa are experiencing the same number of breaks. This reasoning is also valid for East Africa except for Sudan, which has only one break reported around 1980.

Figure 1.11 shows that countries independently experienced several periods of disruption due to changes in median temperature during the rainy season. Chad, Ethiopia, Eritrea and Mauritania each experienced three breaks at almost similar periods with 1980 as the reference year. Djibouti, Sudan and Senegal each experienced two shocks at similar periods, and 1980 also emerges for all these countries. Niger experienced only one shock and Somalia did not experience any observable shock related to this variable over the entire period. There is no particular pattern related to geographical proximity.

Figure 1.12 shows the ruptures related to the maximum temperature during the rainy season in all countries. Chad, Mali, Mauritania, Eritrea, Niger, Nigeria and Somalia each had three shocks that occurred at different times. Unlike other countries where the year 1980 is an important starting point, Somalia has experienced two shocks before the 1980s. This country is known for its situation because the country faces cyclical dryness. Masih et al. (2014) reported that Somalia experienced 13 breaks between 1900 and 2013. In addition,

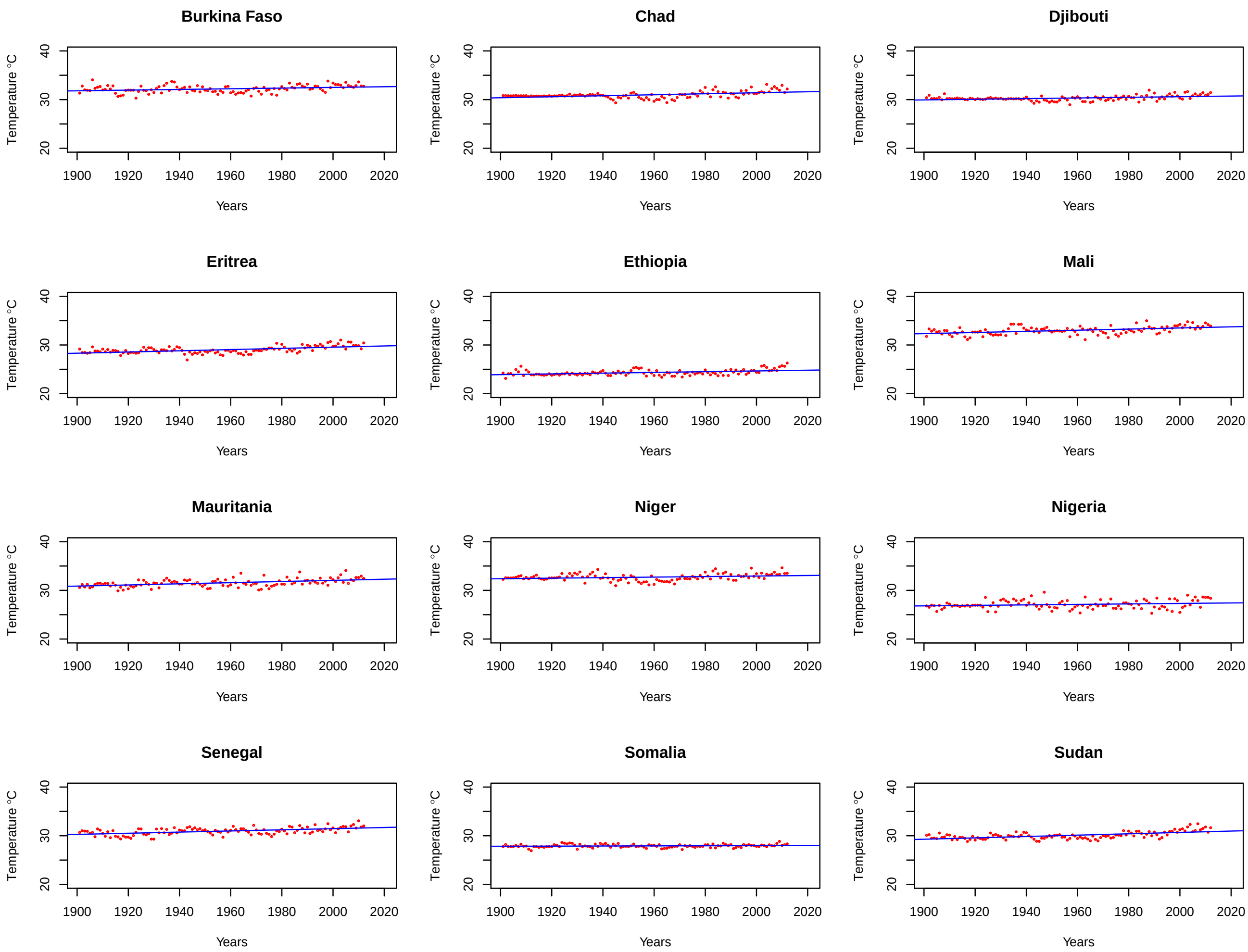
Figure 1.8Annual median temperature during the dry season in Sahel countries from 1901 to 2016



Source: Calculations and achievements by the author.

Djibouti experienced a single break-up period related to maximum temperature during the rainy season over the entire period. Finally, Burkina Faso, Ethiopia, Senegal and Sudan experienced only one shock related to this variable as shown in figure 1.12.
Structural change model results identifying temperature-related breaks during the dry season are presented in figures 1.13, 1.14 and 1.15.
Mali and Somalia each experienced 3 sub-breaks associated with the change in minimum temperature during the dry season over the entire analysis period. Chad, Ethiopia and Niger each experienced 2 sub-periods associated with the evolution of the variable from 1900 to 2013. Djibouti, Mauritania, Sudan and Senegal experienced only one break-up period due to the change in minimum temperature during the dry season over the entire period. Figure 1.13 also indicates that shock periods are distinguished by their period of occurrence: most countries recorded these shocks after the 1980s except for Burkina Faso, Ethiopia, Somalia and Djibouti, which each experienced a shock early in the period. The countries are distinguished by the number of shocks and their period of occurrence. Chad and Sudan experienced the same shock at the same time. Nigeria is the only country that has not experienced a shock related to temperature change during the dry season.

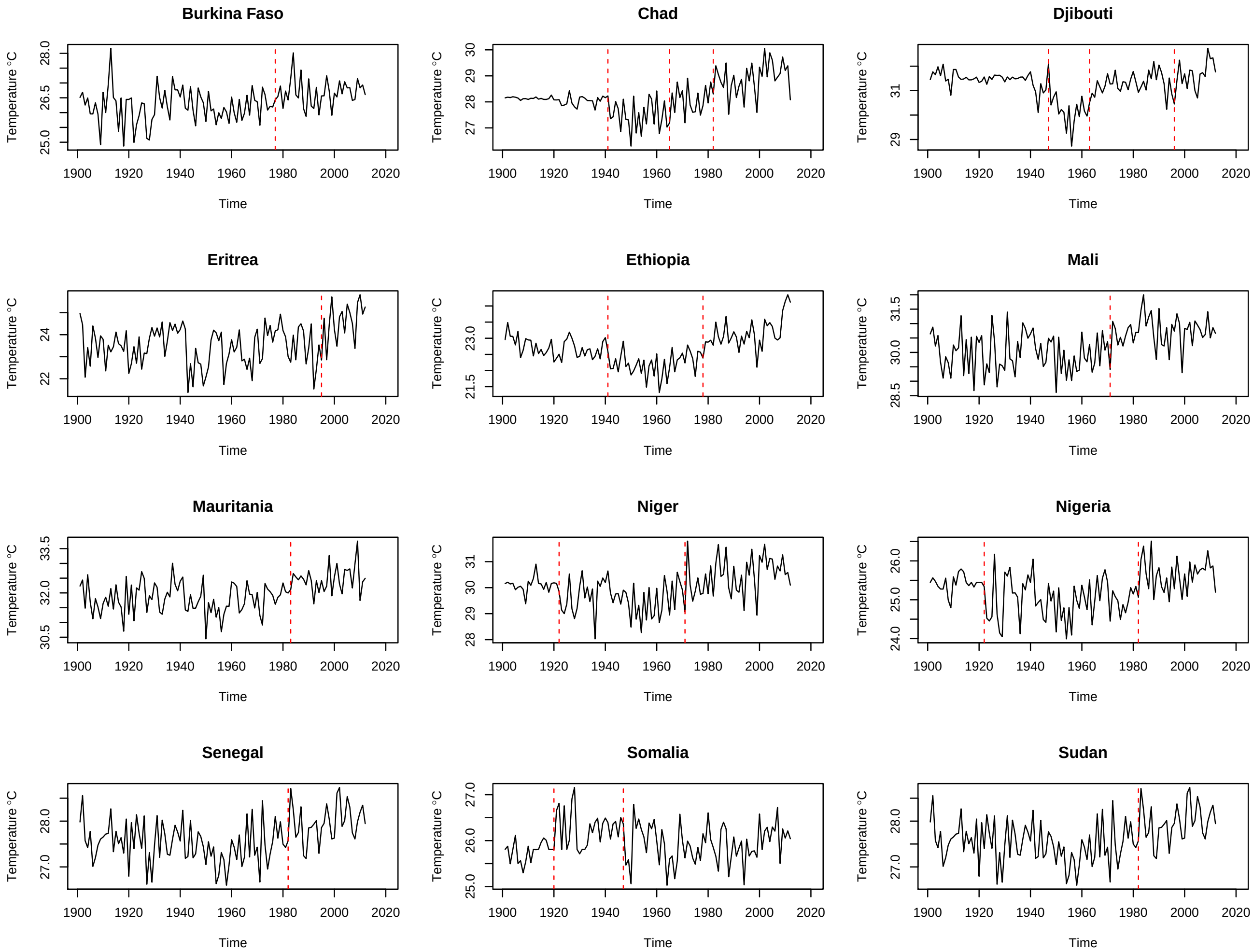
Figure 1.9Maximum annual temperature during the dry season in Sahel countries from 1901 to 2016



Source: Calculations and achievements by the author.

The results of the analysis on the endogenous detection of ruptures related to the evolution of the median temperature during the dry season are represented graphically in table 1.14. It shows that Burkina Faso, Chad, Niger and Nigeria have each experienced 3 ruptures identified between 1900 and 2015 at different times. Then, Mali, Mauritania and Somalia each experienced two breaks at different times. Finally, Djibouti, Eritrea, Ethiopia and Senegal experienced only one shock over the period but at different times. Overall, the 12 countries experienced at least one shock around the 1980s, despite the fact that Burkina, Chad, and Niger recorded ruptures at the beginning of the period.
Figure 1.15 shows the results of the identification of endogenous ruptures on the evolution of the maximum temperature during the dry season in the Sahel countries. We show that Eritrea experienced four shocks and Chad and Mali experienced three shocks at different periods. Before the 1980s, Eritrea experienced three-quarters of these shocks which explains why there have been major changes in the evolution of the maximum temperature during the dry season in this country. Next, Mauritania, Senegal and Sudan also experienced two identified shocks each at different times. In these countries, shocks started at almost similar periods in the 1920s and 1980s, which are the key period in explaining climate change

Figure 1.10Endogenous detection of structural breaks in annual minimum temperature in the Sahel countries during the rainy season from 1901 to 2012.

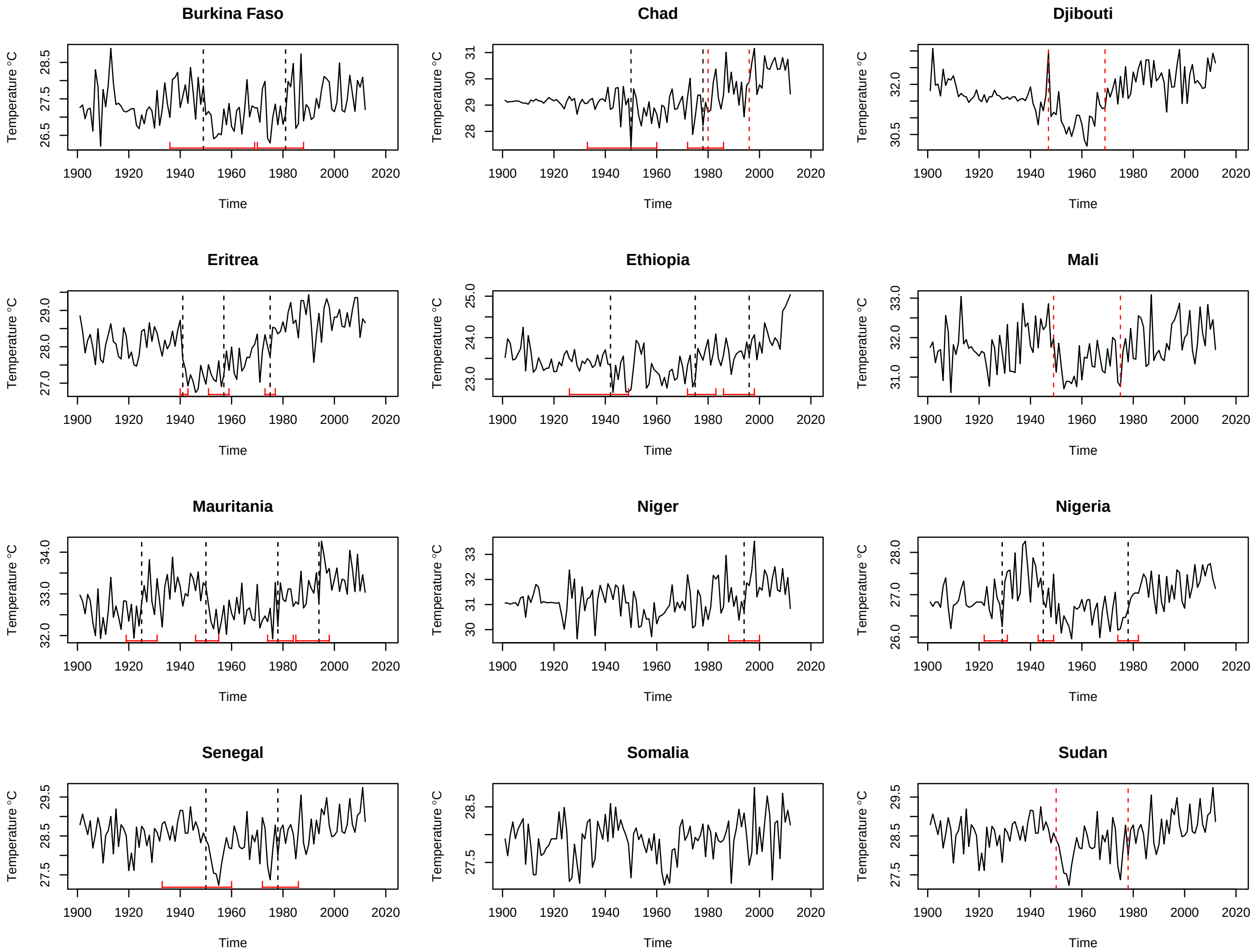


Source: Calculations and achievements of the author.

in the Sahel. Then, Burkina Faso, Djibouti and Ethiopia experienced only one shock that occurred during the period, i.e. in 1980. Finally, Nigeria and Somalia are the countries that experienced no known shock due to the change in maximum temperature during the dry season over the entire period, as shown in tabl 1.15.

Table 1.5 summarizes the number of shocks that Sahelian countries recorded over the entire period based on variables constructed over the two seasons. We now relate our results to the main results found in the literature. Drought is one of the main consequences of climate change in arid countries. It is manifested by an increase in temperature and water deficits(Masih et al., 2014). The results of our temperature-based analyzes show that the temperature variables are gradually increasing according to the seasons and according to each country. This rise in temperature causes dryness and the extension of desertification (Rajaud and de Noblet, 2017), making the sub-Saharan climate drier. Drought and other effects of climate change are causing significant economic and human damage to households (Auffhammer, 2018; Masih et al., 2014). Drought varies in terms of occurrence, intensity, duration and geographical coverage (Masih et al., 2014). Norrgård (2014) explains that

Figure 1.11Endogenous detection of structural breaks in annual median temperature in the Sahel countries during the rainy season from 1901 to 2012.



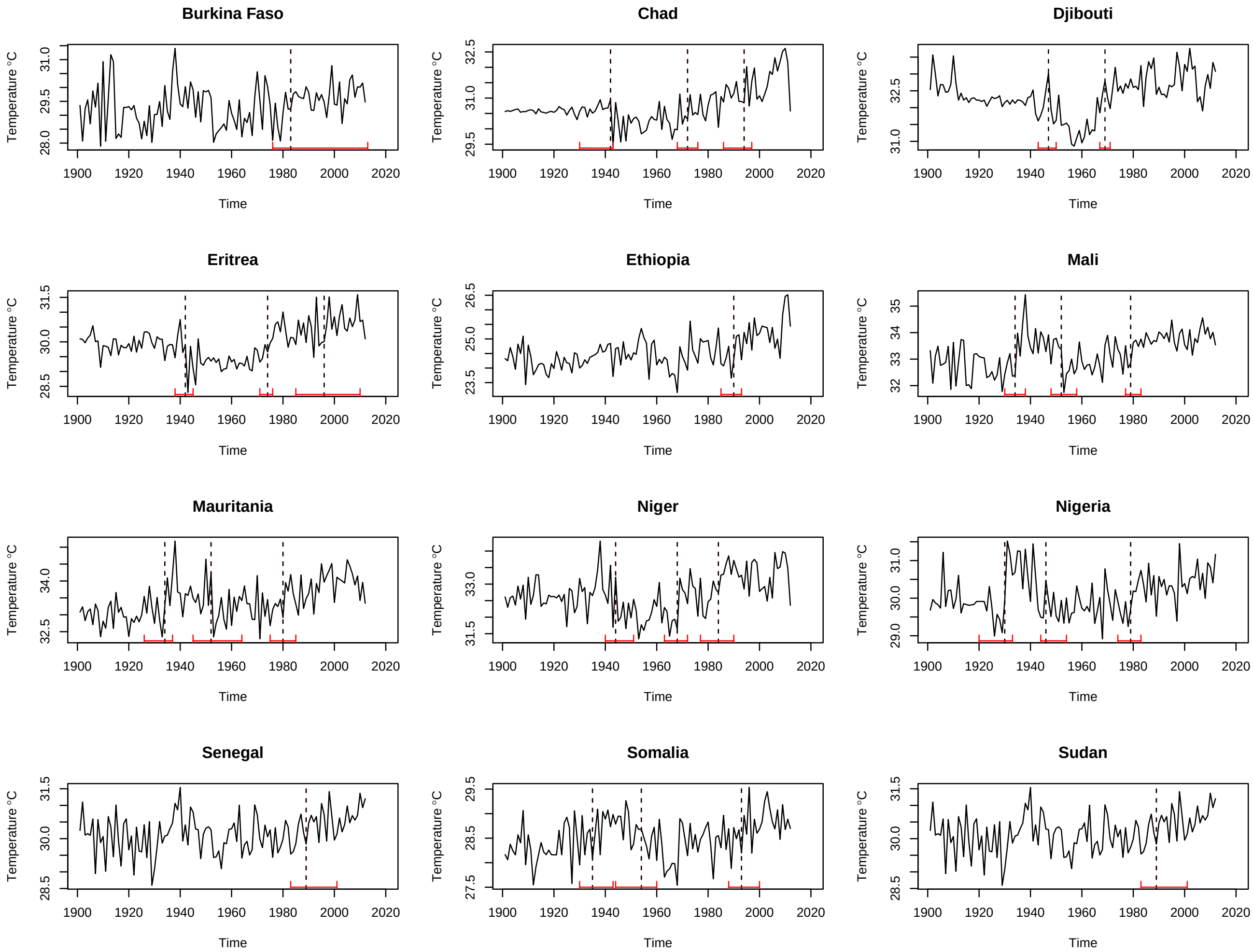
Source: Calculations and achievements of the author.

climate change started well before the beginning of the period of our study. For the author, the most pronounced climatic changes occurred in the 1780s and 1790s. The recent warming observed since the 1980s coincided with the drying trends observed throughout Africa, including in the Ethiopian region, over the period 1950-2008 Dai (2011).

The analyzes of Masih et al. (2014) show that between 1901 and 2013 Mali experienced 11 dryness and without any human loss. The first drought occurred in 1910 and the next two in 1940 and 1966, an average frequency of about thirty years. The other eight droughts occurred in 1976, 1980, 1991, 2001, 2005, 2006, 2010 and 2011. The graphical analysis shows that between 1960 and 2012, the temperature increased considerably, confirming the historical analysis of the occurrence droughts.

West African countries are experiencing severe drying caused by climatic variations. In Mauritania, Masih et al. (2014) report that 12 droughts occurred between 1900 and 2012, affecting more than 7 million people and causing monetary damage estimated at more than 59 million USD (Masih et al., 2014). The first two droughts occurred simultaneously in Mali and Mauritania (1910 and 1940) and the other 10 in 1965, 1969, 1976, 1978, 1980,

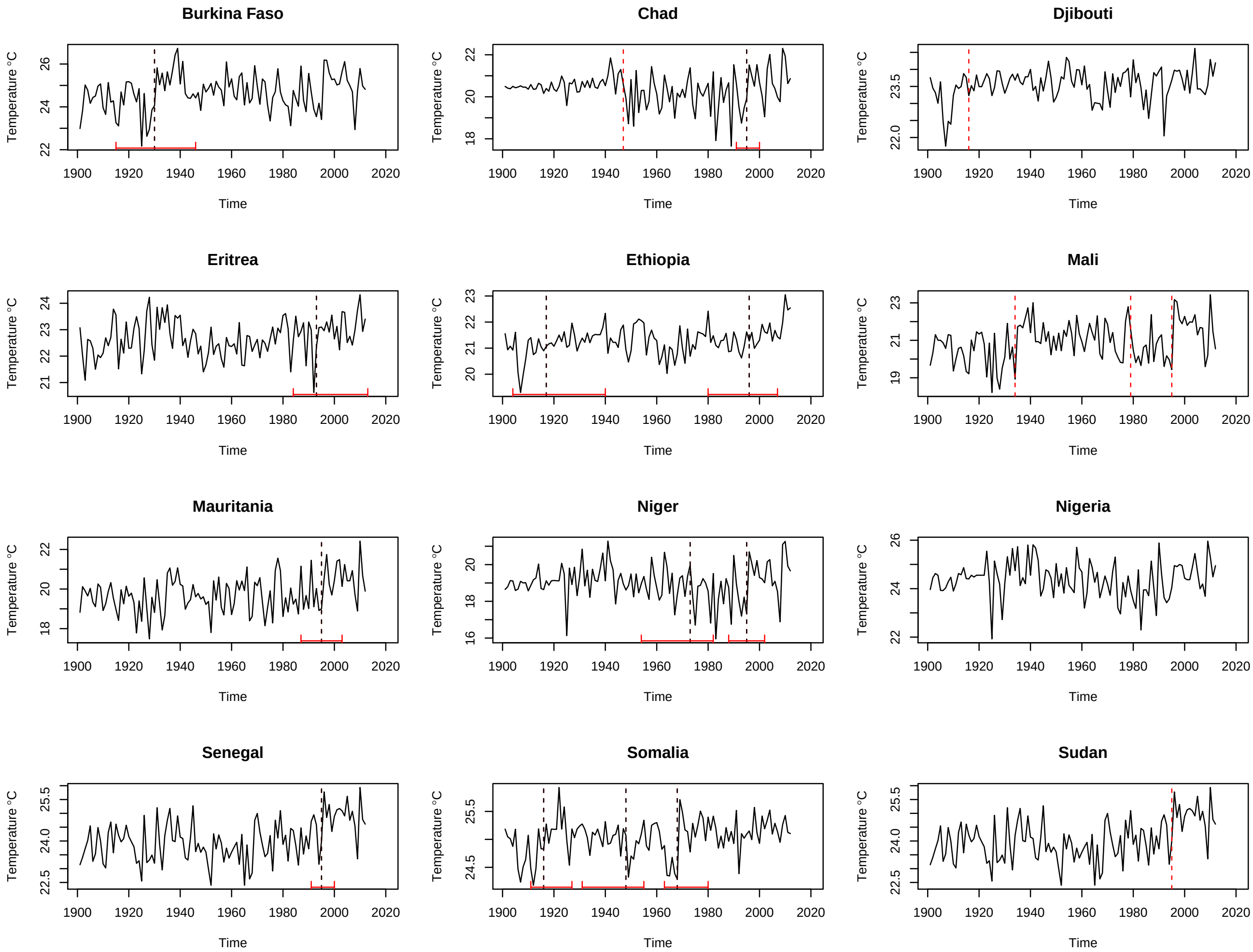
Figure 1.12Endogenous detection of structural breaks in annual maximum temperature in the Sahel countries during the rainy season from 1901 to 2012.



Source: Calculations and achievements of the author.

1993, 1997, 2001, 2010 and 2011. In fact, the droughts of the 1960 and all the others that occurred from the 1980s coincided with the rise in temperature reflected by our graphical analyzes. Senegal has experienced 9 droughts during the same period, affecting more than 8 million people and causing economic damage estimated at more than US$ 300 million (Masih et al., 2014). On the other hand, the droughts of 1980, 2002 and 2011 coincide with our graphical analyzes which show a considerable increase of the temperature. During the same period, Niger and Nigeria experienced 13 and 1 droughts respectively. In Niger, these events affected more than 23 million people and caused the loss of 85,000 people. In this country, the first occurred early and at low frequency (1903, 1906 and 1910). In 1940, the country experienced its fourth drought, followed by the eight other droughts of 1966, 1980, 1988, 1990, 1997, 2001, 2005, 2009 and 2011 (Masih et al., 2014). Given the magnitude of this event, the country has experienced four periods of breaks and the graphical analysis coincides with the historical analysis of the drought. Nigeria is the only country in our sample to record a single drought over the entire period. Though singular, the 1981 drought has hit the country hard, affecting over 3 million people and causing economic damage

Figure 1.13Endogenous detection of structural breaks in annual minimum temperature in the Sahel countries during the dry season from 1901 to 2012.

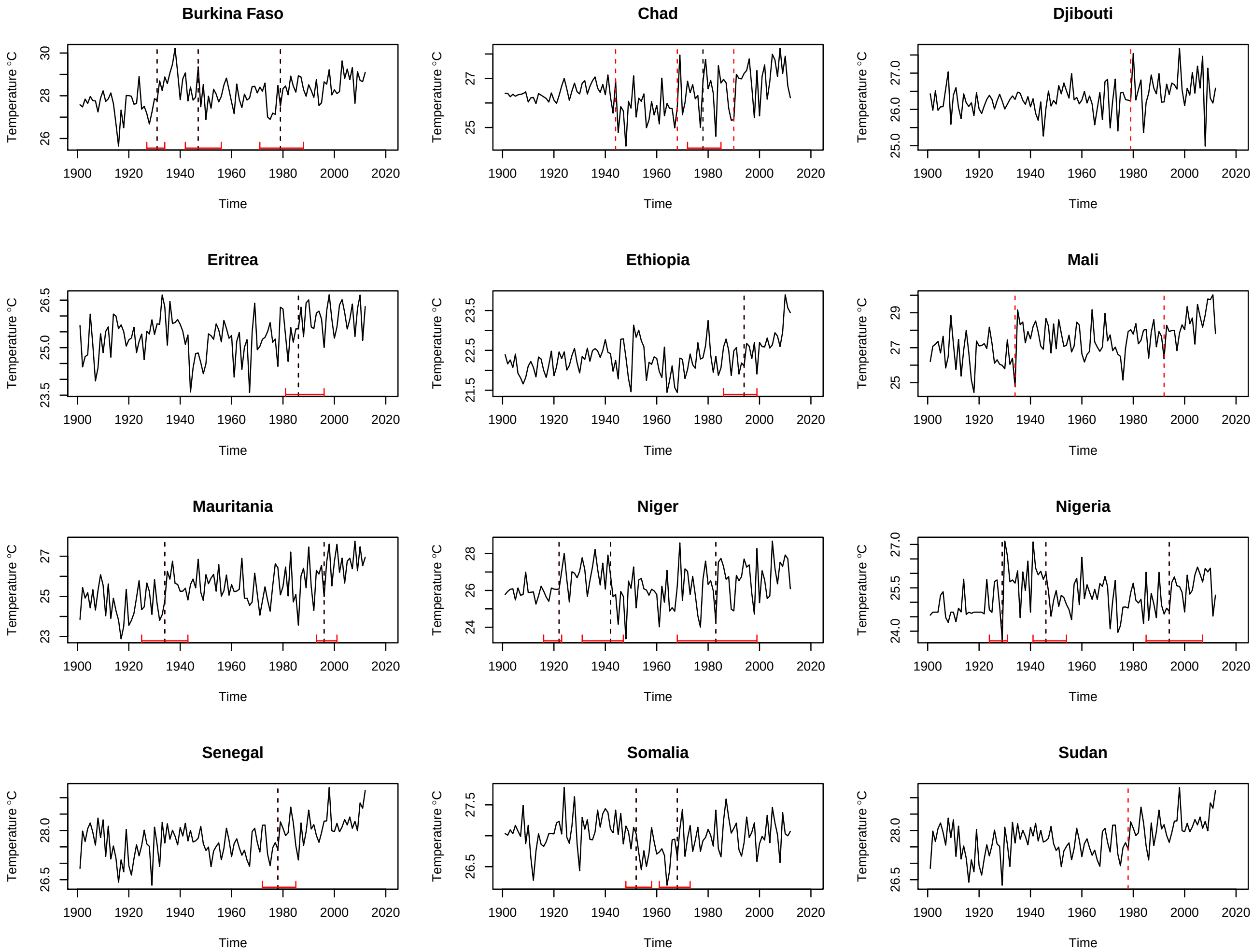


Source: Calculations and achievements of the author.

valued at more than $ 70 million (Masih et al., 2014). The rise in temperature in West African countries coincides with the dryness of the late 2000s and early 1980s Sylla et al. (2018).

Chad and Sudan recorded 9 droughts between 1900 and 2013 (Masih et al., 2014). Chad is the only country in Central Africa to belong to this Sahelian band. Our results correspond to those obtained by Maharana et al. (2018), which indicate that the annual temperature shows an upward trend of 0.015°C and seasonal temperature, a higher rate of increase in the dry season (0.019°C / year). Analyzing the results of Masih et al. (2014), we find that the first three droughts have an occurrence frequency of about 28 years (1910, 1940 and 1966) and have decreased between the droughts of 1969, 1980, 1993, 1997, 2001 and 2012. The results of our analyzes show that the temperature has strongly increased, confirming the thesis of the recurrence of drought. According to Maharana et al. (2018), the temperature in Chad increases at a rate of 0.15°C per decade between 1950 and 2014. Unlike Chad, the 9 events (1980, 1983, 1987, 1990, 1991, 1996, 1999, 2009 and 2012) caused a lot of damage to Sudan. As a result, all these events affected more than 30 million people and caused

Figure 1.14Endogenous detection of structural breaks in annual median temperature in the Sahel countries during the dry season from 1901 to 2012.

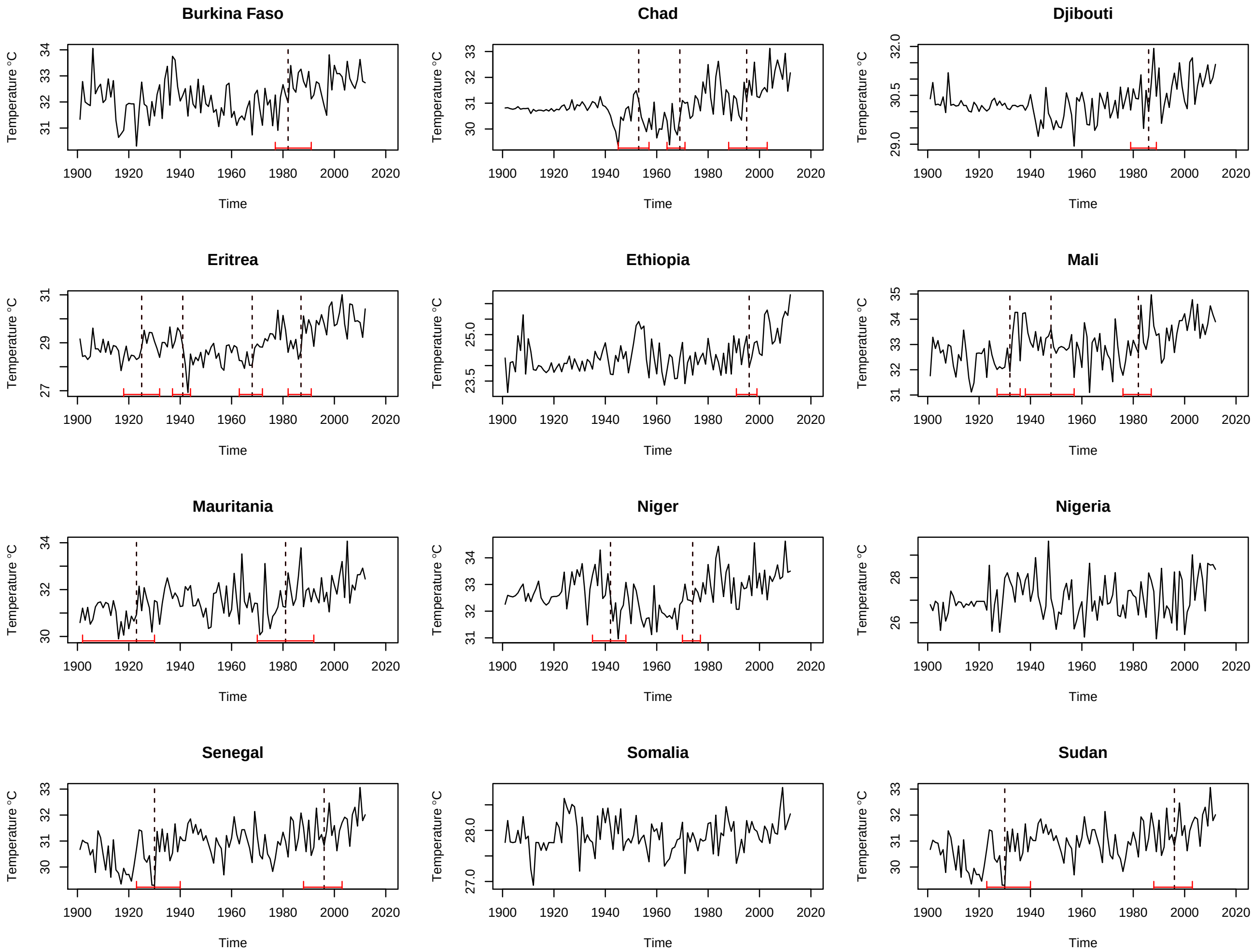


Source: Calculations and achievements of the author.

150,000 casualties. All droughts occurred at times when the country experienced a rise in temperature.

The East African countries included in the study are Djibouti, Eritrea, Ethiopia and Somalia, with 9, 3, 15 and 13 droughts, respectively, from 1900 to 2013 Masih et al. (2014). E Tierney et al. (2015) explain that the drying rate of countries in the Horn of Africa caused by climate change is unusual considering the context of the past 2000 years. Like Chad, Djibouti experienced 9 droughts during the same period but without loss of life and pecuniary damage. These historical analyzes confirm that since the 1980s, the average temperature has increased considerably in this country. Unlike previous countries, the first drying started in 1980, followed by 1983, 1988, 1996, 1999, 2005, 2007, 2008 and 2010. Eritrea experienced drought in the first year of its independence in 1993, followed by drought in 1999 and 2008. Our graphical analysis indicates that the temperature has increased since 1993 and will continue to increase during the rest of the year. the period. These three events affected more than 5 million people without causing loss of life or monetary damage (Masih et al., 2014). Masih et al. (2014) also show that Ethiopia is the country with the highest number of

Figure 1.15Endogenous detection of structural breaks in annual maximum temperature in the Sahel countries during the dry season from 1901 to 2012.



Source: Calculations and achievements of the author.

droughts (15 droughts) from 1900 to 2013 and these ssessesses are climate-related (Brown et al., 2017). Our graphical analyzes indicate that the temperature began to rise in the early 1960s and that the country experienced its first drought in 1965, followed by frequent drying up in 1969, 1973, 1983, 1987, 1989, 1997, 1998, 1999 , 2003, 2005, 2008, 2009 and 2012 (Masih et al., 2014). The structural changes suspected in the country are real. Somalia is the second country in the Sahel after Ethiopia to record a high number of droughts. Thirteen arid areas touched the country from 1900 to 2013, affecting more than 13 million people and killing more than 19,000 people. In 1964, Somalia recorded its first drought, followed by arid lands in 1969, 1973, 1980, 1983, 1987, 1988, 1999, 2004, 2005, 2008, 2010 and 2012. In presenting a detailed record of the temperature and regional aridity of the last 2000 years, E Tierney et al. (2015) explain that Somalia, Djibouti, and Ethiopia are experiencing a historic drying up.

Table 1.5Number of breaks associated with the six variables over the entire period.

Country/Variable	TempminRain	TempmedRainy	TempmaxRain	TempminDry	TempmedDry	TempmaxDry	Total
Burkina faso	1	2	1	1	3	1	9
Chad	3	3	2	2	3	3	16
Djibouti	3	2	2	1	1	1	10
Eritrea	1	3	3	1	1	3	12
Ethiopia	2	3	1	2	1	1	10
Mali	1	2	3	2	2	3	13
Mauritania	1	3	3	1	2	2	12
Niger	2	1	2	2	3	2	12
Nigeria	2	3	3	0	3	0	11
Senegal	1	2	1	1	1	2	8
Somalia	2	0	3	3	1	0	9
Sudan	1	2	1	1	1	2	8

Source: Calculations and achievements of the author.

1.6.3 Precipitation

Precipitation is the second variable chosen to characterize climate change in the Sahel countries. Precipitation and temperature are strongly bound in this area. Rainfall sometimes depends on temperature during the rainy seasons (Nicholson, 2013) . We focus on the annual precipitations i.e. the total annual quantity of rain since the important issue is the total amount of water for a year at a given area. We also focus later on seasonal rainfall. With respect to total precipitations, the same graphical and statistical analyzes are applied to this variable. Figure 1.16 shows sequences marked by decreases or increases in annual precipitation, varying from country to country and independently while table 1.4 shows provides the estimation results.

The graphical results correspond to the analyzes of (Hôte et al., 2002) who also identified a negative break point for precipitation in the Sahel in 1968, but the jump has been significant only since 1980.

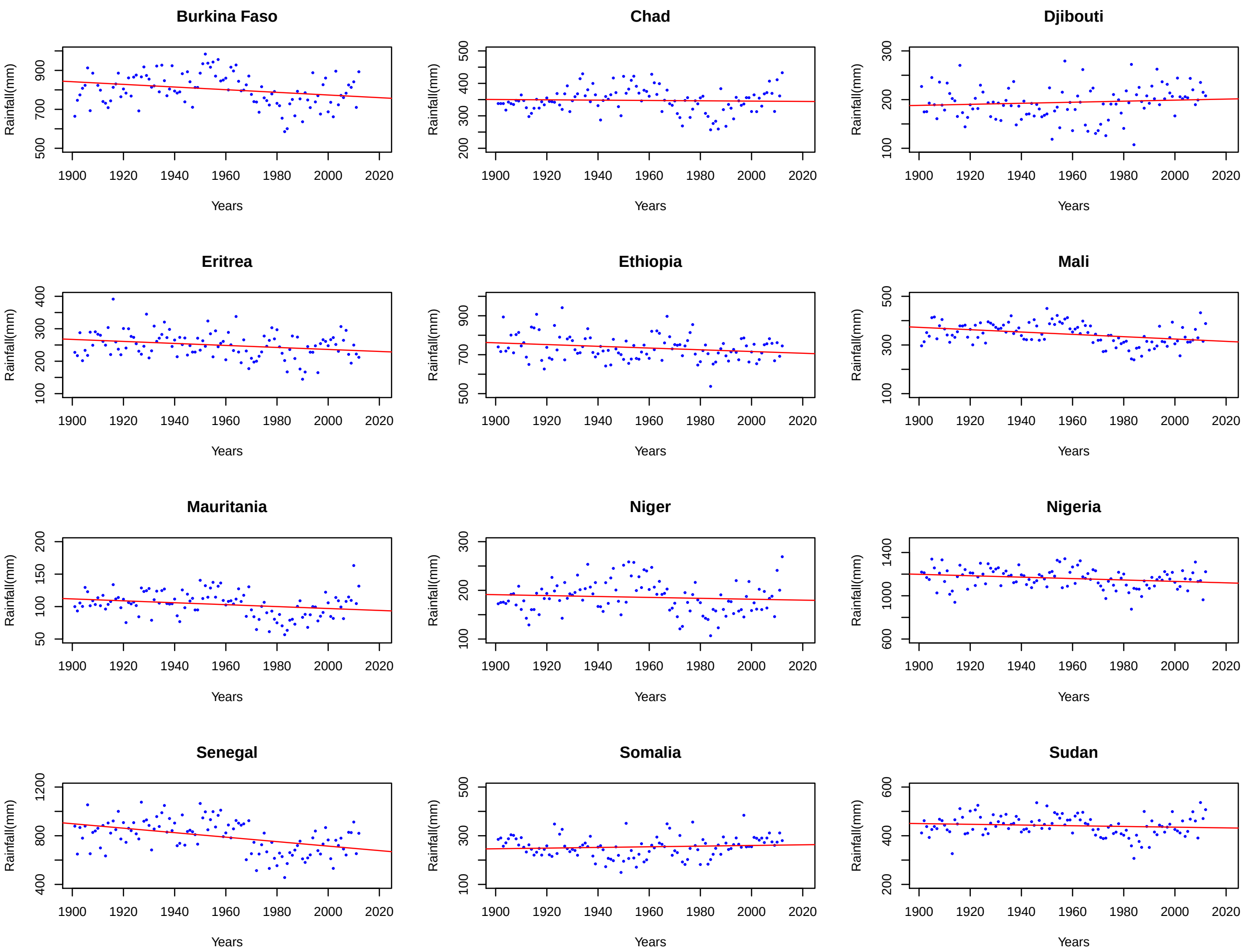
There was a significant decline in annual precipitations in Burkina Faso, Eritrea, Ethiopia, Mali, Nigeria and Senegal. For all the other countries, the slope coefficients are not significant. In Burkina Faso, annual precipitation declined sharply in the early 1980s while a recovery was observed from the 1990s to the end of the period. They were between 500*mm* and 1100 *mm* over the whole period. In Chad and Djibouti, while overall, the slope is not significant, some patterns can be observed for some sub-periods: rainfall declines were observed over two periods, one from the late 1970s and the other from the early 1980s. Annual rainfall varied over the period for the two countries between [200 - 500 *mm*] and [100 - 300 *mm*] respectively, with a recovery in the early 2000s. Over the entire period, Eritrea experienced a decline over a long period from 1980 to 2000 but a slight recovery at the end of the period. Annual precipitation ranges from [100 - 400 *mm*]. Ethiopia registered a slight decline around the 1920s and a sharp decline in the early 1980s, with a resurgence in the early 2000s. Two scenarios were repeated in East Africa (Eritrea, Ethiopia, Djibouti, Somalia and Sudan) in the 1960s, the western regions have experienced persistent aridity since the late 1960s. The eastern regions (Ethiopia, Eritrea, Djibouti and Somalia) recovered somewhat in the 1990s with "near" or "just above" precipitation to the long-term average for some year (Nicholson et al., 2000). In Mali and Mauritania, the decline was observable in the early 1980s, but with a slight fluctuation in annual precipitation. In Niger, a sharp decline can be observed over two periods, one between 1900 and 1930 and another during the late 1970s and early 2000s. Average annual rainfall recovered from the early 2008, which explains that overall the slope is not significant. In Nigeria, the annual variation in rainfall is small over the period as a whole, but has dropped slightly below 1 000 *mm* between 1900 and 1920, and between 1970 and 1990. It is the only country in the sample to receive annually a large amount of water, with rainfall that varies between 600 and 1400 *mm*. In Senegal and Sudan, annual rainfall declined over two periods in the early 1900s and mid-1980s.

Early studies on the variability of the Sahel rains described two important earlier periods that were marked by a drought during the twentieth century. The first study was done in the 1910s and the second was done in the 1940s. There is about a 30-year gap between the two works and the speculation that stemmed from this work foresaw that the next drought would occur 30 years later, i.e. in the 1970s. During the nineteenth and twentieth centuries, precipitation varied considerably in the Sahel and Sudan regions. At this time, precipitation was defined as a moisture index, ranging from -3 to +3 (Nicholson et al., 2012).

Overall, the graph series in figure 1.16 show that annual precipitation has varied strongly over the entire period for all countries. Around the 1980s, they fell sharply before regaining some recovery for all countries. Nicholson and Kim (1997), Nicholson et al. (2000) and Ozer et al. (2010) reported that the West African Sahel recorded above-average rains from 1961 to 1990 which could indicate the end of the severe period of aridity that began in the 1960s. Moreover, over the same period, the same situation is observable in the countries of East Africa (of our Sahel). The thesis that Sahelian dry matter seems to be over in the 1990s (Hôte et al., 2002) is to be refuted because even if there is a slight rise in rainfall in the early 2010s. After 10 years, rainfalls are still low in West African countries and this trend is also spreading in East Africa. citenicholson2012 argue that there is some recovery after a very dry period (1968 -1997). More specifically, moisture recovery was most pronounced in the Western Sahel. The exception was the "north" zone (the Saharan margin, 18 - 20°N), which remained relatively dry. In the southern Sahel, seasonal totals have exceeded the long-term average in all years and conditions were comparable or wetter than those in the wet decade of the 1950s (Nicholson, 2005; Olsson et al., 2005). The series of precipitation graphs also show that the Sahel countries experienced periods of rainfall variability. Even though the latter are not very obvious, they are a good reflection of global warming. Mean annual rainfall in the Sahel is on the order of 100 to 200 *mm* in the north, where the Sahel gives way to desert, and 500 to 600 *mm* at its southern limit (Nicholson, 2013). The rainfall of this band is generally limited to the summer months, with maximum precipitation in August. In the Sahel, the season generally ranges from 1 to 2 months in the north to 4 to 5 months in the south. Occasional winter rains of extratropic origin may occur in some countries, but they usually bring less than 25 *mm* of rain (Nicholson, 2013).

In general, African countries with a semi-arid climate (West, East and Southern Africa) have precipitation that varies widely in time and space. These variations are observable even at the level of a single country, in Ethiopia, the eastern part (semi-arid) receives less precipitation compared to the western part (sub-humid). They are also observable in the regions, most of the rainfall in southern Africa lasts from October to March, while rainfall in the Sahel is concentrated during the summer monsoon season from July to August. Most countries in the Horn of Africa and Equatorial East Africa receive precipitation in two seasons: October-December (short rainy season) and March-May (rainy season). Northwest Africa receives most of the precipitation from October to April (Masih et al., 2014). According to Dutra et al. (2013) the horn of Africa was affected by a precipitation deficit in both the October December 2010 and march-may 2011 rainy seasons.

Figure 1.16Annual quantity of rain in the Sahel countries from 1901 to 2012

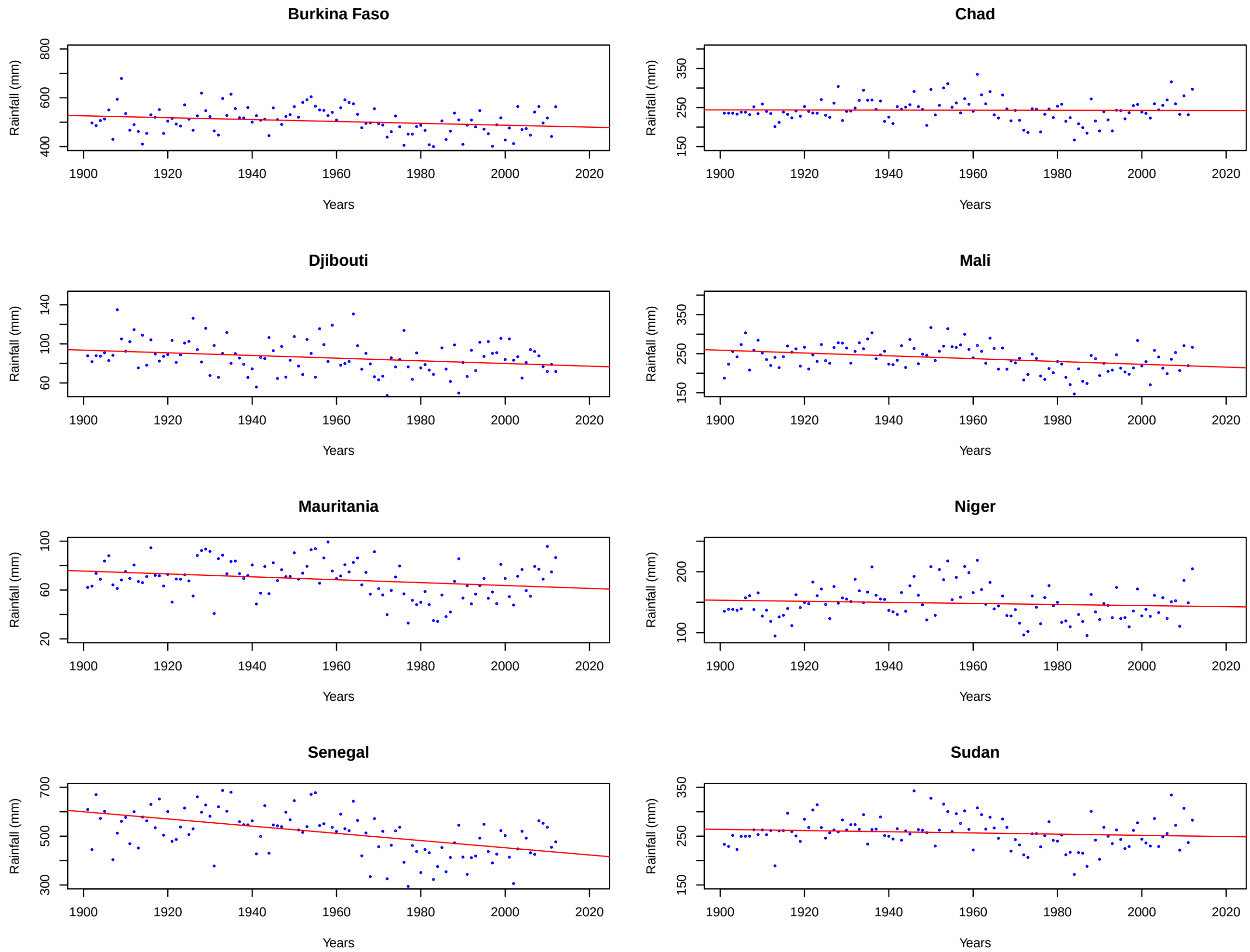


Source: Calculations and achievements by the author.

After presenting this analysis on annual rainfall, we focus on seasonal variability to explain the evolution of the annual rainfall quantity during the rainy season (see figures 1.17 and 1.18) which corresponds to the period of agricultural activities for a rainfed "agricultural system". With respect to temperatures, the question is more crucial and essential, because the annual average mixes the temperatures of dry season and that of vegetative (agricultural) season, but it is only these last that matter so our analysis makes it possible to observe the distribution of the temperature which is highly valid. In addition, we do not seek to substitute the annual rainfall with precipitation from the rainy season, because the two variables are almost equal in countries where rainfall is highly concentrated over time (in the case of Sahelian countries in our sample such as Burkina Faso, Chad, Mali, Niger, Sudan); this explanation is less true in countries with more complex rainfall patterns, such as Nigeria and East African countries such as Ethiopia, Somalia, Eritrea (in these cases there is several seasons to consider).

We see that countries differ strongly. There are countries that have two seasons during the year, a dry season and a rainy season. Generally, the dry season (7 to 9 months, October to June) is longer than the rainy season. The month of August is generally the most watered and the arid climate which varies according to the agroecological zones of each country. The environment of these two-season countries is influenced by a tropical climate and dry, they are arid countries. We selected for the rainy season the months of June, July and August. To our knowledge, the length of the rainy season has not and does not evolve practically in these countries. Figure 1.18 shows that over the entire period rainfall during the rainy

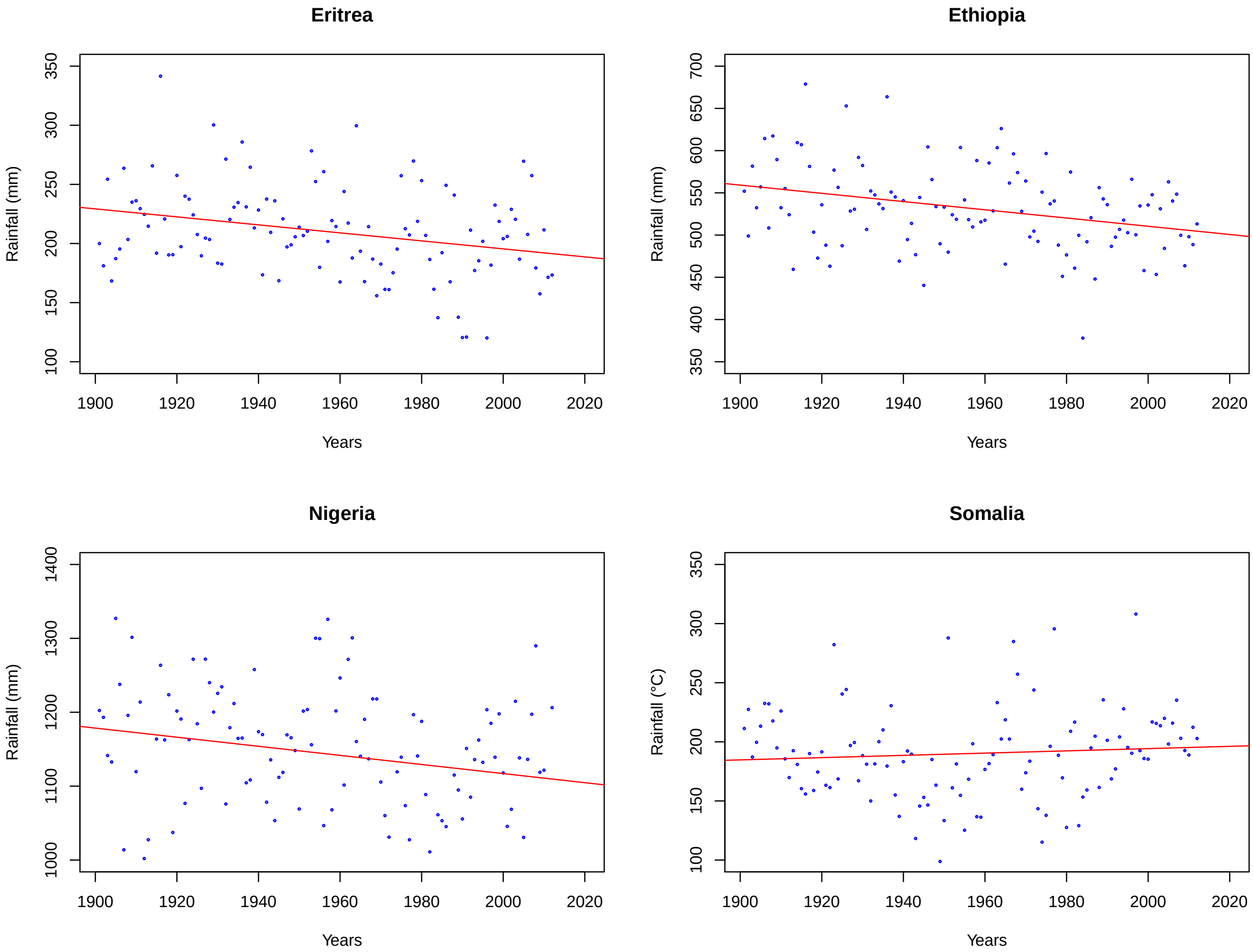
Figure 1.17Precipitation during the rainy season for countries with two seasons from 1901 to 2012



Source: Calculations and achievements by the author.

season has varied in all countries in two seasons, and the year 1980 remains a decisive year as they began to decline with a slight recovery in end of the analysis period. Among these countries, except Senegal and Burkina Faso record the highest annual rainfall in the rainy season, between 300 and 800 *mm*. Chad, Mali, Niger and Sudan receive between 100 and 350 *mm* at the same time. The situation is mixed in Djibouti with a range of 50 to 200 *mm* at the same time. Then we have a group of countries that benefit from several rainy seasons, Nigeria, Ethiopia, Djibouti, Eritrea and Somalia. Ethiopia has a temperate climate especially in the vast central plateau region. The country has two rainy seasons, a first with moderate rains (from March and April) and a second rainy season from June to September. Eritrea has a climate that varies according to climate zones, the coast has an arid

Figure 1.18Precipitation during the rainy season for multi-season countries from 1901 to 2012



Source: Calculations and achievements by the author.

climate (located in the desert with a dry climate) with low and insignificant rainfall and the plateau area located in the center of the country with two seasons, a short rainy season from February to April and a big rainy season from end of June to mid-September (we keep the months entirely because we work with monthly data). Thus, Somalia is characterized by a dry climate with two rainy seasons and two dry seasons in the north and south of the country. To the south, the first rainy season extends from April to June and a second season from October to November. The first dry season (December to March) and second dry season (July to September). In northern Somalia, the first rainy season (April to June) and the second season runs from October to November. Finally, Nigeria has a tropical and varying climate, semi-arid in the north of the country and wetter to the south. The country receives a longer rainy season from June to September in the north, another from April to October in the center, a third from March to October in the south and a last from March to November in the south east precisely in the region Calabar which is the rainy area of the country.

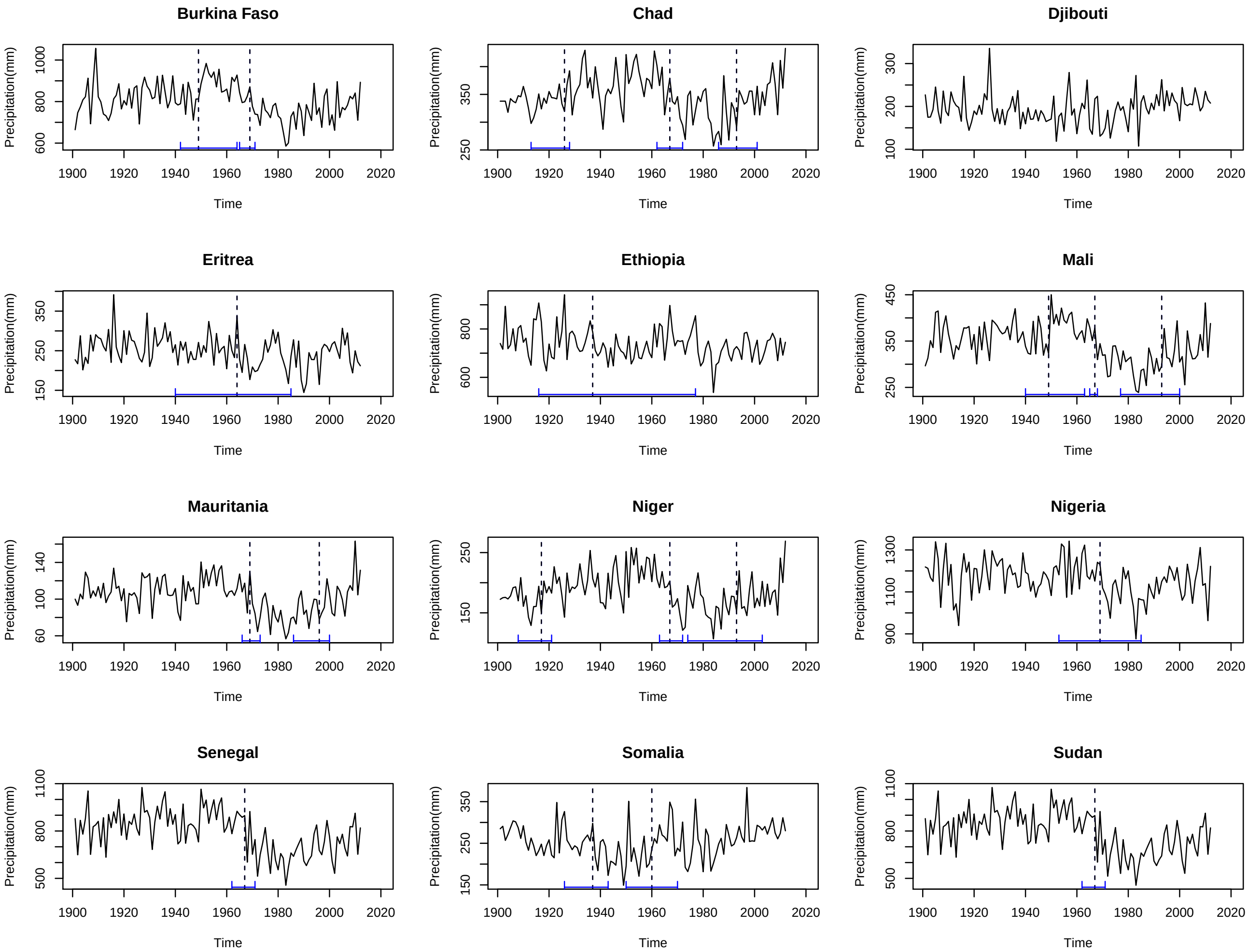
Figure 1.18 shows that Nigeria has the highest amount of rainfall (between 1000 and

1400 *mm*) during the growing season because the country has four rainy seasons spread over its entire territory. Eritrea and Somalia receive very variable seasonal rainfall between 100 to 350 *mm* per year over the entire period. In Somalia, there is a significant fall in two periods around the 1940s and 1980s.

Globally, countries with a single rainy season are likely to receive less rainfall than countries with several rainy seasons. However, Eritrea and Somalia receive less water than a portion of countries with a single rainy season, except for Nigeria and Ethiopia. There is a problem of rainfall distribution at the national level of each country.

The results of the annual precipitation estimates presented in table 1.4 show that the coefficient is negative and statistically significant for Burkina Faso, Mali and Senegal at the 1% level. For Ethiopia and Nigeria, it is negative and significant at the 5% threshold. The drop in precipitations in the rainy saison is strong in Burkina Faso and Senegal. On the other hand, the coefficient is negative but not significant for Chad, Djibouti, Eritrea, Mauritania, Niger, Somalia and Sudan. This means that these countries did not experience a significant decrease in average rainfall over the entire period. For Djibouti and Somalia, unlike the other countries, there was no resumption of precipitation at the end of the period, and both countries had irregular and weak rainfall. In general, countries experienced periods of significant decline in precipitation at different frequencies, but a recovery began in most countries in the early 2000s. The results of endogenous fracture analyzes related to precipitation variables are presented in 1.19 and 1.20. Figure 1.19 illustrates the ruptures related to the evolution of total annual precipitation in the Sahel countries over the entire analysis period. The graph shows that Chad, Mali and Niger each had three shocks at different times. However, the last two shocks occurred in the same period, i.e. after the 1980s. In addition, Chad and Niger experienced their first break-up at the same period, at the end of the 1980s. Burkina Faso, Mauritania and Somalia each suffered two shocks that occurred in the same period in the late 1940s and early 1960s. Ethiopia, Senegal and Sudan each experienced a single break in the early 1990s. Djibouti did not record breaks over the entire period. The results in table 1.20 show the different breaks associated with the evolution of seasonal average rainfall in the Sahel countries. Chad and Eritrea experienced three shocks throughout the period. The first shock occurred at a different time while the last two occurred at similar times. Mauritania and Niger each experienced two shocks that occurred at different times. Burkina Faso, Djibouti, Ethiopia, Mali, Nigeria, Senegal and Sudan recorded only one shock, which globally occurred during the same period. Somalia has not contained periods of ruptures related to the evolution of seasonal average rainfall. Table 1.6 gives a summary of the numbers of shocks recorded by countries according to the two precipitation variables. Overall, precipitation decreased at the country level while recording periods of ruptures. This global warming trend could significantly alter rainfall patterns and water availability in different parts of the world. **?** point to the fact that many parts of Africa, such as the Sahel, the Greater Horn of Africa, and Western and Southern Africa, have been affected by severe droughts in recent decades and millennia and are vulnerable to the adverse effects of climate change. In addition, Di Baldassarre et al. (2010) report that there has been a significant increase in the number of flood-related deaths in different parts of Africa in recent decades. By analyzing recent rainfall patterns in the Sahel, Norrgård (2014) shows that there was great inter-annual and inter-decadal variability in West African rainfall patterns in the 18th century. These results

Figure 1.19Endogenous detection of structural breaks in Total annual precipitation from 1901 to 2012 at the level of the Sahel countries.

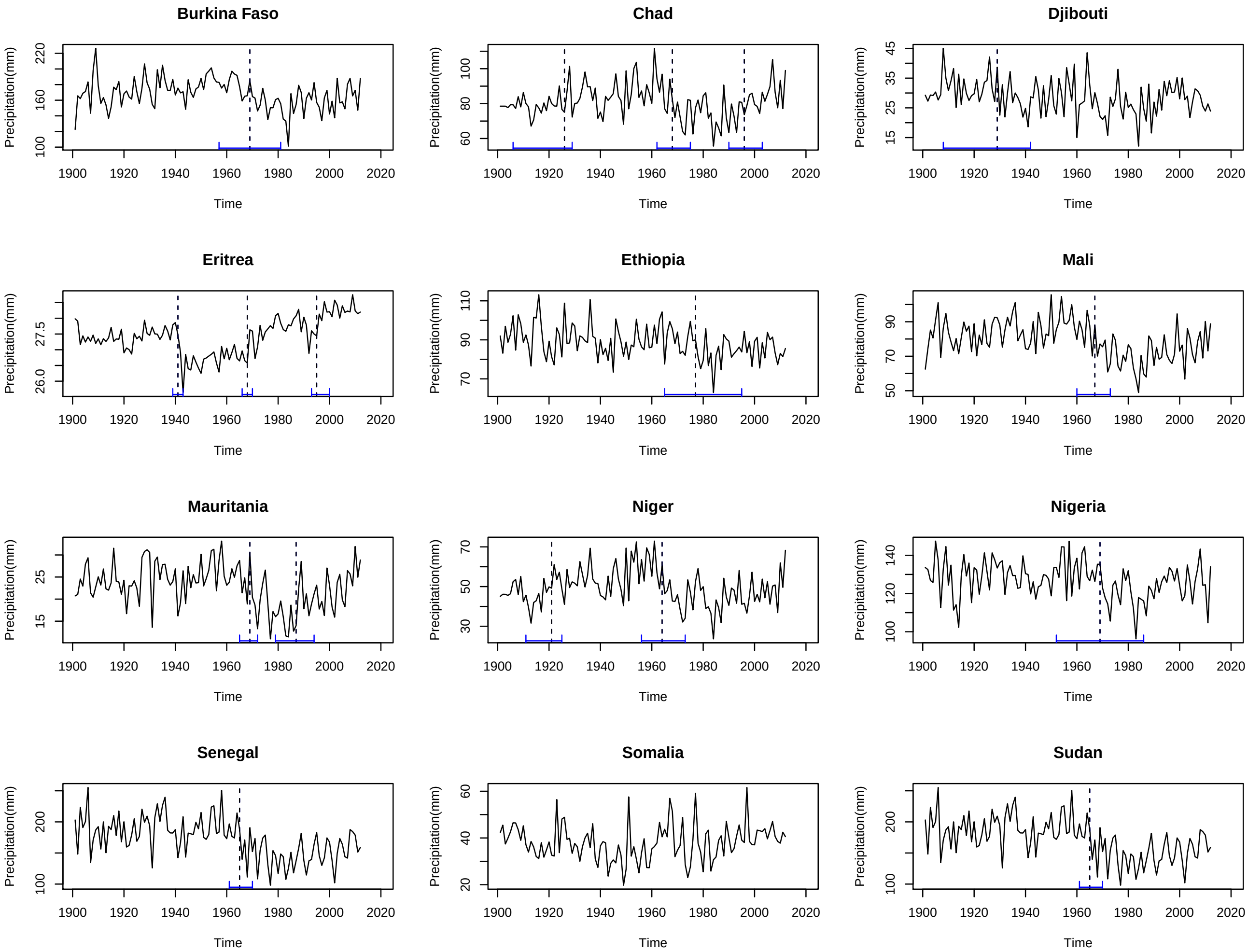


Source: Calculations and achievements by the author.

are in line with our analyzes, which indicate that all the Sahelian West African countries from Senegal to Nigeria have experienced a significant decline and interannual rainfall variability over the entire period.
These studies indicate that recent warming may have contributed to the increase in warm phase activities of ENSO (El Niño), mainly associated with below-normal precipitation in different parts of Africa (Mason and Goddard, 2001). Rising and falling rainfall are both effects of climate change. An increase in precipitation leads to floods. They are considered as one of the main expected impacts of climate change (Dittrich et al., 2016). Floods cause enormous damage in poor countries that do not have good infrastructure (canalisation, dams, drainage system ...). On the other hand, a decrease or absence of rain leads to dryness which also causes significant economic and human damage in the countries as mentioned by (Masih et al., 2014).

Several studies (Ford et al., 2018; Lebel and Ali, 2009a; Mason and Goddard, 2001; Sylla et al., 2018) have shown changes in precipitation in West African countries. Using

Figure 1.20Endogenous detection of structural breaks in seasonal average precipitation from 1901 to 2012 at the level of the Sahel countries.



Source: Calculations and achievements by the author.

multi-model sets of the latest global and regional climate models, Sylla et al. (2018) simulate the hydrological impacts of climate change in five major river basins (Senegal, Niger and Chad), which are the importance of flora in West Africa. The results systematically predict a substantial decrease (from 10 to 40%) of the potential water availability in the five main river basins. The most important changes are expected to occur in the Senegal Basin and the Sahelian part of the other river basins (Ford et al., 2018). Sylla et al. (2018) also argue that in a world of status quo, the reduction in water availability, coupled with rapid population growth in the region, will force West Africa to face a unprecedented water deficit in the second half of the 21st century. In addition, Lebel and Ali (2009a) and Sylla et al. (2018) argue that under current climatic conditions, West African countries will experience significant water stress. They indicate that the main river basins are experiencing a positive trend in the early 1970s, a clear decrease in the 1980s and an increase over the 1990s. The authors explain that this situation is obviously due to the high inter-decadal rainfall variability recorded. in West Africa, with the droughts of the late 1970s and early 1980s and the recent upturn of the 1990s. Mason and Goddard (2001) generally argue that recent

Table 1.6Number of breaks associated with both variables over the entire period.

Country/Variable	Annual precipitation	Seasonal precipitation	Total
Burkina faso	2	1	3
Chad	3	3	6
Djibouti	0	1	1
Eritrea	1	2	3
Ethiopia	1	1	2
Mali	3	1	4
Mauritania	2	2	4
Niger	3	2	5
Nigeria	1	1	2
Senegal	1	1	2
Somalia	2	0	2
Sudan	1	1	2

warming may have contributed to the increase in ENSO (El Niño) warm phase activity, mainly associated with below-normal rainfall in different parts of Africa.
Our results show that East Africa also experiences periods of water stress during this period as the countries of the West African Sahel. E Tierney et al. (2015) indicate that the recent fall in rainfall in the Horn of Africa during the "long rains" season from March to May has caused drought and famine, threatening food security in an already vulnerable region. Over the past 30 years, E Tierney et al. (2015) have argued that the Horn of Africa has experienced a steady decline in rainfall during the March-April-May "long rains" season (MAM) which is the main rainy season for the region. Decreases in precipitation have been observed and validated by our analyzes and coincide with the results of Brown et al. (2017) showing that there has been a reduction in precipitation from March to June in central and eastern Ethiopia, with decreases ranging from -0.4 to -0.6. On the other hand, in northern Ethiopia, precipitation increased between June and September, probably because of the recent rise in climatic conditions associated with La Niña. In addition, Gizaw et al. (2017) reports that a projected increase in average annual discharge due to increasing rainfall over Ethiopia contradicts the downward trends in average annual precipitation over the past several decades. Although the cause of the observed increase in El Niño activity since the late 1970s is questionable, recent studies by **?** have suggested that the increased frequency of El Niño episodes is more likely due to a warmer climate with lower precipitation.

All these studies suggest a substantial reduction in water availability in West Africa, in line with our findings. Sylla et al. (2018) indicate that in the larger basins, such as Niger and Chad, there is a clear contrast between the northern part of the Sahel and the Sahara, dominated by little or no change. and the southern part of basins located mainly in the Sahel where the reduction in potential water availability is substantial. In future climates, different watersheds respond differently to increasing forcing scenarios. In fact, all watersheds where there is predicted a reduction in potential water availability will not experience a water deficit. For example, in Senegal and Chad, the current water deficit will be even more pronounced (Sylla et al., 2018). In Chad, recent studies by Sylla et al. (2018) and Maharana et al. (2018) show overall that the country has experienced a decrease in rainfall. From these facts, our analyzes show that Chad has suffered several shocks and a drop related to precipitation. This result is consistent with Maharana et al. (2018) analyzes, which indicate that rainfall has declined significantly in Chad during the last decades during the dry period. This drop in precipitation has resulted in various years of dryness. For Maharana et al. (2018), the annual precipitation trend shows a decrease of 0.17 $mm/year$ for the entire study period (1950 to 2014) and that the recovery is slow throughout Chad. Seasonal analysis by Maharana et al. (2018) reflects in Chad the highest rate of decline observed in recent decades (1.47$mm/year$). The results of Sylla et al. (2018) indicate a substantial decrease (from 10 to 40%) of the potential water availability in the five main river basins of Senegal, Niger including Chad.

1.7 Application on agroecological zones

After studying climate change and variability at the country level, it is very important to have a clear idea of this analysis on a smaller scale which is the agroecological zone. Thus, this section is devoted to the analysis of climate change and variability in the 52 agroecological zones distributed differently among the 11 countries.

Table 1.7 gives the results of the overall homogeneity tests, constants and slopes between the agroecological zones of each country and each climatic variable. The results indicate that the fixed effects of the zones are indeed significant and important, and that the slopes are also very different from one zone to another. Agroecological zones have their own characteristics that differentiate them from each other. The agroecological zones studied are distinguished within the same country and outside the other zones of the countries of the studied band. The number of agroecological zones varies from one country to another. As mentioned in the case of countries, several factors specific to each zone influence their respective climatic characteristics. This internal and external divergence between agroecological zones requires a separate and individual analysis of the zones.
Thus, the analysis of rainfall and temperature at the level of agroecological zones makes it possible to study, on the one hand, climate change and variability in each country. In other words, it also reveals the remarkable facts in each zone and at the level of each country. On the other hand, it is also a question of classifying the countries between them, that is to say of grouping the countries in which there are no marked differences between the zones and those which present remarkable differences.
Overall, this analysis differs from the first analysis because it focuses on a different, specific and deeper scale. By focusing on agroecological zones, we can observe variability while ignoring the possible effects on agricultural performance of each agroecological zone in terms of past potential productivity. In addition, climate variability in a single agroecological zone considered individually is low unless it is considered an agroecological zone whose agricultural production contributes significantly to the country's domestic food production. As at the scale of the country where the variability is obvious. This analysis over the entire period graphically shows that climatic variables experienced periods marked by decreases ($-$) and increases ($+$).
In addition, the graphical analyzes in the appendix show that temperature variables experienced periods of decline and increase, but in general, they have evolved and are trending upward throughout the analysis period.
The desert areas are the warmest but have the lowest annual minimum temperatures and this result is valid for all agroecological zones and for all countries. The results of the graphical analyzes show that rainfall experiences greater interannual variability than temperature in all agroecological zones over the period as a whole. In addition, total annual precipitation is more variable than seasonal precipitation.

Rainfall generally decreased in level and trend in all agroecological zones during the period, but increased slightly in the 2010s in most countries. The variability is not identical at the level of all agroecological zones. Desert and arid areas receive the lowest water amounts and have low interannual variability.

Agroecological zones are also distinguished by the degree of variability and the level of trend increase in temperature variables.

Graphical analyzes show high variability in the agroecological zones of Burkina Faso (Figures 1.21 and 1.22), Mauritania (Figures 1.61 and 1.62) and Somalia (Figures 1.9 and 1.9) for the dry and rainy seasons. On the other hand, there is little variability in the agroecological zones of Senegal (Figure 1.9 and 1.9) and Sudan (figures 1.9 and 1.9). The results also show that the minimum annual temperature in Sudan (figures 1.9 and 1.9) has low variability in the dense savannah and the equatorial zone and remarkable variability in the dense savannah and the equatorial zone, and great variability in the zones, desert and semi-arid areas, flood-irrigated areas and basin, Jebel Marra area, poor areas and dense savanna zone.

In Nigeria (see figures 1.9 and 1.9), it differs from one agroecological zone to another, with high variability for the Guinean savannah, Sudan savannah, Sahelian savannah and low variability for humid forest, southern savannah and the derived savannah.

For precipitation, there are two variables. Total precipitation is marked by high variability in Burkina Faso (fgure 1.26), with decay periods (1910, 1940 and around the 1980s) for all areas. The results show a very strong inter-annual variability in Chad (figure 1.26), Djibouti (figure 1.42), Ethiopia (figure 1.50), Mali (Sahelian zone, Sudanian-Guinean zones, see Figure 1.42), Mauritania (maritime zone, zone fluvial, Sahelian zone, see Figure 1.66), Niger (see Figure 1.74), Nigeria (see figure 1.82) and Senegal (very large variability in all areas), Somalia (Bay and Bakool, Central Somalia Coastal and Southern, Shabelle valleys and Juba, Somaliland, see figure 1.9), Sudan (dense savannahs and equatorial areas, flooded and basin-irrigated areas, Jebel Marra areas, poor and dense savanna areas, see Figure 1.106). In addition, it has low variability (desert zone in Chad, Figure 1.34), Mali (Saharan zone, Figure 1.58), Mauritania (arid zone, see Figure 1.66), Somalia (Bari, constant linear and at the end of the period see Figure 95), Sudan (Desert and semi-arid desert zone, see figure, see Figure 1.98).

Seasonal rainfall is marked by high variability in Burkina Faso (rainfall decreased with total precipitation, see figure 1.28), Chad (Sahelian and Sudanian zones, see Figure 1.36), Djibouti and Ethiopia , all zones (decline over several years between 1901 and 1940 and around the 1990s, see respectively figures 1.44 and 1.52), in Mali (Sahelian zone, Sudan zone, Sudano-Guinean zone, see figure 1.60), in Mauritania (maritime zone , fluvial zone, Sahelian zone, see figure 1.68), Niger (see figure 1.76), Nigeria (all agroecological zones, see Figure 80), Somalia (Bay and Bakool, Central Coastal Zones, Southern Somalia, Shabelle Valleys) and Juba, Somaliland, see Figure 1.92), Sudan (dense savanna and equatorial zone, flood and basin irrigated areas, Jebel Marra zone, poor and dense savanna zone, see Figure 1.108). On the other hand, there is a small amount of rain and low interannual variability in the desert areas of Chad (see Figure 1.36) and in the Saharan region of Mali (see Figure 1.60); the arid zone in Mauritania (see Figure 1.60); Bari in Somalia (linear at the beginning and end of the period, see Figure 1.100) and Sudan (desert and semi-arid zone, see Figure 1.108).

We turn to the analysis of our climate variables using the structural change model to highlight the sub-periods. We thus compare the countries according to the total number of

breaks identified in the evolution of the temperature and the precipitations.
Overall, the agroecological zones are distinguished by both the number of shocks and the dates of occurrence. In addition, they also vary by the type of season. Table 1.5 in the annex summarizes the number of shocks by country and by climatic variables. For temperature variables, the results obtained at the detection of the sub-periods give the following information:
From 1901 to 2016, the countries of West Africa through their agroecological zones experienced periods of shocks related to the evolution of the different temperature variables. During the rainy season from 1901 to 2016, the agroecological zones of Burkina Faso (see Figure 1.23) and Mali (see Figure 1.55) respectively experienced a single shock respectively related to the evolution of the minimum temperature. Over the same period, the agroecological zones of Mauritania (see Figure 1.63) several shocks, 1 shock for arid zone, 2 shocks for Maritime zone, 2 shocks River zone and 0 shock Sahelian zone.
In general, periods of heat wave were common, such as floods or droughts. We do not have historical information from these areas to comment on these ruptures, but we suggest that climatic events have occurred in these areas. Graphical and econometric analysis shows the existence of historical facts whose knowledge is essential.
In addition, the results of the estimates (see the attached tables (1.8, 1.9, 1.10, 1.11, 1.12, 1.13,1.14, 1.15, 1.16, 1.17 and 1.18 of results) confirm and demonstrate the existence of climate change. The coefficients associated with our *year* variable validate the hypothesis that temperature has increased in most agroecological zones of all countries for all periods. In addition, the assumption of an average decrease in annual rainfall for all periods is also confirmed in most agroecological zones. Each zone taken individually knows particular climatic situations not allowing to assimilate the results.
The econometric analysis thus reinforced our graphical analyzes and analyzes based on the detection of endogenous shocks and breaks which certainly knew the two key variables used to study the sensitivity of the climate. In trying to compare countries through this analysis of agro-ecological zones, we can finally say that all countries are aware of global warming.
It should be added that some agroecological zones in some countries have not suffered from the phenomenon of climate change. For these areas, there are no shocks or econometric indicators indicating a decrease in precipitation or a rise in temperature over the entire period, from 1901 to 2016. Countries can also be ranked according to the total number of shocks recorded by national agroecologies, as we have done above. On the other hand, this type of criterion is not optimal because the countries are different and do not have the same number of agroecological zones.
The difference between the figures of the agroecological zones makes the analysis less relevant, but allows to get a clear idea to show that such a country has experienced more localized shocks during these 112 years.
In comparison with the country analysis, this one on agroecological zones also made it possible to locate the shocks, to identify the zones more affected and to quote to a certain extent the most important agroecological zones. For example, sensitive areas (Somaliland, 5 areas of Nigeria and areas subject to a large number of shocks) to precipitation and /or temperature shocks.
In summary, the results of the estimates confirm the existence of climate change. The temperature has increased dramatically in most agroecological zones of all countries, regardless of the period. In addition, the assumption of an annual decline in rainfall over

all periods is also confirmed in most agroecological zones. Each zone taken individually knows particular climatic situations. In trying to compare countries through this analysis of agroecological zones, we can finally say that all countries are aware of global warming even if some agroecological zones of some countries have not suffered from the phenomenon of climate change. For these areas, there are no shocks or econometric indicators indicating a decrease in precipitation or a rise in temperature over the entire period, from 1901 to 2016. Countries can then be ranked according to the total number of shocks recorded by agroecological zones, as we have done above. Of course, this type of criterion is not optimal because the countries are different and do not have the same number of agroecological zones.
The difference between the number of agroecological zones per country makes the analysis less relevant but still allows us to have an idea of the location of shocks, to identify the most affected agroecological zones and to detect in a certain way the the most important agroecological zones in the country concerned.

1.8 Conclusion

Particular attention has been paid to climate and climate change issues. The global climate system is complex and difficult to identify, hence the creation of several organizations and the organization of various international meetings for several years. The establishment of these structures at different scales allows scientists, politicians and other actors to reflect on the preservation of our planet. These bodies are sensitizing and adopting mechanisms to alert them to the risks of climate change. This chapter shows that global warming has started and exists in the Sahel countries and also in their agroecological zones. This assessment highlighted the causes and effects of climate change on economies. While the estimates of the existence of climate change and its consequences may be full of uncertainties, it is clear that the Sahel countries (and their agroecological zones) have experienced a large variation in climate variables. These climate changes are the result of the interaction between the variation of climatic conditions and the anthropogenic modification on the ecosystem. As a result, several points can be raised:

- Graphical and statistical analyzes showed that the Sahel countries experienced a large change in temperature (+) and precipitation (−) over the period from 1901 to 2012. Beginning in the 1980s, the climatic consequences were enormous with low-frequency drylands weakening countries.

- Most Sahelian countries experienced a prolonged period of low rainfall in the mid-20th century, with annual average precipitation below that of the 21st century. On the other hand, there was an improvement in the late 1990s and from 2003, rainfall increased on average.

- From the end of our study period (year 2010), all countries in the Sahel experienced a slight increase in rainfall.

- The rainfall analysis during the vegetative period has shown that rainfall amounts have varied annually over the period. This trend strongly explains why countries have had a hard time responding to a rainy farming practice. This inter-annual variability may thus justify the decline in agricultural production in these countries.

- The analysis of agroecological zones shows that those receiving a large amount of rainfall are the same with the greatest interannual variability over the entire analysis period. This reasoning is also valid for the temperature of agroecological zones. The hottest areas with high temperatures are those with very variable temperatures over the period.
- It also appears a contrasted result far from the idea that a high temperature is a source of precipitation. Otherwise, the hottest years are those that record a great deal of rain. Indeed, the graphical and econometric results show that an increase in temperature is not always accompanied by a rise in total and seasonal precipitation.
- It also shows that desert areas are the warmest but have the lowest annual minimum temperatures for all agroecological zones and for all countries.

This analysis shows that there were more shocks to temperature in agroecological zones than precipitation. Desert and arid areas are those that recorded a large number of shocks over the period, with the exception of Nigeria with wetlands and non-desert areas that have experienced several shocks. In general, periods of heat wave were frequent as floods or droughts.

At the level of agroecological zones, we show that the Sahara or Desert areas have experienced early climate shocks. As a result, climatic changes began with desert areas before reaching slightly humid areas given the contrasting initial conditions of the dry zones.

The analysis at the level of agroecological zones made it possible to say that climate change started very early at the level of the agroecological zones however this precocity is not observed in the analysis at the level of the countries. Climate change started early in climate zones before being felt at the level of countries and agroecological zones.

After having shown that climate change has started well at the level of Sahelian countries and agroecological zones and that the effects are heterogeneous between the two geographical entities, we assess in the following chapter the link between this secular phenomenon and Sahelian agriculture.

1.9 Appendix

Table 1.7Results of homogeneity tests of intercepts and slopes between agroecological zones

Country	Model	RainSum	RSeason	TminRain	TmedRain	TmaxRain	TminDry	TmedDry	TmaxDry
Burkina	Global test	218.763***	87.654***	127.353***	240.727***	277.685***	57.144***	25.268***	71.298***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	Intercept	0.351	0.153	0.024	0.341	0.063	0.068	0.116	0.08
		(0.928)	(0.928)	(0.995)	(0.796)	(0.979)	(0.977)	(0.951)	(0.971)
	Slope	0.162	0.286	0.015	0.046	0.118	0.032	0.124	0.123
		(0.836)	(0.836)	(0.998)	(0.987)	(0.95)	(0.992)	(0.946)	(0.946)
Chad	Global test	1955.192***	1072.471***	471.778***	478.727***	627.953***	808.657***	524.282***	131.698***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	Intercept	2.264	2.524	0.262	0.038	0.203	0.626	2.76	1.042
		(0.082)	(0.082)	(0.77)	(0.963)	(0.816)	(0.535)	(0.065)	(0.354)
	Slope	0.261	0.647	1.057	0.457	1.009	0.079	1.649	0.632
		(0.524)	(0.524)	(0.349)	(0.633)	(0.366)	(0.924)	(0.194)	(0.532)
Djibouti	Global test	23.336***	26.039***	249.009***	293.692***	245.896***	111.602***	66.883***	294.546***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	Intercept	0.171	0.093	0.357	0.382	0.03	0.068	0.55	0.731
		(0.911)	(0.911)	(0.7)	(0.683)	(0.97)	(0.934)	(0.577)	(0.482)
	Slope	0.092	0.037	0.075	0.059	0.06	0.187	0.296	0.217
		(0.963)	(0.963)	((0.928)	(0.943)	(0.942)	(0.829)	(0.744)	(0.805)
Ethiopia	Global test	216.231***	260.674***	1991.914***	2053.064***	1589.352***	2054.893***	2966.679***	1614.043***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	Intercept	0.3	0.799	2.511	3.012***	3.232	2.797***	4.344***	1.365
		(0.571)	(0.571)	(0.021)	(0.006)	(0.004)	(0.011)	(0.000)	(0.226)
	Slope	0.241	0.305	1.286	2.545**	3.062	3.641***	4.756***	(1.241)
		(0.935)	(0.935)	0.261	(0.019)	(0.006)	(< 0.001)	(< 0.001)	(0.283)
Mali	Global test	1134.442***	934.505***	1240.05***	1879.042***	921.545***	502.984***	181.355***	80.898***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	Intercept	15.364***	10.105***	0.463	0.672	0.239	4.791***	10.537***	1.251
		(< 0.001)	(< 0.001)	(0.708)	(0.569)	(0.869)	(0.003)	(0.000)	(0.291)
	Slope	9.767***	6.015***	2.193*	0.774	0.77	2.859***	9.978***	1.512
		(< 0.001)	(< 0.001)	(0.088)	(0.509)	(0.511)	0.037	(< 0.001)	(0.211)
Mauritania	Global test	491.811***	439.371***	1589.343***	2088.576***	1965.944***	260.33***	427.201***	610.632***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	Intercept	10.702***	13.661***	1.877	4.083	1.207	0.427	1.229	12.473***
		(0.000)	(0.000)	(0.133)	(0.007)	(0.307)	0.734	(0.299)	(< 0.001)
	Slope	7.504***	10.204***	4.175	7.966***	3.384***	0.125	0.735	16.393***
		(0.000)	(0.000)	(0.006)	(0.000)	(0.018)	(0.946)	(0.532)	(< 0.001)
Niger	Global test	100.679***	61.535***	18.613***	33.154***	25.644***	111.41***	8.32***	14.559***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	Intercept	1.645	0.954	0.219	0.617	0.37	1.724	1.394	0.672
		(0.432)	(0.432)	(0.928)	(0.65)	(0.83)	(0.143)	(0.235)	(0.612)
	Slope	1.19	0.681	0.286	0.821	0.367	2.429**	1.516	0.801
		(0.605)	(0.605)	(0.887)	(0.512)	(0.832)	(0.047)	(0.196)	(0.525)
Nigeria	Global test	828.295***	701.534***	118.074***	328.835***	433.995***	170.174***	138.164***	44.011***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	Intercept	2.493	1.083	1.248	0.225	0.462	0.564	0.881	1.152
		(0.368)	(0.368)	(0.285)	(0.952)	(0.805)	(0.728)	(0.493)	(0.331)
	Slope	0.944	0.284	1.848	0.756	1.043	0.668	0.628	0.926
		(0.922)	(0.922)	(0.101)	(0.582)	(0.391)	(0.648)	(0.678)	(0.463)
Senegal	Global test	284.561***	223.206***	284.971***	340.353***	350.376***	88.637***	292.566***	461.119***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	Intercept	3.46	3.638	1.549	1.819	1.871*	0.364	3.852	3.364
		(0.003)	(0.003)	(0.173)	(0.107)	(0.097)	(0.873)	(0.002)	(0.005)
	Slope	2.343**	2.8**	1.182	1.368	2.513***	0.207	3.327***	4.789***
		(0.016)	(0.016)	(0.316)	(0.234)	(0.029)	0.96	(0.006)	(< 0.001)
Somalia	Global test	157.575***	139.65***	114.505***	86.806***	493.524***	328.227***	112.508***	713.257***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	Intercept	0.574	1.513	7.546***	3.013	8.01***	4.568	6.985***	7.945***
		(0.197)	(0.197)	(< 0.001)	(0.018)	(0.000)	0.001	(< 0.001)	(< 0.001)
	Slope	0.333	1.068	8.166***	2.505**	5.874***	6.373***	7.714***	5.448***
		(0.371)	(0.371)	(< 0.001)	(0.041)	(0.000)	< 0.001	(< 0.001)	(< 0.001)
Sudan	Global test	1690.987***	853.298***	679.158***	670.067***	898.081***	316.037***	105.898***	75.187***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	Intercept	1.495	1.861	1.067	1.062	1.273	1.11	1.554	4.310***
		(0.116)	(0.116)	(0.372)	(0.374)	(0.279)	(0.351)	(0.185)	(< 0.001)
	Slope	0.234	0.918	1.226	0.973	0.17	2.102*	1.966*	3.983***
		(0.453)	(0.453)	(0.298)	(0.422)	(0.954)	(0.079)	(0.098)	(< 0.001)
Note:									*p<0.1; **p<0.05; ***p<0.01

Figure 1.21 Annual temperature during the rainy season in the agroecological zones of Burkina Faso from 1901 to 2016.

Figure 29.a: Minimum annual temperature

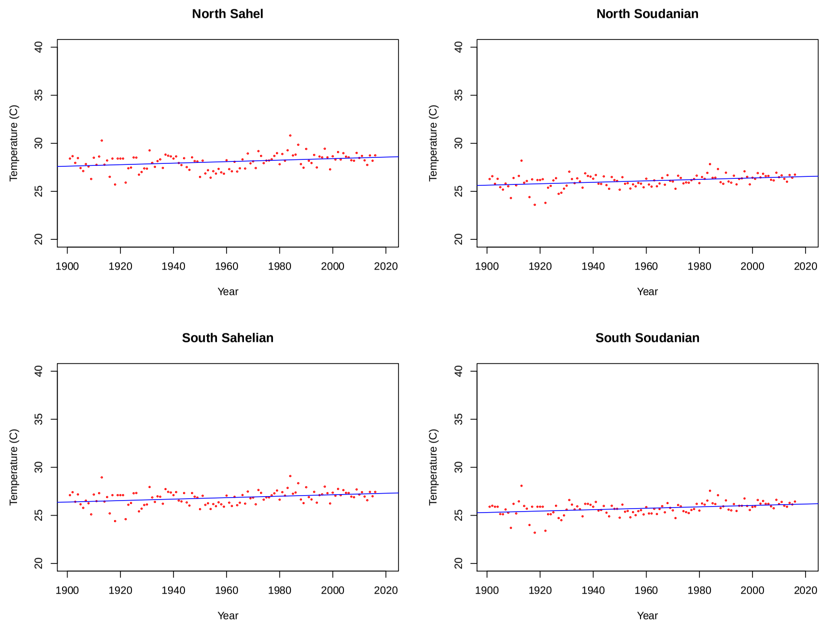


Figure 29.b: Median annual temperature

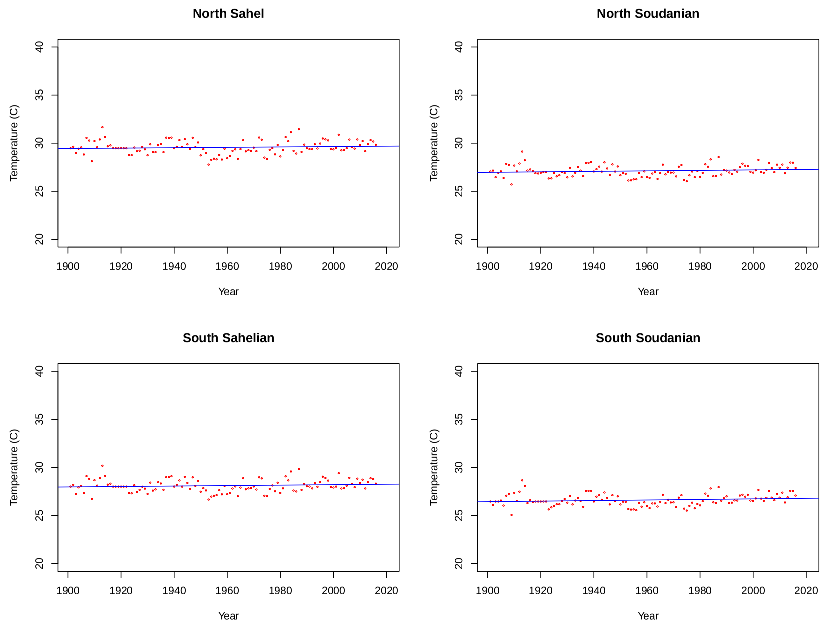
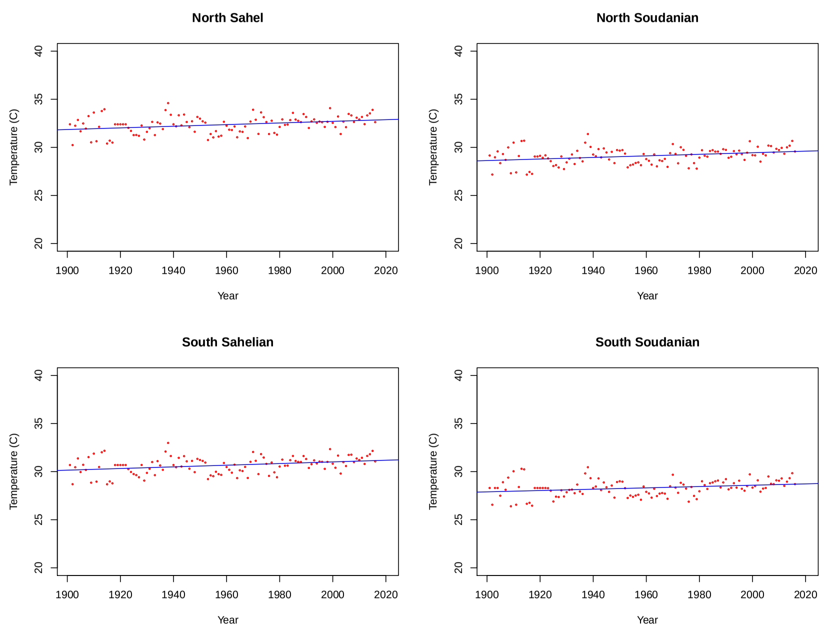


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.22Annual temperature during the dry season in the agroecological zones of Burkina Faso from 1901 to 2016.

Figure 29.a: Minimum annual temperature

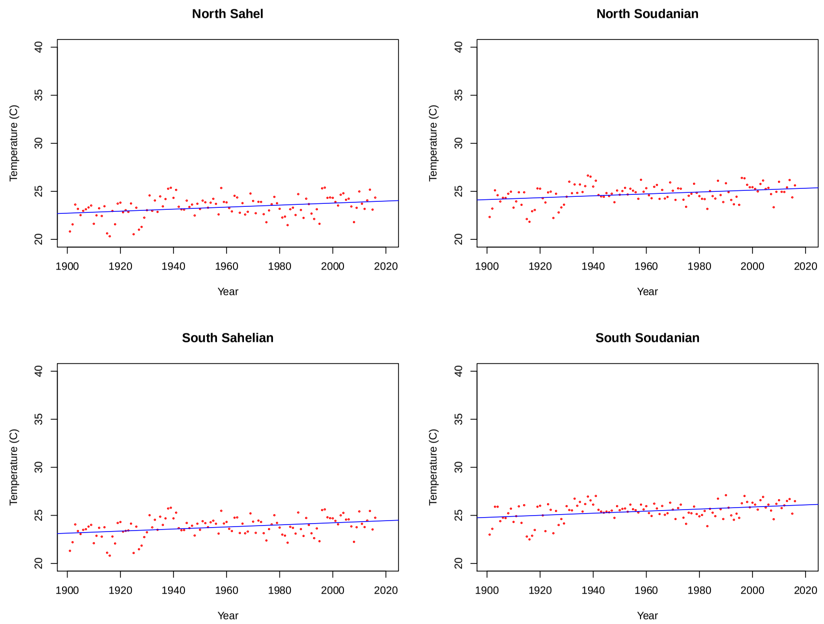


Figure 29.b: Median annual temperature

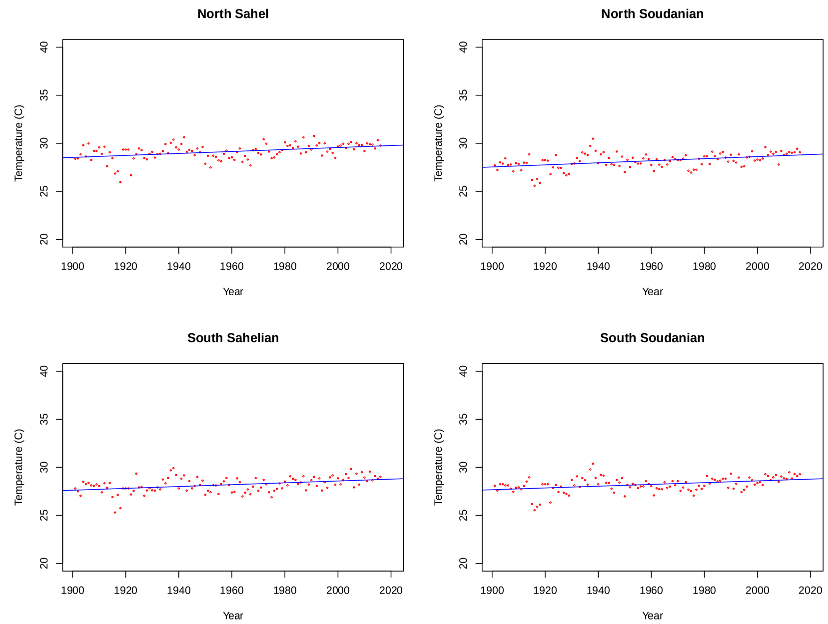
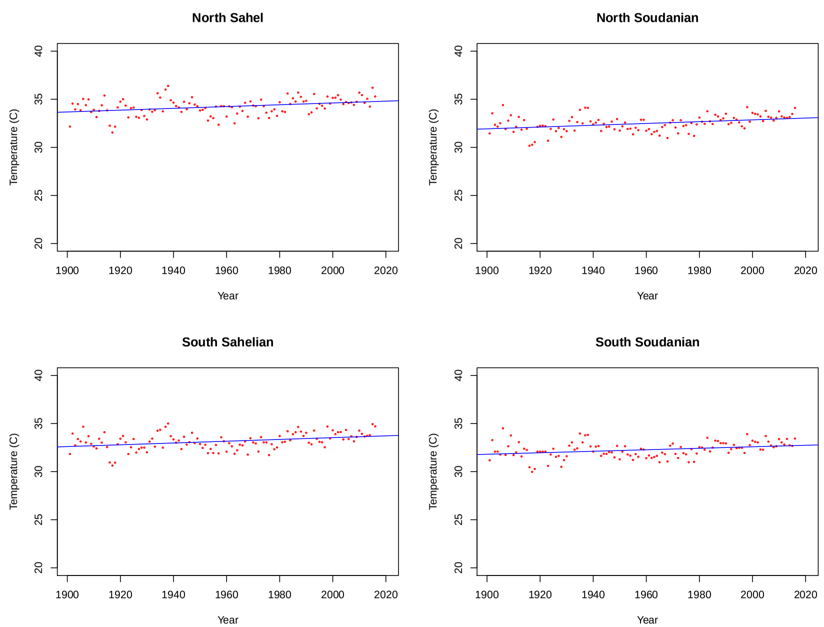


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.23Endogenous detection of structural breaks in agroecological zones of Burkina Faso during the rainy season from 1901 to 2012

Figure 29.a: Minimum annual temperature

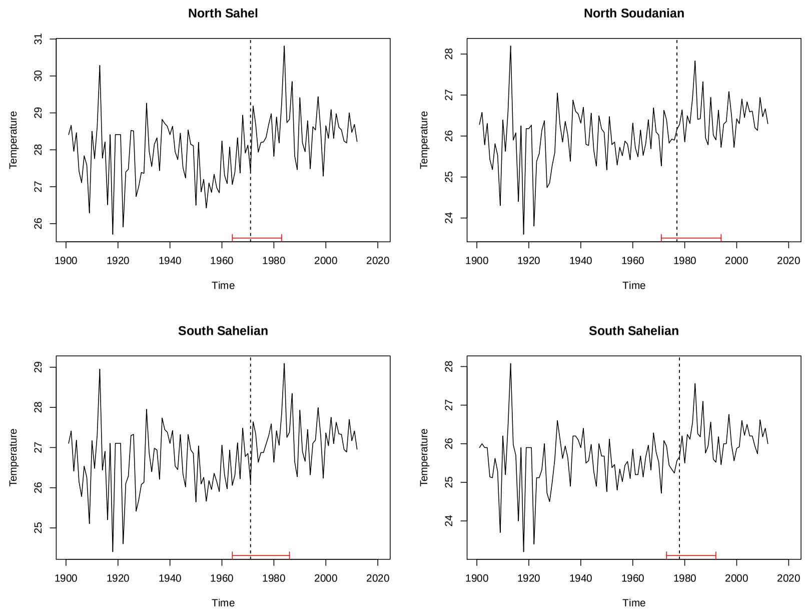


Figure 29.b: Median annual temperature

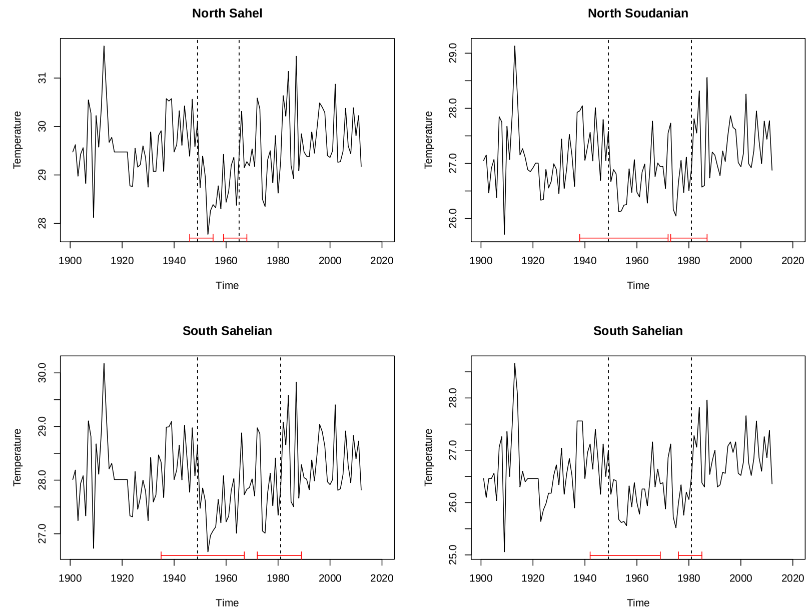
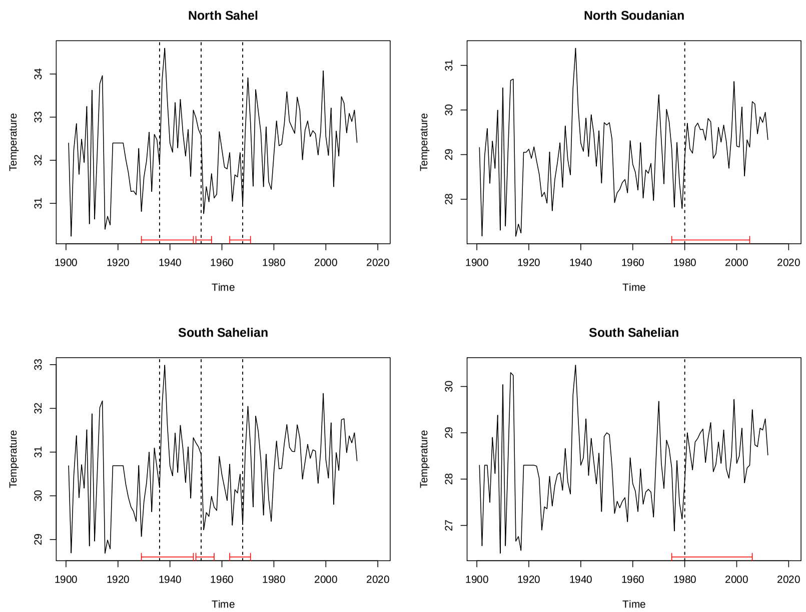


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.24Endogenous detection of structural breaks in agroecological zones of Burkina Faso during the rainy season from 1901 to 2012

Figure 29.a: Minimum annual temperature

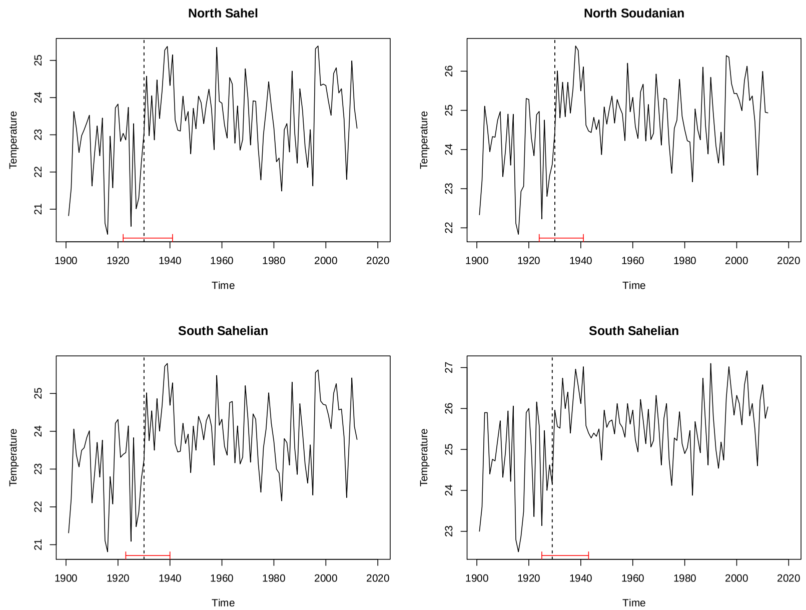


Figure 29.b: Median annual temperature

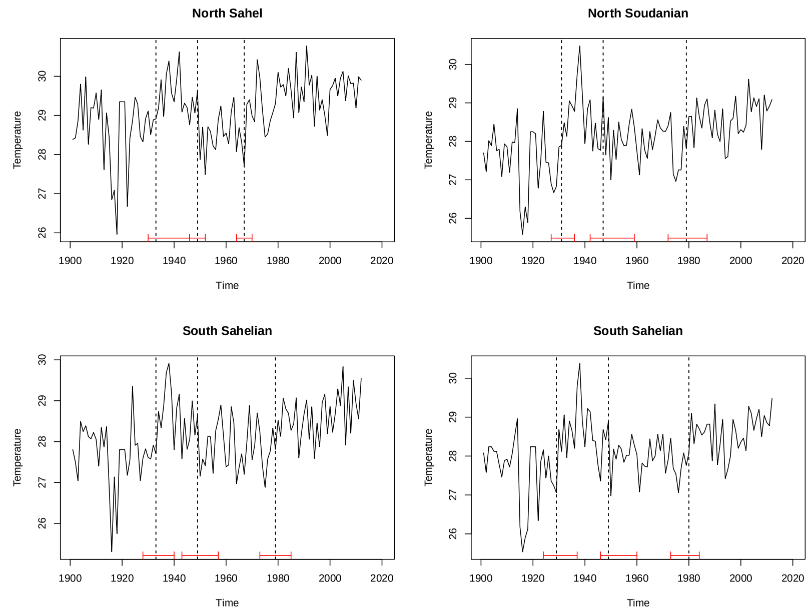
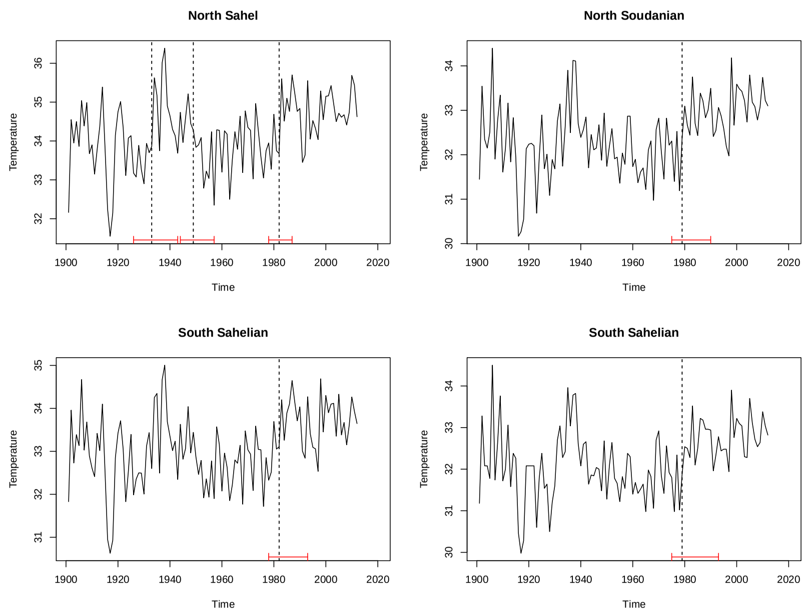


Figure 29.c: Maximum annual temperature



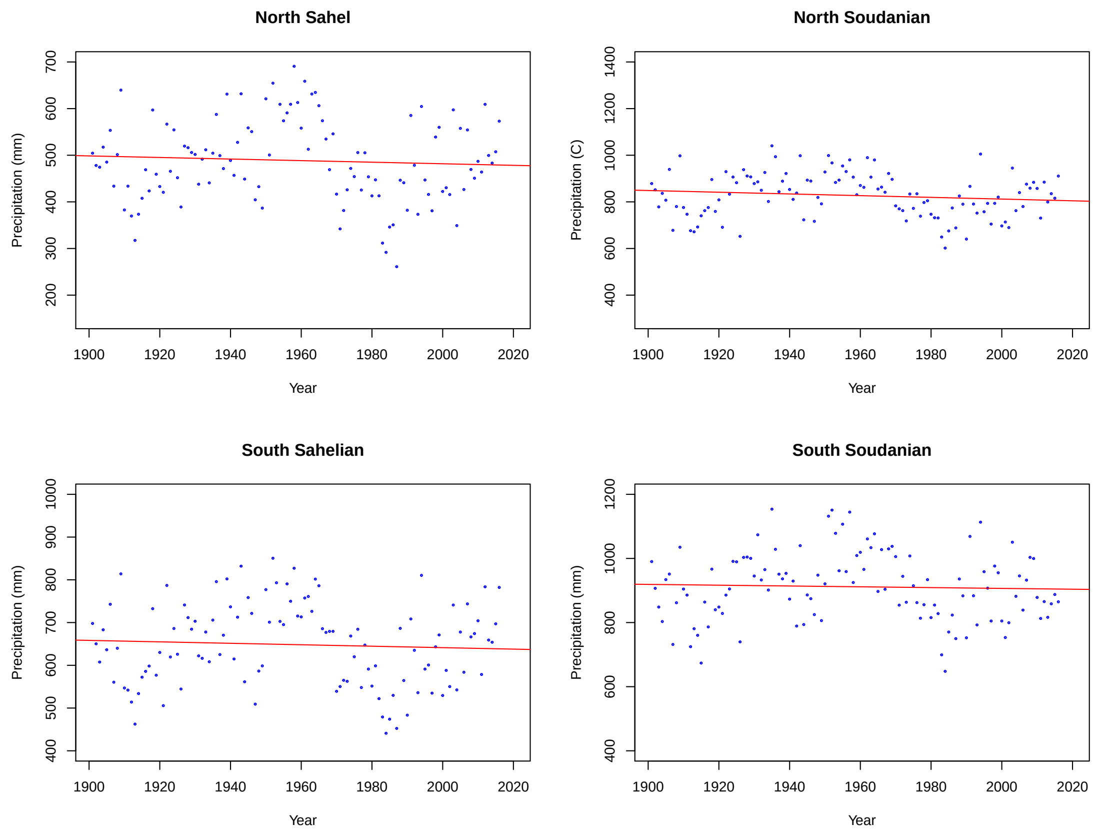
Source: Calculations and achievements by the author

Table 1.8Estimated results for Burkina Faso

	North Sahel							
	Rainfall		Temperature					
	RainSum	RainSeason	TempminRain	TempmedRain	TempmaxRain	TempminDry	TempmedRain	TempmaxDry
Year	−0.168	−0.063	0.008***	0.002	0.009***	0.011***	0.002	0.009***
	(0.251)	(0.065)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)
Constant	818.276*	243.271*	12.617***	25.620***	15.684***	2.745	25.620***	15.911***
	(492.538)	(126.625)	(4.343)	(3.859)	(4.618)	(5.557)	(3.859)	(4.547)
R^2	0.004	0.008	0.100	0.009	0.103	0.108	0.009	0.125
	North Soudanian							
Year	−0.367	−0.042	0.008***	0.003	0.008***	0.010***	0.003	0.009***
	(0.259)	(0.057)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	1,546.927***	256.273**	11.358***	22.189***	13.136***	5.450	22.189***	14.206***
	(507.124)	(111.539)	(3.427)	(3.168)	(4.289)	(4.889)	(3.168)	(4.184)
R^2	0.017	0.005	0.139	0.021	0.108	0.120	0.021	0.143
	South Sahelian							
Year	−0.170	−0.027	0.008***	0.002	0.009***	0.011***	0.002	0.009***
	(0.267)	(0.065)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)
Constant	981.535*	203.802	11.943***	23.495***	13.819***	2.609	23.495***	14.925***
	(522.340)	(127.818)	(3.865)	(3.560)	(4.470)	(5.257)	(3.560)	(4.359)
R^2	0.004	0.002	0.115	0.015	0.111	0.125	0.015	0.133
	South soudanian							
Year	−0.125	0.017	0.007***	0.003*	0.007***	0.011***	0.003*	0.008***
	(0.299)	(0.064)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	1,156.618*	149.563	11.373***	20.868***	14.764***	4.183	20.868***	17.037***
	(585.128)	(124.474)	(3.536)	(3.243)	(4.384)	(4.741)	(3.243)	(4.261)
R^2	0.002	0.001	0.126	0.027	0.077	0.150	0.027	0.101
Observations	116	116	116	116	116	116	116	116
Model	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS

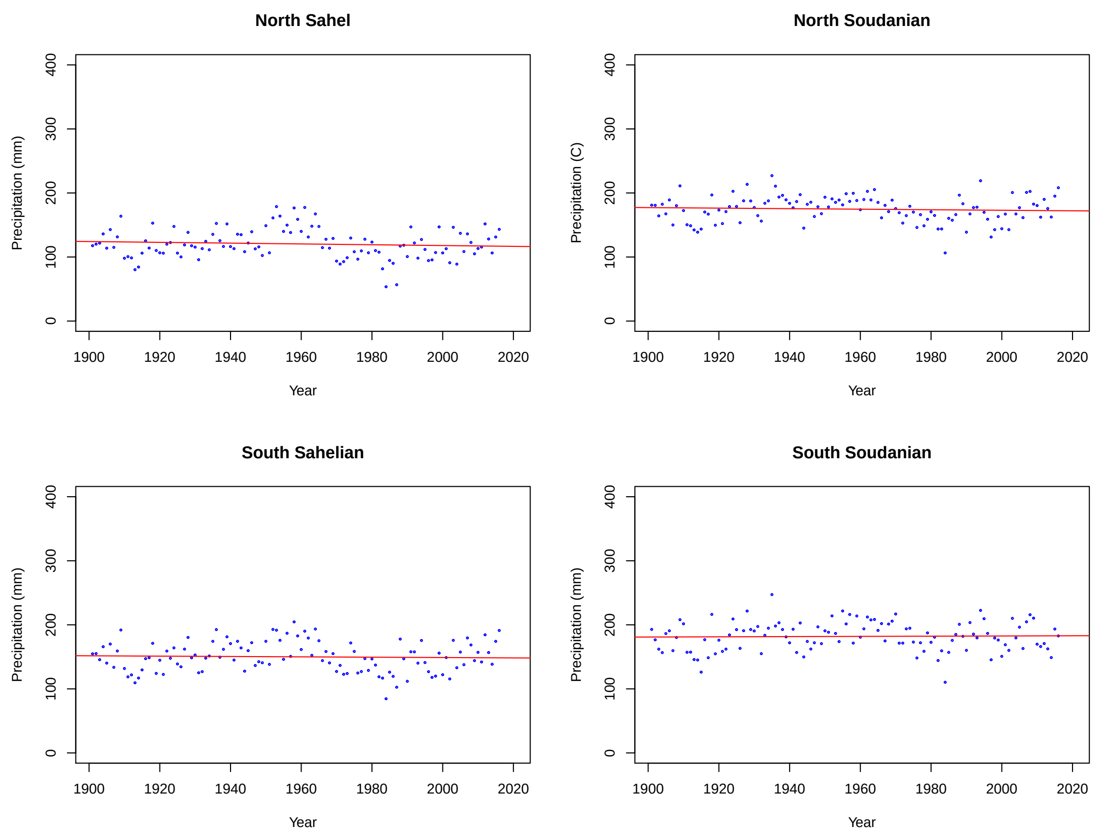
Note: *p<0.1; **p<0.05; ***p<0.01

Figure 1.25 Evolution of the sum annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Burkina Faso



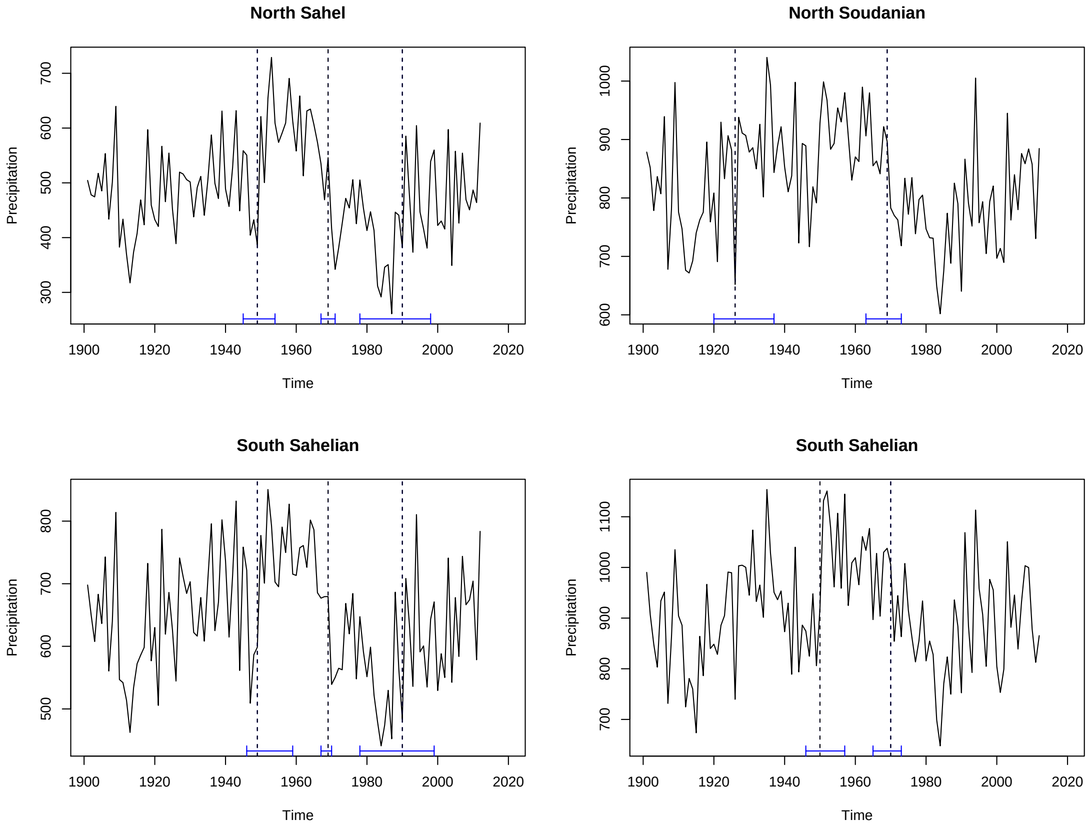
Source: Calculations and achievements of the author

Figure 1.26 Evolution of the seasonal annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Burkina Faso.



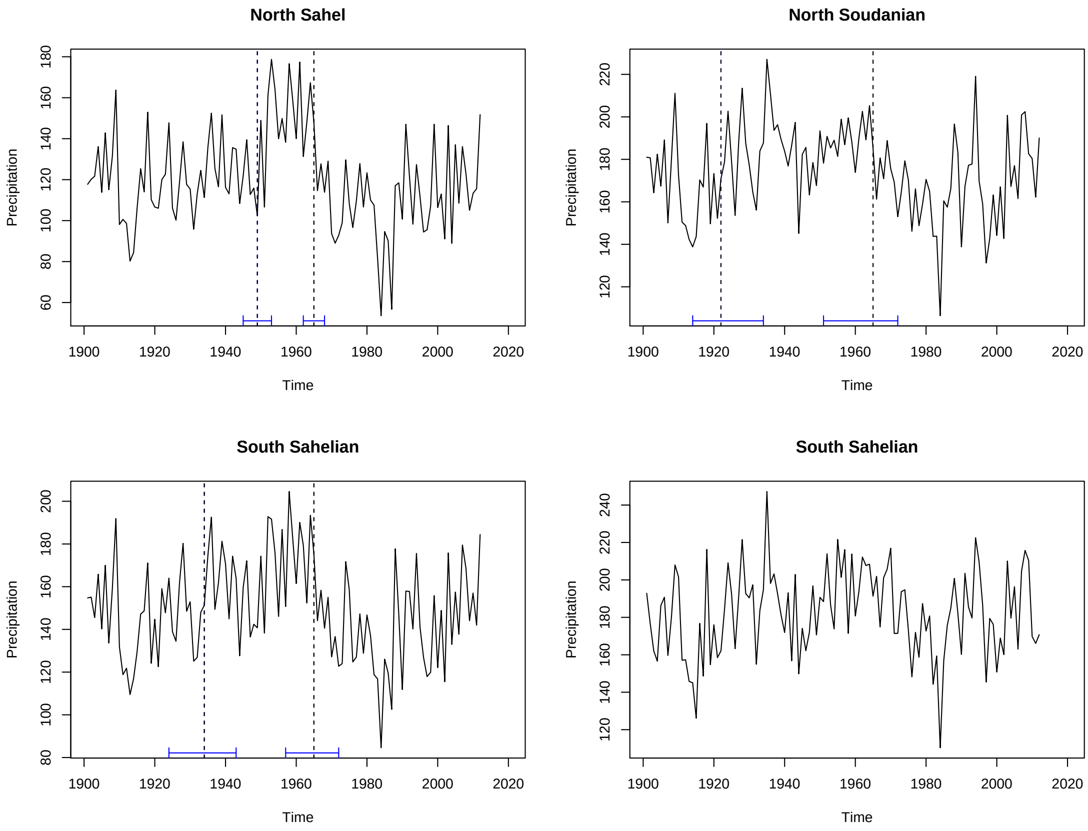
Source: Calculations and achievements of the author

Figure 1.27Breaks in total annual precipitation in the agroecological zones of Burkina Faso.



Source: Calculations and achievements of the author

Figure 1.28Breaks on seasonal precipitation in the agroecological zones of Burkina Faso.



Source: Calculations and achievements of the author

Figure 1.29Annual temperature during the rainy season in the agroecological zones of Chad from 1901 to 2016.

Figure 29.a: Minimum annual temperature

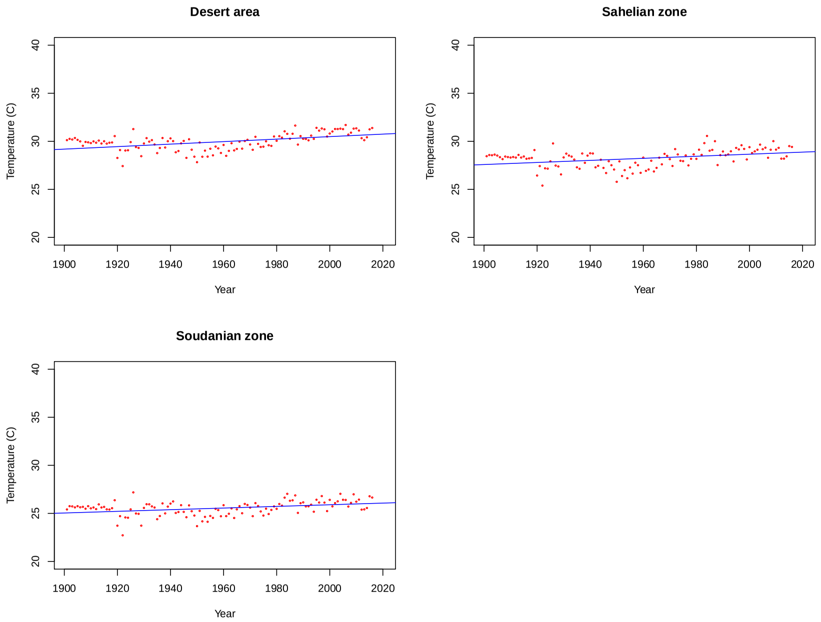


Figure 29.b: Median annual temperature

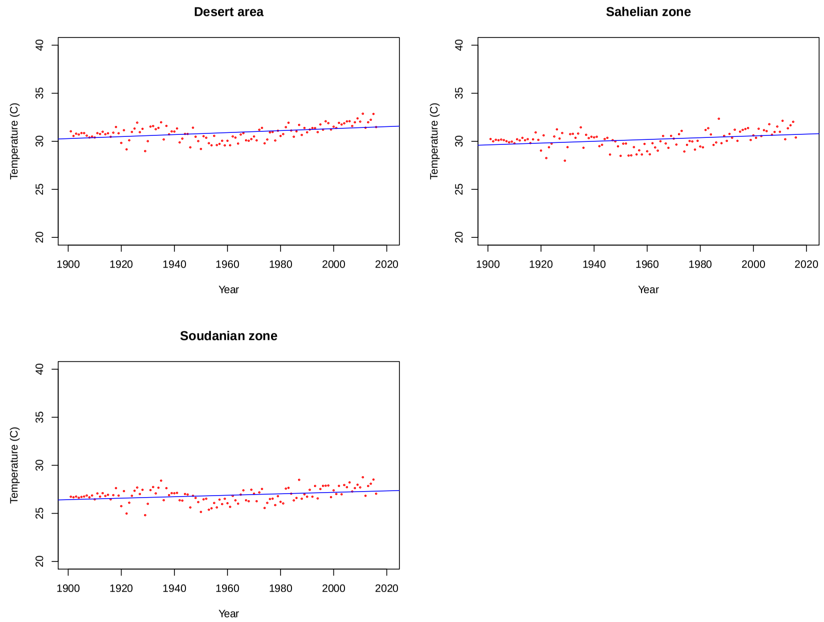
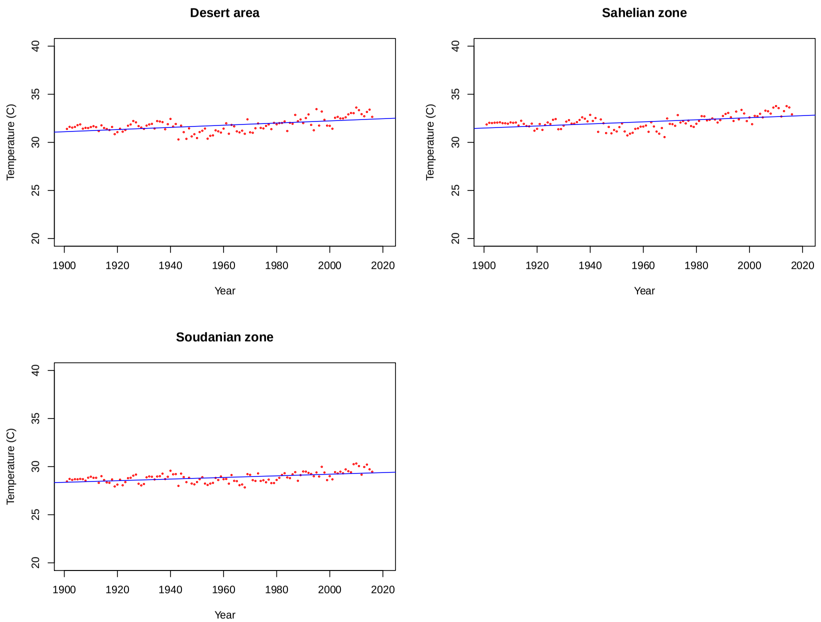


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.30Annual temperature during the dry season in the agroecological zones of Chad from 1901 to 2016.

Figure 29.a: Minimum annual temperature

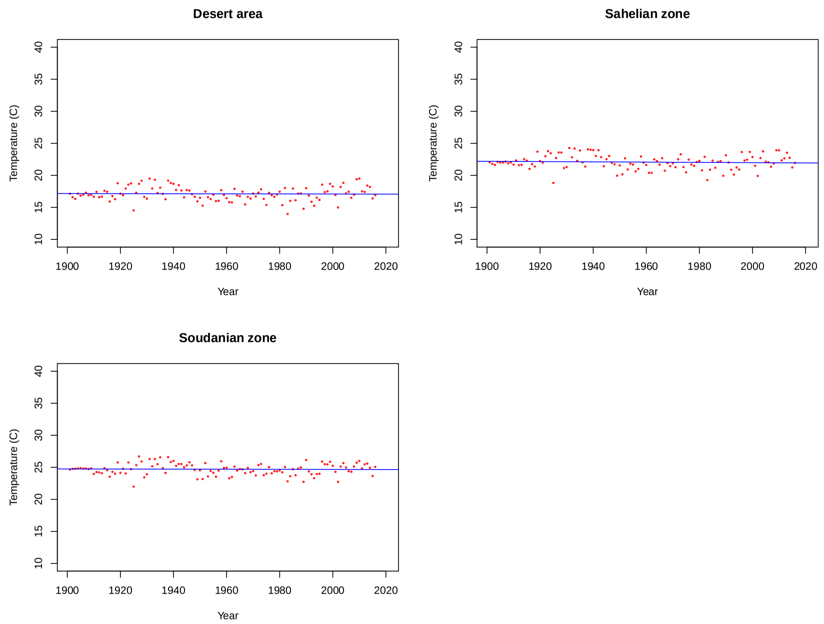


Figure 29.b: Median annual temperature

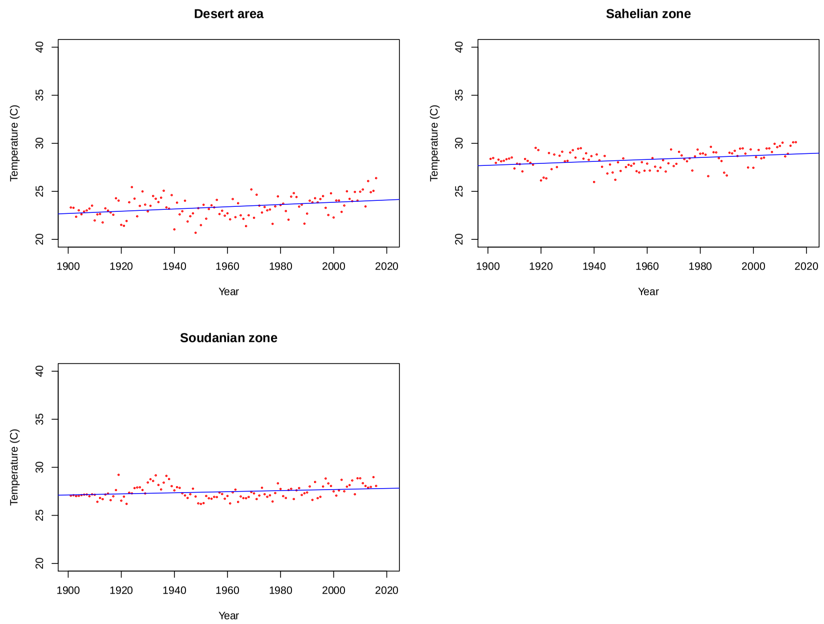
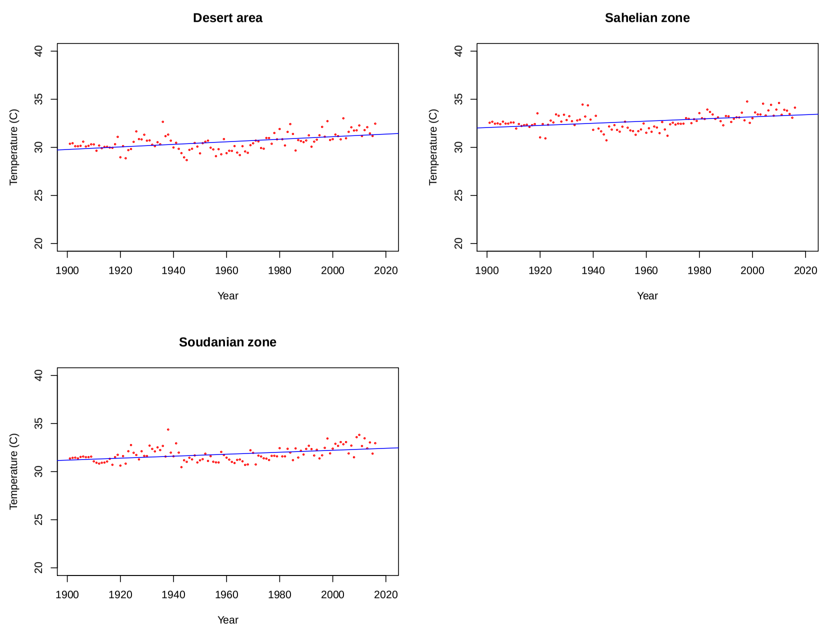


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.31 Endogenous detection of structural breaks in agroecological zones of Chad during the rainy season from 1901 to 2012

Figure 29.a: Minimum annual temperature

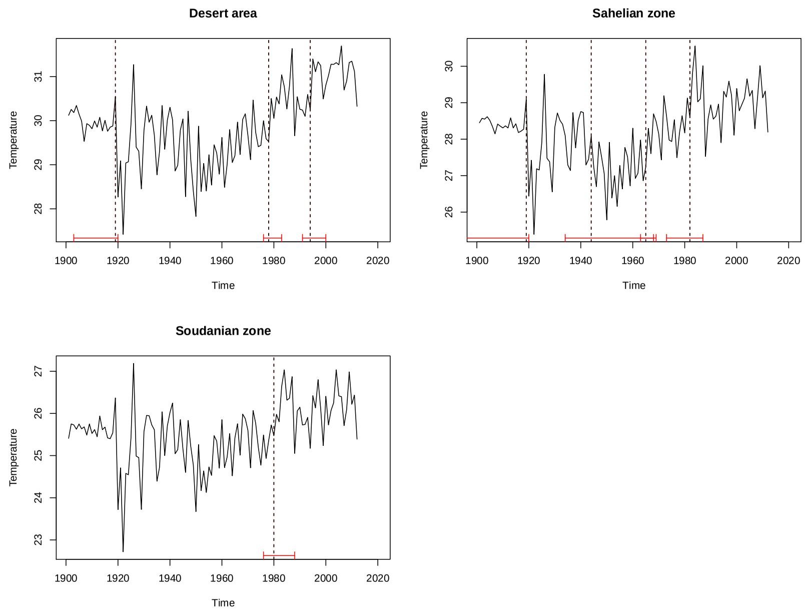


Figure 29.b: Median annual temperature

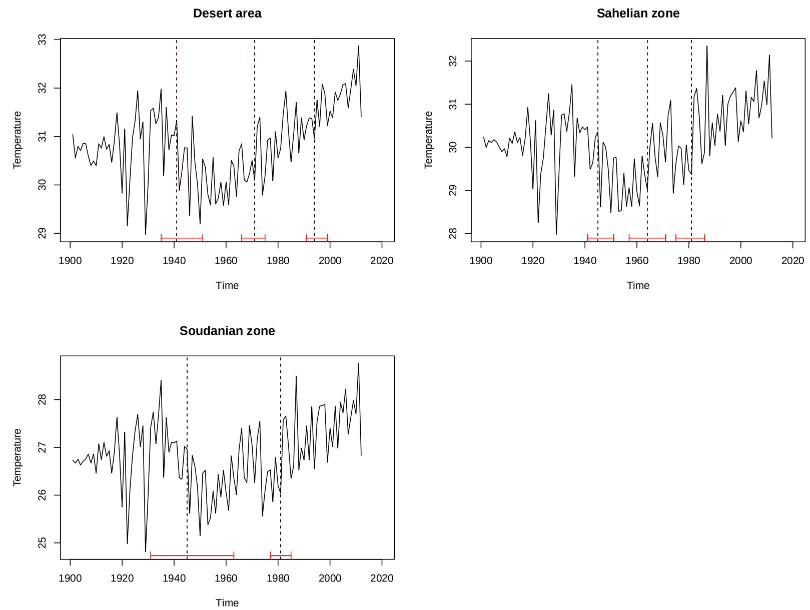
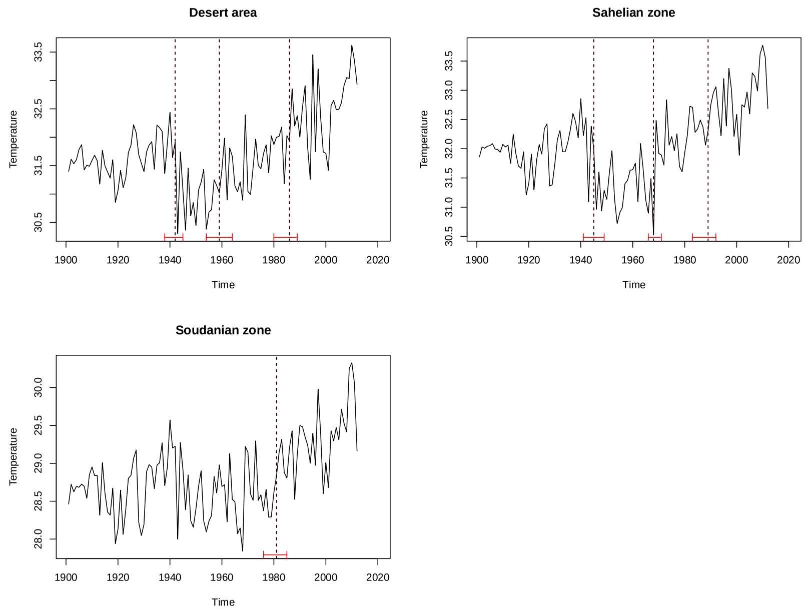


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.32 Endogenous detection of structural breaks in agroecological zones of Chad during the dry season from 1901 to 2012

Figure 29.a: Minimum annual temperature

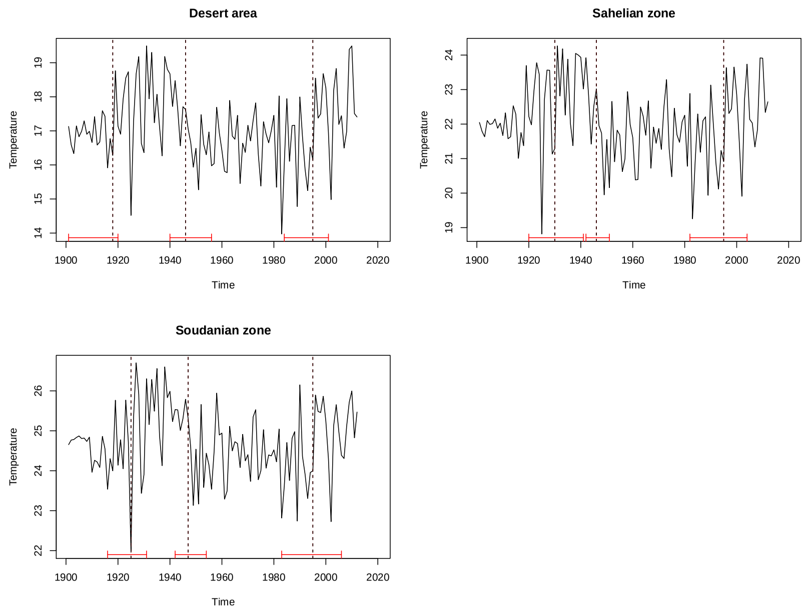


Figure 29.b: Median annual temperature

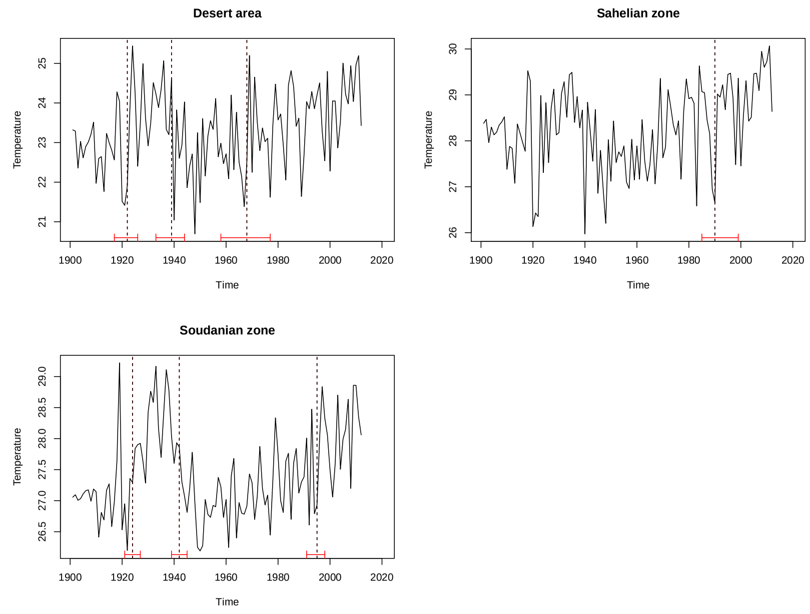
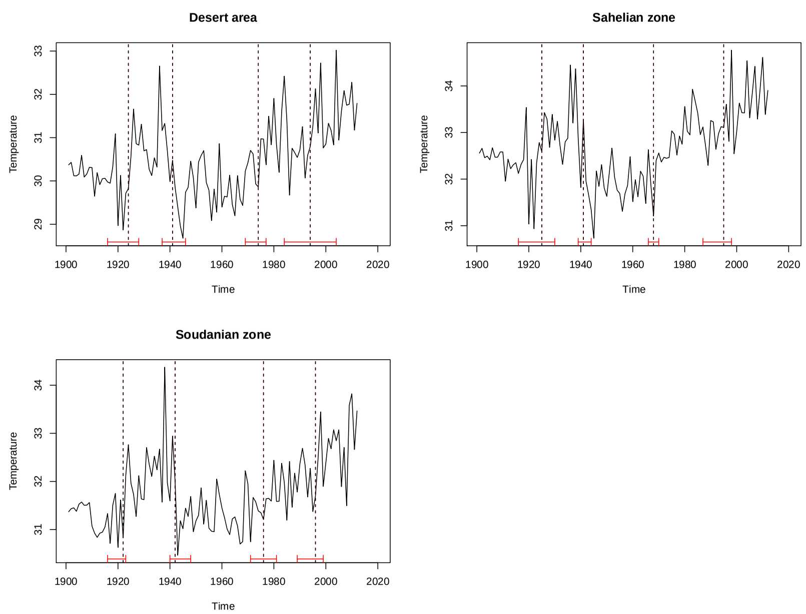


Figure 29.c: Maximum annual temperature



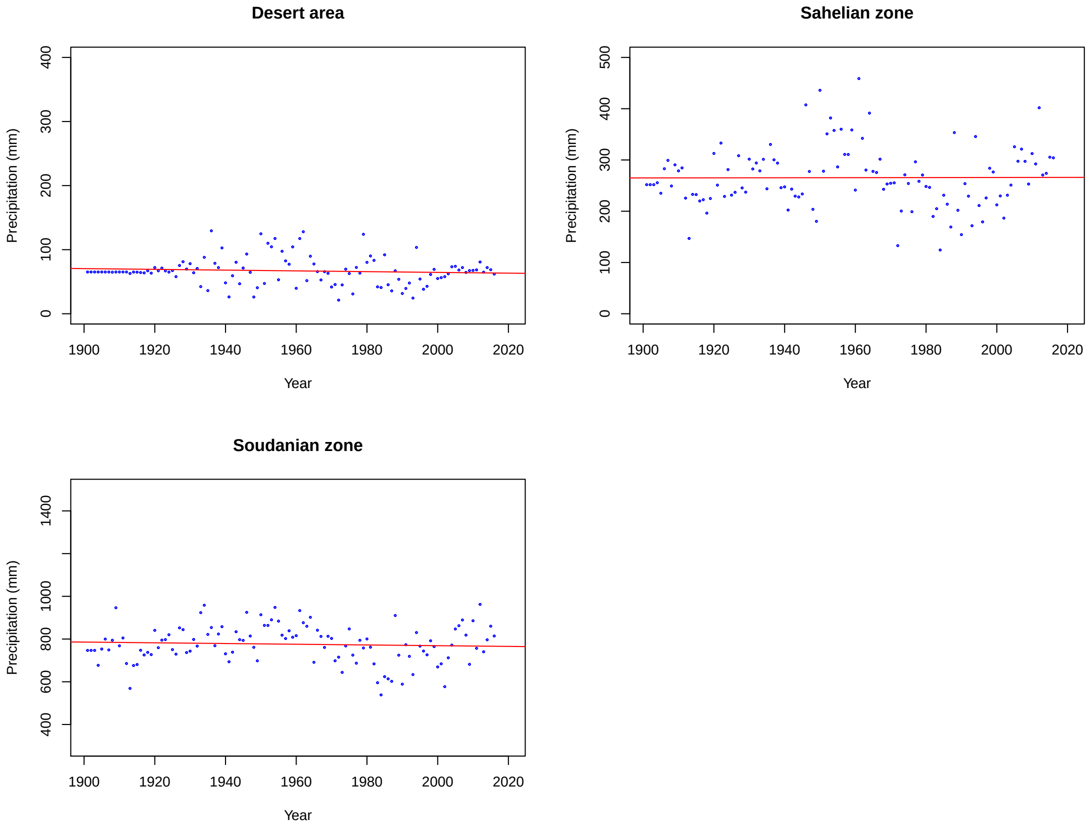
Source: Calculations and achievements by the author

Table 1.9Estimated results for Chad

	Rainfall		Temperature					
	RainSum	RainSeason	TempminRain	TempmedRain	TempmaxRain	TempminDry	TempmedRain	TempmaxDry
	Dependent variable: Desert area							
Year	−0.059	−0.024	0.013***	0.010***	0.011***	−0.001	0.010***	0.013***
	(0.061)	(0.019)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)
Constant	183.009	62.482*	4.473	10.546***	9.694***	18.513***	10.546***	4.456
	(118.705)	(37.400)	(4.121)	(3.858)	(3.219)	(5.887)	(3.858)	(4.123)
R^2	0.008	0.013	0.251	0.196	0.292	0.0005	0.196	0.260
	Dependent variable: Sahelian zone							
Year	−0.168	−0.038	0.009***	0.008***	0.008***	−0.001	0.008***	0.010***
	(0.246)	(0.051)	(0.002)	(0.002)	(0.001)	(0.002)	(0.002)	(0.002)
Constant	1,105.907**	148.039	8.761**	11.954***	12.351***	26.172***	11.954***	11.693***
	(480.889)	(100.594)	(3.828)	(3.928)	(2.403)	(4.873)	(3.928)	(3.627)
R^2	0.004	0.005	0.144	0.112	0.293	0.001	0.112	0.212
	Dependent variable: Soudanian zone							
Year	−0.168	−0.100	0.009***	0.008***	0.008***	−0.001	0.008***	0.010***
	(0.246)	(0.068)	(0.002)	(0.002)	(0.001)	(0.002)	(0.002)	(0.002)
Constant	1,105.907**	367.780***	8.761**	11.954***	12.351***	26.172***	11.954***	11.693***
	(480.889)	(134.011)	(3.828)	(3.928)	(2.403)	(4.873)	(3.928)	(3.627)
R^2	0.004	0.018	0.144	0.112	0.293	0.001	0.112	0.212
Observations	116	116	116	116	116	116	116	116
Model	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS

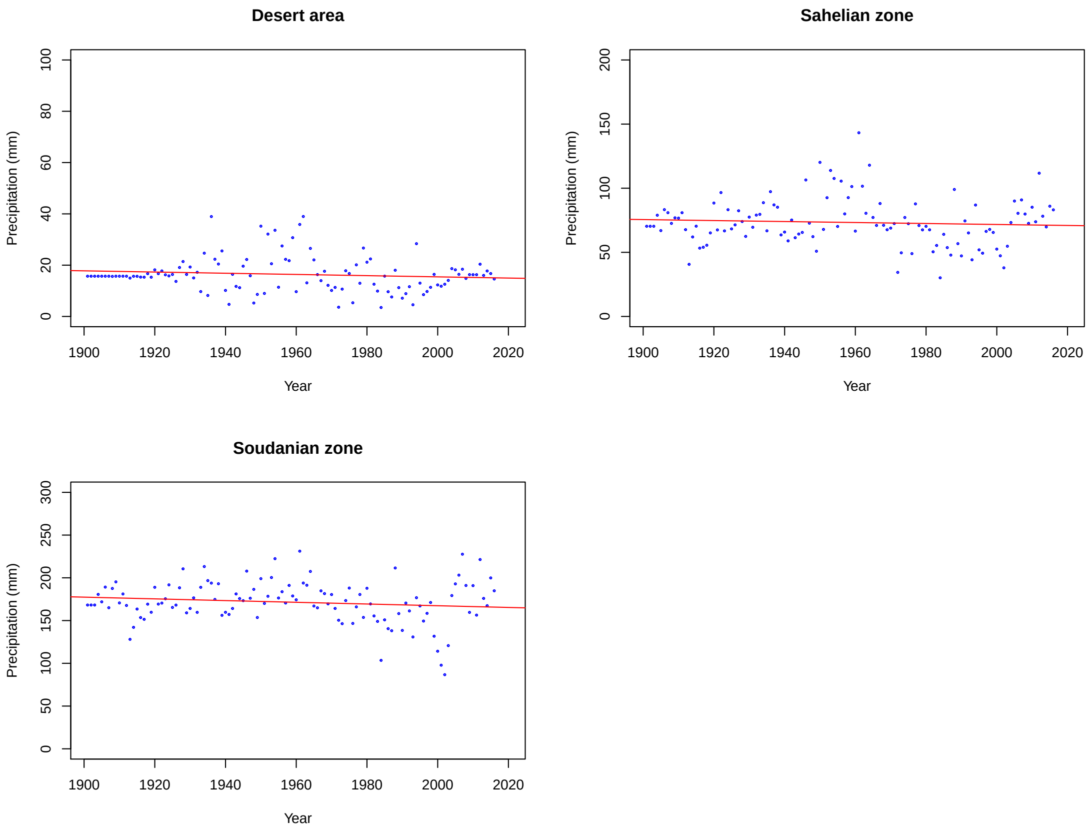
Note: *p<0.1; **p<0.05; ***p<0.01

Figure 1.33Evolution of the sum annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Chad



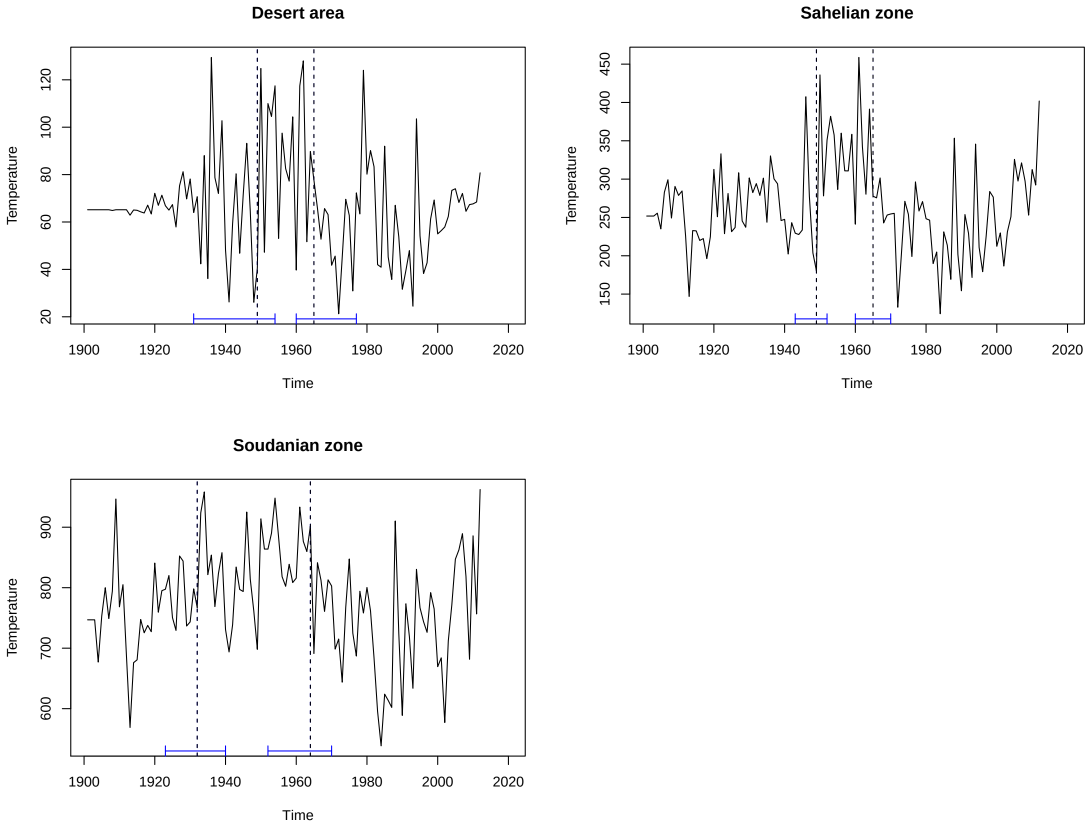
Source: Calculations and achievements of the author

Figure 1.34Evolution of the seasonal annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Chad.



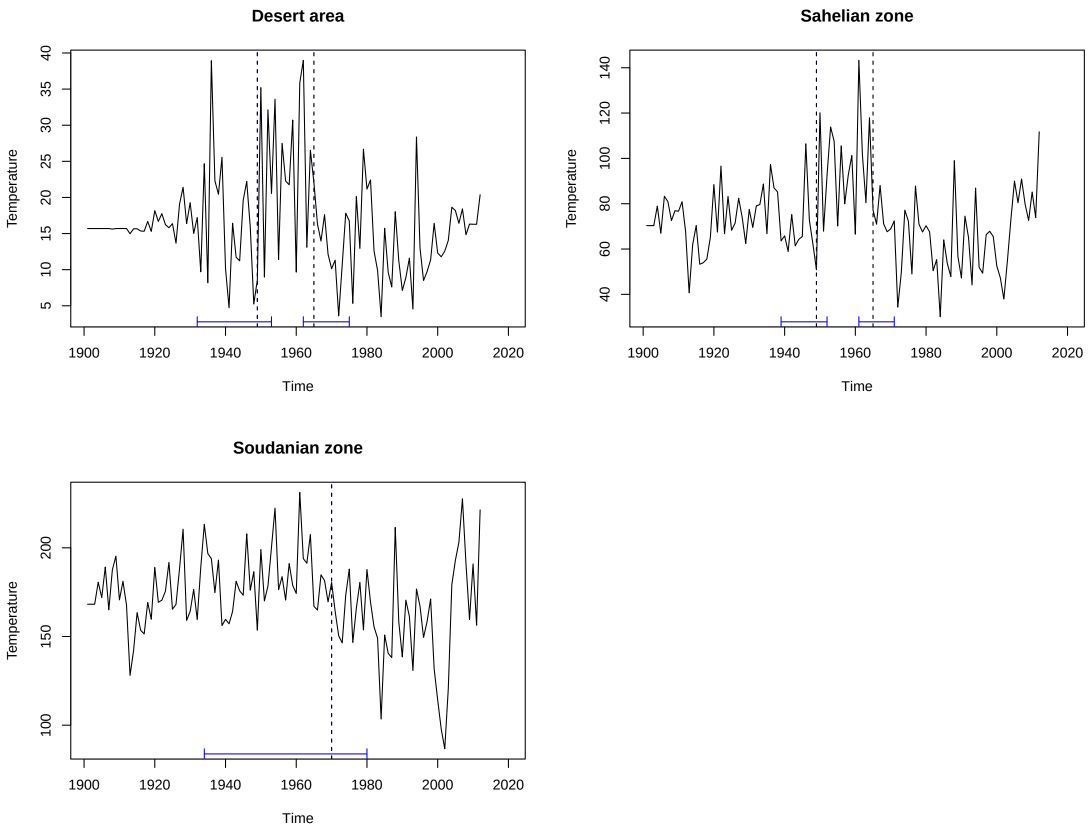
Source: Calculations and achievements of the author

Figure 1.35Breaks in total annual precipitation in the agroecological zones of Chad.



Source: Calculations and achievements of the author

Figure 1.36Breaks on seasonal precipitation in the agroecological zones of Chad.



Source: Calculations and achievements of the author

Figure 1.37 Annual temperature during the rainy season in the agroecological zones of Djibouti from 1901 to 2016.

Figure 45.a: Minimum annual temperature

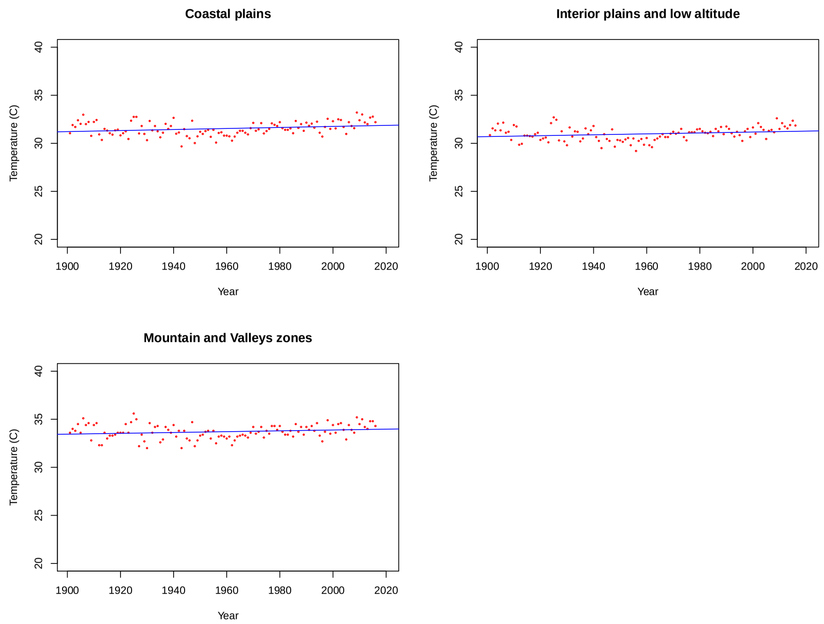


Figure 45.b: Median annual temperature

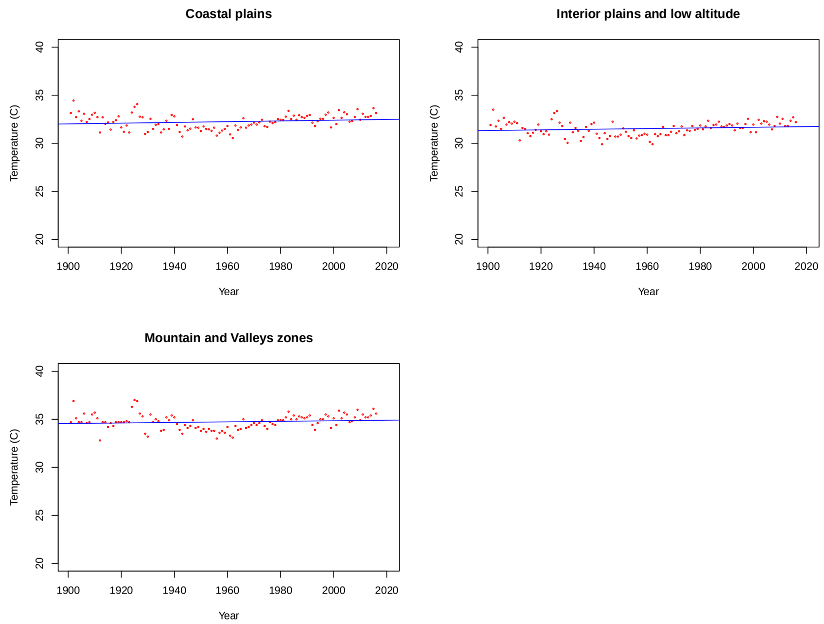
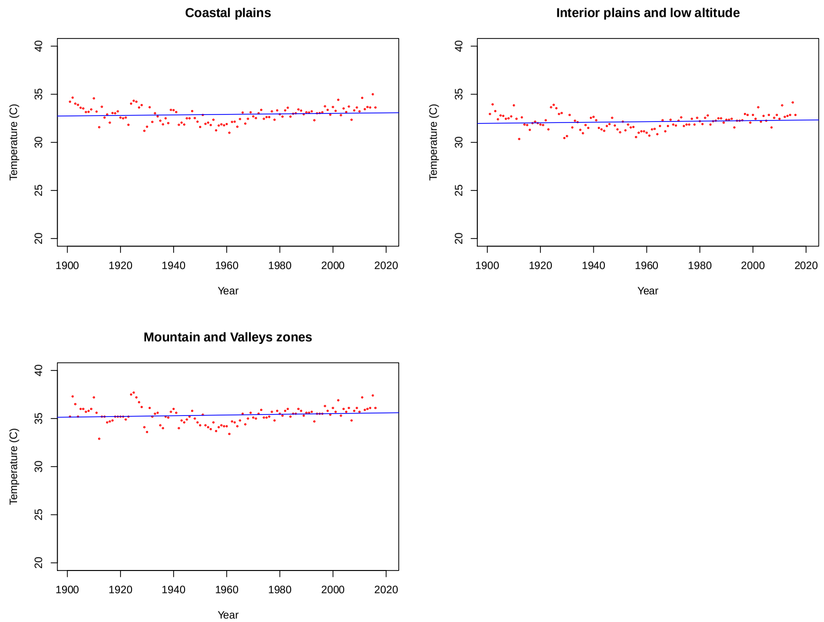


Figure 45.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.38 Annual temperature during the dry season in the agroecological zones of Djibouti from 1901 to 2016.

Figure 46.a: Minimum annual temperature

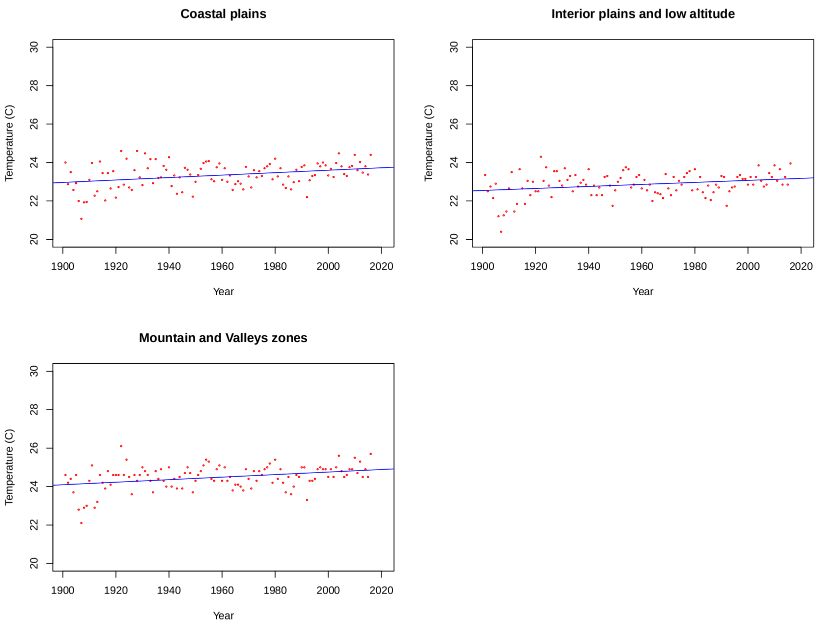


Figure 46.b: Median annual temperature

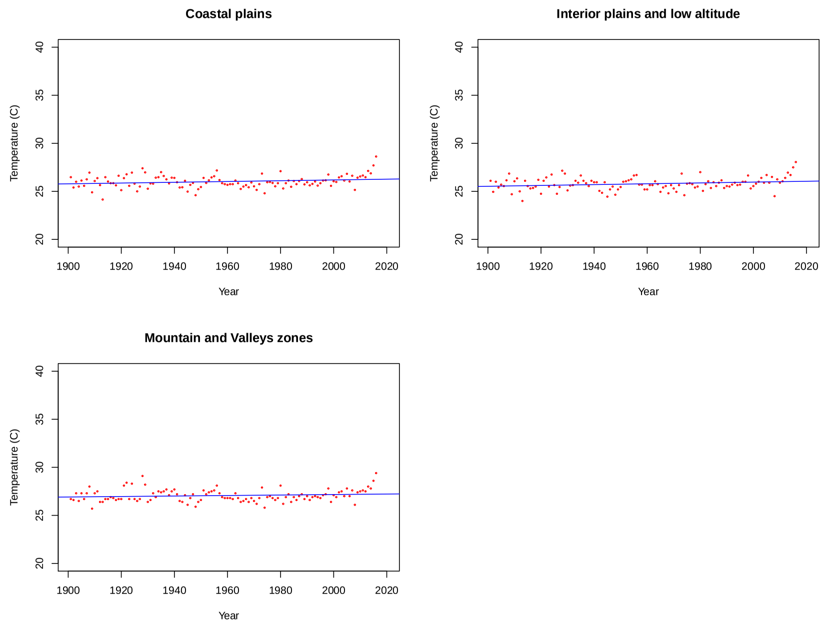
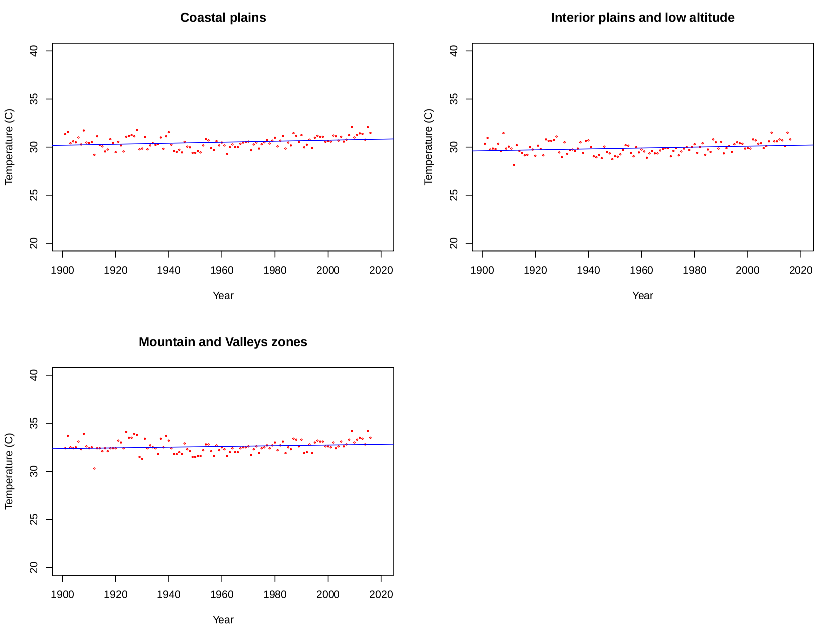


Figure 46.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.39 Endogenous detection of structural breaks in agroecological zones of Djibouti during the rainy season from 1901 to 2012

Figure 29.a: Minimum annual temperature

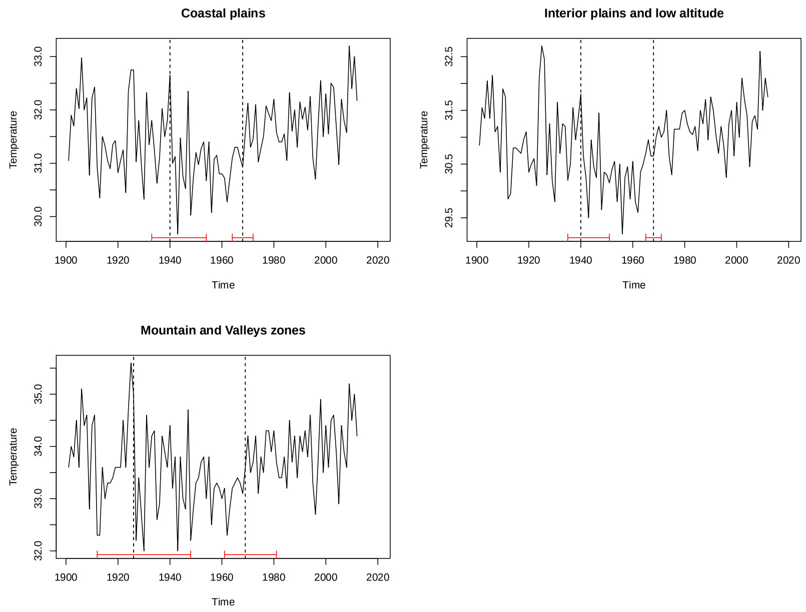


Figure 29.b: Median annual temperature

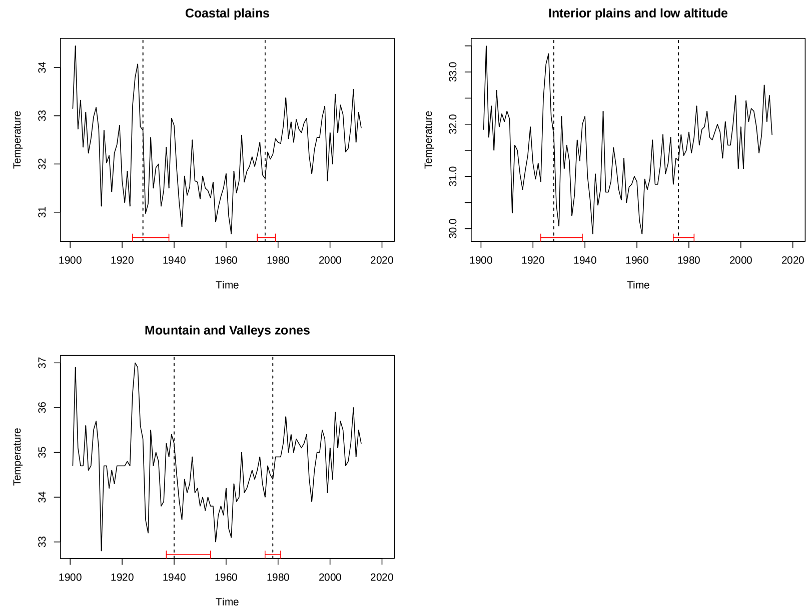
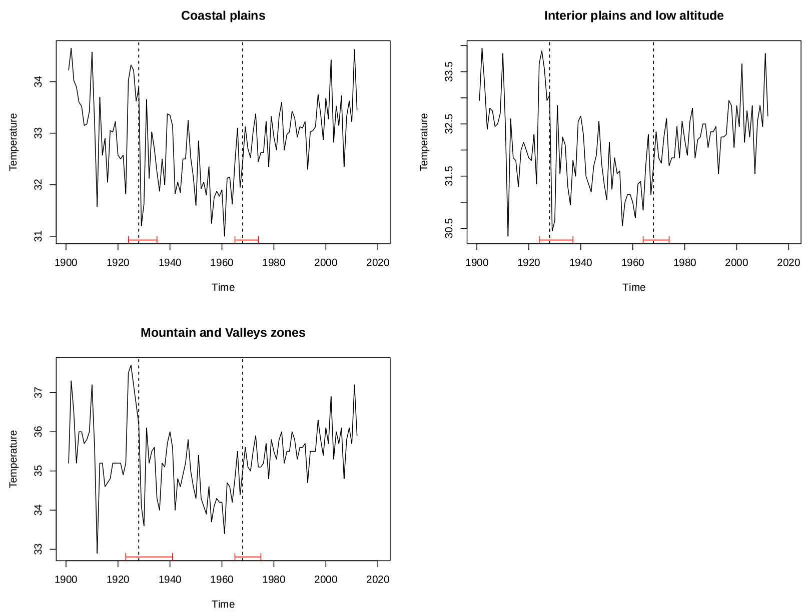


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.40Endogenous detection of structural breaks in agroecological zones of Djibouti during the dry season from 1901 to 2012

Figure 29.a: Minimum annual temperature

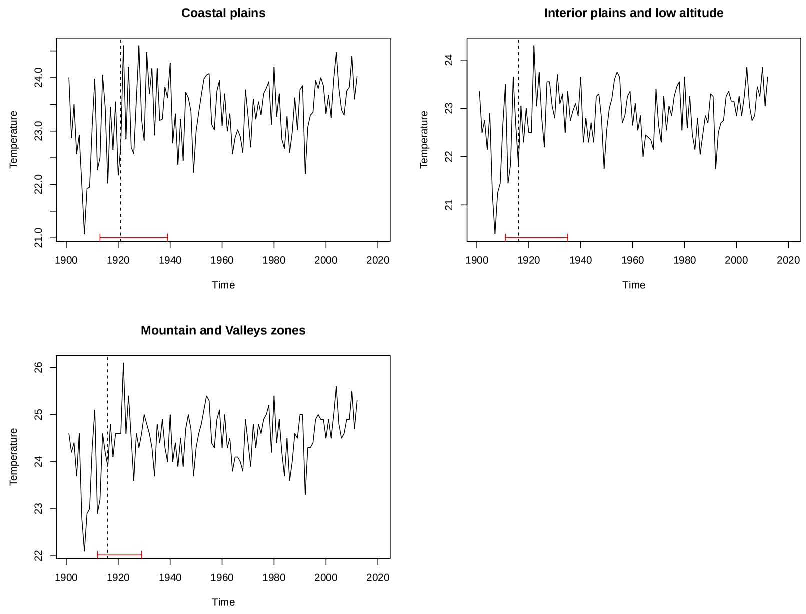


Figure 29.b: Median annual temperature

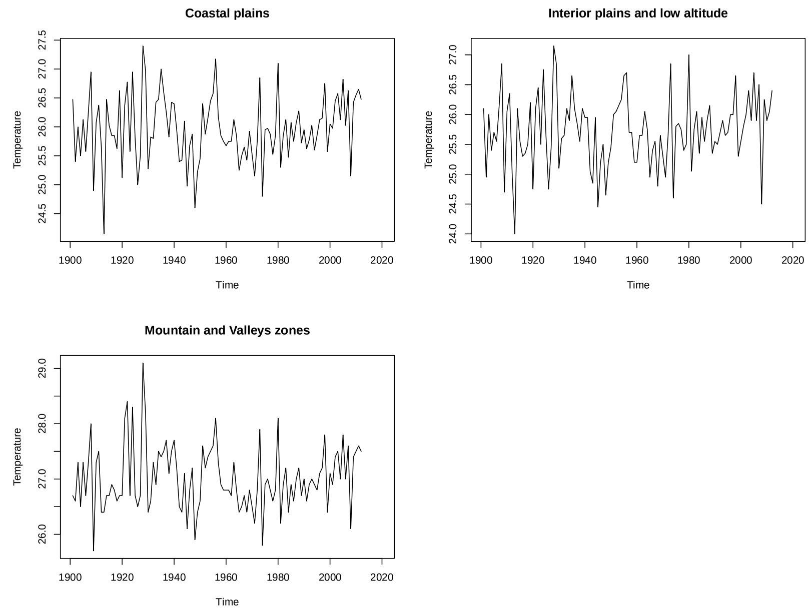
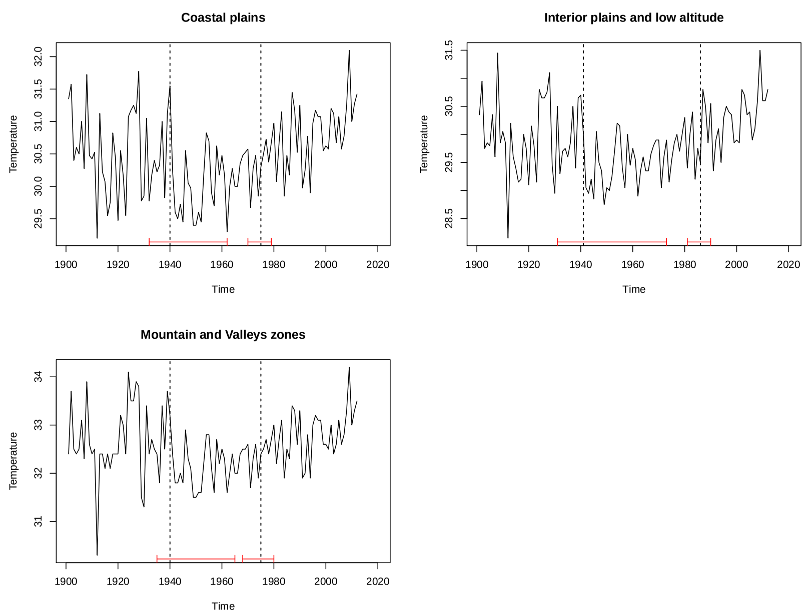


Figure 29.c: Maximum annual temperature

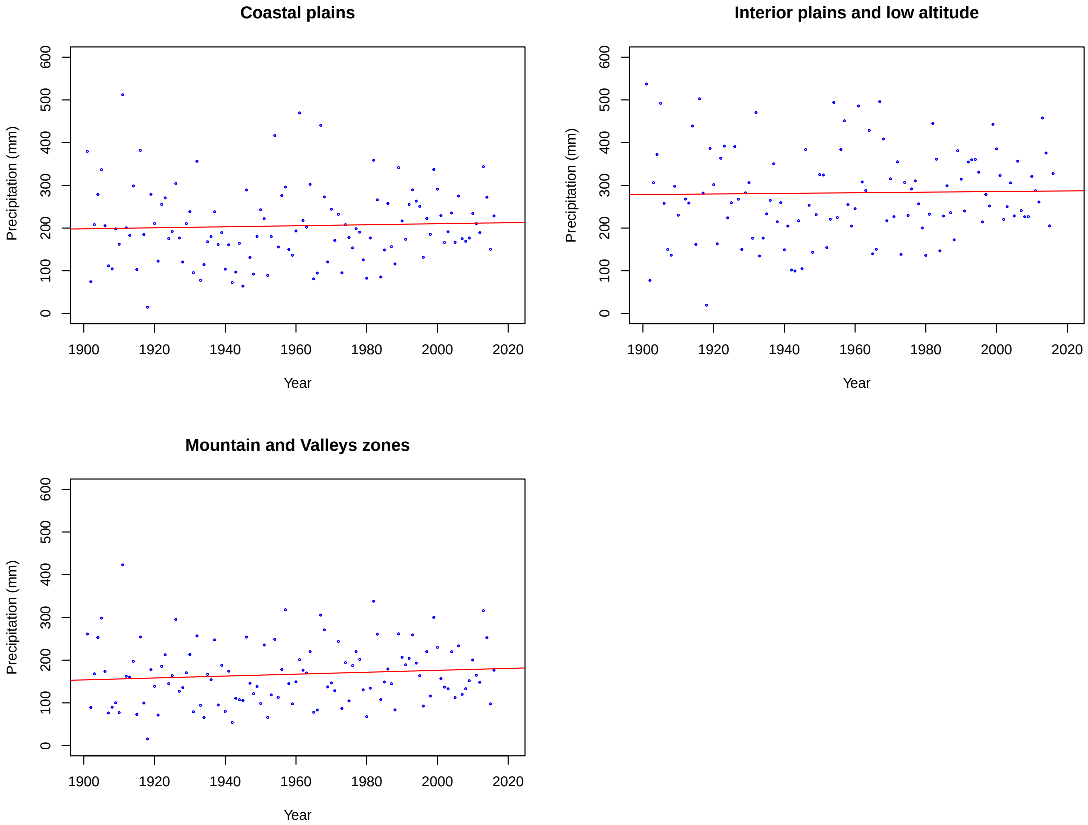


Source: Calculations and achievements by the author

Table 1.10Estimated results for Djibouti

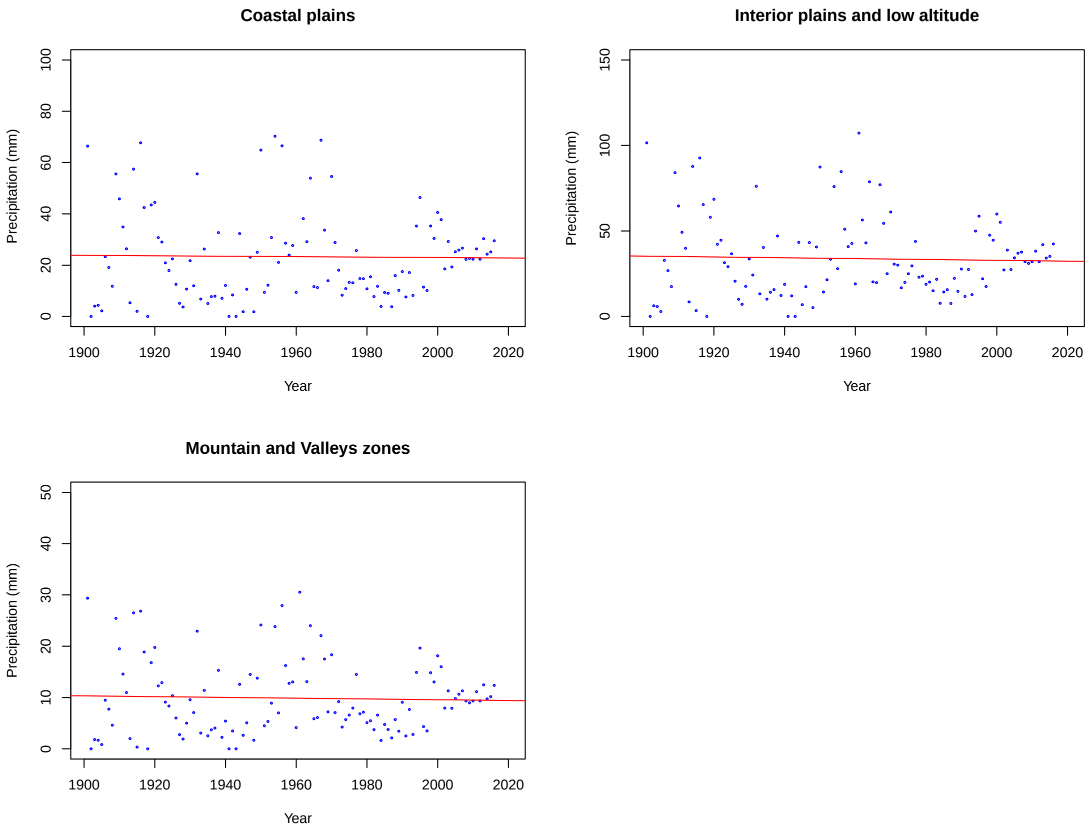
	Dependent variable: Coastal plains							
	Rainfall		Temperature					
	RainSum	RainSeason	TempminRain	TempmedRain	TempmaxRain	TempminDry	TempmedRain	TempmaxDry
Year	0.119	−0.008	0.005***	0.004*	0.003	0.006***	0.004*	0.005***
	(0.250)	(0.052)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	−28.427	39.892	20.966***	24.673***	27.659***	10.882***	24.673***	20.242***
	(490.010)	(102.249)	(3.694)	(4.094)	(4.360)	(3.367)	(4.094)	(3.335)
R^2	0.002	0.0002	0.067	0.029	0.013	0.107	0.029	0.077
	Dependent variable: Interior plains and low altitude							
Year	0.071	−0.025	0.005**	0.003*	0.003	0.005***	0.003*	0.005***
	(0.311)	(0.066)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	142.529	82.041	21.667***	24.903***	26.608***	12.574***	24.903***	20.479***
	(609.619)	(128.427)	(3.696)	(3.840)	(4.206)	(3.280)	(3.840)	(3.304)
R^2	0.0005	0.001	0.053	0.025	0.015	0.079	0.025	0.067
	Dependent variable: Mountain and Valleys zones							
Year	0.224	−0.008	0.004**	0.003	0.004	0.007***	0.003	0.004**
	(0.200)	(0.020)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	−272.477	24.572	25.184***	29.126***	28.107***	11.540***	29.126***	25.387***
	(390.915)	(39.336)	(3.946)	(4.222)	(4.724)	(3.174)	(4.222)	(3.545)
R^2	0.011	0.001	0.039	0.015	0.020	0.127	0.015	0.035
Observations	116	116	116	116	116	116	116	116
Model	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS
Note:								*p<0.1; **p<0.05; ***p<0.01

Figure 1.41 Evolution of the sum annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Djibouti



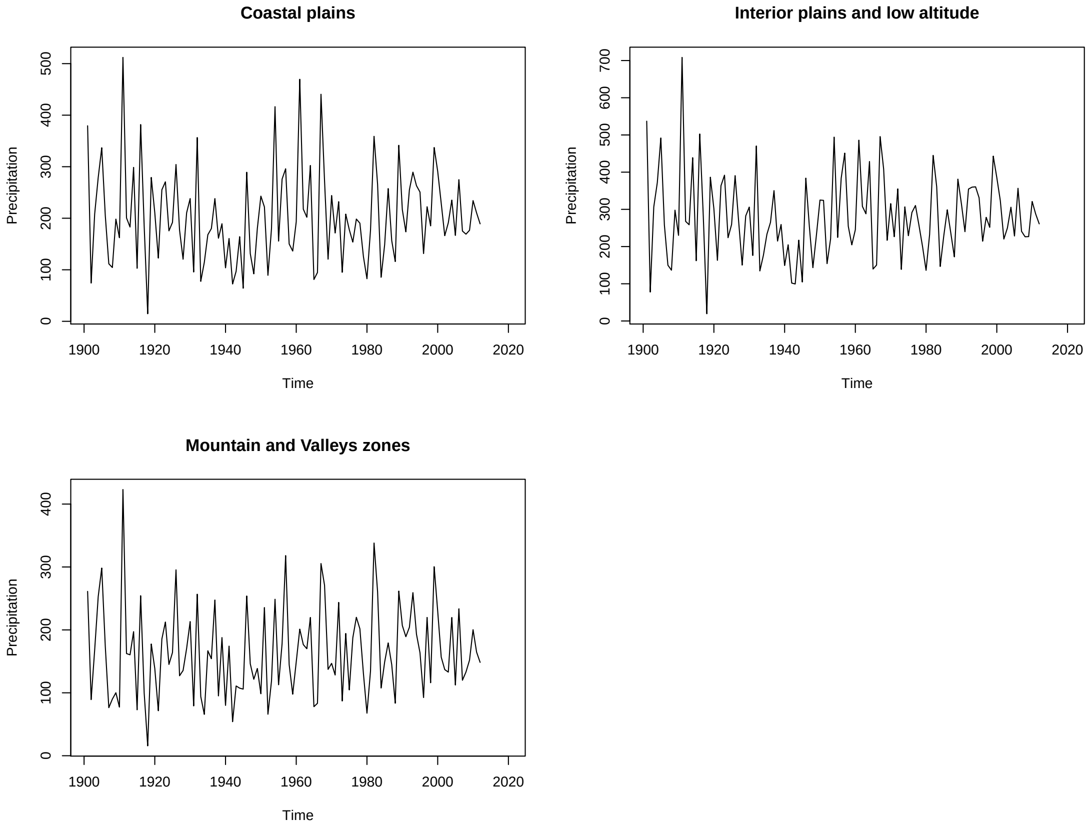
Source: Calculations and achievements of the author

Figure 1.42 Evolution of the seasonal annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Ethiopia.



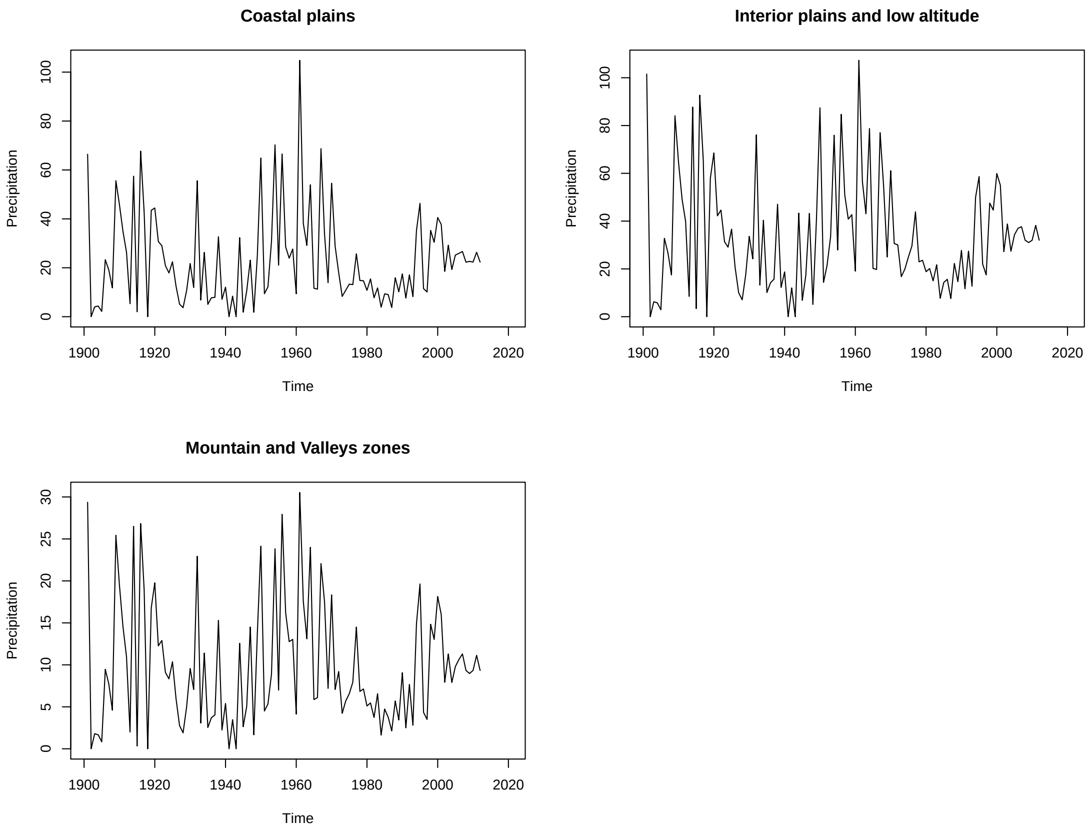
Source: Calculations and achievements of the author

Figure 1.43Breaks in total annual precipitation in the agroecological zones of Djibouti.



Source: Calculations and achievements of the author

Figure 1.44Breaks on seasonal precipitation in the agroecological zones of Djibouti.



Source: Calculations and achievements of the author

Figure 1.45Annual temperature during the rainy season in the agroecological zones of Ethiopia from 1901 to 2016.

Figure 53.a: Minimum annual temperature

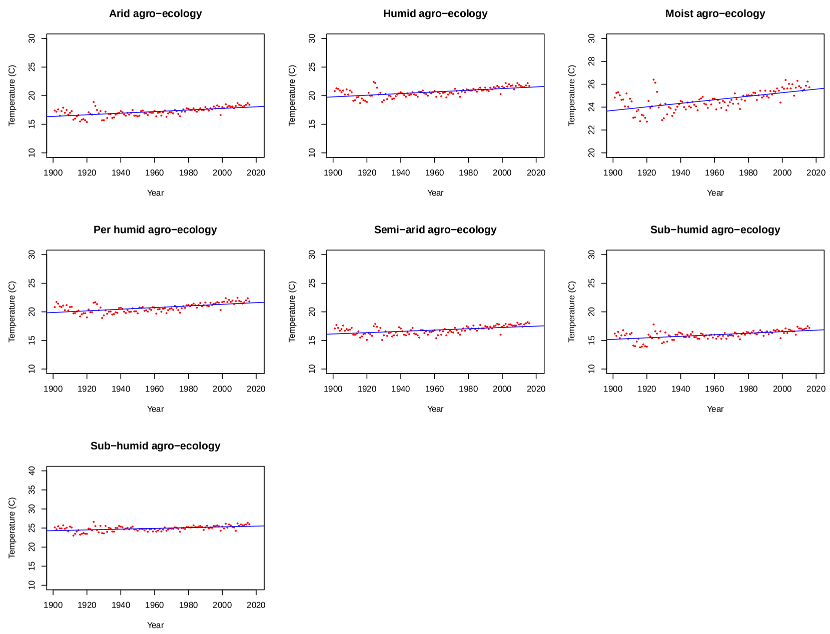


Figure 53.b: Median annual temperature

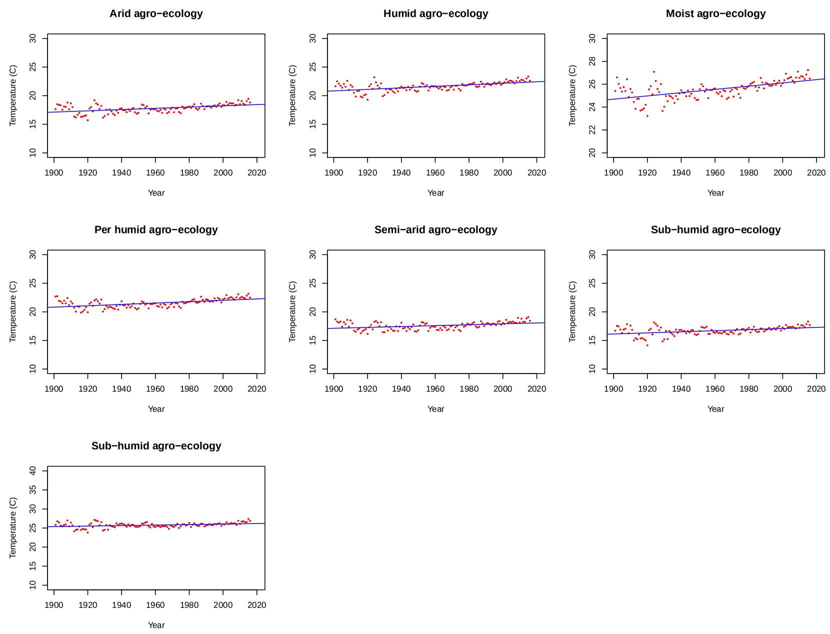
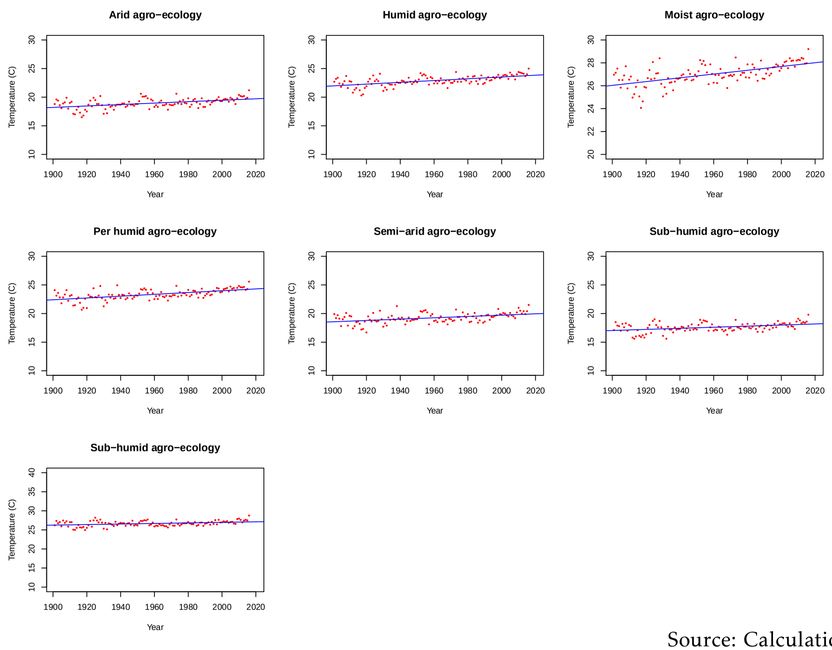


Figure 53.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.46 Annual temperature during the dry season in the agroecological zones of Ethiopia from 1901 to 2016.

Figure 54.a: Minimum annual temperature

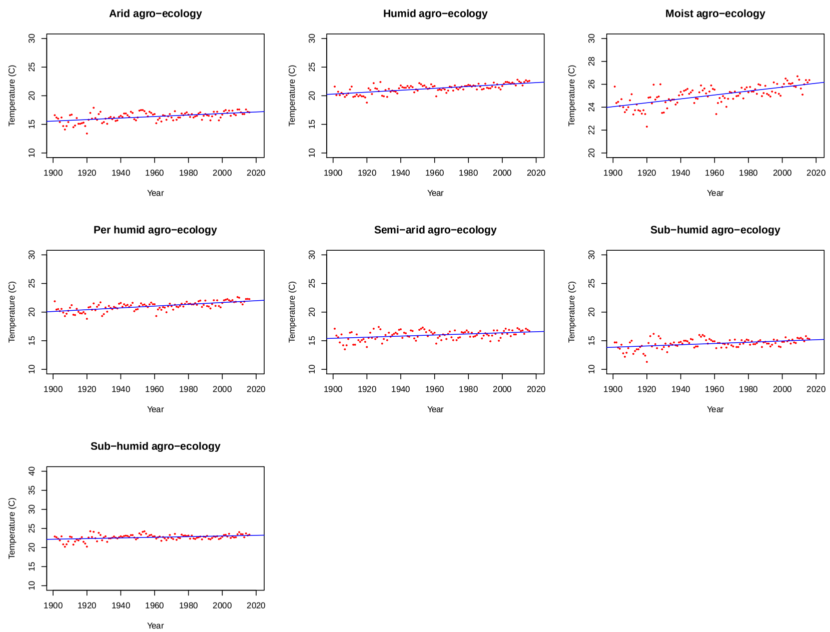


Figure 54.b: Median annual temperature

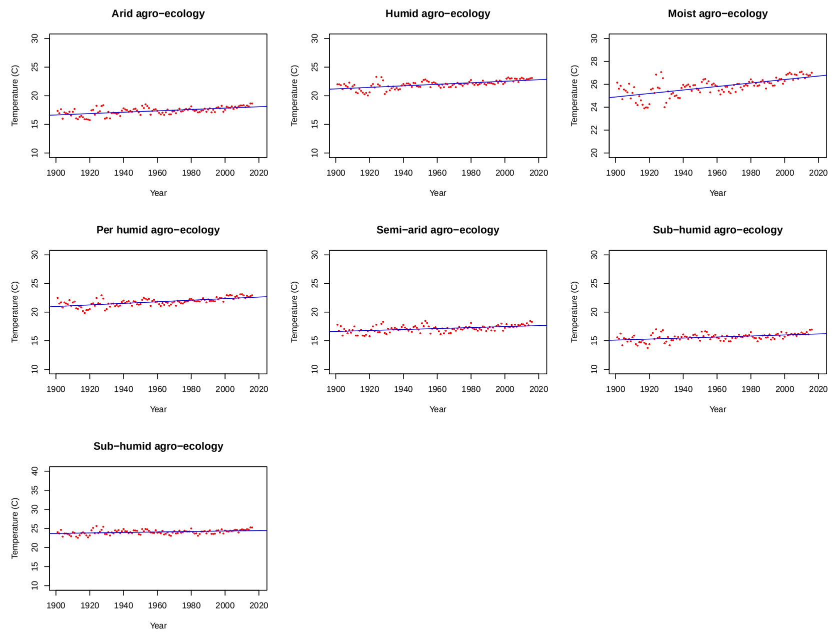
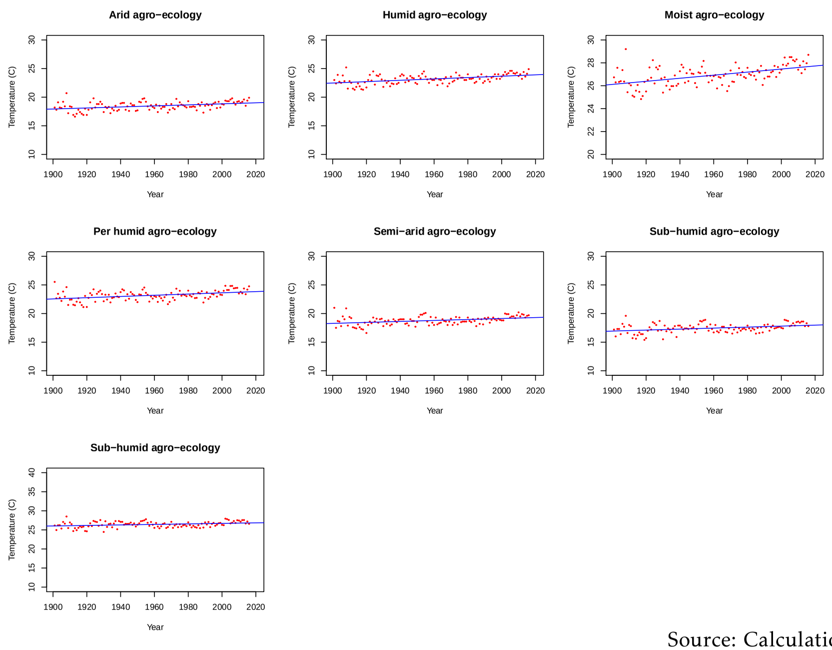


Figure 54.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.47 Endogenous detection of structural breaks in agroecological zones of Ethiopia during the rainy season from 1901 to 2012

Figure 29.a: Minimum annual temperature

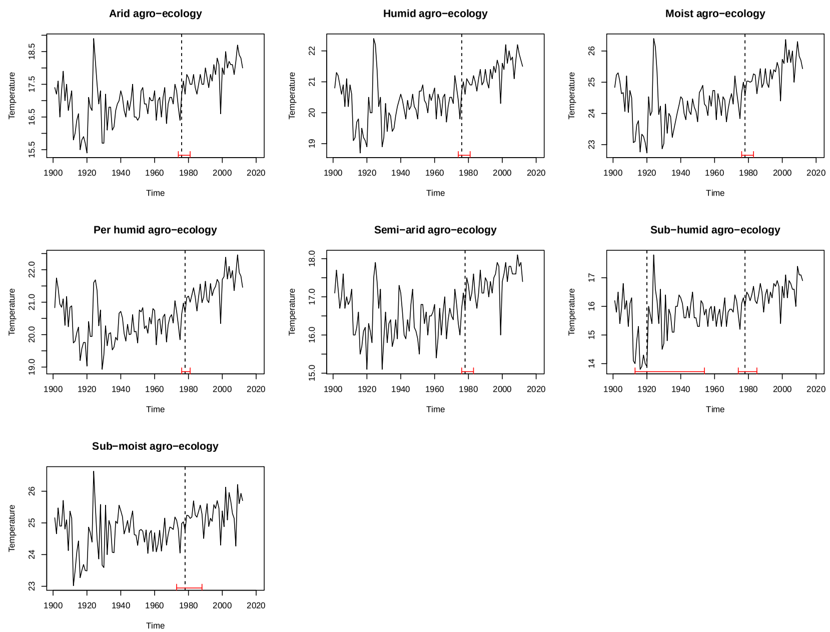


Figure 29.b: Median annual temperature

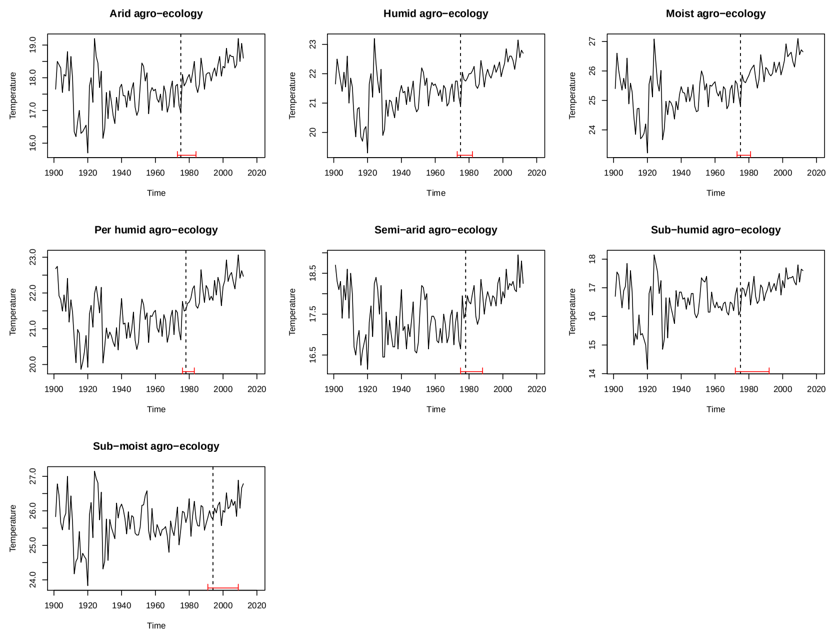
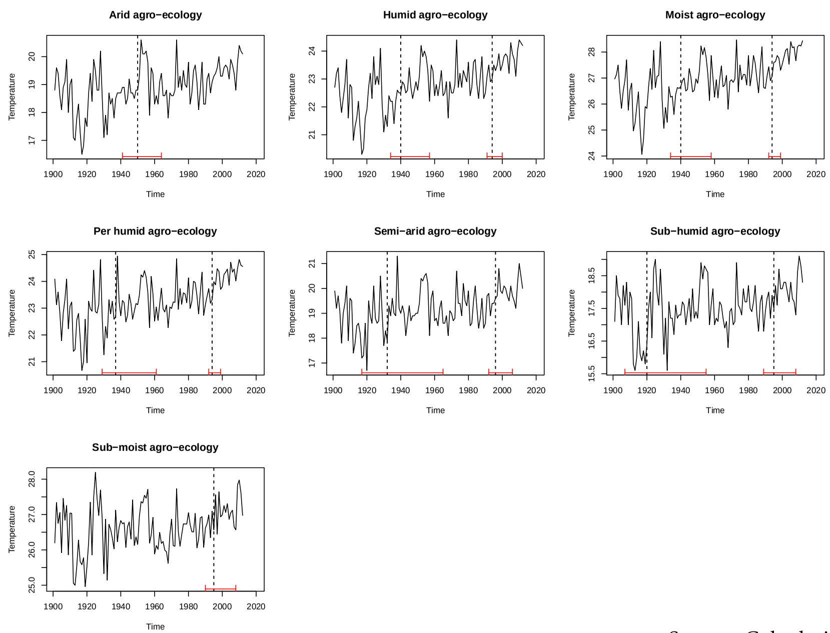


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.48 Endogenous detection of structural breaks in agroecological zones of Ethiopia during the dry season from 1901 to 2012

Figure 29.a: Minimum annual temperature

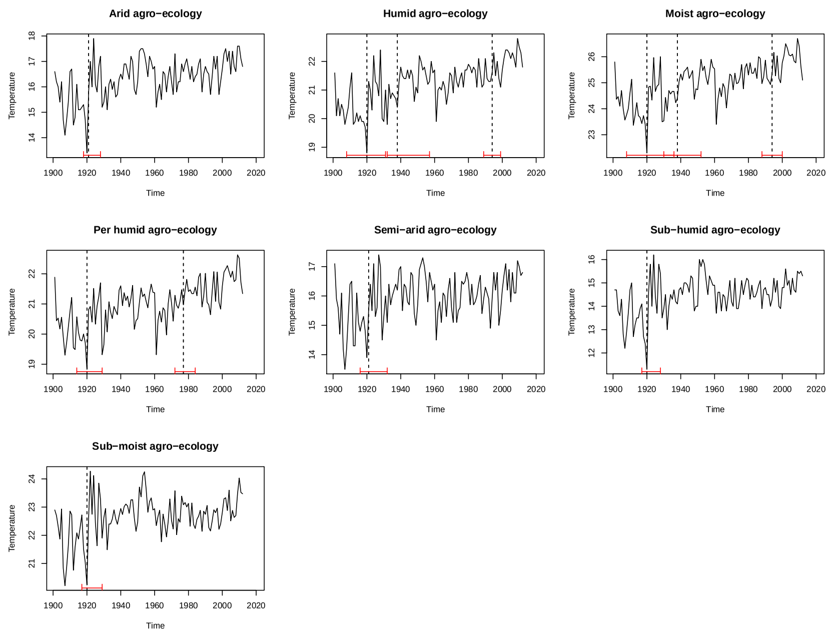


Figure 29.b: Median annual temperature

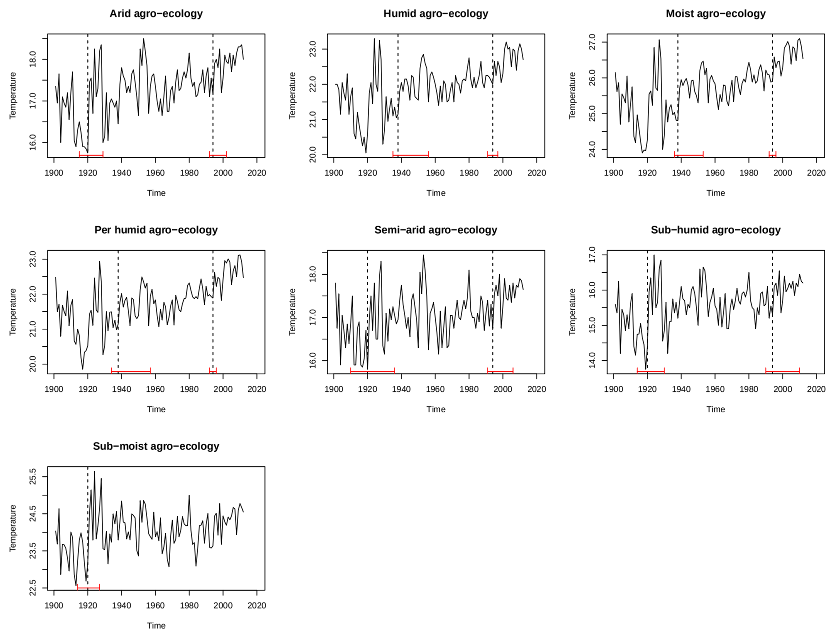
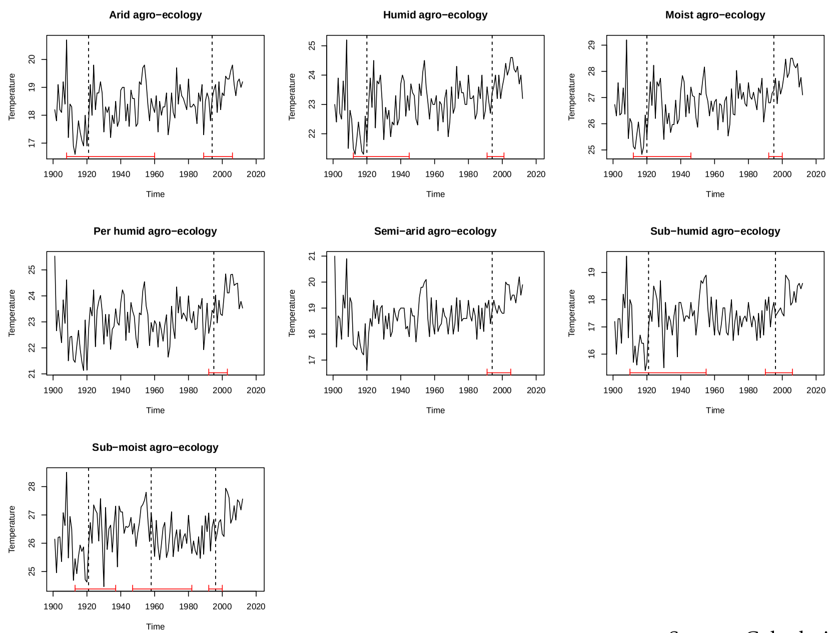
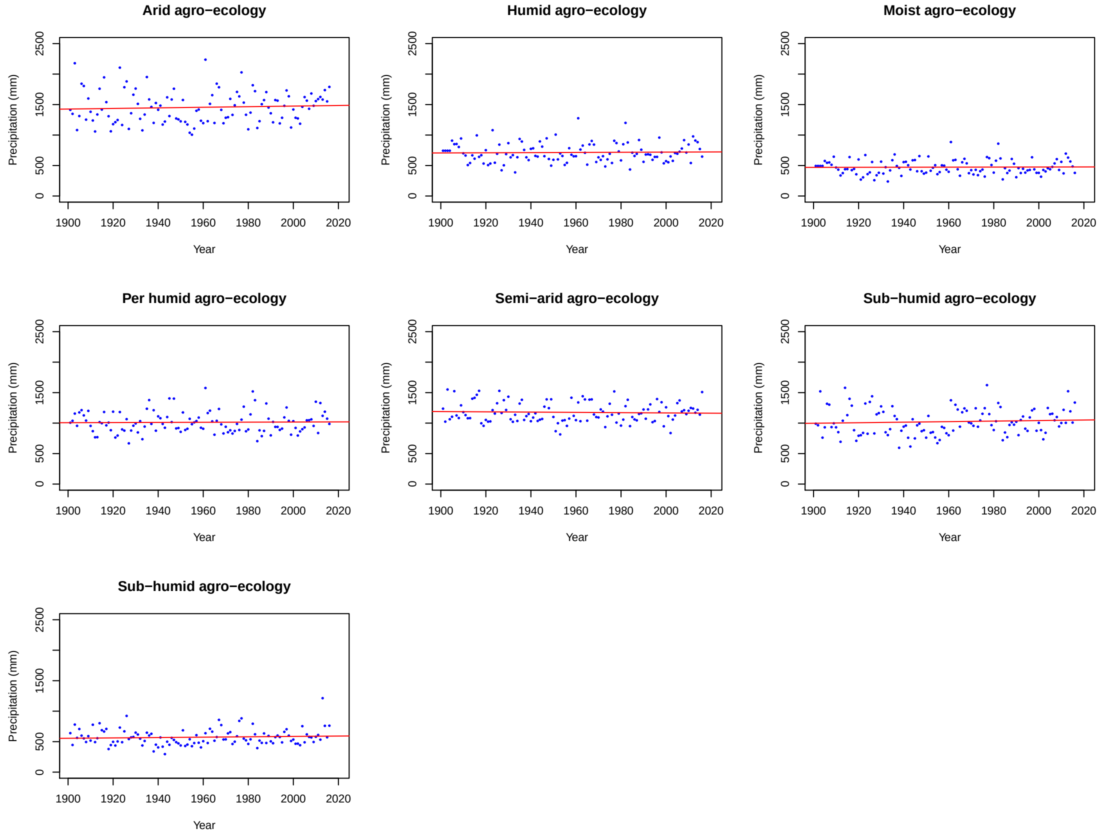


Figure 29.c: Maximum annual temperature



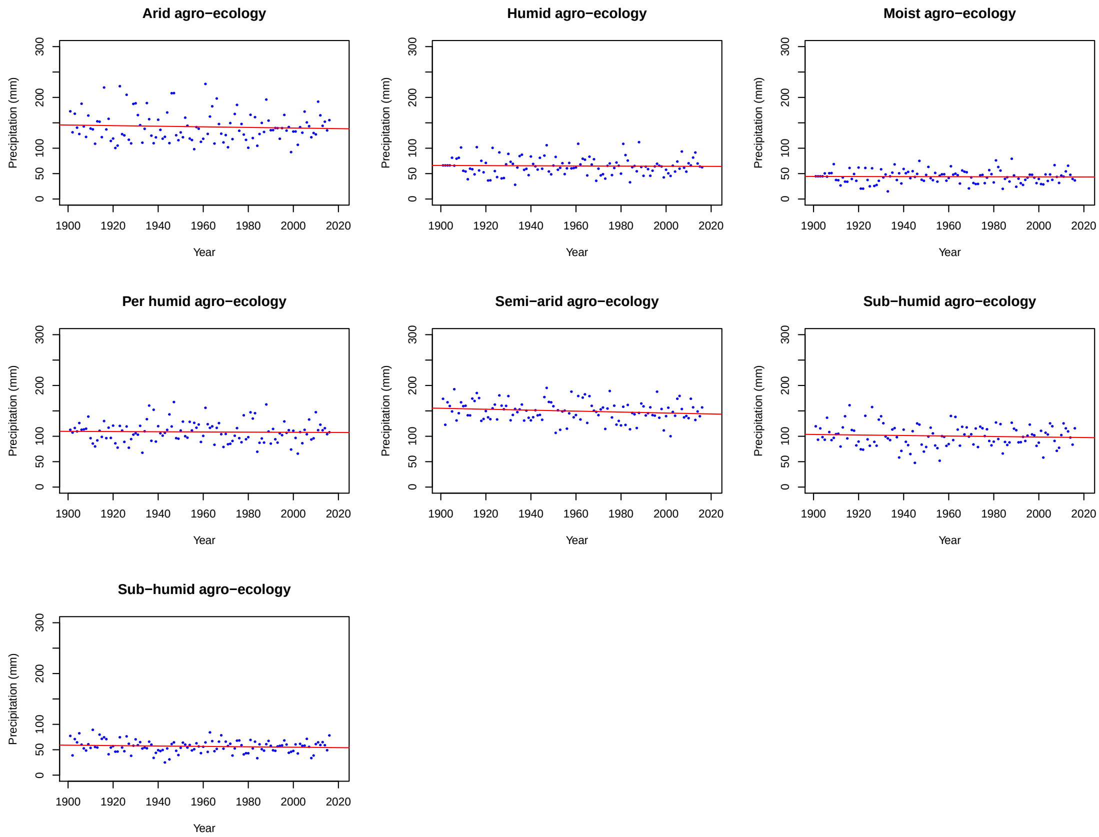
Source: Calculations and achievements by the author

Figure 1.49 Evolution of the sum annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Ethiopia



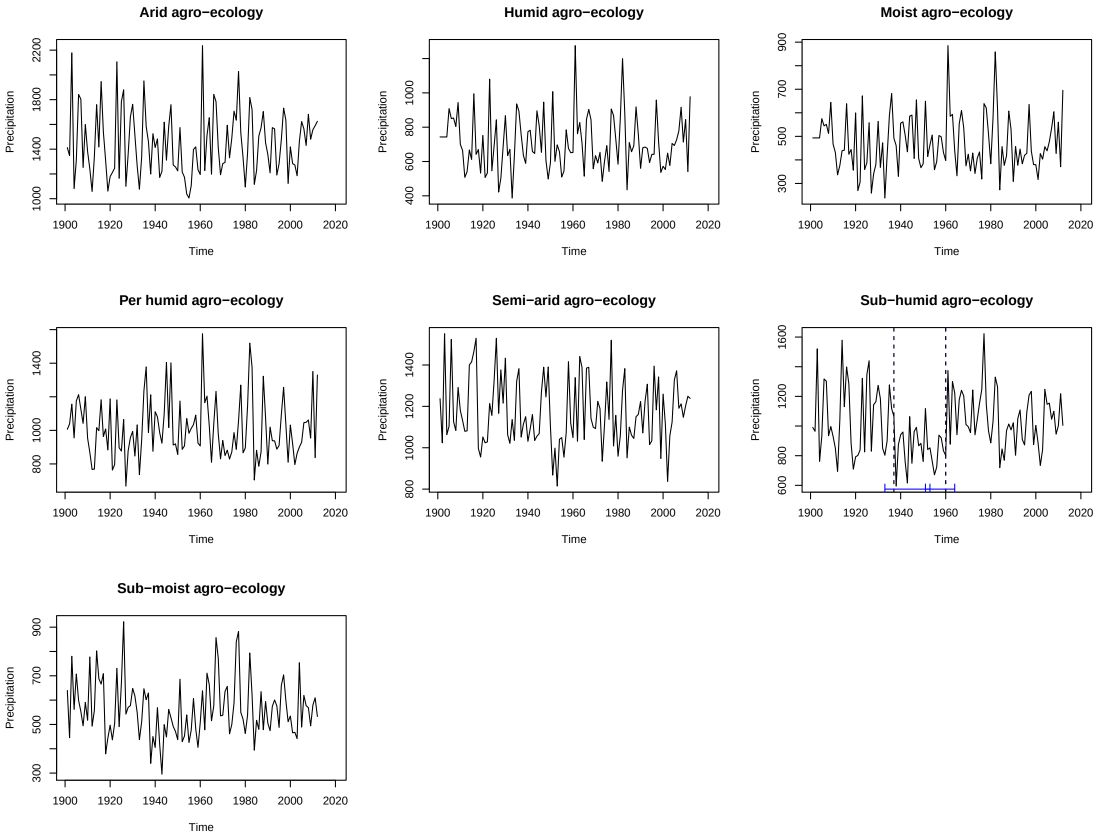
Source: Calculations and achievements of the author

Figure 1.50 Evolution of the seasonal annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Ethiopia.



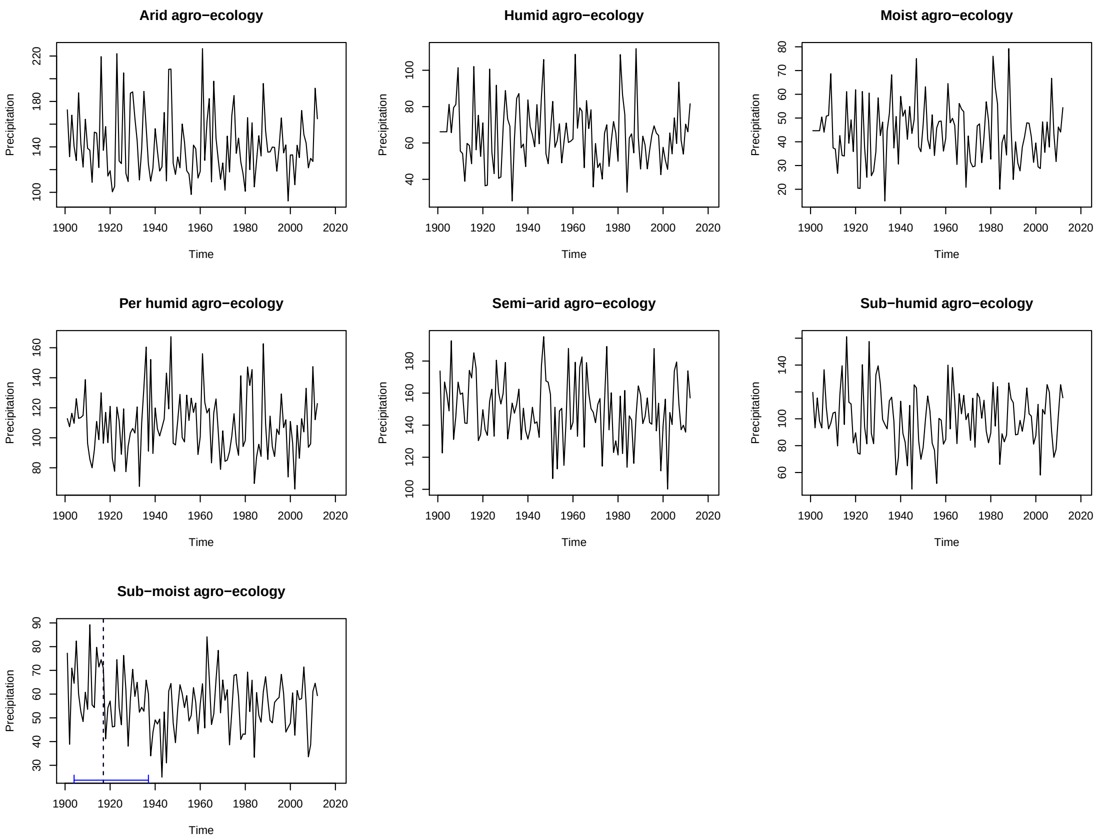
Source: Calculations and achievements of the author

Figure 1.51Breaks in total annual precipitation in the agroecological zones of Ethiopia.



Source: Calculations and achievements of the author

Figure 1.52Breaks on seasonal precipitation in the agroecological zones of Ethiopia.



Source: Calculations and achievements of the author

Table 1.11Estmated results for Ethiopia

	Rainfall		Temperature					
	RainSum	RainSeason	TempminRain	TempmedRain	TempmaxRain	TempminDry	TempmedRain	TempmaxDry
	Dependent variable: Arid agroecology							
Year	0.486	−0.059	0.014***	0.011***	0.013***	0.013***	0.011***	0.009***
	(0.728)	(0.081)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	502.642	258.314	−10.176***	−3.676	−5.626	−9.693**	−3.676	0.802
	(1,425.115)	(158.025)	(3.170)	(3.488)	(4.032)	(3.726)	(3.488)	(3.777)
R^2	0.004	0.005	0.395	0.249	0.246	0.300	0.249	0.161
	Dependent variable: Humid agroecology							
Year	0.136	−0.015	0.015***	0.013***	0.016***	0.017***	0.013***	0.012***
	(0.440)	(0.048)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	447.224	95.258	−7.883**	−4.393	−7.598**	−11.437***	−4.393	−0.157
	(862.450)	(93.231)	(3.489)	(3.455)	(3.791)	(3.062)	(3.455)	(3.889)
R^2	0.001	0.001	0.370	0.332	0.362	0.500	0.332	0.240
	Dependent variable: Moist agroecology							
Year	0.059	−0.008	0.015***	0.014***	0.016***	0.017***	0.014***	0.013***
	(0.326)	(0.035)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	357.679	58.823	−5.739	−2.335	−5.300	−8.392**	−2.335	0.627
	(638.358)	(68.578)	(3.584)	(3.439)	(3.867)	(3.276)	(3.439)	(4.008)
R^2	0.0003	0.0004	0.386	0.365	0.380	0.478	0.365	0.274
	Dependent variable: Per humid agroecology							
Year	0.108	−0.018	0.014***	0.012***	0.016***	0.016***	0.012***	0.011***
	(0.485)	(0.057)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	801.469	144.388	−7.364**	−1.824	−7.653*	−9.735***	−1.824	2.331
	(949.897)	(111.401)	(3.350)	(3.364)	(3.994)	(3.082)	(3.364)	(4.347)
R^2	0.0004	0.001	0.381	0.297	0.346	0.466	0.297	0.168
	Dependent variable:Semi-arid agroecology							
Year	−0.226	−0.093*	0.011***	0.008***	0.012***	0.010***	0.008***	0.009***
	(0.455)	(0.054)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	1,618.668*	332.065***	−5.511	2.387	−3.539	−2.748	2.387	2.127
	(891.102)	(106.653)	(3.338)	(3.317)	(4.185)	(4.068)	(3.317)	(3.806)
R^2	0.002	0.025	0.282	0.155	0.206	0.157	0.155	0.144
	Dependent variable: Sub-humid agroecology							
Year	0.444	−0.050	0.013***	0.010***	0.009***	0.011***	0.010***	0.009***
	(0.600)	(0.059)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	154.783	198.856*	−10.270***	−2.011	−0.991	−6.817*	−2.011	0.467
	(1,174.769)	(115.638)	(3.516)	(3.616)	(3.937)	(4.088)	(3.616)	(4.041)
R^2	0.005	0.006	0.328	0.190	0.164	0.193	0.190	0.134
	Dependent variable: Sub-moist agroecology							
Year	0.305	−0.040	0.010***	0.007***	0.007***	0.009***	0.007***	0.007***
	(0.367)	(0.033)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	−24.547	134.764**	5.496*	12.693***	12.457***	6.000	12.693***	13.135***
	(719.443)	(64.621)	(3.290)	(3.306)	(3.566)	(3.769)	(3.306)	(4.028)
R^2	0.006	0.013	0.234	0.121	0.122	0.147	0.121	0.087
Observations	116	116	116	116	116	116	116	116
Model	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS

Note: *p<0.1; **p<0.05; ***p<0.01

Figure 1.53Annual temperature during the rainy season in the agroecological zones of Mali from 1901 to 2016.

Figure 61.a: Minimum annual temperature

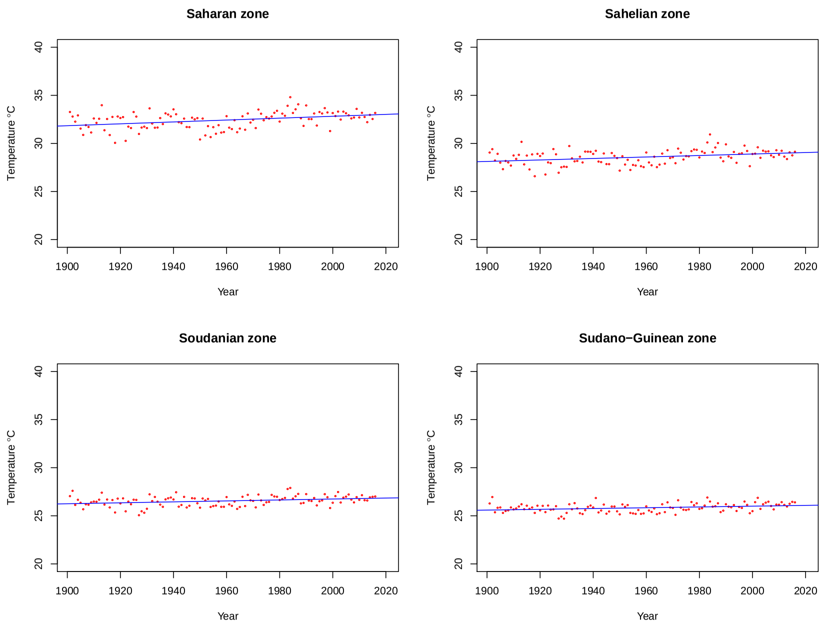


Figure 61.b: Median annual temperature

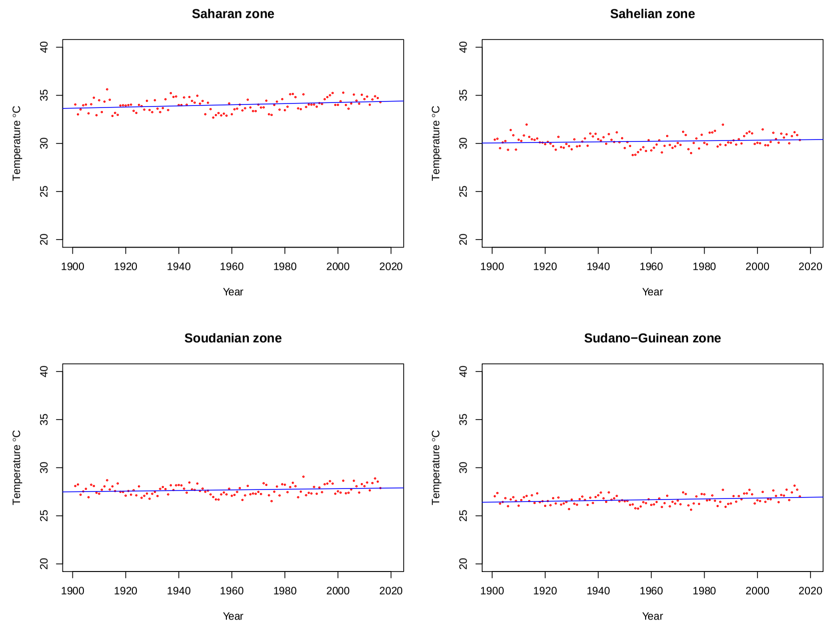
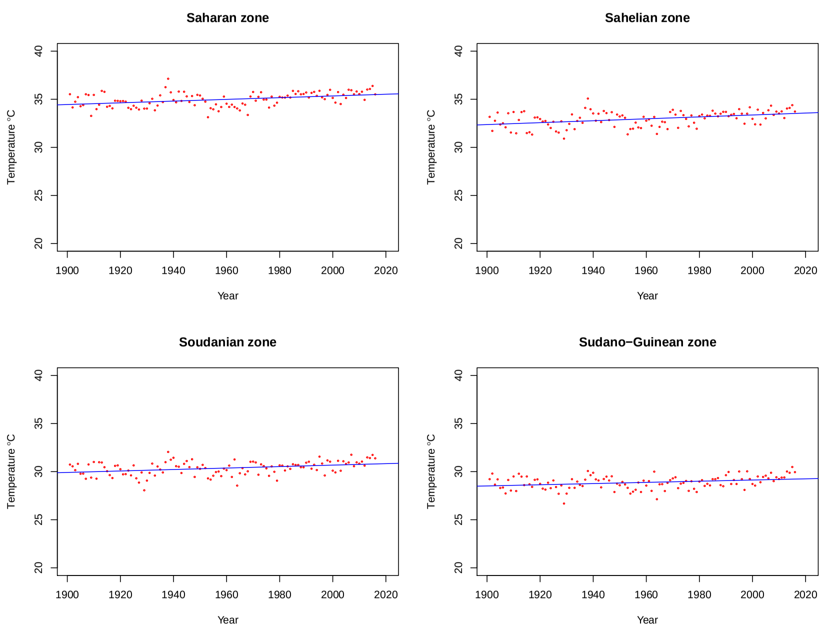


Figure 61.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.54 Annual temperature during the dry season in the agroecological zones of Mali from 1901 to 2016.

Figure 62.a: Minimum annual temperature

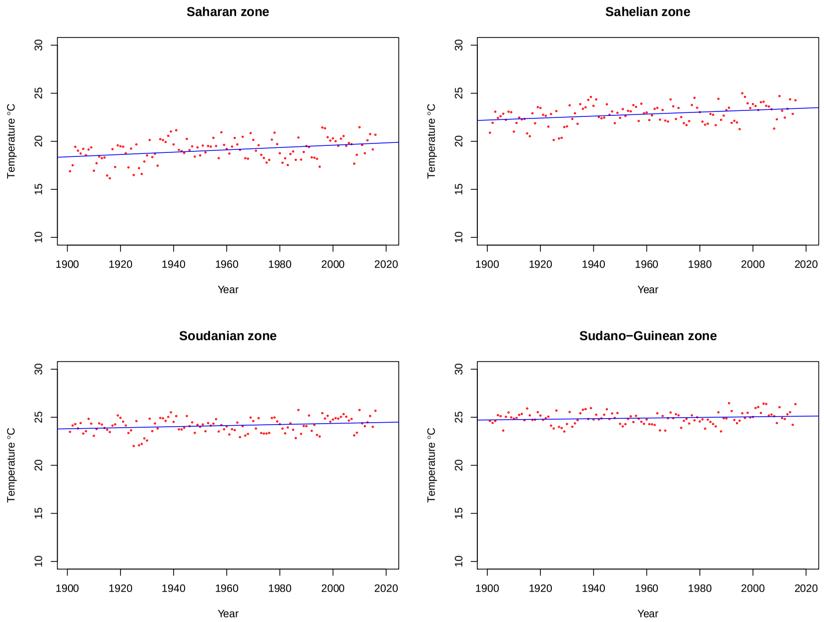


Figure 62.b: Median annual temperature

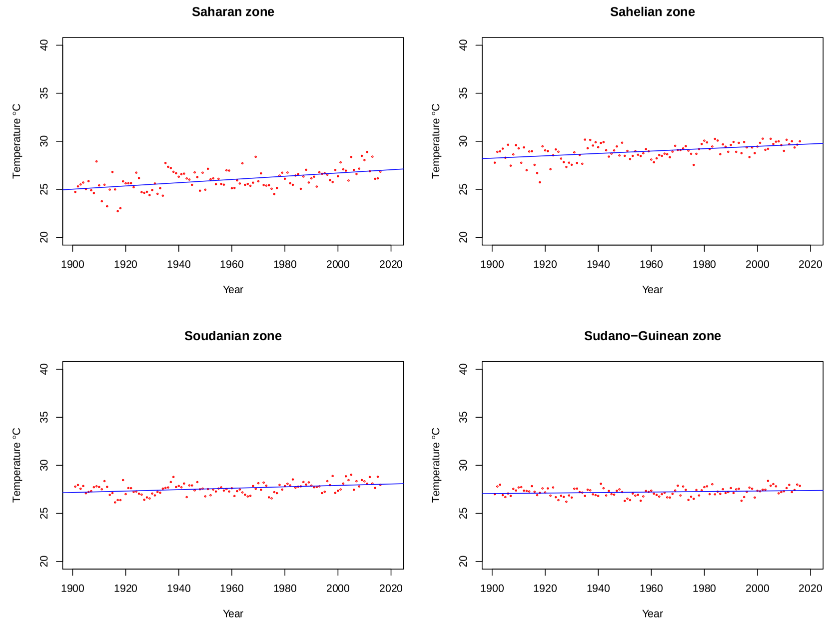
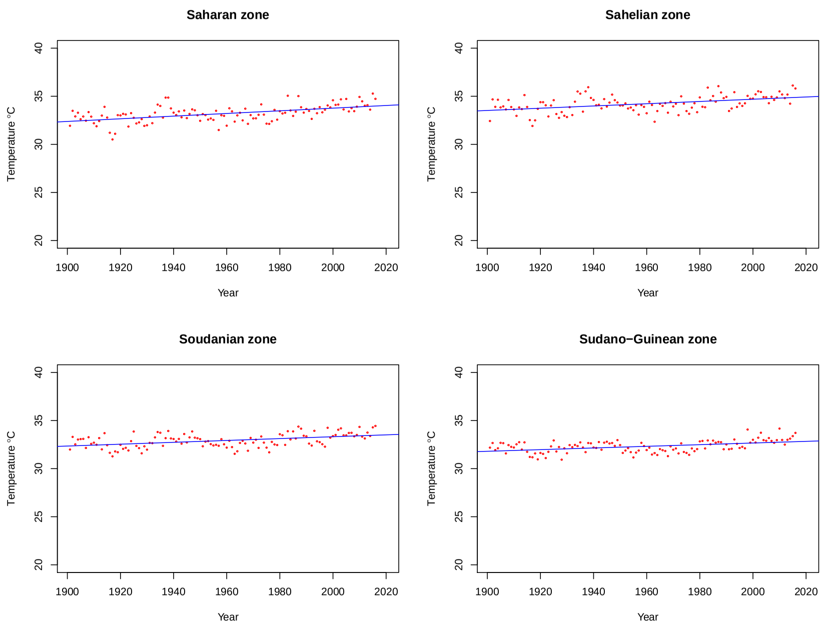


Figure 62.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.55Endogenous detection of structural breaks in agroecological zones of Mali during the rainy season from 1901 to 2012

Figure 29.a: Minimum annual temperature

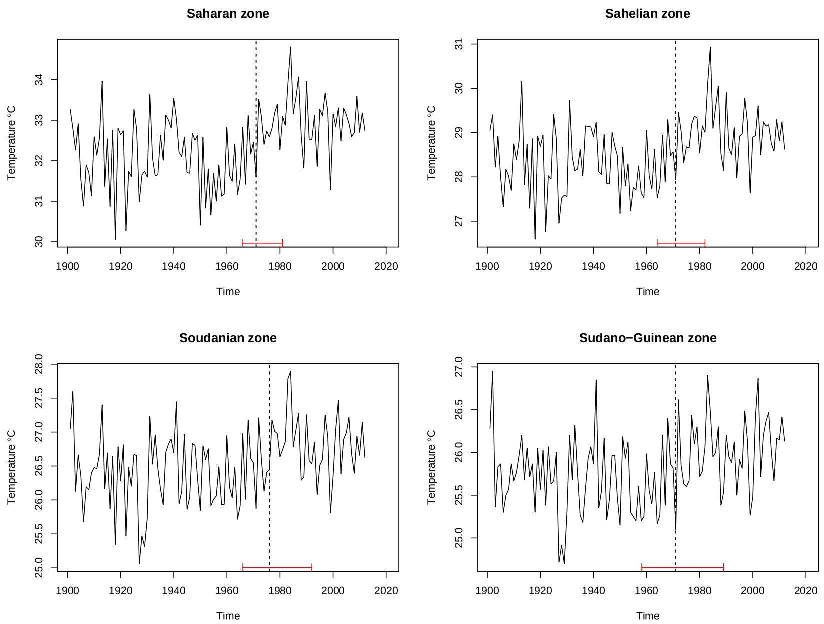


Figure 29.b: Median annual temperature

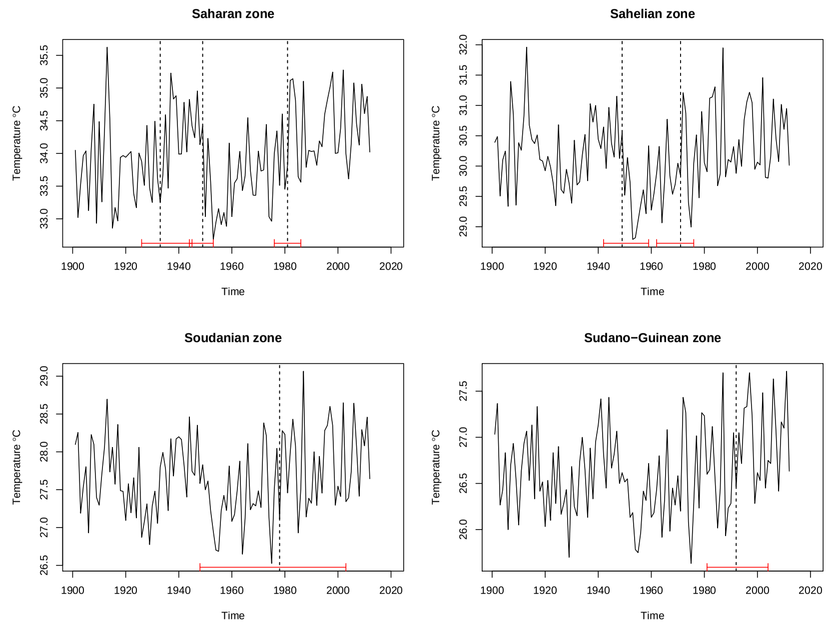
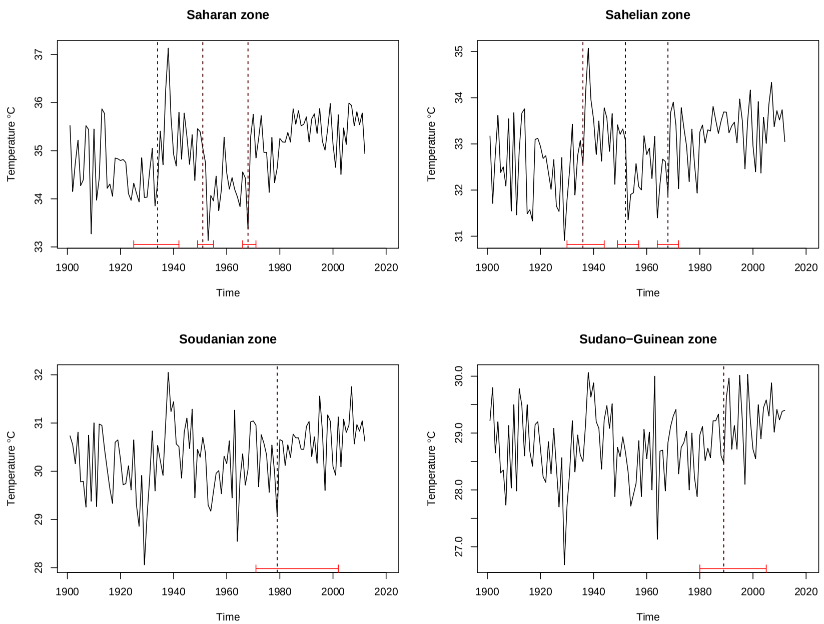


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.56Endogenous detection of structural breaks in agroecological zones of Mali during the dry season from 1901 to 2012

Figure 29.a: Minimum annual temperature

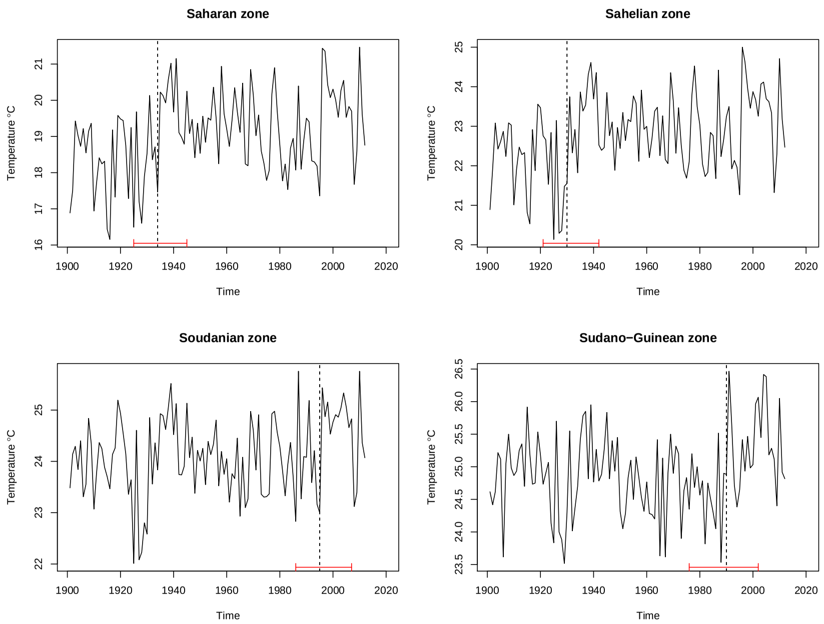


Figure 29.b: Median annual temperature

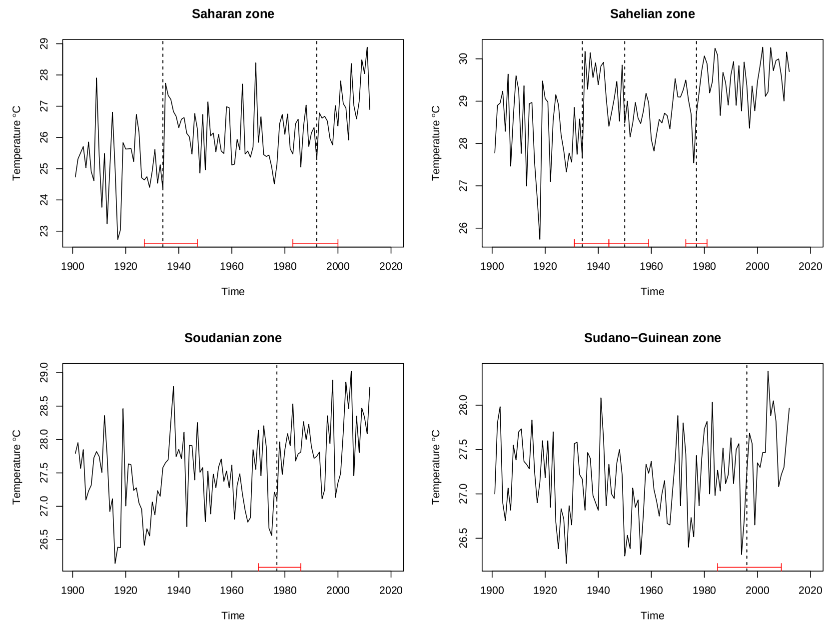
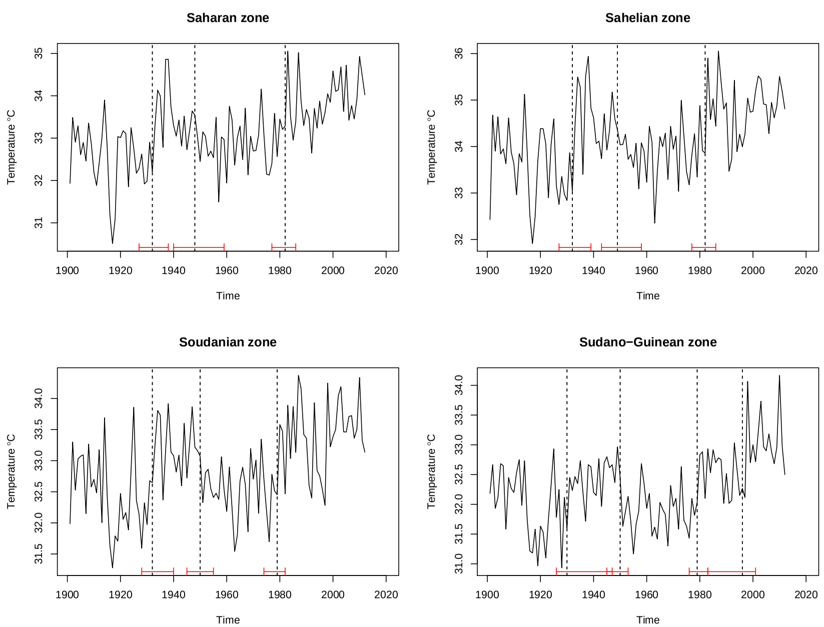


Figure 29.c: Maximum annual temperature



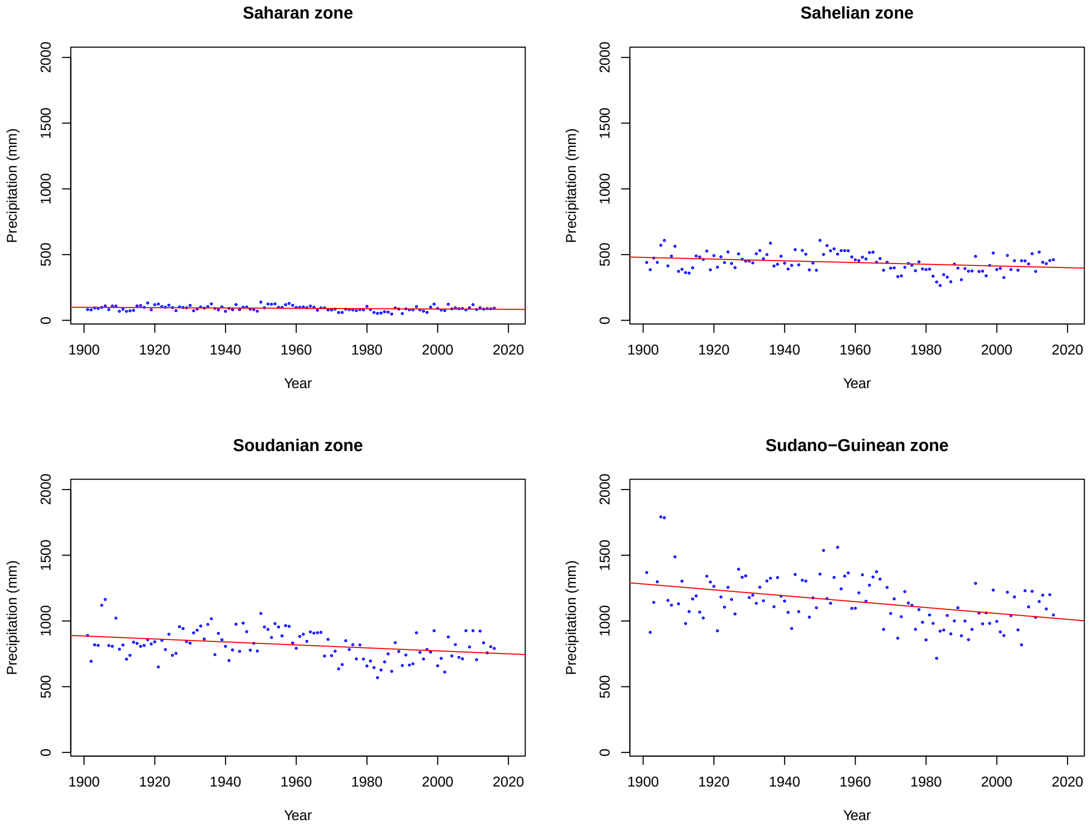
Source: Calculations and achievements by the author

Table 1.12The regression results in Mali

	Saharan zone							
	Rainfall		Temperature					
	RainSum	RainSeason	TempminRain	TempmedRain	TempmaxRain	TempminDry	TempmedDry	TempmaxDry
Year	−0.128**	−0.045***	0.010***	0.006***	0.009***	0.012***	0.017***	0.014***
	(0.051)	(0.015)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.002)
Constant	341.914***	112.196***	13.201***	22.283***	17.494***	−4.628	−7.013	6.123
	(99.829)	(29.795)	(4.469)	(3.435)	(3.632)	(5.883)	(5.211)	(3.976)
R^2	0.052	0.071	0.140	0.093	0.169	0.125	0.260	0.289
	Sahelian zone							
Year	−0.654***	−0.191***	0.008***	0.003	0.010***	0.010***	0.012***	0.012***
	(0.184)	(0.051)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)
Constant	1,721.541***	483.388***	13.445***	24.633***	13.407***	2.511	4.801	11.338***
	(361.117)	(99.591)	(3.882)	(3.475)	(3.990)	(5.193)	(4.012)	(4.121)
R^2	0.099	0.110	0.118	0.022	0.174	0.118	0.241	0.213
	Soudanian zone							
Year	−1.133***	−0.260***	0.005***	0.003**	0.008***	0.006***	0.007***	0.010***
	(0.291)	(0.070)	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)	(0.002)
Constant	3,038.968***	693.530***	16.873***	21.364***	15.436***	13.256***	13.181***	13.932***
	(570.120)	(136.558)	(2.759)	(2.842)	(3.641)	(4.139)	(2.938)	(3.426)
R^2	0.117	0.109	0.097	0.042	0.128	0.057	0.175	0.212
	Sudano guinean zone							
Year	−2.244***	−0.426***	0.004***	0.004***	0.006***	0.003*	0.003**	0.009***
	(0.460)	(0.095)	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)	(0.002)
Constant	5,544.850***	1,073.201***	17.836***	18.444***	16.821***	18.495***	21.940***	15.454***
	(901.118)	(185.440)	(2.363)	(2.650)	(3.495)	(3.464)	(2.426)	(3.013)
R^2	0.173	0.151	0.091	0.078	0.094	0.029	0.040	0.215
Observations	116	116	116	116	116	116	116	116
Model	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS

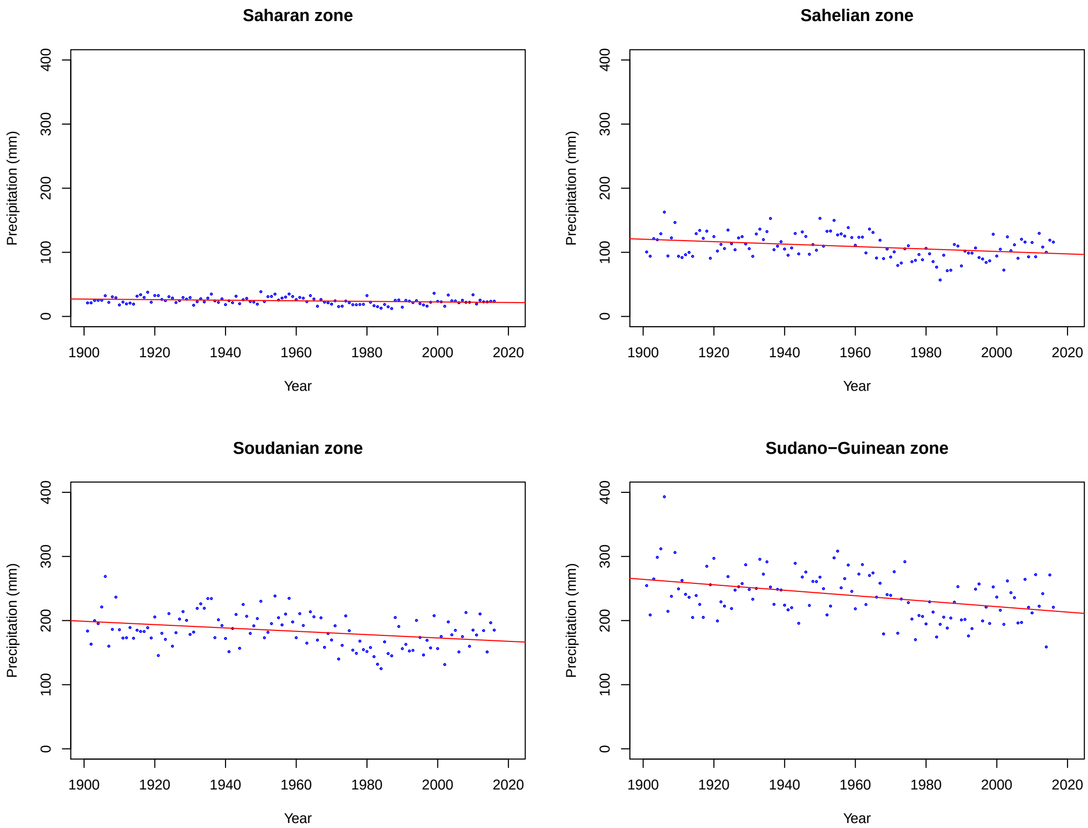
Note: *p<0.1; **p<0.05; ***p<0.01

Figure 1.57 Evolution of the sum annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Mali



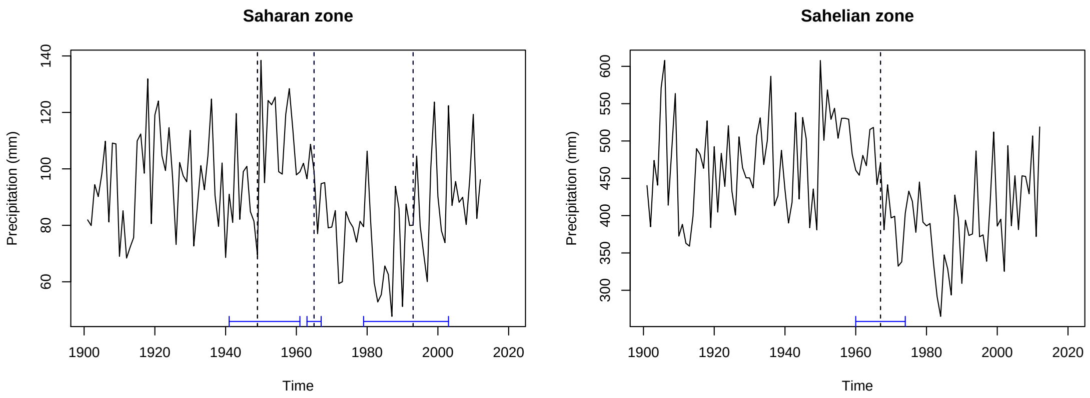
Source: Calculations and achievements of the author

Figure 1.58 Evolution of the seasonal annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Mali.



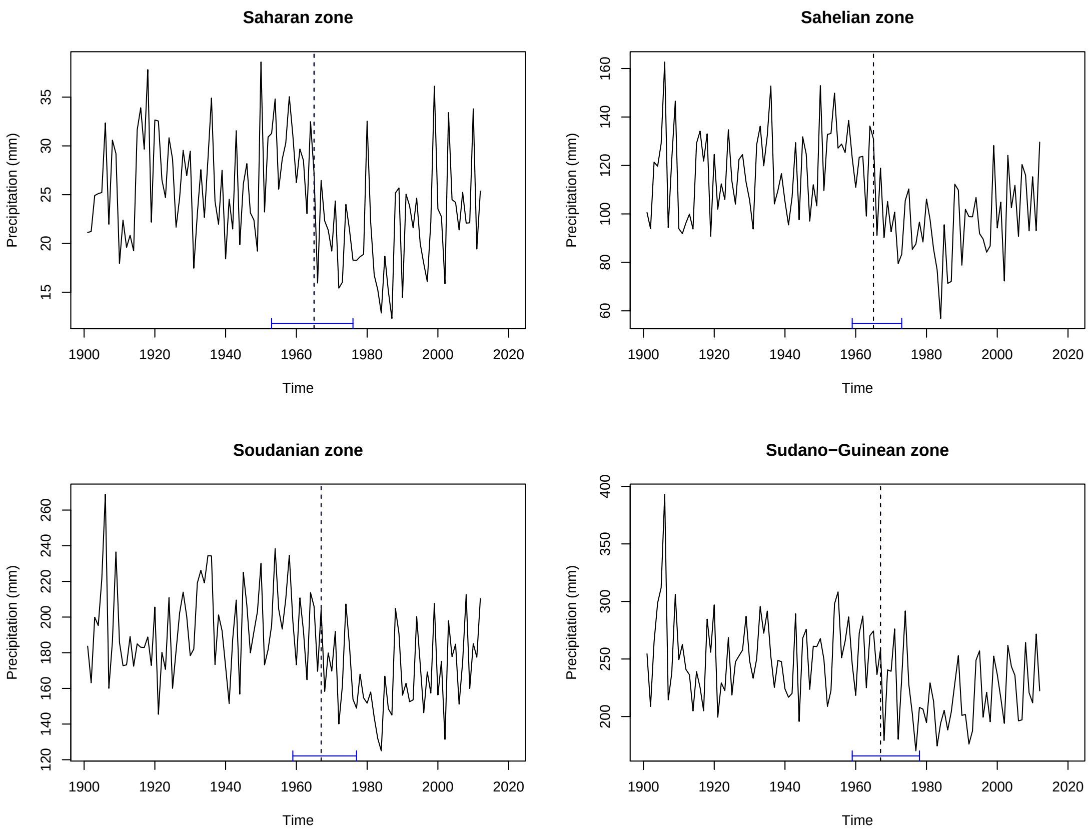
Source: Calculations and achievements of the author

Figure 1.59Breaks in total annual precipitation in the agroecological zones of Mali.



Source: Calculations and achievements of the author

Figure 1.60Breaks on seasonal precipitation in the agroecological zones of Mali.



Source: Calculations and achievements of the author

Figure 1.61 Annual temperature during the rainy season in the agroecological zones of Mauritania from 1901 to 2016.

Figure 29.a: Minimum annual temperature

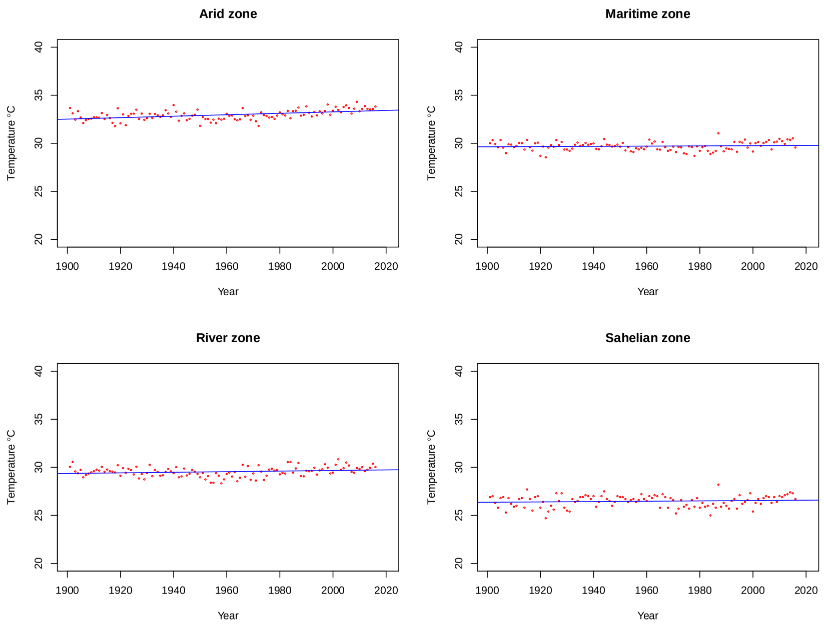


Figure 29.b: Median annual temperature

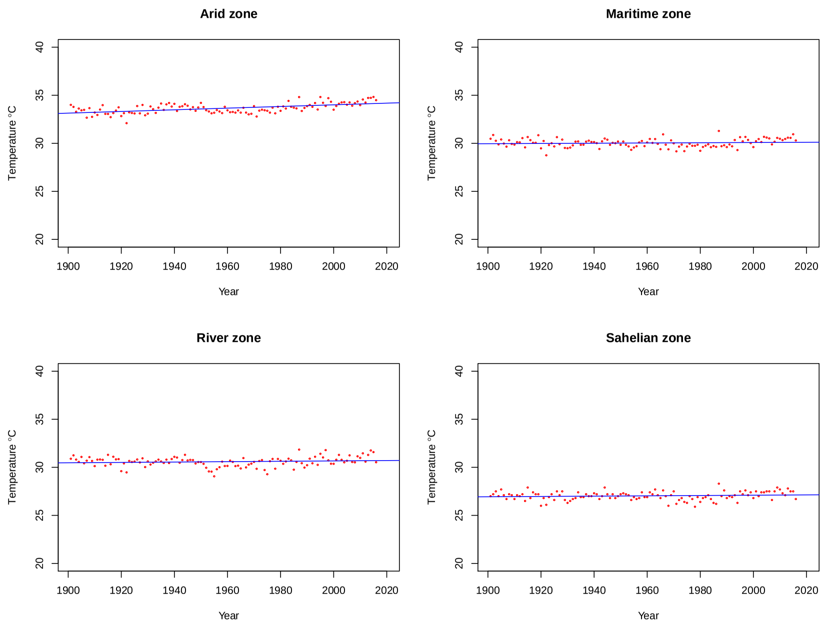
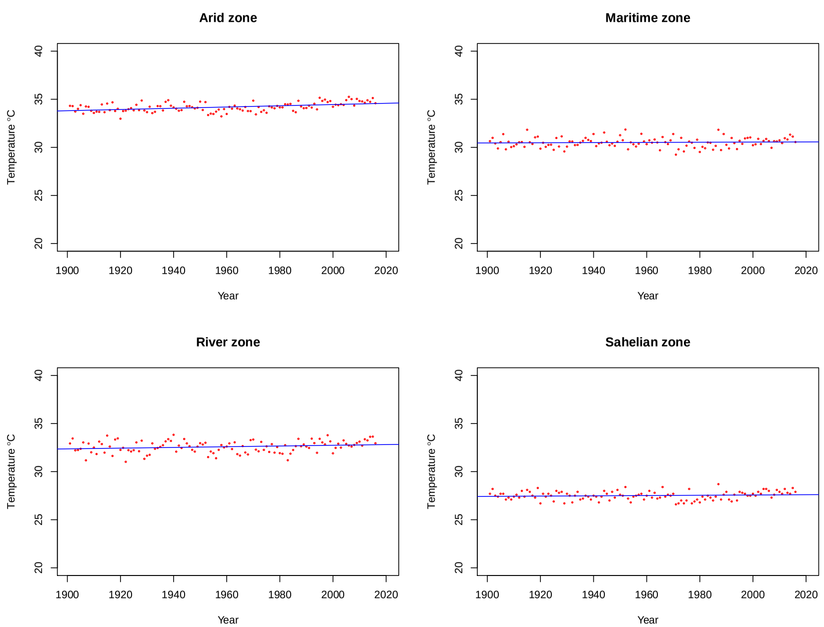


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.62Annual temperature during the dry season in the agroecological zones of Mauritania from 1901 to 2016.

Figure 29.a: Minimum annual temperature

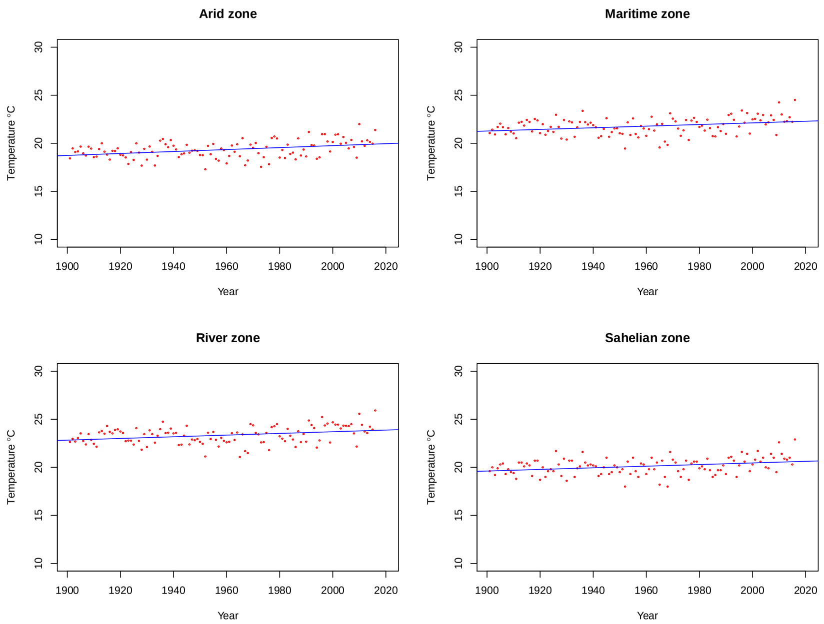


Figure 29.b: Median annual temperature

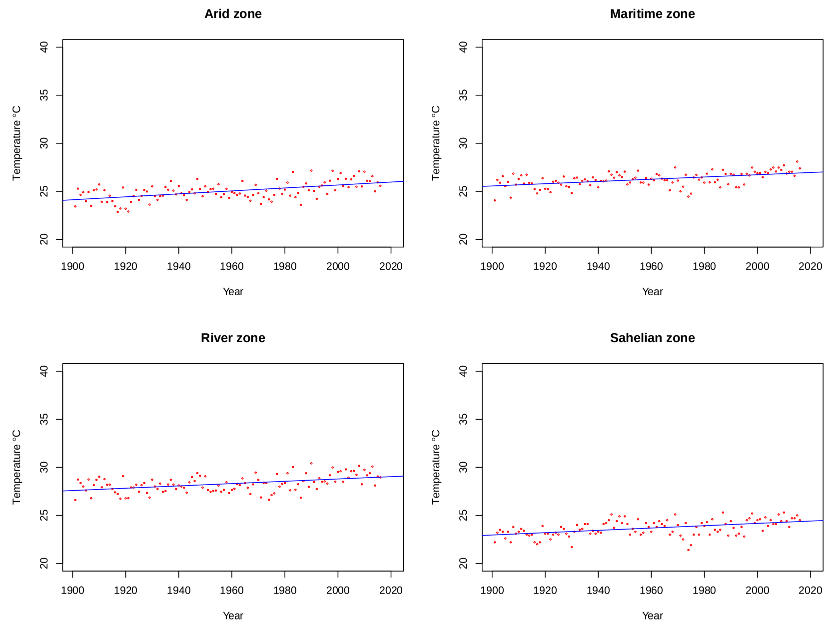
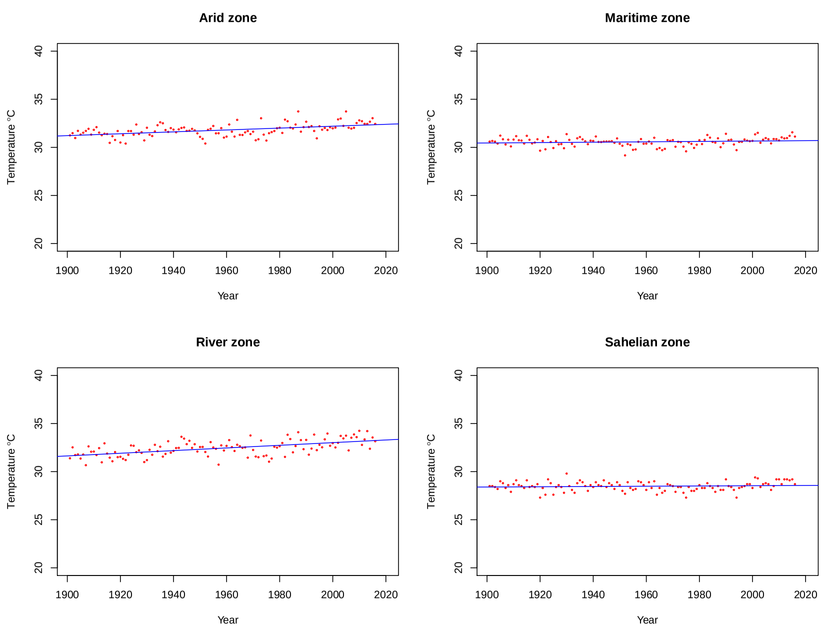


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.63 Endogenous detection of structural breaks in agroecological zones of Mauritania during the rainy season from 1901 to 2012

Figure 29.a: Minimum annual temperature

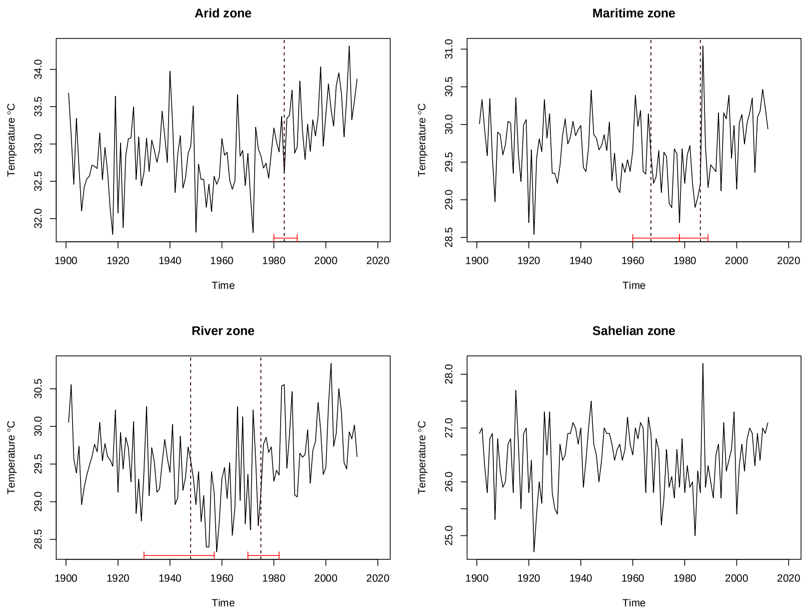


Figure 29.b: Median annual temperature

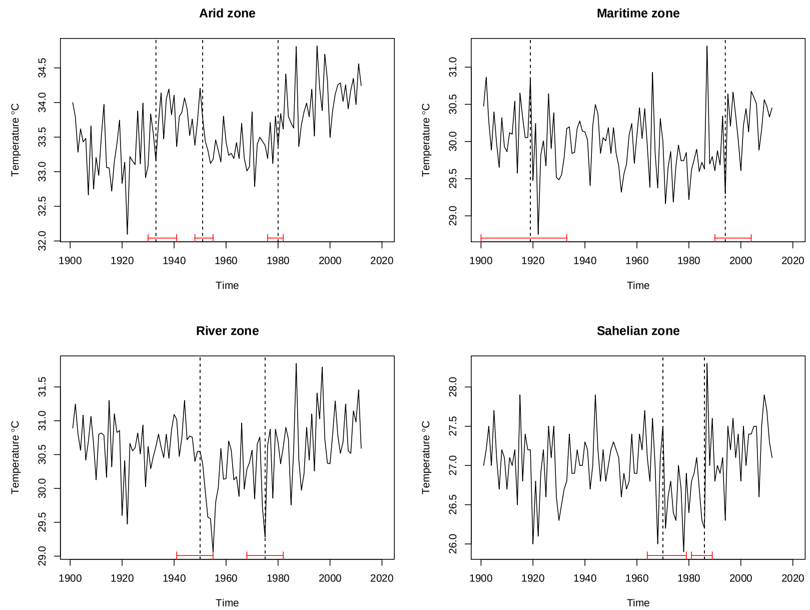
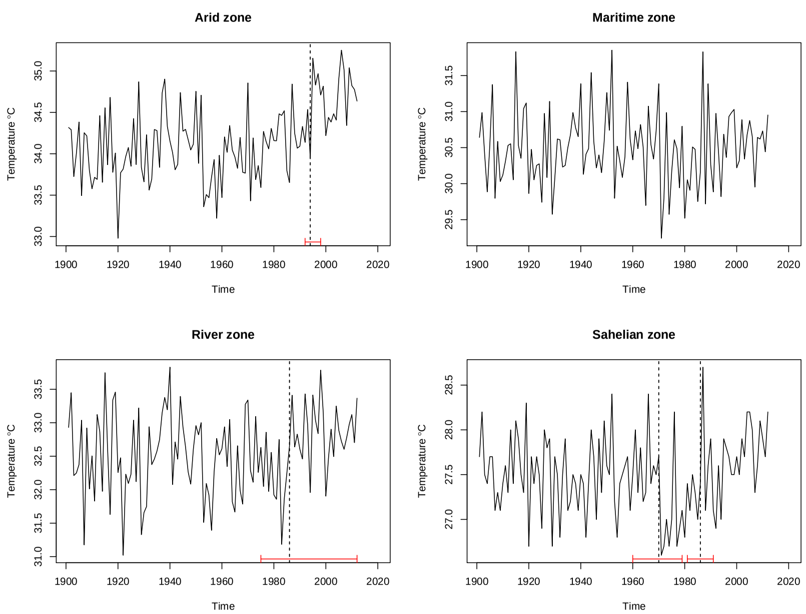


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.64Endogenous detection of structural breaks in agroecological zones of Djibouti during the dry season from 1901 to 2012

Figure 29.a: Minimum annual temperature

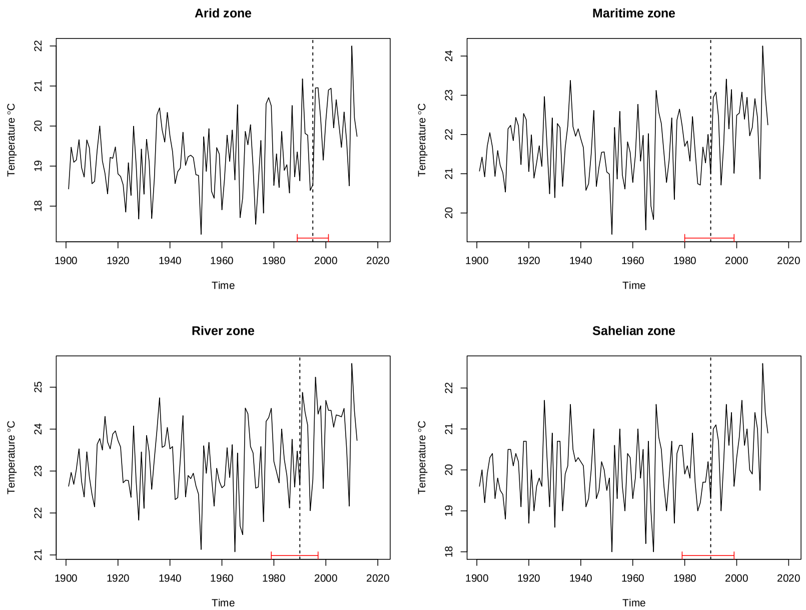


Figure 29.b: Median annual temperature

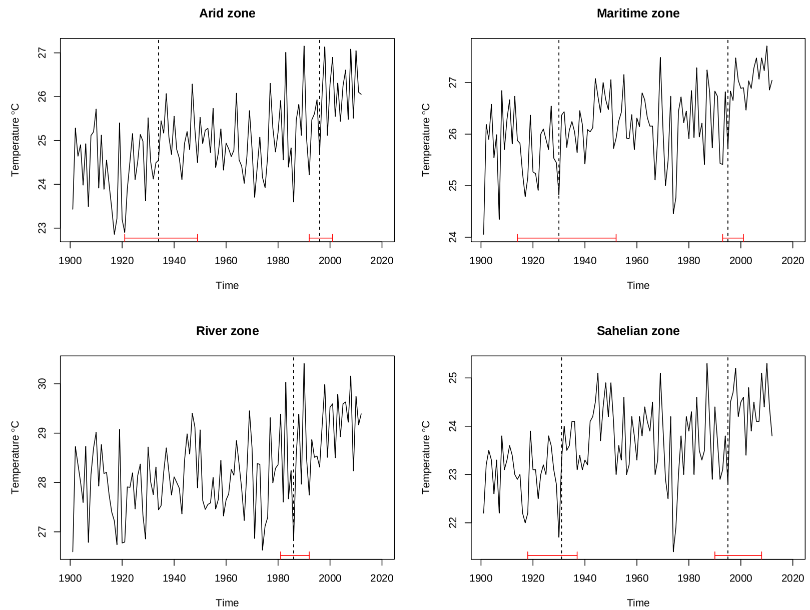
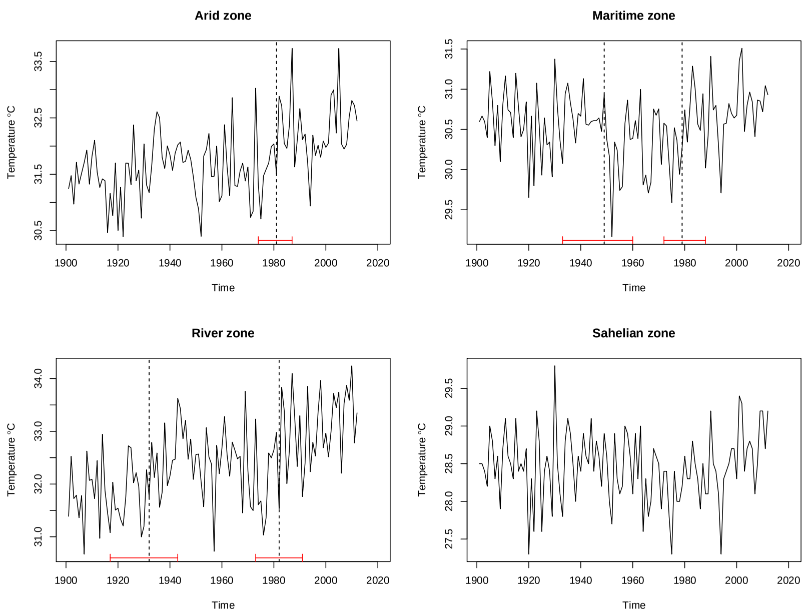


Figure 29.c: Maximum annual temperature



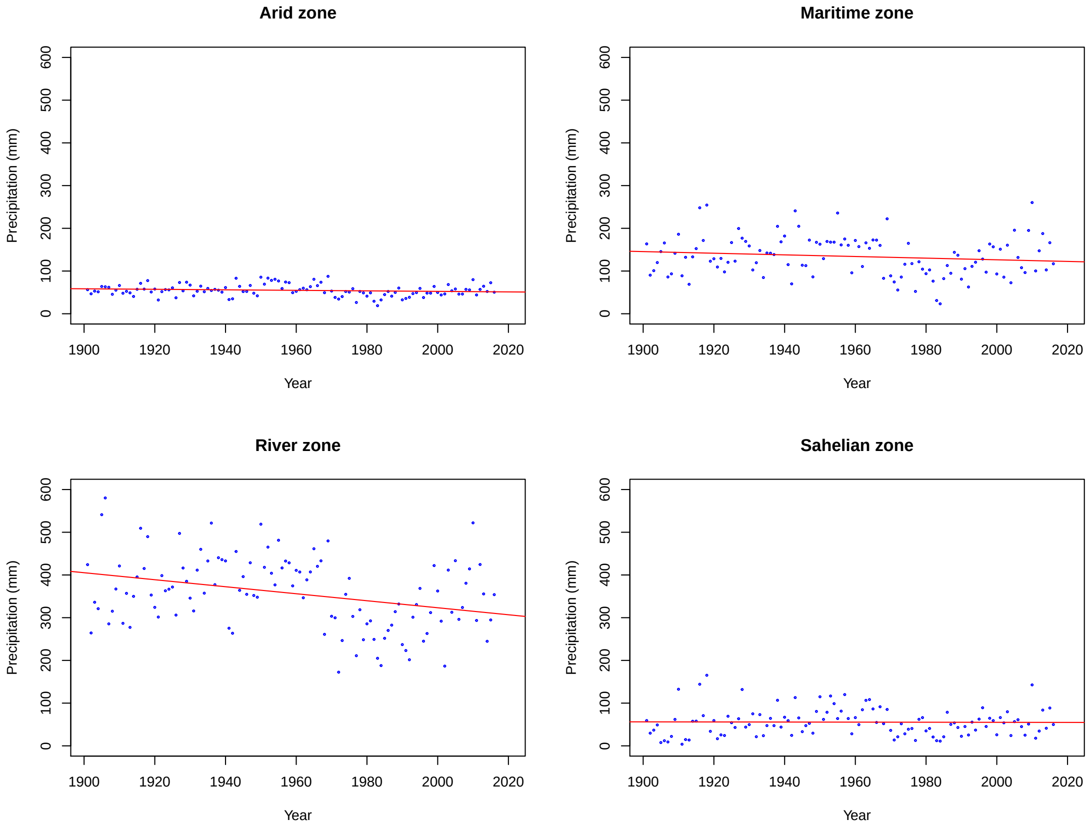
Source: Calculations and achievements by the author

Table 1.13The regression results in Mauritania

	Arid zone							
	Rainfall		Temperature					
	RainSum	RainSeason	TempminRain	TempmedRain	TempmaxRain	TempminDry	TempmedDry	TempmaxDry
Year	−0.061	−0.017*	0.008***	0.009***	0.006***	0.010***	0.015***	0.010***
	(0.037)	(0.009)	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)
Constant	173.645**	44.391**	18.208***	16.681***	21.601***	−0.599	−5.044	12.616***
	(72.570)	(17.832)	(2.490)	(2.326)	(2.234)	(4.490)	(4.181)	(3.033)
R^2	0.023	0.030	0.235	0.318	0.218	0.147	0.312	0.260
	Maritime zone							
Year	−0.192	−0.083***	0.001	0.001	0.001	0.008***	0.012***	0.002*
	(0.127)	(0.029)	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)
Constant	509.908**	189.672***	27.407***	27.591***	28.804***	5.165	3.387	26.647***
	(249.446)	(57.722)	(2.433)	(2.346)	(2.785)	(4.658)	(3.517)	(2.364)
R^2	0.020	0.066	0.008	0.009	0.003	0.100	0.270	0.024
	River zone							
Year	−0.820***	−0.239***	0.003**	0.002	0.004**	0.009***	0.012***	0.014***
	(0.221)	(0.056)	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	1,963.668***	547.317***	23.473***	26.763***	25.307***	6.204	4.725	5.421
	(432.557)	(108.947)	(2.689)	(2.730)	(3.249)	(4.647)	(4.099)	(3.656)
R^2	0.108	0.139	0.043	0.017	0.042	0.107	0.225	0.324
	Sahelian zone							
Year	−0.011	−0.008	0.002	0.002	0.001	0.008***	0.012***	0.001
	(0.090)	(0.021)	(0.002)	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)
Constant	78.004	23.610	22.964***	23.827***	24.675***	3.605	−0.033	25.831***
	(177.222)	(40.787)	(3.306)	(2.396)	(2.370)	(4.523)	(3.887)	(2.519)
R^2	0.0001	0.001	0.010	0.015	0.012	0.105	0.246	0.010
Observations	116	116	116	116	116	116	116	116
Model	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS

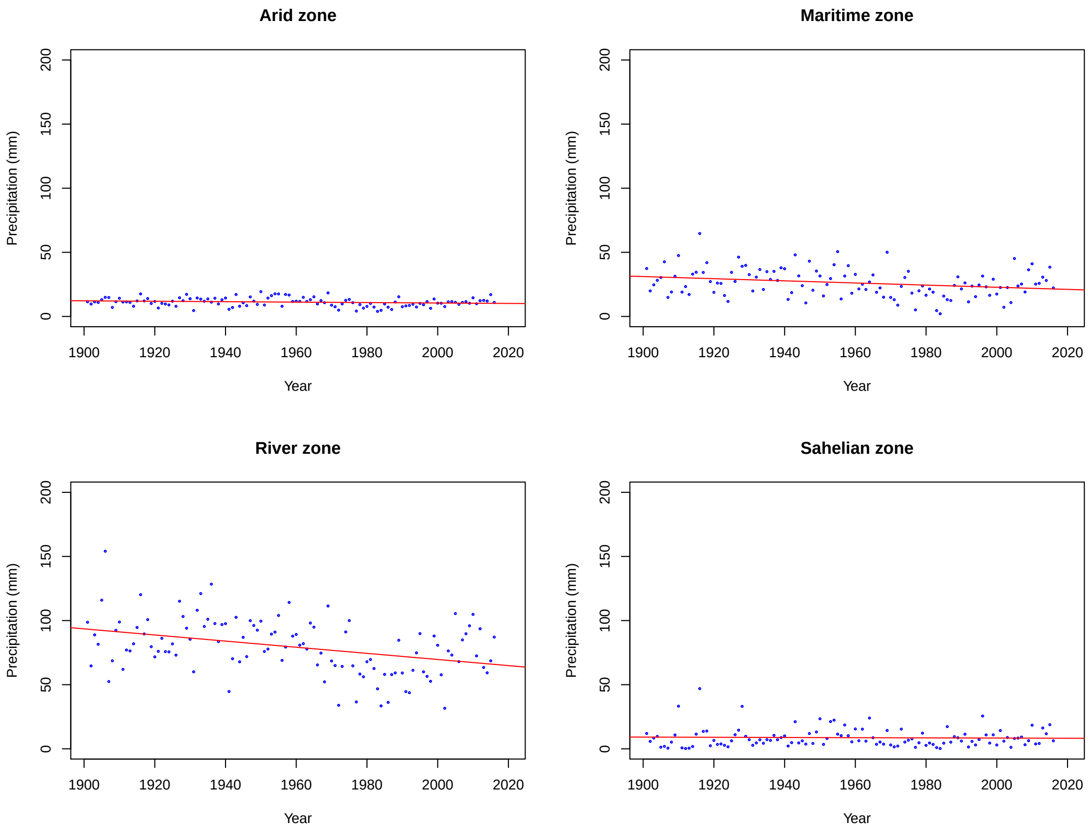
Note: *p<0.1; **p<0.05; ***p<0.01

Figure 1.65Evolution of the sum annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Mauritania



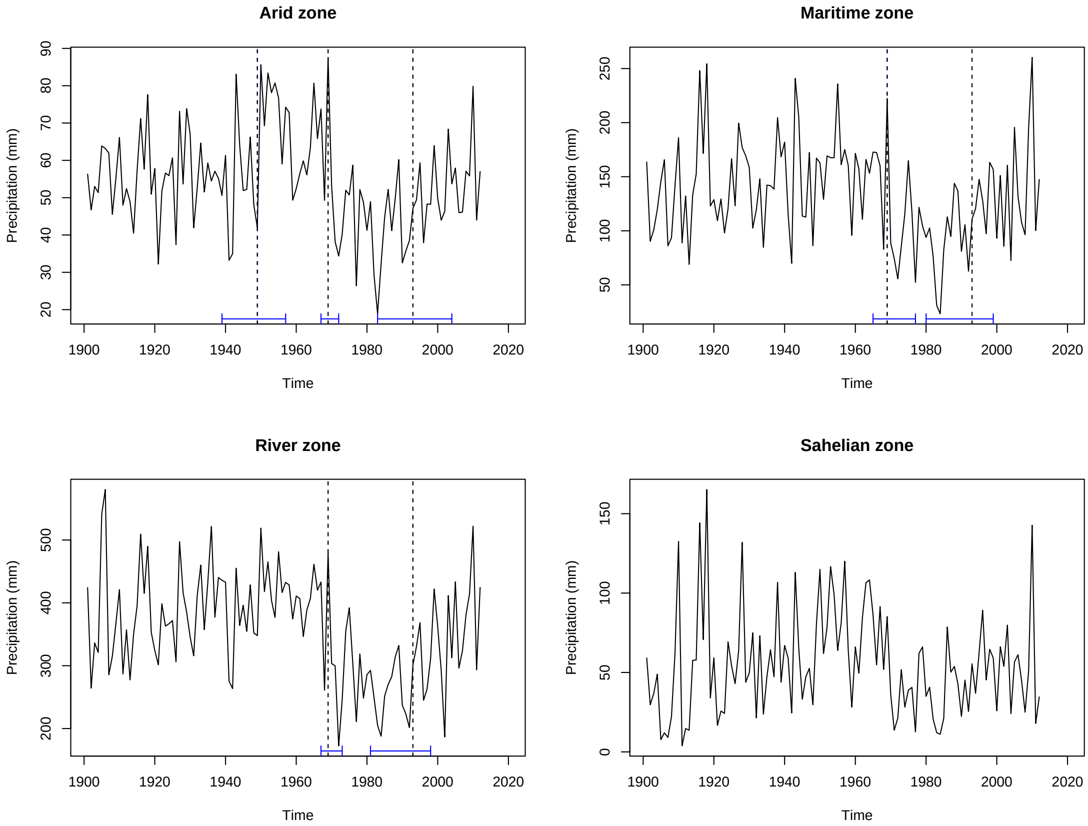
Source: Calculations and achievements of the author

Figure 1.66Evolution of the seasonal annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Mauritania.



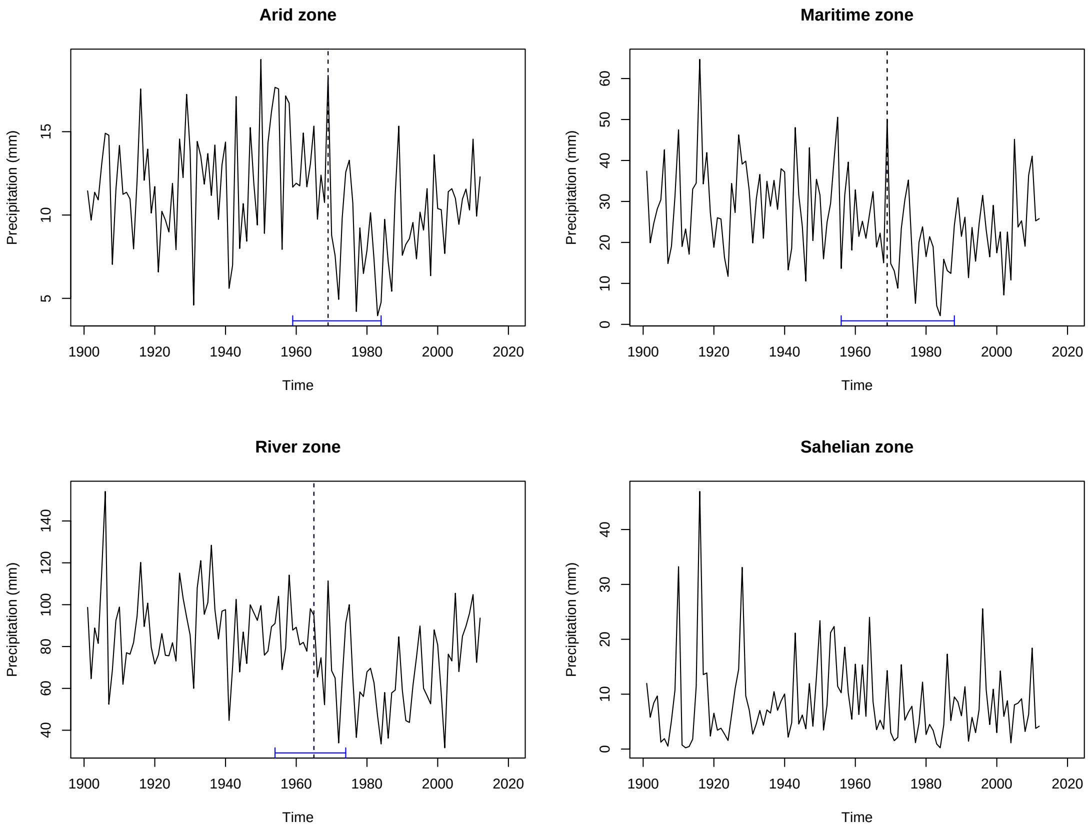
Source: Calculations and achievements of the author

Figure 1.67Breaks in total annual precipitation in the agroecological zones of Chad.



Source: Calculations and achievements of the author

Figure 1.68Breaks on seasonal precipitation in the agroecological zones of Chad.



Source: Calculations and achievements of the author

Figure 1.69Annual temperature during the rainy season in the agroecological zones of Niger from 1901 to 2016.

Figure 29.a: Minimum annual temperature

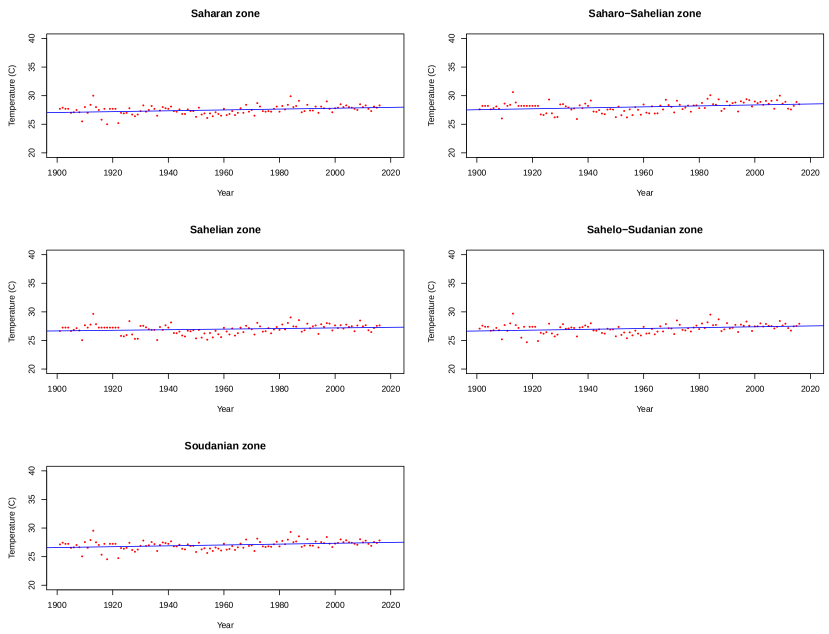


Figure 29.b: Median annual temperature

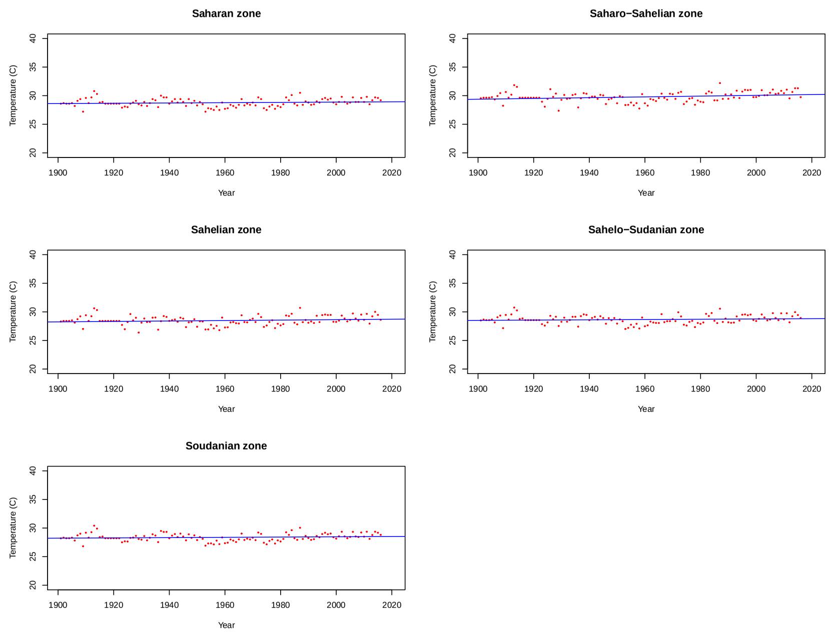
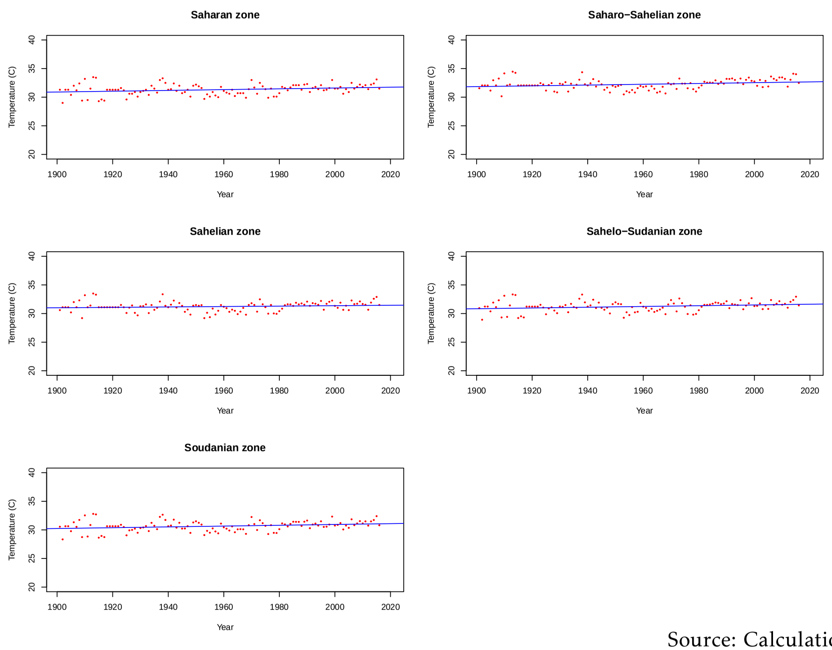


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.70Annual temperature during the dry season in the agroecological zones of Niger from 1901 to 2016.

Figure 29.a: Minimum annual temperature

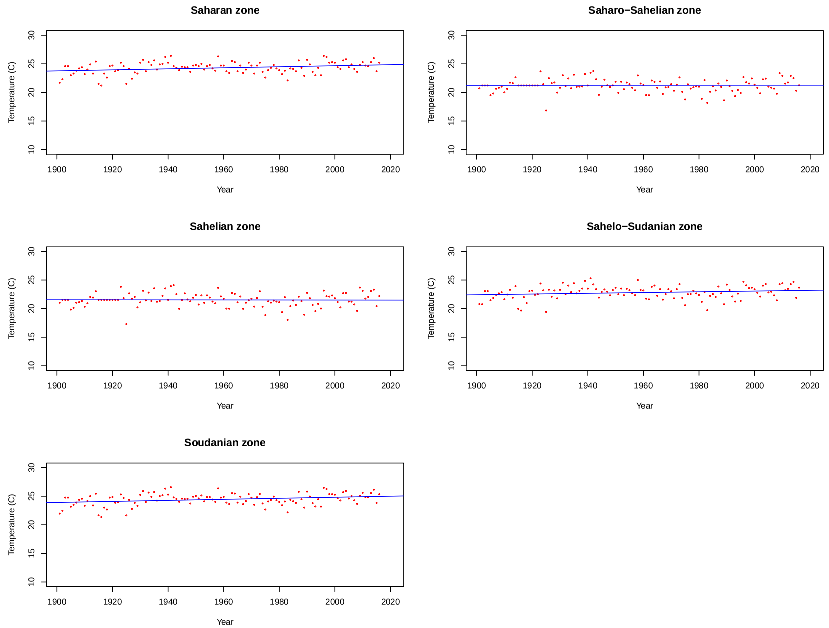


Figure 29.b: Median annual temperature

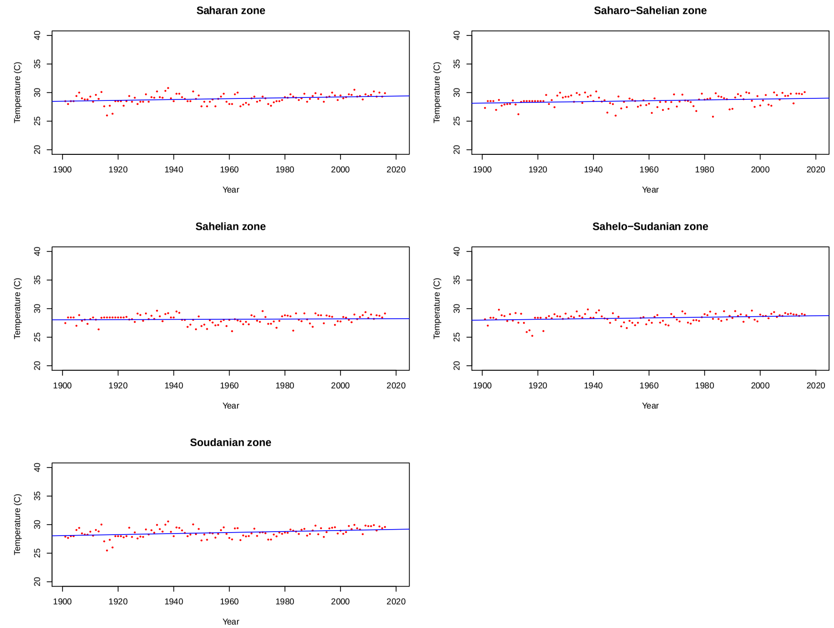
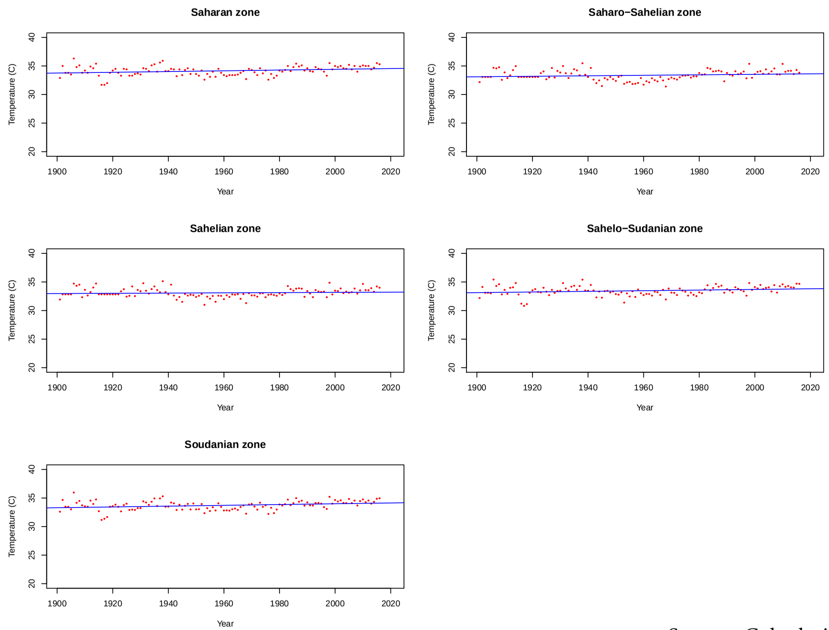


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.71 Endogenous detection of structural breaks in agroecological zones of Niger during the rainy season from 1901 to 2012

Figure 29.a: Minimum annual temperature

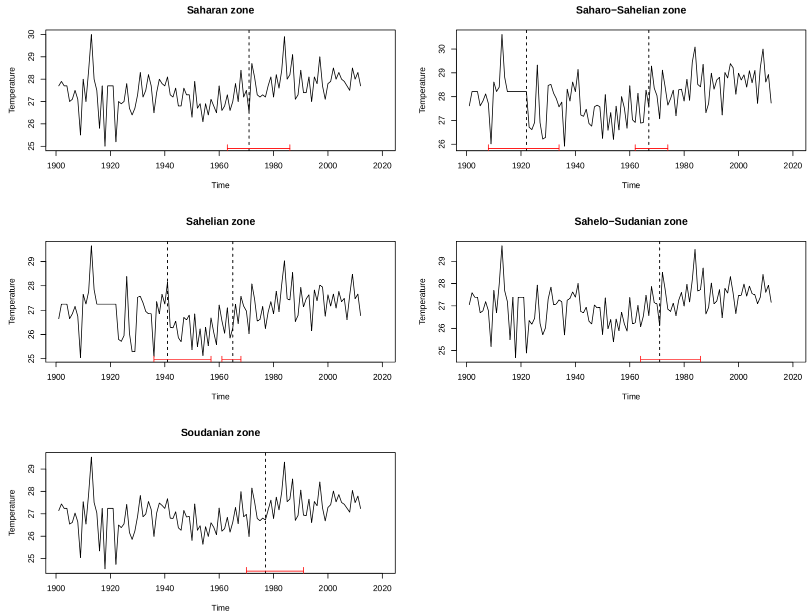


Figure 29.b: Median annual temperature

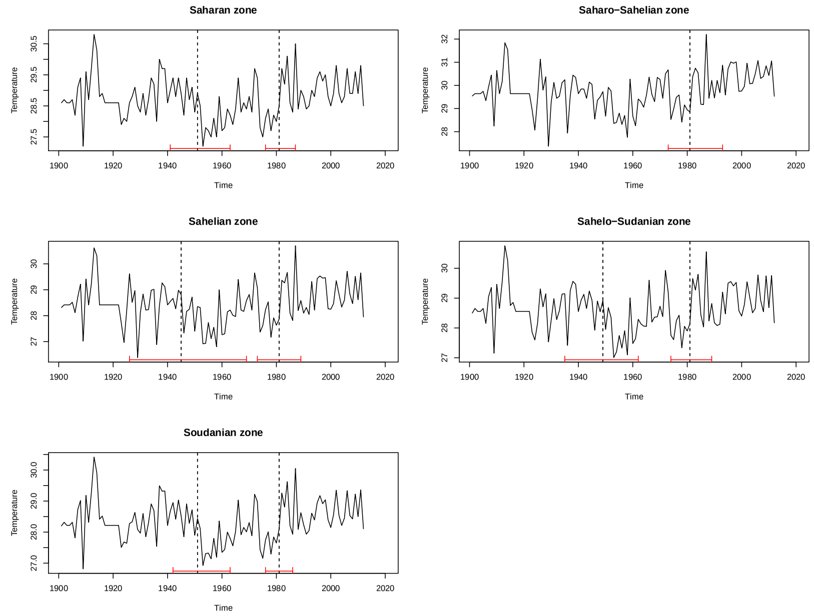
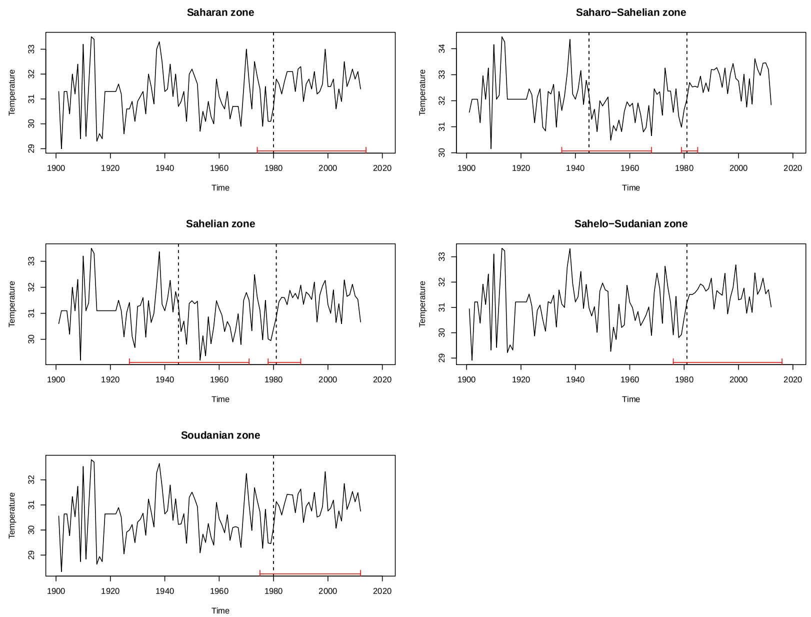


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.72Endogenous detection of structural breaks in agroecological zones of Niger during the dry season from 1901 to 2012

Figure 29.a: Minimum annual temperature

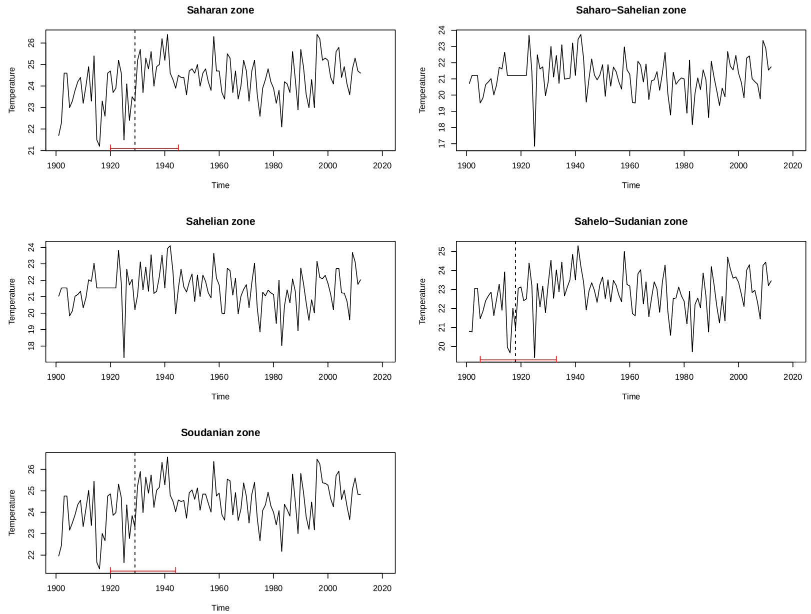


Figure 29.b: Median annual temperature

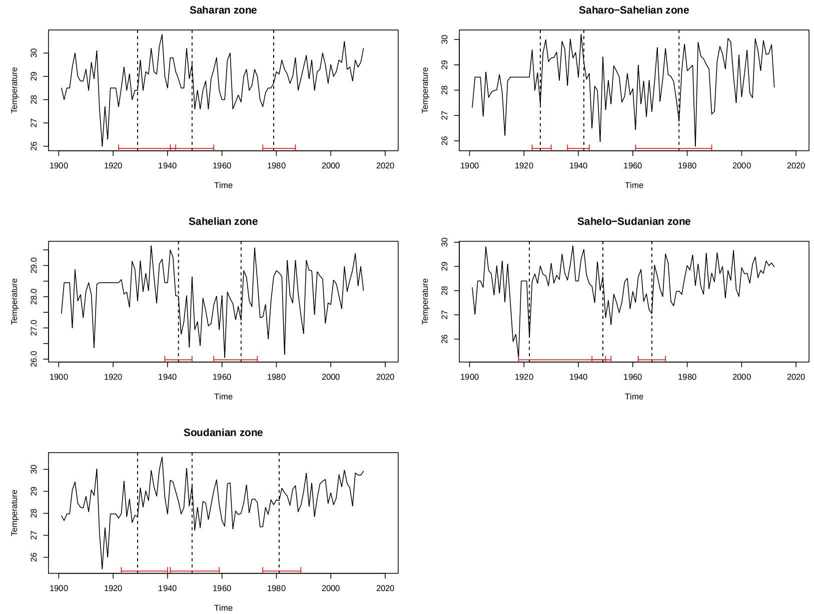
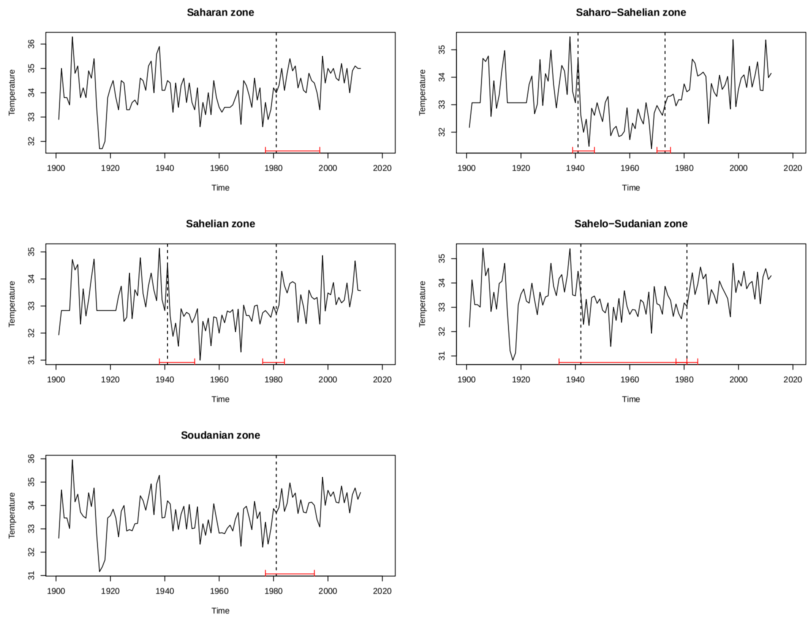


Figure 29.c: Maximum annual temperature



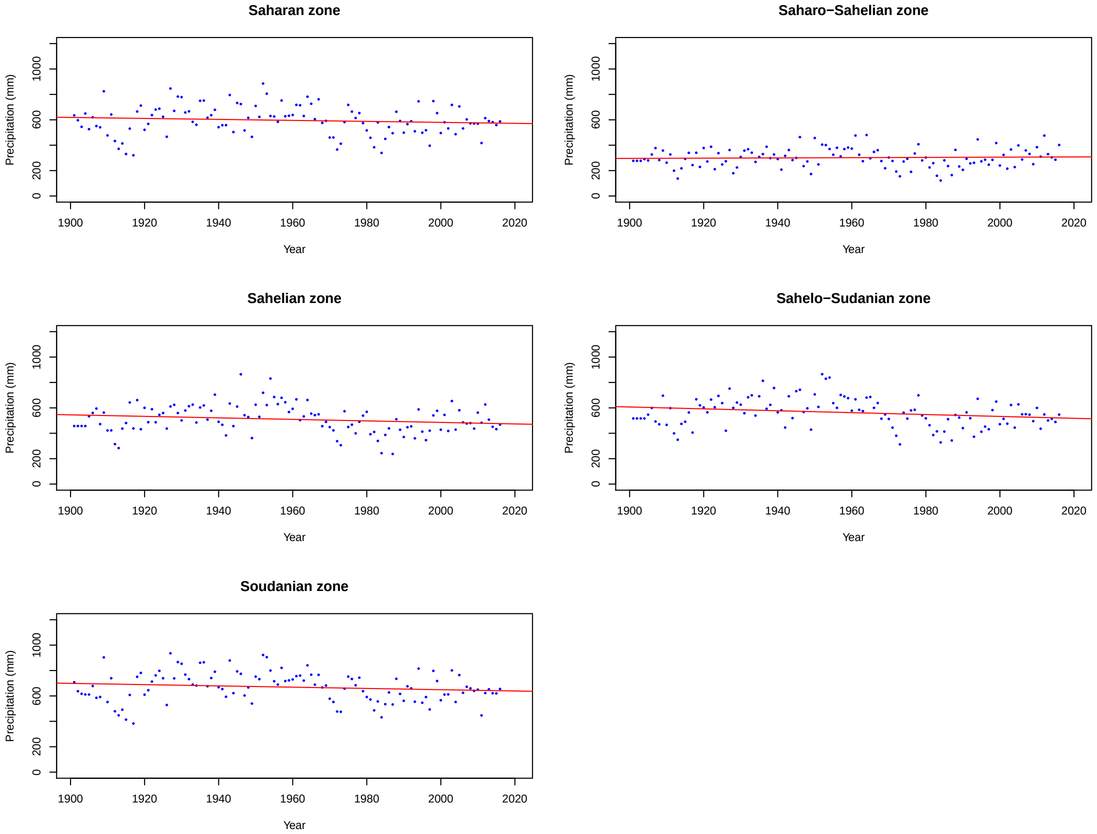
Source: Calculations and achievements by the author

Table 1.14Estimated results for Niger

	Rainfall		Temperature					
	RainSum	RainSeason	TempminRain	TempmedRain	TempmaxRain	TempminDry	TempmedRain	TempmaxDry
	Dependent variable: Saharan zone							
Year	−0.388	−0.102	0.007***	0.003	0.007***	0.009***	0.003	0.007***
	(0.320)	(0.081)	(0.002)	(0.002)	(0.003)	(0.003)	(0.002)	(0.002)
Constant	1,355.415**	343.594**	12.848***	23.795***	17.614***	6.660	23.795***	21.315***
	(627.631)	(158.785)	(4.048)	(3.713)	(4.940)	(5.492)	(3.713)	(4.356)
R^2	0.013	0.014	0.103	0.016	0.063	0.083	0.016	0.071
	Dependent variable: Saharo-sahelian zone							
Year	0.097	−0.006	0.008***	0.007***	0.007***	−0.0002	0.007***	0.004*
	(0.208)	(0.061)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)
Constant	111.266	94.169	11.631**	16.460***	18.742***	21.474***	16.460***	24.947***
	(407.878)	(118.922)	(4.648)	(4.551)	(4.535)	(6.271)	(4.551)	(4.620)
R^2	0.002	0.0001	0.098	0.070	0.072	0.00002	0.070	0.028
	Dependent variable: Saharo-sahelian zone							
Year	0.097	−0.006	0.008***	0.007***	0.007***	−0.0002	0.007***	0.004*
	(0.208)	(0.061)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)
Constant	111.266	94.169	11.631**	16.460***	18.742***	21.474***	16.460***	24.947***
	(407.878)	(118.922)	(4.648)	(4.551)	(4.535)	(6.271)	(4.551)	(4.620)
R^2	0.002	0.0001	0.098	0.070	0.072	0.00002	0.070	0.028
	Dependent variable: Sahelian zone							
Year	−0.596**	−0.156*	0.005**	0.004*	0.004	−0.0004	0.004*	0.002
	(0.300)	(0.081)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)
Constant	1,677.757***	438.309***	16.760***	20.937***	24.062***	22.334***	20.937***	29.065***
	(587.837)	(158.969)	(4.431)	(4.333)	(4.498)	(6.470)	(4.333)	(4.169)
R^2	0.033	0.031	0.045	0.026	0.022	0.0001	0.026	0.008
Year	−0.744**	−0.160**	0.007***	0.002	0.007***	0.006**	0.002	0.006**
	(0.304)	(0.074)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)
Constant	2,021.095***	449.819***	12.686***	23.858***	18.292***	10.093	23.858***	22.515***
	(595.981)	(144.822)	(4.317)	(4.008)	(4.790)	(6.174)	(4.008)	(4.328)
R^2	0.050	0.039	0.089	0.012	0.060	0.036	0.012	0.053
Year	−0.500	−0.107	0.007***	0.002	0.007***	0.009***	0.002	0.007***
	(0.321)	(0.077)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)
Constant	1,648.463***	365.560**	12.414***	23.606***	16.804***	6.629	23.606***	20.050***
	(628.862)	(151.384)	(3.975)	(3.620)	(4.799)	(5.454)	(3.620)	(4.227)
R^2	0.021	0.017	0.106	0.015	0.068	0.086	0.015	0.084
Observations	116	116	116	116	116	116	116	116

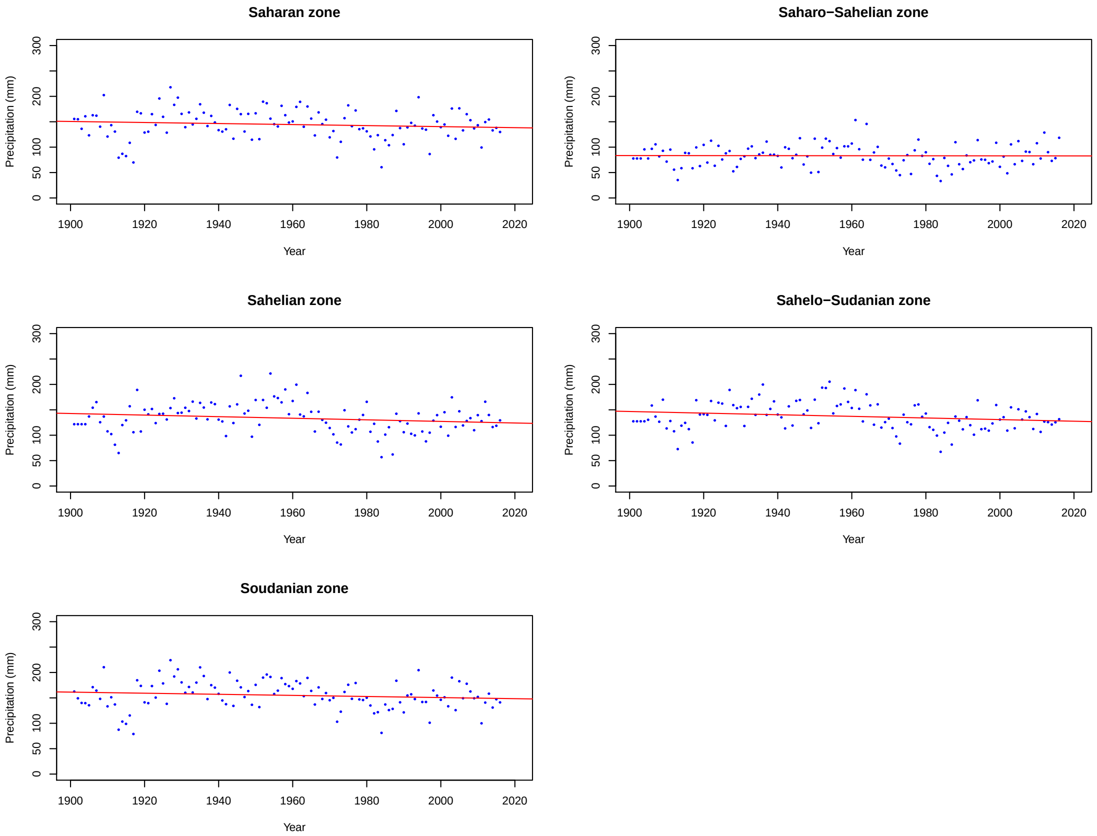
Note: *p<0.1; **p<0.05; ***p<0.01

Figure 1.73Evolution of the sum annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Niger.



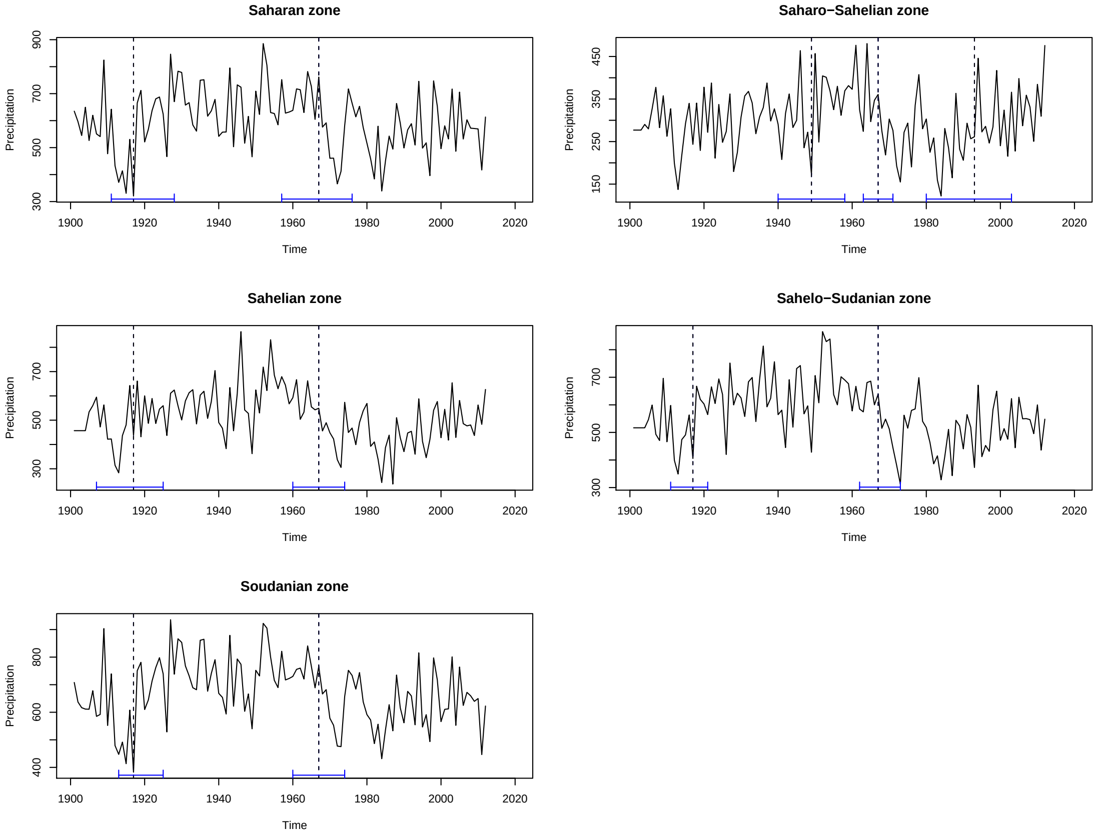
Source: Calculations and achievements of the author

Figure 1.74Evolution of seasonal precipitation (mm) from 1901 to 2016 in the agroecological zones of Niger.



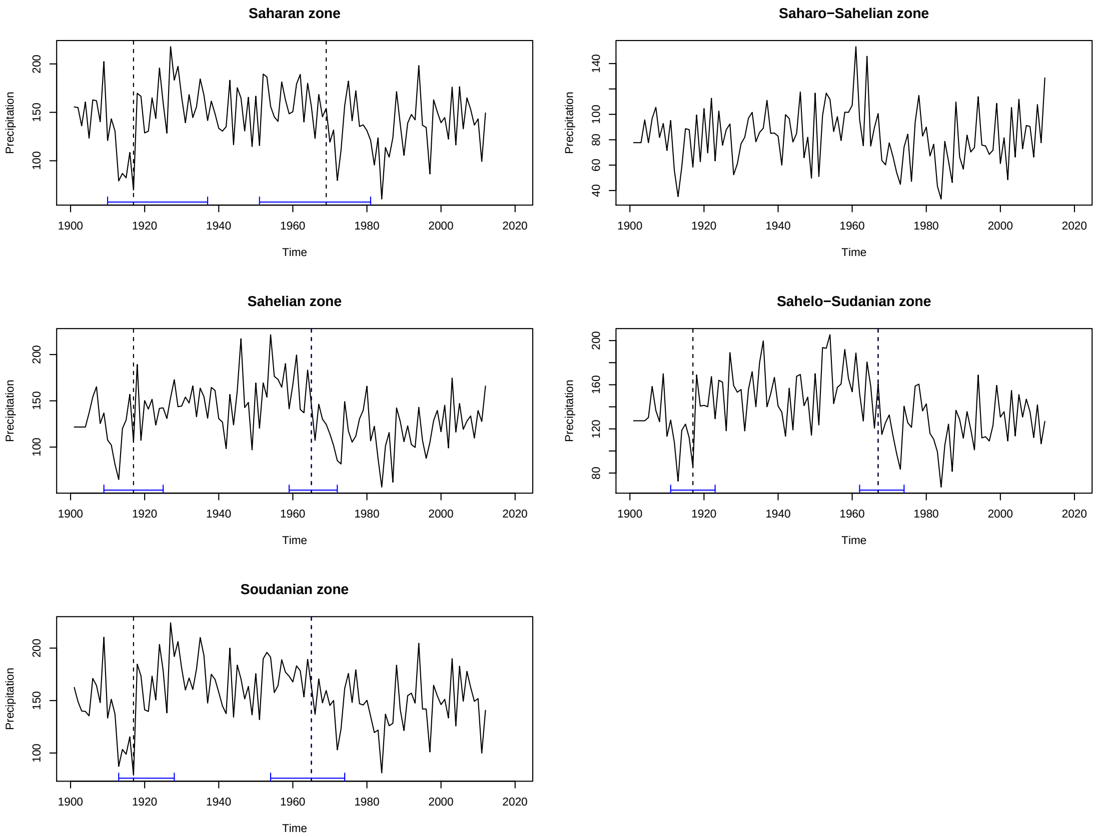
Source: Calculations and achievements of the author

Figure 1.75Breaks in total annual precipitation in the agroecological zones of Niger.



Source: Calculations and achievements of the author

Figure 1.76Breaks on seasonal precipitation in the agroecological zones of Nigeria.



Source: Calculations and achievements of the author

Figure 1.77 Annual temperature during the rainy season in the agroecological zones of Nigeria from 1901 to 2016.

Figure 29.a: Minimum annual temperature

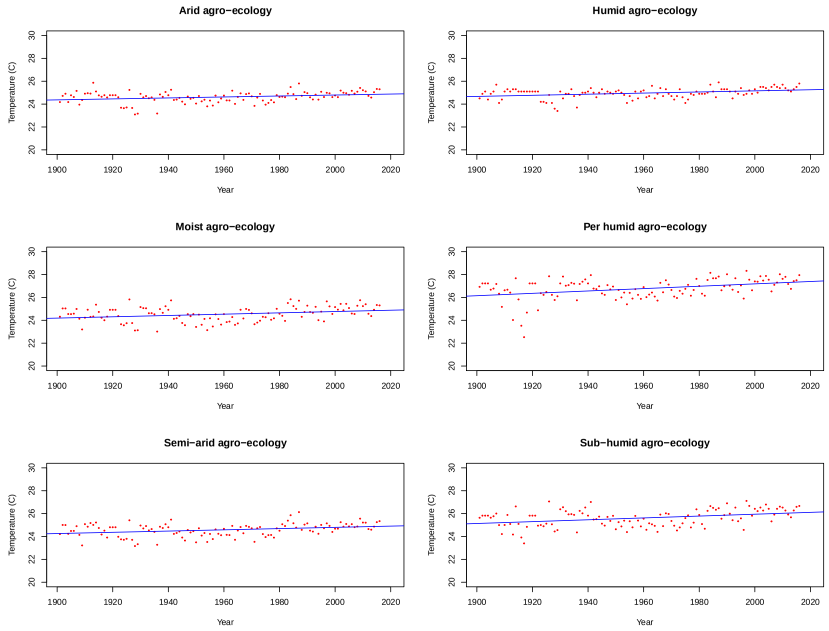


Figure 29.b: Median annual temperature

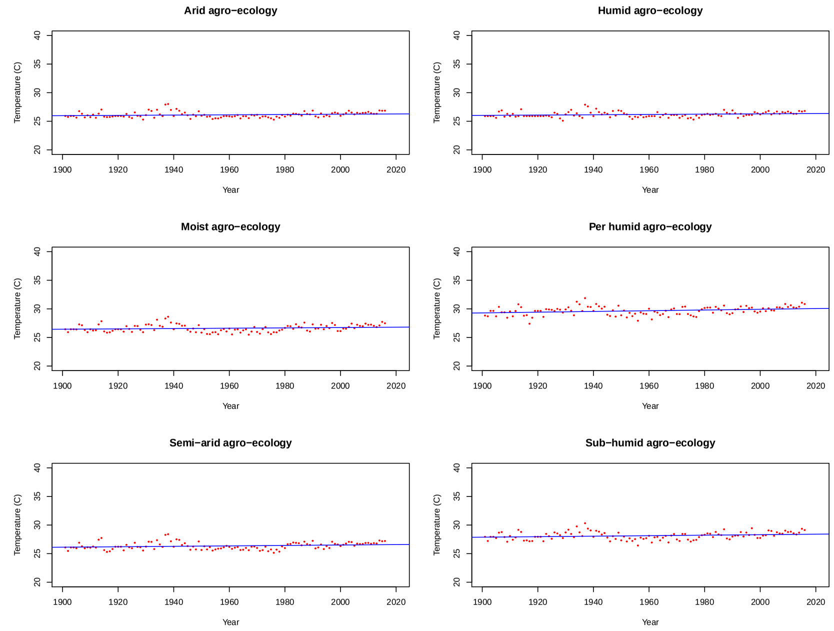
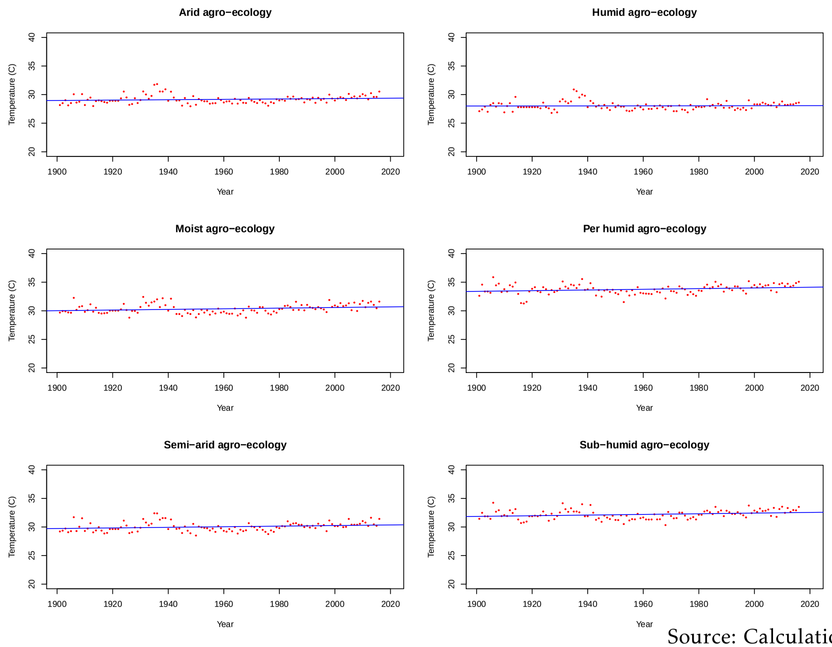


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.78 Annual temperature during the dry season in the agroecological zones of Nigeria from 1901 to 2016.

Figure 29.a: Minimum annual temperature

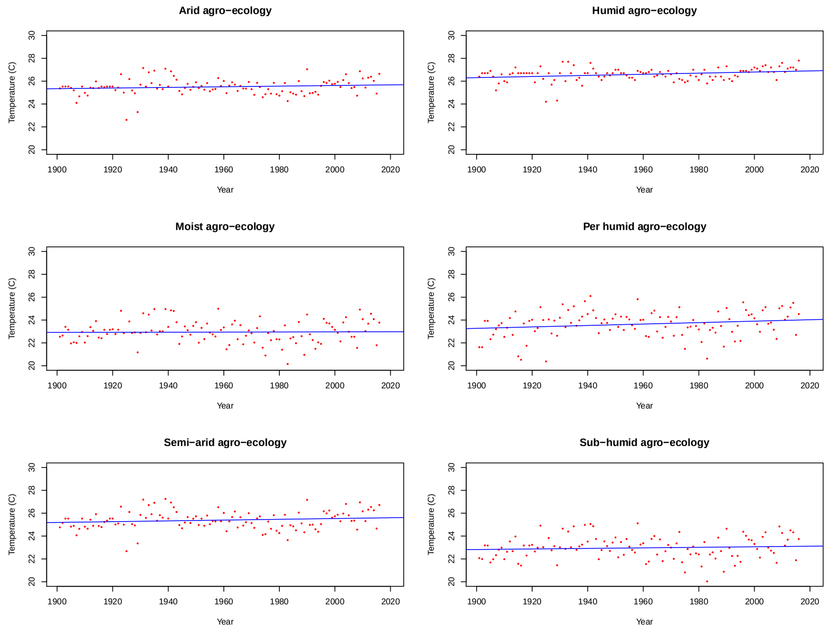


Figure 29.b: Median annual temperature

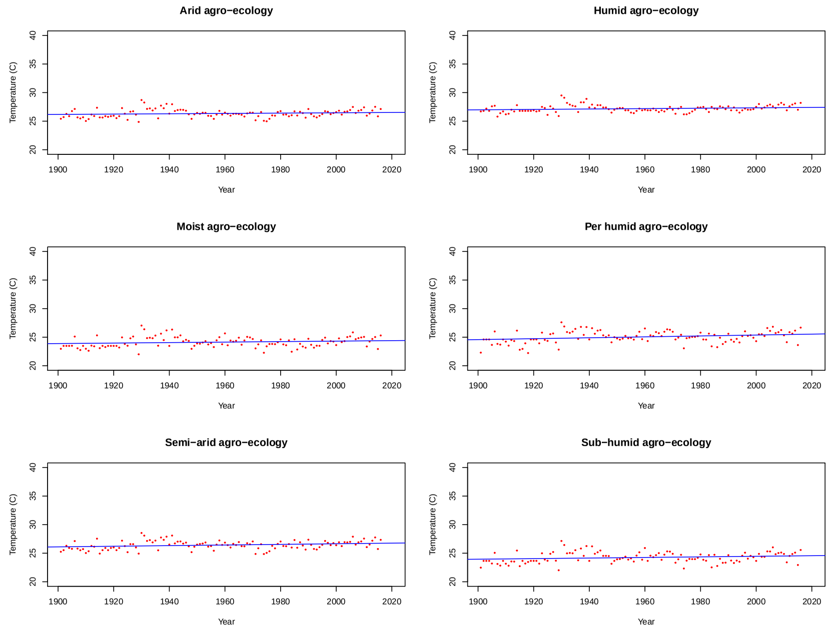
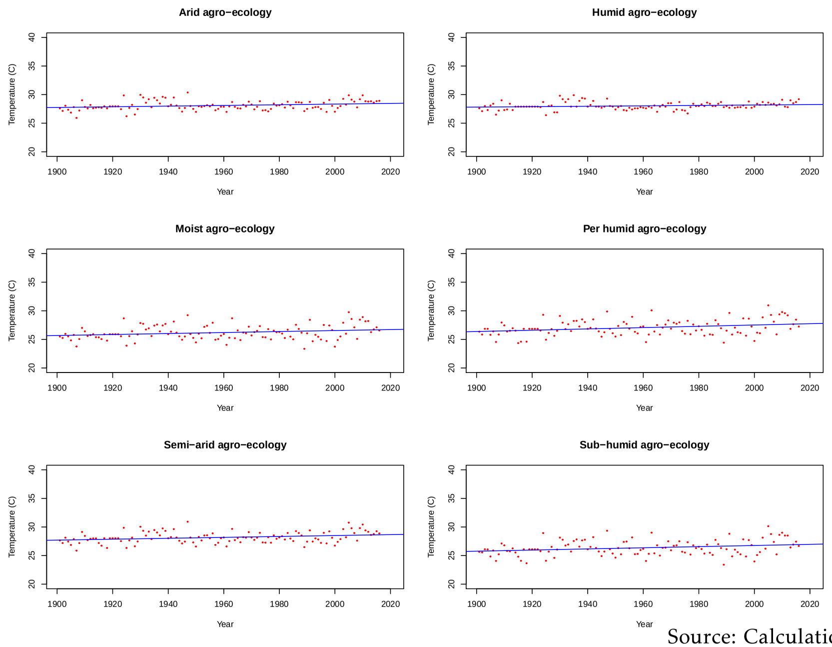


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.79Endogenous detection of structural breaks in agroecological zones of Nigeria during the rainy season from 1901 to 2012

Figure 29.a: Minimum annual temperature

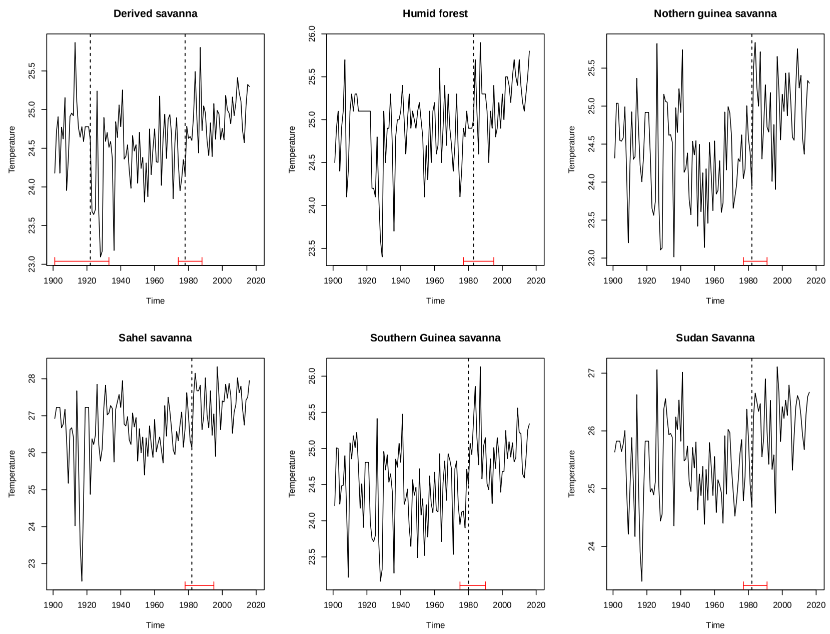


Figure 29.b: Median annual temperature

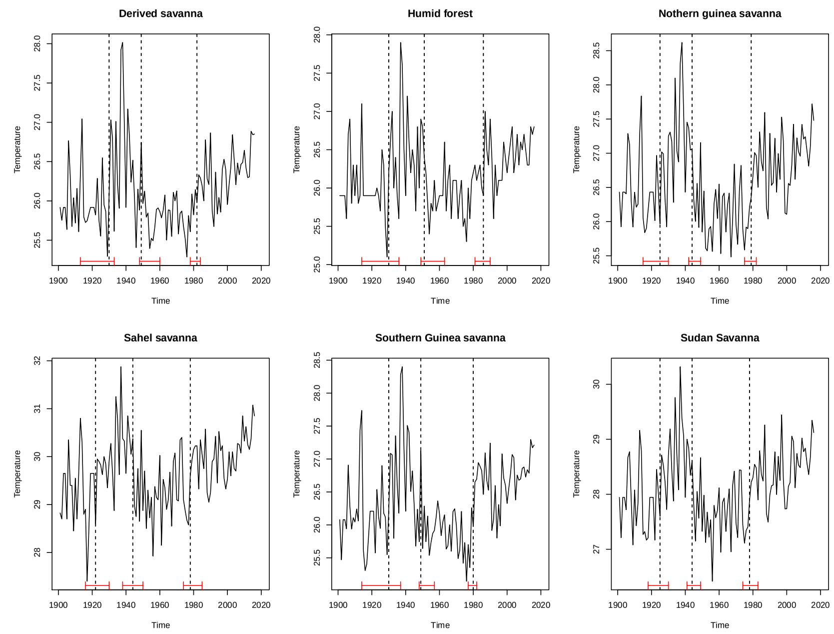
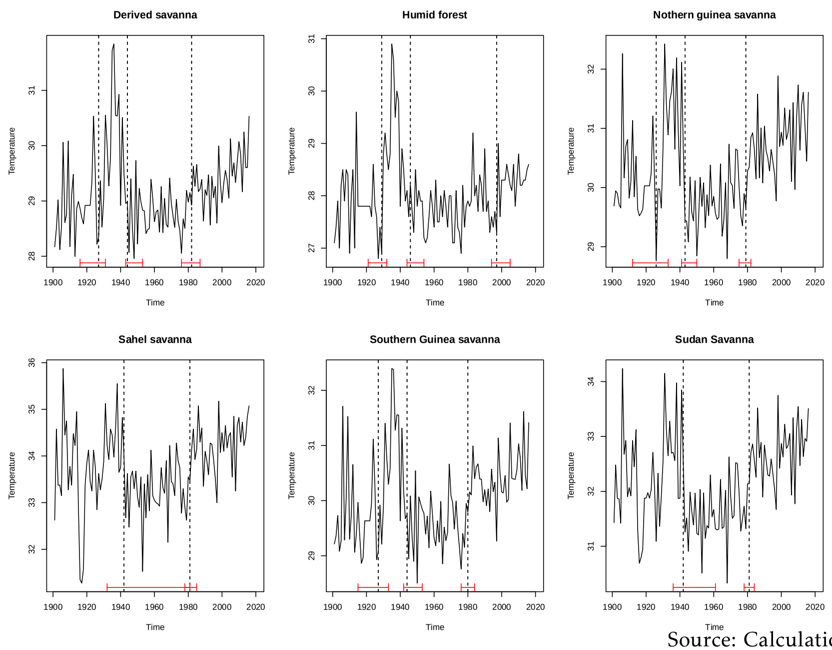


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.80 Endogenous detection of structural breaks in agroecological zones of Nigeria during the dry season from 1901 to 2012

Figure 29.a: Minimum annual temperature

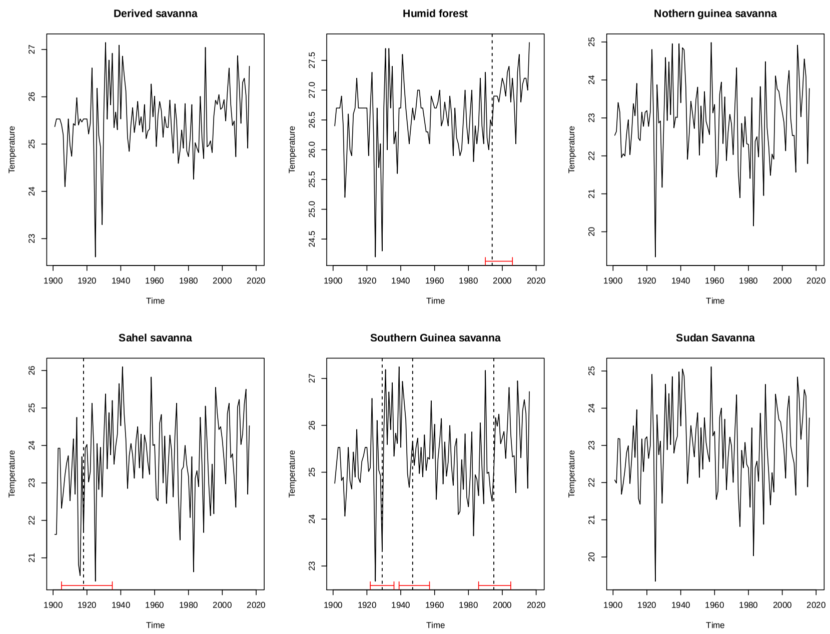


Figure 29.b: Median annual temperature

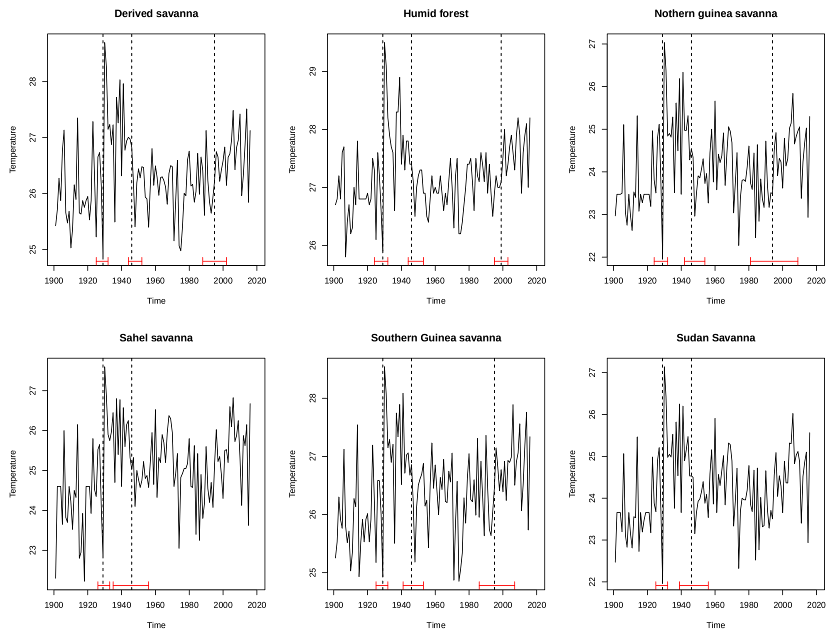
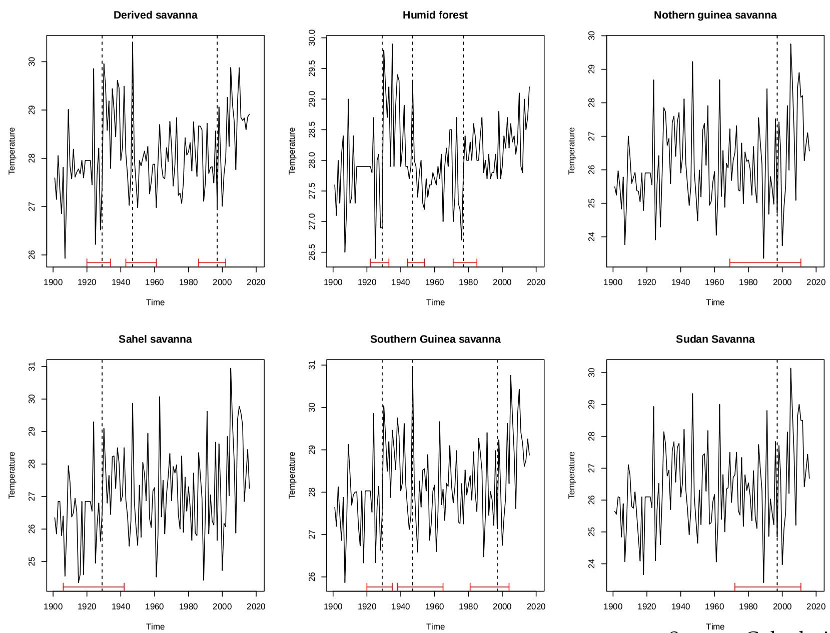


Figure 29.c: Maximum annual temperature



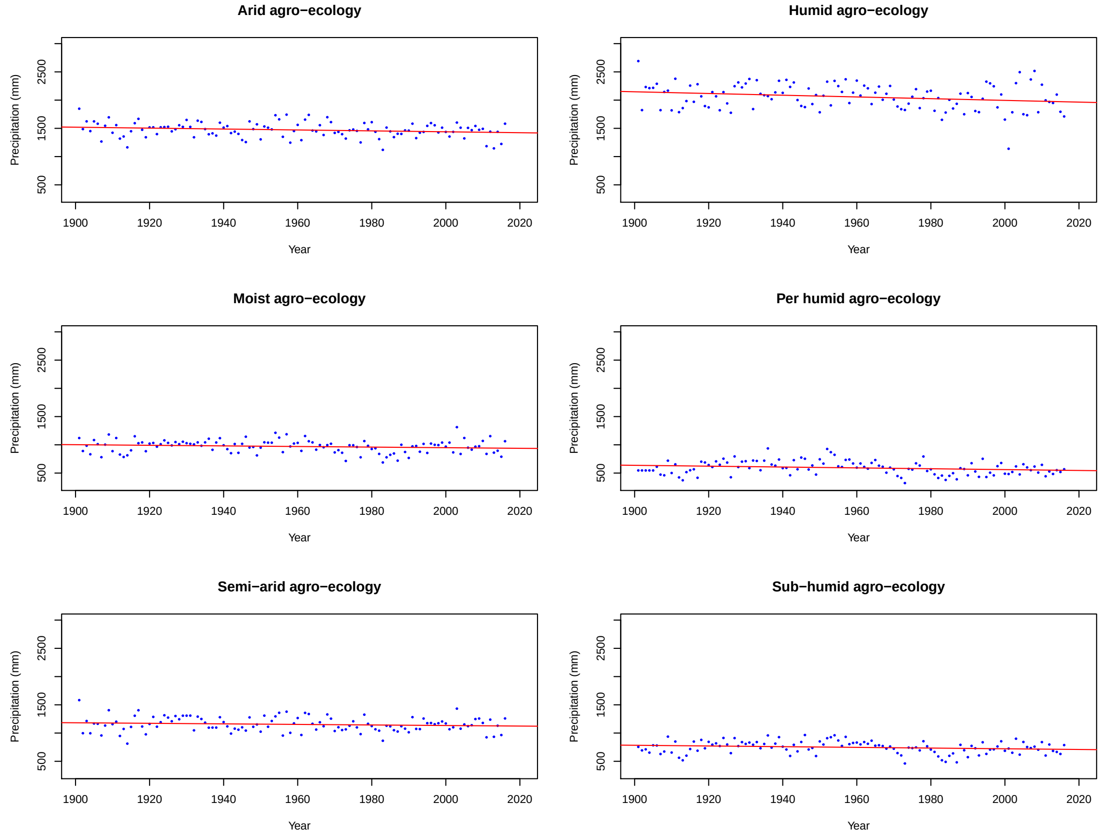
Source: Calculations and achievements by the author

Table 1.15Estimated results for Nigeria

	RainSum	RainSeason	TempminRain	TempmedRain	TempmaxRain	TempminDry	TempmedRain	TempmaxDry
	Dependent variable: Derived savanna							
	Rainfall		Temperature					
Year	−0.813**	−0.079*	0.004***	0.003*	0.003*	0.003	0.003*	0.006***
	(0.359)	(0.040)	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)	(0.002)
Constant	3,064.222***	315.517***	16.316***	21.220***	22.684***	20.062***	21.220***	16.530***
	(703.505)	(78.265)	(2.551)	(2.634)	(3.869)	(3.729)	(2.634)	(4.265)
R^2	0.043	0.033	0.085	0.030	0.024	0.018	0.030	0.061
	Dependent variable: Humid forest							
Year	−1.524**	−0.113*	0.005***	0.003**	0.0005	0.005***	0.003**	0.004**
	(0.616)	(0.059)	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)	(0.002)
Constant	5,043.950***	428.159***	15.436***	20.940***	27.094***	17.006***	20.940***	20.871***
	(1,206.354)	(115.908)	(2.300)	(2.477)	(3.895)	(2.973)	(2.477)	(3.435)
R^2	0.051	0.031	0.131	0.038	0.001	0.084	0.038	0.037
	Dependent variable: Nothern guinea savanna							
Year	−0.531*	−0.059*	0.006***	0.003*	0.006**	0.0005	0.003*	0.009**
	(0.312)	(0.035)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.003)
Constant	2,011.597***	222.577***	13.275***	20.832***	19.433***	22.033***	20.832***	9.183
	(611.695)	(67.937)	(3.386)	(3.394)	(4.180)	(5.517)	(3.394)	(6.605)
R^2	0.025	0.024	0.088	0.025	0.056	0.0002	0.025	0.055
	Dependent variable: Sahel savanna							
Year	−0.759**	−0.084**	0.010***	0.006***	0.006***	0.006**	0.006***	0.011***
	(0.324)	(0.036)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.004)
Constant	2,079.766***	229.475***	6.487	17.236***	22.023***	11.322*	17.236***	4.689
	(634.566)	(70.461)	(4.570)	(3.894)	(4.381)	(6.073)	(3.894)	(6.919)
R^2	0.046	0.045	0.147	0.082	0.059	0.035	0.082	0.084
	Dependent variable: Southern guinea savanna							
Year	−0.487	−0.051	0.005***	0.004**	0.005**	0.003	0.004**	0.008***
	(0.356)	(0.040)	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)
Constant	2,108.488***	228.409***	13.969***	18.819***	19.795***	18.659***	18.819***	12.473**
	(696.772)	(77.486)	(2.894)	(3.310)	(4.156)	(4.313)	(3.310)	(5.104)
R^2	0.016	0.015	0.105	0.043	0.051	0.021	0.043	0.077
	Dependent variable: Sudan savanna							
Year	−0.620**	−0.068**	0.008***	0.004**	0.006***	0.002	0.004**	0.010***
	(0.298)	(0.033)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.004)
Constant	1,961.546***	216.469***	9.731**	19.590***	20.870***	18.242***	19.590***	6.813
	(582.921)	(64.772)	(3.815)	(3.597)	(4.188)	(5.744)	(3.597)	(6.899)
Observations	116	116	116	116	116	116	116	116
R^2	0.037	0.036	0.132	0.047	0.060	0.006	0.047	0.066
Observations	116	116	116	116	116	116	116	116

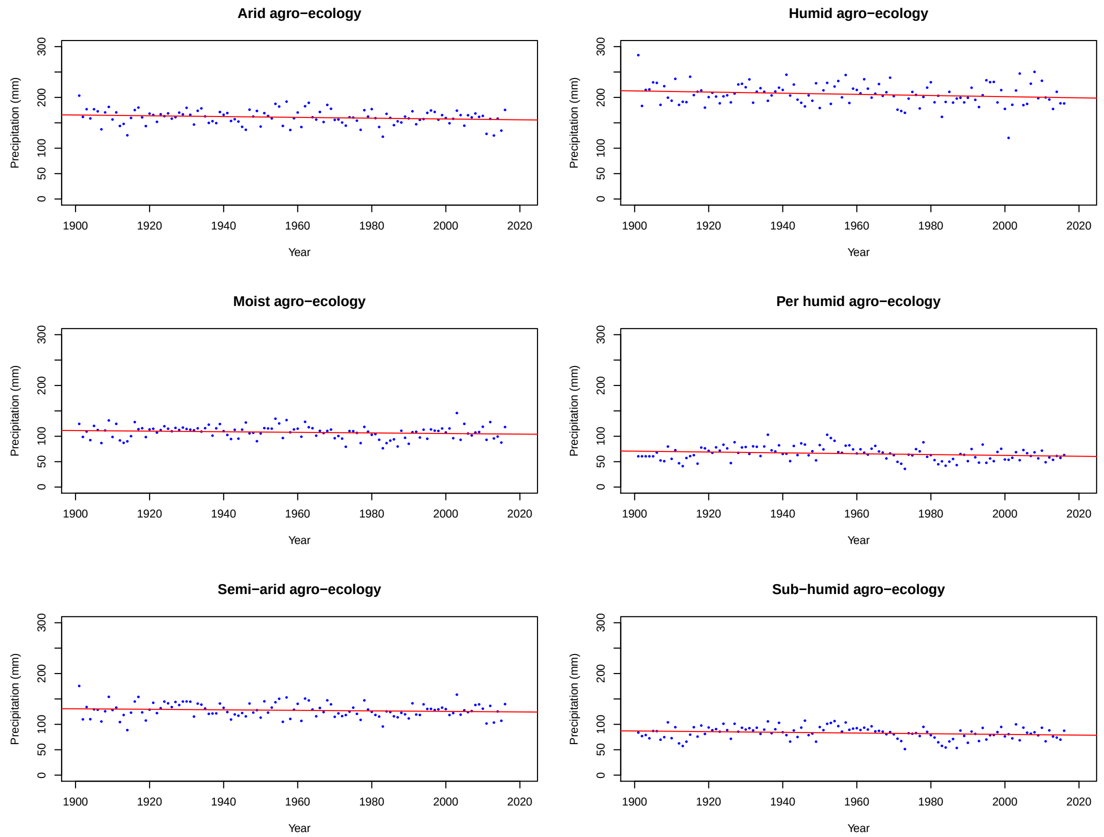
Note: *p<0.1; **p<0.05; ***p<0.01

Figure 1.81 Evolution of the sum annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Nigeria



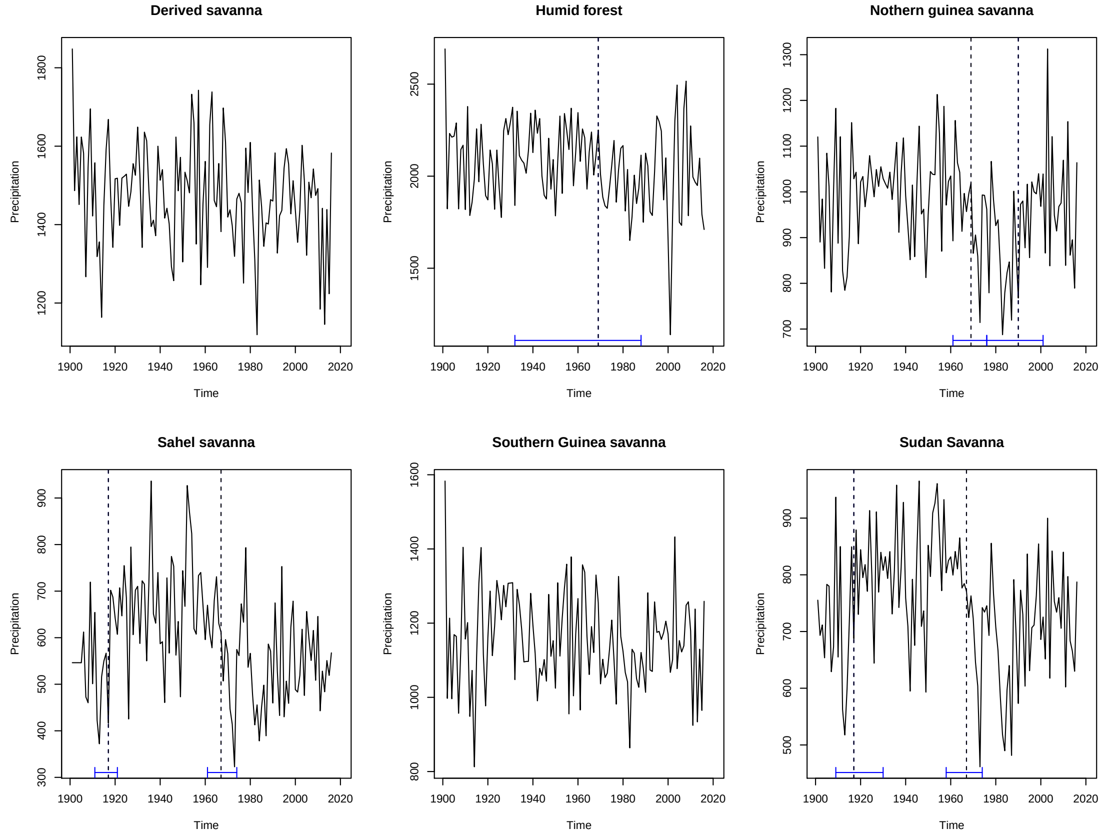
Source: Calculations and achievements of the author

Figure 1.82 Evolution of the seasonal annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Nigeria



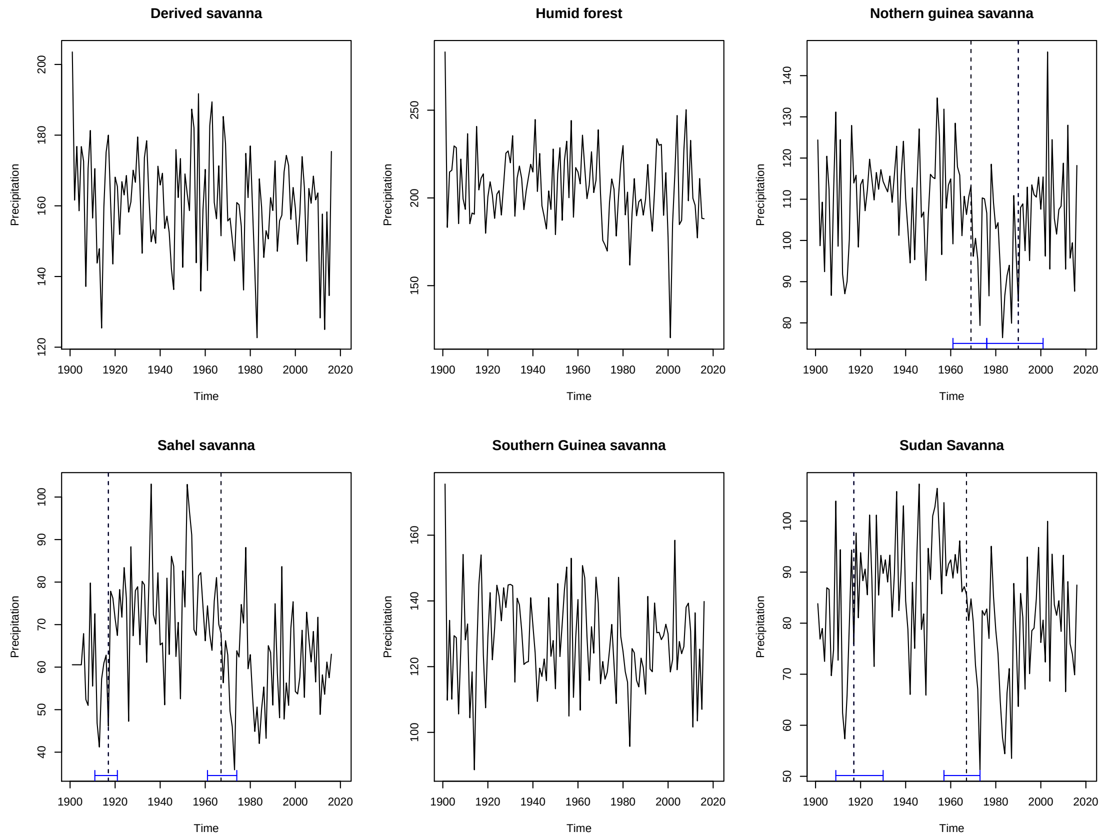
Source: Calculations and achievements of the author

Figure 1.83Breaks in total annual precipitation in the agroecological zones of Nigeria.



Source: Calculations and achievements of the author

Figure 1.84Breaks on seasonal precipitation in the agroecological zones of Nigeria.



Source: Calculations and achievements of the author

Figure 1.85 Annual temperature during the rainy season in the agroecological zones of Senegal from 1901 to 2016.

Figure 29.a: Minimum annual temperature

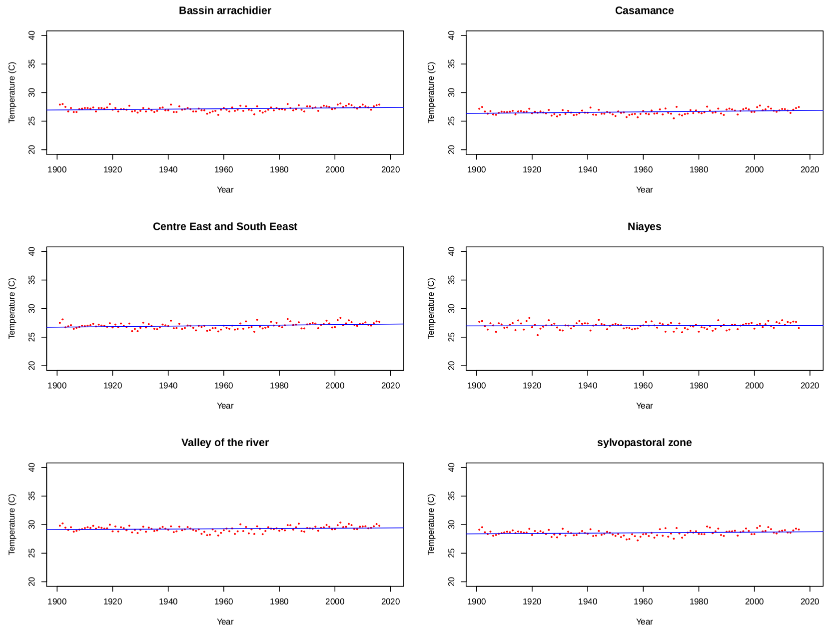


Figure 29.b: Median annual temperature

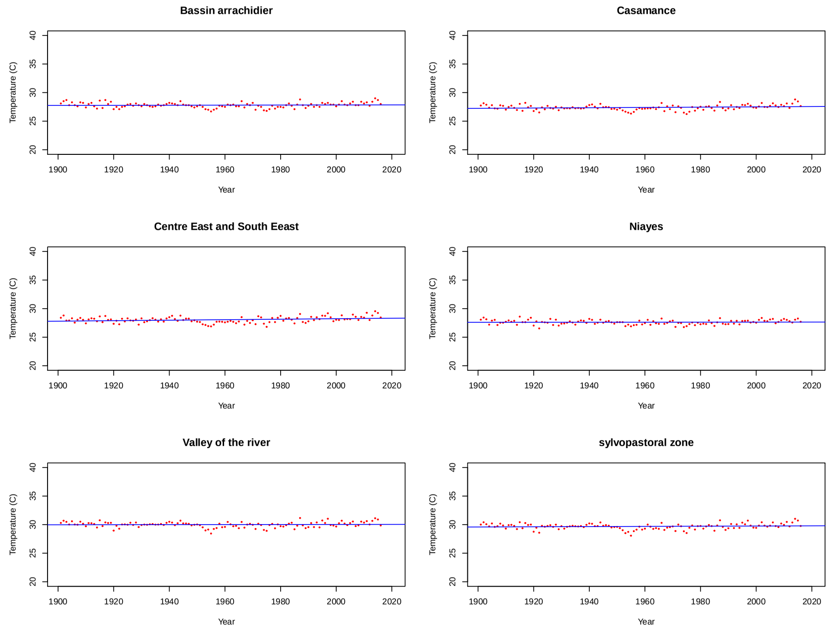
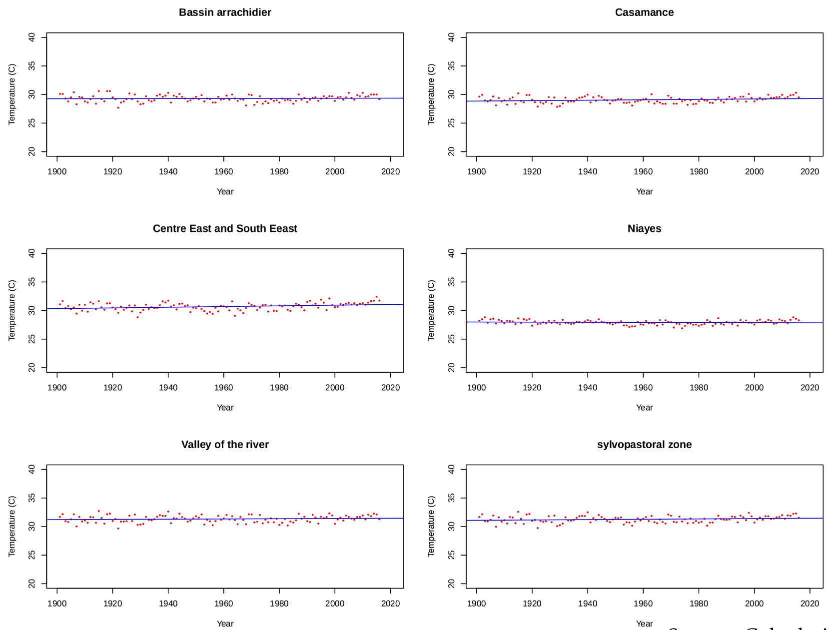


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.86Annual temperature during the dry season in the agroecological zones of Senegal from 1901 to 2016.

Figure 29.a: Minimum annual temperature

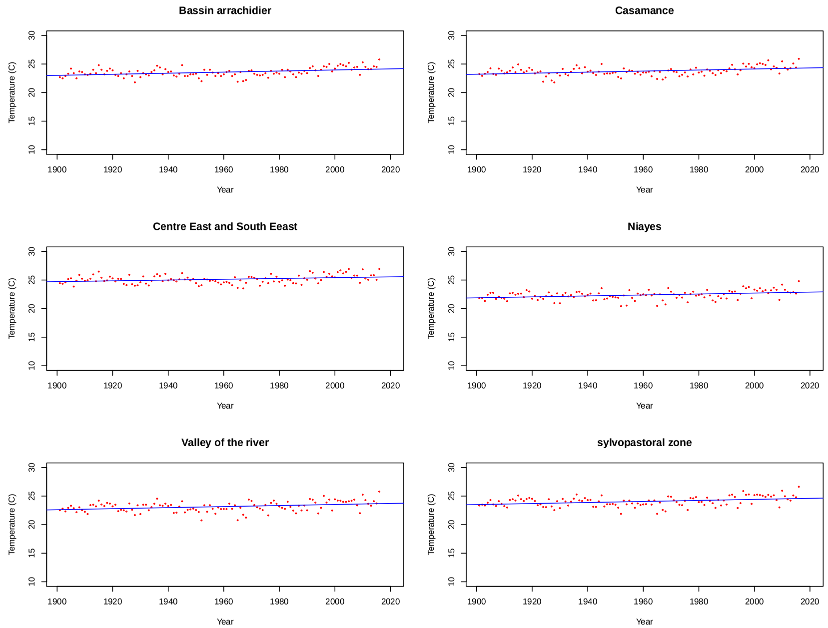


Figure 29.b: Median annual temperature

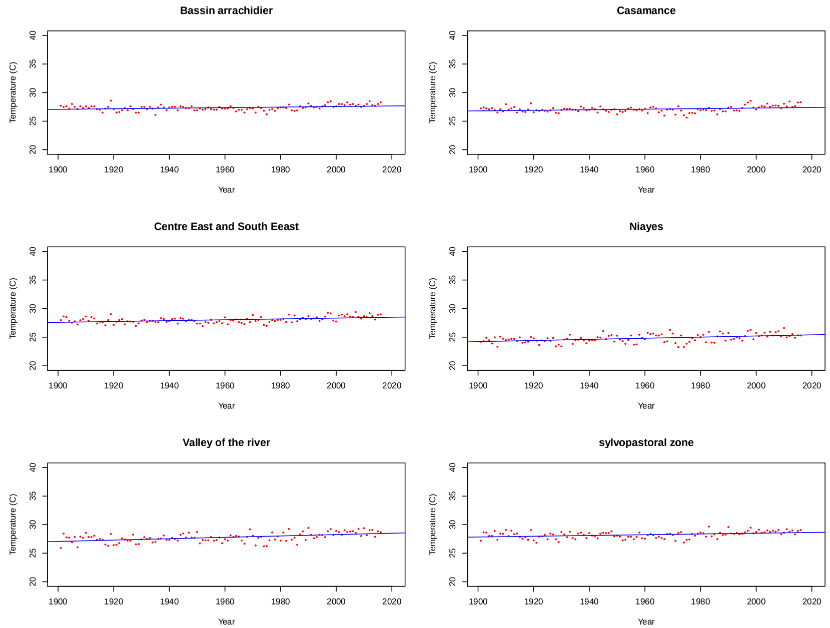
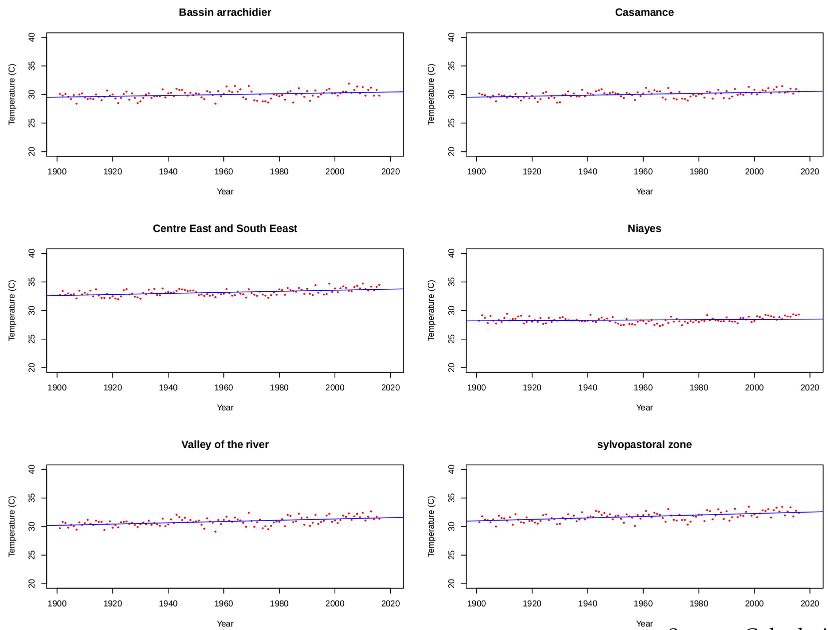


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.87 Endogenous detection of structural breaks in agroecological zones of Senegal during the rainy season from 1901 to 2012

Figure 29.a: Minimum annual temperature

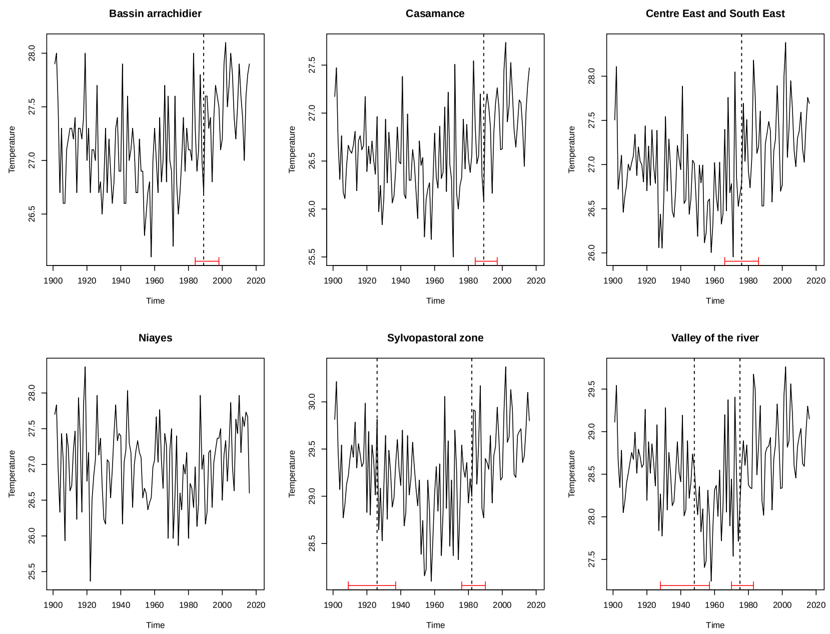


Figure 29.b: Median annual temperature

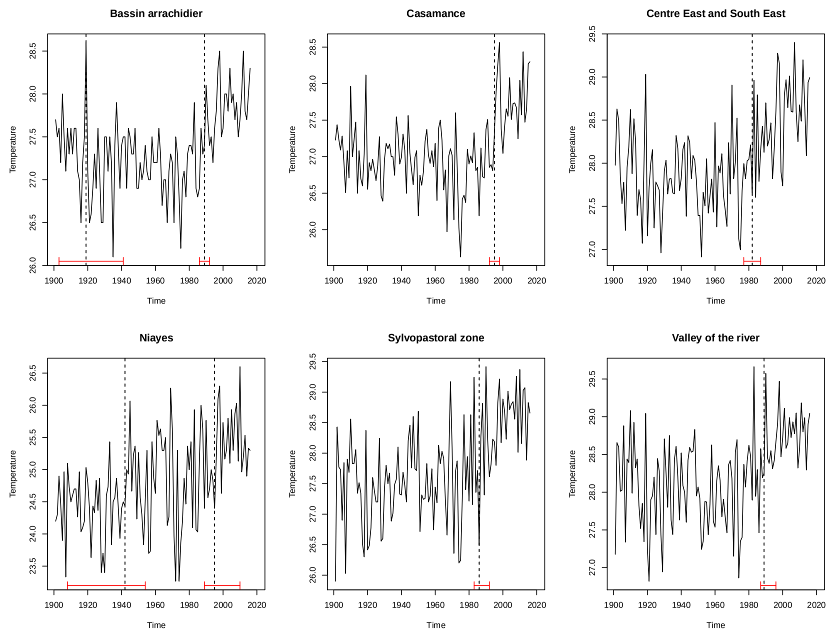
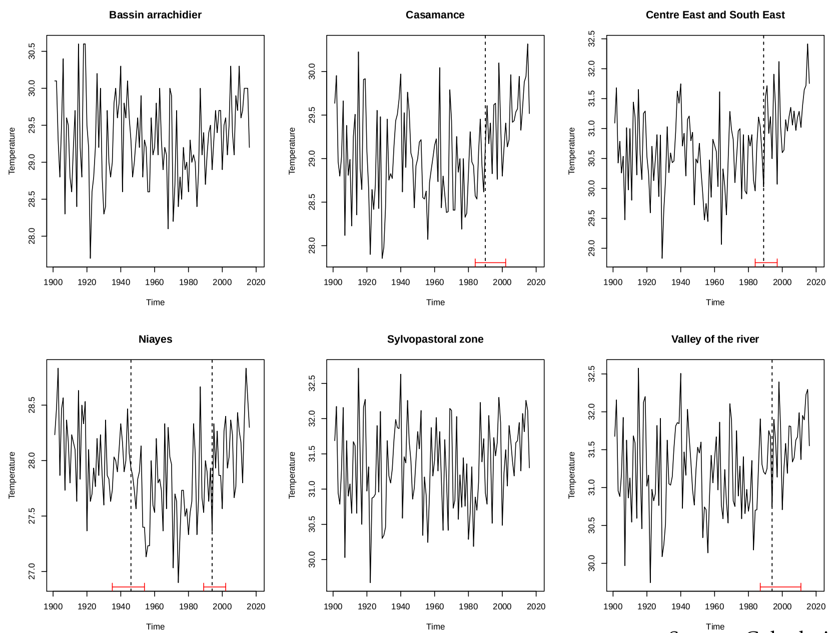


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.88Endogenous detection of structural breaks in agroecological zones of Senegal during the dry season from 1901 to 2012

Figure 29.a: Minimum annual temperature

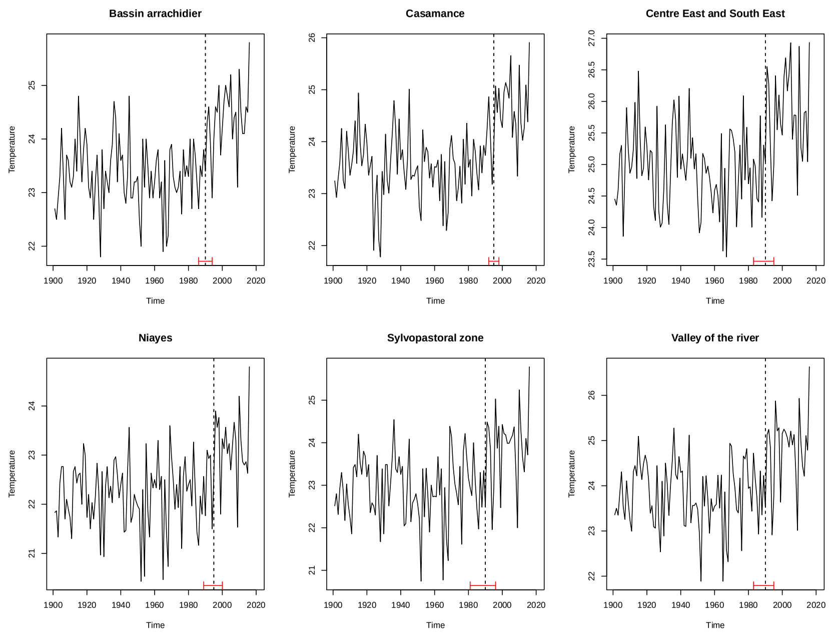


Figure 29.b: Median annual temperature

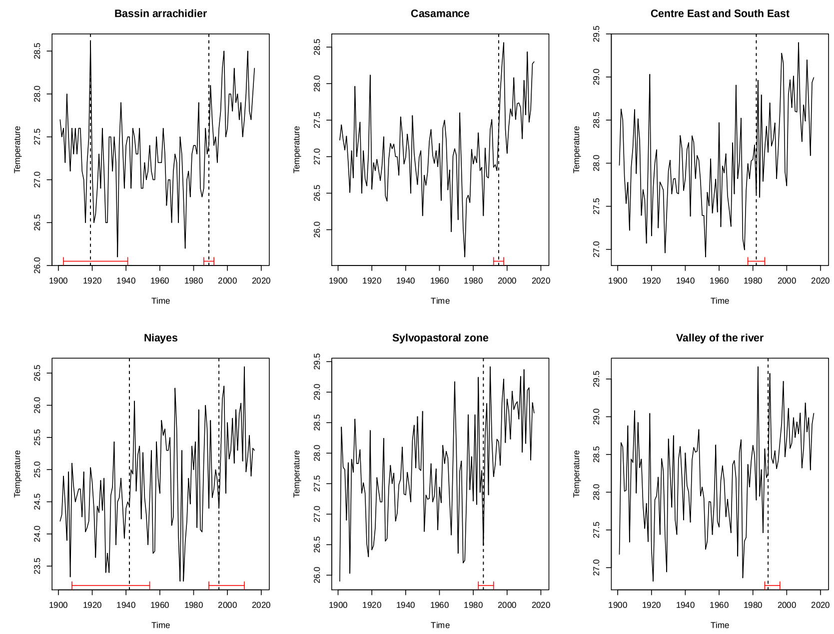
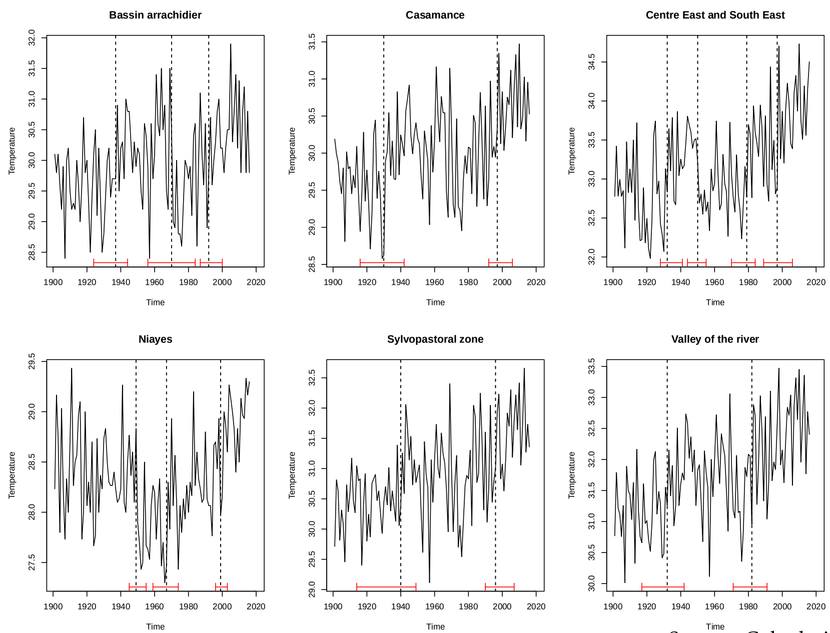


Figure 29.c: Maximum annual temperature

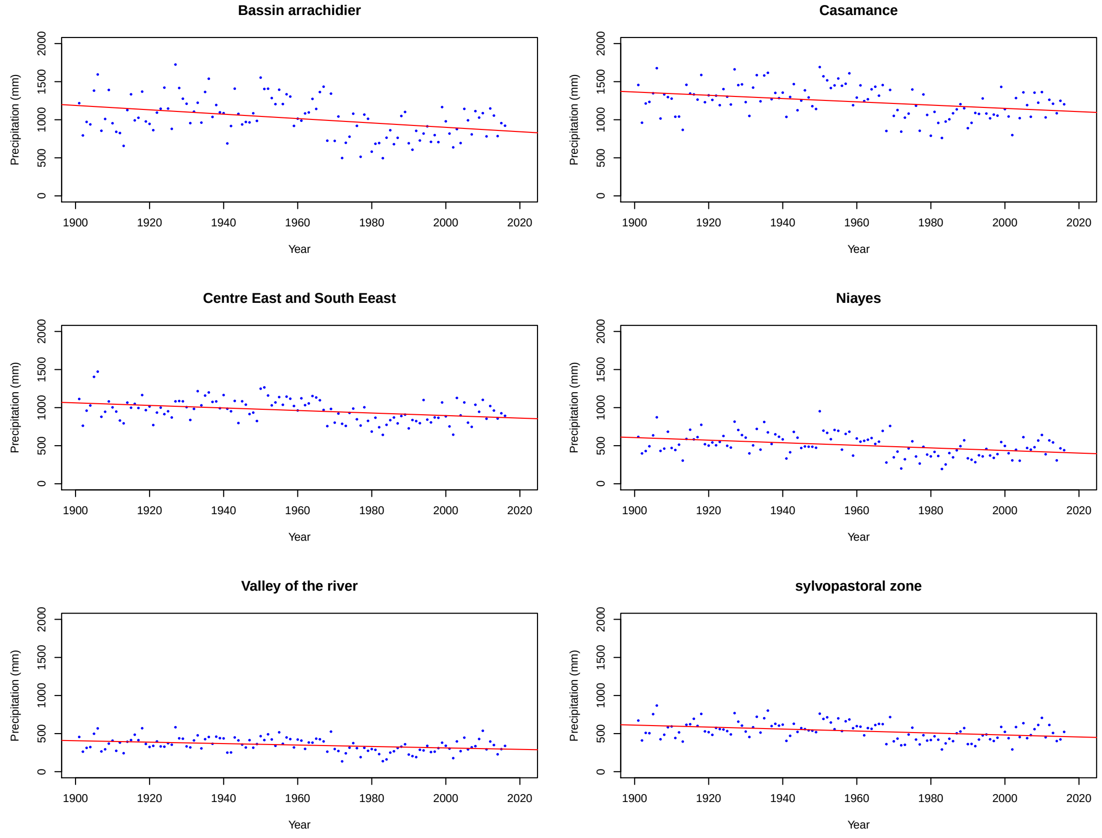


Source: Calculations and achievements by the author

Table 1.16Estimated results for Senegal

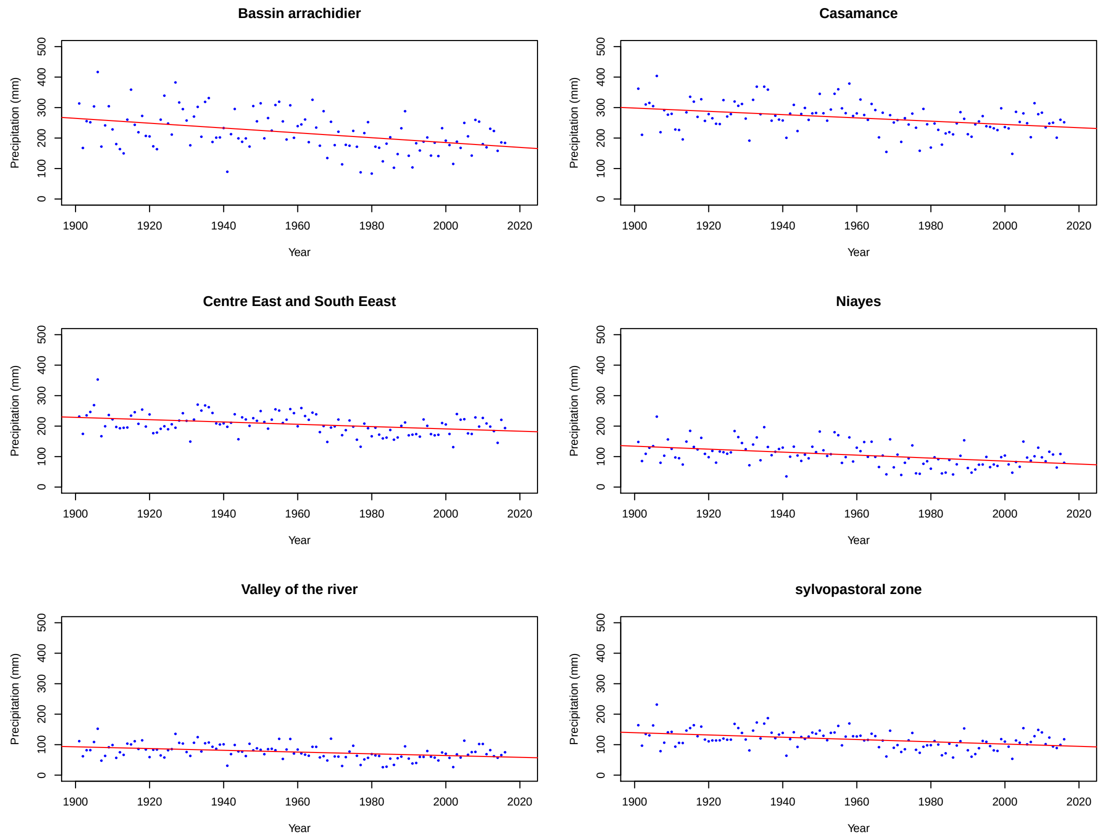
	Rainfall		Temperature					
	RainSum	RainSeason	TempminRain	TempmedRain	TempmaxRain	TempminDry	TempmedRain	TempmaxDry
	Dependent variable: Bassin arachidier							
Year	−2.876***	−0.795***	0.004***	0.001	0.001	0.009***	0.001	0.007***
	(0.662)	(0.164)	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)	(0.002)
Constant	6,652.264***	1,774.259***	20.080***	26.358***	27.660***	5.021	26.358***	15.294***
	(1,296.986)	(321.752)	(2.263)	(2.421)	(3.175)	(3.755)	(2.421)	(3.757)
R^2	0.142	0.170	0.079	0.003	0.002	0.176	0.003	0.118
	Dependent variable: Casamance							
Year	−2.149***	−0.538***	0.004***	0.003**	0.004**	0.009***	0.003**	0.008***
	(0.541)	(0.125)	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)	(0.002)
Constant	5,447.739***	1,320.617***	18.279***	22.369***	21.880***	5.729	22.369***	13.764***
	(1,059.808)	(245.752)	(2.300)	(2.448)	(2.900)	(3.749)	(2.448)	(2.998)
R^2	0.122	0.139	0.103	0.036	0.051	0.169	0.036	0.205
	Dependent variable: Centre East and South East							
Year	−1.668***	−0.378***	0.004***	0.004***	0.006***	0.007***	0.004***	0.009***
	(0.389)	(0.088)	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)	(0.001)
Constant	4,231.770***	947.122***	18.394***	19.667***	18.901***	11.501***	19.667***	14.861***
	(762.650)	(172.528)	(2.618)	(2.763)	(3.462)	(3.847)	(2.763)	(2.829)
R^2	0.139	0.139	0.087	0.075	0.092	0.099	0.075	0.269
	Dependent variable: Niayes							
Year	−1.696***	−0.489***	0.001	0.0004	−0.001	0.008***	0.0004	0.002*
	(0.372)	(0.095)	(0.002)	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)
Constant	3,829.021***	1,064.266***	25.977***	26.871***	30.193***	6.019	26.871***	23.501***
	(728.059)	(185.793)	(3.046)	(2.173)	(2.109)	(3.999)	(2.173)	(2.664)
R^2	0.154	0.189	0.001	0.001	0.010	0.128	0.001	0.028
	Dependent variable: Sylvopastoral zone							
Year	−0.948***	−0.287***	0.002*	0.001	0.002	0.009***	0.001	0.011***
	(0.240)	(0.061)	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)	(0.002)
Constant	2,207.237***	638.989***	24.391***	28.881***	27.452***	5.186	28.881***	8.955***
	(469.482)	(120.462)	(2.510)	(2.590)	(3.334)	(4.544)	(2.590)	(3.390)
R^2	0.121	0.161	0.032	0.002	0.012	0.121	0.002	0.268
	Dependent variable: Valley of the river							
Year	−1.298***	−0.373***	0.003**	0.002	0.003*	0.009***	0.002	0.013***
	(0.301)	(0.076)	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)	(0.002)
Constant	3,076.915***	848.758***	22.705***	26.479***	25.339***	6.166	26.479***	6.618*
	(588.927)	(149.450)	(2.699)	(2.695)	(3.100)	(4.311)	(2.695)	(3.441)
Observations	116	116	116	116	116	116	116	116
R^2	0.140	0.174	0.040	0.012	0.031	0.131	0.012	0.319
Observations	116	116	116	116	116	116	116	116
Note:								*p<0.1; **p<0.05; ***p<0.01

Figure 1.89Evolution of the sum annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Senegal



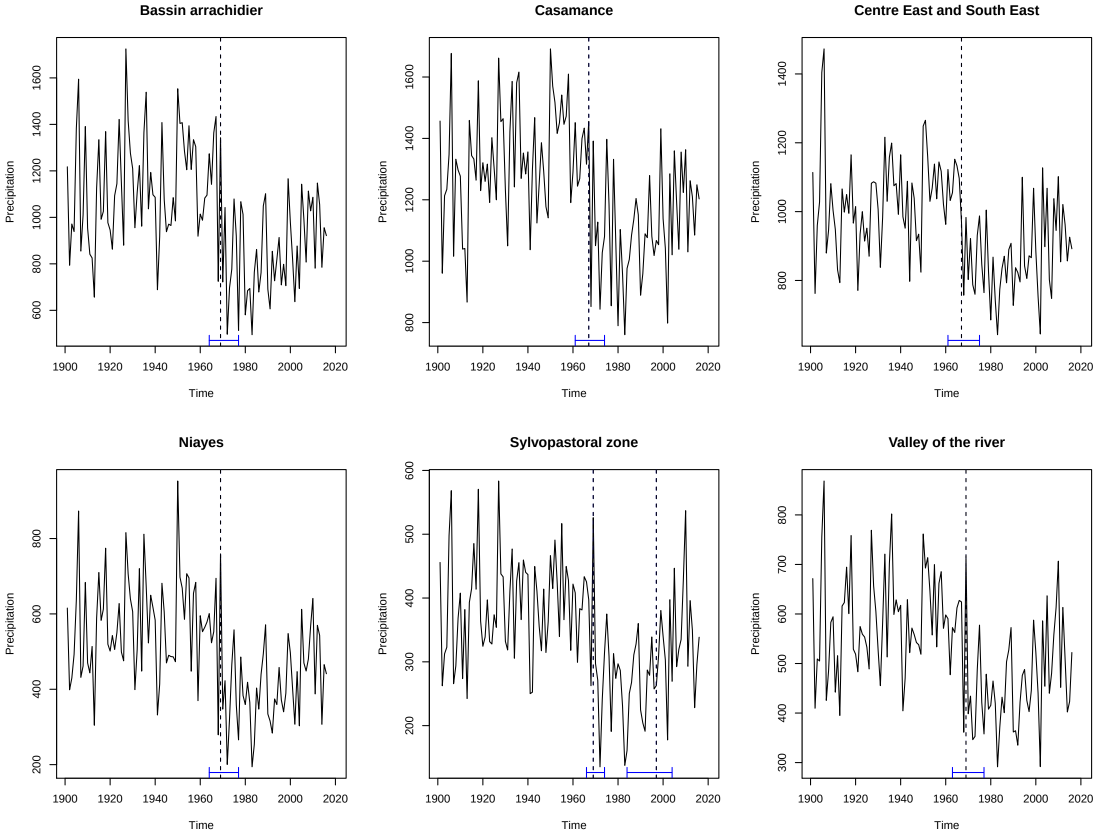
Source: Calculations and achievements of the author

Figure 1.90Evolution of the seasonal annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Senegal.



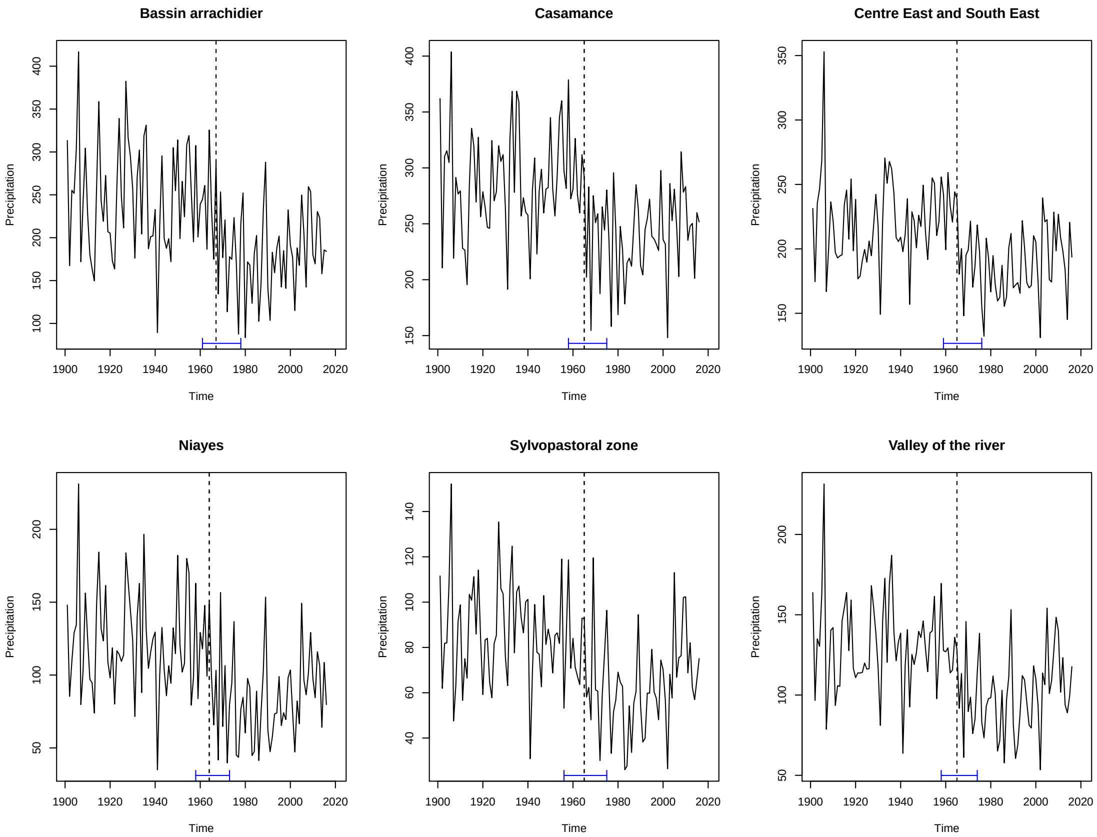
Source: Calculations and achievements of the author

Figure 1.91Breaks in total annual precipitation in the agroecological zones of Senegal.



Source: Calculations and achievements of the author

Figure 1.92Breaks on seasonal precipitation in the agroecological zones of Senegal.



Source: Calculations and achievements of the author

Figure 1.93 Annual temperature during the rainy season in the agroecological zones of Somalia from 1901 to 2016.

Figure 29.a: Minimum annual temperature

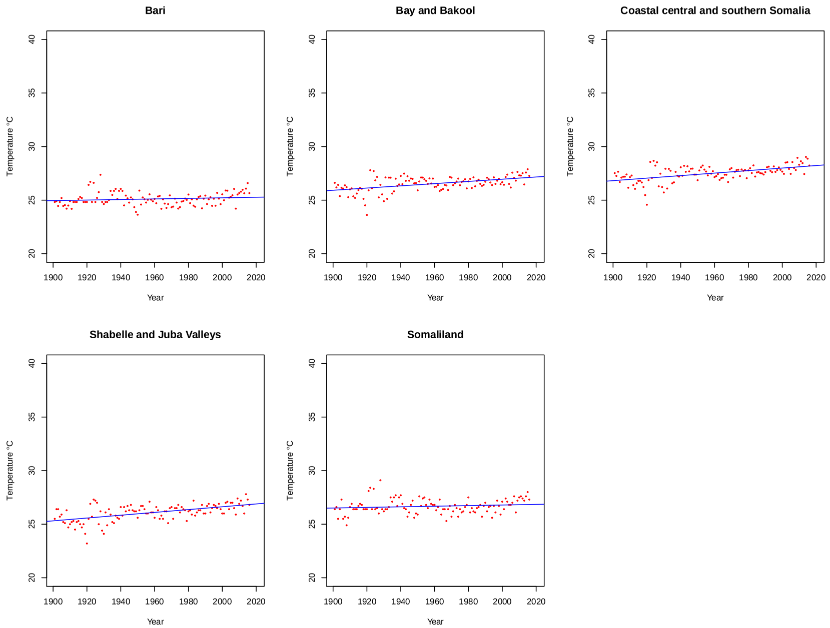


Figure 29.b: Median annual temperature

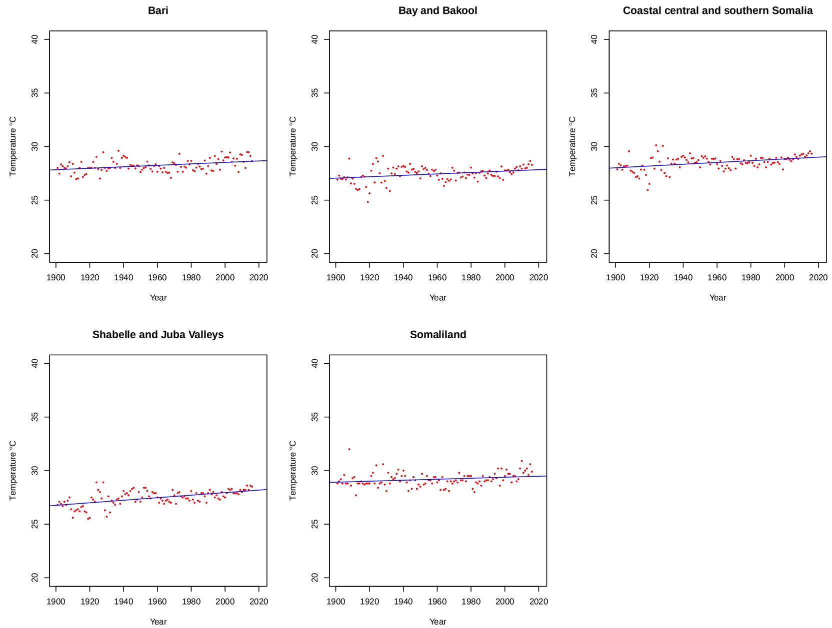
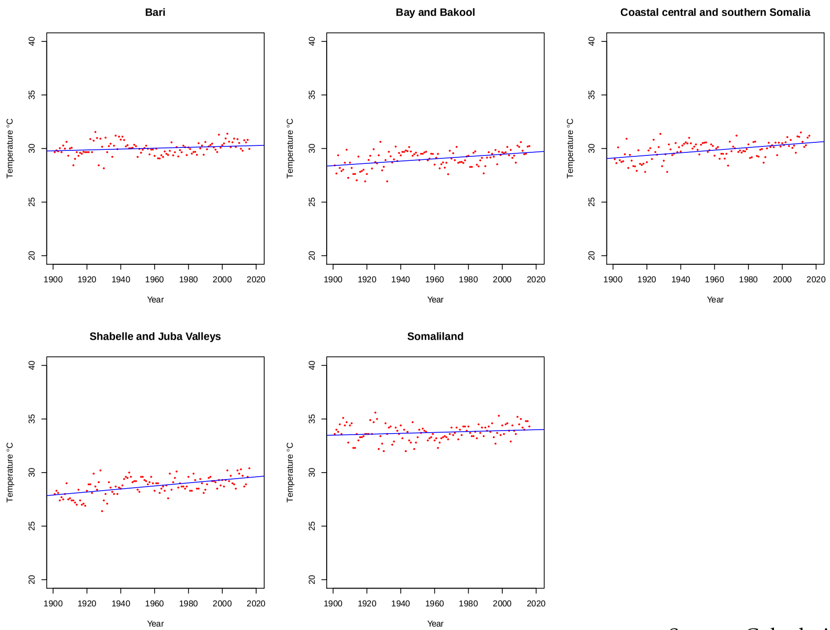


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.94Annual temperature during the dry season in the agroecological zones of Somalia from 1901 to 2016.

Figure 29.a: Minimum annual temperature

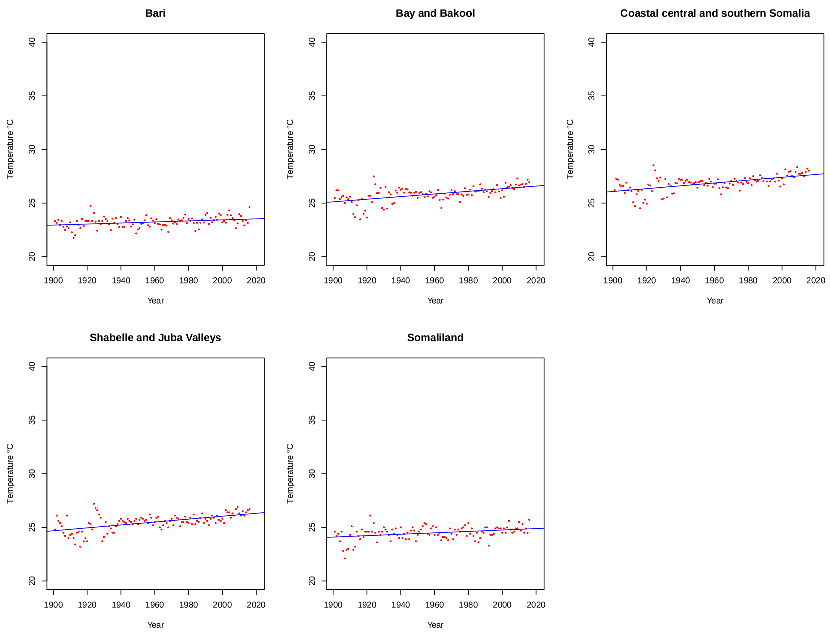


Figure 29.b: Median annual temperature

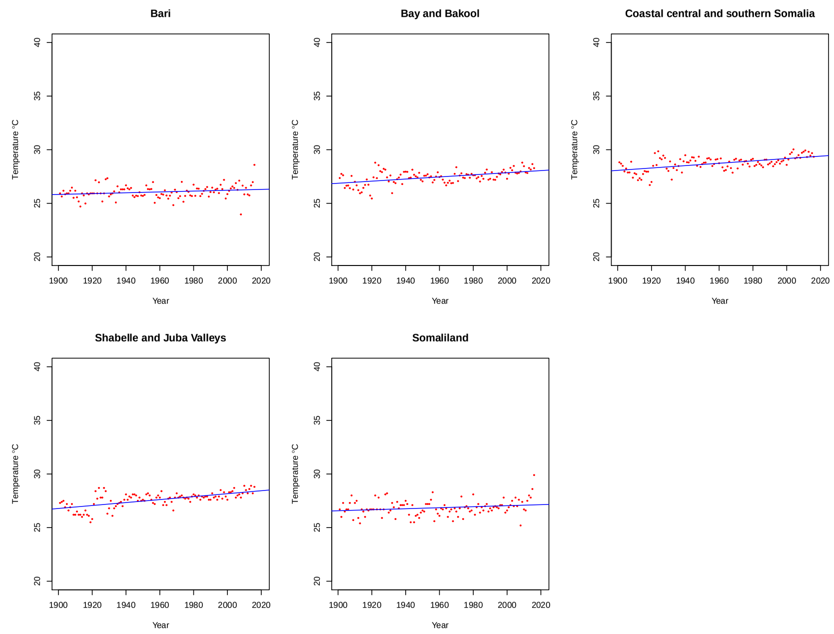
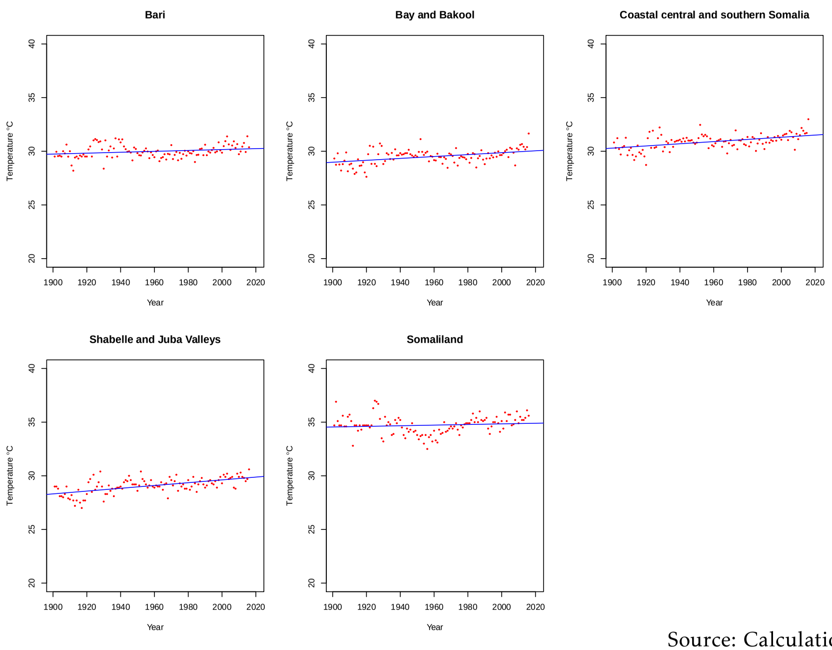


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.95Endogenous detection of structural breaks in agroecological zones of Somalia during the rainy season from 1901 to 2012

Figure 29.a: Minimum annual temperature

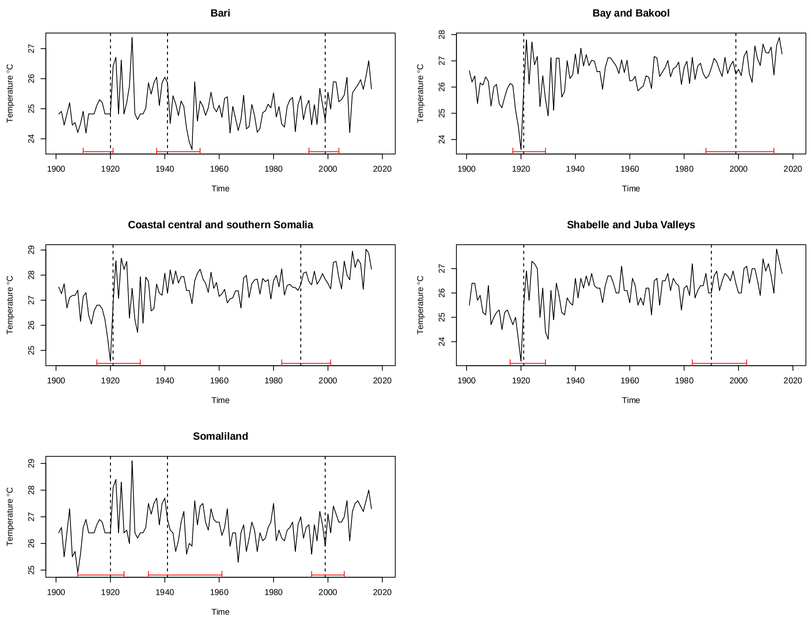


Figure 29.b: Median annual temperature

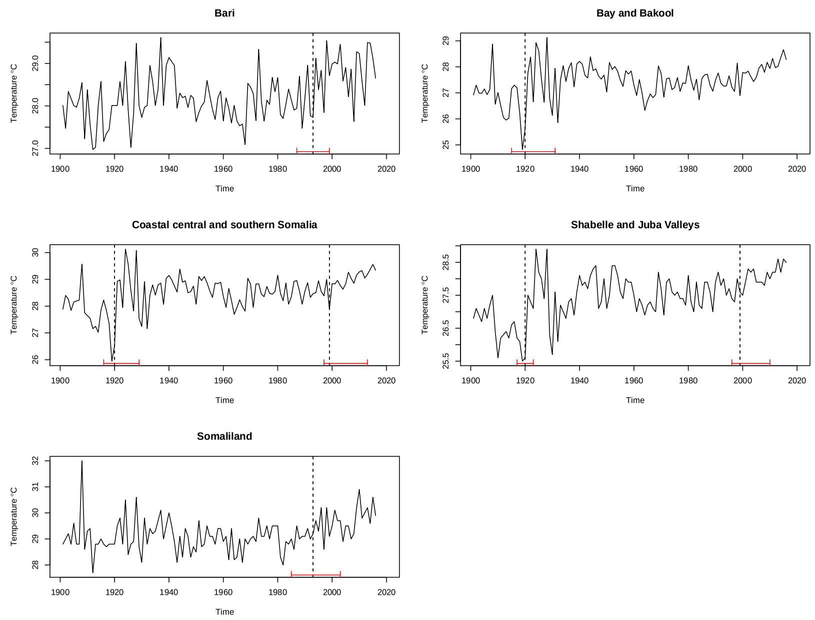
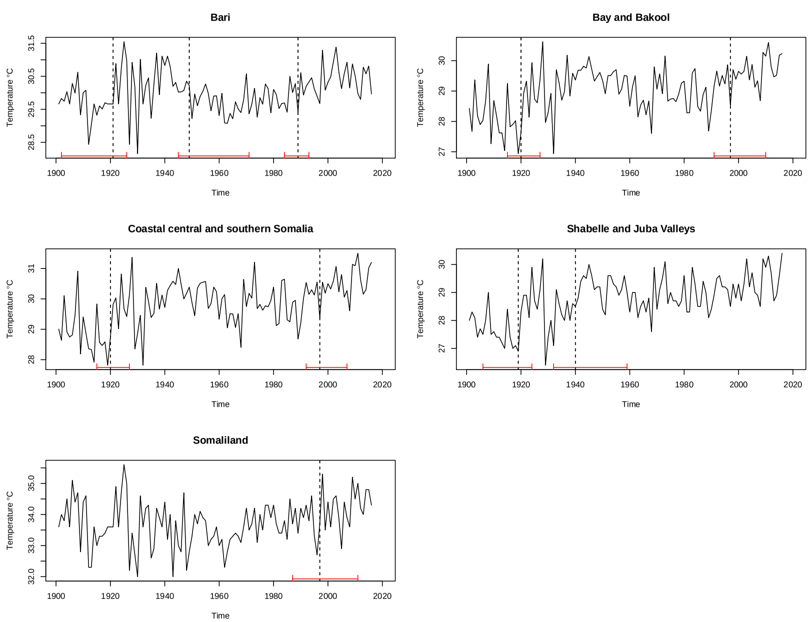


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.96 Endogenous detection of structural breaks in agroecological zones of Somalia during the rainy season from 1901 to 2012

Figure 29.a: Minimum annual temperature

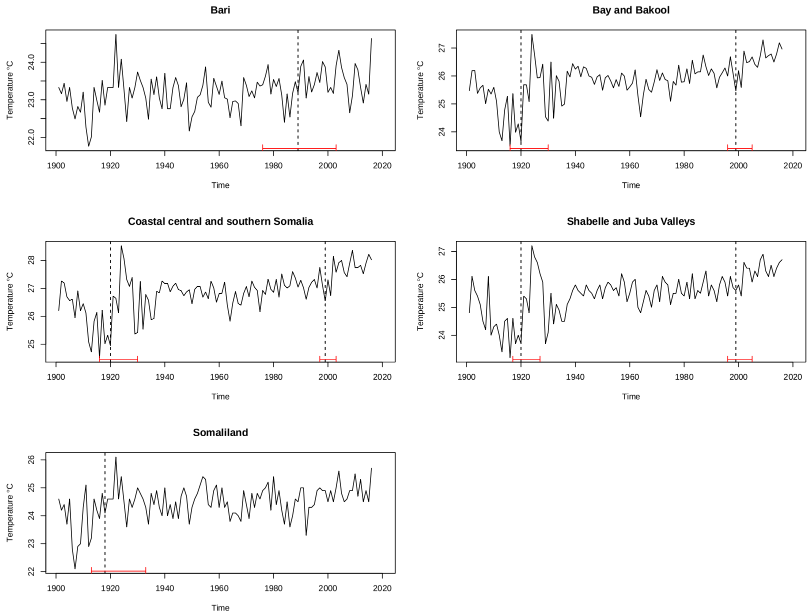


Figure 29.b: Median annual temperature

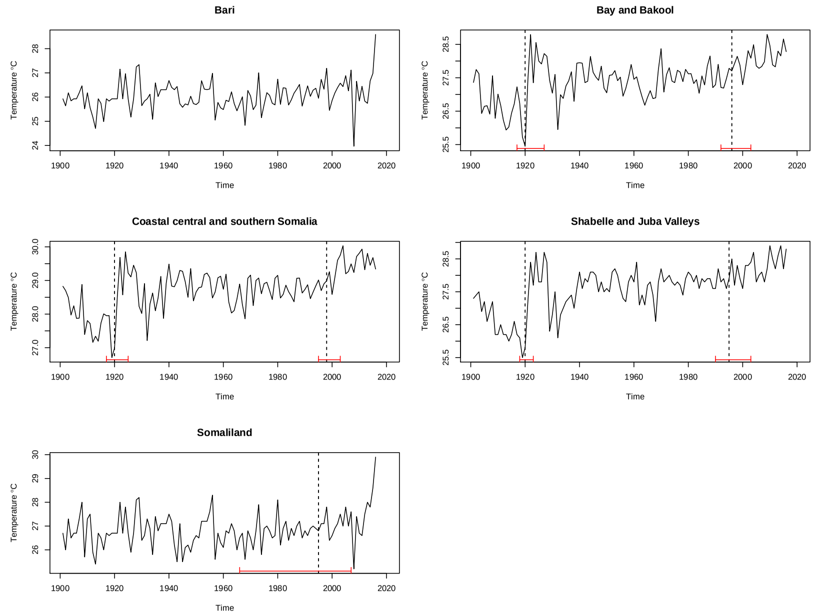
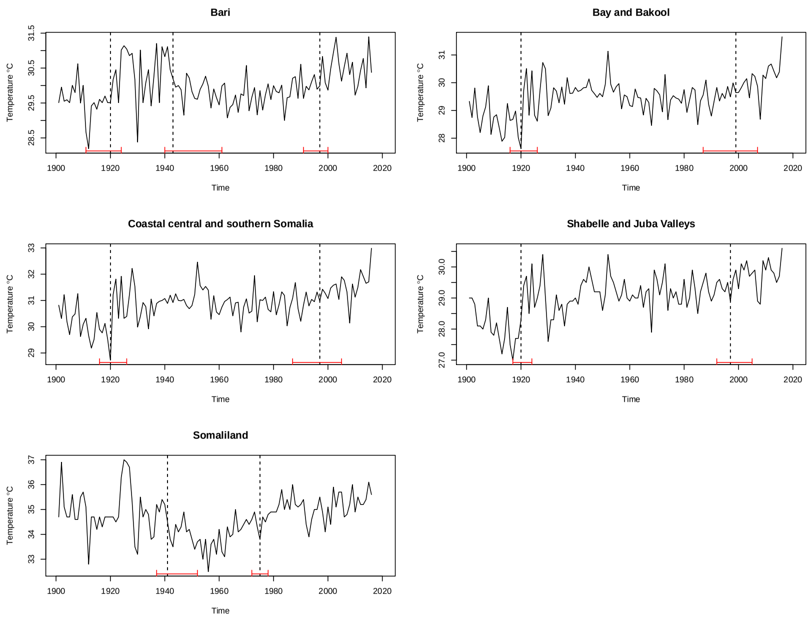


Figure 29.c: Maximum annual temperature



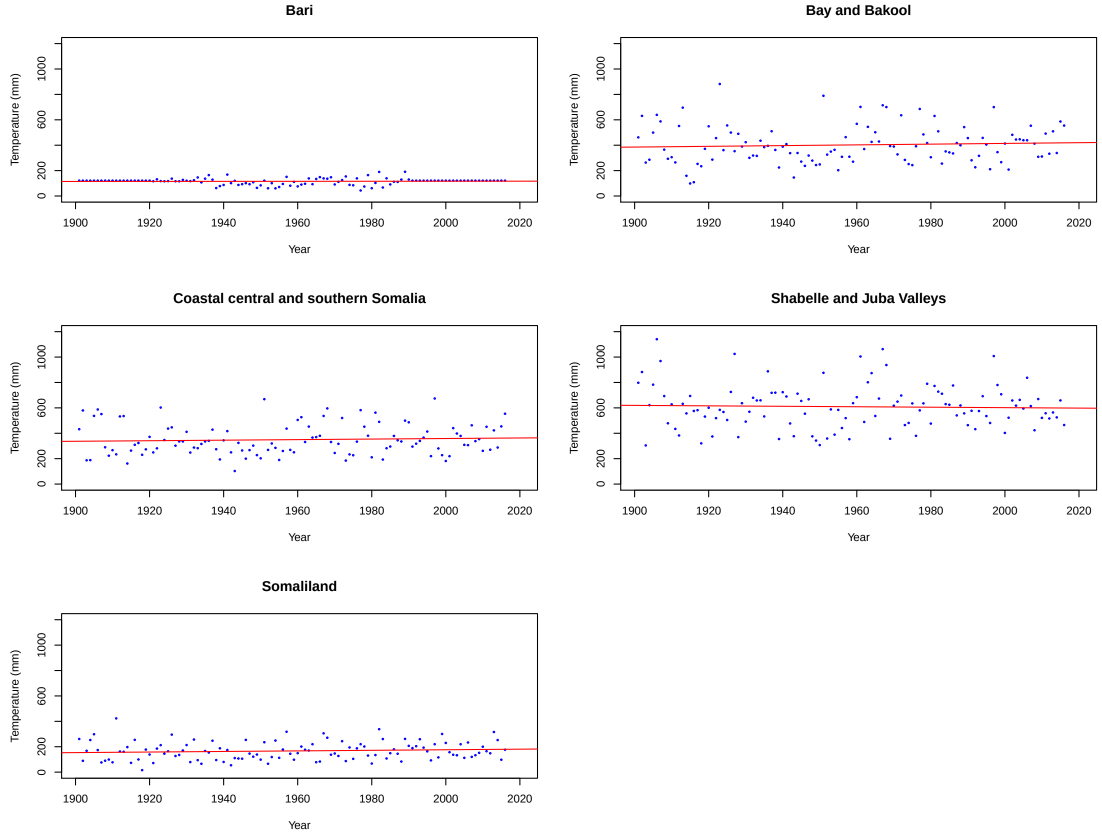
Source: Calculations and achievements by the author

Table 1.17The regression results in Somalia

	Rainfall		Temperature					
	RainSum	RainSeason	TempminRain	TempmedRain	TempmaxRain	TempminDry	TempmedDry	TempmaxDry
	Bari							
Year	0.019	0.002	0.003	0.007***	0.004**	0.005***	0.004**	0.004**
	(0.069)	(0.011)	(0.002)	(0.002)	(0.002)	(0.001)	(0.002)	(0.002)
Constant	78.263	12.970	19.962***	14.879***	21.998***	13.739***	18.375***	21.717***
	(134.845)	(22.339)	(3.359)	(3.047)	(3.272)	(2.542)	(3.187)	(3.189)
R^2	0.001	0.0003	0.020	0.144	0.050	0.109	0.049	0.056
	Bay and Bakool							
Year	0.287	0.049	0.010***	0.007***	0.011***	0.012***	0.010***	0.009***
	(0.409)	(0.074)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	−160.169	−29.043	6.310*	14.480***	8.226**	1.848	8.166***	12.105***
	(801.237)	(145.827)	(3.321)	(3.597)	(3.931)	(3.347)	(2.954)	(3.293)
R^2	0.004	0.004	0.245	0.102	0.197	0.311	0.272	0.197
	Coast central and southern Somalia							
Year	0.217	0.028	0.012***	0.008***	0.012***	0.013***	0.011***	0.010***
	(0.337)	(0.059)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	−75.498	1.500	4.509	12.287***	5.795	0.940	7.077**	11.074***
	(660.445)	(116.526)	(3.347)	(3.317)	(3.825)	(3.281)	(2.969)	(3.252)
R^2	0.004	0.002	0.293	0.173	0.257	0.354	0.318	0.246
	Shabelle and Juba Valleys							
Year	−0.178	−0.072	0.013***	0.012***	0.014***	0.014***	0.014***	0.013***
	(0.477)	(0.081)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	958.044	227.844	0.335	4.269	1.020	−1.164	0.587	3.530
	(933.399)	(159.221)	(3.535)	(3.204)	(3.757)	(3.396)	(2.958)	(3.135)
R^2	0.001	0.007	0.318	0.315	0.323	0.351	0.422	0.368
	Somaliland							
Year	0.225	0.087***	0.003	0.005***	0.004**	0.007***	0.005**	0.003
	(0.200)	(0.026)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	−272.994	−155.920***	21.181***	20.113***	25.446***	11.540***	17.591***	29.012***
	(390.973)	(50.559)	(3.699)	(3.409)	(3.970)	(3.174)	(3.831)	(4.564)
R^2	0.011	0.090	0.019	0.059	0.037	0.127	0.049	0.014
Observations	116	116	116	116	116	116	116	116
Model	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS

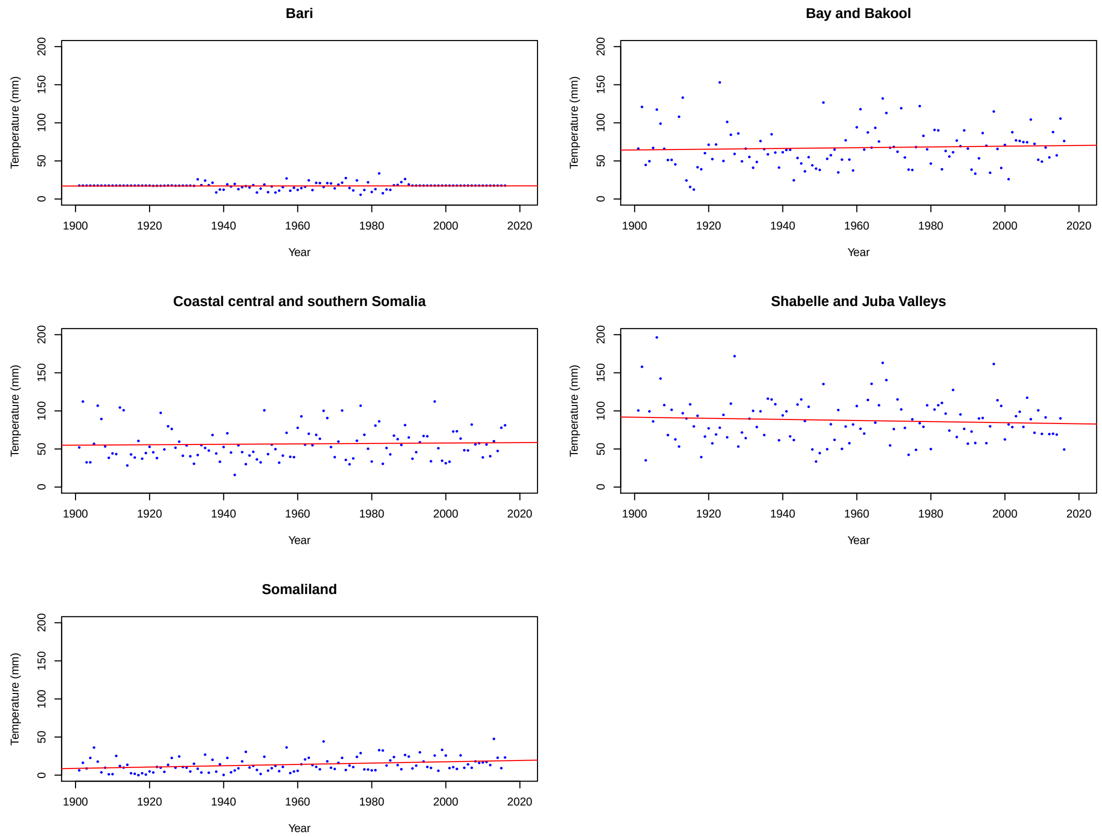
Note: *p<0.1; **p<0.05; ***p<0.01

Figure 1.97 Evolution of the sum annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Somalia



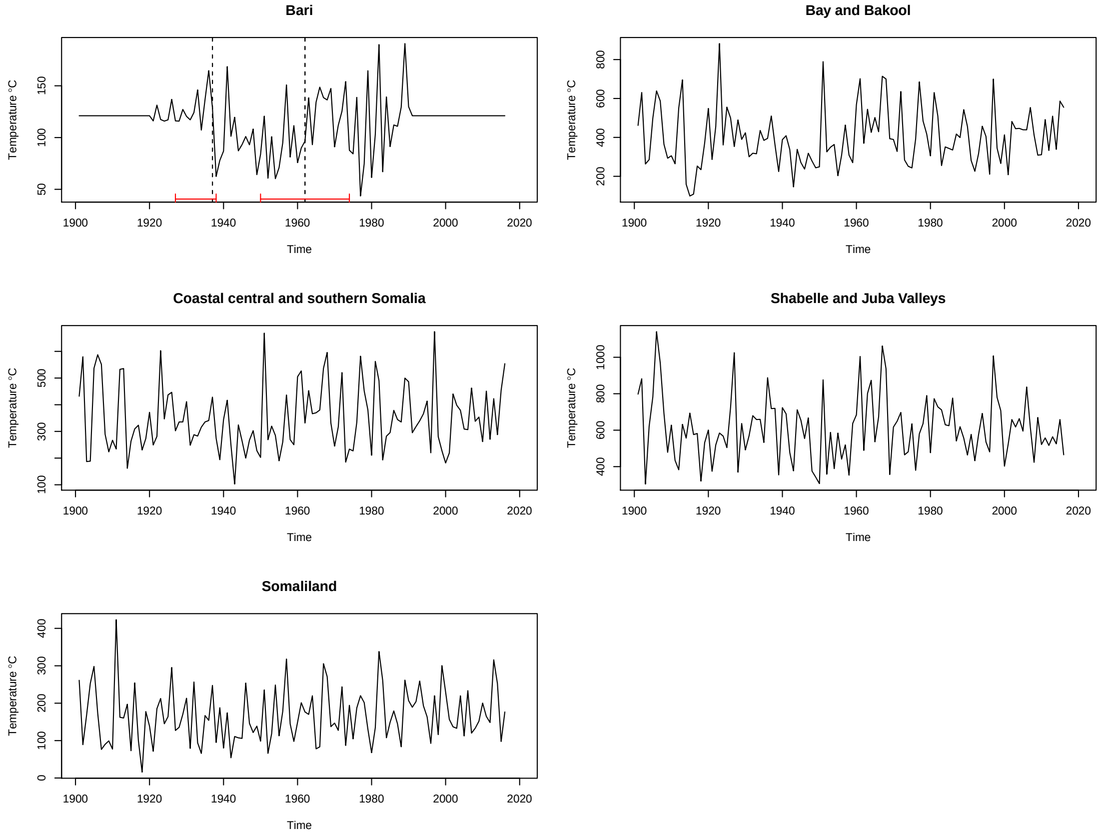
Source: Calculations and achievements of the author

Figure 1.98 Evolution of the seasonal annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Somalia.



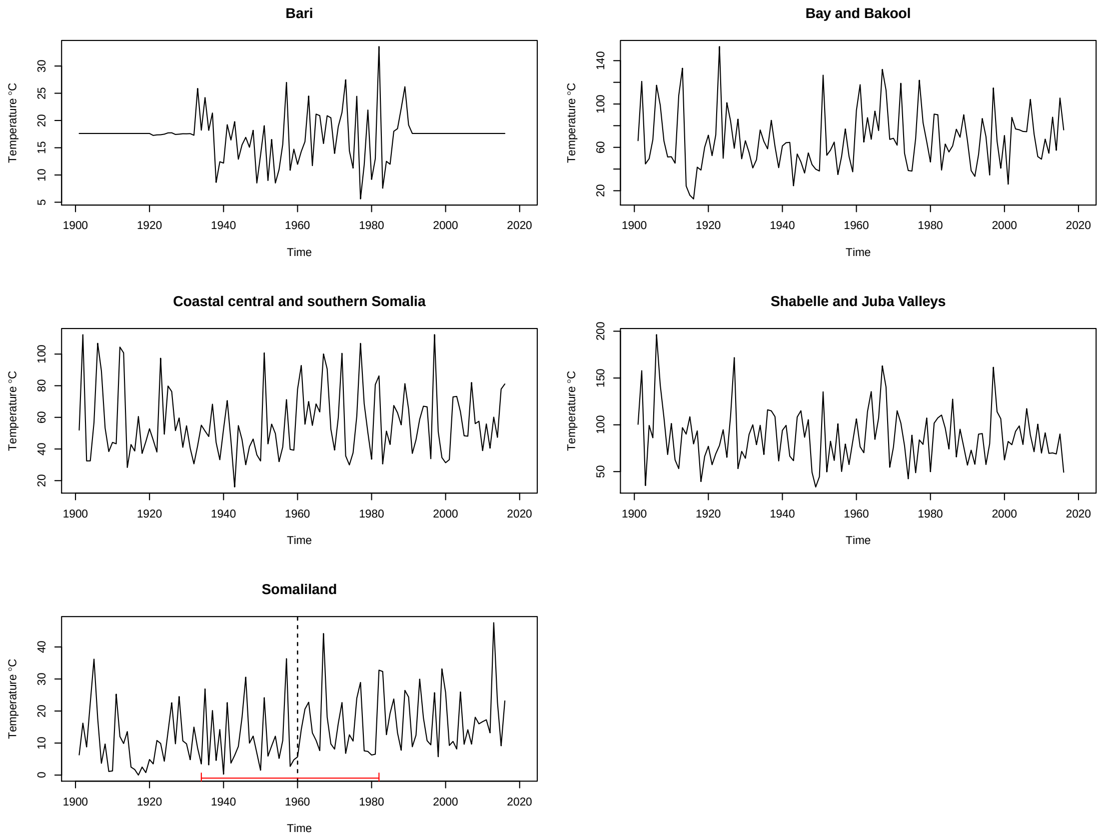
Source: Calculations and achievements of the author

Figure 1.99Breaks in total annual precipitation in the agroecological zones of Somalia.



Source: Calculations and achievements of the author

Figure 1.100Breaks on seasonal precipitation in the agroecological zones of Chad.



Source: Calculations and achievements of the author

Figure 1.101 Annual temperature during the rainy season in the agroecological zones of Sudan from 1901 to 2016.

Figure 29.a: Minimum annual temperature

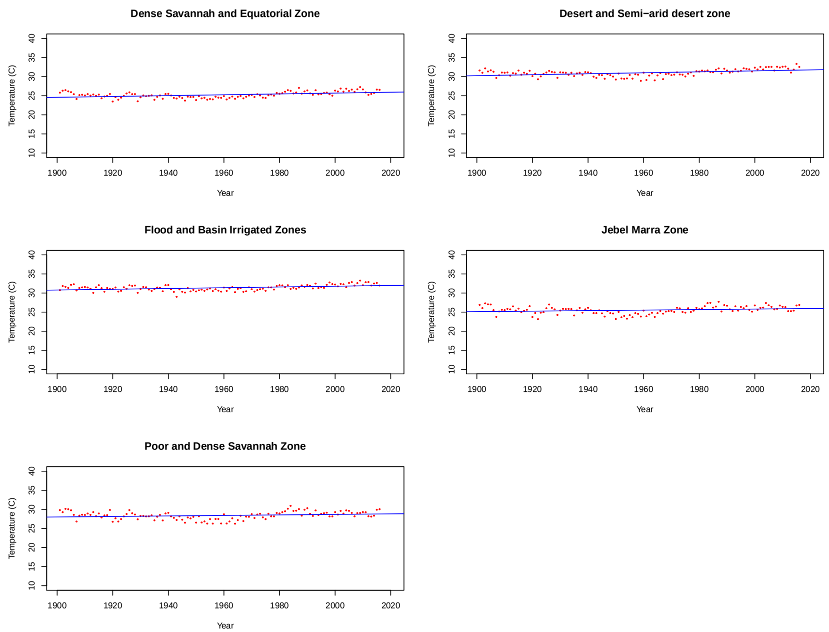


Figure 29.b: Median annual temperature

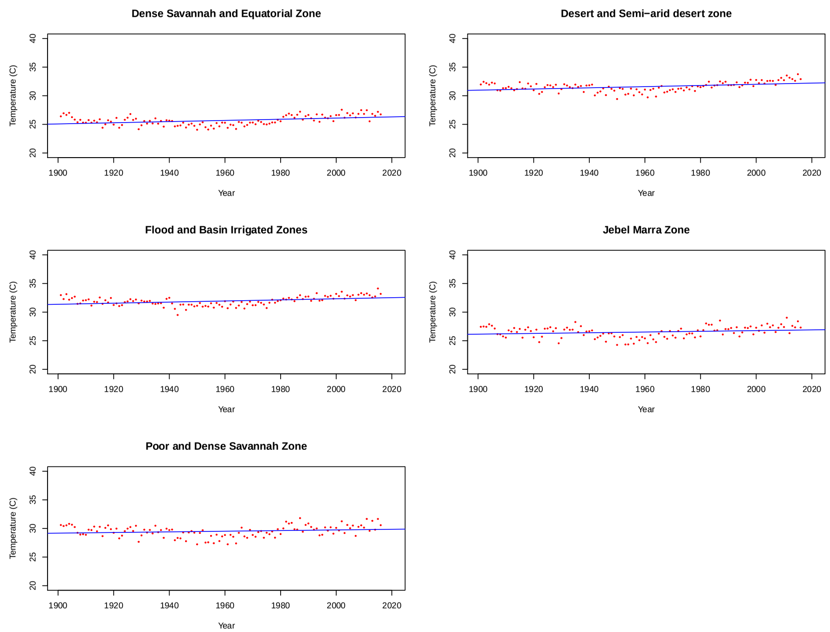
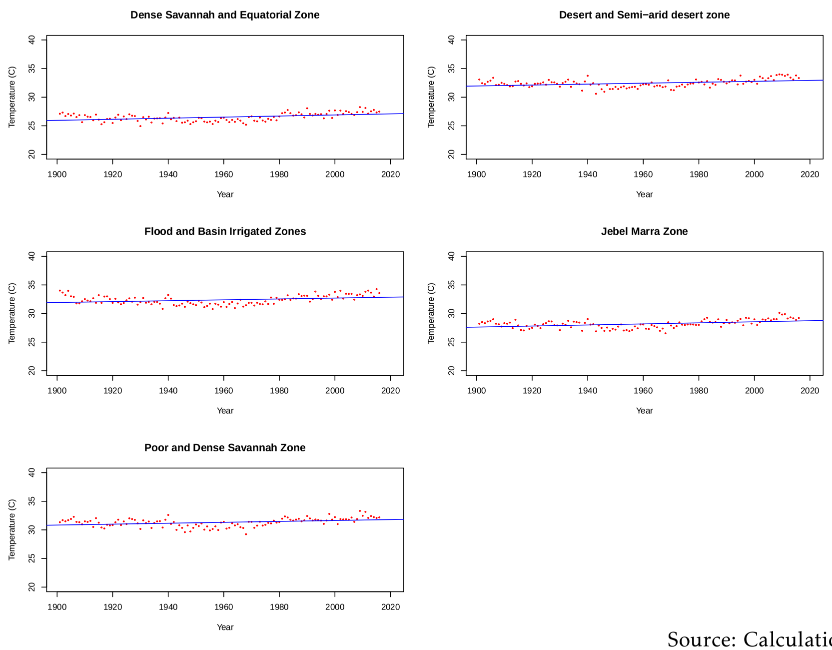


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.102Annual temperature during the dry season in the agroecological zones of Sudan from 1901 to 2016.

Figure 29.a: Minimum annual temperature

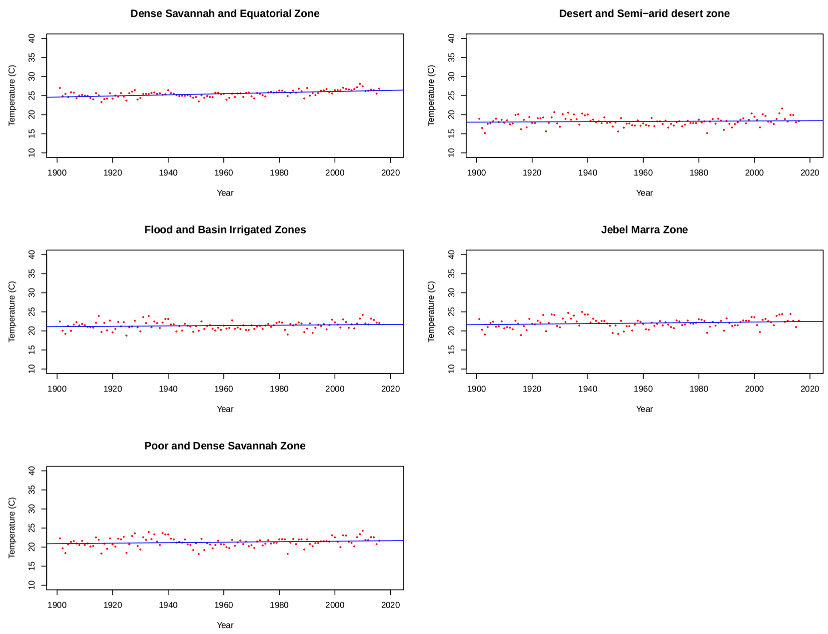


Figure 29.b: Median annual temperature

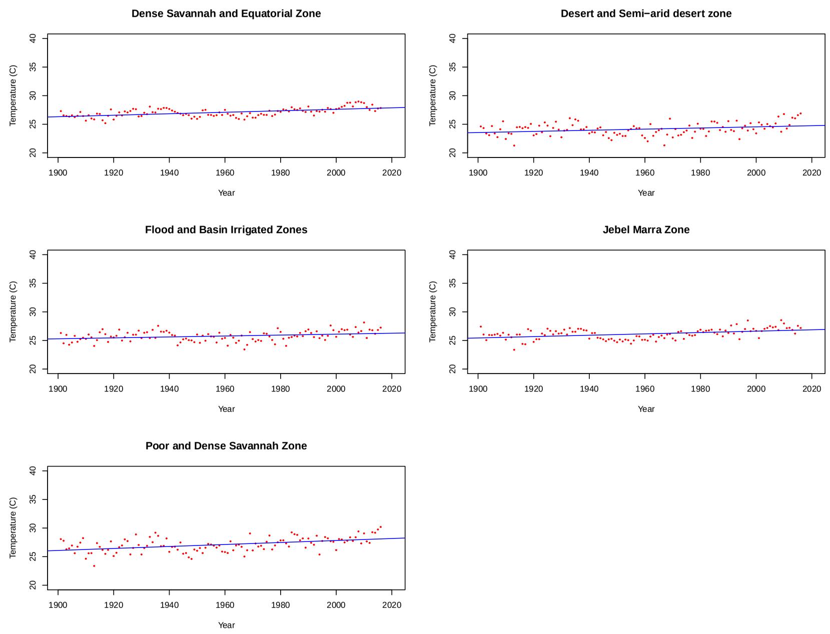
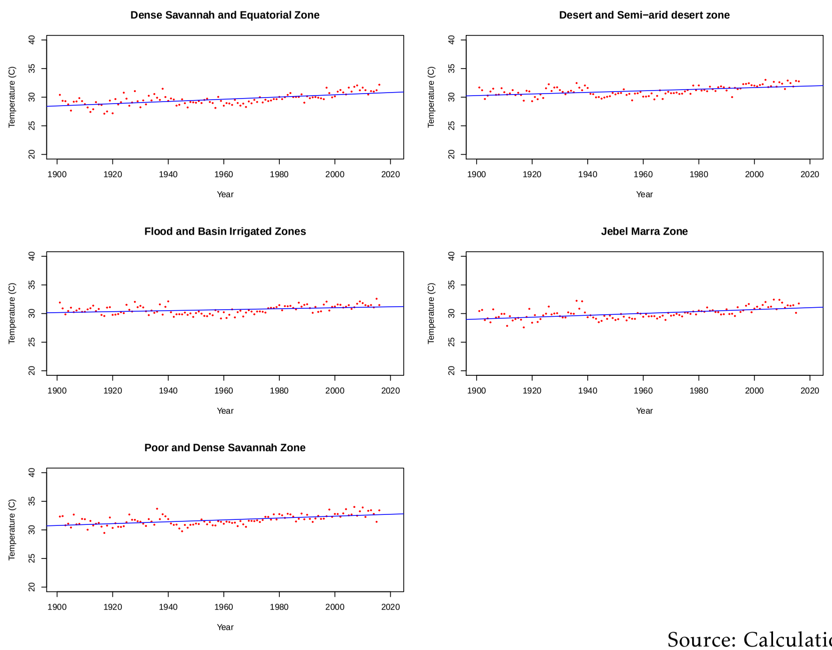


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.103 Endogenous detection of structural breaks in agroecological zones of Sudan during the rainy season from 1901 to 2012

Figure 29.a: Minimum annual temperature

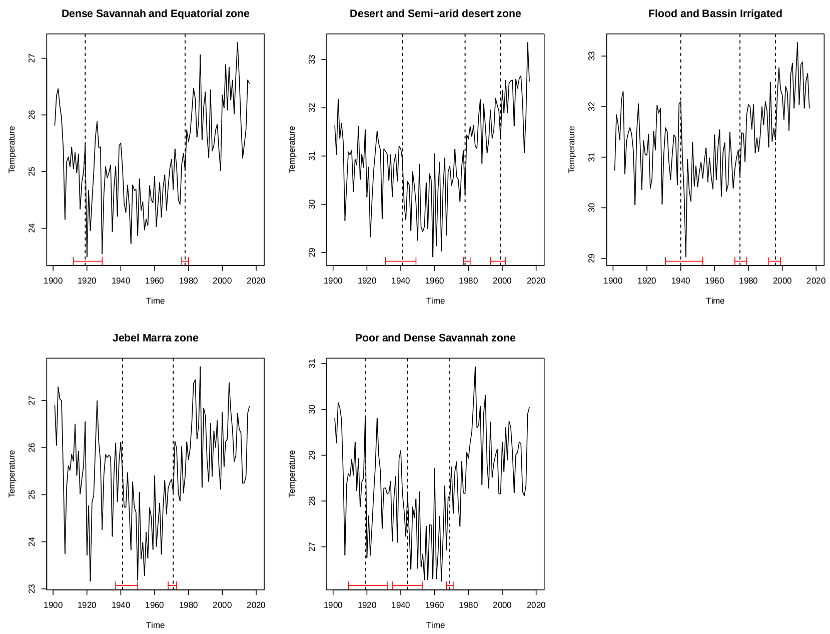


Figure 29.b: Median annual temperature

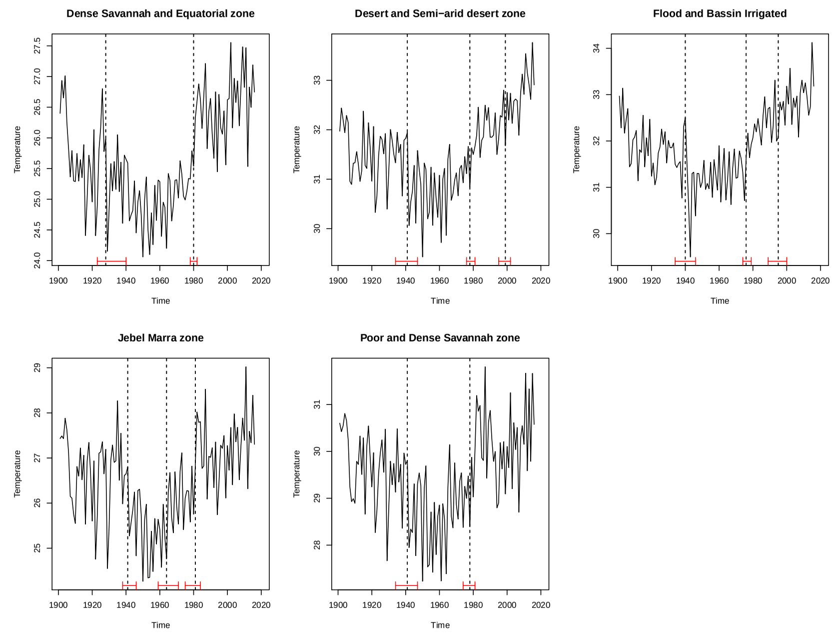
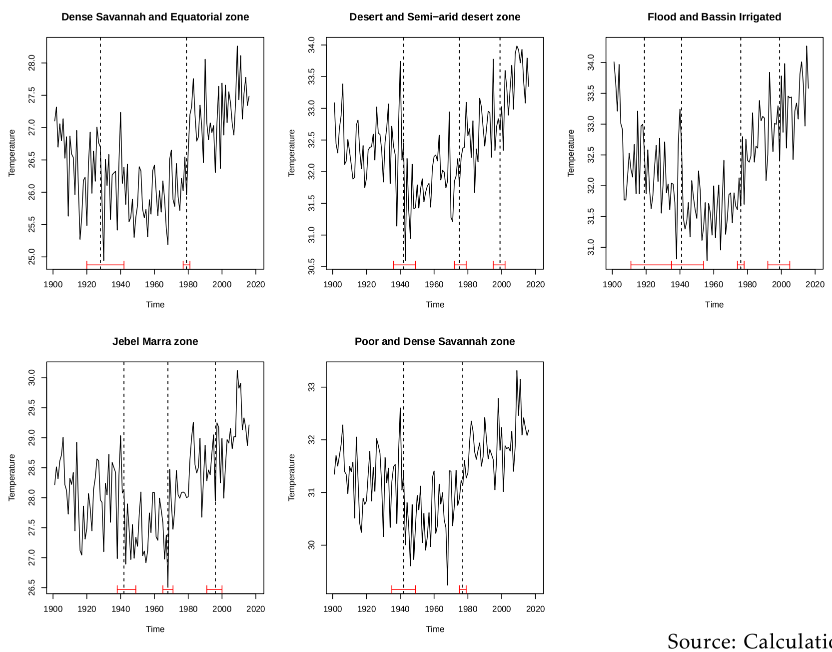


Figure 29.c: Maximum annual temperature



Source: Calculations and achievements by the author

Figure 1.104Endogenous detection of structural breaks in agroecological zones of Sudan during the dry season from 1901 to 2012

Figure 29.a: Minimum annual temperature

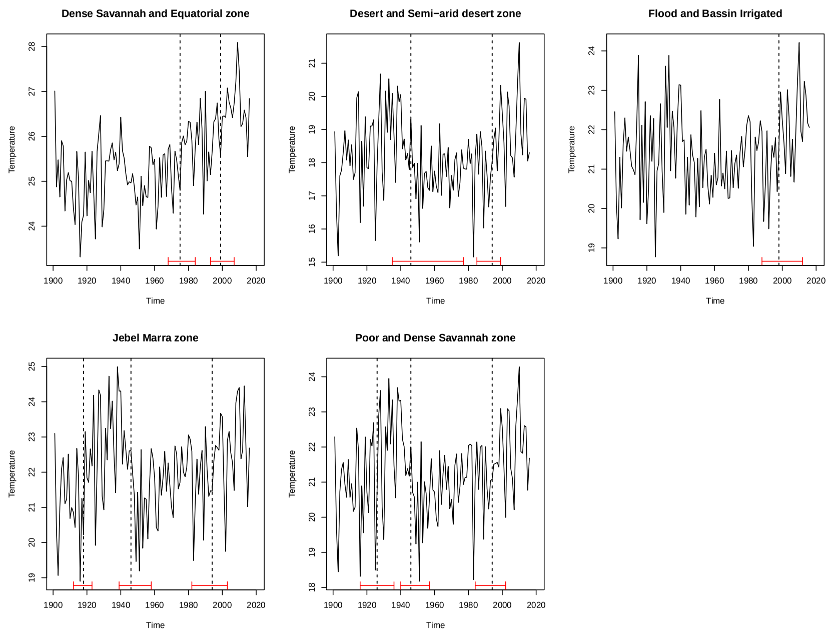


Figure 29.b: Median annual temperature

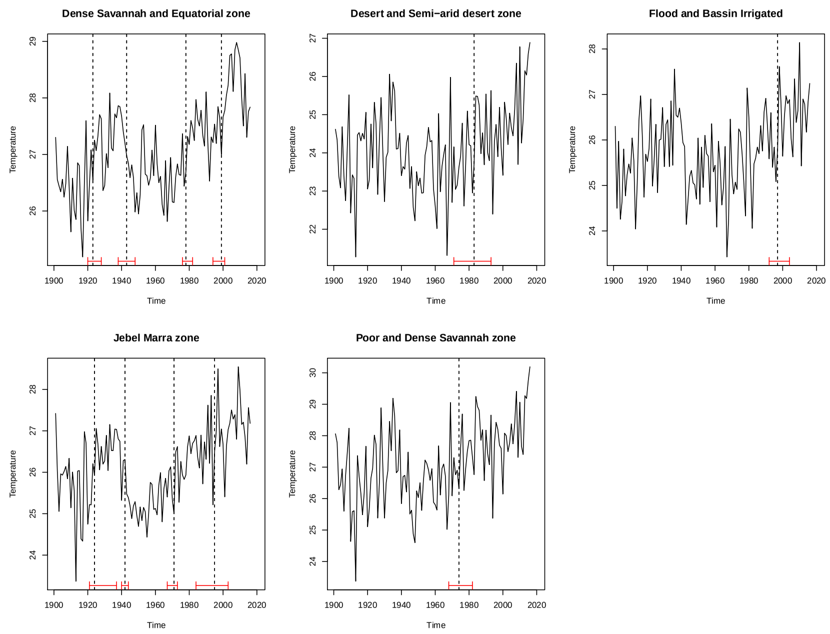
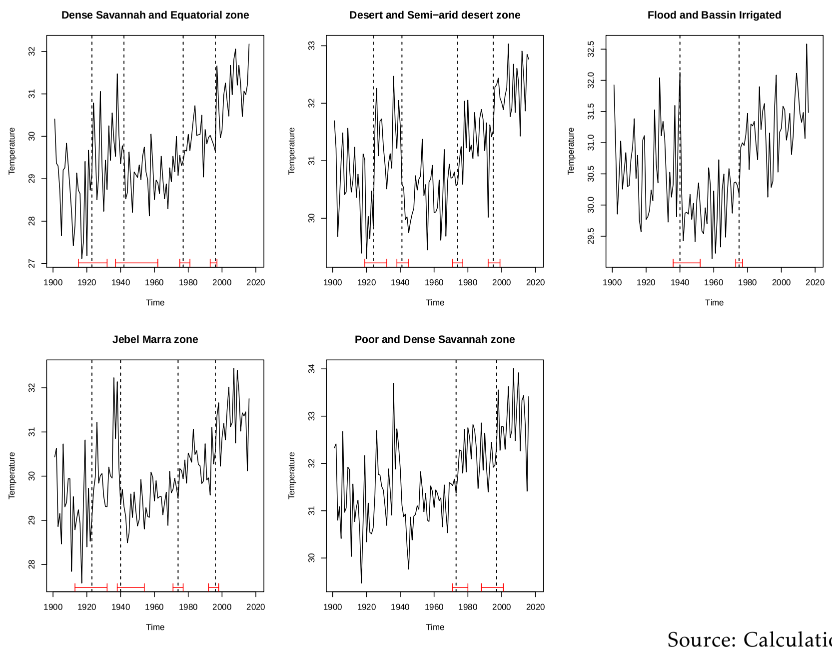


Figure 29.c: Maximum annual temperature

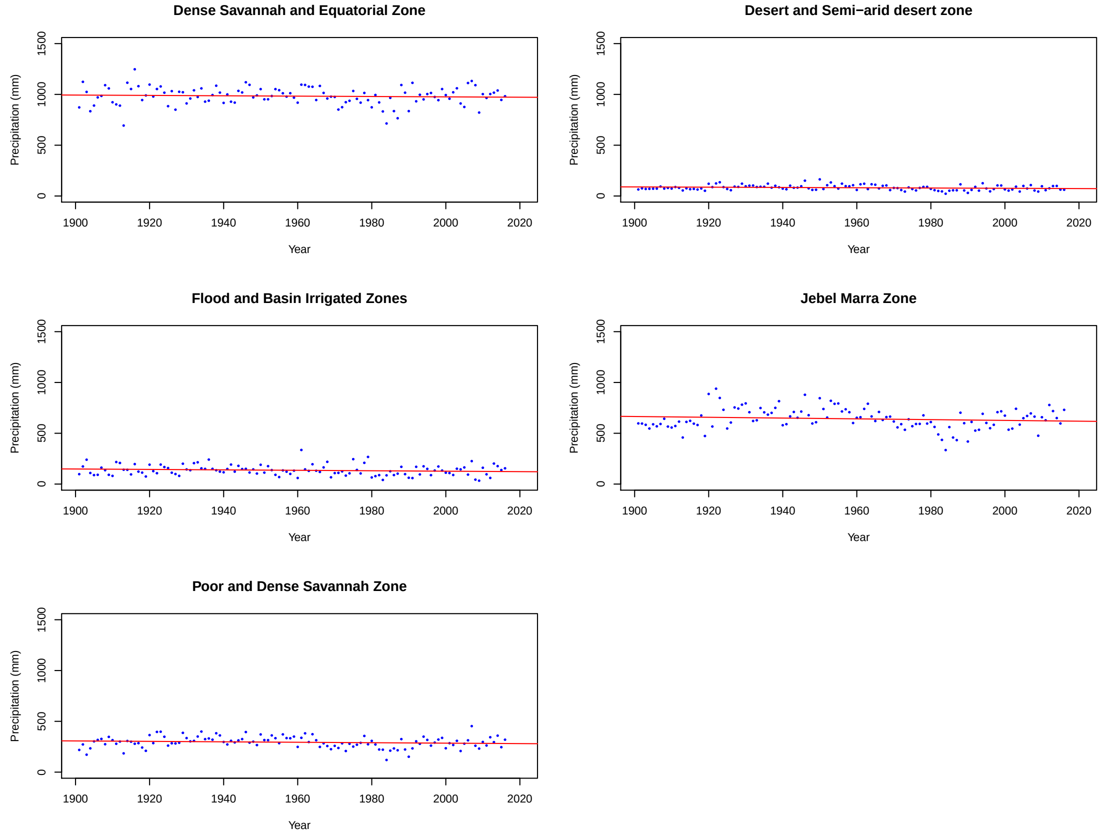


Source: Calculations and achievements by the author

Table 1.18Estimated results for Sudan

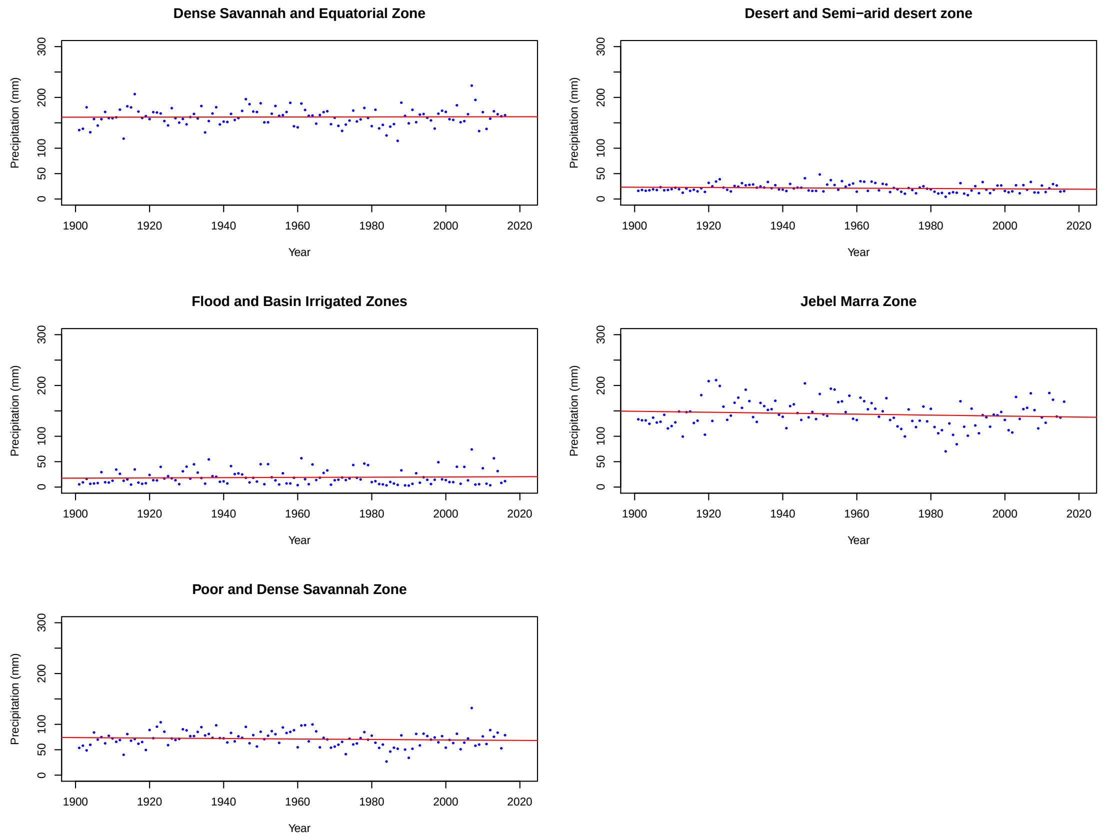
	Rainfall		Temperature					
	RainSum	RainSeason	TempminRain	TempmedRain	TempmaxRain	TempminDry	TempmedRain	TempmaxDry
	Dependent variable: Dense Savannah and Equatorial zone							
Year	−0.176	0.007	0.011***	0.010***	0.009***	0.015***	0.010***	0.019***
	(0.246)	(0.049)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	1,328.143***	148.228	3.462	5.574	8.010**	−3.246	5.574	−8.531*
	(481.989)	(95.271)	(3.988)	(4.170)	(3.493)	(4.004)	(4.170)	(4.374)
R^2	0.004	0.0002	0.207	0.169	0.197	0.311	0.169	0.400
	Dependent variable: Desert and semi-arid desert zone							
Year	−0.136*	−0.032	0.013***	0.010***	0.008***	0.003	0.010***	0.014***
	(0.069)	(0.022)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)
Constant	347.973**	84.941**	6.232	11.446***	16.559***	12.231*	11.446***	3.794
	(134.763)	(42.736)	(4.392)	(4.059)	(3.443)	(6.437)	(4.059)	(3.929)
R^2	0.033	0.019	0.218	0.178	0.157	0.008	0.178	0.298
	Dependent variable:Flood and Basin Irrigated zones							
Year	−0.217	0.023	0.010***	0.010***	0.008***	0.005	0.010***	0.008***
	(0.142)	(0.041)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)
Constant	561.228**	−26.724	11.827***	13.001***	17.184***	12.094**	13.001***	14.172***
	(278.616)	(79.370)	(3.643)	(3.853)	(4.158)	(5.770)	(3.853)	(3.738)
R^2	0.020	0.003	0.202	0.175	0.105	0.022	0.175	0.146
	Dependent variable:Jebel Marra zone							
Year	−0.384	−0.094	0.007**	0.006**	0.009***	0.007**	0.006**	0.017***
	(0.285)	(0.073)	(0.003)	(0.003)	(0.002)	(0.003)	(0.003)	(0.002)
Constant	1,394.637**	328.076**	12.094**	14.390***	10.042***	8.432	14.390***	−2.632
	(558.470)	(142.972)	(5.279)	(5.267)	(3.531)	(6.849)	(5.267)	(4.265)
R^2	0.016	0.014	0.054	0.044	0.188	0.033	0.044	0.339
Year	−0.220	−0.047	0.007**	0.006**	0.008***	0.006*	0.006**	0.016***
	(0.154)	(0.043)	(0.003)	(0.003)	(0.002)	(0.003)	(0.003)	(0.002)
Constant	724.673**	162.463*	15.175***	18.495***	15.666***	8.711	18.495***	−0.239
	(301.052)	(84.923)	(5.516)	(5.298)	(3.824)	(6.629)	(5.298)	(4.041)
R^2	0.018	0.010	0.048	0.037	0.128	0.031	0.037	0.354
Observations	116	116	116	116	116	116	116	116
Note:								*p<0.1; **p<0.05; ***p<0.01

Figure 1.105Evolution of the sum annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Sudan



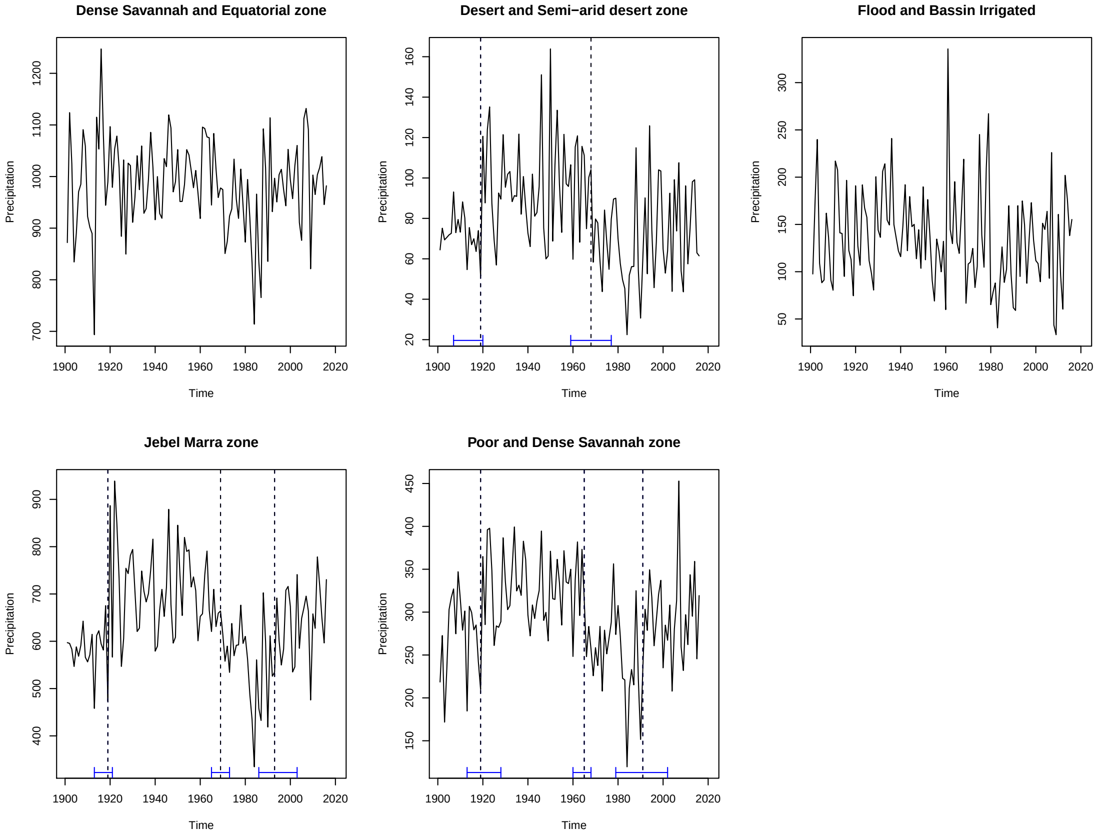
Source: Calculations and achievements of the author

Figure 1.106Evolution of the seasonal annual rainfall (mm) from 1901 to 2016 in the agroecological zones of Sudan



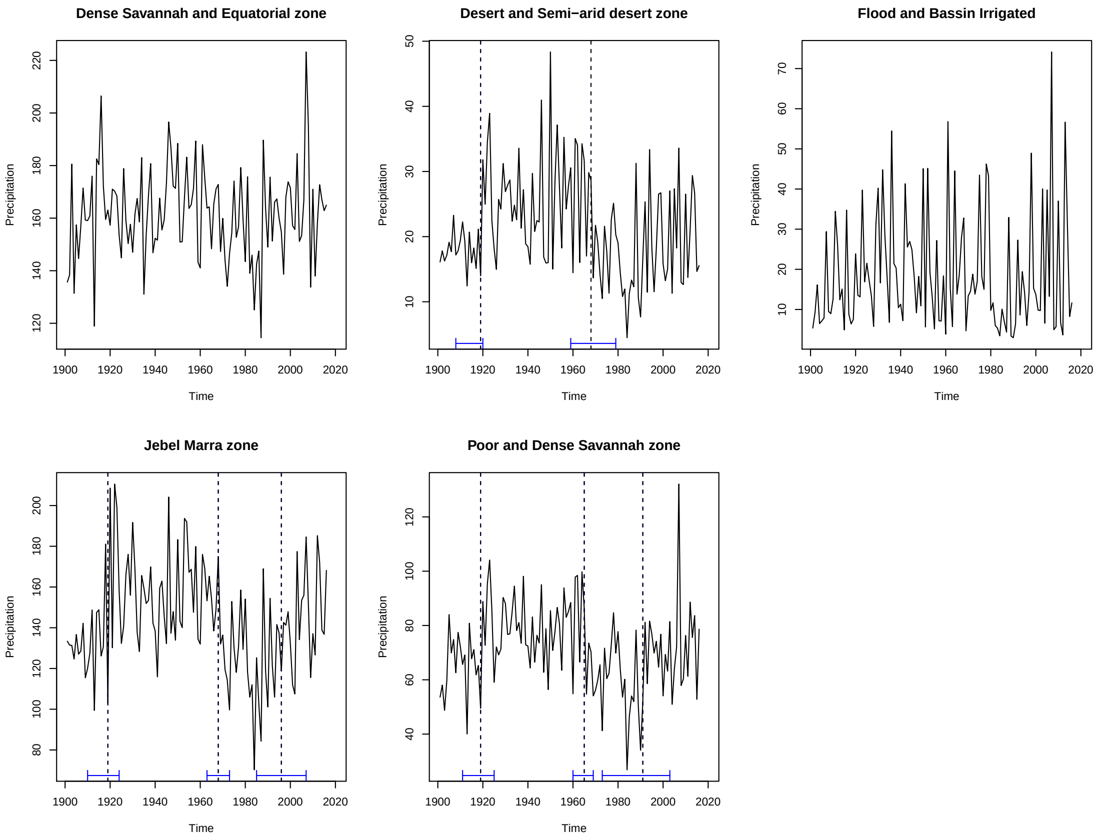
Source: Calculations and achievements of the author

Figure 1.107 Breaks in total annual precipitation in the agroecological zones of Sudan.



Source: Calculations and achievements of the author

Figure 1.108 Breaks on seasonal precipitation in the agroecological zones of Sudan.



Source: Calculations and achievements of the author

Table 1.19Number of shocks for each agro-ecological zone by country and climatic variables.

		Rainfall		Rainy season			Dry season		
Country	Zones	Sum	season	Tmin	Tmed	Tmax	Tmin	Tmed	Tmax
Burkina Faso	North Sahel	3	2	1	2	3	1	3	3
	North Soudania	2	2	1	2	1	1	3	1
	South Sahelian	3	2	1	2	3	1	3	1
	South Soudanian	2	0	1	2	1	1	3	1
Chad	Desert area	2	2	3	3	3	3	3	4
	Sahelian zone	2	2	4	3	3	3	1	4
	Soudanian zone	2	1	1	2	1	3	3	4
Djibouti	Coastal plains	0	0	2	2	2	1	0	2
	Interior plains	0	0	2	2	2	1	0	2
	Mountain	0	0	2	2	2	1	0	2
Ethiopia	Arid agroecology	0	0	1	1	1	1	2	2
	Humid	0	0	1	1	2	3	2	2
	Moist	0	0	1	1	2	3	2	2
	Per humid	0	0	1	1	2	2	2	1
	Semi arid	0	0	1	1	2	1	2	1
	Sub humid	0	0	2	1	2	1	2	2
	Sub moist	0	1	1	1	1	1	1	3
Mali	Saharan zone	3	1	1	3	3	1	2	3
	Sahelian zone	1	1	1	2	3	1	3	3
	Sudanian zone	1	1	1	1	1	1	1	3
	Sudano Guinean	1	1	1	1	1	1	1	4
Mauritania	Arid zone	3	1	1	3	1	1	2	1
	Maritime zone	2	1	2	2	0	1	2	2
	River zone	2	1	2	2	1	1	1	2
	Sahelian zone	0	0	0	2	2	1	2	0
Niger	Saharan zone	2	2	1	2	1	1	3	1
	Saharo sahelian	3	0	2	1	2	0	3	2
	Sahelian zone	2	2	2	2	2	0	2	2
	Sahelo sudanian	2	2	1	2	1	1	3	2
	Soudanian zone	2	2	1	2	1	1	3	1
Nigeria	Derived savanna	0	0	2	3	3	0	3	3
	Humid forest	1	0	1	3	3	1	3	3
	Nothern guinea	2	2	1	3	3	0	3	1
	Sahel savanna	2	2	1	3	2	1	2	1
	Southern Guinea	0	0	1	3	3	3	3	3
	Sudan Savanna	2	2	1	3	2	0	2	1
Senegal	Bassin arachidier	1	1	1	2	0	1	2	3
	Casamance	1	1	1	1	1	1	1	2
	Centre East	1	1	1	1	1	1	1	4
	Niayes	1	1	0	2	2	1	2	3
	Sylvopastoral	2	1	2	1	0	1	1	2
	Valley of the river	1	1	2	1	1	1	1	2
Somalia	Bari	2	0	3	1	3	1	0	3
	Bay and Bakool	0	0	2	1	2	2	2	2
	Coastal central	0	0	2	2	2	2	2	2
	Shabelle and Juba	0	0	2	2	2	2	2	2
	Somaliland	0	1	3	1	1	1	1	2
Sudan	Dense Savannah	0	0	2	2	2	2	4	4
	Desert and Semi	2	2	3	3	3	2	1	4
	Flood	0	0	3	3	4	1	1	2
	Jebel Marra zone	3	3	2	3	3	3	4	4
	Poor and Dense	3	3	3	2	2	3	1	2

Chapter 2

Climate and Agriculture : Empirical evidence for Countries and Agroecological Zones of the Sahel

This chapter investigates the relationship between climate change and variability, measured by temperature and rainfall conditions, and agricultural production at the country and agroecological zones levels of the Sahel. We focus on a crop production index and five cereals (maize, millet, sorghum, wheat and rice). To investigate this relationship, we have constructed an original database with socioeconomic and climatic variables. Based on an agricultural production function estimated for the period 1961-2016, we show that average rainfall and temperature during the growing season globally have highly heterogeneous effects on agricultural production according to the cereal and agriculture zone, depending on the specific needs and stress of each cereal and agronomic and climatic conditions of each zone.

Note: This chapter is a paper submitted with Julie Le Gallo

The paper was presented at the 93rd conference of the Association of Agricultural Economists (AES, 2019) in Warwick (England), at the 13ième Journées de Recherches en Sciences Sociales (JRSS, 2019) in Bordeaux (France) and at the PhD students day of the Dynamics and Regional Planning axis (CESAER, 2019).

2.1 Introduction

Even if, at the global level, the contribution of agriculture to Gross Domestic Product (GDP) is low, it remains the key to food production and it provides a large range of ecosystemic services. In developing countries, the agricultural sector still is, both from an economic and social point of view, the most important sector and the main engine for economic growth. As agriculture is strongly sensitive to climate change and variability (Ward et al., 2014; Burke et al., 2009; Misra, 2013; Faurès and Santini, 2008), the expected impacts of climate change and variability are considerable for developing countries with rainfed agricultural systems. For instance, in sub-Saharan Africa, rainfed agriculture accounts for about 97% of total cultivated land (Burke et al., 2009; Faurès and Santini, 2008) while in the Sahel, only 8% of the land is suitable for agriculture and irrigated agriculture currently accounts for only about 5% of this land.

Climate change manifests itself in episodes of variability in temperature and precipitation and the rise in the stock of greenhouse gases in the atmosphere. This change is often associated with the more or less frequent occurrence of extreme events such as floods and droughts. Over the past century, Sahelian countries have experienced some noticeable climate change with also substantial weather variability within the growing seasons Yobom (2020). Climate shocks pose a major problem for Sahelian farm households, which are the main victims of this phenomenon given their heavy dependence on agricultural activity (Faurès and Santini, 2008). As adverse weather shocks affect agricultural production, the implied food shortage leads to higher prices for agricultural commodities. According to data from EM-DAT (2019), the 12 Sahelian countries we study in this chapter recorded 127 drought events between 1901 and 2018 corresponding to more than 50% of the drought events that took place throughout the African continent over this period. The consequences were dramatic, exposing nearly 40 million people to food insecurity. By 2018, most of the food crises were caused by dryness and have plunged some 39 million people into acute food insecurity. The largest number of people affected and significant economic damage are found in our sample of 12 countries.

In this context, this chapter aims to assess the impact of climate change and variability on the Sahelian agriculture. For that purpose, we use an agricultural production function that we estimate on a sample of 12 countries and 49 agroecological zones for the period 1961-2015 using a panel data model with climate variables (average temperature and precipitation of the growing season, within growing season variability of temperature and precipitation), input variables, individual fixed effects and a quadratic time trend. In addition to providing causal evidence, the fixed-effect model here captures the effects of short-term climate change. We perform this analysis on an aggregate index of crop production and on the production of five different cereals: maize, millet, sorghum, rice and wheat. The agricultural production function has been used by a large number of authors to assess the link between climate change and agricultural production at different levels (countries, regions, etc.) with varying methodologies (Jones et al., 2017) and various climate indicators, going from the usual mean temperature and precipitation measures to other measures capturing solar radiation, droughts and floods. We follow for instance Barrios et al. (2008), Deschênes and Greenstone (2007) and Kahsay and Hansen (2016) but, by focusing on the Sahel countries, our chapter contributes to the literature in several ways.

First, to the best of our knowledge, no studies deal with the impact of climate change and variability on agriculture in the wider Sahel comprising 12 countries and the 49 identified agroecological zones and the present chapter attempts to fill this gap. Some studies have investigated this link for sub-Saharan Africa (Barrios et al., 2008; Schlenker and Lobell, 2010; Blanc, 2012; Ward et al., 2014) or East Africa (Kahsay and Hansen, 2016). With respect to Sahel, other studies use the Ricardian model to explain the link between agricultural production and climate change at a more microeconomic level (Wood and Mendelsohn, 2015b; Bello and Nafiou Malam Maman, 2015). We investigate this link at two levels: countries and agroecological zones and do so using a single-output agricultural production function rather than a Ricardian approach.

Second, we assess the impact of climate change on agriculture not only on aggregate crop production as in Kahsay and Hansen (2016), but we also consider a wide range of cereals, namely maize, millet, sorghum, rice and wheat in order to analyze the potential heterogeneous impact of climate change on cereal production. These cereals constitute the majority in Sahelian agricultural production, representing 80% of cultivated areas and are important for the food security of the Sahelian population. Moreover, in the West African Sahel, millet and sorghum account for 80% of cereal production (FAO).

Third, as is usual in the literature, we measure climate change and variability using the means and coefficients of variation of temperature and precipitation in the growing seasons. However, we use more precise temperature and precipitation variables than country averages. Indeed, based on the data of the Climate Research Unit (2016), we reconstructed all climatic variables at the agroecological zone level. This has two consequences. On the one hand, in the analysis that we perform at the country level, which is the level at which the production and the input variables are observed, we construct cereal-specific climatic variables by including only the climatic information of the agroecological zones in which these cereals are cultivated. This is important as the production of cereals within countries is spatially heterogeneous so that it is important to capture more precisely the local climatic conditions faced by each cereal production rather than using country averages. On the other hand, after allocating all variables measured at the country level to the agroecological zones using a distribution key based on agricultural surface, we can perform an analysis at the agroecological level, which, to the best of our knowledge, has never been performed.

Finally, we allow for the possibility of an heterogeneous impact of temperature and precipitation on production at the country and at the agroecological zones level.

The remainder of the chapter is organized as follows. Section 3.3 provides a brief literature review. Section 3.4 presents the empirical specification. Section 3.5 describes the data used at the country and agroecological zone level. Section 3.6 presents the results. Sub-sections 2.5.1 and 2.5.2 present respectively the different results obtained at the level of countries and agroecological zones. We conclude in section 2.6.

2.2 Literature review

In the empirical literature, various approaches have been used to assess the link between climate and agriculture (Mendelsohn and Dinar, 2009) : crop simulation models (Bassu et al., 2014; Rosenzweig et al., 2014), agricultural production or yields functions (Lobell et al., 2011; Chen et al., 2016), net income approaches (Deschênes and Greenstone, 2007) and the ricardian approach (Mendelsohn et al., 1994) based on property values. All approaches contain an agronomic component but those based on production/yields, income and land values are regression-based explaining their regular use by economists.

Despite its drawbacks, and notably that these models do not easily account for the responses to changes in weather made by profit-maximizing farmers (this is the "silent farmer scenario" (Mendelsohn et al., 1994)), the agricultural production function has been used by a large number of authors to analyze the link between climate change and agricultural production at different levels (countries, regions, etc.) with varying specifications and estimation methods (Jones et al., 2017). In this chapter, we also adopt the statistical version of the agricultural production approach as this framework assumes that climatic conditions (precipitation and temperature) are uncontrollable factors and thus exogenous variables needed in the context of agricultural activities.

Table 2.1 summarizes the papers that estimate agricultural production or yields functions to investigate the link between climate change and agricultural outputs or yields. Starting with Barrios et al. (2008), African countries have been largely studied given the accute problems of food security faced by these countries, albeit with a focus on Sub-saharian countries (Rowhani et al., 2011; Blanc, 2012; Ward et al., 2014). The spatial scales of analysis are diverse: grid cells (Ward et al., 2014), regions or counties within a country (Deschênes and Greenstone, 2007; You et al., 2009; Cabas and Olale, 2009; Rowhani et al., 2011; Chen et al., 2016; Xu et al., 2019) or countries (Barrios et al., 2008; Blanc, 2012; Kahsay and Hansen, 2016).

The explained variables are total production, or production or yields for specific crops. These variables are regressed against climate variables and other control variables corresponding to the inputs of the production process. The climate variables usually refer to temperature and precipitations that are either averaged over the year (Barrios et al., 2008) or over the growing season (Chen et al., 2016; Xu et al., 2019) or that are included by distinguishing different periods (Deschênes and Greenstone, 2007; Kahsay and Hansen, 2016). In order to account for possible linear effects of these variables, their squared are sometimes included or they are interacted. Using cross-sectional or panel data versions of agricultural production functions, all papers find significant effects of temperature and precipitations on production and yields with varying extents depending on the crop. There is however no consensus on the level of impact of climate change as the results vary from one model to another and from one region to another. For example, Ward et al. (2014) shows that cereal yields in sub-Saharan Africa decrease with increasing temperature and increase with high total precipitation while Liu et al. (2004) indicate that a higher temperature and more rainfall will have a positive overall impact on Chinese agriculture. Lobell et al. (2011) show a negative impact of temperature on yields of maize, wheat, rice and soybeans reducing yields by about 3.8%, 5.5%, −0.1% and −1.7, respectively with a presence of regional heterogeneity. Rowhani et al. (2011) and You et al. (2009) find that variability in precipitation and temperature increase during the growing season and have a negative effect on cereals.

Table 2.1Summary table of papers on the agricultural production function

Authors	Period + Unit of analysis	Explained variables	Climate variables	Other control variables	Model and estimation methods	Main results
Barrios et al. (2008)	40 Sub-Saharan African countries and 67 non Sub-Saharan African countries for the period 1961-1997.	Total agricultural output	Mean annual temperature and mean annual rainfall	Labor, livestock, fertilizer, capital and land	Panel data for a single output agricultural production function with individual and time fixed effects	Climate is a determining factor in agricultural production in sub-Saharan African countries while non-sub-Saharan African are not affected. Simulations show that adverse climate change since the 1960s may account for a substantial part of the agricultural output gap between sub-Saharan Africa and the rest of the developing world.
Deschênes and Greenstone (2007)	2,268 US counties for 1978, 1982, 1987, 1992, 1997 and 2002 (agriculture censuses)	Bushels per acre of corn for grain, bushels per acre of soybeans	January mean temperature, April mean temperature, July mean temperature, October mean temperature, January total precipitation, April total precipitation, July total precipitation, October total precipitation, growing season degree-days, growing season total precipitation	Soil varieties (K-factor of top soil, slope length, floodable fraction sand fraction, clay fraction, irrigated fraction, permeability, moisture capacity, wetlands, salinity), socioeconomic variables (per capita income, per capita income squared, population density and population density squared	Hedonic model, agricultural production function with county and year fixed effects, state by year fixed effects	The increase in temperature is harmful for yields and the increase in rainfall is beneficial. Projected increases in temperature and precipitation will have virtually no effect on yields for the most important crops (i.e corn for cereals and soybeans).
You et al. (2009)	22 wheat producing provinces in China for the period 1979-2000	Wheat yield	Monthly temperature and precipitation, solar radiation.	Fertilizers, agricultural land, irrigations, seeds, machinery.	Cobb - Douglas agricultural function for wheat yield with regional dummies and a time trend.	A 1°C increase in the temperature of the wheat growing season reduces wheat yields by about 3 to 10%. Rising temperatures account for a 4.5% decline in wheat yields in China.
Cabas and Olale (2009)	8 counties in southwestern Ontario, Canada for the period 1981-2006.	Crop yields for corn, soybean and winter wheat	Average temperature and precipitation for varying units of time (from a month to a year) and their coefficients of variations	Output to input price ratio, site characteristics	Stochastic production function, which breaks down the production function into a deterministic function related to the output level and a second related to the variability of this output in order to estimate the impacts of climate on the expected production and its variance. The specification also includes county dummies and a time trend.	Climate variables have a major impact on average yield, with the length of the growing season being the main determinant of all three crops. The increase in temperature and precipitation variability decreases the average yield and increases its variance. Projections of future climate change suggest that average crop yield will increase with increasing temperatures and a longer growing season, which are only partially offset by projected increases in temperature and rainfall variability.
Rowhani et al. (2011)	19 regions of mainland Tanzania for the period 1992-2005.	Crops yield for maize, sorghum and rice	Temperature and its square, precipitation and its square, coefficient of variation	Region and year fixed effects	Mixed models	Variations in temperature and precipitation during the season and offseason affect cereal yields in Tanzania. Seasonal increases in temperature have the greatest impact on yields. By 2050, expected seasonal temperature increases of 2°C will reduce average yields of maize, sorghum and rice by 13%, 8.8% and 7.6% respectively. A 20% increase in intra-seasonal rainfall variability will reduce agricultural yields of maize, sorghum and rice by 4.2%, 7.2% and 7.6% respectively.
Blanc (2012)	37 Sub-Saharan African countries for the period 1961-2002	Crop yields for millet, maize, sorghum and cassava	Temperature, precipitation, evapotranspiration, standardized precipitation index (SPI), droughts and floods	Land, labor and capital inputs	Panel data for a single output agricultural production function with individual and time fixed effects, quadratic terms for climatic variables, interactions terms between climatic variables	Crop yields up to 2100 are predicted with climate change predictions Compared to a situation without climate change, yield variations in 2100 are close to zero for cassava and range from −19% to + 6% for maize, from −38% to −13% for maize. millet and −47% to −7% for maize. sorghum in alternative scenarios of climate change.
Ward et al. (2014)	2123 grid cells in sub-Saharan Africa in 2000.	Cereal yield	Average growing season monthly temperature and its square, average growing season monthly temperature and its square, diurnal temperature range, coefficient of variation of average growing season monthly precipitation	Fertilizers (nitrogen and phosphorus), irrigated plot percentage, soil Ph level.	Cross-sectional single-output production function with spatial error autocorrelation and endogenous sample selection	Yields decrease with increasing temperature and increase with high total precipitation.
Chen et al. (2016)	Counties in China for the period 2000-2009.	Crop yields for corn and soybean	Heat accumulated over the crop growing seazon and its quadratic form, sum of precipitation and radiation over the growing seaon and their quadratic forms	Land use change, ratio price/fertilizer, ratio price/wage, Irigation ratio	Panel data for a single output agricultural production founction with county and time fixed effects and spatial error autocorrelation	High temperatures above 34°C have negative impacts on corn yields, but negligible impacts for soybeans. The increase in irrigation area reduce the negative effect of high temperature on corn yields. Yields increase with temperature up to 29°C for corn and 28°C for soybean, and temperatures above these thresholds are very harmful to crop growth.
Kahsay and Hansen (2016)	9 countries in East Africa for the period 1980-2006	Agricultural output	Mean temperature in spring, summer and fall, mean precipitation in spring, summer and fall, variability of temperature and precipitations in spring, summer and fall	Physical inputs (labor, land, machinery, livestock, fertilizers and irrigation)	Panel data for a single output agricultural production function with individual and time fixed effects	Mean temperature and precipitation of the growing season and their variance have important effects.
Xu et al. (2019)	751 counties in the Yangtze River Basin in China for the period 1990-2015,	Crop output per capita	Precipitation and mean temperature during the growing season, climate variation	Sown area, fertilizer use intensity, and population size	Agricultural production function with year fixed effects	Seasonal precipitation and duration have significant positive effects on agricultural production while average temperature during crop growing seasons has significant and negative relationship with crop production.

2.3 Econometric specification

Our baseline production function is, using a Cobb-Douglas form:

$$
\begin{aligned}
\log(Output_{it}) &= \beta_0 + \beta_1\log(Labor_{it}) + \beta_2\log(Land_{it}) + \beta_3\log(Machinery_{it}) + \\
&\quad \beta_4\log(Livestock_{it}) + \beta_5\log(Fertilizer_{it}) + \beta_6\log(Irrigation_{it}) + \\
&\quad \beta_7 t + \beta_8 t^2 + \mu_i + u_{it} \qquad (2.1)
\end{aligned}
$$

where i stands for the country/agroecological zone index, t is the yearly index, $Output_{it}$ is the value of production (total or production by crop) of country/agroecological zone i in year t. We assume that there are three capital inputs: *Land*, *Machinery* and *Livestock*. There is one aggregate *Labor* inputs. Finally, there are two other inputs *Fertilizer* and *Irrigation*. This choice of inputs follows that of Barrios et al. (2008) and Kahsay and Hansen (2016) and was largely constrained by the availability of data for our sample of countries. We also include a trend variable with a quadratic term which captures technological progress. μ_i is the unobserved country/agroecological time-invariant specific effect and u_{it} is the idiosyncratic error term. The βs are the parameters to be estimated and that can be interpreted as elasticities.

In order to assess the impact of climate change and climate variability, we augment the production function (2.1) with temperature and precipitation variables. The estimated specifications are versions of the Cobb-Douglas production function which can also be written as follows:

$$
\begin{aligned}
\log(Output_{it}) &= \beta_0 + \beta_1\log(Labor_{it}) + \beta_2\log(Land_{it}) + \beta_3\log(Machinery_{it}) + \\
&\quad \beta_4\log(Livestock_{it}) + \beta_5\log(Fertilizer_{it}) + \beta_6\log log(Irrigation_{it}) + \\
&\quad \gamma_1\log(Temp_{it}) + \gamma_2\log(Precip_{it}) + \\
&\quad \gamma_3\log(CVTemp_{it}) + \gamma_4\log(CVPrecip_{it}) + \beta_7 t + \beta_8 t^2 + \mu_i + u_{it} \qquad (2.2)
\end{aligned}
$$

where $Temp_{it}$ and $Precip_{it}$ are mean temperature and precipitation of the growing season of year t specific to country/agroecological zone i. $CVTemp_{it}$ and $CVPrecip_{it}$ are the coefficient of variations of temperature and precipitation in order to capture within-growing season variability.
Note that for the country level and the analysis by crop, only the temperature and precipitations of the agroecological zones where the crop is cultivated are taken into account to compute the means and coefficient of variations.

Finally, while the Sahel countries in our sample share similar economic characteristics, the farming conditions may differ with a variety of agricultural systems. Therefore, in order to assess heterogeneity between and within countries, we also provide results when $Temp_{it}$ and $Precip_{it}$ are interacted with μ_i.
Model (2.2) is estimated with a within estimator and clustered-robust by country/agroecological zones and year. The fixed effects panel data model

turns out to be the preferred methodology (Deschênes and Greenstone, 2007; Blanc and Schlenker, 2017; Mérel and Gammans, 2018) and commonly used (Carter et al., 2018) to uncover the effects of climate change using historical weather data. However, it has advantages and disadvantages. First, it should be remembered that we are working on an area facing considerable lack of data, so this model is preferred in our case. While it has been criticized for its alleged inability to take into account long-term effects (Lobell et al., 2011; Blanc and Schlenker, 2017; Carter et al., 2018) and at least partially reflects long-term effects (Mérel and Gammans, 2018; Blanc and Schlenker, 2017), it also has the advantages of providing more degrees of freedom and allowing to discover a causal relationship (Blanc and Schlenker, 2017; Mérel and Gammans, 2018). In addition, they are ideal for climate change impact assessments, because they use group fixed effects to absorb all the invariant variations over time and therefore rely on meteorological deviations from the average which are random and exogenous (Carter et al., 2018; Blanc and Schlenker, 2017).

2.4 Data

2.4.1 Perimeter

The analysis covers two scales: countries and agroecological zones for the period 1961-2016. First, our perimeter covers 12 countries (see Figure 2.1) forming the entire Sahelian belt, 6 countries in West Africa (Burkina Faso, Mali, Mauritania, Niger, Nigeria and Senegal), 3 in East Africa (Ethiopia, Somalia and Sudan) and one country in Central Africa (Chad). The countries we have chosen have similar climatic conditions marked by high climatic variability and have practically the same rainfed agricultural practices based. Irrigated agricultural areas are not well developed given the high costs of mechanization and the low rate of investment in the agricultural sector.

Second, the Food and Agriculture Organization of the United Nations (FAO) has defined a zoning of countries in agroecological zones, which aim at assessing the productivity potential of agricultural land. This design focuses on climate, soils and soil conditions in relation to agricultural production. Hence, we also consider this level. FAO's information on agroecological zones and their agricultural practices comes from the "Crop Calendar" system. The last update of this instrument dates from 2010 and we built the agroecological maps in all the countries of our sample on this basis, allowing to identify 49 agroecological zones[1].

Table 2.2 presents the number and names of the agroecological zones in each country and Figure 2.1 provides an overview of the study area: countries and

[1] We also constructed the agroecological zones of Eritrea and Djibouti as they can be considered as being part of the extended Sahel (see the red outlines in Figure 2.1), but, in the absence of production data for these countries, they were removed of the sample.

agroecological zones.

Table 2.2Presentation of agroecological zones

Country	Number	Name
Burkina Faso	4	North Sahel, North Soudania, South Sahelian, South Soudania.
Chad	3	Desert area, Sahelian zone, Soudanian zone.
Ethiopia	7	Arid agroecology, Humid agroecology, Moist agroecology, Per humid agroecology, Semi-arid agroecology, Sub-humid agroecology, Sub-moist agroecology.
Mali	4	Saharan zone, Sahelian zone, Soudanian zone, Sudano guinean zone.
Mauritania	4	Arid zone, Maritime zone, River zone, Sahelian zone.
Niger	5	Saharan zone, Saharo-sahelian zone, Sahelian zone, Sahelo-Sudanian zone, Soudanian zone.
Nigeria	6	Derived savanna, Humid forest, Northern guinea savanna, Sahel savanna, Southern Guinea Savanna, Sudan Savanna.
Senegal	6	Bassin arrachidier, Casamance, Centre East and South East, Niayes, Sylvopastoral zone, Valley of the reiver.
Somalia	5	Bari, Bay and Bakool, Coastal central and southern Somalia, Shabelle and Juba Valleys, Somaliland.
Sudan	5	Dense Savannah and Equatorial Zone, Desert and Semi-arid desert zone, Flood and Basin irrigated zones, Jebel Marra zone, Poor and Dense savannah zone.

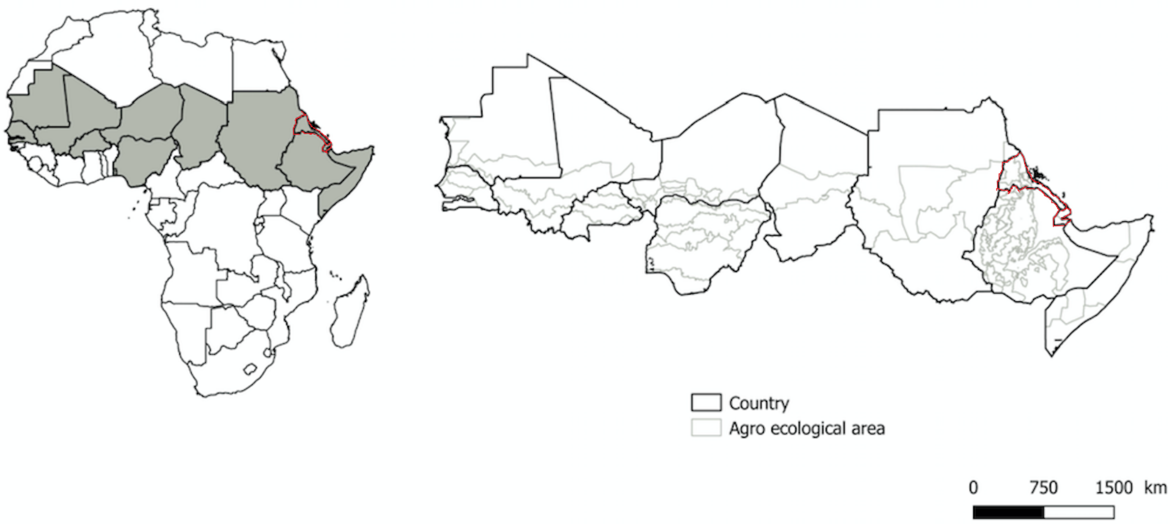
Source: Identification of agroecological zones by the authors using FAO data and information.

2.4.2 Production variables

We first consider the FAO net production index, which represents the net quantities of each cereal produced by the agricultural sector weighted by the 2004-2006 average of the international commodity prices in 2006. It is expressed in US dollars and is divided by the average aggregate of the 2004-2006 reference period.

In addition, we focus on the five major cereals (maize, millet, sorghum, wheat and rice) used by most Sahelian countries (Nyong et al., 2007), which are used in the form of flour for consumption or consumed directly freshly. Focusing on specific cereal production is of particular interest as the level of production of these cereals depends on the climatic conditions, some agroecological zones do not favor the

Figure 2.1 Study area: countries and agroecological zones



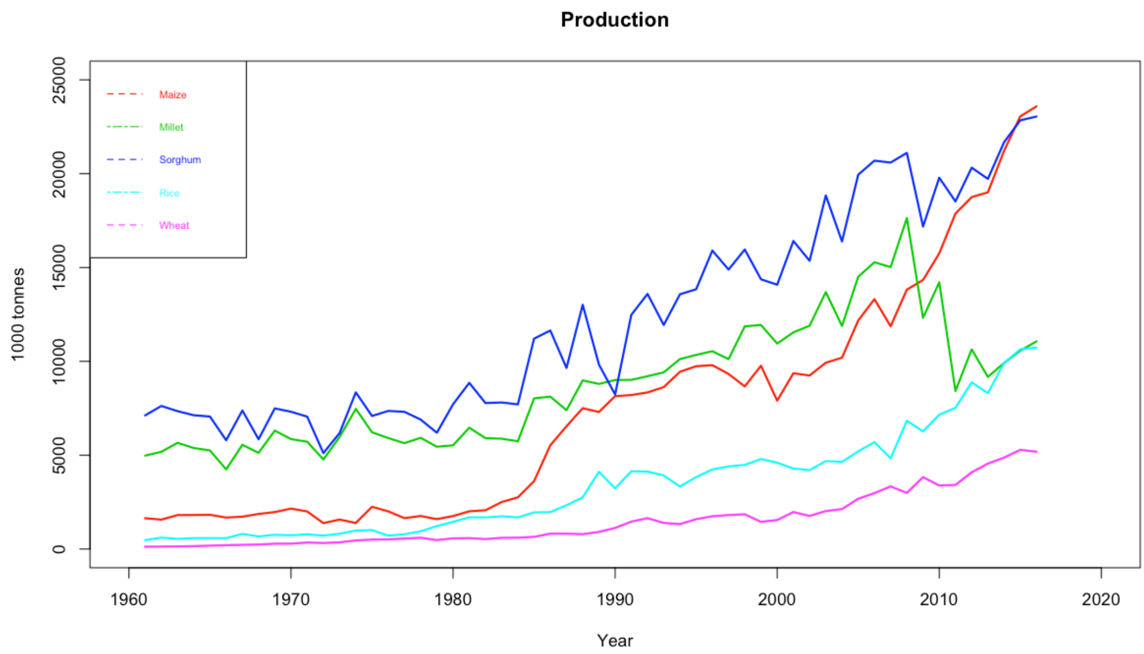
Source: Authors

cultivation of all five cereals, but it can also depend on the importance given to each type of cereal in the national agricultural economy following national food preferences. Table 2.15 in the appendix 2.7 gives the number of agroecological zones in each country in which each cereal is cultivated while the characteristics of these cereals in terms of agronomic needs and stress are summarized in Table 2.16.

These cereals represent the major share of agricultural production in the Sahel countries. Their cultivation is practiced under two agricultural systems: the rainfed system, which is the most widespread covering about 90% of the agricultural productions, and the irrigated system, which is weakly developed and only concerns Nigeria. While this country has the greatest agricultural potential of the Sahel region, other countries have very limited irrigated areas for small-scale off-season crops (eg market gardening for legumes and other crops). The two agricultural systems are distinguished by the plurality of annual harvests. Under the first system, countries only practice agriculture during the growing season while the irrigated system allows to have at least two crops in a single year.

All agricultural output variables come from FAOSTAT (2019) and cover the period 1961-2016 for both countries and agroecological zones. Our samples then contain 560 observations at the country level and 2744 observations at the agroecological zone level. Figure 2.2 shows the cumulative total production of the different cereals for all Sahel countries. Sorghum is the cereal whose production is the highest throughout the period and is produced by all countries. On the other hand, wheat production represents a small portion of cereal production over the entire period. Note that the national demand for these cereals largely exceeds the domestic cereal production. To make up for this deficit, countries are resorting to imports and also benefiting from food aid for these grains from their bilateral and multilateral partners. Table 2.3 presents the descriptive statistics for the 6

Figure 2.2 Aggregate total production of the five cereals at the Sahelian country level over the period 1961 - 2016 in thousands of tons



Source: Calculations by the authors

production variables, expressed in thousands of tons, at the country level. The

Table 2.3Descriptive statistics for the production variables

Variables	Net index		Maize		Millet		Sorghum		Rice		Wheat	
Countries\Params	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.
Burkina Faso	59.37	39.14	412.69	451.83	659.57	319.25	1007.12	469.66	91.38	91.03	0.00	0.00
Chad	73.22	41.25	97.27	119.74	330.96	166.99	434.41	226.54	87.96	77.77	4.01	2.49
Ethiopia	59.28	52.23	2120.89	2096.04	236.37	272.55	1128.13	1401.86	25.45	37.85	1124.81	1256.45
Mali	64.18	47.01	439.67	599.20	813.72	426.57	626.80	351.23	630.02	663.86	7.40	11.01
Mauritania	80.53	44.72	7.11	5.43	4.46	2.62	70.08	34.09	57.87	71.68	1.18	2.01
Niger	69.67	55.70	7.24	10.02	1765.83	930.65	540.93	415.92	50.41	22.37	4.20	3.72
Nigeria	56.84	32.66	4037.90	3076.49	3933.23	1886.58	5404.77	1966.25	2232.39	1758.59	50.18	35.41
Senegal	88.99	28.81	121.76	104.48	526.57	149.51	121.67	39.15	213.00	184.16	0.00	0.00
Somalia	92.73	17.80	155.70	76.82	0.00	0.00	151.32	56.29	6.64	6.17	1.09	0.15
Sudan	63.12	24.83	40.03	18.50	438.92	177.66	2803.32	1366.55	8.74	8.98	313.24	212.12

data for the production variables and all other control variables are provided at the country level. Therefore, an analysis at the level of agroecological zones raises the problem of the distribution of national agricultural production, i.e. the way in which the production variables must be allocated to each agroecological zone.

We used the share of the area of each agricultural zone dedicated to agriculture with respect to the total agricultural area in the country as a distribution key. In order to compute this distribution key, we used the FAO land use map, a raster file with pixels corresponding to 1 square kilometer. Using the shapefiles of the agroecological maps that we constructed, we were then able to compute the total number of pixels allocated to agricultural uses (dryland cropland and pasture; irrigated cropland and pasture; cropland/grassland mosaic; cropland/woodland mosaic) in each agroecological zone and then to estimate the agricultural area in each agricultural zone from which we derived the distribution key. Figure 2.19 in appendix 2.7 displays for each cereal the reconstructed annual production at the agroecological zone level, in the form of standard deviation maps.

2.4.3 Climatic variables

From the range of available climatic variables, we focus on temperature and precipitation as most papers estimating an agricultural production function. Climatic Research Unit (CRU) is our main source of climate data and we get it through two channels.
At country level, we build our climate variables on the basis of monthly average data from the time-series (TS) version 4.01 of the Climate Research Unit (CRU) provided on high resolution grids (0.5x0.5 degree) for the 1901 to 2016. They are available on the World Bank's climate change knowledge portal at the national level.

To construct climatic variables at the level of the agroecological zone, we used the dataset from the Climatic Research Unit TS 4.02. This data-set comprises 1200 monthly grids of observed climate, for the period 1901 to 2016, and covering the global land surface at 0.5 resolution. We used the shapefiles of the agroecological zones that we previously constructed, which allowed us to obtain the mask of the geographic coordinates of all the polygons forming the agroecological zones. We finally used these masks to reconstruct monthly average temperature and precipitation data for each agroecological zone on the KNMI data center site (2017).

In both cases, as the rainy season is obviously the most important in rainfed agricultural systems, we focused on this season and gathered information on the duration and number of growing seasons for each country (see Table 2.14 in appendix 2.7) and constructed the following variables: 1/ *TempmeanRain* and *RainMeanRain*, which respectively refer to average temperature and average rainfall during the growing season specific to each country or each agroecological zone, and 2/ *CV temperature* and *CV precipitation*, which refer respectively to the variability of temperature and precipitation during the rainy season measured by the coefficient of variation. Importantly, as the crops are not grown in every agroecological zone of our dataset, we only include in our calculations for averages at the country level the climate variables of the agroecological zones where the cereal was produced, as we gathered this information. Table 2.4 presents the descriptive statistics of the climate

data for the two levels.
Figure 2.5 displays the distribution in mean temperature and seasonal precipitation

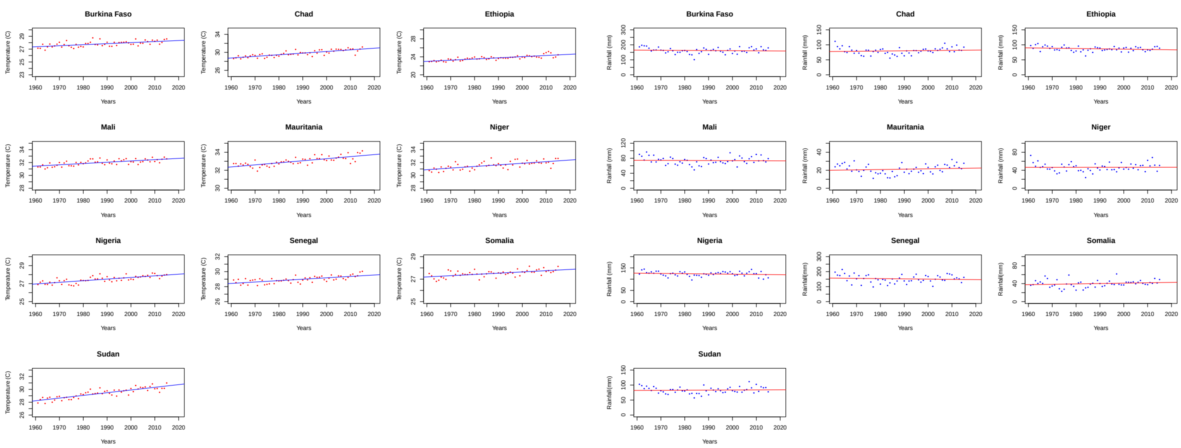
Table 2.4Descriptive statistics of the climate variables

	Statistical unit : country											
Cereals	Net index		Maize		Millet		Sorghum		Rice		Wheat	
Variables/parms	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.
Mean temp	29.38	2.64	28.47	2.76	28.28	2.11	28.73	2.74	27.91	2.02	29.14	3.21
mean precip	81.53	47.27	105.16	55.09	105.63	46.75	97.89	51.53	128.23	41.98	81.72	34.53
cv temp	4.05	1.66	7.25	3.47	8.60	3.23	8.06	3.22	6.87	3.73	8.36	4.17
cv precip	53.95	18.21	72.14	26.24	77.60	30.49	79.39	30.24	59.18	23.65	78.88	26.40
	Statistical unit : agroecological zone											
	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.
Mean temp	27.95	3.50	27.95	3.50	27.95	3.50	27.95	3.50	27.95	3.50	27.95	3.50
mean precip	103.03	64.82	103.03	64.82	103.03	64.82	103.03	64.82	103.03	64.82	103.03	64.82
cv temp	4.96	2.32	4.96	2.32	4.96	2.32	4.96	2.32	4.96	2.32	4.96	2.32
cv precip	66.19	31.17	66.19	31.17	66.19	31.17	66.19	31.17	66.19	31.17	66.19	31.17

at the beginning (i.e. 1961) of the analysis period with classes representing 0.5 standard deviation of the centered distribution, so that areas in red (resp. blue) are areas where mean temperature are above (resp. below) the sample average. Figure 2.3 displays the evolution of temperature and precipitation by country from 1961 to 2015. These figures show that generally temperatures have increased over the last 60 years, while precipitation have generally decreased in most of the Sahel countries considered in this chapter. Figure 2.4 identifies the break periods in the evolution

Figure 2.3Evolution and trend of average annual temperature and precipitation during the growing season in the Sahel countries

Fig 4.a Average temperature   Fig 4.b Average precipitation



Source: Calculations by the authors using data from the Climate Research Unit (2016)

of our two variables from a simple structural change model (**?**) applied to a linear regression of the climate variable over time. Overall, countries have experienced periods of shocks at different times and they are also distinguished by the number of shocks. The year 1980 appears as a period of reference in the start of climate change in the countries forming the Sahelian band (**??**).

Figure 2.4Endogenous detection of structural breaks in average annual temperature and precipitation in the Sahel countries during the growing season

Fig 5.a Average temperature

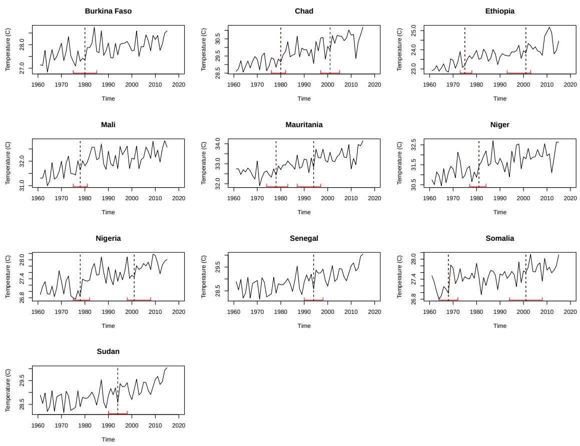
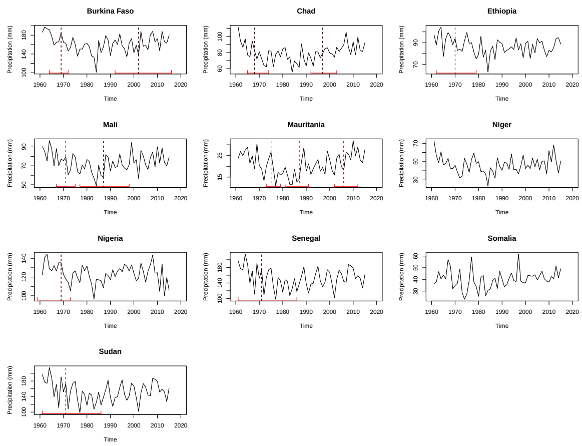


Fig 5.b Average precipitation



Source: Calculations by the authors using data from the Climate Research Unit (2016)

Figure 2.5Average temperature and average seasonal precipitation during the growing season for the first five years, 1961 to 1965. Standar deviation map

Fig 1.a Temperature

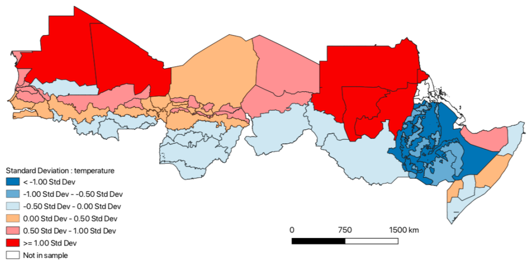
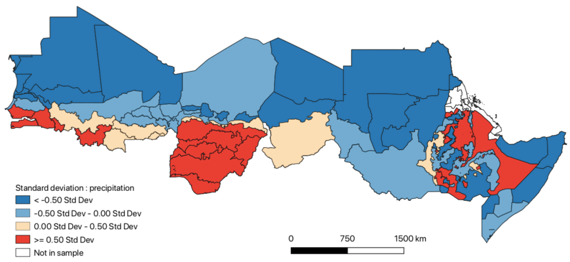


Fig1.b Precipitation



Source: Calculations by the authors using data from the Climate Research Unit (2016)

2.4.4 Other control variables

Control variables are inputs used in agricultural production. We include the labor force in the agricultural sector, which is measured by the active population in agriculture and is expressed in thousands of people. We also use the variable agricultural land as input, expressed by thousands of hectares. FAO defines this variable as the arable land, permanent crops and permanent pastures. For the machine input, we use the number of tractors used in agriculture. Livestock includes the total number of cattle, sheep and goats. The variable fertilizer capital refers to different fertilizers i.e. the total of nitrogen, phosphate and potash expressed in tons. Finally, the last input we include is irrigation, which is measured by irrigated agricultural areas in thousands of hectares. For FAO, it is the equipped surface and actually irrigated. Table 2.5 presents descriptive statistics for the control variables at the country and agroecological levels using for the latter the same distribution key as for production variables. Because of the important proportion of missing observations for tractors and fertilizers, we subsequently present estimation results with and without these variables.

Table 2.5Descriptive statistics for the control variables

Statistical unit	Country		Agroecological zones	
Variables/parms	Mean	Std.Dev.	Mean	Std.Dev.
AgriPop (1000 persons)	5102.78	6231.06	92813.55	2379152.00
Agriland (1000 of hectares)	43383.62	30922.33	8845.43	13479.61
Tractors	3706.81	6620.29	766.45	1948.94
Livestock (head)	30437367.00	32662856.00	6653983.00	10973499.00
Fertilizers (tonnes)	58329.41	94324.87	12072.48	27384.46
IrrigArea (1000 of hectares)	279.80	514.16	57.27	143.27
Number	10		49	
Sample size	560		2744	

2.5 Results

The first sub-section provides the estimation results at the country level while the second sub-section provides estimation results at the agroecological zones level. All models were estimated using a within estimator[2].

2.5.1 Results at the country level

Tables 2.6 and 2.7 present the benchmark estimation results for model (2.2) without the climate variables. For each dependent variable, the first column presents the estimation results of the model with all inputs. Then, we remove *Tractors*, as this variable contains the most important proportion of missing observations (second column). The estimation results without *Tractors* and *Fertilizers* are in the third column.

Most control variables have, as expected, positive effects on the net index of crop production except agricultural population that has an insignificant effect when both *Tractors* and *Fertilizers* variables are present. Focusing on the results without *Tractors* and *Fertilizers* (column 3), a 1% change in the labor force induces a 0.21% increase in the index of net agricultural production. This impact is also significant for the production of maize (0.79%), millet (0.48%) and sorghum (0.88%). On the other hand, the impact of agricultural labor force is not significant for rice and wheat production. When included, *Fertilizers* and *Tractors* have a positive impact on

[2]The Hausman test results allowed us to choose the fixed effects model over the random effects model.

production. Conversely, irrigation has a negative effect on cereal production if it is used as an input in the presence of *Labor*, *Livestock* and *Fertilizers* but its effect turns out significant and positive without *Tractors* and *Fertilizers* for all productions except rice and wheat. The high proportion of missing observations in both these variables may explain these change of signs when they are included but may also reflect a trade-off between these inputs. Finally, the presence of livestock has a positive and significant effect on the net index of agricultural production and the production of maize, millet, sorghum, rice and wheat when *Fertilizers* and *Tractors* are not included. These results are consistent with those of Kahsay and Hansen (2016) and Eriksen et al. (2008) who point out that 95% of the agricultural activity in the region is highly traditional, non-mechanized and small scale. Table 2.8 presents the

Table 2.6Regression results for benchmark model at the country level

	Dependent variable:								
	log Crops index			log Maize production			log Millet production		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
log AgriPop	−0.024	−0.146	0.210***	−0.495	0.331	0.795***	0.882***	0.201	0.483***
	(0.092)	(−0.146)	(0.062)	(0.374)	(0.220)	(0.191)	(0.232)	(0.158)	(0.128)
log AgriLand	2.104***	2.297	1.935***	1.148	1.126*	0.014	2.526***	2.968***	2.522***
	(0.194)	(2.297)	(0.145)	(0.750)	(0.684)	(0.523)	(0.411)	(0.420)	(0.315)
log Tractors	0.116***			0.436***			−0.079		
	(0.045)			(0.129)			(0.075)		
log Livestock	−0.029	0.174	0.234***	0.310	0.402**	0.837***	0.162	0.690***	0.397***
	(0.064)	(0.174)	(0.036)	(0.208)	(0.185)	(0.106)	(0.112)	(0.109)	(0.070)
log Fertilizers	0.079***	0.092		0.116*	0.160***		0.016	0.017	
	(0.017)	(0.092)		(0.059)	(0.053)		(0.035)	(0.034)	
log IrrigArea	−0.094**	−0.017	0.174***	−0.038	−0.138	0.189**	−0.147*	0.116	0.325***
	(0.044)	(−0.017)	(0.034)	(0.142)	(0.132)	(0.095)	(0.076)	(0.083)	(0.060)
trend	0.016***	0.022	−0.006*	−0.026*	0.011	−0.031***	0.027***	0.006	−0.020***
	(0.005)	(0.022)	(0.003)	(0.014)	(0.011)	(0.008)	(0.009)	(0.008)	(0.006)
trend squared	0.00004	−0.0001	0.0002***	0.001***	0.0001	0.0005***	−0.001***	−0.0005***	−0.0001
	(0.0001)	(−0.0001)	(0.00004)	(0.0002)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Observations	264	353	560	264	353	560	264	353	560
R^2	0.895	0.919	0.889	0.540	0.644	0.683	0.480	0.645	0.570
Adjusted R^2	0.888	0.915	0.886	0.510	0.627	0.674	0.446	0.628	0.558
Note:	*p<0.1; **p<0.05; ***p<0.01								

Table 2.7Regression results for benchmark model at the country level, continued

	Dependent variable:								
	log Sorghum production			log Rice production			log Wheat production		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
log AgriPop	0.492***	0.382	0.885***	−0.544**	0.060	−0.284	−0.683*	−0.073	−0.320
	(0.151)	(0.255)	(0.179)	(0.246)	(0.218)	(0.229)	(0.352)	(0.251)	(0.310)
log AgriLand	1.896***	5.399***	4.129***	−0.696	−0.361	−2.439***	2.366***	3.526***	2.675***
	(0.321)	(0.714)	(0.466)	(0.479)	(0.468)	(0.481)	(0.629)	(0.630)	(0.642)
log Tractors	0.100			0.719***			−0.321***		
	(0.071)			(0.137)			(0.108)		
log Livestock	0.137	1.995***	0.912***	0.009	0.312*	0.380***	−0.308*	0.500***	0.169
	(0.104)	(0.226)	(0.115)	(0.189)	(0.174)	(0.143)	(0.178)	(0.183)	(0.122)
log Fertilizers	0.091***	−0.010		0.132***	0.198***		0.055	−0.034	
	(0.031)	(0.060)		(0.042)	(0.047)		(0.046)	(0.048)	
log IrrigArea	−0.190***	−0.095	0.353***	−0.033	−0.004	0.172	0.214*	0.142	0.061
	(0.068)	(0.163)	(0.101)	(0.123)	(0.124)	(0.111)	(0.122)	(0.136)	(0.127)
trend	−0.007	0.065***	−0.017*	−0.078***	−0.031***	0.054***	0.036***	0.003	0.027***
	(0.009)	(0.020)	(0.010)	(0.018)	(0.011)	(0.012)	(0.012)	(0.012)	(0.011)
trend squared	0.00001	−0.002***	−0.0004***	0.001***	0.001***	0.00001	−0.0002	−0.0004**	−0.0002
	(0.0001)	(0.0003)	(0.0001)	(0.0002)	(0.0001)	(0.0001)	(0.0002)	(0.0002)	(0.0001)
Observations	264	353	560	264	353	560	264	353	560
R^2	0.576	0.596	0.526	0.536	0.511	0.574	0.212	0.385	0.338
Adjusted R^2	0.548	0.577	0.513	0.506	0.487	0.562	0.161	0.356	0.320
Note:	*p<0.1; **p<0.05; ***p<0.01								

results of the estimation results for model (2.2). To save space, we do not present the estimation results including *Tractors* and *Fertilizers*[3]. For each dependent variable, the first column displays the estimation results of model (2.2) including the climate variables while the second column further interacts the climate variables with the country fixed effects. We first find that mean temperature has contrasting effects: it has a positive and significant impact on millet and sorghum production, which can be explained by the fact that these cereals, have, with rice, an optimal temperature growth above 28°C (see Table 2.16 in the appendix 2.7). The impact is insignificant for the net index of production, which probably reflects a cancelling out of the contrasting impacts of temperature for the various cereals. It is also insignificant for wheat and significant and negative for maize and rice. For maize, the results is consistent as the optimum temperature is 25°C while the average temperature in the Sahel is temperature is 28°C, already above the optimum. The result is more surprising for rice since its optimum is 30-34°C and needs further investigation. Temperature variability mostly has insignificant effects on all crop productions. Second, mean precipitations during the rainy season has a positive impact on total production, maize, millet and sorghum and an insignificant impact on rice and wheat. Variability of rainfall during the rainy season has positive and significant effects on maize and rice production, but does not have a significant impact on the net index of agricultural production and the other crops.

Next, we include interactions between climate variables and countries to further investigate possible heterogeneity of the impacts of temperature and precipitation. The results, displayed in the second column for each crop, indeed show the presence of marked heterogeneity both between countries and between crops. For instance, for the net index of agricultural production, the impact of temperature is insignificant in Niger and Nigeria; significant and positive for Chad, Ethiopia, Mali and Mauritania and significant and negative for Burkina Faso, Senegal, Somalia and Sudan. The impact of precipitation is not significant for Burkina Faso and Ethiopia, significant and positive for Chad, Mali, Mauritania, Niger and Nigeria and significant and negative for Somalia and Sudan. The specificities of agriculture together with climate characteristics in each country might explain these disparities, such as the short duration of the rains in Somalia despite the plurality of rainy seasons. Second, a vast amount of heterogeneity arises when looking at these impacts by countries for the various crops. We do not detail all the results but provide insights for some of the findings. For instance, the results of column 6 of Table 2.8 show that precipitation during the rainy season increases millet production to different degrees in most countries except Burkina and Nigeria where the effect is not significant. Technically, this cereal is known for its water needs (see Table 2.16) and these are countries where mean precipitation are already important. On the other hand, the impact of temperature varies widely between countries, but it strongly increases millet production in Ethiopia, where mean temperature is among the lowest of our sample, and Mali. In Chad, average temperature and average rainfall during the rainy season

[3] The results are available upon request.

have a positive and significant impact on cereal production and maize, millet and sorghum production while average temperature has a negative and very significant effect on the production of rice and wheat. The effect of rainfall is positive and weakly significant on rice production but insignificant for wheat. Indeed, climatic conditions are favorable (see Table 2.16) for maize, sorghum and millet crops in Chad whereas rice and wheat are low-yielding cereals and domestic demand is met by imports.

Table 2.8Regression results for the model with climatic variables at the country level

	log Crops index		log Maize production		log Millet production		log Sorgo production		log Rice production		log Wheat production	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
log AgriPop	0.185***	0.133**	0.813***	0.898***	0.628***	0.414**	0.742***	0.291	−0.231	0.110	−0.722*	−0.231
	(0.063)	(0.064)	(0.193)	(0.212)	(0.149)	(0.180)	(0.184)	(0.182)	(0.232)	(0.271)	(0.408)	(0.514)
log AgriLand	1.997***	2.143***	0.181	1.438***	2.706***	2.522***	4.121***	3.684***	−2.158***	−2.010***	0.824	−0.042
	(0.141)	(0.146)	(0.524)	(0.546)	(0.320)	(0.371)	(0.475)	(0.468)	(0.490)	(0.532)	(0.857)	(0.837)
log Livestock	0.221***	0.240***	0.785***	0.648***	0.533***	0.470***	0.771***	0.554***	0.345**	0.248	0.291*	0.316*
	(0.036)	(0.036)	(0.108)	(0.115)	(0.089)	(0.102)	(0.116)	(0.106)	(0.142)	(0.157)	(0.161)	(0.175)
log IrrigArea	0.173***	0.072**	0.137	−0.078	0.302***	0.206***	0.413***	0.142*	0.095	0.042	0.639***	0.654***
	(0.034)	(0.032)	(0.094)	(0.099)	(0.066)	(0.064)	(0.103)	(0.076)	(0.111)	(0.114)	(0.170)	(0.197)
log mean temperature	0.827		−3.860**		4.558***		9.905***		−6.531**		−3.021	
	(0.680)		(1.791)		(1.601)		(2.852)		(2.604)		(3.927)	
log mean precipitation	0.347***		0.288**		0.814***		0.819***		−0.111		0.022	
	(0.065)		(0.119)		(0.135)		(0.182)		(0.234)		(0.273)	
log mean temp Burkina		−2.904**		−3.819		−5.629**		−18.109***		−12.470**		
		(1.153)		(3.425)		(2.520)		(4.847)		(4.989)		
log mean temp Chad		2.575**		13.578***		2.832		3.237		−13.819***		−39.055***
		(1.019)		(3.486)		(3.071)		(3.156)		(4.250)		(10.160)
log mean temp Ethiopia		5.385***		−2.474		19.992***		58.138***		−0.242		9.665***
		(0.892)		(1.996)		(2.218)		(8.167)		(4.170)		(3.528)
log mean temp Mali		13.887***		20.515***		8.766***		0.040		3.855		5.686
		(2.809)		(5.394)		(3.393)		(4.141)		(4.491)		(7.303)
log mean temp Mauritania		11.443***		−6.679		−4.566		5.039		40.405***		37.287***
		(1.872)		(4.675)		(5.899)		(5.335)		(10.250)		(9.807)
log mean temp Niger		0.289		−33.769***		1.622		−7.868*		−12.822***		4.065
		(1.331)		(8.587)		(2.503)		(4.172)		(4.456)		(9.316)
log mean temp Nigeria		−2.182		4.735		−9.640*		−17.307***		12.356**		−0.024
		(1.347)		(5.580)		(4.955)		(4.482)		(5.422)		(7.942)
log mean temp Senegal		−5.013***		−4.457		2.795		−0.325		−20.862***		
		(1.826)		(4.880)		(3.133)		(3.180)		(6.128)		
log mean temp Somalia		−7.728***		−14.384***				3.141		−19.377*		
		(2.293)		(4.374)				(4.361)		(11.478)		
log mean temp Sudan		−5.709***		−17.060***				−4.967*		−7.419		8.714*
		(0.990)		(3.548)				(2.760)		(5.136)		(4.463)
log mean prec Burkina		0.090		1.092***		0.435		−0.248		0.237		
		(0.138)		(0.381)		(0.280)		(0.467)		(0.556)		
log mean prec Chad		0.774***		1.219***		1.304***		1.309***		0.657*		−0.920
		(0.147)		(0.309)		(0.269)		(0.281)		(0.362)		(0.890)
log mean prec Ethiopia		0.178		0.006		0.247		−1.692		0.128		0.162
		(0.166)		(0.142)		(0.207)		(1.170)		(0.419)		(0.124)
log mean prec Mali		0.825***		1.998***		0.778**		0.241		1.885***		1.196*
		(0.281)		(0.589)		(0.354)		(0.459)		(0.466)		(0.718)
log mean prec Mauritania		0.556***		0.403*		1.146***		1.187***		−0.292		0.480
		(0.100)		(0.214)		(0.272)		(0.222)		(0.463)		(0.333)
log mean prec Niger		0.378***		−2.344***		0.355*		0.134		−1.295***		0.099
		(0.115)		(0.786)		(0.213)		(0.347)		(0.403)		(0.808)
log mean prec Nigeria		0.307*		1.216*		−0.021		−0.375		0.912		−0.202
		(0.157)		(0.724)		(0.463)		(0.481)		(0.577)		(0.522)
log mean prec Senegal		0.688***		0.468		0.582***		0.816***		0.894**		
		(0.143)		(0.323)		(0.168)		(0.208)		(0.383)		
log mean prec Somalia		−0.250**		−0.049				0.363*		−0.678		
		(0.115)		(0.212)				(0.201)		(0.558)		
log mean prec Sudan		−0.336*		−0.706**				0.413*		0.723		0.066
		(0.174)		(0.302)				(0.234)		(1.210)		(0.390)
log CV temperature	0.044	0.022	−0.286	0.028	−0.012	0.118	−0.276	−0.074	−0.064	−0.078	0.088	0.189
	(0.031)	(0.025)	(0.175)	(0.200)	(0.171)	(0.158)	(0.245)	(0.188)	(0.198)	(0.193)	(0.255)	(0.294)
log CV precipitation	0.023	0.009	0.371**	0.251*	−0.122	−0.118	−0.007	0.115	0.198	0.218*	0.260	0.156
	(0.036)	(0.029)	(0.148)	(0.147)	(0.124)	(0.112)	(0.208)	(0.174)	(0.129)	(0.124)	(0.240)	(0.232)
trend	0.001	0.005	−0.022***	−0.013	−0.009	0.003	−0.003	0.025**	0.058***	0.056***	0.045***	0.027*
	(0.003)	(0.003)	(0.008)	(0.008)	(0.007)	(0.008)	(0.011)	(0.010)	(0.012)	(0.013)	(0.014)	(0.015)
trend squared	0.0001*	0.0001	0.0004***	0.0003***	−0.0005***	−0.0005***	−0.001***	−0.001***	0.00004	−0.00004	−0.0003	−0.0002
	(0.00004)	(0.00004)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0002)	(0.0001)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
Observations	550	550	550	550	440	440	550	550	550	550	385	385
R^2	0.894	0.932	0.684	0.746	0.646	0.718	0.541	0.731	0.578	0.644	0.451	0.564

Note: *p<0.1; **p<0.05; ***p<0.01

Next, we include interactions between climate variables and countries in order to take into account the heterogeneity between the different countries (Tables 2.9 and 2.10). The climatic conditions are not identical for all countries, despite the fact that these countries are characterized by high climatic variability. The average temperature has insignificant effects in Burkina Faso, Nigeria, Senegal and Somalia on the net index of agricultural production, production of maize and millet.
During the rainy season, optimal temperature plays a very important role in the metabolism of cereals. However, these effects have marginal impacts on the three outputs. In addition, the effects are enormous for cereals sorghum, rice and wheat because the associated parameters are negative and very significant. On the other hand, the average temperature has positive but insignificant effects for Chad, Ethiopia, Mali, Mauritania and Niger for the five cereals. In these countries, temperature does not contribute to greatly improving agricultural production. In addition, the parameter associated with temperature becomes positive and very significant for Chad, Mauritania and Ethiopia without the use of fertilizers. We also find that the parameters become negative and very significant in the presence of fertilizers for Senegal, Somalia, Senegal, Sudan and Burkina.
The intuition behind these results brings us back to the question about the choice of uses of fertilizer inputs. These inputs must be used in the case where the farmers face a climatic problem ie in the absence of water and optimal temperature. This is not the case in these areas where farmers are not aware of the use of fertilizers and other organic materials. They tend to use fertilizers even under normal weather conditions.
Average rainfall has negative and insignificant effects for Sudan and Somalia for all outputs. These effects become still negative and significant without the use of fertilizers. On the other hand, the parameters are positive and significant for Burkina Faso, Chad, Ethiopia, Mali, Mauritania, Niger and Senegal. The parameters become positive and very significant without the use of inputs for most specifications except in Niger and Nigeria for some cereals (maize, sorghum and wheat).
These results show and confirm the idea that countries are very heterogeneous even if they are characterized by cyclical declines in agricultural production and food insecurity.

Table 2.9Regression results for model with climatic variables at the country level

	log Crops index				log Maize production				log Millet production			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
log AgriPop	−0.143**	−0.155	0.185***	0.133**	0.406*	0.487**	0.813***	0.898***	0.297*	0.248	0.628***	0.414**
	(0.064)	(−0.155)	(0.063)	(0.064)	(0.221)	(0.245)	(0.193)	(0.212)	(0.166)	(0.187)	(0.149)	(0.180)
log AgriLand	2.292***	1.980	1.997***	2.143***	1.110	1.577**	0.181	1.438***	3.031***	2.833***	2.706***	2.522***
	(0.163)	(1.980)	(0.141)	(0.146)	(0.675)	(0.729)	(0.524)	(0.546)	(0.403)	(0.473)	(0.320)	(0.371)
log Livestock	0.189***	0.209	0.221***	0.240***	0.429**	0.358*	0.785***	0.648***	0.694***	0.349***	0.533***	0.470***
	(0.055)	(0.209)	(0.036)	(0.036)	(0.188)	(0.196)	(0.108)	(0.115)	(0.117)	(0.112)	(0.089)	(0.102)
log Fertilizers	0.091***	0.078			0.158***	0.134***			0.040	0.018		
	(0.015)	(0.078)			(0.052)	(0.051)			(0.035)	(0.032)		
log IrrigArea	−0.015	−0.024	0.173***	0.072**	−0.180	−0.220	0.137	−0.078	0.128	0.092	0.302***	0.206***
	(0.040)	(−0.024)	(0.034)	(0.032)	(0.133)	(0.135)	(0.094)	(0.099)	(0.086)	(0.079)	(0.066)	(0.064)
log mean temperature	1.841**		0.827		−3.099		−3.860**		4.332**		4.558***	
	(0.738)		(0.680)		(2.155)		(1.791)		(1.796)		(1.601)	
log mean precipitation	0.389***		0.347***		0.233		0.288**		0.730***		0.814***	
	(0.074)		(0.065)		(0.168)		(0.119)		(0.162)		(0.135)	
log mean temp Burkina		−2.278		−2.904**		−1.459		−3.819		−1.887		−5.629**
		(−2.278)		(1.153)		(4.003)		(3.425)		(2.416)		(2.520)
log mean temp Chad		0.140		2.575**		6.346		13.578***		−7.211**		2.832
		(0.140)		(1.019)		(5.076)		(3.486)		(3.644)		(3.071)
log mean temp Ethiopia		5.541		5.385***		0.402		−2.474		20.605***		19.992***
		(5.541)		(0.892)		(2.003)		(1.996)		(2.494)		(2.218)
log mean temp Mali		8.600		13.887***		3.062		20.515***		1.758		8.766***
		(8.600)		(2.809)		(6.389)		(5.394)		(3.925)		(3.393)
log mean temp Mauritania		7.707		11.443***		−6.425		−6.679		−1.234		−4.566
		(7.707)		(1.872)		(10.032)		(4.675)		(8.193)		(5.899)
log mean temp Niger		4.143		0.289		−32.234**		−33.769***		−2.944		1.622
		(4.143)		(1.331)		(14.086)		(8.587)		(3.317)		(2.503)
log mean temp Nigeria		−2.564		−2.182		−2.113		4.735		−8.523		−9.640*
		(−2.564)		(1.347)		(8.088)		(5.580)		(8.979)		(4.955)
log mean temp Senegal		−1.344		−5.013***		−8.569		−4.457		1.268		2.795
		(−1.344)		(1.826)		(8.084)		(4.880)		(3.939)		(3.133)
log mean temp Somalia		−8.456		−7.728***		−11.442		−14.384***				
		(−8.456)		(2.293)		(9.038)		(4.374)				
log mean temp Sudan		−5.280		−5.709***		−18.982***		−17.060***				
		(−5.280)		(0.990)		(7.313)		(3.548)				
log mean prec Burkina		0.319		0.090		1.432***		1.092***		0.677**		0.435
		(0.319)		(0.138)		(0.465)		(0.381)		(0.266)		(0.280)
log mean prec Chad		0.521		0.774***		0.880*		1.219***		0.699**		1.304***
		(0.521)		(0.147)		(0.482)		(0.309)		(0.348)		(0.269)
log mean prec Ethiopia		0.241		0.178		0.122		0.006		0.271		0.247
		(0.241)		(0.166)		(0.128)		(0.142)		(0.220)		(0.207)
log mean prec Mali		0.785		0.825***		1.203*		1.998***		0.391		0.778**
		(0.785)		(0.281)		(0.685)		(0.589)		(0.409)		(0.354)
log mean prec Mauritania		0.478		0.556***		0.187		0.403*		1.593***		1.146***
		(0.478)		(0.100)		(0.540)		(0.214)		(0.440)		(0.272)
log mean prec Niger		0.688		0.378***		−2.770***		−2.344***		0.112		0.355*
		(0.688)		(0.115)		(1.075)		(0.786)		(0.276)		(0.213)
log mean prec Nigeria		0.186		0.307*		0.702		1.216*		−0.417		−0.021
		(0.186)		(0.157)		(0.858)		(0.724)		(0.659)		(0.463)
log mean prec Senegal		0.623		0.688***		0.935*		0.468		0.642***		0.582***
		(0.623)		(0.143)		(0.494)		(0.323)		(0.218)		(0.168)
log mean prec Somalia		−0.249		−0.250**		−0.273		−0.049				
		(−0.249)		(0.115)		(0.345)		(0.212)				
log mean prec Sudan		−0.432		−0.336*		−0.378		−0.706**				
		(−0.432)		(0.174)		(0.423)		(0.302)				
log CV temperature	0.048	0.020	0.044	0.022	−0.286	−0.095	−0.286	0.028	0.043	0.127	−0.012	0.118
	(0.032)	(0.020)	(0.031)	(0.025)	(0.204)	(0.270)	(0.175)	(0.200)	(0.219)	(0.198)	(0.171)	(0.158)
log CV precipitation	−0.033	−0.006	0.023	0.009	0.357*	0.312	0.371**	0.251*	−0.141	−0.121	−0.122	−0.118
	(0.038)	(−0.006)	(0.036)	(0.029)	(0.189)	(0.191)	(0.148)	(0.147)	(0.129)	(0.112)	(0.124)	(0.112)
trend	0.025***	0.026	0.001	0.005	0.018	0.016	−0.022***	−0.013	0.009	0.018**	−0.009	0.003
	(0.004)	(0.026)	(0.003)	(0.003)	(0.011)	(0.012)	(0.008)	(0.008)	(0.009)	(0.009)	(0.007)	(0.008)
trend squared	−0.0002***	−0.0001	0.0001*	0.0001	0.00002	0.0001	0.0004***	0.0003***	−0.001***	−0.001***	−0.0005***	−0.0005***
	(0.00005)	(−0.0001)	(0.00004)	(0.00004)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Observations	353	353	550	550	353	353	550	550	311	311	440	440
R^2	0.928	0.943	0.894	0.932	0.653	0.698	0.684	0.746	0.700	0.784	0.646	0.718

Note: *p<0.1; **p<0.05; ***p<0.01

Table 2.10Regression results for model with climatic variables at the country level, continued

	log Sorghum production					log Rice production			log Wheat production			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
log AgriPop	0.272	−0.075	0.742***	0.291	0.118	0.394	−0.231	0.110	−0.467	−0.095	−0.722*	−0.231
	(0.256)	(0.230)	(0.184)	(0.182)	(0.218)	(0.246)	(0.232)	(0.271)	(0.299)	(0.364)	(0.408)	(0.514)
log AgriLand	5.404***	4.015***	4.121***	3.684***	−0.205	0.162	−2.158***	−2.010***	2.054**	2.609**	0.824	−0.042
	(0.710)	(0.629)	(0.475)	(0.468)	(0.473)	(0.529)	(0.490)	(0.532)	(0.966)	(1.040)	(0.857)	(0.837)
log Livestock	1.801***	1.117***	0.771***	0.554***	0.317*	0.188	0.345**	0.248	0.850***	0.631**	0.291*	0.316*
	(0.224)	(0.191)	(0.116)	(0.106)	(0.173)	(0.184)	(0.142)	(0.157)	(0.221)	(0.253)	(0.161)	(0.175)
log Fertilizers	−0.007	0.013			0.175***	0.168***			0.055	0.036		
	(0.059)	(0.044)			(0.046)	(0.044)			(0.072)	(0.074)		
log IrrigArea	−0.031	−0.116	0.413***	0.142*	0.016	−0.006	0.095	0.042	0.973***	0.859***	0.639***	0.654***
	(0.160)	(0.122)	(0.103)	(0.076)	(0.120)	(0.124)	(0.111)	(0.114)	(0.180)	(0.190)	(0.170)	(0.197)
log mean temperature	12.011***		9.905***		−2.894		−6.531**		4.531		−3.021	
	(4.011)		(2.852)		(2.375)		(2.604)		(2.828)		(3.927)	
log mean precipitation	0.742**		0.819***		−0.185		−0.111		−0.108		0.022	
	(0.291)		(0.182)		(0.202)		(0.234)		(0.189)		(0.273)	
log mean temp Burkina		−18.204***		−18.109***		−12.122***		−12.470**				
		(6.119)		(4.847)		(3.728)		(4.989)				
log mean temp Chad		−6.599		3.237		−1.094		−13.819***		−4.193		−39.055***
		(4.685)		(3.156)		(5.933)		(4.250)		(7.491)		(10.160)
log mean temp Ethiopia		55.780***		58.138***		−0.018		−0.242		7.673***		9.665***
		(8.081)		(8.167)		(3.622)		(4.170)		(2.721)		(3.528)
log mean temp Mali		−1.562		0.040		2.186		3.855		10.086		5.686
		(5.624)		(4.141)		(5.432)		(4.491)		(6.566)		(7.303)
log mean temp Mauritania		5.970		5.039		16.288***		40.405***		6.809		37.287***
		(8.442)		(5.335)		(5.861)		(10.250)		(6.410)		(9.807)
log mean temp Niger		0.433		−7.868*		−15.688**		−12.822***		−6.257		4.065
		(6.645)		(4.172)		(7.876)		(4.456)		(13.975)		(9.316)
log mean temp Nigeria		−11.297		−17.307***		−6.962		12.356**		12.214		−0.024
		(7.693)		(4.482)		(5.359)		(5.422)		(10.304)		(7.942)
log mean temp Senegal		3.224		−0.325		−3.484		−20.862***				
		(6.256)		(3.180)		(4.670)		(6.128)				
log mean temp Somalia		−20.578***		3.141		−34.336**		−19.377*				
		(5.585)		(4.361)		(16.393)		(11.478)				
log mean temp Sudan		−2.601		−4.967*		−0.918		−7.419		7.738		8.714*
		(8.533)		(2.760)		(11.102)		(5.136)		(9.366)		(4.463)
log mean prec Burkina		0.527		−0.248		−0.812**		0.237				
		(0.634)		(0.467)		(0.407)		(0.556)				
log mean prec Chad		0.760*		1.309***		0.984*		0.657*		0.171		−0.920
		(0.448)		(0.281)		(0.563)		(0.362)		(0.711)		(0.890)
log mean prec Ethiopia		−1.339		−1.692		−0.277		0.128		0.127		0.162
		(1.041)		(1.170)		(0.336)		(0.419)		(0.133)		(0.124)
log mean prec Mali		1.128*		0.241		0.345		1.885***		0.571		1.196*
		(0.628)		(0.459)		(0.574)		(0.466)		(0.667)		(0.718)
log mean prec Mauritania		1.337***		1.187***		−0.222		−0.292		−0.320		0.480
		(0.392)		(0.222)		(0.320)		(0.463)		(0.265)		(0.333)
log mean prec Niger		0.459		0.134		−1.960***		−1.295***		−1.208		0.099
		(0.542)		(0.347)		(0.616)		(0.403)		(1.042)		(0.808)
log mean prec Nigeria		−1.799***		−0.375		0.816		0.912		−0.544		−0.202
		(0.696)		(0.481)		(0.526)		(0.577)		(0.643)		(0.522)
log mean prec Senegal		1.079***		0.816***		0.597**		0.894**				
		(0.399)		(0.208)		(0.280)		(0.383)				
log mean prec Somalia		−0.182		0.363*		−0.871		−0.678				
		(0.204)		(0.201)		(0.630)		(0.558)				
log mean prec Sudan		0.470		0.413*		−0.438		0.723		0.215		0.066
		(0.452)		(0.234)		(1.558)		(1.210)		(0.510)		(0.390)
log CV temperature	−0.105	−0.129	−0.276	−0.074	0.253	0.253	−0.064	−0.078	0.573**	0.463	0.088	0.189
	(0.395)	(0.293)	(0.245)	(0.188)	(0.191)	(0.195)	(0.198)	(0.193)	(0.224)	(0.307)	(0.255)	(0.294)
log CV precipitation	−0.011	0.045	−0.007	0.115	0.192*	0.250**	0.198	0.218*	−0.075	−0.019	0.260	0.156
	(0.277)	(0.232)	(0.208)	(0.174)	(0.113)	(0.116)	(0.129)	(0.124)	(0.211)	(0.222)	(0.240)	(0.232)
trend	0.065***	0.090***	−0.003	0.025**	−0.030***	−0.036***	0.058***	0.056***	−0.012	−0.016	0.045***	0.027*
	(0.020)	(0.019)	(0.011)	(0.010)	(0.012)	(0.012)	(0.012)	(0.013)	(0.013)	(0.015)	(0.014)	(0.015)
trend squared	−0.002***	−0.002***	−0.001***	−0.001***	0.001***	0.001***	0.00004	−0.00004	−0.0005***	−0.0004**	−0.0003	−0.0002
	(0.0003)	(0.0003)	(0.0002)	(0.0001)	(0.0001)	(0.0001)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
Observations	353	353	550	550	353	353	550	550	249	249	385	385
R^2	0.611	0.767	0.541	0.731	0.529	0.586	0.578	0.644	0.590	0.609	0.451	0.564

Note: *p<0.1; **p<0.05; ***p<0.01

2.5.2 Results at the agroecological zone level

The estimation results at the agroecological zone level including only the control variables are displayed in Tables 2.11 and 2.12. Overall, the results are similar to those obtained previously at the country level for the control variables except for *Agricultural Population*, the impact of which is positive without the two inputs for maize whereas for rice and wheat, it remains significantly negative. Agriculture is mostly traditional and is practiced on small agricultural areas: at the level of small farms, it is not efficient to mobilize a large number of labor for rice. *Irrigation* has a positive and very significant impact for all five cereals and the net index of agricultural production. Finally, we confirm that the presence of *Livestock* is an essential factor contributing to production.

The estimation results including climatic variables are displayed in Table 2.13 excluding *Tractors* and *Fertilizers*[4]. When included without being interacted with the agroecological zone fixed effects (first column for each depdendent variable), some changes compared to the results obtained at the country level are in order. Mean temperature has, as previously, a significant and positive impact on sorghum production but also on wheat production (the overall impact for wheat was insignificant at the country level). The impact is again negative for maize and insignificant for the net index of production. For millet and rice production, the impact turns out insignificant. Mean precipitation mostly has a positive impact for all crops while temperature variability now has a strong negative impact of sorghum production. The results for millet and for rice are similar to the previous ones obtained at a country level.

Table 2.11Regression results for benchmark model at the agroecological zone level

	Dependent variable:								
	log Crops index			log Maize production			log Millet production		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
log AgriPop	−0.046	−0.062	0.087***	−0.527***	0.211*	0.597***	1.001***	0.594***	0.821***
	(0.041)	(−0.062)	(0.030)	(0.167)	(0.111)	(0.097)	(0.099)	(0.084)	(0.063)
log AgriLand	2.196***	2.409	2.225***	1.450***	1.566***	0.569**	2.731***	3.179***	2.548***
	(0.082)	(2.409)	(0.063)	(0.326)	(0.303)	(0.230)	(0.171)	(0.178)	(0.138)
log Tractors	0.124***			0.397***			−0.059*		
	(0.021)			(0.061)			(0.034)		
log Livestock	−0.016	0.190	0.242***	0.304***	0.404***	0.723***	0.215***	0.801***	0.426***
	(0.030)	(0.190)	(0.016)	(0.099)	(0.089)	(0.050)	(0.050)	(0.051)	(0.030)
log Fertilizers	0.065***	0.079		0.135***	0.184***		−0.028**	−0.023	
	(0.008)	(0.079)		(0.030)	(0.026)		(0.013)	(0.015)	
log IrrigArea	−0.066***	0.014	0.250***	−0.048	−0.159**	0.156***	−0.164***	0.152***	0.311***
	(0.022)	(0.014)	(0.016)	(0.069)	(0.065)	(0.046)	(0.035)	(0.041)	(0.029)
trend	0.014***	0.019	−0.004***	−0.020***	0.017***	−0.017***	0.027***	−0.003	−0.021***
	(0.003)	(0.019)	(0.001)	(0.007)	(0.005)	(0.004)	(0.004)	(0.004)	(0.002)
trend squared	0.00004	−0.0001	0.0001***	0.0005***	−0.00001	0.0003***	−0.001***	−0.001***	−0.0002***
	(0.00003)	(−0.0001)	(0.00002)	(0.0001)	(0.0001)	(0.00005)	(0.0001)	(0.00005)	(0.00003)
Observations	1,166	1,645	2,464	1,166	1,645	2,464	1,166	1,645	2,464
R^2	0.902	0.938	0.920	0.537	0.683	0.694	0.540	0.746	0.712
Adjusted R^2	0.899	0.936	0.918	0.519	0.673	0.688	0.522	0.738	0.706
Note:							*p<0.1; **p<0.05; ***p<0.01		

The estimation results of the specifications with interactions between climatic variables and agroecological zones are projected on maps displaying the marginal effects of temperature and precipitation on the net index (Figures 2.6 and 2.7), maize

[4]Complete results including these two variables are available upon request.

Table 2.12Regression results for benchmark model at the agroecological zone, continued

	Dependent variable:								
	log Sorghum production			log Rice production			log Wheat production		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
log AgriPop	0.523***	0.877***	1.126***	−0.528***	−0.016	−0.485***	−0.742***	0.016	−0.613***
	(0.064)	(0.147)	(0.103)	(0.109)	(0.104)	(0.100)	(0.156)	(0.125)	(0.123)
log AgriLand	2.107***	5.510***	4.820***	−0.535***	−0.142	−1.535***	2.262***	3.350***	3.211***
	(0.130)	(0.339)	(0.233)	(0.202)	(0.199)	(0.191)	(0.275)	(0.284)	(0.249)
log Tractors	0.131***			0.707***			−0.311***		
	(0.033)			(0.065)			(0.050)		
log Livestock	0.179***	2.414***	1.042***	0.058	0.293***	0.675***	−0.306***	0.625***	0.289***
	(0.048)	(0.108)	(0.059)	(0.090)	(0.081)	(0.063)	(0.084)	(0.087)	(0.050)
log Fertilizers	0.042***	−0.094***		0.106***	0.194***		0.027	−0.065**	
	(0.012)	(0.034)		(0.021)	(0.023)		(0.025)	(0.026)	
log IrrigArea	−0.160***	0.020	0.569***	−0.019	0.045	0.278***	0.250***	0.273***	0.387***
	(0.032)	(0.091)	(0.058)	(0.061)	(0.061)	(0.049)	(0.059)	(0.070)	(0.057)
trend	−0.010**	0.075***	−0.011*	−0.075***	−0.031***	0.023***	0.037***	−0.002	0.032***
	(0.004)	(0.009)	(0.006)	(0.008)	(0.005)	(0.005)	(0.006)	(0.005)	(0.004)
trend squared	−0.00002	−0.003***	−0.001***	0.001***	0.001***	0.0002***	−0.0002**	−0.0004***	−0.0005***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Observations	1,166	1,645	2,464	1,166	1,645	2,464	1,166	1,645	2,464
R^2	0.627	0.680	0.600	0.529	0.537	0.600	0.215	0.500	0.512
Adjusted R^2	0.613	0.670	0.591	0.511	0.522	0.592	0.184	0.485	0.502
Note:									*p<0.1; **p<0.05; ***p<0.01

(Figures 2.8 and 2.9), millet (Figures 2.10 and 2.11), sorghum (Figures 2.12 and 2.13), rice (Figures 2.14 and 2.15) and wheat (2.16 and 2.17). Agroecological zones in "white" are those associated to non significant climate parameters. All agroecological zones associated with positive (resp. negative) and significant coefficients are displayed in red (resp. blue). The results show further heterogeneity between agroecological zones within the same country.

Table 2.13Regression results for the model with climatic variables at the agroecological zone level

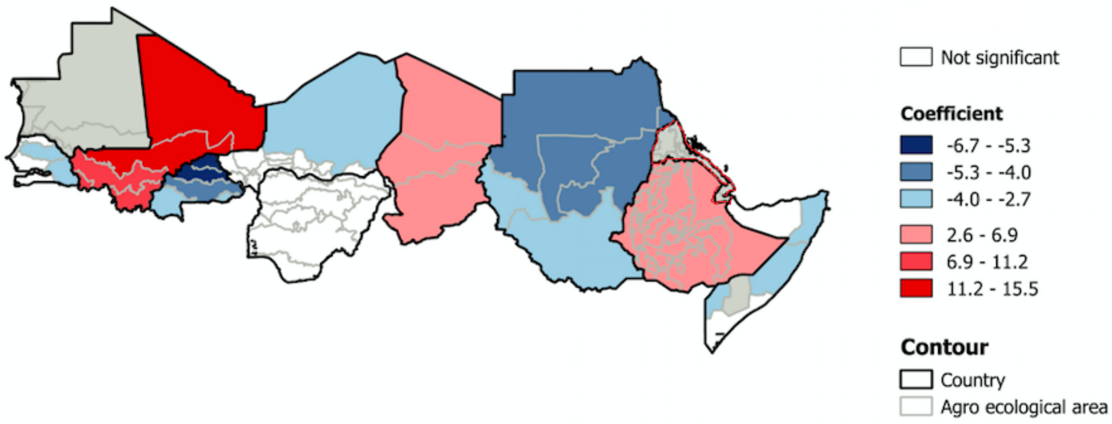
	Dependent variable:											
	log Crops index		log Maize production		log Millet production		log Sorghum index		log Rice production		log Wheat production	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
log AgriPop	0.172***	0.250***	0.672***	0.905***	0.073*	0.309***	−0.428***	0.121**	0.365***	0.513***	−0.515***	−0.191**
	(0.022)	(0.025)	(0.069)	(0.073)	(0.040)	(0.041)	(0.069)	(0.052)	(0.062)	(0.070)	(0.088)	(0.096)
log AgriLand	2.342***	2.402***	0.912***	2.076***	2.043***	1.736***	3.331***	2.680***	−0.895***	−0.907***	2.714***	1.215***
	(0.059)	(0.059)	(0.230)	(0.234)	(0.144)	(0.151)	(0.216)	(0.159)	(0.190)	(0.199)	(0.253)	(0.248)
log Livestock	0.273***	0.276***	0.744***	0.580***	0.077**	0.154***	0.322***	0.370***	1.061***	0.944***	0.330***	0.305***
	(0.011)	(0.013)	(0.042)	(0.046)	(0.031)	(0.036)	(0.040)	(0.033)	(0.035)	(0.044)	(0.044)	(0.052)
log IrrigArea	0.230***	0.145***	0.124***	−0.119**	0.411***	0.164***	0.806***	0.336***	0.133***	0.158***	0.395***	0.413***
	(0.016)	(0.016)	(0.044)	(0.048)	(0.028)	(0.025)	(0.059)	(0.042)	(0.049)	(0.050)	(0.054)	(0.056)
log mean temperature	−0.068		−3.061***		0.503		5.433***		1.063		5.359***	
	(0.250)		(0.761)		(0.546)		(1.306)		(0.954)		(0.910)	
log mean precipitation	0.122***		0.137***		0.209***		0.103*		0.168***		−0.011	
	(0.013)		(0.038)		(0.027)		(0.056)		(0.061)		(0.044)	
log CV temperature	0.032***	0.018*	0.052*	0.027	0.040*	0.025	−0.168***	−0.164***	0.082*	0.039	0.014	0.014
	(0.012)	(0.011)	(0.031)	(0.029)	(0.024)	(0.021)	(0.058)	(0.051)	(0.045)	(0.047)	(0.035)	(0.034)
log CV precipitation	0.0002	0.010	0.065**	0.082***	−0.020	0.008	0.042	0.106***	0.118***	0.128***	0.033	−0.007
	(0.010)	(0.009)	(0.030)	(0.029)	(0.020)	(0.017)	(0.048)	(0.038)	(0.038)	(0.038)	(0.034)	(0.032)
trend	0.001	0.001	0.004*	0.004*	−0.002	−0.003*	0.003	0.003	0.0002	0.003	−0.002	−0.00000
	(0.001)	(0.001)	(0.003)	(0.002)	(0.002)	(0.002)	(0.004)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
trend squared	−0.00002	−0.00002	−0.0001	−0.0001*	0.00002	0.0001**	−0.00005	0.00000	0.00002	−0.00002	0.00003	0.00002
	(0.00001)	(0.00001)	(0.00004)	(0.00004)	(0.00003)	(0.00003)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.00005)
Heterogenous coefficients for temperature and precipitation	no	yes	no	yes	no	yes	no	yes	no	yes	no	yes
Observations	2,464	2,464	2,464	2,464	2,464	2,464	2,464	2,464	2,464	2,464	2,464	2,464
R^2	0.921	0.940	0.696	0.761	0.674	0.793	0.547	0.744	0.599	0.635	0.506	0.616
Adjusted R^2	0.919	0.936	0.689	0.747	0.667	0.780	0.537	0.728	0.590	0.613	0.495	0.593

Note: *p<0.1; **p<0.05; ***p<0.01

The impact of temperature on the net production index (Figure 2.6) is positive and significant for all agroecological zones of Mali where the impact is particularly strong as the production structure is driven by maize, millet and sorghum, which are cereals with a high temperature optimum. The impact is also positive for Chad and Ethiopia, in which the desert area has a very low average temperature so that any rise would be beneficial, all the more that desert areas can be cultivated thanks to new agricultural techniques. Conversely, the effect is significant and slightly negative for some agroecological zones of Sudan (*Desert* and *Semi-arid desert*, *Flood and Basin Irrigated* and *Poor and Dense Savannah*), negative and highly significant in Burkina (*North Sahel*, *South Sahelian*, *South Sudanian and North Soudanian*), Sudan (*Jebel Marra and Dense Savannah and Equatorial*), Somalia (*Bari* and *Central Costal and Southern Somalia*), Senegal (*Bassin Arachidier and Center East and South East*). In most these areas, the land is not arable and temperature is already very high during the growing season (see figure 2.5). The insignificant global effect therefore masks high heterogeneity of the impacts among agroecological zones depending on climatic conditions and production structures. Figure 2.7 shows the effects of precipitation on the net index of agricultural production. It is positive and significant for all agroecological zones of Mali, Senegal and Chad. As shown by Figure 2.5 displaying the distribution of precipitation at the beginning of the period, these results can be explained by the fact that these agroecological zones globally have an annual rainfall which is below the Sahelian average in comparison with the agroecological zones located in South Nigeria or Ethiopia, where water quantity during the rainy season is high. In Niger, the effects are not significant for most agroecological zones except for *the Soudanian* and *Sahelo-Sudanian*. The effect in Nigeria is positive and weakly positive for *Derived Savannah* and is not significant for the rest of the agroecological zones. Ethiopia and Somalia are countries in which the effect is not significant for all agroecological zones. Overall, the effect is not significant in agroecological zones that have a low rainfall at the beginning of the period.
In Sudan, the effects of precipitation on the net index of agricultural production are negative in the *Jebel Marra* zone only. Because of its height, this area is characterized by its different climates and obviously the land which is not favorable for cereal cultivation.

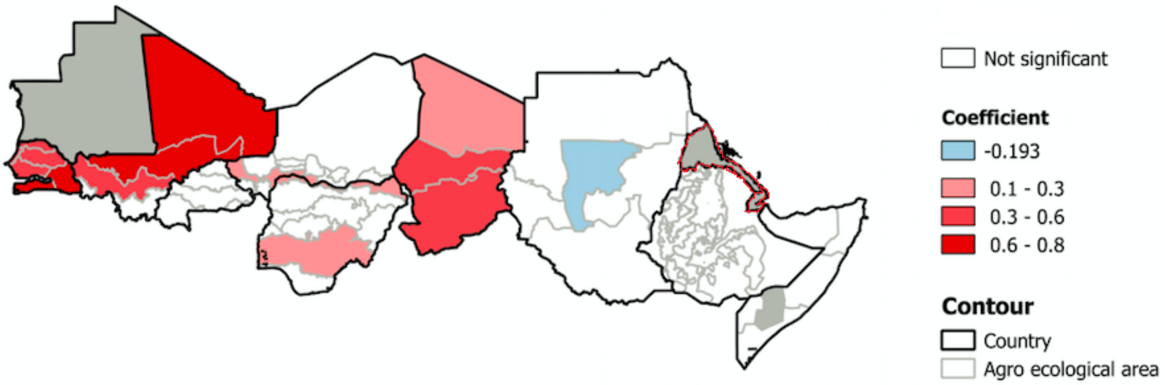
Figures 2.8 and 2.9 show the distribution of the marginal effects of temperature and precipitation on maize production. The effects of temperature are significant and positive and highly significant for the agroecological zones of Chad and Mali for *Derived Savanna* in Nigeria. This can be explained by the prevailing soil conditions and requirements of maize which play an important role. In addition, agricultural practices must be supervised, for example by respecting the agricultural calendar and helping farmers more during the whole cultivation process given their educational level. They are negative and highly significant for all the agroecological zones of Somalia and Sudan. Figure 2.8 shows that the northern agroecological zones in Sudan have the highest temperature so that any further increase in temperature has negative effect on maize production. In Somalia, the agricultural sector faces several difficulties linked to the agricultural system, lack of vulgarisation and the cyclical

Figure 2.6 Distribution of coefficients of the mean temperature during the growing season; Impact on the net index of agricultural production



Source: Authors

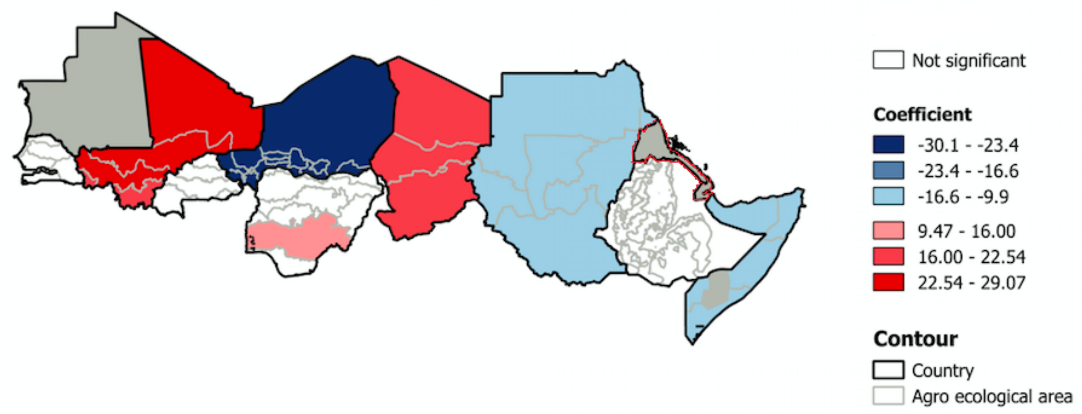
Figure 2.7 Distribution of coefficients of mean precipitation during the growing season; Impact on the net index of agricultural production



Source: Authors

droughts that this country has faced for decades. The effects are not significant for all agroecological zones of Burkina Faso, Ethiopia, Senegal and Nigeria (except *Derived Savanna*). Figure 2.9 shows that the effect of rainfall on maize production is positive and highly significant for all agroecological zones in Chad and Mali. At the beginning of the period, all these agroecological zones received low rainfall (Figure 2.5) so that all other things being equal, an increase in rainfall will increase maize production there. In Niger, the effect is negative and significant in *Sudanian*, *Sahelo-Sudanian*, *Saharan zone* and *Saharo-Sahelian zone*, the situation is linked to technical problems and lack of agricultural infrastructure, and most of the country is occupied

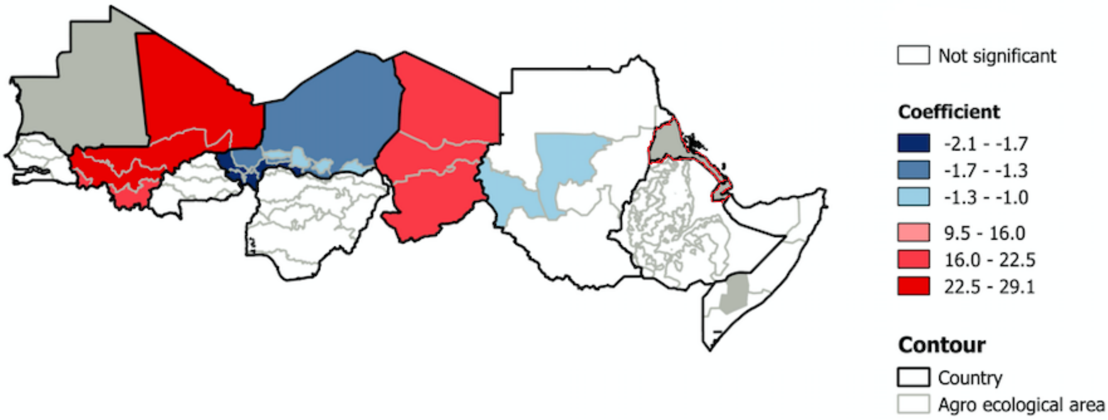
Figure 2.8 Distribution of coefficients of the mean temperature during the growing season for maize, Impact on the maize production



Source: Authors

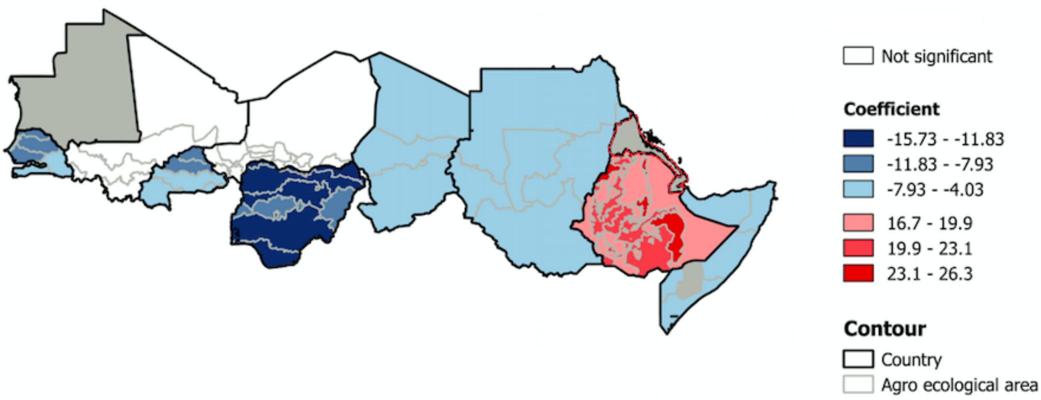
by the desert. In addition, meteorological and agricultural monitoring systems are sorely needed to provide good information to the agricultural sector. In the Sahel and Niger in particular, the low level of education and knowledge of farmers is an obstacle to the development of agricultural practice. The climatic context and the meteorological fluctuations randomly affect cereals, and this is done distinctly from one cereal to another (like the case of corn).
In Sudan, the effect is negative and weakly significant only for *Jebel Marra* and *Poor and Dense Savannah* and is not significant for other Sudanese agroecological zones. These two areas are different. Most of the land in the *Poor and Dense Savannah Zone* is covered by floods and exploited by rain, irrigated and agricultural forests. *Jebel Mara* is not suitable for growing cereals, it is located in altitude and is suitable for growing apples and strawberries. Finally, the effect is not significant for all zones of Ethiopia, Somalia, Burkina Faso, Senegal and Nigeria. Figure 2.10 shows that the effect of temperature on millet production is positive and significant in all the agroecological zones of Ethiopia, which is the country with the lowest temperature during the year in most of these zones and below the optimum for millet (see Figure 2.5). Thus, any further increase in temperature helps increasing millet production in these zones. Conversely, it is negative and highly significant in the agroecological zones of Nigeria and the agroecological zones of Niger bordering Nigeria (*Sahelo-Sudanian* and *Soudanian zone*). The effect is negative and significant in all agroecological zones of Chad, Sudan, Somalia and Burkina Faso because in these zones the average temperature is higher than 28°C, which is the optimum for millet. The effect of temperature is insignificant in all the agroecological zones of Mali and in most of the agroecological zones of Niger except those bordering Nigeria. Figure 2.11 shows that the effect of average rainfall on millet production is positive and highly significant for two zones of Chad (*Sahelian and Sudanian*) and one zone of Nigeria (*Derived Savanna*),

Figure 2.9 Distribution of coefficients of the mean precipitation during the growing season for maize; Impact on the maize production



Source: Authors

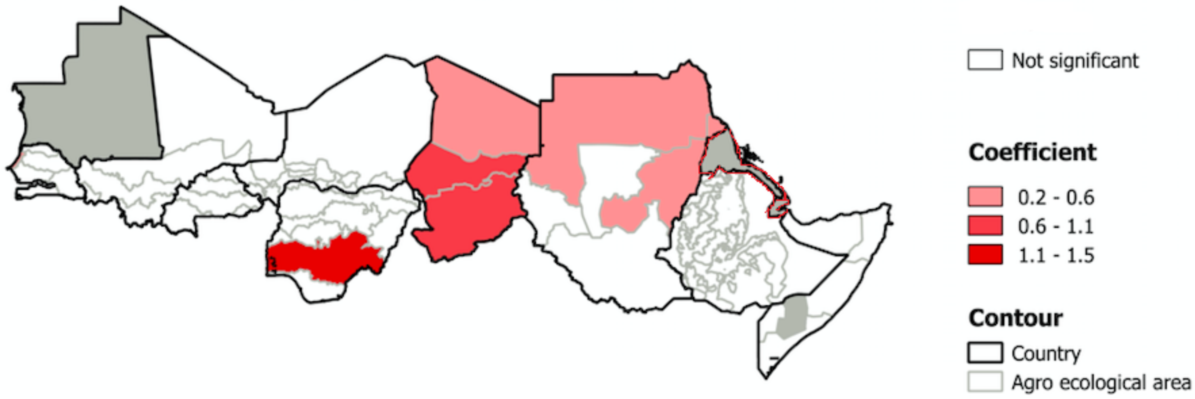
Figure 2.10 Distribution of coefficients of the mean temperature during the growing season for millet; Impact on the millet production



Source: Authors

positive and weakly significant for an agroecological zone in Chad (*Desert Zone*) and for two zones of Sudan (*Flood and Basin Irrigated* and *Desert and Semi-arid desert*) because in these areas there is little amount of rain like the Millet requirement for its growth cycle (see 2.16). In other words, any increase in rain improves production. The effect of average rainfall during the rainy season is not significant for all agroecological zones of Ethiopia, Mali, Sudan, Somalia, Senegal, Mauritania, Burkina Faso, Niger, Nigeria (except *Derived Savanna*) and Sudan (except *Flood and Basin Irrigated* and *Desert and Semi-arid desert*). Technically, millet requires appropriate conditions from sowing to flowering (Table 2.16) and globally, our results show that this cereal is not adapted to the climatic conditions of the East African countries of our sample Figure 2.19). Figures 2.12 and 2.13 show the results for sorghum

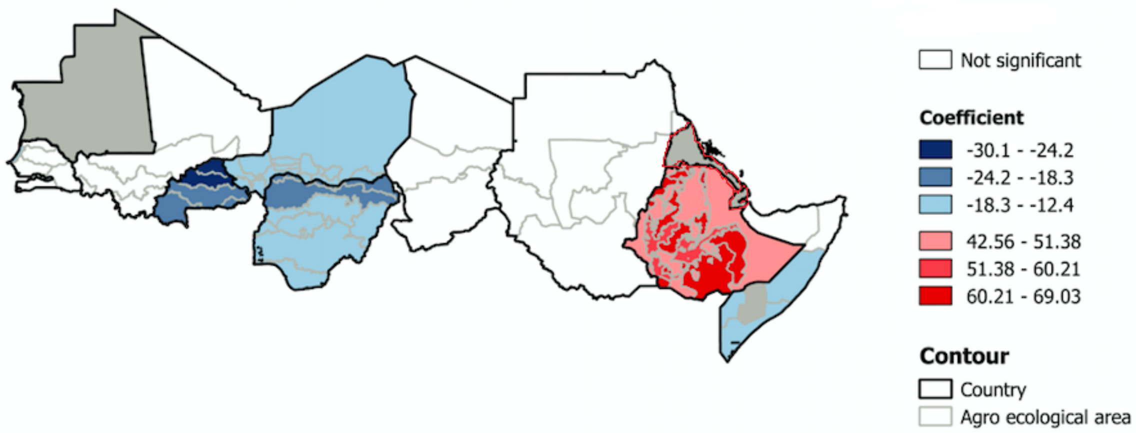
Figure 2.11 Distribution of coefficients of the mean precipitation during the growing season for millet; Impact on the millet production



Source: Authors

production. The effect of temperature of the 2.12 is positive and significant for all agroecological zones in Ethiopia, with the same explanation as before. Conversely, it is negative and significant for all agroecological zones in Burkina Faso, Niger, Nigeria and three zones of Somalia (*Bay and Bakool*, *Coastal Central and Southern Somalia* and *Shabelle and Juba Valleys*), by the fact that the average temperature during the rainy season is higher in these zones even if sorghum is tolerant and tends to withstand the heat. The effect of rainfall of the figure 2.13 is not significant for all agroecological

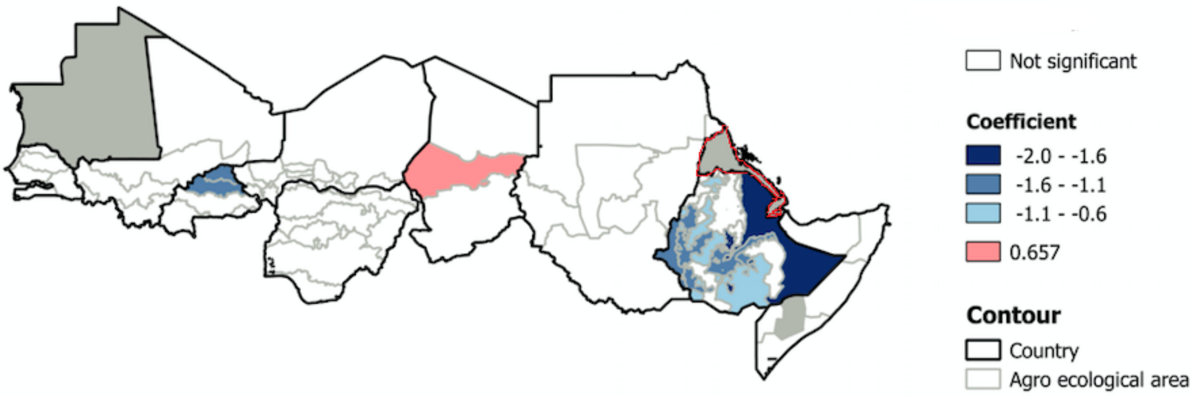
Figure 2.12 Distribution of coefficients of the mean temperature during the growing season for sorghum; Impact on the sorghum production



Source: Authors

zones in Chad, Senegal, Mali, Senegal and parts of Somalia. In contrast, the effect of the rainfall is positive and significant only in the Sahelian zone of Chad. In Ethiopia, it is negative and highly significant for *agroecological arid*, and negative and significant for *Humid agroecology, Moist agroecology, Per-humid agroecology* and *Sub-humid agroecology* and for two agroecological zones of Burkina Faso (*North Sahel and South Sahelian*). The effect is not significant for all agroecological zones of Mali, Senegal, Burkina (except *North Sahel* and *South Sahelian*), Niger, Nigeria, Chad (except *Sahelian zone*), Sudan and Somalia. Sorghum is a cereal widely practiced in the Sahel (Figure 2.19) and is known for its climatic tolerance (Table 2.16), explaining why, except in Ethiopia, its production is relatively less impacted than other cereals by climatic variations. Figure 2.14 shows that the effect of temperature

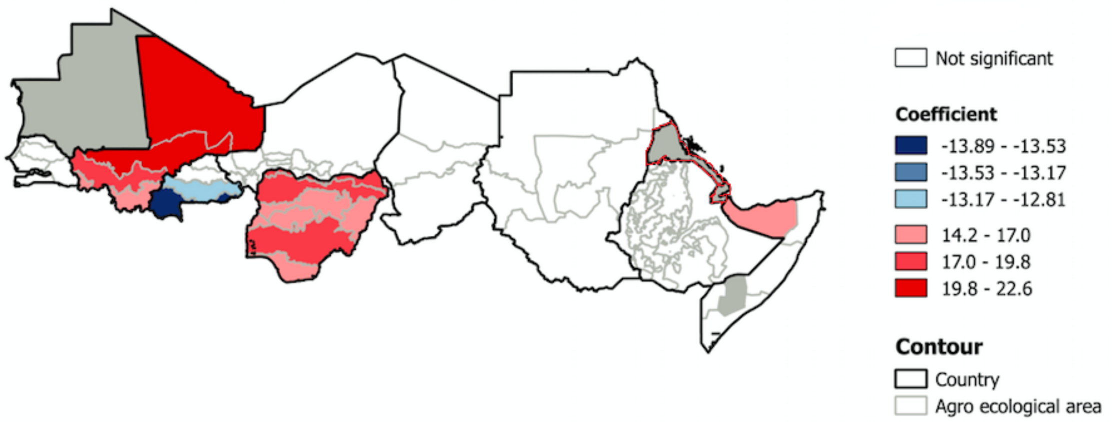
Figure 2.13 Distribution of coefficients of the mean precipitation during the growing season for sorghum; Impact on the sorghum production



Source: Authors

on rice production is positive and highly significant for the three agroecological zones (*Saharan zone*, *Sahelian zone* and *Sudanian zone*) of Mali and the two zones (*Sudan Savanna and Derived Savanna*) of Nigeria. It is positive and significant for the *Sudano-Guinean zone* of Mali, the *Somaliland zone* in Somalia and the two agroecological zones of Nigeria (*Southern Guinea Savanna* and *Humid Forest*). On the other hand, the effect is not significant for all the agroecological zones of Niger, Senegal, Chad, Sudan, Ethiopia and Somalia (except, *Somaliland*). Not all agroecological zones have climatic potential for rice cultivation (Figure 2.16), because growing rice in non-flooded land requires considerable amount of water and a temperature between 13 to 40 °C for its development and growth (see table 2.16) because all these agro-ecological zones, the water potential is negligible, and the rice cultivation is done in rain so it receives less water. Figure 2.15 shows that the effect of rainfall on rice production is positive and highly significant in the agroecological zones of Mali (except *Sudano-Guinean zone*), in the *Casamance zone* (Senegal) and in the *Jebel zone Marra* (Sudan). The effect is positive and significant for the *Sahelian zone* in Chad, *Flood and Basin Irrigated* in Sudan and *Bassin Arrachier* in Senegal. Moreover, the effect is negative and significant

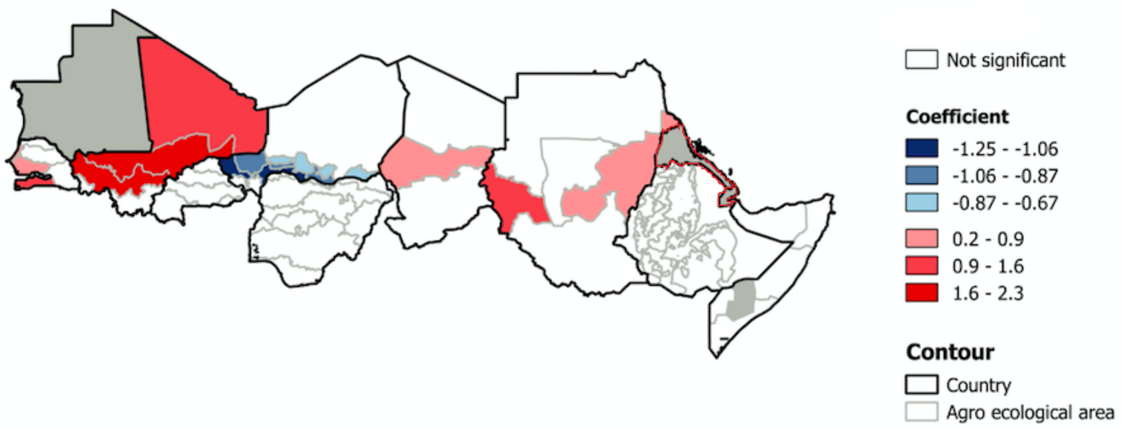
Figure 2.14 Distribution of coefficients of the mean temperature during the growing season for rice; Impact on the rice production



Source: Authors

only for three agroecological zones (*Sahelian*, *Sahelo-Sudanian zone* and *Soudania zone*) of Niger due to the low precipitation of agro-ecological zones. The effect is not significant for all the agroecological zones of Burkina Faso, Ethiopia, Nigeria and Somalia, and for most agroecological zones of Chad, Mauritania and Niger. Field cultivation is the most widespread in these countries and the figure 2.5 shows that Nigeria and Ethiopia are the countries whose agroecological zones receive a large quantity of water thus having a quantity produced of rice greatly superior (see figure 2.19 and 2.18 , appendix 2.7). Finally, Figure 2.16 shows that the effect of temperature

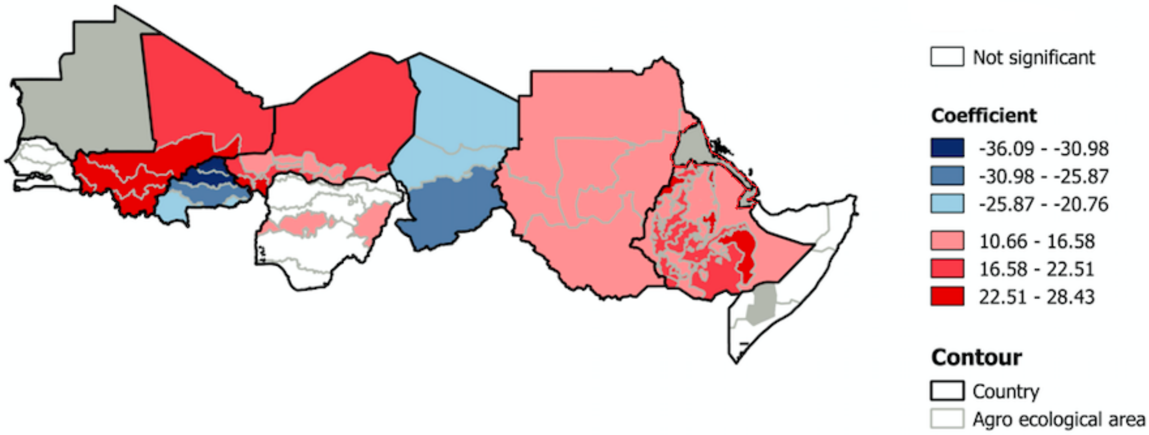
Figure 2.15 Distribution of coefficients of the mean precipitation during the growing season for rice; Impact on the rice production



Source: Authors

on wheat production is positive and strongly positive for all agroecological zones of Mali, Niger (except *Sahelo-Sudanian* and *Sudanian zones*) and in the zone *Sub-moist agroecology* from Ethiopia. It is positive and significant for all the agroecological zones of Sudan, Ethiopia (except *Sub-moist agroecology*), *Southern Guinea Savanna* (Nigeria) and both (*Sahelo-Sudanian* and *Sudanian zones*) of Niger.
Wheat is a demanding cereal as shown in table 2.16, which requires specific temperature levels at each stage of its growth until sowing. In these zones, the lowest temperatures can improve wheat production. On the other hand, the effect is not significant for Somalia, Senegal and Nigeria (except *Southern Guinea Savanna*). Senegal is known for low wheat production given its agricultural potential. Figure

Figure 2.16 Distribution of coefficients of the mean temperature during the growing season for wheat; Impact on the wheat production

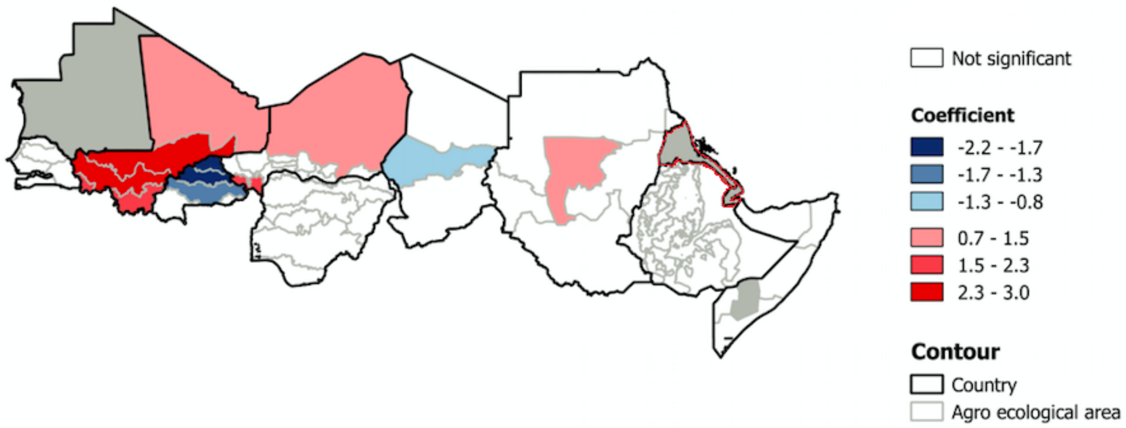


Source: Authors

2.17 shows that the effect of rainfall is positive and highly significant for the three agroecological zones (*Sahelian*, *Sudanian* and *Sudano-Guinean zones*) of Mali. It is positive and significant for *Saharan area* of Mali and Niger, and for the *Poor and Dense Savannah area* of Sudan. On the other hand, the effect is negative and highly significant for Burkina Faso's two agroecological zones (*North Sahel* and *South Sahel*) and negative for *North Sudanian* (Burkina Faso) and *Sahelian Zone* (Chad). The effect is negative for all agroecological zones of Senegal, Ethiopia, Somalia, Sudan (except *Poor and Dense Savannah*), Nigeria and the zones (except *Sahelo-Sudanian and Sudanian zones*) of Niger bordering Nigeria. In the *Sahelian zone*, wheat is imported into several countries because domestic production is deficient because climatic conditions are high in the table 2.16 and most agro-ecological zones can produce wheat. Our results are logical and true for Ethiopia, where the climatic conditions are favorable, with low temperatures and good precipitation, showing a higher level of total annual production of the figure 2.19.
Then, zones with good rainfall (see Figure 2.5) do not see any positive effects on wheat production. Temperature requirements are also essential. This may point to

other problems such as lack of vulgarisation and infrastructure, and an outdated farming system. In addition, the absence of flooded land and poor development of the irrigated system. In addition to the problems mentioned in the Table 2.16, there are parasitic plants that affect the production of cereals and cause a great loss of cereals.

Figure 2.17 Distribution of coefficients of the mean precipitation during the growing season for wheat; Impact on the wheat production



Source: Authors

2.6 Conclusion

This chapter assesses the effects of climate change on agricultural production in 12 countries and 49 agroecological zones across the Sahelian belt. By feeding the existing literature on the link between climate change and variability and agriculture in the Sahel, it makes several contributions. First, the chapter is interested in a new configuration of the Sahelian band. To this end, we provide a broader definition of the Sahel that includes all countries of the Sahelian belt, from Senegal to the countries of the Horn of Africa. Second, we work at two scales, both at the country level and at the level of agroecological zones. To our knowledge, studies of this type in agroecological zones are very rare. Finally, we take into account possible heterogeneous impacts of climate variables depending on the type of cereal and on the level of spatial scale.

The results obtained first show that the effects of temperature and precipitation are heterogeneous at the level of both countries and agroecological zones. On the basis of variables constructed from observations of the cropping season, which is the main period of agricultural practice in this region, the results confirm that mean temperature and mean precipitation in the growing season play a very important role in the production of the five cereals and the net index of agricultural production.

In addition, changes in temperature and precipitation also affect cereal production and the net index of agricultural production. Given our results and knowledge of the socioeconomic, agronomic and climatic conditions of the countries of the Sahelian band, the results shed light on the lack of vulgarisation and knowledge that farmers in the Sahel face. From a climatic point of view, farmers do not benefit from relevant information to better allocate their inputs over the entire agricultural period. The lack of information partly explains our results in this region. Our results also show that countries have to choose the types of crops according to their agricultural potential because a poor choice of crop does not allow countries to obtain better harvests.
Through these analyzes, we hope that in the coming years, researchers will be interested in this wider Sahel, which will have to take into account Chad and the countries of East Africa to the countries of the Horn of Africa.
Furthermore, the availability of data will eventually help us to use other approaches in our future work on assessing the effects of climate change.

After showing that climate change affects agriculture in the Sahel, Chapter 4 assesses its effect on food security because the agricultural sector plays an important role in food and constitutes a source of income for most Sahelian households.

2.7 Appendix

A . Data on agricultural practices in agroecological countries and zones.

Table 2.14Month corresponding to rainy seasons in different countries.

	Country	Rainy season months
1	Burkina	June, July, august
2	Chad	June, July, august
3	Ethiopia	March, April, June, July, August, September
4	Mali	June, July, august
5	Mauritania	June, July, august
6	Niger	June, July, august
7	Nigeria	April, May, June, July, August, September, October
8	Senegal	June, July, august
9	Somalia	Mars, April, May, September, October, November, December
10	Sudan	June, July, august

Table 2.15Number of agroecological zones where cereals are cultivated by country

country	Maize	Millet	Sorghum	Rice	Wheat
Burkina Faso	4	4	4	4	0
Chad	2	2	2	2	2
Ethiopia	7	4	7	3	5
Mali	3	3	3	3	1
Mauritania	2	3	2	1	2
Niger	2	3	3	2	4
Nigeria	4	2	3	4	2
Senegal	4	6	5	4	0
Somalia	3	0	3	1	0
Sudan	2	3	4	1	2
Total	33	30	36	25	18

Table 2.16Needs and stress of the cereals related to cultural practices and climatic and agronomic conditions

Cereals	Agronomic needs	Stress
Maize	Temperature: maize has its photosynthetic metabolism in C4** and a temperature requirement rather high for germination whose optimum is 25°C and impossible below 10°C. Water requirements and crop duration: The cultivation of a 120-day corn type in the Sudanian zone requires at least 600 mm of well-distributed rainfall and a little more in other agro-ecological zones.	Climate: drought at the time of planting damages the crop, and negatively affects the yield during the flowering period. The violent winds of the Sahel during the rainy season cause the lodging or breaking of the stems.
	Fertility and soils: maize is very sensitive to deficiencies and production reacts positively to fertilizer inputs, particularly nitrogen. Corn prefers soils rich in organic matter and with good physical properties. It reacts positively to manure.	Excess water and temperature: flood asphyxiates and rots the roots. Farmers must avoid hydromorphic or poorly drained soils. During the dry season in the Sahel, high temperatures accompanied by a dry or windy climate can cause burns on the leaves. Biological factors: maize cultivation faces frequent diseases in tropical environments, rust and helminthosporiosis.
Millet	Temperature: Penicillaries evolve under average temperatures of 28°C during the growing season.	Cryptogamic diseases: Striga hermantontica is a parasitic plant which constitutes a formidable danger for millet. There are also stemborers, the leafminer, cantharides and cecidomylids.
	Water and crop duration: In Africa, two types of mils are cultivated, early or early (75 to 100 days) and late (110 days to 150 days) mils. The former are grown in low rainfall areas (guero in Niger and Nigeria, and souna in Senegal and Mali). The second type is grown in the most humid regions (maiwa or somno in Niger and Nigeria, and sanio in Senegal and Mali). Soil: Millet is grown on light, well-drained, sandy loam soils with low pH.	Climate: it is known for its tolerance for drought, low soil fertility and high temperatures. Grasses of warm semi-arid areas.
Sorghum	Temperature: If temperatures are higher than 20°C, the seeds rise in 3 or 4 days, the optimum temperature of growth is about 30°C.	Climate: The particularity of sorghum is that the farmer is assured that his varieties will mature at the end of the rainy season regardless of the difficulties he has experienced during planting.
	Water requirements and duration of crops: The earlier the sowing, the longer the vegetative cycle. The total water consumption depends on the variety of sorghum. For 90-day varieties, precipitation is required around 400 mm. In addition, varieties of 110-120 days require precipitation between 550 to 600 mm. Fertility and soils: For its germination, sorghum requires moist soil and average daily temperatures above 12°C.	Excess water and temperature: the water requirements of sorghum are higher than those of maize. The particularity of sorghum is a better ability to withstand periods of drought especially at the beginning of crops.
Wheat	Temperature: the minimum germination temperature is 3°C, the optimum is set at 27°C. To begin, flowering needs a temperature not exceeding 14°C and is optimal at 16.6°C. The optimum temperature for flowering is around 20°C. Water requirements and duration of cultivation: In tropical zones, the duration is 120 to 150 days. The 100-day requires 400 to 500 mm of precipitation during the five phases of the cycle. Soil fertility: To develop, wheat needs deep, well-structured soils with a near-neutral pH and does not tolerate waterlogging.	
Rice	Temperature: In aquatic culture, the temperature of the water is also essential. The minimum temperature is 13-14°C, the optimum is 30-34°C, and the maximum is between 38 and 40° C. Above 50°C, the plant dies.	Climat: strong winds and destroy young plants or cause lodging. The sky cover in the equatorial zone limits production.
	Water requirements and crop time: In dry cultivation, 160 to 300 mm / month is required throughout the cycle, ie 1000 to 1200 mm. The panicle initiation phase is specifically sensitive. In irrigated farming, 12 000 to 20 000 m^3 are required to keep the soil submerged for the duration of the rice cycle. Excessive rain has harmful effects during flowering and harvesting.	Water requirements: the highest yields are obtained in irrigated crops in very dry climates (Egypt, Australia and California). Flowering needs a humidity of 70 to 80% and strongly elevated, diseases will develop.
	Soil fertility: In aquatic culture, the most suitable soils are those with a clay-silty texture (70% fine elements) rich in organic matter with a pH of 6 to 7. The most Adapted are the alluvial soils of the lowlands, the flood plains and the deltas of the great rivers.	Soils: Most Sahelian countries and agro-ecological zones are arid and semi-arid. In dry cultivation, rice requires a rich soil with a good capacity in the field because rice is particularly sensitive to drought. The optimum pH is 6 to 7.

**This is an agronomic terminology, there is a metabolism in C3 too. It is so called with reference to oxaloacetate, a molecule having four carbon atoms formed from the first stage of the process in a small group of plants often collectively referred to as "C4 plants".

Source: The table was prepared by the authors on the basis of information from the "Memento de l'Agronome" of CIRAD et al (2002), which provides technical data, agronomic information and knowledge on the different cereals studied in this document.

Table 2.17Share of agro-ecological zones at the national level of the countries

Pays	Number	Agroecological zones	Share of areas
Burkina Faso			1
	1	North Sahel	0.00158902312911443
	2	North Soudania	0.617549877670442
	3	South Sahelian	0.376144474991803
	4	South Soudanian	0.00471662420864126
Chad			1
	1	Desert area	0.0188318287798171
	2	Sahelian zone	0.0735935911998565
	3	Soudanian zone	0.907574580020326
Ethiopia			1
	1	Arid agro-ecology	0.112909009
	2	Humid agro-ecology	0.188941853
	3	Moist agro ecology	0.221392172
	4	Per humid agro-ecology	0.03967391
	5	Semi-arid agro-ecology	0.302732504
	6	Sub-humid agro-ecology	0.039338886
	7	Sub-moist agro-ecology	0.095011667
Mali			1
	1	Saharan zone	0.019960247
	2	Sahelian zone	0.51994625
	3	Soudanian zone	0.451303155
	4	Sudano-Guinean zone	0.008790347
Mauritania			1
	1	Arid zone	0.0718206770356816
	2	Maritime zone	0.0324794144556267
	3	River zone	0.785452881976212
	4	Sahelian zone	0.110247026532479
Niger			1
	1	Saharan zone	0.0542742541990474
	2	Saharo-Sahelian zone	0.0162948107295061
	3	Sahelian zone	0.0542742541990474
	4	Sahelo-Sudanian zone	0.233830533968413
	5	Soudanian zone	0.641326146903986
Nigeria			1
	1	Derived savanna	0.130052665
	2	Humid forest	0.03884646
	3	Nothern guinea savanna	0.15194825
	4	Sahel savanna	0.072892148
	5	Southern Guinea Savanna	0.024765888
	6	Sudan Savanna	0.58149459
Senegal			1
	1	Bassin arrachidier	0.50738120867292
	2	Casamance	0.135834742939156
	3	Centre East and South Eeast	0.0932902762827413
	4	Niayes	0.0282946332461941
	5	Valley of the river	0.0182223589112717
	6	sylvopastoral zone	0.216976779947716
Somalia			1
	1	Bari	0.00106044538706257
	2	Bay and Bakool	0.00934201888602737
	3	Coastal central and southern Somalia	0.000908953188910771
	4	Shabelle and Juba Valleys	0.945967782659193
	5	Somaliland	0.0427207998788062
Sudan			1
	1	Dense Savannah and Equatorial Zone	0.211445477
	2	Desert and Semi-arid desert zone	0.014314798
	3	Flood and Basin Irrigated Zones	0.490671523
	4	Jebel Marra Zone	0.221068202
	5	Poor and Dense Savannah Zone	0.0625

B . Maps of total cereal production in agroecological countries and zones.

Figure 2.18Total cereal production by country over the whole period, 1961-2016.

Fig 8.a Maize

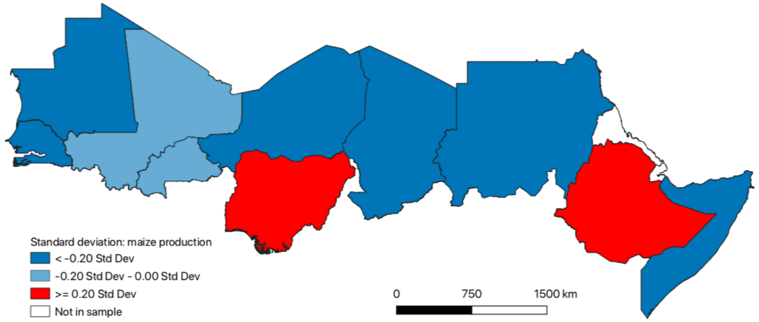


Fig 8.b Millet

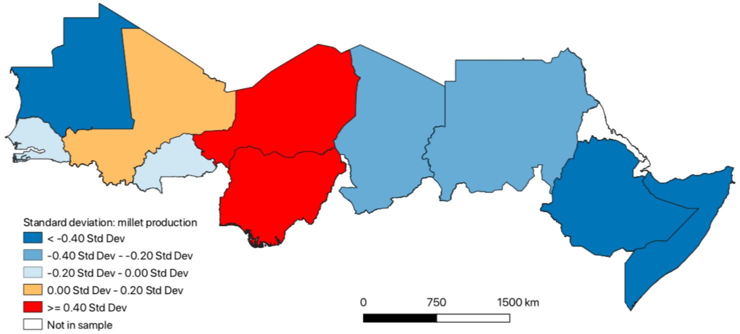


Fig 8.c Sorghum

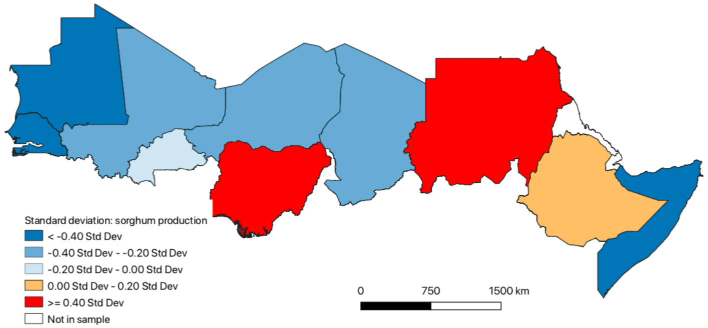


Fig 8.d Rice

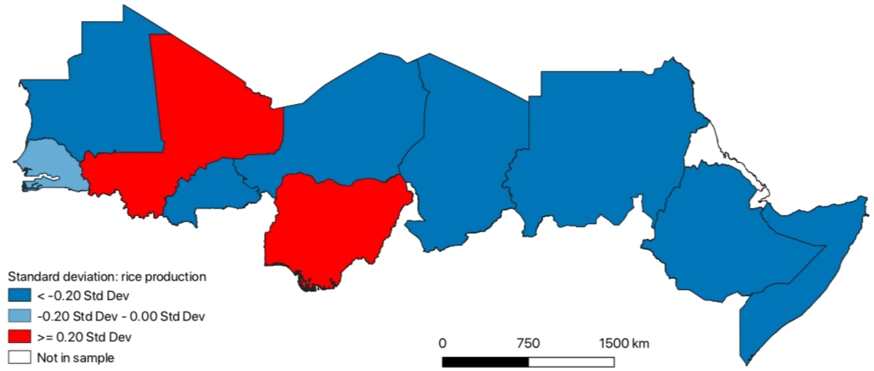
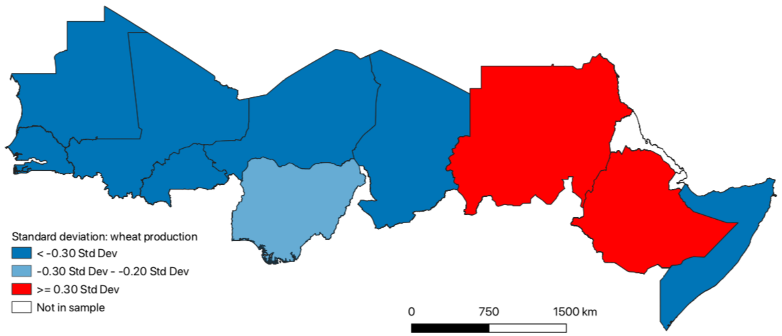


Fig 8.e Wheat



Source: Authors' calculations using FAO cereal production data and crop calendar (2016)

Figure 2.19Total cereal production by agroecological zones over the whole period, 1960-2016.

Fig 8.a Maize

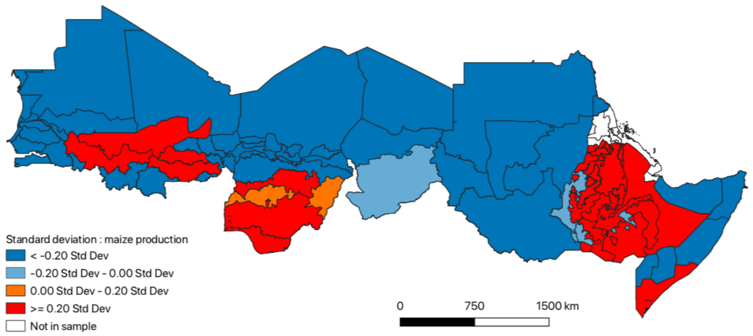


Fig 8.b Millet

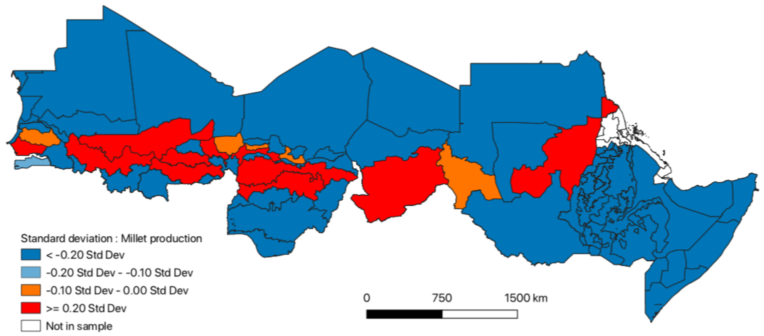


Fig 8.c Sorghum

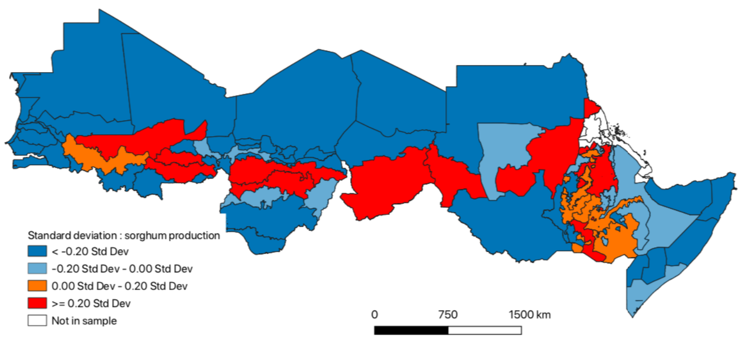


Fig 8.d Rice

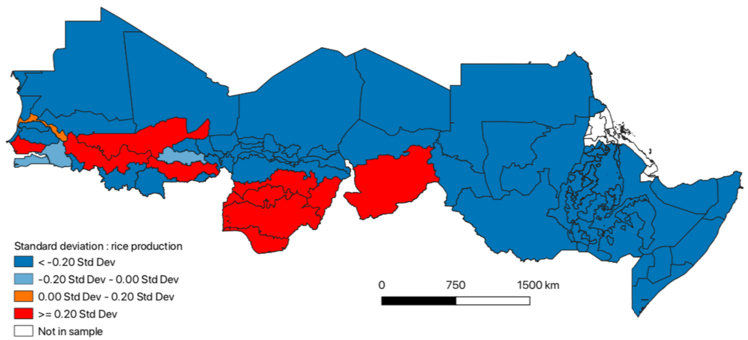
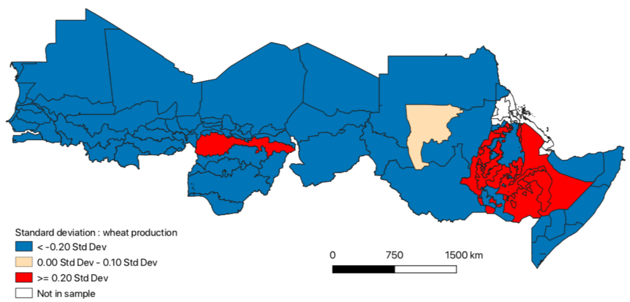


Fig 8.e Wheat



Source: Authors' calculations using FAO cereal production data and crop calendar (2016)

Chapter 3

Climate change and food security: a multidimensional analysis in the Sahel for the period 2000-2016

Although Sahel is an area with available agricultural and arable land, countries in this part of the world are unable to achieve food self-sufficiency. At the national level, weakness in food production hampers the domestic food supply. This chapter analyzes the climatic factors that affect food security in the Sahel during the 2000-2016 period. We base the empirical analysis on the four dimensions of food security provided by the FAO taking into account socioeconomic factors and climatic conditions, which have considerably affected the Sahel in recent decades. The impact is assessed by the use of a panel data model with lagged variables of interest. The results show that drought and floods negatively affect food security. In the presence of these climatic disasters, flood causes more damage to food security. Socioeconomic factors also play an important role in food security. Our results then emphasize that food security in the Sahel cannot be explained only by climatic problems.

Note: The content of this chapter has been presented in the poster session (*Indicators of food security in the Sahel countries*) during the École-chercheurs, Métaprogramme GloFoods, from March 20 to 23, 2018 in Montpellier (France) under the theme *"Food and nutritional security indicators: which issues and methods? "*.

3.1 Introduction

Food security was first mentioned in Rome in 1976 at the World Food Conference, and its definition and measurement have considerably evolved (Maxwell, 1996; Ashley, 2016) and has even changed (Jones et al., 2013). There are almost 200 definitions of this concept (Hoddinott, 1999; Ashley, 2016) and 450 different indicators (Hoddinott, 1999). Nowadays, other indicators surely complete the list given the search for a composite indicator. In the context of this chapter, we retain the definition of FAO (2002): "Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their their dietary needs and dietary preferences for an active and healthy lifestyle". Conversely, food insecurity results from the fact that people do not have adequate physical, social or economic access to food. Climate change has indirect effects by affecting growth and income distribution, demand for agricultural products and thus affects different dimensions of food security Smith et al. (2000).

Food security has four components: food availability, accessibility, use and stability of food (FAO., 2014; Ashley, 2016). The first dimension deals with the issue of availability. Food may be available in the family farm, attic, kitchen, store and local market (Ashley, 2016; Reig et al., 2012). At the country or regional level (Reig et al., 2012), food supply can come from domestic production, imports, stocks and food aid. The second dimension is essential because it raises an essential problem linked to inequalities (poverty), especially in countries where infrastructure is not developed (Ashley, 2016). Food security must take into account ease of access to people's food. Then, the use comes from the effects of eating the food. It also relates to better use of food, water quality and access to care for individuals. Finally, the concept of stability can refer to the first three dimensions of food security. The interaction of these three determines the food security status and stability of a country or a household over time.

According to the World Food Crisis Report (2019), more than 113 million people in 53 countries are severely food insecure and in urgent need of food, nutrition and livelihoods. The situation in the Sahel countries is receiving attention and is exacerbated by terrorism. For instance, according to Cilss (2019), although food availability is satisfactory, civil insecurity is the main cause of the destruction of livelihoods and severe food insecurity in the Lake Chad basin and north of Mali. Conflicts and instability do not allow the mobilization and transport of food and livestock in certain areas or countries. Although these countries have domestic production, they use imports to meet domestic needs. This mismatch between the drop in domestic production and domestic demand poses a major problem for the Sahelian economies. It is expected to continue due to climate change.

Other factors affect food security in the Sahel. Rising commodity prices are often seen on local and international markets. Most Sahelian households have a very low income so any increase in income will cause food insecurity for these individuals. Climate change is affecting agricultural productivity and 80% of the Sahelian agricultural population (Davis et al., 2010) is at risk of being food insecure, following an increase in the occurrence of drought or flooding. This can limit the purchasing power of poor households and push these individuals to focus on cheaper grains and other less nutritious foods. Faced with soaring prices, households cannot make a trade-off between consumption or spending on health care or access to education for children.

In recent decades, widespread inflation has become one of the main sources of migration from urban populations to rural areas. The growing rural population also causes density condensation which is likely to lead to food insecurity. The opposite effect is also observable and has become more significant, the influx of migrants towards the city also creates a significant imbalance but often unobservable in the countries of the Sahel. Any increase in the population in a given data will lead to an increase in food demand within this zone. The occurrence of drought and floods directly affects agricultural production. These phenomena cause significant human loss and economic damage in the Sahel countries due to the lack of good quality infrastructure and structures.

In this context, our aim is to assess the impact of climate change on food security by controlling for the other factors by using a fixed effects panel model estimated on a sample of 12 countries for the period 2000-2016. Fixed effects allow controlling for unobserved heterogeneity (Blanc and Schlenker, 2017) while the use of lagged climatic variables mitigate the problem of simultaneity. The fixed effects specification is well suited to assess the impacts of climate change, because it uses group fixed effects to absorb all the invariant variations over time. By building food security indices and using climate shock variables such as drought and floods as in (Eric and Kinda, 2016; Karfakis et al., 2011), the chapter contributes to the literature in several ways by focusing on the Sahel countries.
First, this chapter builds on the new dimensions of FAO to build composite food security indices in order to better capture each dimension of food security, unlike (Belloumi, 2014; Celia Reyes and Calubayan, 2014; Asfaw, 2015; Ahmad Munir and Iqbal, 2015; Eric and Kinda, 2016) which directly use proxies (i.e. Food production for Belloumi, 2014; vulnerability index for Karfakis et al., 2011; crop net income for Asfaw, 2015; value of food consumed by adult equivalent for Celia Reyes and Calubayan, 2014 etc ...) to directly assess food security. To our knowledge, no study has empirically assessed food security by adopting a multidimensional analysis in the Sahel countries. For example, some studies have studied this link in East African countries (Belloumi, 2014), in households in Ethiopia (Asfaw, 2015), in South Africa (Masipa, 2017) and (Eric and Kinda, 2016) in 53 developing countries. Next, this chapter contributes to the literature on the challenges of climate change and food security in the Sahel countries by showing the importance of climatic shocks (floods and droughts) of the previous year on all dimensions of food security. Also, the chapter examines the important role that other socio-economic factors can play in improving food security in the Sahel. Finally, we assess this link for a newly defined Sahel taking into account all the countries from Senegal to the Horn of Africa.
The remainder of the paper is organized as follows. Section 3.2 briefly presents a review of the literature on the issue of climate change and food security and its economic implications. Then, section 3.3 presents the methodology used to assess the determinants of food insecurity in the Sahel countries. Section 3.4 presents the scope of analysis and the data used to assess the effects of the changes on food security. The results and implications are presented in section 3.5. Finally, conclusion and implications in section 3.6.

3.2 Literature review

3.2.1 Definitions of concepts around food security

In this section, we discuss the definitions and indicators that best fit the Sahelian food security situation that differs from that of other regions or countries. The purpose of revising these two aspects (definitions and indicators) is to find a complete description of

this concept. This change also makes it possible to adapt food security to the evolution of the global food system, which has profoundly evolved with the increase in human needs.
This term also has a long-standing history. In 1960, it was used by agricultural economists and nutritionists to designate "an objective of sufficient food availability (calories and proteins) to feed the population of a country" (Ghersi and Rastoin, 2010). This first definition remains quantitative and does not include the qualitative aspect that is essential for human health. Hence the need for a revision of definitions at the World Food Summit was coined in 1996 under the auspices of FAO. Following this summit, a new multidimensional definition was adopted and invariably accepted by the community (Ashley, 2016). Food security is defined as follows: "Food security exists when everyone, at all times, has physical, social and economic access to sufficient food that meets their food and preferences for a healthy and active life" (Babu et al., 2014; Ashley, 2016). For Jones et al. (2013), this definition indicates that food insecurity is the absence of one or more of these conditions. These authors also claim that this definition shows that food insecurity can be classified as chronic or transitory, and seasonal food insecurity is between the first two.
This new definition of FAO is based on four dimensions: (1) food availability, (2) economic and physical accessibility to food, use (3) and stability (4) of food over time (FAO., 2014; Ashley, 2016).

The first dimension deals with the question of availability in terms of quantity of food regardless of where it comes from. Food may be available in the family farm, attic, kitchen, store and local market (Ashley, 2016; Reig et al., 2012). At the level of a country or region (Reig et al., 2012), food supplies can come from domestic production, imports, stocks and food aid. This first dimension has limitations because it is based solely on availability (Ashley, 2016). Food supply and production have increased but malnutrition and hunger persists worldwide (Haile, 2005; FAO., 2014; Ashley, 2016).
As such, this concept does not consider the issue of accessibility because it assumes that available food is distributed and accessible directly to the population (Pinstrup-Andersen, 2009; Ashley, 2016). The current situation has shown that availability does not measure food security (Ashley, 2016).

The second dimension is essential because it raises an essential issue based on inequality (poverty), especially in countries where infrastructures are not developed (Ashley, 2016). The issue of "accessibility" is a key issue in measuring food insecurity. She talks about the issue of distribution. For example, the existence of food availability at the global level or in a given country does not necessarily imply that individuals or households have access to this food. Ashley (2016) discusses social, religious and political barriers that may arise from class conflict, lack of education and some cultural norms. As a result, improved availability and accessibility do not ensure food security unless there is rational or optimal use.

Third, the "utilization" or "consumption" dimension shows how people use available food (Ashley, 2016). This dimension also provides insight into the effect of food on consumers while allowing the assessment of health status of consumers (FAO., 2014; Ashley, 2016). The consumption of certain food products causes more or less serious health problems for human health. Excess consumption of a food also causes health problems for the consumer. To talk about food security, it is necessary that the three dimensions are reached in addition to the stability in time of the food.

Recently, the Committee on World Food Security (2012) added the stability dimension to the determinants above (Babu et al., 2014).
Finally, the fourth dimension refers to the stability and sustainability of the food source over time (Aurino, 2014; FAO., 2014; Ashley, 2016). In other words, this dimension is related to availability, access and predictability. So with the fourth dimension, "Food security exists when everyone, at all times, has physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and dietary preferences for an active and healthy life. The pillars of food security are availability, access, utilization and stability. The nutritional dimension is an integral part of the concept of food security" (Committee on World Food Security, 2012).

Several authors have also given specific definitions of food security, and some also validate the FAO definition, which put virtually all researchers in the same light. These definitions sometimes have macro or microeconomic scopes. We retain here the definitions of Ghersi and Rastoin (2010) and Ashley (2016).
For their part, Ghersi and Rastoin (2010) defined food security as a "state that characterizes a country capable of ensuring a healthy and balanced diet" to theoretically analyze food safety and policy. For these authors, this definition takes into account access to food, economic conditions and psychological satisfaction. Ashley (2016) defines food security as "a term that refers to the ability of a community, family or individual to eat enough, in terms of quantity and quality, as prescribed by international standards for the consumption of calories, protein and vitamins".

Food security is a complex concept because it tends to be confused with other terms. Indeed, we can find associated to food insecurity some terms such as "hunger", "undernourishment", "malnutrition", "food deficiency" and "food crisis". They are often used even if they do not designate the same situation. However, the occurrence of one of these states actually leads to a situation of food insecurity. Objectively, all these situations evoke a precarious situation that can directly and indirectly cause health, human and economic damage.

To remove doubt and debate around these terms, we define these terms independently which complicates the definition of food security by giving it the "multidimensional" character. This illustration makes it possible to understand with a certain precision the definition and the construction of the indicators.

Hunger is a situation that is likely to upset even the socially, economically and psychologically the lives of people. The definition of famine that we consider as a generalized state of hunger was given by Sen (1981) in these terms: "Starvation is the characteristic of some people not having enough food to eat. It is not the characteristic of being not enough food to eat ". In addition, Ashley (2016) defines hunger as "a feeling of discomfort or weakness caused by lack of food, associated with the desire to eat. It is used in this book as a close equivalent to chronic undernutrition". Another definition provided by WFP indicates that hunger is the primary health risk that causes more than every year victims of malaria, HIV / AIDS and tuberculosis combined (FAO et al., 2014; Ashley, 2016). In that respect, the situation remains precarious and alarming according to Ashley (2016):

"The vast majority (98%) of hungry people live in developing countries, where almost 15% of the population is undernourished". Two-thirds of the world's hungry (526 million) live in Asia, while in sub-Saharan Africa, one in four people remains hungry, Latin America and the Caribbean is the region that has shown the greatest progress in hunger reduction, with the prevalence of hunger reduced by almost two-thirds the early 1990s". However, the world wants to reach the millennium goal for development with the slogan "zero hunger". Organizations such as FAO, IFAD and WFP are at the center of the fight against hunger. The results are encouraging, but hunger remains uncontrollable and continues to destroy lives. Estimates indicate that the prevalence of undernourishment has increased from 18.7% to 11.3% worldwide and from 23.4% to 13.5% in developing countries (FAO et al., 2014; Ashley, 2016).

Malnutrition can also cause confusion. The concept of nutritional security is closely linked to food security, the former being partly dependent on the latter. The nutritional needs of the human body are very necessary because the nutrients contribute strongly to the development of the body of the man. If the nutrients are provided properly and regularly, the individual is in good health. On the other hand, the absence of nutrients causes a health imbalance in the individual (Ashley, 2016).

The food crisis was defined by Ghersi and Rastoin (2010) as a "serious event (real or perceived as such) that marks a break, a significant change in the evolution of a phenomenon." It also causes psychological and material damage. From 1996 to 2008, the world experienced two major food crises. The first crisis of 1996 was caused by mad cow disease caused by consumption of feed from cattle. Secondly, the second crisis of 2007 is caused by rising food prices making food inaccessible to the poorest and most vulnerable populations.

"Food deprivation or food shortage" is the main source of food insecurity in the world. They are caused by nature or by man. The food shortage can be caused by armed conflicts (influx of refugees and other riots), natural disasters (floods, droughts ...) or conditions of access to food (for example, rising price). Ghersi and Rastoin (2010) have historically traced the number of food deficits that have been declared as emergencies. In the early 1980s, the authors identified 25 to 40 cases that occurred. On the other hand, they evoke a high frequency after the 1980s, more than 60 cases in 2007 (Ghersi and Rastoin, 2010).
Undernourishment directly affects health and indirectly the economy. It can be caused by undernourishment of calories, proteins or micronutrients. It is said to be responsible for 53% of all deaths of children under five in the world. As a result, it is responsible for marasmus and kwashiorkor (Ghersi and Rastoin, 2010). These two diseases all linked to malnutrition. The first is severe malnutrition which affects people with nutritional deficiencies, marked by an energy deficiency. The second is a protein deficiency malnutrition syndrome.

To contextualize our topic and finalize this section on definitions, we do a small comparative analysis of bridging food insecurity and nutrition insecurity. This comparison is based on the work of Ashley (2016) and comes to bring a notorious effect after the definition of the terms above. The first nuance, food insecurity has a quantitative aspect, while nutritional insecurity is qualitative in nature. This clearly explains that people who are in a state of

food security are not necessarily in a state of nutritional safety. Food security does not provide nutritional security (Ashley, 2016).
Ashley (2016) also reports two illustrative examples. The first example was the work of Kaufmann (2009) who studied the case of the population of Laos in Asia, he mentioned that the population is eating enough but they are in a state of nutritional insecurity due to two problems: the inadequacy health care and the existence of provisions that underestimated women and mothers who were in a state of nutritional insecurity. The second example of the same author but this time on Nigeria. This study was conducted in 2014 in a clinic in northern Nigeria. Kaufmann (2009) mentioned that mothers who were waiting for therapeutic food were well-made women dressed in quality dresses and obviously not poor and ate enough. The author explained the situation in Nigeria by the fact that these women lacked knowledge about the adoption of a quality diet for their infants and certain nutritional standards that caused their children to stun.

From these two examples, we can go forward by reporting Ashley (2016) who said that "food security is a necessary but insufficient condition for overall nutritional security". As mentioned above, nutritional safety is qualitative. Based on these two examples, we can say that in the presence of food security, nutrition security can be achieved by mobilizing behavioral factors such as literacy and knowledge about child nutrition. A correct definition incorporating food security is given by Ashley (2016) "nutrition security requires simultaneous availability and access to safe food, good health and good care in general (including hygiene, clean drinking water and proper feeding of a young child who is not old enough to feed independently of the caregiver)".

All the definitions and debates on the issue of food security have shown that this phenomenon covers both a quantitative and qualitative aspect. Thus, we discuss in the next section the various proposals made to measure food security for an individual, household, country or region.

3.2.2 Measures of food security

Babu et al. (2014) indicate that food security is a flexible concept and is used at three levels of aggregation: national, regional and domestic or individual. Food security measures can focus on its determinants of availability, access, use, food stability over time, or a combination of these determinants (Babu et al., 2014; Jones et al., 2013). However, it generally remains difficult to evaluate because it has several causes (FAO., 2014; Ashley, 2016) and different forms. The successful measurement of these different indicators should be a first step in quantifying the food security of the population (Babu et al., 2014). Empirically then,proxies should be used. The use of indicators also refers to an optimal choice of entities whose profile is to be evaluated. In this section, we discuss the measures that have been developed by scientists over time, but other avenues are yet to be explored to obtain a comprehensive indicator that encompasses all dimensions of food security. Thus, we will discuss the indicators that can judge the food status of a person, a household or a population.

Measures based on the four dimensions

According to Babu et al. (2014), food security can be measured based on its four dimensions.
To measure food availability, Babu et al. (2014) advocates "the small area estimation method" developed by Hentschel et al. (2000) and Elbers et al. (2001) is one of the most common methods for measuring household food availability" despite the existence of other methods. This two-stage statistical method is based on survey and census data to assess the welfare of geographic units (rural areas and municipalities). The first step is to estimate a household welfare model using data from the household survey. Then, parameter estimates are applied to the census data in the second step assuming that the relationship is valid for the entire population (Babu et al., 2014).
In addition, the results obtained are used for global analyzes. The results obtained at the household level are then aggregated by a region or a larger geographical area taking the average of the probabilities for the zone. This practice is intended to facilitate the construction of maps for different levels of food insecurity disaggregated across geographic units (Babu et al., 2014).

Household food access is measured through food or nutrient intake at the household level (Babu et al., 2014). The idea is to have "equivalent adult" units in order to make comparisons between individuals within households as well as among households. Babu et al. (2014) define the equivalent unit as "a weighting system of household members based on calorie requirements for different age groups and sex groups". This information is obtained following household surveys. They collect data on household composition, household food expenditure, consumption of main commodities and other socioeconomic characteristics of households.

To measure the use of food, Babu et al. (2014) discuss the fact that the nutrients consumed can be compared to the nutrient standards recommended by WHO and FAO. Nutrient requirements help to keep a person healthy. In addition, they vary considerably among individuals and the nutritional requirements may be the same for a category of people (age, sex, body size and physical activity). Such information is provided but incompletely by household surveys. In this case, more energy expenditure must be considered in order to have an estimate of the energy requirements. For children, there is an additional allocation for growth. In fact, energy needs come from data from healthy populations, but they need to be adjusted in communities that suffer from malnutrition and other debilitating diseases. To implement the food security assessment, it is advisable to consider that the group distribution of energy and nutrient needs of individuals is assumed to be normally distributed (Babu et al., 2014).
Stable food availability is an additional measure of food security (Babu et al., 2014) in addition to the previous three. This dimension is to be measured by the inadequate drinking water installations and the insufficient level of food consumption. Other information on the measurement of this dimension is given in the following paragraph 3.2.2 on alternative approaches (see interaction approach, adaptation strategy/chronic vulnerability approach and scale approach).

Measures based on other approaches

In the literature on food insecurity measures, other approaches that assess the food insecurity of an entity according to the specificity of the context have been proposed (Babu et al., 2014).

Approach based on energy intake of foods: De Haen et al. (2011) indicate that this approach is used by FAO to measure under-nutrition and can also be considered as an indicator of food security. This approach takes into account the percentage of all people who are unable to meet the minimum energy needs a person must consume to be in good health (De Haen et al., 2011; Ghersi and Rastoin, 2010). In this case, a person or household is in a position of undernourishment if the amount of food energy is below a normal threshold (Shapouri et al., 2009; Ghersi and Rastoin, 2010). Indeed, this situation of undernourishment leads to food insecurity.
At the country level, this approach measures the proportion of undernourished people relative to the total population. On the other hand, this approach has been criticized (Pinstrup-Andersen, 2009; De Haen et al., 2011). Indeed, this indicator does not capture the importance of certain nutrients (iron, zinc and vitamins) in the diet thus qualifying this indicator as partial. Moreover, De Haen et al. (2011) point that this approach does not take into account an essential dimension of food security that is "access to food". For these authors, food availability does not justify accessibility, especially in countries with poor infrastructure (Ashley, 2016; De Haen et al., 2011).
This issue of accessibility has mixed configurations because the problem of accessibility is also present in countries where there are significant disparities between cities and regions creating a problem of lack of communication. In such a situation, information is often not known by policy makers, thus limiting policy strategies (Babu et al., 2014; De Haen et al., 2011).

Approach to chronic vulnerability or scaling approach: This approach was developed by Maxwell (1996) and relates to an adaptation strategy for households with insufficient food consumption. The cumulative index developed focuses on six food adaptation strategies. To put this approach into practice, Maxwell (1996) has implemented a scale that takes into account the frequency of each individual strategy and has been multiplied by the gravity weighting factor based on the ordinal ranking to obtain the score. food security (Babu et al., 2014). Unlike most approaches above, this approach does not require specialized enumerators or complex statistical procedures. This approach has the advantage of understanding food shortage in the short term. On the other hand, it is limited because it can not distinguish between short-term food insecurity and long-term vulnerability indicators. In addition, it does not take into account the nutritional status of children (Babu et al., 2014).

Scaling approach: This approach assesses the way and stages by which households find themselves in a situation of food insecurity over time. In practice, it focuses on a set of six questions whose aim is to have a single global scale for food security. The higher the values of the index, the more food insecure households are. The downside of this approach is that it cannot capture the nutritional status of children Babu et al. (2014).

Bickel et al. (2000) indicates that it is widely used to measure household food security in the United States.

Difference and change of diet: This approach takes into account the difficulties that the analyzed entities (households and countries) may encounter during a given consumption period. Thus, it makes it possible to measure food security through the existence of episodes of food shortages at the level of households and countries. This approach provides information on the number of months a household faced a food shortage (Berhane et al., 2011; Headey, 2011). It also makes it possible to measure food security at a country level by giving the amount of food needed to increase consumption in comparison with nutritional needs (Lee et al., 2013; Shapouri et al., 2009).

Interaction approach: This approach is an overlap technique developed by Haddad et al. (1994). It aims to determine the extent to which a proportion of households are insecure on a particular dimension, given that the authors are unsure of another dimension Babu et al. (2014). The advantage of this approach is its ability to include several indicators to measure food insecurity. On the other hand, the fact is that there are several indicators, so the combinations of factors are infinite. The approach is therefore described as suggestive (Babu et al., 2014).

Approaches based on natural experiences: This approach is special because it consists of a self-evaluation. According to Greer and Thorbecke (1986), this method allows individuals to personally locate and discuss their state of food security. This approach is a natural experience because it allows individuals to evoke the real information themselves. The data and information collected make it possible to categorize by giving information on their nutritional and nutritional status.

Approaches based on consumption and expenditure surveys: Demeke et al. (2011) and Wang (2010) discuss the use of data-based methods through consumption and expenditure surveys. The data collected from these surveys allow statisticians to assess household food security. The analysis of the consumed products makes it possible to see if the food needs of the households are covered by respecting the recommended caloric contributions. The idea is to convert monetary expenses into quantities, which are converted into calorie equivalents. In this case, any consumption of calories above the predefined standard reflects the fact that the person or household is in a situation of food security. And the opposite is reflected in a situation of food insecurity. This method has advantages and drawbacks. It is advantageous because at the end of the survey information on consumption habits and a representative result of the study population are available (De Haen et al., 2011).
However, it can be biased because one can not convert and analyze all the products in order to obtain their caloric equivalence. For the reliability of this approach, it is necessary to focus on a relatively short period (a week or two weeks). In addition, this method should be conducted regularly to understand the dynamics of food security (De Haen et al., 2011; Pinstrup-Andersen, 2009).

In order to assess food security within an entity, we need to understand the different causes that we develop in the following subsection that put people, states and international organizations in difficulty.

3.2.3 Causes of food insecurity

Starting from the definition, according to which a person is in a situation of food security when it has access at any moment to a food to lead a healthy and active life.
Smith et al. (2000) have argued that the causes of food insecurity in a country are many and varied. A food insecurity crisis may arise from one or more of the following factors: political instability, civil wars and unrest, macroeconomic imbalances and trade upheavals, environmental degradation, poverty, population growth, gender inequality, inadequate education and poor health. The causes of food insecurity differ from country to country. Standards and food rations are not the same, so the causes of this phenomenon can be of various origins. In addition, Ashley (2016) mentions that food insecurity can come from one factor or the conjunction of several factors. He cites nine causes of food insecurity in developing countries: muldimensional etiology, poverty and poor awareness, environmental degradation and climate change, food price hikes and price instability, conflict, weak institutional environment, predisposition of the community disease and intestinal affliction, land lease, and large area of arable land set aside for biofuel production.

The main causes of food insecurity in sub-Saharan Africa are: low agricultural productivity, lack of agricultural policies, inadequate infrastructure and high transport costs, lack of appropriate marketing strategies, frequency of extreme weather events high morbidity, including malaria and HIV / AIDS, weak financial support systems, lack of safety net systems and political conflict (Haile, 2005). For that purpose, we categorize all the determinants in order to group them into the following causes : economic and social problems, weather conditions, diseases, weak institutions and the governance system, instability and insecurity.
However, all of these factors are closely related to the two root causes of food insecurity: inadequate national food availability and insufficient access by households and individuals to food (Smith et al., 2000). The analyzes we conduct in this section touch on one important macroeconomic factor that is "consumption". Through this classification, we identify the factors that directly or indirectly affect the household income (or country) causing an imbalance on consumption in general in the countries and particularly in the Sahel. As a result, we retain the sources of income cited by Verwimp et al. (2012) for an average household are production for own consumption, crop sales, livestock products, non-farm income and transfers received from farmers. other people. This allows us to refine our analysis of the causes of food insecurity. In other words, we seek to explain how the income of an entity (farmer, farm household, rural population, country) is impacted and causing a situation of food insecurity.

Social and economic problems

This cause of food insecurity directly refers to the poverty of the population, the decline in income, the lack of knowledge about food and the problems also related to the literacy of households and farmers.
Poverty is defined by the OECD as a situation characterized by deprivation of human capacities such as consumption and food security, health, education, rights, voice, security, dignity and decent work. In contrast, the definition of poverty given by US state organizations is broad and includes the aspect of equity. For them, poverty takes into account and involves undernutrition, unemployment, illiteracy (especially among women),

environmental risks and limited access to social and sanitation services, including health services (Ashley, 2016).
Both definitions indicate how poverty is a brake on individuals. Poverty leads to food insecurity but as Ashley (2016) points out, hunger, undernutrition and food insecurity are factors that prevent people from escaping poverty and being unable to care of themselves and their loved ones.
Poverty is widespread in the world, and statisticians in Unicef say that about 3 billion people live in poverty on less than $ 2.5 a day. Extreme poverty affects about 1.3 billion of them with $ 1.25 a day. Children are the most vulnerable because of the 3 billion, there are 1 billion children and 22,000 children die every day because of poverty (Ashley, 2016). These statistics also indicate that almost half of the world's population lives in poverty. Most of the poor are in sub-Saharan Africa and South Asia. In these countries, most of the income is spent on food and people eat less frequently. About one third of the African population is facing hunger and chronic malnutrition and is exposed to a constant threat of acute food crisis and famine Haile (2005). These poor countries are vulnerable to economic shocks and changes in food prices. In addition, in these countries a complicated relationship is built around food insecurity, health and poverty. Ashley (2016) summarizes this causality as "food insecurity and poor health are bicausally linked, but poverty is also bicausally associated with this relationship".

In studying food security in South African countries, Drimie (2003) reports that poor macroeconomic structures and low growth rates prevent the incidence of poverty. In referring to the case of Zimbabwe, Drimie (2003) cited two following causes. First, the deterioration of the economic climate has plunged Zimbabwe into a food crisis lowering the country's economic gains. In 2000, the country had a negative growth rate and is facing inflation affecting the purchasing power of the population. In such a configuration, poor and rural people do not have access to food. Secondly, the decline in transfers of funds from urban areas to rural areas has aggravated the vulnerability of the rural population. The causes of food insecurity may also vary within the same country. Ashley (2016) discusses Zambia's precarious situation, with 64 to 80 percent of the rural population living in poverty. The context does not allow farmers to have loans to invest in their farms. Low agricultural productivity leads to poverty and hunger, and high infant mortality. In slums, undernutrition (food insecurity) is caused by unhealthy and sanitary infants. To these hygienic causes, it is also added the irresponsibility of some parents because they abandon the children who eat dirty food causing infections.

Ashley (2016) points out that "the physiological causes of undernutrition are well understood, while the complex socio-economic reasons for how and why they occur are often community-based". This shows that the food problem persists and the causes are numerous and some are incomprehensible. The chain of causation can be very long, going back several generations, and durable solutions and beneficial results are difficult to obtain, even with the benefit of a full understanding of socio-economic causality. Gender, age and ethnicity are often key determinants of food insecurity and poverty in the family and community (Ashley, 2016). There are also factors such as household size and the nature of the household head (woman, child) that affect household food security (Haile, 2005).

The fight against poverty is at the center of national, regional and international exchanges.

All institutions seek to end this phenomenon but the results are unsuccessful. In addition, Brazil has distinguished itself largely by its prowess of the fight against undernutrition. Poor nutrition leads to growth retardation. Lima et al. (2010) pointed out that in northeastern Brazil the policy adopted has led to an improvement in the lives of children, stunting has increased from 34% in 1986 to only 6% in 2006. To quickly reduce the scourge of "chronic undernutrition," Monteiro et al. (2009) explain that comprehensive statistical models increase the incomes of the poor associated with access to basic needs: schooling, sanitation, access to drinking water and health structures. For Ashley (2016), there is a very strong positive correlation between water security and nutrition security.

Weather conditions and environmental degradation

The way in which climate and the environment affect food security goes back in history because climate change is an old phenomenon but it is still relevant today due to population growth and changes in the ecosystem. Climate events are the main causes of food insecurity as shown by Haile (2005), Dilley et al. (2005), Dercon (2004) and Ashley (2016). Climate change is one of the major causes of food insecurity in the world as it affects the four dimensions of food security: food availability, food accessibility, food use and food system stability Ashley (2016).

In Africa, the majority of major food crises in recent years are caused by extreme events (Haile, 2005; Dilley et al., 2005; Dercon, 2004) has shown that the food crises of 1974, 1984/85, 1992 and 2002 that caused the loss of lives and livelihoods of millions of rural households were mainly caused by droughts. Ashley (2016) illustrates this link by two facts that have occurred in the African continent. The first event took place in the world where the Sahara dried up, people migrated to the Nile Valley in search of a comfortable and habitable area. Declining rainfall has led to the reduction of the Nile, which does not favor irrigation, and Egypt has experienced some difficulties. This extreme precariousness has led adults to eat their own children to survive. The second occurred in Ethiopia, with over-exploitation and inadequate exploitation of the ecosystem contributing to environmental degradation. At a time when the population was lower and rainfall was good, every Ethiopian household had 10 hectares but nowadays, with about 80 million Ethiopians, a household has only 0.4 hectare of arable land. Mismanagement of land also contributes to declining agricultural production and food insecurity.

Environmental degradation has become the norm in countries with concise environmental legislation. For example, the Somali environment is severely degraded due to high pastoral density, desertification, dry climate and deforestation. Countries with a large portion of the population that is rural and vulnerable (food insecurity) are often the first to be negatively impacted by climate shocks (Haile, 2005; Verwimp et al., 2012; Ashley, 2016). In sub-Saharan Africa, the poorest farming households have marginal lands vulnerable to disaster risk (Haile, 2005). Hence, those most affected are rural households whose livelihoods are highly dependent on traditional rain-fed agriculture Haile (2005).

Climate shocks disrupt and directly affect the process of agricultural production (Haile, 2005; Verwimp et al., 2012) and subsistence systems that are based on agriculture (Ashley, 2016). Haile (2005) evokes the fact that the precipitation pattern in sub-Saharan Africa is influenced by the high variability of climate, often resulting in extreme weather events such as droughts and floods that reduce agricultural production leading to food shortages. The effects of climate change on food security can be immediate or spread over time. For Ashley (2016), "the impacts will be short-term, resulting from more frequent and more intense extreme weather events, and in the long run, caused by changes in temperature and precipitation". In fact, a failure of the rainy season also causes agricultural failure while reducing food availability. Drimie (2003) also points that rural areas are the most exposed to climate hazards because most African households devote a large part of their agricultural production to personal consumption (Verwimp et al., 2012). It should also be added that the rural population derives the means for its subsistence in the agricultural sector, so agricultural households confronts themselves to the immediate risks of climatic shocks. These effects are an increase in poor harvests, new types of pests and diseases, and loss of livestock.

In addition, this situation is explained by the lack of basic infrastructure (roads and canals) and poor sanitation (Haile, 2005). In Zimbabwe, drylands are vulnerable and often experience acute food insecurity crises (Drimie, 2003). In the face of climate change, farmers do not have the right adaptation mechanisms to increase their production. Thus, poor agricultural policies lead to low productivity (Drimie, 2003). The food insecurity of the years 2001/2002 in Mozambique is explained by the lack of infrastructures that could create a connection between the different parts of the country. Drimie (2003) reported that the southern part had a good agricultural season and the infrastructure did not allow food to be transported to the center, which had a bad season. However, the effects are not concentrated only on individuals living in rural areas. They can affect all living people on the coast and in floodplains and in the mountains, drylands and the Arctic are the most endangered (Fao, 2015; Ashley, 2016). Even if the effects are not immediate on a category of people. Ashley (2016) cites the fact that low-income people all over the world, but especially in urban areas, will be food insecure due to asset loss and lack of adequate insurance coverage. It can also lead to changing vulnerabilities in developing and developed countries.

Internal and international migration caused by climate change is also a source of food insecurity because population growth certainly affects food systems (Ashley, 2016). They create situations of conflict and civil unrest. Migration, especially to poor countries, affects these countries because they do not have provisions and capacities to feed newcomers because of their economic and financial difficulties. They have failed to maintain their own population against hunger and other socioeconomic problems.

Institutional environment and governance system

States that do not have coordinated policies and invest little in agriculture and public services are not spared from food insecurity. For Ashley (2016)., "investments in public services such as roads and drainage, water supply and sanitation, health services and housing can all contribute to simultaneously reducing misery, urban decay and rural, food and nutrition insecurity ".

Failing policies can also come from international institutions (FAO, WFP, World Bank,

CILSS ...) that fight against poverty. The efforts of these institutions have also improved the situation in recent years, especially in West Africa. These institutions can also be given some responsibility for persistent food insecurity over several years. Haile (2005) pointed out that the multitude of these institutions and the plurality of policies do not make it possible to absorb food security in the countries of sub-Saharan Africa. For example, to make progress on nutrition security, nutrition-related policies, laws and institutions must be mastered.
Efforts and commitment must be visible at the national level for good coordination. Experiences and early warning mechanisms have enabled these institutions to become more dynamic and adopt more effective approaches (Ashley, 2016). ECOWAS, UEMOA, CILSS, Club Sahel and West Africa have put in place action plans to sustainably strengthen resilience in the Sahel in partnership with the European Commission. Participants under this partnership called "Global Alliance for Resilience Initiative (AGIR)" aim to "zero hunger" over the next twenty years. The goal is to strengthen the resilience of vulnerable populations by consolidating responses to food crises and the structural causes of food insecurity, as well as chronic undernutrition.
Poor countries do not allocate a large budget to the primary sector such as agriculture and livestock (Ashley, 2016). These countries often have corrupt governments whose public investment only concerns the defense and purchase of arms. To have good harvests and a better standard of living for farm households, governments need to revise their social systems and allocate a huge budget to the agricultural sector. In the era of globalization, the agricultural sector must be renewed and mechanized to achieve a certain productivity. Agriculture has become a highly competitive sector.

The quality of government and its policy determines to a certain extent the state of food security of the population. During civil wars, governments are reluctant and often refuse outside food intervention for fear of losing some information about the content of food aid. The delay in the completion of food aid can worsen the situation of the population. For example, the speed with which food aid is allowed to enter the zone or the existence of a food security problem depends on the political system (Haile, 2005; Verwimp et al., 2012).

In developing countries, financing for agriculture is a real problem. The absence of banks specializing in financing the agricultural sector is an obstacle to the development of the agricultural sector. Farmers should be encouraged and sensitized to adopt several varieties of crops, since crop diversification is a source of insurance requiring significant and regular financial support.
The lack of diversification of financing methods also poses a problem for the development of the agricultural sector. The current financing methods are not promising and do not make it possible to finance certain large-scale agricultural projects. The absence of public-private partnerships does not improve development results. This alliance is necessary to improve food availability and economic access for people (Ashley, 2016).

The fluidity of information makes it possible to have precise information as to a possible emergency mobilization in the event of a food crisis. The role of the media and civil society actors in the evolution of the food situation has also been the subject of several studies (Drèze and Sen, 1989; Devereux, 2001; Ashley, 2016).

Drèze and Sen (1989) point that by studying the couple "democracy and dictatorship" that the freedom of the media to report on the food situation will determine the rights of individuals and of course this information will serve as a warning to specialized bodies. For example, information on the influx of refugees and the conditions of reception in a refugee camp is information that must be provided in real time.
Governments must also be able to characterize the nature of famines and food crises (Drèze and Sen, 1989) in order to declare an emergency. To have a good image, governments do not reveal real information on the situation of local populations to their partners and donors. The television media never shows the majority of people living in disastrous conditions. The images presented remain superficial and do not shed any light on the situation of the majority of the population. They tend to disclose information and images from major regions and cities. Knowledge of the information allows NGOs and organizations to be active in helping vulnerable populations so as not to sink and end up in extreme insecurity, the exit of which requires additional costs and efforts.
In these countries, there is also a lack of resilience policies so that rural populations can face difficult situations so as not to become seriously food insecure (Haile, 2005; Ashley, 2016).

Political instability and insecurity

Insecurity and political instability is one of the main sources of food insecurity. In developing countries, and particularly in sub-Saharan Africa, food insecurity is persistent and is especially compounded by widespread political instability and conflict (Haile, 2005; Ashley, 2016). As a result, the socio-political system, the extent to which conflict affects the local food chain, and the income generation of the farm household will determine the (in) food security of the farmer (Verwimp et al., 2012). In the case of conflicts, farmers are forced to leave the fields and refuges in other areas (Verwimp et al., 2012) as their farmland becomes a battlefield and other factors of production are destroyed (Flores, 2004).
For example, the two civil wars in Liberia and the ethnic conflicts in Sudan and the two-year war in Eritrea (1998 with Ethiopia) are responsible for the long-term food insecurity that prevails until today in these countries. This food insecurity persists in Eritrea because the border zone of fighting "Gash Barka" is semi-arid and livelihoods were precarious and the conflict exacerbated precariousness. Thus, the poverty that prevails in this area has gone to structural poverty because the animals were stolen, the cultural material was looted. All these conditions made agriculture impossible Ashley (2016). This situation was concluded by (Ashley, 2016) : "Poverty in the region is so great, that many people there cannot afford to buy replacement batteries for their radios, which would enable them to listen to the news or government announcements on how they may relieve their poverty".

The decade-long civil war in Burundi caused the displacement of 50 percent of households. Households say they have moved several times a little over a year. These migrations were spread out over three agricultural seasons and during this period agricultural production fell sharply (Bundervoet et al., 2009). In addition, the war is causing migration and increasing food insecurity in these countries (Ashley, 2016).

In addition to reducing agricultural production, conflicts also affect household farm incomes by lowering crop sales and disrupting distribution channels (Verwimp et al., 2012).

For example, terrorist groups tend to feed themselves through road robberies, robberies and even sometimes by unequal occupation of fields. Armed robberies in times of security distress are commonplace and often involve livestock. However, livestock is an important source of income after agriculture for rural and agricultural households.

The plurality of sources of income allows households to hedge against hunger and famine, an act that economists call smoothing consumption (Verwimp et al., 2012). In the event of war, agricultural activity becomes a risky investment and the remaining choices for raising income is livestock. For farm households, livestock is a less risky but low-yielding investment (Dercon, 2004), and livestock distress sales in Burundi have been considered a trap of poverty and a loss of wealth (Verwimp et al., 2012; Bundervoet et al., 2009; Ashley, 2016). During Burundi's civil war, livestock numbers declined due to looting, forced migration, disease and distress sales (Verwimp et al., 2012).

The loss of household income explains malnutrition and of course food insecurity. Farmers tend to select crops in times of instability. For example, farming households decided to devote to subsistence crops during the civil war in Mozambique (Bozzoli and Brück, 2009). As a result, they abandon marketing crops that disrupt agricultural supply at the market level (Verwimp et al., 2012).

African societies often live in communities and some members of the family benefit from income from other agricultural activities. These may be teachers in local community schools or small traders. In the event of climate shocks, these incomes can be a stepping stone for families. In contrast, conflict shocks can affect and exacerbate the effects of climate shocks on the household situation (Verwimp et al., 2012). Faced with this decline in incomes and jobs, terrorist groups are recruiting more of the former agricultural population by offering high and consistent incomes (Verwimp et al., 2012). The increase in the number of terrorists weakens the area and the number of excesses increases and creates human and food insecurity.

Several studies (International Food Policy Research Institute, 1998 (Teodosijevic, 2003; De Soysa et al., 1999)) have linked food production and food security at the country level. The study of food production conducted by the International Food Policy Research Institute in 1998 on 14 countries whose purpose is to compare periods with and without conflict. The results showed that in 13 out of 14 countries food production was low during the war period. For example, the decreases were 3.4% in Kenya and 44% in Angola. Based on 38 countries facing conflict between 1961 and 2000, (Teodosijevic, 2003) shows that conflict impacts production by reducing the daily energy supply. FAO has also put in place a method for capturing agricultural losses during conflict periods from 1970 to 1997 in all developing countries. The results differ but remain very confused for the population of the countries and regions analyzed.
They show that in sub-Saharan Africa the losses recorded over this period correspond to about 75% of the total aid received by the countries affected by the conflicts. The disruption of the food chain (production, storage, and distribution) reduces the supply capacity of local markets and increases the demand for food. Indeed, the nature of the conflicts also have an important role on the food situation. Conflicts high extent isolate the interconnection between cities, regions and even countries exacerbate food insecurity blocking roads, rising

commodity prices, hunger, low supply (De Soysa et al., 1999).

Leasing agricultural land as a source of food insecurity

Today, renting farmland has become an economic model for some countries in need of land and water resources. This agriculture practiced outside the national territory allows these countries to fill their gaps and to be dynamic on the world market. However, this does not apply to all countries, but only to countries that lease part of their agricultural land to foreign companies and governments. In fact, land leasing can only be considered a cause of food insecurity in this category of countries.

Asian countries are the main tenants. Between 2008 and 2009, Ashley (2016) claims that 56 million hectares of land were contracted, compared to only 4 million hectares before 2008. The countries granting these lands are often the countries whose agriculture is not developed. or countries with a large national area. In granting land, these countries also consider filling some of the gaps (creation of employment, trade, etc.). The majority (about 2/3) of the land is in Africa (Liberia, Ethiopia, Sudan and Mozambique, Uganda and Tanzania). On the other hand, this creates a strong migration which creates an imbalance of population between the regions. Smallholders and some individuals will migrate to agricultural areas allocated to look for work and hope for higher incomes.

This trend does not ensure the sustainability of countries with a large number of small farmers. Hence this question from the Deininger and Byerlee (2011) and Chatterjee et al. (2012) reported by Ashley (2016), do such arrangements really benefit the host countries and farmers who previously cultivated the land ? The debates often turn on serious shortcomings of these tenants: the non-respect of agreements, temporary and poorly paid jobs, the payment of taxes. By engaging in these countries, they always come with the following formula: we will help to fight against poverty and participate in the development of the host country (Ashley, 2016).

This practice is referred to as "land grabbing" and is a threat to the food and nutrition security of smallholder farmers. Land tenure affects the land and water resources of villagers who depend on subsistence farming. They are also disregarded for derisory rights and they go to settle in unknown areas to rebuild a new life. In Africa, villagers have a strong relationship with their homeland. Tenants often practice intensive farming and large scale. This practice weakens the soil and degrades the ecosystem. Multinational firms are known for their poor protection of the environment. Smallholders do not contribute significantly to environmental degradation, unlike large agricultural industries, which are major agrochemical polluters favoring the loss of biodiversity (Ashley, 2016).

The sanitary environment and food security

Diseases weaken the human body. The sick person loses appetite and has difficulty eating certain foods. For Ashley (2016), to fight the food and nutritional insufficiency of an individual, this person must be healthy, that is to say in good health. Currently, sub-Saharan countries regularly suffer from malaria, cholera or HIV / AIDS. Indeed, the HIV / AIDS pandemic contributes to increased food insecurity and household vulnerability (Haile, 2005). In the agricultural sector, HIV / AIDS reduces the ability of households to

produce their own food leading to food insecurity (Haile, 2005). All these diseases weaken the immune system of man. Farmers or households where the primary member is in one of the situations are destabilized because the individual is unable to perform ER activity Ashley (2016). This lack of remuneration leads the individual or household to a situation of poverty and undernutrition.
The disease also affects the household budget because the costs and health costs are high. Medical examinations are difficult for poor households, the family and even some countries (Haile, 2005).
The causes and measures provide a clear idea of how much damage can be caused by food insecurity. Like any major problem, it has several consequences for the economic activity of individuals, households and states.

3.2.4 Economic consequences of food insecurity

Hunger and undernutrition can be both the main consequences of food insecurity and the cause. These two situations can also lead to political and personal insecurity at the national and regional levels (Ashley, 2016). In this section, we discuss the social and economic consequences of food insecurity.

Food insecurity and stability

Food insecurity is a source of conflict (Verwimp et al., 2012) since popular revolutions and uprisings are often protests related to poverty. These events often produce significant economic losses and damages (breakages, clashes between police and demonstrators, loss of life, etc.). The population can manifest following the rise in food prices. Rising food prices are a source of food insecurity for the poor and an additional gain for farmers selling crops. Given this situation, riots are created (Ashley, 2016; Verwimp et al., 2012) and call for a price review and control of inflation. For example, Ashley (2016) reported that urban riots in much of the developing world after the 2008 food price hike showed how political security and national balance can be disrupted. The situation in Liberia is a good illustration of this situation. The dismissal of the Liberian president in the 1980s was driven by rising food prices. Inconsistent policies and the situation of the population created stability (Flores, 2004).
During episodes of food insecurity, mortality increases and also the murders caused by witchcraft as indicated by Justino (2006) and reported by Verwimp et al. (2012) in these terms: "A particular type of violence, to wit the killing of so-called Witches deserves to be mentioned as it relates directly to bad weather, droughts and food insecurity. Miguel (2005) documents how the killing of witches occurs much more frequent in dryer years and how the victims are most often older women from poor families.

Poverty drives people to look for ways to over-live. Hungry people, for example, do not have national border boundaries, many become refugees in search of food and a stable environment where they can cultivate or earn income to buy food and eat properly. Often, the influx of these refugees into a host country causes problems, such as Syrian refugees in Lebanon, Ecuador in difficulty under the influx of Colombians and economic refugees from elsewhere. In Central America, they are employed on plantations in Belize rather than among Belizean nationals (Ashley, 2016). There is also the African case with Darfur, the refugees go to Chad and the Central African Republic to try to escape the famine. Local agencies allow these refugees to practice agriculture and other income-generating activities. It should also be remembered that the arrival of these refugees creates a problem for the host countries.

Impact on nutrition and psychology

Malnutrition has contrasting and harmful effects as it affects several spheres of the life cycle of humans (especially children). Indeed, the child's situation can not be captured by a single indicator because it depends on the state of food and other factors (Verwimp et al., 2012). These effects are continuous, irreversible and dangerous for physical growth (Verwimp et al., 2012) and the future life of the child. In other words, the economic conditions prevailing in early childhood often have lasting effects on children's health and socioeconomic outcomes in their lives.

Several studies (Alderman et al., 2006; Yamauchi et al., 2008; Ashley, 2016; Verwimp, 2006) focus on the impact of food security on children's health.
Alderman et al. (2006) studied the situation in Zimbabwe and find that malnutrition has negative effects on future human capital. This can be explained by the fact that pre-school malnourished children often have difficulties with their training. Ashley (2016) also points that undernutrition often leads to morbidity and death. However, the effect is very serious on infants and children because they have an organism in growth that requires the input of nutrients. In general, morbidity has a negative effect on educational and occupational outcomes and often a situation of poverty. Conversely, Yamauchi et al. (2008) show for South Africa athat well-nourished children tend to be productive, that is to say, they obtain good grades and scholarly results. Verwimp (2006) also showed that undernourished children have a higher probability of dying in the near future than children who are fed. This explains the difference in life expectancy between people in developing and developed countries. Life expectancy in developed countries is well above that of poor countries.

Impacts on the economic potential of countries

Food insecurity is an economic burden for a country. Developing countries are losing sight of this because they are based on operational policies by abandoning long-term strategic policies. Already in developing countries, governments are failing to combine population growth and economic growth. This inconsistency is a risk for the long term because these newborns are not well fed, cared for and educated. In the long run, all these children will grow up and be handicapped by illnesses related to poor nutrition. Economically, countries will have a shortfall since they will have several disabled people inactive to perform certain professional activities.

Ashley (2016) reports that hunger and malnutrition cause 2.6 million deaths a year. In developing countries, children are vulnerable and statistics are alarming. One in three children suffer from malnutrition. The social systems of these countries are not up to par because the malnutrition of infants and young children is caused by the poor diet of the mother. Undernutrition has adverse effects on the life of the child and the country, as Ashley (2016) points out: "It lowers intellectual and physical development, it reduces the capacity of tomorrow's adults to cope with adverse events. Gross domestic product

(GDP) each year, extending the cycle of poverty and impeding economic growth". Thus, persistent hunger and undernutrition reduce the economic potential of poor countries. It is impossible for countries to develop if food insecurity is putting pressure on different generations of the population. To develop, these countries must improve the food security situation and prevent the development of poverty (Ashley, 2016). In addition, Maccini and Yang (2009) mention that diseases and food security problems weigh on the family budget and represent a shortfall for the country in the long run. An active, healthy and well-educated population is an economic gain for families and the country.

After understanding the phenomenon of food security, we set up in the section an econometric model that allows us to analyze and understand more (in) food security in the Sahel countries.

3.2.5 Climate change and food security

In the empirical literature, different strategies and approaches have been used to assess the link between climate change and food security. All the studies are distinguished by the definition and construction of the food security variable and by the type of identification strategy used, i.e. linear regression models with Ordinary Least Squares (OLS) or instrumental variables (Jeronim Capaldo, 2010; Karfakis et al., 2011; Celia Reyes and Calubayan, 2014; A. Ervin and Gayoso de Ervin, 2019; Asfaw, 2015). Some authors use proxies (Belloumi, 2014; Eric and Kinda, 2016) while others construct a Food Security index (Ahmad Munir and Iqbal, 2015). Table 3.11 summarizes the articles that construct food security indicators and estimate the link between climate change and food security. Most studies focus on the poorest and therefore most vulnerable countries where food insecurity is a major problem for populations. Starting with Eric and Kinda (2016), developing countries have been widely studied given the serious food security challenges facing these countries, but with a focus on the countries of South America (Jeronim Capaldo, 2010; Karfakis et al., 2011; Celia Reyes and Calubayan, 2014; A. Ervin and Gayoso de Ervin, 2019), Asia (Ahmad Munir and Iqbal, 2015) and African countries (Belloumi, 2014; Asfaw, 2015; Masipa, 2017).

The spatial scales of analysis are diverse: agricultural producers (Ahmad Munir and Iqbal, 2015), households (Jeronim Capaldo, 2010; Karfakis et al., 2011; Asfaw, 2015; A. Ervin and Gayoso de Ervin, 2019), provinces (Celia Reyes and Calubayan, 2014), or countries (Belloumi, 2014; Eric and Kinda, 2016; Masipa, 2017).

The variables explained are also different. Some authors (Belloumi, 2014; Celia Reyes and Calubayan, 2014; Asfaw, 2015; Ahmad Munir and Iqbal, 2015; Eric and Kinda, 2016) use proxies directly (i.e. food production for Belloumi, 2014; vulnerability index for Karfakis et al., 2011; net income of crops for Asfaw, 2015; value of food consumed by the adult equivalent for Celia Reyes and Calubayan, 2014 and Eric and Kinda, 2016; combinations of proxies (agricultural productivity, calories consumption per capita, food consumption for A. Ervin and Gayoso de Ervin, 2019) and others such as Ahmad Munir and Iqbal, 2015 construct a food security index.

These variables are regressed in relation to the climatic variables and to the other control variables corresponding to the socioeconomic data. Climate variables generally refer to temperature and precipitation (Karfakis et al., 2011; Belloumi, 2014; Celia Reyes and Calubayan, 2014; Asfaw, 2015; Ahmad Munir and Iqbal, 2015; Masipa, 2017; A. Ervin and Gayoso de Ervin, 2019), or climatic shocks such as drought, floods and extreme temperatures (Jeronim Capaldo, 2010; Eric and Kinda, 2016).

Using binary models, linear regression with instrumental variable or panel data, the effects of climatic variables vary according to scales and but remain almost unanimous. Climate change affects food security. It disrupts agricultural production, reduces food availability and also affects the distribution of food. For example (Eric and Kinda, 2016) show that climate change (variability in the water balance, droughts, floods and extreme temperatures) reduces food availability in the affected countries A. Ervin and Gayoso de Ervin (2019) show that increasing temperatures and decreasing rainfall will reduce agricultural productivity and caloric consumption, and increase vulnerability to food insecurity. In addition, Masipa (2017) shows that climate change poses a high risk for food security in sub-Saharan countries, from agricultural production to food distribution and consumption.

However, these models and approaches do not take into account the fact that food security is a multidimensional aspect and therefore we argue that using only one proxy or variable used does not give a correct and relevant measure with the evolution of the definition of food security. In this chapter, we set up a multidimensional approach (see section 3.2.2 for the four dimensions) and we build our dimensional indices on the basis of several components and indices of the FAO (2019). We turn to the construction of our indices below.

3.3 Methodology and application: food security in Sahel

3.3.1 Construction of indices of the four dimensions of food security

In our analysis, we use the measurement based on the four dimensions as described in the following section 3.2.2. Food security measures must capture the four dimensions of availability, access, use, food stability over time or a combination of these determinants (Babu et al., 2014; Jones et al., 2013). However, it is impossible to capture each dimension of food security with just one variable. We therefore develop a global food security indicator and separate indices for each of the dimensions of food security. For that purpose, we use principal components analysis (Husson et al., 2016; Ahmad Munir and Iqbal, 2015), which constructs linear combinations of a set of correlated indicators, reducing them into factors while extracting the greatest variance from the original variables.
The variables on which we base the principal component analysis are as follows: (1) *availability* (average dietary energy supply adequacy, average value of food production, average proteine supply, average supply of protein of animal origin, share of dietary energy supply derived from cereals, roots and tubers), (2) *accessibility* (prevalence of undernourishment, number of people undernourished), (3) *utilization* (people using at least basic drinking water services, percentage of population using at least basic sanitation services, prevalence of anemia among women of reproduction age, prevalence of obesity in the adult population) and (4) *stability* (cereal import dependency ratio, percent of arable

land equipped for irrigation, rate of dependance on cereal imports (%), value of food imports in total merchandise exports, per capita food production variability, per capita food supply variability, variability in food production per capita, variability in food availability per capita). Further information on these indicators is detailed in section 3.4.2.
The proposed factorial model can be represented econometrically as follows:

$$Y_i = a_1 X_{1i} + a_2 X_{2i} + ... + a_n X_{ni} \tag{3.1}$$

where Y_i represents factors or a linear combination of variables. It can be a global indicator of food security or an index constructed to represent one of the four dimensions (availability, accessibility, use and stability) of food security, X_{ni} represent indicators from 1 to n for the factor i and a indicates factor charges. Our model uses the global index of food insecurity and the four sub-indices of availability, accessibility, utilization and stability of food security as dependent variables.

3.3.2 Econometric specification

In addition to climate, food security in the Sahel countries also depends on other socioeconomic factors. These factors can strongly affect the food demand of local populations. We use panel data because these models because it allows us to have an overview of the phenonema over several years and delay our variable of interest because the past climate shock affects present consumption.
The standard model 3.2 that we use takes the following form:

$$FS_{k,i,t} = \alpha_i + \beta_1 Shock_{i,t-1} + X'_{i,t}\beta + \epsilon_{i,t} \tag{3.2}$$

where $FS_{k,i,t}$ is the food security indicator k of country i in year t, α_i is the country specific constant if the model is estimated by a fixed effects model and is part of the error term if estimated by random effects, $Shock_{i,t-1}$ is the occurrence of $drought$ and $flood$ for country i if there is a shock in year $t-1$.
The use of this specification makes it possible to check whether food insecurity in the Sahel is caused solely by climatic shocks or other essential factors: $X'_{i,t}$ represents the vector of control variables that affect food security and $\epsilon_{i,t}$ represents the error term.

Model 3.3 is the version of the model 3.2 without the variables of interest ($drought$ and $flood$), but only taking into account the control variables:

$$\begin{aligned} FS_{k,i,t} = \alpha_i + \beta_1 Yield_{i,t} + \beta_2 GDP_{i,t} + \beta_3 Pop_{i,t} + \beta_4 Import_{i,t} \\ + \beta_5 Stability_{i,t} + \beta_6 Inflation_{i,t} + \epsilon_{i,t} \end{aligned} \tag{3.3}$$

$Yield_{i,t}$ is the cereal yield of country i for year t. $GDP_{i,t}$ is the Gross Domestic Product per capita of country i for year t. $Pop_{i,t}$ denotes the population growth of the country i in year t. $Import_{i,t}$ and $Stability_{i,t}$ respectively represent cereal imports and the stability and absence of violence in country i during year t. Finally, $Inflation_{i,t}$ denotes the inflation of consumer product prices for country i in year t. Insitutional variables are very stable in time, so that we consider them to be included in the individual effects.

Finally, we also use the following final model 3.4:

$$\begin{aligned} FS_{k,i,t} = \alpha_i + \beta 1 Drought_{i,t-1} + \beta 2 Flood_{i,t-1} + \beta_3 Yield_{i,t} + \beta_4 GDP_{i,t} + \\ \beta_5 Pop_{i,t} + \beta_6 Import_{i,t} + \beta_7 Stability_{i,t} + \beta_8 Inflation_{i,t} + \epsilon_{i,t} \end{aligned} \tag{3.4}$$

where $Drought_{i,t-1}$ and $Flood_{i,t-1}$ are the occurrence of these two climatic shocks of country i in year t.

These events are independent and the occurrence differs from one country to another. We adopt this specification strategy because during a year, three cases can arise:

i Neither flood nor drought: leading to a regression on socio-economic variables.

ii One of two events, either flood or drought.

iii Both phenomena at the same time.

Then, our specification takes account the fact that an event of the previous year $(t-1)$ can have a considerable impact on the food security of year (t). The Hausman test shows that the fixed-effect panel model is more appropriate.

3.4 Data

3.4.1 Study area

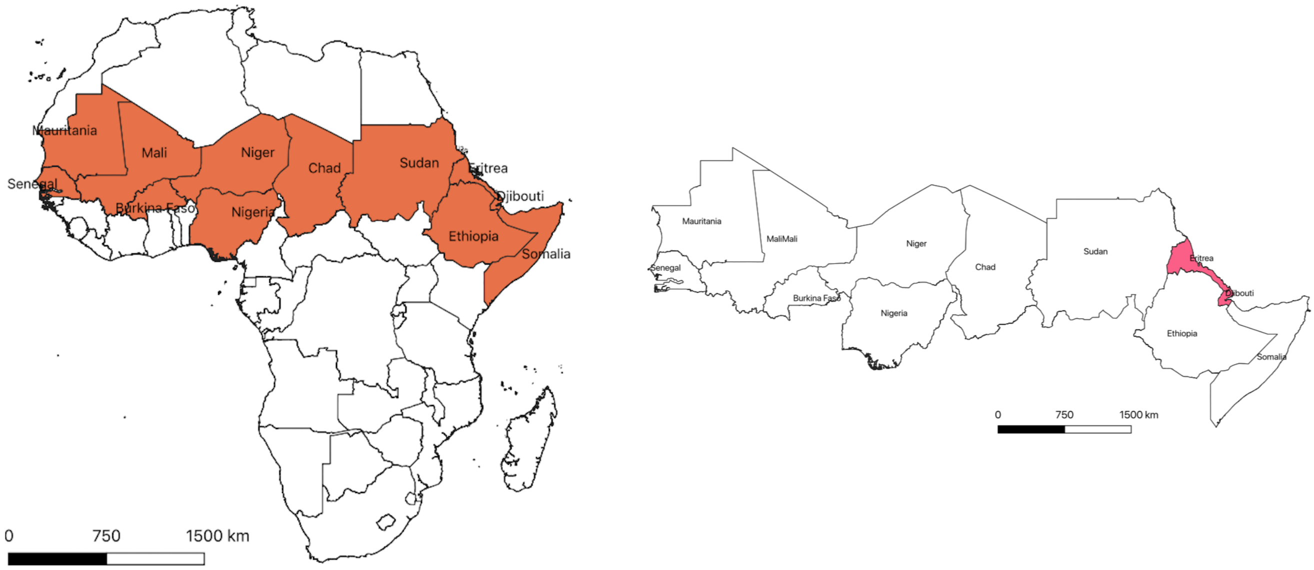
Our perimeter covers 12 countries in the Sahel (Burkina Faso, Chad, Djibouti, Eritrea, Ethiopia, Mali, Mauritania, Niger, Nigeria, Senegal, Somalia and Sudan, see figure 3.1), and covers a period from 2000 to 2016. This choice of period is justified by the unavailability of data on food security security variables, which are provided by FAO from 2002 onwards in the countries of the Sahel. Furthermore, this definition of the Sahel is special because we have chosen countries with the same climatic characteristics and cyclically confronted with food crises. Although Eritrea and Djibouti are part of this new definition of the Sahel, they are removed from the sample due to the lack of data. All variable for food security data are from the Food and Agriculture Organization of the United Nations (2019).

3.4.2 Food security indicators

As mentioned in the section 3.4.2, food security is based on four dimensions. FAO (2019) provides a whole list of food security indicators according to these dimensions. We therefore select 16 indicators distributed according to the four dimensions with their descriptive statistics.

We then implement four principal component analyzes to build the four food security indices (availability index, accessibility index, use index and stability index), the results of which are displayed in figures 3.4, 3.5, 3.6 and 3.7 in the appendix. The objective of this principal component analysis is to capture the weights of the variables on the first dimension in order to use them in the construction of food security indices. The red dotted line on the different graphs 3.4, 3.5, 3.6 and 3.7 in the appendix gives the expected average contribution. If the contribution of the variables was uniform, the expected value would be $1/length(variables) = 1/10 = 10\%$ (Kassambara, 2017). For the construction of our indices and for each given component, all the variables with a contribution above this threshold are considered important to contribute to the component.

Figure 3.1Study area



Source: Author

Availability

This first dimension captures the availability of food and includes all types of food regardless of their source (domestic production, imports, stocks and food aid). In addition, food may be available in the family farm, the attic, the kitchen, the store and the market (Ashley, 2016; Reig et al., 2012). The set of indicators included to capture this dimension reflects the supply of food in terms of energy, per capita value and supply. The principal component analysis is applied to 5 indicators for this first dimension and and their descriptive statistics are given by table 3.1.

1 **Average dietary energy supply adequacy (percent) (3-year average)**:
This indicator measures food energy intake as a percentage of average food energy needs in each country. They are expressed in terms of calories and depend on the social and demographic structure of their population.

2 **Per capita value of food production** This indicator is the ratio between the total value of annual food production and the total population of each country, and gives essential information on the food availability of each inhabitant.

3 **Share of food energy intake derived from cereals, roots and tubers in%**
This indicator is expressed as a percentage of the total Dietary Energy Supply (DES) (in kcal/caput/day) and captures the diversity of food supply at the country level. In other words, it indicates the range of consumption choices and nutrients available to the population.

4 **Average protein supply (g / cap / day) (3-year average)**
This indicator measures the average national protein supply (expressed in grams per capita and per day) and provides information on the quality of the diet of the population of the countries.

5 **Average supply of protein of animal origin (g / cap / day) (3-year average)**
The indicator measures the average national protein supply (expressed in grams per capita per day, for example, meat, seafood, fish) and also provides details on the quality of the diet.

Table 3.1Descriptive statistics of the indicators of the first dimension of food security.

Dimension	Indicator	Description	Source	Mean	Std.Dev.
Availability	Av_dienergy	Average dietary energy supply adequacy (percent) (3-year average)	FAO, 2019	109,90	16,27
	va_fodprod	Average value of food production (constant 2004-2006 I$/cap) (3-year average)	FAO, 2019	151,61	41,92
	Sha_dietary	Share of dietary energy supply derived from cereals, roots and tubers (kcal/cap/day) (3-year average)	FAO, 2019	63,85	7,89
	av_Proteine	Average proteine supply (g/ cap / day)(3-year average)	FAO, 2019	67,63	9,03
	av_Proteinanim	Average supply of protein of animal origin (g/ cap / day)(3-year average)	FAO, 2019	15,21	7,72
Sample	10				
Indicators	19				
Sample size	170				

The results of the construction of the first dimension are grouped in the graphic series in the appendix (see figure 3.4 and the table 3.12). Axis 1 has an inertia of 61.90%. Furthermore, graph 3.4 of the correlation circle and table 3.12 show that all the variables are correlated to axis 1 but contribute distinctly to its construction. The variables *av_protein* (26.32%), *av_proteinanim* (21.50%) and *Sha_dietary* (20.74%) are those which contribute the most to the construction of this axis. For these three variables, we have a very high and positive correlation close to 1 indicating that they are very related to the coordinates on the axis 1. Finally, figure 3.4 and table 3.12 show that the three variables are also very well projected because they are close to the circle of correlation. These contributions are used to build the availability index called "*Availability_index*".

Accessibility

This second dimension captures all aspects related to the social, physical and economic access of populations to available food. Being an important component in the definition of food security, it evokes a key problem based on inequalities (poverty, income disparities), especially in countries whose infrastructure is not developed (Ashley, 2016). Both of the two indicators covered by the principal component analysis below relate to people's accessibility to food (see descriptive statistics in the table 3.2).

Due to data unavailability, we only have two variables for this second dimension for the countries in our sample. Consequently, the implementation of a principal component analysis on two variables is questionable as it amounts to averaging the two variables but this choice is justified by a question of integrated methodology for all dimensions.

1 **Prevalence of undernourishment**
This indicator is expressed in terms of the proportion of undernourished people in the population of a given country or region. Furthermore, the measure is not based on

the actual count of undernourished people in a country, but on the probability that a person is undernourished.

2 **Number of people undernourished (million) Average number of undernourished people**
This indicator measures the number of undernourished people in each country. It brings together all the people suffering from malnutrition and who are in a situation of undernourishment.

Table 3.2Descriptive statistics of the indicators of the second dimension of food security.

Dimension	Indicator	Description	Source	Mean	Std.Dev.
Accessibility	Prev_ under	Prevalence of undernourishment (percent) (3-year average)	FAO, 2019	19,75	12,05
	NumPeo_un	Number of people undernourished (million) (3-year average)	FAO, 2019	6,84	9,00
Sample	10				
Indicators	19				
Sample size	170				

The results of the construction of the second dimension are given by the graphic series 3.5 and the table 3.13 in the appendix. We recall that the factors used only depend on the availability of data, here we only have two variables. The results indicate that the variables have the same inertias and contribute identically to the construction of axis 1. The variance is explained by the first dimension, i.e 76.90%, using the elbow criterion which allows the axes to be selected before the offset. In addition, the variables are highly projected due to their proximity to the circle of correlations. The factors $Prev\_under$ and $NumPeo\_un$ contribute to the same height of 50% both in the first dimension and in the second dimension. These contributions make it possible to build the accessibility index called "$Index\_acessibility$".

Utilization

It relates to the use of food and is concerned with the use people make of available food in terms of nutritional value (Ashley, 2016). Overall, it provides an overview of the effect of food on consumers while allowing the assessment of the health status of consumers (FAO., 2014; Ashley, 2016).
Table 3.3 gives the descriptive statistics of the 5 indicators used in the implementation of the principal component analysis of this third dimension.

1 **People using at least basic drinking water services (% of population)**
Percentage of people using at least basic water services. This indicator covers both people using basic water services and those using safely managed water services (drinking water services). Access to better water and sanitation services directly supports the proper use of food.

2 **Percentage of population using at least basic sanitation services (% of population)**
This indicator includes both people using basic sanitation services and those using safely managed sanitation services, individuals and not shared with other households. In other words, it indicates the proportion of the population with at least adequate access to basic human waste disposal facilities.

3 **Prevalence of anemia among women of reproductive age (15-49 years)**
Prevalence of anemia in pregnant women (anaemiapreg) This indicator captures the prevalence of anemia during periods of pregnancy. It captures the proportion of pregnant women whose hemoglobin level is below the minimum required (110 grams per liter at sea level). Iron deficiency is mainly considered to be the root cause of anemia.

4 **Prevalence of obesity in the adult population (18 years and older**
It designates the prevalence of obesity in the adult population, i.e. 18 years and over, and is expressed as % of the total population.

Table 3.3Descriptive statistics of the indicators of the third dimension of food security.

Dimension	Indicator	Description	Source	Mean	Std.Dev.
Utilization	bsicwter_ ser	Percentage of population using at least basic drinking water services (percent)	FAO, 2019	49,27	14,15
	bsicsan_ser	Percentage of population using at least basic sanitation services (percent)	FAO, 2019	22,35	12,46
	anem_wom	Prevalence of anemia among women of reproductive age (15-49 years)	FAO, 2019	46,13	10,50
	Prv_obsty	Prevalence of obesity in the adult population (18 years and older)	FAO, 2019	4,56	1,92
Sample	10				
Indicators	19				
Sample size	170				

The results of the construction of the third dimension are given by the graphic series 3.6 and the table 3.14 in the appendix. Axis 1 groups together 66.50% of inertia, thus explaining the large part of the variability. The factors *bsicwter_ser*, *Prv_obsty* and *bsicsan_ser* contribute respectively to 33.25%, 31.60% and 34.80% in the construction of dimension 1. All these variables are very correlated and positive to axis 1, close to 1. In addition, they are also well projected because they are close to the circle of correlations while being very linked to the coordinates on axis 1.

Stability

At the country level, food stability is achieved when the entire population receives food at all times and has an active and healthy life. It concerns the stability and sustainability of the food source over time (Aurino, 2014; FAO., 2014; Ashley, 2016).

Five indicators are used for the construction of the component analysis for this fourth dimension, the descriptive statistics of which are shared in table 3.4.

1 **Percent of arable land equipped for irrigation (%) (3-year average)**
This indicator is the ratio between arable land equipped for irrigation and total arable land (dependence of a country on irrigation).
It captures the vulnerability of agriculture to water stress and climate shocks (such as droughts and floods). At the country level, this imbalance is likely to have effects on national food security due to production and trade patterns.

2 **Rate of dependance on cereal imports %**
The dependence ratio on cereal imports indicates the share of domestic food supply

available in cereals that has been imported and the share of domestic production. In addition, it gives a measure of the dependence of a country or a region on grain imports. The larger the indicator, the higher the dependency.

3 **Value of food imports in total merchandise exports (percent) (3-year average)**
It is the share of the value of food imports (excluding fish) in total merchandise exports. In addition, it provides a measure of vulnerability and captures the adequacy of foreign exchange reserves to pay for food imports. At the country level, this situation has effects on national food security depending on production and business models.

4 **Per capita food production variability (constant 2004-2006 thousand int $ per capita)**
This indicator corresponds to the variability of the "value of net food production per capita in constant international dollars 2004-2006". Indeed, it compares variations in food production per capita from one country and from one period to another.

5 **Per capita food supply variability (kcal / cap / day)**
This indicator corresponds to the variability of "food supply in kcal / capita / day" and makes it possible to compare variations in food supply from one country and from one period to another.

Table 3.4Descriptive statistics of the indicators of the fourth dimension of food security.

Dimension	**Indicator**	**Description**	**Source**	**Mean**	Std.Dev.
	Pe_ara_land	Percent of arable land equipped for irrigation (percent) (3-year average)	FAO, 2019	4,95	5,48
	Td_M	Rate of dependence on cereal imports (%) (3-year average.	FAO, 2019	30,75	35,50
Stability	Va_M_alim	Value of food imports relative to total merchandise exports (%) (3-year average)	FAO, 2019	26,08	21,36
	Per_capitaFoodPro	Per capita food production variability (constant 2004-2006 thousand in $ per capita)	FAO, 2019	9,20	5,73
	Per_capFoodSupply	Per capita food supply variability (kcal / cap/ day)	FAO, 2019	32,03	15,10
Sample	10				
Indicators	19				
Sample size	170				

The results of the construction of the fourth dimension are given by the graphic series 3.7 and the table 3.15 in the appendix. Axis 1 represents 40% of inertia and axis 2 approximately 27.4%. The factors *Td_M* and *Pe_ara_land* contribute respectively to 42.51 % and 38.36 % in the construction of axis 1. We have a very high correlation for the two variables close to , meaning that *Td_M* and *Pe_ara_land* are very much linked to the coordinates on axis 1. In addition, the analysis of the results of the figure 3.7 and the table 3.15 shows that these variables are well projected because they are close to the circle of correlations. These contributions are sufficient to build the stability index called "*Index_stability*".

Summarizing, in the four Principal Component Analyzes, the first component explains respectively 61.90%, 76.90%, 66.50% and 40% of the total variance of the variables. These figures are higher that the ones in Bilan et al. (2018) who used a factor with an inertia of

48.37% to assess the impact of environmental determinants on the state of food security in 28 post-socialist countries, of Reig et al. (2012) studied food security in African and Arab countries and obtained a proportion of 56.2%, of Demeke et al. (2011) who used 32.5% to study the effects of climate change on food security in Ethiopia and Nyaga et al. (2009) extracted a proportion of 34% to predict the factors affecting food security in the district of Murang'a in Kenya.

3.4.3 Variables of interest

We measure climate change by the occurrence of extreme events such as droughts and floods (as in Eric and Kinda, 2016). These two events are natural disasters and are provided by the database (EM-DAT) of the Center for Research on the Epidemiology of Disasters (CRED). The definitions of drought and floods given by CRED are presented in Table 3.5, which also gives their descriptive statistics. The inclusion of these two variables of climatic interest makes it possible to verify their direct links with the food security situation in the Sahel countries. They measure the number of events that occurred in a country in a given year, because these two shocks are distinguished by their intensity and the damage (human loss, economic and monetary damage) caused in the countries. In addition, they are distinguished by their impact on food security, in particular on the four dimensions. In

Table 3.5Statistical description of the variables of interest.

Variables	Description	Source	Mean	Std.Dev.
Drought	An extended period of unusually low precipitation that produces a shortages of water for people, animals and plants. Drought is different from most other hazards in that it develops slowly, sometimes even years, and its onset is generally difficult to detect. Drought is not solely a physical phenomenon because its impacts can be exacerbated by human activities and water supply demands. Drought is therefore often defined both conceptually and operationally. Operational definitions of drought, meaning the degree of precipitation reduction that constitutes a drought, vary locality, climate and environmental sector.	EM DAT(2019)	0,23	0,42
Flood	A general term for the overflow of water from a stream channel onto normally dry land in the floodpain (riverine flooding), higher than normal levels along the coast and in lakes or reservoirs (coastal flooding) as well as ponding of water at or near the point where the rain fell (flash floods)	EM DAT(2019)	1,14	1,11
Number	10			
Sample size	170			

the Sahel, climate is an essential input in agricultural activities and the agricultural sector constitutes the main source of household income and food for most households. Intuitively, droughts should have a considerable impact on the food security of these populations. Figure 3.2 shows the spatial distribution of droughts and floods in the Sahel countries from 1961 to 2016.

3.4.4 Socioeconomic variables

This set of variables is composed of agricultural factors (cereal yield), the level of economic development (measured by real GDP per capita), demographic characteristics of population (demographic growth), imports (cereal imports), political stability and the absence of violence (stability) and inflation (consumer prices). The control variables selected are

Figure 3.2Total occurrence of the two natural climatic disasters from 1961 to 2016 in the Sahel countries.

Fig 3.2.a. Drought

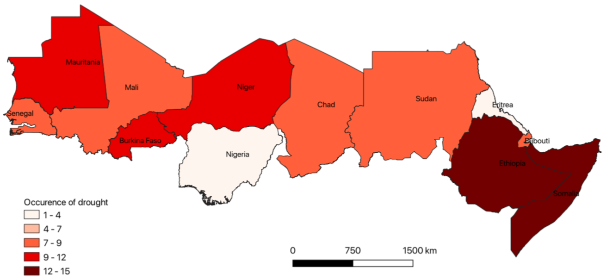
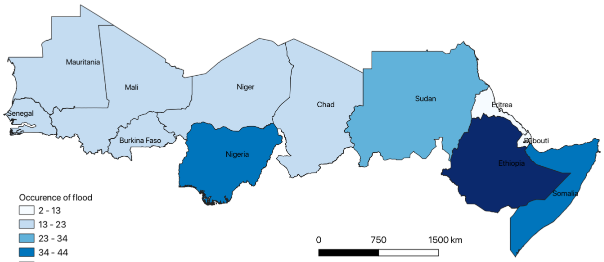


Fig 3.2.b. Flood



Source: Calculations and achievements by the author using data from the EM-DAT Unit (2019)

presented in Table 3.6 and described in the following points are the main determinants of food security.

1 Cereal yield
The cereal yield gives an idea of the cereal production of the countries. Cereal yield can contribute to food security as it can inform about the availability of cereals at country level. This variable thus makes it possible to control the impact of agricultural production on food security.

2 Gross Domestic Product
The inclusion of GDP per capita helps control the impact of economic growth or the wealth of the population on food security. It plays an important but indirect role in improving food security. Indeed, it allows populations to access available food, and it can also have effects on all the other dimensions.

3 Population growth
The growing population leads to increased demand for food. Faced with limited food resources (water resources, agricultural land and infrastructure), population growth reduces these resources and constitutes an obstacle to the achievement of food security. Intuitively, higher population growth will lead to poor food security.

4 Cereal imports
Cereal imports are intended to help met the domestic food deficit. Logically, an import improves domestic food availabilty. Although its effect is mixed, it positively affects food security if the other dimensions are satisfied.

5 Stability
Stability is a very important aspect in the definition of food security. In other words, people can have food in the absence of conflict and insecurity. Political and social stability can guarantee the achievement of food security. Instability linked to terrorism and armed/civil conflicts can disrupt the food chain from to marketing.

6 Inflation
Inflation affects people's food purchasing decisions and can even affect producers. Inflation has negative effects on food security by reducing food availability, making food inacessible to people. Based on all four dimensions, inflation can lead to reduced food use.

The descriptive statistics of socioeconomic variables are presented in Table 3.6.

Table 3.6Descriptive statistics of socioeconomic variables

Variables	Description	Source	Mean	Std.Dev.
GDP per capita	GDP at market prices is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not includes in the value of the product (US$)	FAO(2019)	735,74	593,36
Population growth	Annual population growth rate for year t is the exponential rate of growth of midyear population from year t-1 to t, expressed as a percentage . Population is based on the de facto definition of population, which counts all residents regardless of legal status or citizenship.	FAO(2019)	2,94	0,41
Cereal yield	Cereal yield mesured as kilograms per hectare of harvester land, includes wheat, rice, maize, barley, oats, rye, millet, sorghum, bucketwheat, and mixed grains. Production data on cereals relate to crops harvested for dry grain only. Cereal crops harvested.	FAO(2019)	9870,5	4422,6
Inflation price	Inflation as measured by the consumer price index reflects the annual percentage change in the cost to the average consumer of acquiring a basket of goods and services that may be fixed or changed at specified intervals, such as yearly. The Laspeyres formula is generally used.	FAO(2019)	6,14	8,03
Cereal imported	Imports data (in metric tons) on cereals relate to crops harvested for dry grain only. Cereal crops harvested green for food, feed, or sillage and those used for grazing are excluded. (000 metric tons)	FAO(2019)	1268,1	1609,87
Political Stability	Political Stability and Absence of Violence/Terrorism measures perceptions of the likelihood of political instability and/or politically-motivated violence, including terrorism. Estimate gives the country's score on the aggregate indicator, in units of a standard normal distribution, i.e. ranging from approximately -2.5 to 2.5.	FAO(2019)	-1,20	0,94
Number	10			
Sample size	204			

3.5 Results and discussion

In all our tables, the first column presents the estimation results including only the socioeconomic variables. The second column presents the estimation results for the occurrence of the floods on food security. The third column presents the estimation results for the occurrence of drought on food security. Finally, the last model assesses the effect of both drought and floods on food security.

The results in column 1 of Table 3.7 show that population growth, consumer inflation and imports have negative and very significant effects on food availability. Most of the Sahelian population lives below the poverty line on less than a dollar a day. The permanent rise in prices makes certain foods sometimes inaccessible and indirectly increases the food insecurity of the population. In other words, they cannot access markets and consume very nutritious food. Price affects the choice of consumer decisions and affects the basket of very poor households. Although grain imports are made to compensate for the domestic food deficit. Not all people have access due to low income and high food prices on local markets. GDP per capita has a positive and very significant impact even in the case of drought and floods. Intuitively, individuals who create more wealth or have sufficient financial resources will not be affected in the short term by food insecurity. Monetary availability improves the food security situation for the people of the Sahel. The current effect will be less for less poor populations. The impact of cereal yield is negative but not significant even in the case of droughts and floods on food availability. The stability or absence of violence has positive and very significant effects on food security for all models (see all columns of table 3.7). In the Sahel, conflicts and civil wars are also one of the sources of declining agricultural production and income, exacerbating the food situation. Terrorism generates to some extent cyclical food crises.
The effect of drought and floods in the previous year is positive but not significant on food availability. In other words, these two events have no negative and significant effects on the national supply of proteins, animal proteins and the food energy supply of the populations. Intuitively, the availability and the quality of food of the Sahelian populations were not disturbed by the occurrence of drought and floods. These results can be explained by the fact that households generally have stocks of cereals which cover their food consumption for a short period (lean period). In addition, certain populations benefit from food aid to be able to adjust and compensate for their food for a certain period.
In addition to the negative effects of other socioeconomic variables, other configurations may explain this first dimension. The absence of infrastructure and the absence of nearby local markets make food unavailable in households (Haile, 2005). The techniques are not developed to keep the crops well because of the lack of infrastructure. Food waste and crop losses are recurrent causing food insecurity. Farmers lack the training to adapt to climate change and reduce the loss of agricultural crops (Drimie, 2003). Diseases that make farmers vulnerable preventing any agricultural activity therefore no food availability to cover food consumption.

The estimation results of table 3.8 in column 1 show that even in the absence of drought or flooding, all factors (cereal yield, population growth, cereal import) have negative effects on food accessibility. These results are motivated by the situation in the Sahel countries, the current determinants do not guarantee accessibility to food, thus deteriorating food

Table 3.7Results of estimation for the first dimension of food security

	First dimension: availabilty			
	Indice_availability			
	(1)	(2)	(3)	(4)
Flood		0.152		0.143
		(0.132)		(0.132)
Droughts			0.485	0.464
			(0.363)	(0.363)
Cereal_yield	−0.00004	−0.00004	−0.00003	−0.00003
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
GDP_Capita	0.003***	0.003***	0.003***	0.003***
	(0.0005)	(0.0005)	(0.0005)	(0.0005)
Pop_growth	−6.957***	−7.004***	−7.026***	−7.008***
	(1.125)	(1.133)	(1.130)	(1.129)
CerealM	−0.001***	−0.001***	−0.001***	−0.001***
	(0.0003)	(0.0003)	(0.0003)	(0.0003)
stability	1.348***	1.357***	1.385***	1.387***
	(0.365)	(0.365)	(0.365)	(0.365)
Inf_consprices	−0.057**	−0.058**	−0.067***	−0.068***
	(0.023)	(0.023)	(0.024)	(0.024)
Observations	106	105	105	105
R^2	0.536	0.544	0.547	0.553
Adjusted R^2	0.464	0.467	0.470	0.471
F Statistic	17.500*** (df = 6; 91)	15.183*** (df = 7; 89)	15.327*** (df = 7; 89)	13.584*** (df = 8; 88)
Model	Individual	Individual	Individual	Individual
Note:				*p<0.1; **p<0.05; ***p<0.01

security in the Sahel countries. The effect is negative and very significant for cereal yields, population growth, food market inflation and cereal imports. Low cereal yields and imports that do not cover domestic demand mean that no population has access to food. The Sahel is characterized by a drop in food production resulting in an increase in food prices thus limiting the accessibility to food of a large part of the population. In addition, the rate of population growth is growing faster than the rate of economic growth. The effect is negative but not significant for GDP per capita. Stability has a positive and significant effect for improving food security in all models (see table 3.8) even in the absence of climatic phenomena. It plays an important role in explaining food security.
The situation is exacerbated by the occurrence of flooding. Its effect is negative and not significant when one of the two events occurs. It also appears that when the two events occur, the effect is only negative for floods. Therefore, the results show that drought has negative and non-significant effects on diet, causes undernourishment and increases the likelihood that a person will be undernourished. In the presence of drought, floods further increase the number of malnourished people. On the other hand, the effects of drought on the malnutrition of people are positive but not significant. This corresponds to the reality of the Sahel, the floods do a lot of damage (see figure 3.3 in the appendix).

The results in column 1 of Table 3.9 show that the effect on use is negative and very significant for cereal yield, GDP per capita, cereal imports and food inflation in the absence of climate shocks. These results are valid for the four models. For people to make good

Table 3.8Results of estimation for the second dimension of food security.

	Second dimension: Accessibility			
	Indice_accessibility			
	(1)	(2)	(3)	(4)
Flood		−0.370		−0.371
		(0.233)		(0.235)
Droughts			0.054	0.102
			(0.655)	(0.650)
Cereal_yield	−0.001***	−0.001***	−0.001***	−0.001***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
GDP_Capita	−0.001	−0.001	−0.001	−0.001
	(0.001)	(0.001)	(0.001)	(0.001)
Pop_growth	−6.463***	−6.627***	−6.563***	−6.626***
	(2.001)	(2.003)	(2.031)	(2.014)
CerealM	−0.002***	−0.002***	−0.002***	−0.002***
	(0.001)	(0.001)	(0.001)	(0.001)
stability	1.497**	1.495**	1.508**	1.502**
	(0.647)	(0.644)	(0.655)	(0.649)
Inf_consprices	−0.174***	−0.174***	−0.176***	−0.176***
	(0.042)	(0.042)	(0.044)	(0.044)
Observations	105	104	104	104
R^2	0.616	0.626	0.616	0.626
Adjusted R^2	0.556	0.563	0.550	0.558
F Statistic	24.018*** (df = 6; 90)	21.077*** (df = 7; 88)	20.148*** (df = 7; 88)	18.241*** (df = 8; 87)
Model	Individual	Individual	Individual	Individual
Note:				*p<0.1; **p<0.05; ***p<0.01

use of food, it must be available and accessible properly. The effect is positive and very significant for political stability and absence of violence for all models. The peace and tranquility of the institutional framework ensures a good climate allowing populations to eat properly and healthily.

The effect of the floods is negative and significant on the use or consumption of food. With the floods, many diseases appear due to the lack of infrastructure and hygiene. The lack of hygiene and the consumption of certain foods cause certain diseases, including cholera and malaria, which affect a large part of the Sahelian population.

The unique effect of past drought is negative and not significant on food use and consumption. When the two shocks occur at the same time, the effect of the floods remains negative and very significant (see column 4 of table 3.9). The effect of floods becomes positive and not significant and that of seasonal precipitation also becomes positive and not significant.

Overall, the results show that the floods do not allow people to have basic drinking water, basic sanitation services for the disposal of human waste, also negatively affect the prevalence of obesity. In addition, drought provides the same effects but less pronounced than those of floods.

Figure 3.3 with data from EM-DAT (2019) shows that despite the high occurrence of floods, drought affects people more than floods. Thus, the number of people affected by the two events caused human and economic damage. In other words, floods and droughts significantly disrupt the proper use of food. Therefore, improved availability and accessibility does not guarantee food security unless it is used rationally or optimally.

Table 3.9Results of estimation for the third dimension of food security.

	Fouth dimension: Utilization			
	Indice_utilization			
	(1)	(2)	(3)	(4)
Flood		−0.248**		−0.248**
		(0.108)		(0.108)
Droughts			−0.002	0.015
			(0.307)	(0.301)
Cereal_yield	−0.0004***	−0.0004***	−0.0004***	−0.0004***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
GDP_Capita	−0.002***	−0.002***	−0.002***	−0.002***
	(0.0003)	(0.0003)	(0.0004)	(0.0003)
Pop_growth	0.545	0.529	0.611	0.528
	(0.879)	(0.867)	(0.889)	(0.872)
CerealM	−0.001***	−0.001***	−0.001***	−0.001***
	(0.0003)	(0.0003)	(0.0003)	(0.0003)
stability	1.502***	1.488***	1.494***	1.489***
	(0.311)	(0.305)	(0.314)	(0.307)
Inf_consprices	−0.081***	−0.081***	−0.080***	−0.081***
	(0.019)	(0.019)	(0.020)	(0.020)
Observations	117	116	116	116
R^2	0.730	0.742	0.729	0.742
Adjusted R^2	0.693	0.703	0.688	0.700
F Statistic	45.953*** (df = 6; 102)	41.118*** (df = 7; 100)	38.341*** (df = 7; 100)	35.620*** (df = 8; 99)
Model	Individual	Individual	Individual	Individual
Note:				*p<0.1; **p<0.05; ***p<0.01

The results in column 1 of Table 3.10 show that all controls (GDP per capita, growth population, cereal import) have negative and insignificant effects on the stability of food over time, except for cereal yield and inflation where the effect is positive and insignificant. Political stability and the absence of violence have positive and very significant effects on the sustainability of food. The absence of violence and conflict contributes to improving food security by enabling people to have access to food over time.
For this dimension, the effect of floods is negative and very significant on both models even in the presence of floods. The effect of drought is negative and not significant in both models. Previous climate shocks did not allow people to consume healthily and sustainably over time. To achieve food security, individuals must have access to food and have good use of it over time. The economic and social situation in the Sahel does not guarantee food security for the populations. Climate shocks (drought and flooding) exacerbate food insecurity for populations.
The results may be explained by the fact that the floods have negative and very significant effects on the share of irrigated land and the dependence rates on cereal imports while the effects of droughts are negative but not significant. Indeed, floods can make irrigable land unavailable for agricultural activities, thus not favoring cereal production causing the decline in food availability. In addition, the floods do not favor trade due to the lack of road,

rail and air infrastructure in the Sahel countries. The effects are therefore similar but less with the occurrence of drought.

Table 3.10Results of estimation for the fourth dimension of food security.

	Fourth dimension: stability			
	Indice_stability			
	(1)	(2)	(3)	(4)
Flood		−2.653***		−2.642***
		(0.864)		(0.870)
Droughts			−0.978	−0.636
			(2.511)	(2.404)
Cereal_yield	0.0001	0.0001	0.0001	0.00004
	(0.001)	(0.0005)	(0.001)	(0.0005)
GDP_Capita	−0.002	−0.003	−0.002	−0.003
	(0.003)	(0.003)	(0.003)	(0.003)
Pop_growth	−0.174	1.016	1.451	1.006
	(7.859)	(7.412)	(7.790)	(7.451)
CerealM	−0.002	−0.003	−0.002	−0.003
	(0.002)	(0.002)	(0.002)	(0.002)
stability	10.205***	10.007***	10.012***	9.965***
	(2.541)	(2.384)	(2.512)	(2.402)
Inf_consprices	0.063	0.089	0.102	0.101
	(0.165)	(0.155)	(0.170)	(0.162)
Observations	104	103	103	103
R^2	0.236	0.312	0.240	0.313
Adjusted R^2	0.126	0.203	0.119	0.194
F Statistic	4.640*** (df = 6; 90)	5.706*** (df = 7; 88)	3.965*** (df = 7; 88)	4.948*** (df = 8; 87)
Model	Individual	Individual	Individual	Individual
Note:				*p<0.1; **p<0.05; ***p<0.01

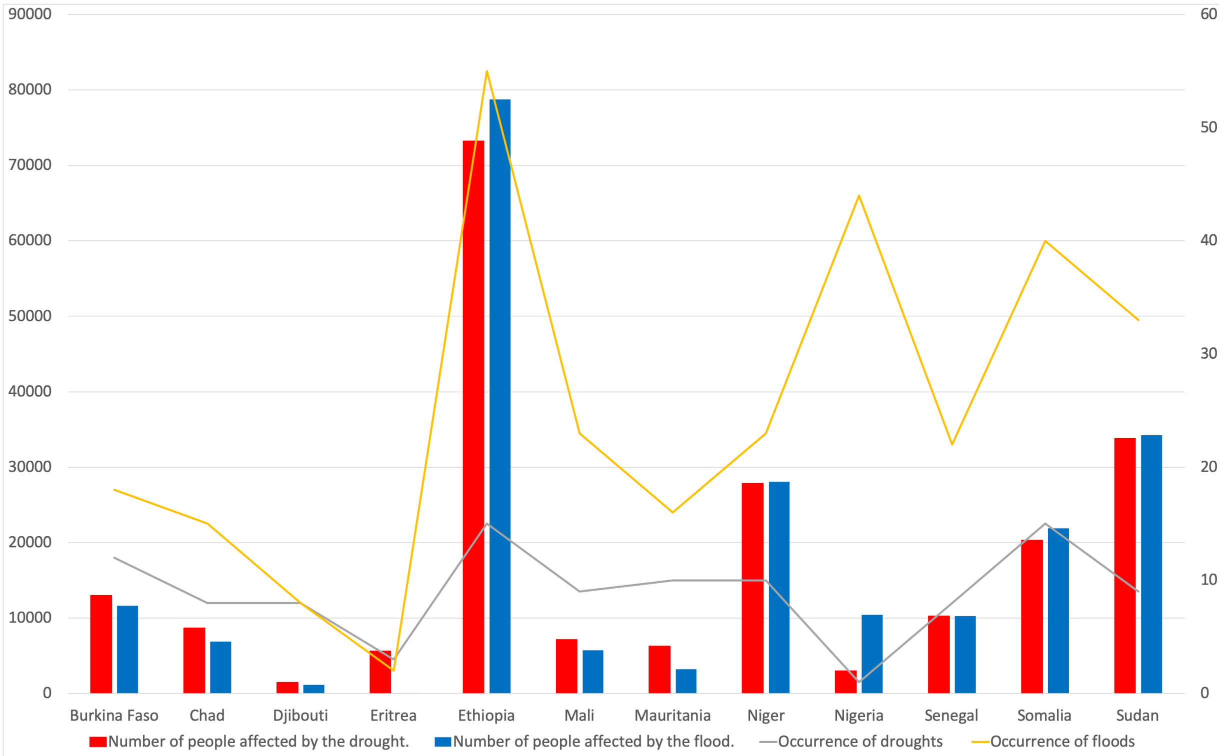
3.6 Conclusion

This chapter examines the link between climate change and food security in the Sahel countries. In this study, several variables were used to capture the effect of the factors or determinants of food security. A robust model also made it possible to isolate the effect of climatic shocks (flood and drought) based on the four dimensions of food security (availability, accessibility, stability and use) for the period from 2002 to 2016 . The results show overall that although climate shocks impact food security in countries. It also shows that the level of wealth creation and inflation are key determinants of food security. Political stability and the absence of violence more than an imperative. In other words, even in the absence of climatic shocks this variable plays an important role in ensuring a food security situation.

Based on our results, a multitude of recommendations can be taken and implemented to increase and improve the level of food security in the Sahel countries. Based on this multi-dimensional econometric study, all stakeholders (political decision-makers, international and national institutions, national programs to combat insecurity) have the choice between orienting their policy based on the combination of dimensions . Our results show that food availability does not ensure food security. Inflation must be controlled and the standard of living of the population improved so that it can create more wealth. The current state and the level of incomes does not ensure food security, especially in a context of generalized inflation as our results show. The basis of the results clearly shows that political stability and the absence of violence improves food security at all levels, from availability to consumption.

3.7 Appendix

Figure 3.3 Drought and flood events and affected people (in thousands) in the Sahel countries over the period.



Source: Calculations and achievements by the author using data from the EM-DAT Unit (2019)

Table 3.11Summary table of articles modeling food security

Authors	Period + Unit of analysis	Explained variables	Climate variables	Other control variables	Model and estimation methods	Main results
Jeronim Capaldo (2010)	1831 rural households from Nicaragua for the year 2001	**Daily per capita kilocalorie consumption**. The authors construct a vulnerability index that is an easy (multistep) estimation procedure to be reproduced using data from a single household survey and whose results are directly interpretable. They propose a model of vulnerability analysis that can improve policy design.	**Drought shock** The "drought shocks" variable was not constructed but was provided by the survey and is assessed by whether or not households received assistance.	land cultivated, irrigation, and shares of income from farm activities and farm sales	Linear regression with instrumental variable methods to solve the endogeneity problem of some explanatory variables.	One third of rural households face an unstable food security situation. Past exposure to shocks that affect agricultural production, and illness in the family, drought, and market related shocks increase the probability that households will be food insecure in the future. Education, access to public infrastructure and other assets represent positive factors that reduce overall vulnerability to food insecurity.
Karfakis et al. (2011)	1242 households in Nicaragua for the year 2001	The authors built a vulnerability index as the probability of a household experiencing food insecurity in the future. This construction allows the authors to approximate the distribution of expected household consumption.	Temperature and rainfall	Age head, female headed, number of rooms, Irrigation access	Linear regression with instrumental variable to solve the problem of endogeneity caused by the value of total agricultural production that is essential to explain farm household consumption.	The prospective vulnerability analysis shows that in the context of climate change in Nicaragua, transient food insecure households and chronically food insecure households can be distinguished. Localization, asset ownership and the propensity to sell agricultural products on the market have significant effects on reducing the vulnerability of farm households.
Belloumi (2014)	10 countries in South-East Africa during the period 1961-2011.	Food production index, mortality rate of people under five years of age, and life expectancy at birth.	Rainfall, temperature	Income per capita, inflation, population growth, agriculture land under cereal production	They use a set of proxy variables that are agricultural infrastructure, access to fertilizer and temperature.	The results show that GDP per capita, inflation, population growth, and land under cereal production are significant in explaining the indicators of food security. For climate variables, overall rainfall has a positive and significant effect on food security, whereas the effect of temperature is negative.
Celia Reyes and Calubayan (2014)	16 provinces in Philippines for the period 2007-2010.	**Food security** The variable is approximated by the value of food consumed by adult equivalent	Temperature (change)	Agricultural productivity, characteristics of the head of the household, Access to migration channels, characteristics of household dwelling, communication infrastructure, availability of farmland, social infrastructure, social protection	Instrumental variable linear regression model because agricultural productivity is correlated with the error term	Changes in climatic variables probably transmit effects on households through farm incomes in the form of food insecurity. The extreme increase in the level of rainfall decreases income from agriculture and gardening and therefore increases vulnerability to food insecurity. Temperature changes are leading to increased vulnerability to food insecurity, which is also true in some provinces.
Asfaw (2015)	3,969 household and about 32,000 plots in Ethiopia for the period 2011/12	The outcome variable (crop net income and the subjective food insecurity indicator)	Coefficient of variation of rainfall, Climate variables(temp and precip), Potential Wetness Index ,	land size in hectares, Nutrient availability, household size, Terrain Roughness, Workability, Wealth index, Number of oxen, Access to credit services ,number of population of the community,Access to extension program (1=yes), distance to nearest population centre,	A multivariate probit model on plot level observations to model simultaneous and interdependent adoption decisions and utilize a conditional mixed process estimator (CMP) and instrumental variable method for the impact estimates.	Average precipitation and temperature during the rainy season is positively correlated with crop net income and food security. Household demographic structure also seems explain the variation in crop net income and food insecurity status of the households. Results also show that crop income and food security is higher for men than women and that this result is robust across the different estimation technique. Average precipitation and temperature during the rainy season is positively and significantly associated with food security and crop net income.
Ahmad Munir and Iqbal (2015)	3298 food crop producers in Pakistan for the 2012-13 campaign.	**Food Security Index** The authors constructed a time variant Food Security Index (FSI) using various combinations of food security indicators and applying Principal Component Analysis (PCA).	Precipitation Normal kharif, Precipitation Normal rabi, Temp. Deviation khareef, Temp. Deviation rabi, Precip. Devition kharif , Precip. Devition rabi	Education of male head, Formal credit, Informal credit , Age of male head , Non-farm income , Owner cultivator , Owner-cum-tenant , Cotton-wheat zone, Rice-wheat zone , Arid zone Electronic media,	Endogenous switching regression treatment effect model, binary and general propensity score matching approaches. Based on FSI, the households were classified into relative food security groups and their determinants were assessed using fixed effects instrumental variable regression procedure.	The households which adapted to climate changes are statistically significantly more food secure as compared to those who did not adapt. The results also show that education of the male and female heads, livestock ownership, the structure of house—both bricked and having electricity facility, crops diversification, and non-farm income are among the factors which raise the food security of farm households and their impacts are statistically significant.
Eric and Kinda (2016)	53 developing countries and covers the period from 1971 to 2010.	**Food security** For the estimation, the authors used food availability to approximate food security. Food availability is the sum of production, stocks and trade balance (imports - exports) of the main cereals of each of 53 countries.	Drought, Flood, Extreme temperature, Water balance. The variables are not built but the data comes from a database.	GDP per capita, population density, cereal yields, arable lands	Samuelson's spatial equilibrium model (theoretically) and Spatial Durbin Model with fixed effect panel data	First, they show the existence of a strategic substitutability between levels of food availability in countries. In other words, an increase in food availability in a given country decreases food availability in neighboring countries. Secondly, climate change (water balance variability, droughts, floods and extreme temperatures) reduces food availability in both the affected countries and its major trading partners. Third, food demand drivers in one country may have an opposite (asymmetric) effect on its major trading partners. Fourth, supply factors have a symmetrical impact on food availability.
Masipa (2017)	1 country, South Africa.		Average temperature, amount of rainfall, severity of drought, extreme events		Desktop study approach : Previous studies, reports, surveys and policies on climate change and food (in)security.	Climate change presents a high risk to food security in sub-Saharan countries from crop production to food distribution and consumption.
A. Ervin and Gayoso de Ervin (2019)	10,554 household in Paraguay for the period 1997/98, 2003, 2006, and 2009, and 2011-2012.	**Food security (agricultural productivity, calories consumption per capita, food consumption)**. The authors define vulnerability to food insecurity as the probability that household j may experience a shortfall of caloric consumption or caloric deficit conditional on household characteristics.	Precipitation and temperature (wet and dry season), Minimum and maximum temperature (dry and wet season)	Household agriculture production per hectare, household size, Members under 5 years old (%), Female members (%), rooms per person, access inside the house, Household has transportation, Share of agricultural income, Household water access inside the house	To address endogeneity, the authors apply the Instrumental Variables (IV) methodology. This methodology requires a set of instruments that should be correlated to agricultural productivity but not to caloric consumption. Because climate is exogenous to the farmer and mostly affects caloric consumption through agricultural productivity and income, climate variables appear to be valid instruments. To estimate vulnerability to food insecurity due to climate change, the authors apply 2 Stage Least Squares (2SLS).	Increasing temperatures and reduced precipitation will reduce agricultural productivity and caloric consumption, and increase vulnerability to food insecurity. A 5 percent reduction in agricultural productivity translates into nearly a 1 percent reduction in caloric consumption. Vulnerability to food insecurity in Paraguay is expected to increase by 28 percentage points by 2100 due to climate change, increasing fastest in areas where temperatures are increasing and rainfall is diminishing. They also estimate that improvements in infrastructure, farm technology, and education may reduce nearly half of the expected future adverse effects of climate change on household vulnerability to food insecurity.

Figure 3.4 ACP results for the construction of the availability dimension.

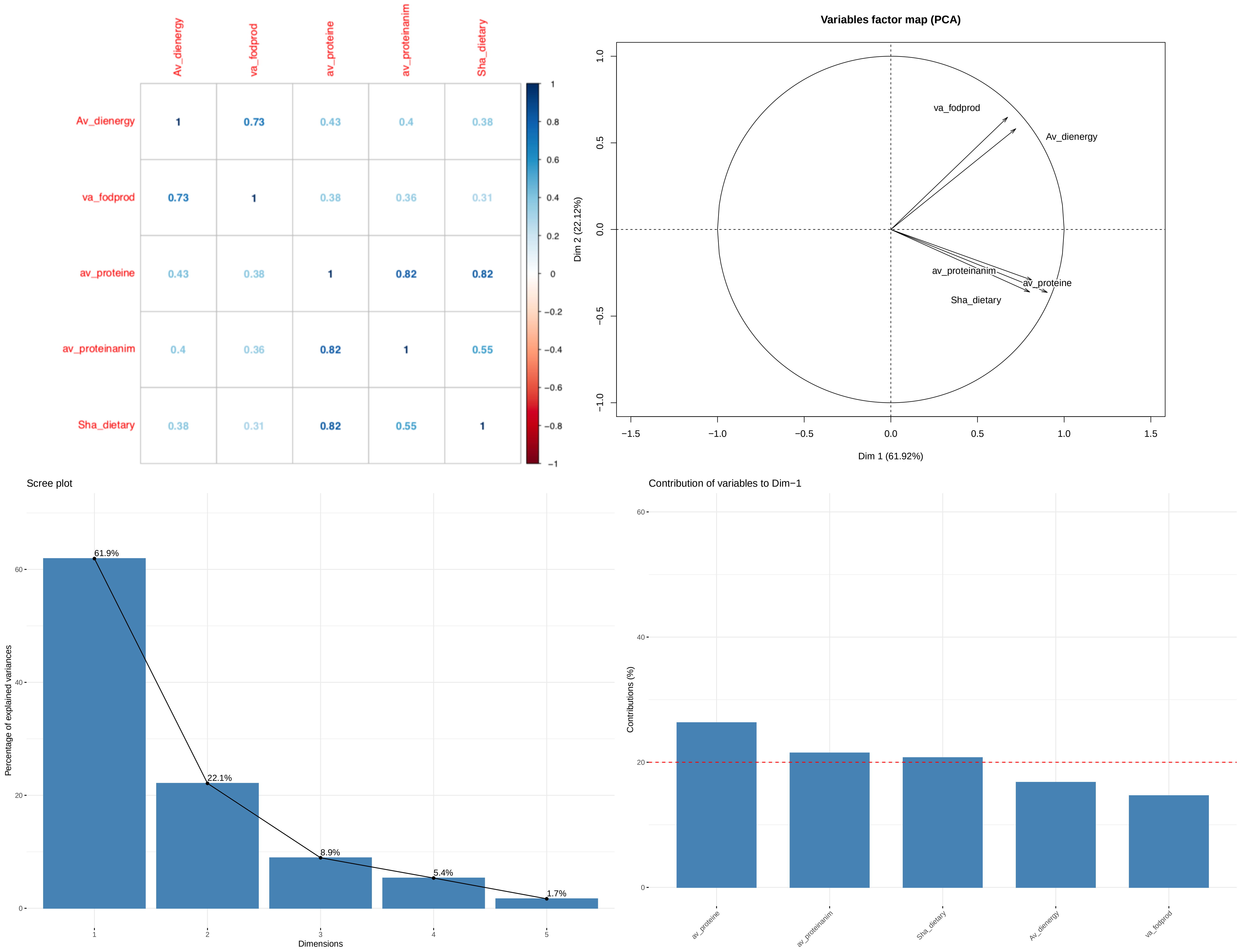


Figure 3.5 ACP results for the construction of the accessibility dimension.

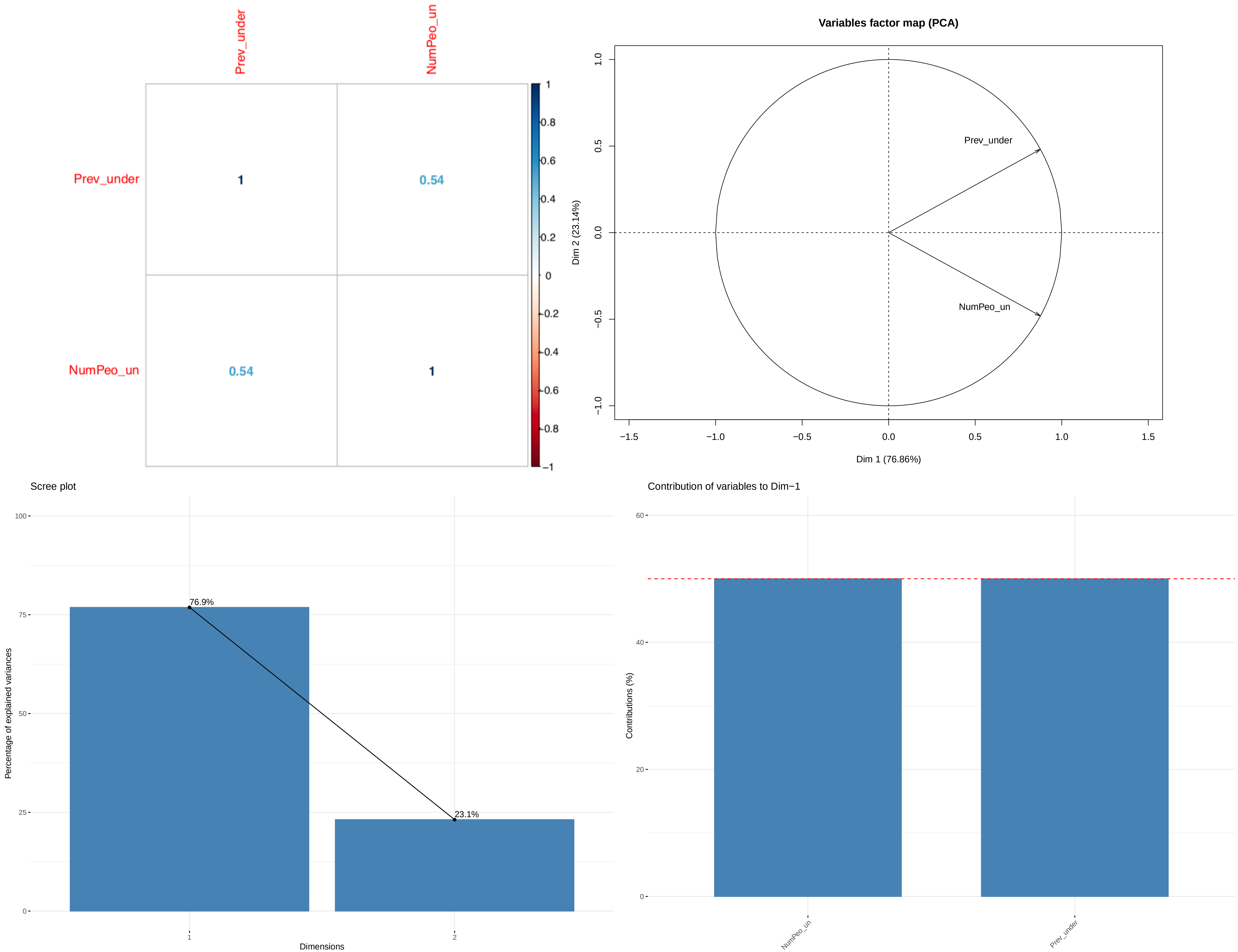


Figure 3.6 ACP results for the construction of the utilization dimension.

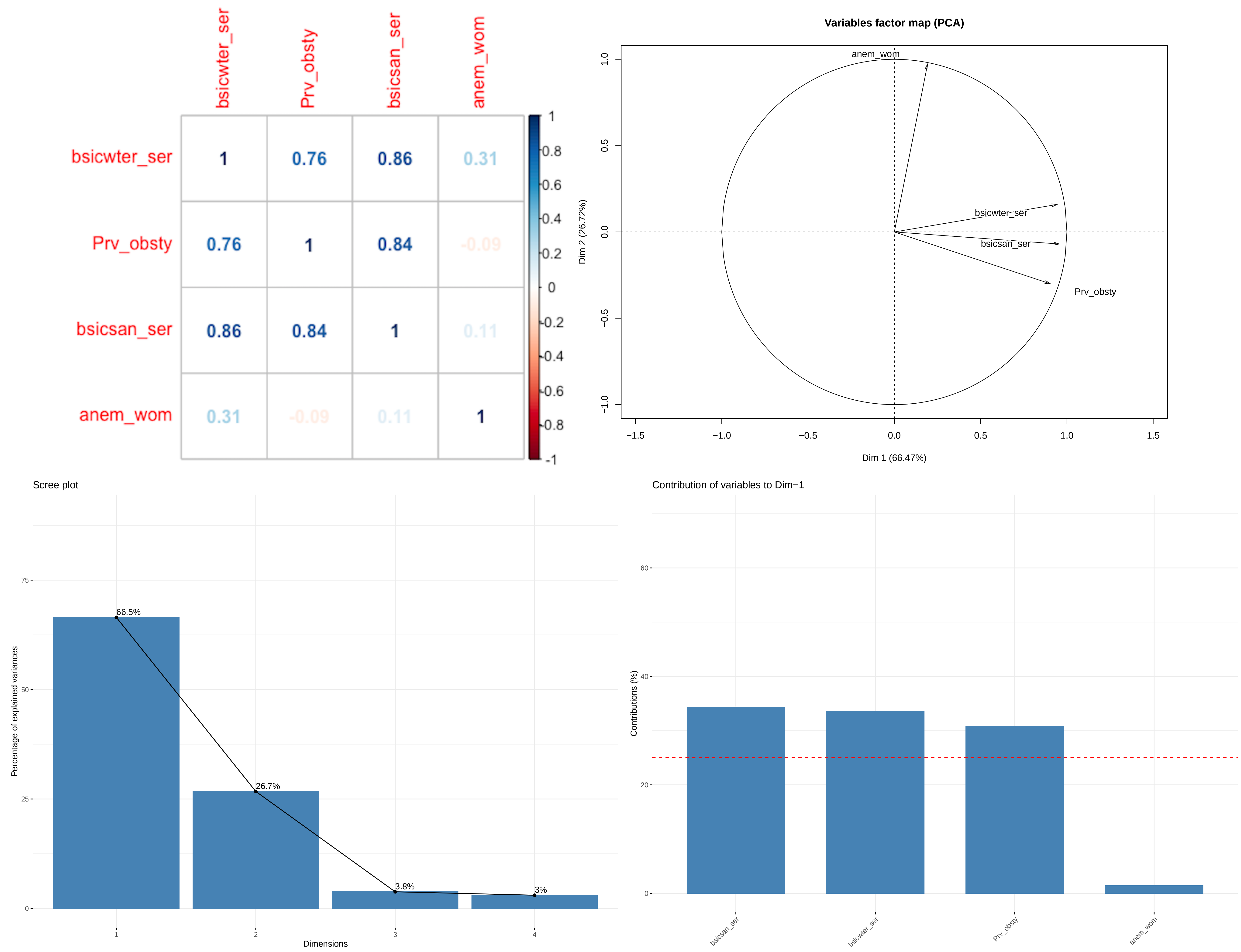


Figure 3.7 ACP results for the construction of the stability dimension.

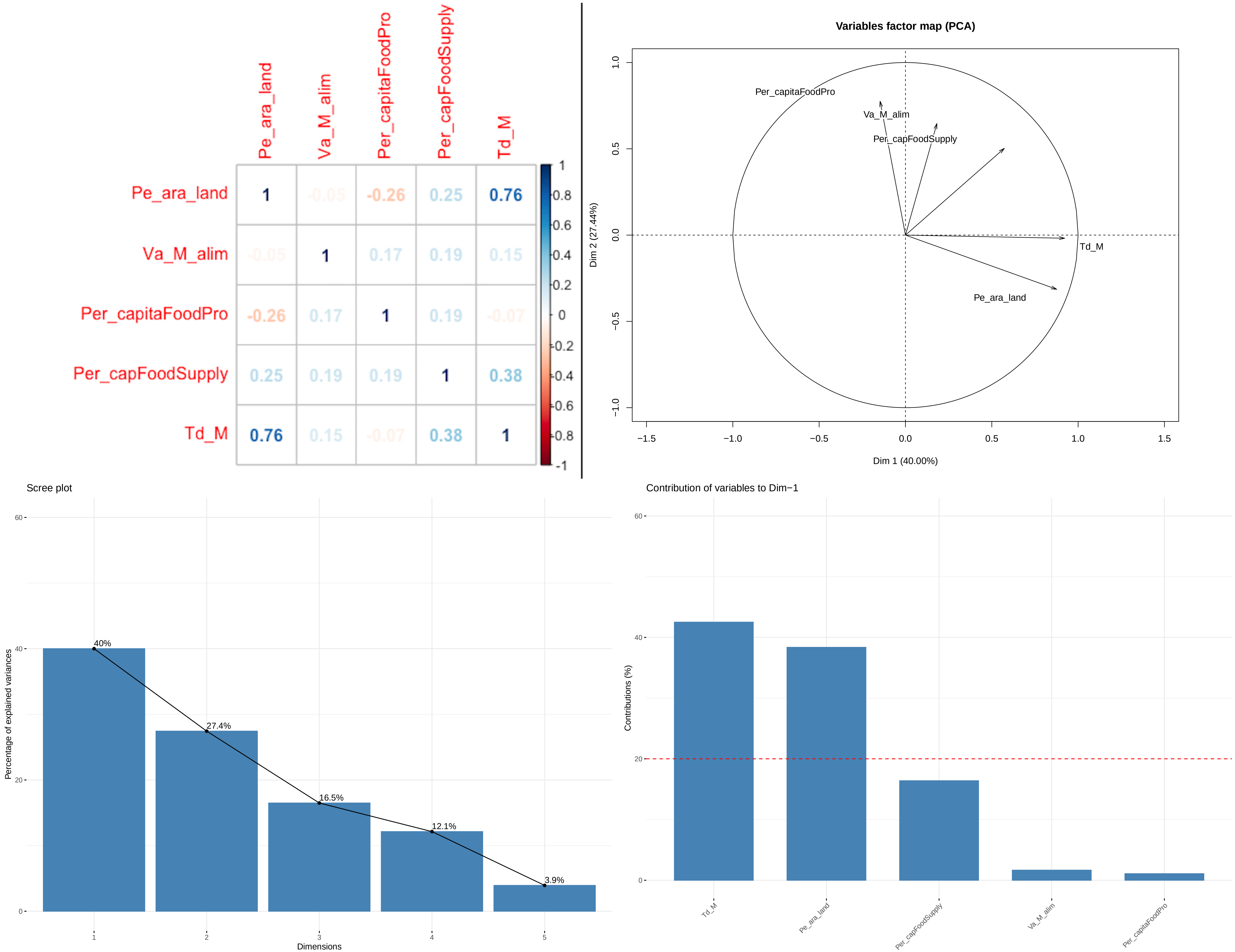


Table 3.12Summary table of the first dimension

Variables	Dim.1	ctr	cos2	Dim.2	ctr	cos2	Dim.3	ctr	cos2
Av_dienergy	0.721	16.793	0.520	0.582	30.593	0.338	0.062	0.874	0.004
va_fodprod	0.674	14.660	0.454	0.648	37.950	0.420	-0.022	0.104	0.000
av_proteine	0.903	26.324	0.815	-0.363	11.929	0.132	-0.005	0.006	0.000
av_proteinanim	0.816	21.486	0.665	-0.293	7.752	0.086	-0.482	51.984	0.232
Sha_dietary	0.801	20.737	0.642	-0.361	11.776	0.130	0.458	47.032	0.210

Table 3.13Summary table of the second dimension

Variables	Dim.1	ctr	cos2	Dim.2	ctr	cos2
Prev_under	0.877	50.000	0.769	0.481	50.000	0.231
NumPeo_un	0.877	50.000	0.769	-0.481	50.000	0.231

Table 3.14Summary table of the third dimension

Variables	Dim.1	ctr	cos2	Dim.2	ctr	cos2	Dim.3	ctr	cos2
bsicwter_ser	0.937	33.255	0.878	0.169	2.654	0.029	-0.264	45.407	0.070
Prv_obsty	0.914	31.595	0.835	-0.276	7.025	0.076	0.264	45.374	0.070
bsicsan_ser	0.959	34.784	0.919	-0.005	0.002	0.000	-0.006	0.020	0.000
anem_wom	0.098	0.367	0.010	0.988	90.319	0.976	0.119	9.199	0.014

Table 3.15Summary table of the fourth dimension

Variables	Dim.1	ctr	cos2	Dim.2	ctr	cos2	Dim.3	ctr	cos2
Pe_ara_land	0.876	38.362	0.767	-0.314	7.187	0.099	0.033	0.129	0.001
Va_M_alim	0.182	1.660	0.033	0.647	30.483	0.418	-0.738	66.077	0.545
Per_capitaFoodPro	-0.147	1.079	0.022	0.776	43.875	0.602	0.429	22.287	0.184
Per_capFoodSupply	0.573	16.391	0.328	0.503	18.430	0.253	0.308	11.499	0.095
Td_M	0.922	42.508	0.850	-0.018	0.024	0.000	-0.008	0.008	0.000

Table 3.16Following the results of the estimates on the different dimensions of food security

	Availability				Acessibility			
	Indice_availability				Indice_accessibility			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Flood		0.094		0.083		0.099		0.098
		(0.151)		(0.150)		(0.210)		(0.211)
Droughts			0.608	0.595			0.137	0.126
			(0.411)	(0.414)			(0.592)	(0.596)
Cereal_yield	−0.0002**	−0.0002**	−0.0002*	−0.0002*	−0.0003***	−0.0003**	−0.0003**	−0.0003**
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
GDP_Capita	0.002**	0.002**	0.002**	0.002**	0.003***	0.004***	0.003***	0.004***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Pop_growth	−7.366***	−7.365***	−7.427***	−7.421***	−5.762***	−5.920***	−5.935***	−5.925***
	(1.136)	(1.149)	(1.137)	(1.142)	(1.621)	(1.599)	(1.601)	(1.610)
CerealM	−0.002***	−0.002***	−0.002***	−0.002***	−0.001	−0.0005	−0.001	−0.0005
	(0.0003)	(0.0004)	(0.0003)	(0.0004)	(0.0005)	(0.0005)	(0.0005)	(0.0005)
stabilite	1.834***	1.809***	1.856***	1.835***	−0.216	−0.320	−0.290	−0.315
	(0.402)	(0.409)	(0.403)	(0.406)	(0.571)	(0.567)	(0.565)	(0.571)
Inf_consprices	−0.095***	−0.096***	−0.110***	−0.110***	−0.158***	−0.157***	−0.160***	−0.159***
	(0.027)	(0.027)	(0.029)	(0.029)	(0.039)	(0.039)	(0.041)	(0.041)
Observations	106	105	105	105	105	104	104	104
R^2	0.597	0.599	0.608	0.610	0.446	0.465	0.464	0.465
Adjusted R^2	0.465	0.458	0.471	0.466	0.262	0.275	0.273	0.266
Model	Twoways	Twoways	Twoways	Twoways	Twoways	Twoways	Twoways	Twoways

Note: *p<0.1; **p<0.05; ***p<0.01

Table 3.17Continuation of the results of the estimates on the different dimensions of food security (continued).

	Utilization				Stability			
	Indice_utilization				Indice_stability			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Flood		−1.824*		−1.827*		0.007		0.007
		(0.993)		(1.000)		(0.072)		(0.073)
Droughts			−0.014	0.192			0.107	0.107
			(2.858)	(2.817)			(0.195)	(0.196)
Cereal_yield	0.001*	0.001	0.001*	0.001	−0.0001***	−0.0001***	−0.0001***	−0.0001***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.00004)	(0.00004)	(0.00004)	(0.00004)
GDP_Capita	0.008*	0.005	0.007*	0.005	0.002***	0.002***	0.002***	0.002***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
Pop_growth	1.453	2.057	2.235	2.049	1.018**	0.991*	0.973*	0.974*
	(7.809)	(7.563)	(7.729)	(7.614)	(0.509)	(0.511)	(0.511)	(0.514)
CerealM	0.002	0.0004	0.001	0.0004	0.0001	0.0002	0.0001	0.0002
	(0.002)	(0.002)	(0.002)	(0.002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
stabilite	6.702**	7.526***	7.070**	7.534***	0.349*	0.336*	0.346*	0.344*
	(2.753)	(2.680)	(2.729)	(2.700)	(0.195)	(0.197)	(0.196)	(0.198)
Inf_consprices	0.206	0.199	0.200	0.195	−0.063***	−0.062***	−0.065***	−0.065***
	(0.190)	(0.184)	(0.197)	(0.194)	(0.012)	(0.012)	(0.013)	(0.013)
Observations	104	103	103	103	117	116	116	116
R^2	0.159	0.200	0.164	0.200	0.491	0.495	0.497	0.497
Adjusted R^2	−0.111	−0.074	−0.121	−0.088	0.343	0.340	0.343	0.335
Model	Twoways	Twoways	Twoways	Twoways	Twoways	Twoways	Twoways	Twoways
Note:								*p<0.1; **p<0.05; ***p<0.01

Conclusion générale

Cette thèse propose une analyse approfondie du changement climatique et des secteurs agricoles des pays du Sahel. Les trois chapitres contribuent à la littérature sur le changement climatique et ses conséquences sur l'agriculture et la sécurité alimentaire.

Afin de mettre en oeuvre les analyses de la thèse, nous avons mené un travail de construction des bases de données et des cartes agroécologiques. Nous avons ainsi identifié 52 zones agroécologiques reparties au sein des douze pays du Sahel de notre échantillon et nous les avons cartographié sous forme de fichiers shapefiles exploitables et disponibles pour d'autres études. Ces travaux préliminaires ont permis de mettre à jour les cartes agroécologiques de certains pays et d'en construire pour d'autres sur des nouvelles informations de la base des données "Crop Calendar" de la FAO (2011). En outre, les coordonnées géographiques de chaque zone agroécologique et la construction des calendriers agricoles des pays et des zones agroécologiques ont permis de mettre en place des bases de données des variables climatiques en fonction des différentes saisons de toutes les régions d'études.

Dans le premier chapitre, nous avons mis en évidence l'existence du changement et de la variabilité climatiques à la fois aux niveaux des 12 pays et des 52 zones agroécologiques du Sahel. Les résultats obtenus contribuent à la littérature en apportant plusieurs éclaircissements aux débats sur l'existence du changement climatique au niveau de chaque pays sahélien et dans toute la bande sahélienne. Ce travail est le premier à analyser le changement climatique à la fois à l'échelle des pays et à celle des zones agroécologiques. Nous utilisons un modèle de régression linéaire estimé par la méthode des Moindres Carrés Ordinaires (MCO) et un modèle de changement structurel endogène sur les températures et les précipitations saisonnières.
D'une part, nous avons montré que le changement climatique existe au niveau des pays du Sahel et que ce phenomène a bien commencé à partir des années 1980 où nous avons identifié la plupart des ruptures. D'autre part, les résultats ont montré qu'il existe une forte hétérogenéité entre les pays du Sahel en termes d'évolution de la température et des précipitations en termes de niveau et tendance. Autrement dit, le changement climatique a bien debuté dans les pays et zones agroécologiques mais d'une manière différente.

Dans le deuxième chapitre, nous avons évalué l'impact du changement climatique sur la production agricole en estimant l'effet des variables climatiques sur la production céréalière au Sahel tout en contrôlant l'apport des inputs nécessaires dans les activités agricoles. Le principal apport de ce chapitre reste également le choix d'échelle, c'est à dire l'étude agrégrée sur 12 pays et spécifiquement la prise en compte des zones agroécologiques, ce qui constitue une première à notre connaissance. La construction des cartes agroécologiques et la construction d'une clé de repartition ont permis d'obtenir une base des données à cette échelle pour les 52 zones agroécologiques. Les résultats indiquent que les effets de la température et des précipitations sont hétérogènes au niveau des deux pays et des zones agroécologiques. Ensuite, ils confirment que la température moyenne et les précipitations moyennes pendant la saison de croissance jouent un rôle très important dans la production des cinq céréales et l'indice net de la production agricole. De plus, les changements de température et de précipitations affectent également la production céréalière et l'indice net de la production agricole. Ce chapitre fournit également des résultats importants quant à la mobilisation et l'utilisation des inputs tels que la main d'oeuvre agricole, les tracteurs et les fertilisants. Ce résultat renvoie à une implication de politiques publiques dans l'allocation des ressources agricoles rares dû à l'hétérogénéité observée entre les différentes échelles et les production des différentes céréales. Le choix des céréales doit se faire en fonction des caractéristiques climatiques de chaque région, permettant d'accroître ainsi le rendement agricole des régions. La spécialisation agricole semble être nécessaire en l'absence des variétés des céréales appropriées. Ainsi, l'allocation des inputs doit se faire également en fonction de ces choix permettant aux agriculteurs de faire des mobilisations optimales des ressources.

Dans le dernier chapitre, nous avons étudié, sur la base d'une analyse multidimensionnelle, le lien entre changement climatique et la sécurité alimentaire dans les pays du Sahel. En construisant des indices de sécurité alimentaire, les résultats indiquent que la situation alimentaire dans les pays du Sahel peut être améliorée si les déterminants socioéconomiques sont importants et meilleurs. Dans les pays où 50 à 80% des revenus sont allouées à la consommation, les populations ne peuvent pas être en situation de sécurité alimentaire (Burney et al., 2010). Il ressort également de cette analyse que la mise en place des politiques économiques importantes permettent de créer de la richesse et de maîtriser l'inflation. Les États doivent également veiller à la stabilié et d'éviter les conflits car en présence de conflits toutes les dimensions de la sécurité seront pertubées. Concernant l'analyse empirique du chapitre 3, nous avons été confronté à l'absence des données qui peut avoir une portée sur nos résultats. Premièrement, nous étions obligés de limiter notre période d'étude. Deuxièmement, le choix des variables pour l'analyse en composantes principales a été fait en fonction de la disponibilité des données.

Les implications globales de cette thèse sont claires pour les pays du Sahel. La meilleure manière de lutter contre la pauvreté dans une région où 80% de la population vit de l'agriculture et tire ses revenus dans le secteur agricole (Davis et al., 2010), est d'encourager tous les types d'agriculteurs (petites et grandes exploitations) et renouveler le système agricole en apportant des investissements colossaux. Toute amélioration du secteur agricole aura des impacts directs et positifs sur la sécurité alimentaire des populations. Les résultats pointent aussi la nécessité du développement du système agricole basé sur l'irrigation. Le système irrigué est une statégie de réduction de la pauvreté, d'adaptation au climat et de promotion de la sécurité alimentaire (Polak and Yoder, 2006; Byerlee et al., 2007). Le rôle de l'irrigation dans la réduction de la pauvreté est avérée car les agriculteurs surtout les petits exploitants ne se focaliseront pas uniquement sur la saison pluvieuse de trois mois (Yobom, 2020) mais seront actifs économiquement sur toute la période de l'année (Burney et al., 2010). L'accroissement des superfices agricoles irriguées est un impératif à promouvoir par les États sahéliens dans la stratrégie de lutte et d'atténuation contre les effets néfastes du changement climatique sur l'agriculture. L'accès à l'eau d'irrigation via la pompe à moteur a augmenté l'épargne des ménages et l'assurance sociale informelle sous forme de transferts dans le nord du Mali (Dillon, 2008); la production de légumes toute l'année facilitée par l'irrigation des canaux dans le nord du Sénégal a augmenté l'apport de vitamine A et C et diminué l'incidence de l'émaciation chez les adultes et les enfants plus âgés (Bénéfice and Simondon, 1993; Burney et al., 2010).

Dans l'avenir, les analyses sur les impacts du climat sur la sécurité alimentaire pourraient être étendues aux zones agroécologiques pour donner une image plus complète ou même au niveau des ménages avec les données d'enquêtes qui sont en cours de collecte par la Banque Mondiale.

D'autres recherches futures pourraient également être effectuées sur les effets à court terme des chocs métérologiques sur les revenus et consommation des ménages sahéliens. Par exemple, il pourrait être intéressant d'approfondir les faits empiriques pour des futurs travaux en allant à une échelle plus petite que les zones agroécologiques, des données sur les champs. Par conséquent, il peut être intéressant d'étudier la manière dont le changement climatique peut affecter les inégalités sociales.

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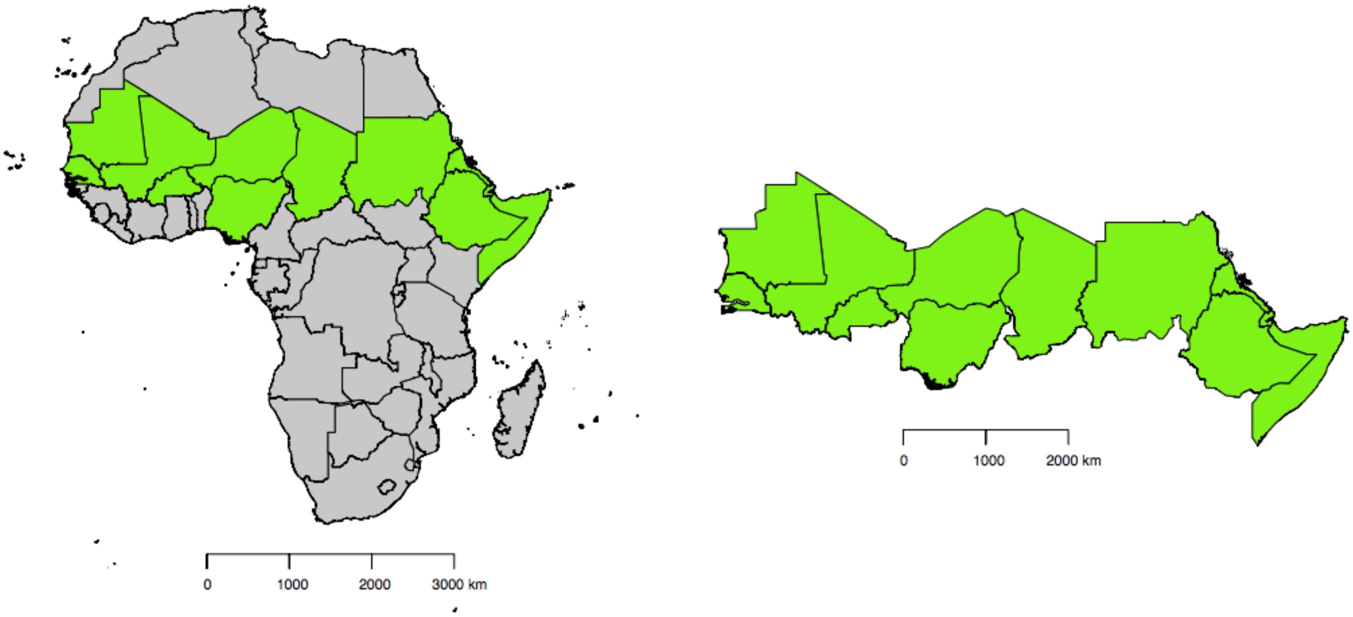
Appendix

3.8 Scope of study

Figure 3.8Study perimeter covering all twelve Sahelian countries



Source: Map of study area by author

3.8.1 Main economic characteristics by country

Burkina Faso

Burkina Faso is a landlocked country without access to the sea of West Africa. It covers an area of 274,500 square kilometers and its total population is estimated at 18.6 million (World Bank, 2016).

Figure 3.9Location of Burkina Faso

Burkina Faso's economic performance depends on agriculture, which employs 80% of the population and is highly dependent on rainfall. The country is the largest producer and exporter of conon on the African continent (Bank, 2018). Gross domestic product and per capita gross domestic product are estimated at US $ 12.12 billion and US $ 640 respectively (Bank, 2016). According to the World Bank (2016), the services sector is a major contributor to the improvement in gross domestic product (45%), followed by agriculture (33%) and industry (22%). Despite this situation, the country is ranked 185th out of 188 countries with a human development index of 0.402 (UNDP, 2016). Exports are destined to China, India, Indonesia and Bangladesh and imports are mainly from Côte d'Ivoire, France and Togo (WTO, 2015). In recent years, the development of agriculture and the orientation of mining activity have allowed the country to have a rebound in real GDP growth rates (Bank, 2018).

Chad

Chad is a country in Central Africa with a national area of 1,284,000 square kilometers and a population of 14.5 million (World Bank, 2016).

Figure 3.10Location of Chad

Before the exploitation of oil in 2002, the Chadian economy was focused on agriculture, trade and livestock. Industrial activity has slightly increased with oil exploitation but remains low and marginal. The fall in oil prices has put the country in distress, creating a disastrous economic and financial situation because of its low economic diversification (Bank, 2018). The Chadian economy is vulnerable and partly informal, the sectors of activity creating wealth are as follows: primary (32% of GDP), secondary (36% of GDP) and tertiary (32% of GDP). Chad's GDP is US $ 9.6 billion and gross national income per capita is US $ 662 (World Bank, 2016). This situation is a good illustration of its poor Human Development Index ranking, 186th out of 188 countries UNDP (2018). Chadian exports are mainly destined to the United States (58.61%), followed by India (9.19%), China (6.83%) and France (6.62%). Imports are mainly from France (19.74%), China (15.67%) and Cameroon (15.04%) Organization (2016).

Djibouti

Located in the Horn of Africa, the country has an area of 23,000 square kilometers and a population of 942,333 (Bank, 2016).


Figure 3.11Location of Djibouti

The country faces a problem of lack of water and food insecurity due to the climatic variations. Djiboutian economic activities are not diversified (AfDB Economic Outlook for Africa, 2018). They are based essentially on services (80%), industry (16.3%) and agriculture (3%). Agriculture is a small part of the country's gross national product. In 2015, the World Bank estimated GDP at USD 1.727 billion and GDP per capita (2016) at USD 1788. The country is ranked 164 th out of 189 countries in the Human Development Index (UNDP, 2018). Djiboutian exports are mainly destined to Somalia (81.4%) followed by Yemen (5.4%) and UAE (4.7%). In contrast, the country imports mainly from China (28.2%) followed by Saudi Arabia (16.9%) and India (10%) (WTO, 2014).

Ethiopia

Ethiopia is a landlocked country in East Africa without access to the sea like the majority of Sahelian countries. It has a surface area of 1,104,300 square kilometers and an estimated population of 102 million (Bank, 2016).


Figure 3.12Location of Ethiopia

In the last decade, the country has opted for an economic transformation that has allowed the country to grow at double digits: GDP per capita has doubled in 10 years (Bank, 2018). This growth is stimulated by public investment with the construction of infrastructure (water dams, rail link between the capital Addis Ababa and Djibouti). Part of the population is regularly affected by the cycle of food insecurity and dryness causing a decline in economic performance (Bank, 2018). Agriculture is the largest contributor to GDP (80%) followed by industry (16.3%) and services (42.8%) (World Bank, 2016). The efforts have enabled the country to reach a GDP of US $ 72.5 billion and a per capita GDP estimated at US $ 795 (World Bank, 2016). The country has a development index of 0.442 and ranks 174th out of 188 countries (UNDP, 2016). Ethiopia and Sudan have an important economic partnership given their geographic proximity (Bank, 2018). Ethiopia is one of the African countries receiving more official development assistance because of its political and economic stability and its reception for refugees. The country is also hit by drought cycles that require international assistance.

Eritrea

Eritrea is a country with an aread of 117,600 square kilometers and an estimated population of 5,187 million (Bank, 2016).

Figure 3.13Location of Eritrea

As a poor country, its GDP is estimated at US $ 4.7 billion and the services sector is a major contributor to wealth creation (63%). The service sector is developed in the country because of its geographical position. Catering and tourism contribute significantly to the development of this sector. In the primary sector, agriculture also contributes to GDP (about 15%) employing about 70% of the population, but it faces climate hazards that drastically impact activities (Bank, 2018). The economy is not diversified because of the virtual non-existence of the private sector. However, the industry contributes an estimated 22% because the country has gold reserves, iron ore and other raw materials (World Bank, 2016). This economic weakness is well illustrated by its position on the Human Development Index (0.442), ranked 179th out of 187 countries (UNDP, 2016). The country also benefits from official development assistance from the Global Fund and the European Commission.

Mali

Located in West Africa, Mali covers an area of 1,241,231 square kilometers for a population of 17,994,837 inhabitants Bank (2016).

Figure 3.14Location of Mali

The country has achieved some economic performance over the last five years despite the climatic and security problems it faces (Bank, 2018). It records a short-term but positive growth and the economic situation remains vulnerable according to the World Bank. The Malian economy is based and remains highly dependent on the mining sector and agriculture. Agriculture is the largest contributor to GDP 38.5%, followed by services (37%) and industry (24.4%). Mali trades with several countries, exports are destined for China, India, Indonesia and Bangladesh and imports come mainly from France, Senegal, Cote d'Ivoire and China (Organization, 2016). According to the World Bank (2016), the GDP was around 13.767 billion US dollars with a gross national income of

770 US dollars. Per capita income remains low compared to the world average. It ranks 175 out of 188 countries for the Human Development Index (UNDP, 2018).

Mauritania

Mauritania is a West African country with a total area of 1,030,700 square kilometers for a population of 4.1 million (Bank, 2016).

Figure 3.15Location of Mauritania

Following the 2008 economic crisis, the country was hit hard with a 2% drop in GDP. The economy is based on agriculture (23% of GDP), the services sector (42%), industry (36%) and fisheries (Bank, 2016). It also exports raw materials such as iron, gold, copper and petroleum. Economic diversification helps support and give sustainability to a given domestic economy. It is an additional gain if countries succeed in diversifying their exports. National GDP and GDP per capita are respectively \$ 5.1 billion and \$ 1270 (World Bank, 2016). In the rankings of the Human Development Index, the country ranks 156 out of 188 countries (UNDP, 2018). According to the data of the Organization (2016), Mauritania exchanges with several trading partners, the main exports are destined for China, the European Union, Switzerland, Andorra, Ivory Coast and Imports from the European Union, the United States, the United Arab Emirates, China and Morocco.

Niger

Niger is a West African country with an area of 1,267,000 square kilometers for a population estimated at 20.6 million inhabitants (World Bank, 2016).

Figure 3.16Location of Niger

Over the last few decades, the country has been experiencing tremendous population growth and famine situations have been reported in the country. This famine crisis caused by drought cycles has affected a large part of the population. The country ranks 187th out of 188 countries in the Human Development Index (UNDP, 2018). Niger's economy is dominated by agriculture (36.5%) and services (43.73%). The industrial sector is not developed and contributes only 17.6% (Bank, 2016). Nigeria is Niger's main customer, followed by France, China and Ghana. Imports mainly come from China, France, Nigeria and Togo.

Nigeria

Located in West Africa, Nigeria covers an area of 923,773 square kilometers and is the most populous country on the African continent with 193 million inhabitants (Bank, 2016).

Figure 3.17Location of Nigeria

Nigeria is the leading African economy with a national GDP of US $ 481 billion and a per capita GDP of US $ 2,742 in 2015 (World Bank, 2016). It is also leader in West Africa (75% of ECOWAS GDP in 2015) thanks to its economic performance. The Nigerian economy remains good (Bank, 2018) and focuses primarily on the exploitation and export of gas and oil, contributing about 14.4% of GDP. Agriculture and the services sector also contribute to GDP, respectively 22% and 52%. According to figures from the World Bank, 90% of these exports come from oil and gas. The country faces a problem of inequality and poverty despite its good economic reputation on the continental and international stages. The country trades with several partners. Its main customers are the European Union (35.6%), the United States (11.3%), India (12.1%) and Brazil (10%), and the main suppliers are the European Union (23%), China (21%), the United States (11.3%) and India (4.6%). The African continent remains a great outlet for Nigerian exports (Organization, 2016).

Senegal

Senegal is located on the west coast of Africa and covers an area of 196,722 square kilometers with an estimated population of 15.41 million (Bank, 2016).

Figure 3.18Location of Senegal

The primary sector employs 50% of the labor force and contributes 16.6% of GDP. Agriculture faces the challenges of climate change and needs to put in place development mechanisms. Senegal has a secondary sector that contributes 23.5% to its national GDP and provides good growth (Bank, 2018). The tertiary sector accounts for 60.2% of GDP dominated telecommunications. National GDP and GDP per capita are estimated at US $ 14.6 billion and US $ 950 respectively (Bank, 2016). However, the country is ranked 162 out of 188 countries in the Human Development Index (UNDP, 2016). Senegalese exports are destined to Mali, Switzerland, India, and Ivory Coast. The main imports come from France, Nigeria, China and India (Organization, 2016).

Somalia

Located at the eastern end of the Horn of Africa, Somalia covers an area of 637,657 square kilometers for a population of 14.32 million (Bank, 2016).

Figure 3.19Location of Somalia

The informal sector predominates in the country's economy. For decades, the country has been facing regular problems of insecurity. In this context, the economy depends heavily on international humanitarian aid, the agricultural sector (60% of GDP), services (32% of GDP) and industry (8% of GDP). Exports are for United Arab Emirates, Yemen and Oman. Imports come from Djibouti, Kenya, China and Turkey. National GDP is estimated at US $ 6.217 billion and GDP per capita is estimated at US $ 549 (Bank, 2016).

Sudan

With 1,886,068 square kilometers, Sudan is the third largest country in the continent with an estimated population of 39.3 million (Bank, 2016).

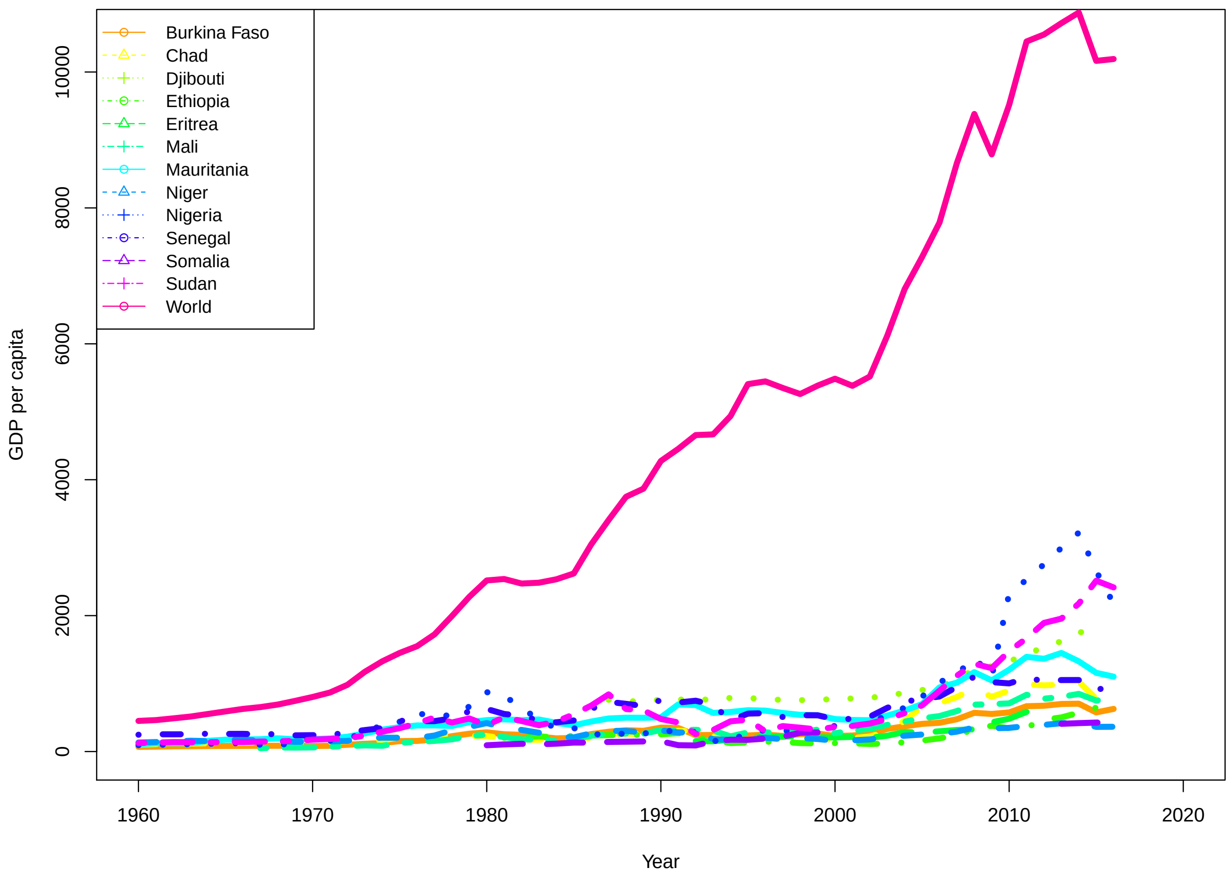
Figure 3.20Location of Sudan

The country is experiencing a particular economic situation because of the independence of South Sudan but the economy is expected to experience a revival given the final cessation of US sanctions (Bank, 2018). The Sudanese economy is heavily based on agriculture (31%) and services (48%). The country has also started an industrial development that allows this sector to contribute 23% of GDP (Bank, 2016). National GDP is estimated at 70.03 billion US dollars and per capita GDP (1781 US dollars) is slightly higher than that of several African countries (Bank, 2016). Sudanese exports are destined for China (57%), the United Arab Emirates (15%) and Saudi Arabia (6%). In contrast, Sudanese imports come from China (23%), India (8%) and Egypt (6%) Organization (2016). The country maintains economic and trade cooperation with China.

3.8.2 General situation of Sahel countries

From this individual country analysis, we find that the Sahelian population is predominantly agricultural so that climatic trends come as a major determinant of incomes of rural agricultural households in rural areas. Climate and agricultural activity also explain economic growth in countries with a strong agricultural economy. The Sahel countries are among the poorest countries in the world with low incomes and low GDP per capita growth rate. Figure 3.21 shows the evolution of per capita GDP growth for all Sahelian countries for the period 1980-2012. Despite an upward trend toward the end of the period, GDP per capita remains very low compared to that of advanced countries. The standard of living of the population is also low given the low income and lack of basic structures. Sudan has the highest growth rate of around US $ 2,000 per year. Ethiopia, Nigeria and Senegal also have an annual GDP per capita slightly above US $ 500. The situation is mixed for the other countries in the sample with an annual GDP per capita of less than US $ 500 over the entire period.

Figure 3.21Evolution of the gross domestic product per capita of the Sahel countries (in US dollars)



Source: Realization of the author from World Bank data

3.9 Agronomic and food characteristics of the Sahel countries

Sub-Saharan Africa is the part of the world where malnutrition rates are highest at around 30% and the agricultural sector is the only sector able to meet the challenge of food insecurity in the face of population growth, Africa for Development (2011)). In the Sahelian countries, cereals play an important role in the domestic consumption of the

population. Access to cereals helps to assess the ability to feed, the health and welfare of the population. The various flows of these food products vary considerably from one country to another. These differences can be explained by the consumption patterns and the level of economic development of each country. To observe the different variations, we represent the production, export, import, food supply, and domestic supply for each country for all countries. The analysis of the food balance data provided by the African Development Bank shows that the majority of countries in our sample do not export their agricultural production. It also appears that food aid plays a considerable role in the diet of countries. For all countries, we find that food aid began to be provided from 1987 onwards. In addition, food imports depend on the ability of countries to respond to each country's domestic food demand. Corn, millet, wheat, sorghum and rice are the five major crops in the agricultural economy of the Sahel countries. However, we will only rely on the four foodstuffs in our analysis (maize, millet, wheat, sorghum). According to the for Development (2009), millet is the basis for the daily diet of the 50 million people in the Sahel. It originated from Niger and Mali, before being disseminated in other countries to India through genetic adaptation. It is known for its resistance to drought and poor soils, and remains the most adapted to the natural environment (arid and semi-arid zones) and Sahelian food. As the main source of energy for millions of people, millet is a pillar of food security in the Sahel (for Development, 2009).
Sorghum is the fifth largest cereal in the world in terms of production volume after maize, rice, wheat and barley (for Development, 2009). In 2012, world sorghum production exceeded 58 million tons. The agricultural area under cultivation is estimated at more than 37 million hectares and is ranked sixth in the world in terms of agricultural area (for Development, 2014). According to FAO, global sorghum production is about 60 million tones per year. It also asserts that over 95% of production is used for food consumption in Africa and Asia. Sorghum bicolor is a crop that resists heat and dryness, and requires little irrigation and grows in poor and arid soils. An account of the climatic characteristics of the Sahel, sorghum remains an important culture adapted to the Sahelian environment. Overall production in sub-Saharan Africa has increased in recent decades, due to the expansion of cultivated areas.

For three decades, sub-Saharan Africa has been characterized by high population growth, decreased precipitation and soil depletion. These disturbances have an impact on the agricultural practices of sorghum and millet, which are the main crops in the region. The loss of land contributes to the decline in agricultural production. It is estimated that each year 12 million agricultural land is lost, producing 20 million tons of cereals due to soil degradation (Bai et al., 2008).

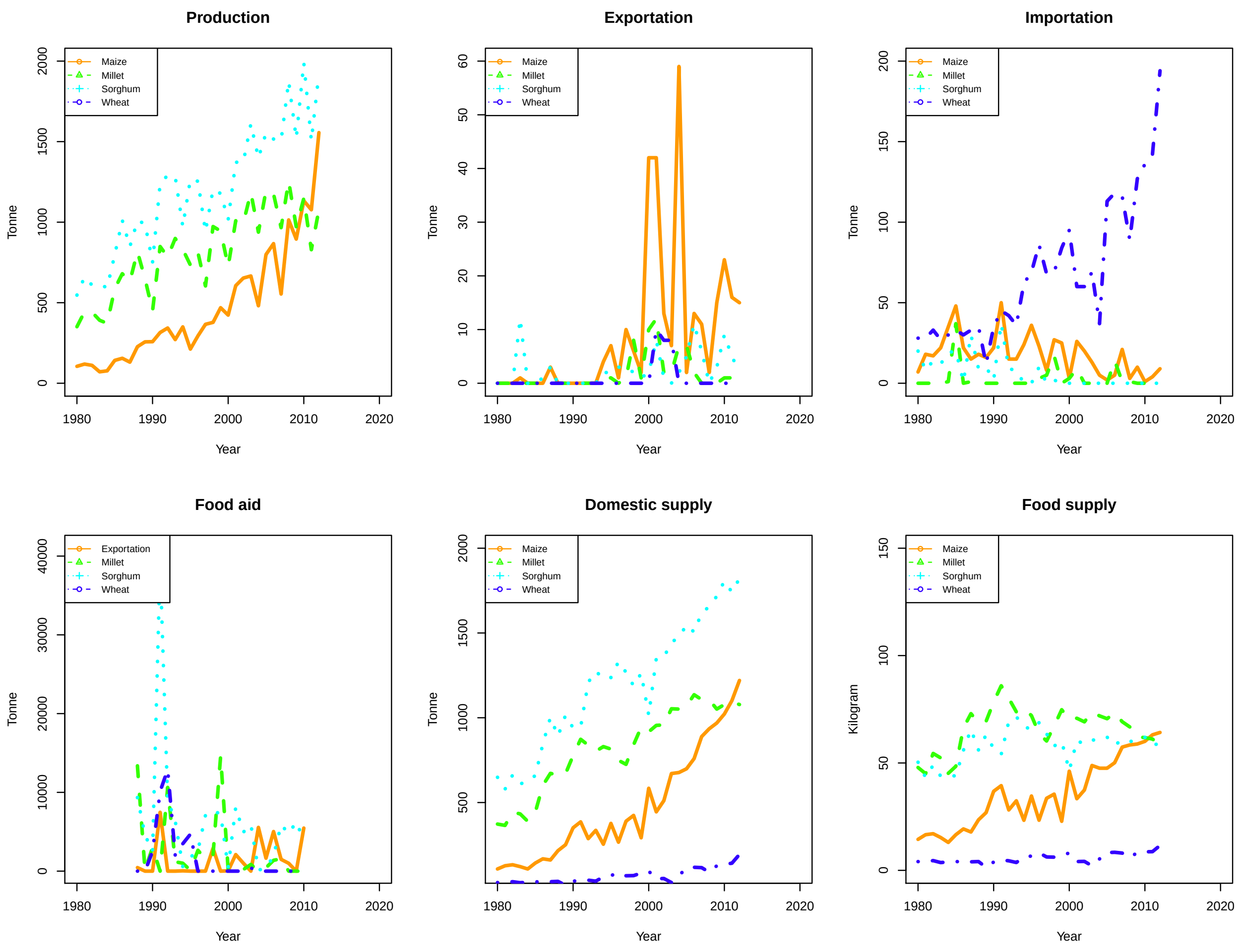
For each country, we have constructed agroecological maps on the basis of information provided by the FAO. They are units for mapping land resources specific to different countries and are constructed on the basis of the characteristics of the climate, soil and plant cover specific to the country. Thanks to the "Crop Calendar" system, we exploited the information and identified 52 agroecological zones with specific individual characteristics. They are distinguished by their area, recorded temperature and seasonal precipitation or the quantities of water received annually. During our research and to our knowledge, we found that some countries in the study area did not have agroecological maps and the old maps available (from the 1990s or early 2000s) do not correspond to the new information provided and updated by FAO on ecological zones. For example, the number of agro-ecological zones on old maps differs from the information provided by FAO on its crop calendar application (update from 2010). The originality of this work is that all agro-ecological maps and crop calendars are based on new information from FAO in 2010.

3.9.1 Burkina Faso

Bank (2016) describes Burkina Faso as a landlocked low-income country with limited natural resources. The population grows at an annual rate of 3% and is estimated at almost 18.46 million in 2016.

Flow of cereals

Figure 3.22Food flows in Burkina Faso



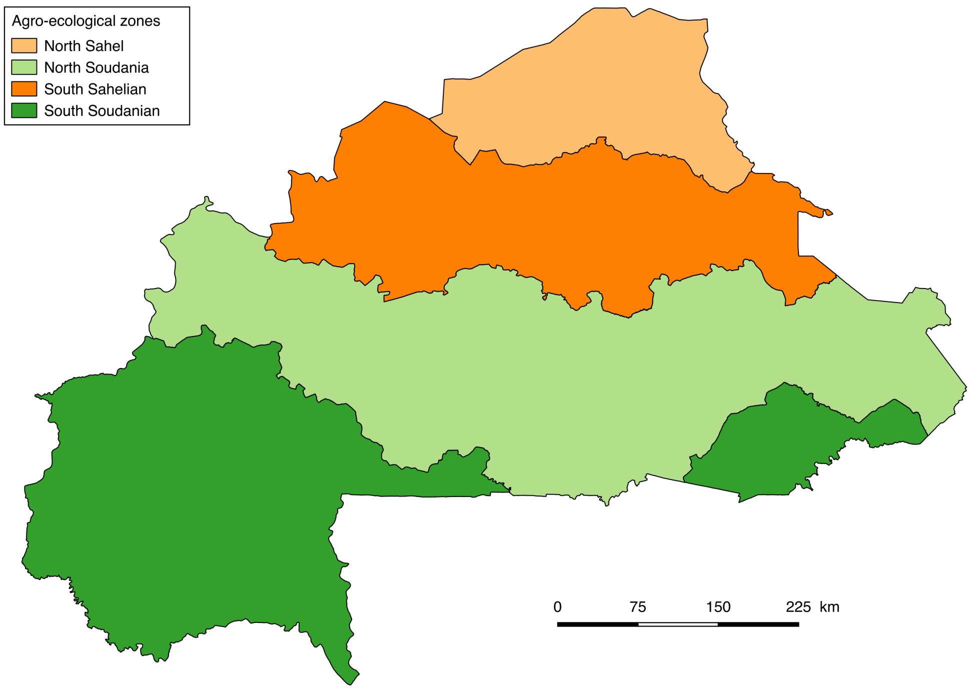
Source: Realization of the author using data from the African Development Bank

In all the countries of the Sahel, there is an increase in agricultural areas. For example, Burkina's agricultural area increased from 8,785,000 ha in 2000 to 1,200,000 ha in 2012. Over the same period, maize production increased from 105 tonnes to 1556 tonnes. In terms of quantity of production, Burkina Faso produced more sorghum than millet and wheat over the period 1980 to 2012 (see Figure 3.22). However, it is one of the few countries in our sample that is able to export its cereal production. Burkina Faso does not produce wheat, part of the imported wheat is exported because domestic demand for wheat is low. The country also benefits from a large amount of food aid in sorghum. Thus, this analysis shows the importance of sorghum in the economy and consumption in Burkina Faso.

Agro-ecological zones

The country has a climate that differs throughout the national territory and whose agroecological zones are graphically reproduced in Figure 3.23 and the main characteristics are described in Table 3.18. FAO identifies five agro-ecological zones (see table 3.18) in Burkina Faso and each zone has specific climatic characteristics and a specific agricultural calendar.

Figure 3.23Burkina Faso agro-ecological map



Source: Author's production based on data from the UN Food and Agriculture Organization

Crop Calendar

For Burkina Faso, the information gathered has made it possible to establish the agricultural calendar (see figure 3.24) for growing millet that is practiced in the country in addition to sorghum and maize. In Burkina, there are several varieties of millet that are grown throughout the country. These varieties are described in the table above (see table 3.19). They are differentiated mainly by the duration of the crops and the water needs. These different varieties of millet are grown according to the following agricultural calendar. However, we do not have the information needed to build the agricultural calendar of other crops. The millet is grown according to the following schedule, the blue and red color indicates respectively the duration of the sowing and the harvest of each variety of millet.

Table 3.18Agro-ecological zones in Burkina Faso

Agro-ecological area	Description	Agricultural practices
Center area (central plateau)	An area of 94,000 square kilometers. Average annual rainfall of between 500 and 900 mm and a mean annual temperature of 36°C (between April and May) and 18°C (between December and January).	Rainfed agriculture (millet, maize, sorghum, cowpeas, tubers), cash crops (cotton) and irrigated crops.
East zone	An area of 60,660 square kilometers, with a climate of Sudanese and Sahelian type in the north.	Extensive rainfed agriculture (millet, maize, sorghum, cowpea, cotton) and irrigated agriculture are practiced.
North zone (Sahel)	An area of 36,896 square kilometers. Average annual precipitation ranging from 300 to 600 mm per year. The average annual temperature is 28°C, the maximum is between [40 - 41°C] and is between april and may, and the minimum temperature [11 - 13°C] between december and january.	Rainfed agriculture (millet and cowpea); irrigated agriculture (below dams).
North west zone	This area has an area of 30,817 square kilometers with precipitation ranging from 600 to 900 mm from north to south.	Rainfed agriculture (millet, maize, sorghum, cowpeas), cash crops (vegetable crops).
West zone	The area is 52,000 square kilometers. Precipitation ranges from 600 to 900 mm in the north and 900 to 1200 mm in the south. The average temperature is 27 °C. An average annual thermal amplitude of 5 °C and a minimum of 18 to 20 °C in January - February.	Rainfed agriculture (millet, maize, sorghum, cowpeas, roots, fonios), cash crops (cotton) and irrigated crops (rice, sugar cane, vegetable crops).

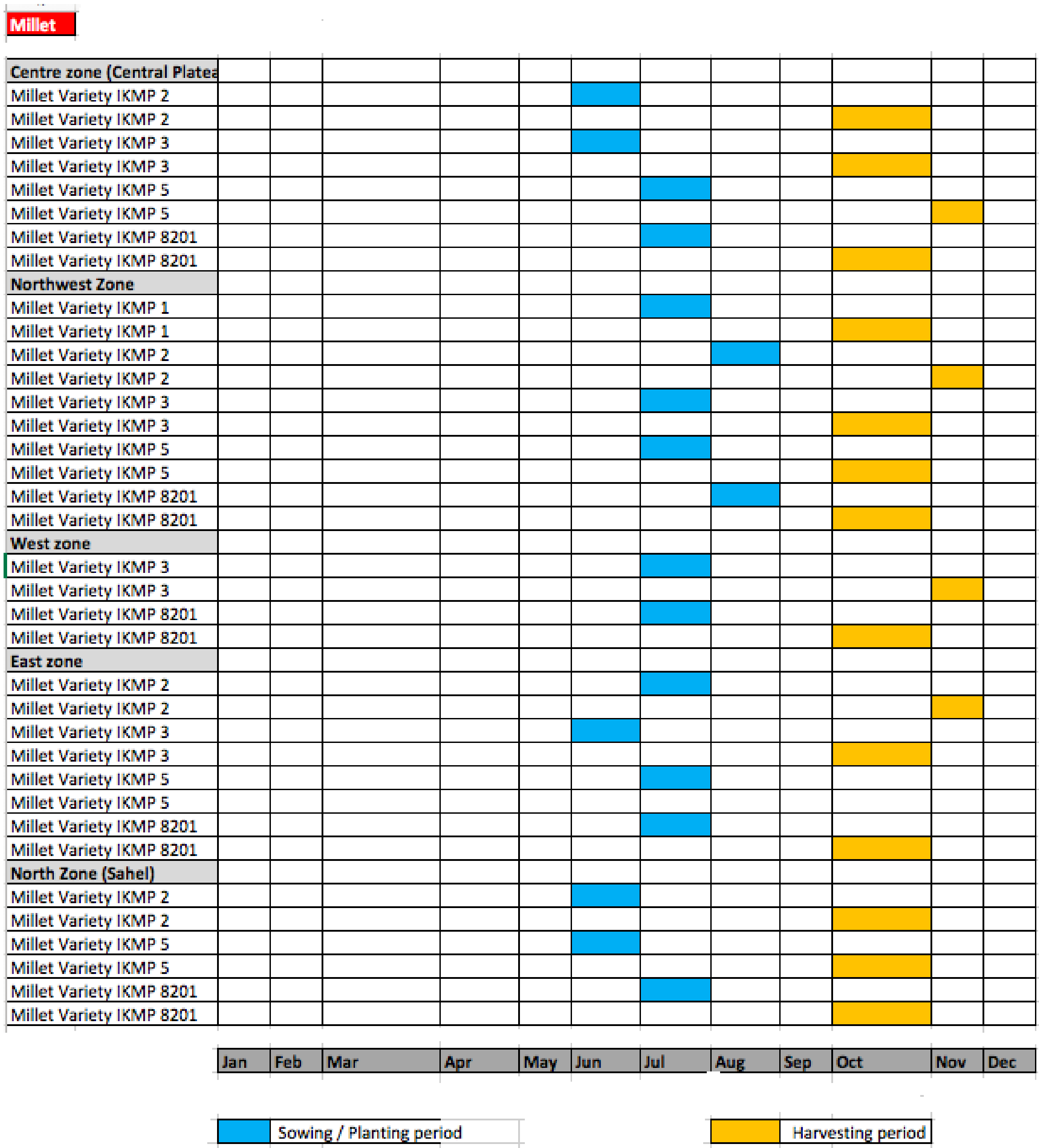
Source: Extract from Crop Calendar proposed by FAO

Table 3.19The varieties of millet grown in Burkina Faso

Variety	Duration (days)	Water (mm)	Difficulty
IKMP 1	115 to 120	700 to 900	
IKMP 2	105	500 to 800	There is a possibility of bird damage on early planting.
IKMP 3	115 to 120	700 to 1100	The variety is susceptible to stem borers and Striga.
IKMP 5	110	500 to 800	There is a possibility of bird damage on early planting.
IKMP 8201	90	500 to 700	There is a possibility of bird damage on early planting.

Source: Comparison table of explanation and description proposed by the author from the information obtained on the different varieties.

Figure 3.24Agricultural calendar of the millet culture



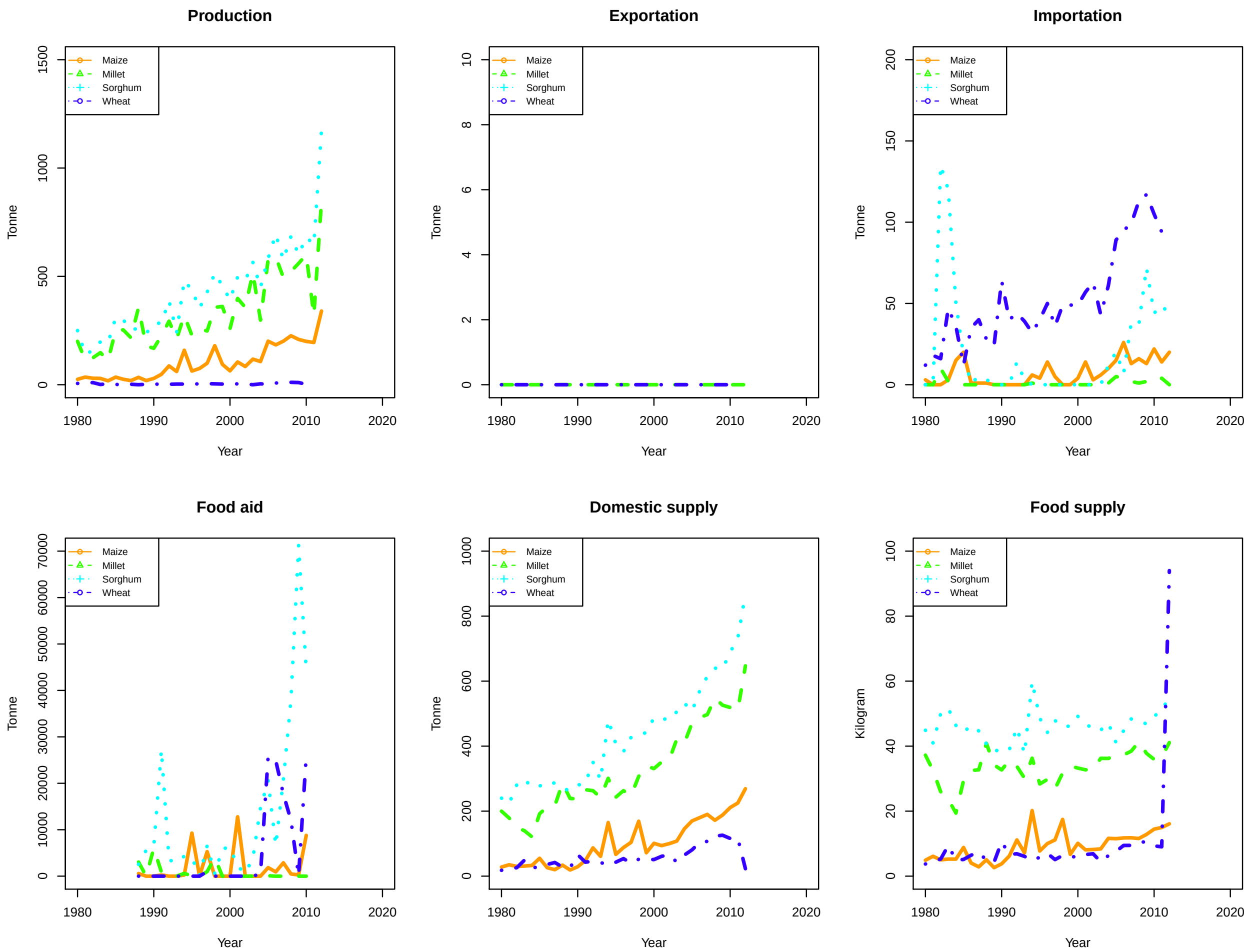
Source: UN Food and Agriculture Organization

3.9.2 Chad

Flow of cereals

Despite the large domestic production of Sorghum (see Figure 3.25), Chad relies heavily on sorghum imports and food aid to meet domestic demand. The lack of wheat production and the low production of the other three food products are offset by a large import over the entire period. The absence of export can be interpreted by the fact that Chad faces a food problem, i.e. Chad does not have a food self-sufficiency. Thus, to meet domestic demand, Chad is dependent on imports and food aid that have been increasing since the early 2000s. Note also that Chad is experiencing a special situation because of the many refugees on its territory from the Central African Republic, Libya, Nigeria and Sudan. The Boko Haram sect is at the origin of the displacements of the last years and of the food problems in the region of Lake Chad. There are about 456 000 people in need of emergency assistance throughout the country (FAO-GIEWS, 2016a).

Figure 3.25Food flows in Chad

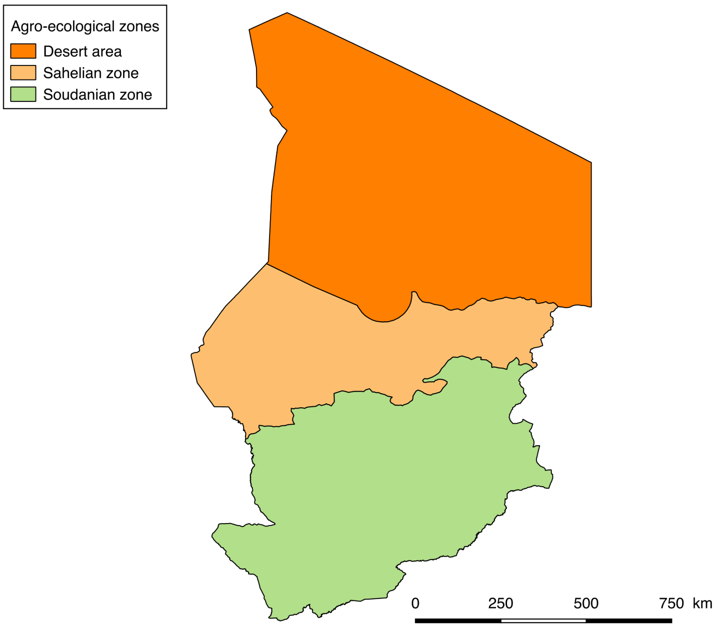


Source: Realization of the author using data from the African Development Bank

Agro-ecological zones

Chad has a climate that differs throughout the national territory and whose agroecological zones are reproduced graphically in Figure 3.26. The vast majority of the country is occupied by the desert and agriculture is practiced in the Sudanian zone which has a climate wetter than the rest of the country. However, gardening and other agricultural practices are practiced in most parts of the country. The Lake Chad polders are also used for large-scale farming.

Figure 3.26Chad agro-ecological map

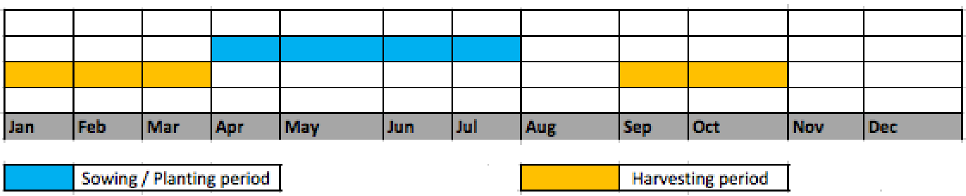


Source: Author's production based on data from the UN Food and Agriculture Organization

Crop Calendar

Large-scale agriculture is essentially based on the rainy season. Farmers begin to prepare the soil for April and follow the planting from June to August, a period corresponding to the large quantities of water. Harvests can begin from September to November. There are also some so-called "off-season" farming practices that allow farmers to be active. Thus, the following figure 3.27 gives a general idea of the general agricultural calendar for Chad.

Figure 3.27Agricultural calendar in Chad



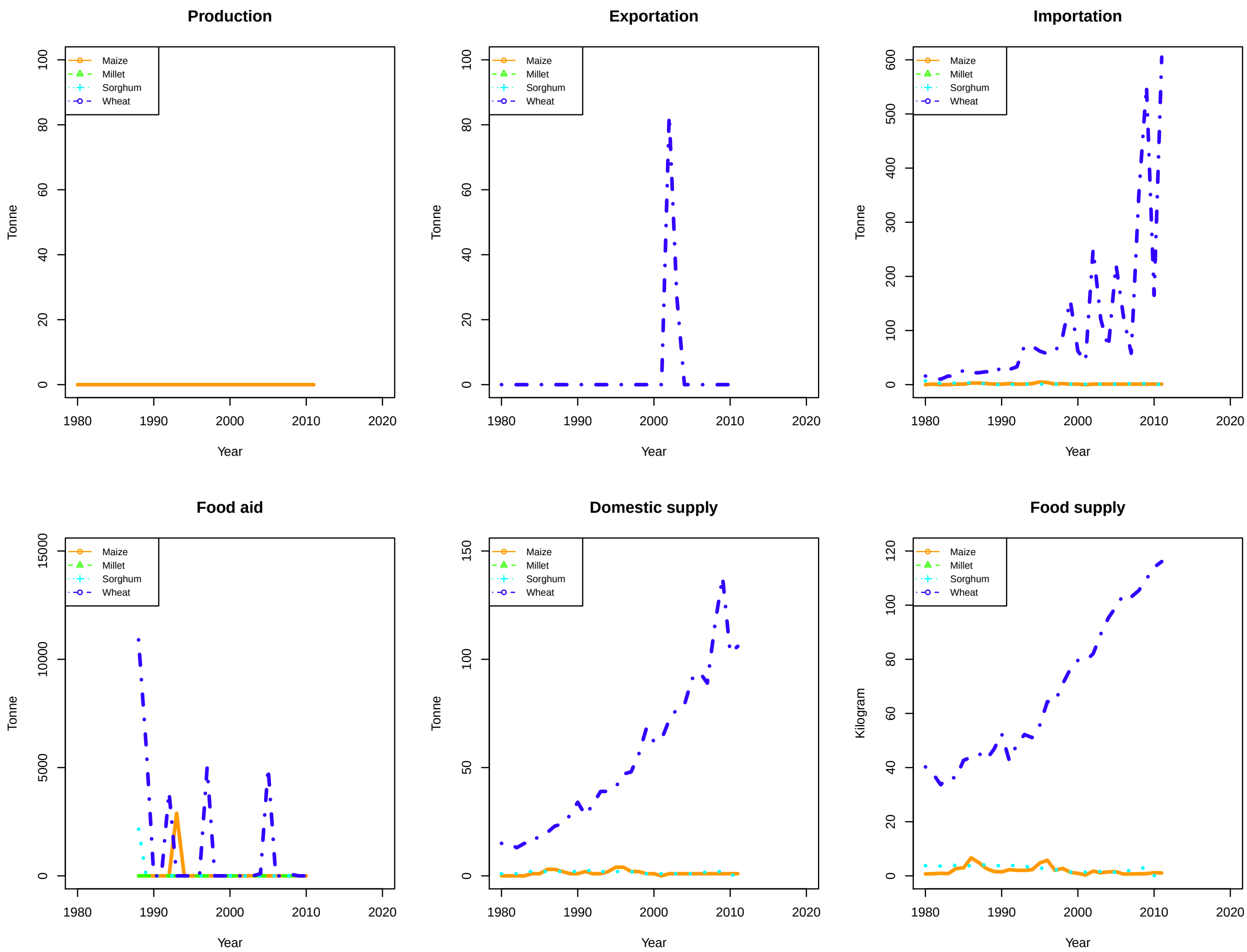
Source: UN Food and Agriculture Organization

3.9.3 Djibouti

Flow of cereal

The flows in Figure 3.28 show that wheat is a key food for the Djiboutian economy. Production data were not provided, this absence can be explained by the country's low production or by unavailability of the data. In 2011, Djibouti imported 605 tonnes of wheat, which represented a large part of its domestic supply. Moreover, the country also has food aid over the whole period and they also concern more wheat than other cereals. FAO-GIEWS (2016a) estimates that 270,000 people are in need of humanitarian assistance. These affected persons are mainly small farmers and herders who live in regions that have experienced a decrease in rainfall over several consecutive seasons. The organization also reports that there are 48,000 people from Yemen and Somalia living in refugee camps and are awaiting humanitarian aid.

Figure 3.28Food flows in Djibouti



Source: Realization of the author using data from the African Development Bank

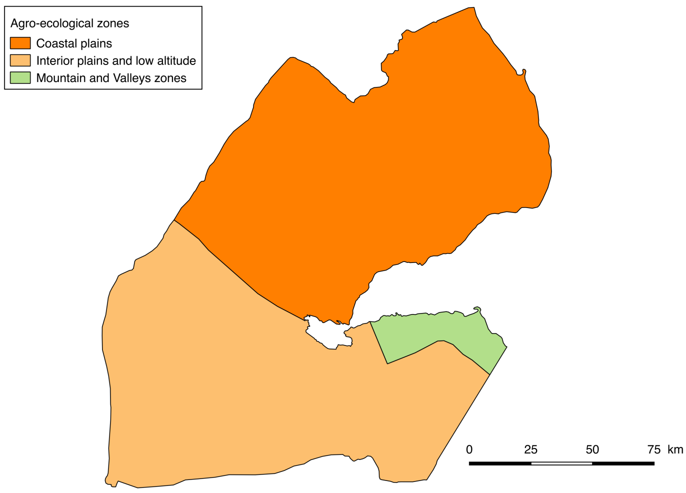
Agroecological zones

The country has three agro-ecological zones (see Figure 3.29) whose agricultural characteristics and practices are summarized in Table 3.20. Djibouti is a small country with an agricultural area and has grown from 1,301,000 ha in 1980 to 1,702,000 ha in 2012.

Crop Calendar

FAO's available data have made it possible to construct agricultural calendars for maize (Figure 3.30) and sorghum (Figure 3.31). In the agroecological zone of the mountains and

Figure 3.29Djibouti agro-ecological map



Source: Author's production based on data from the UN Food and Agriculture Organization

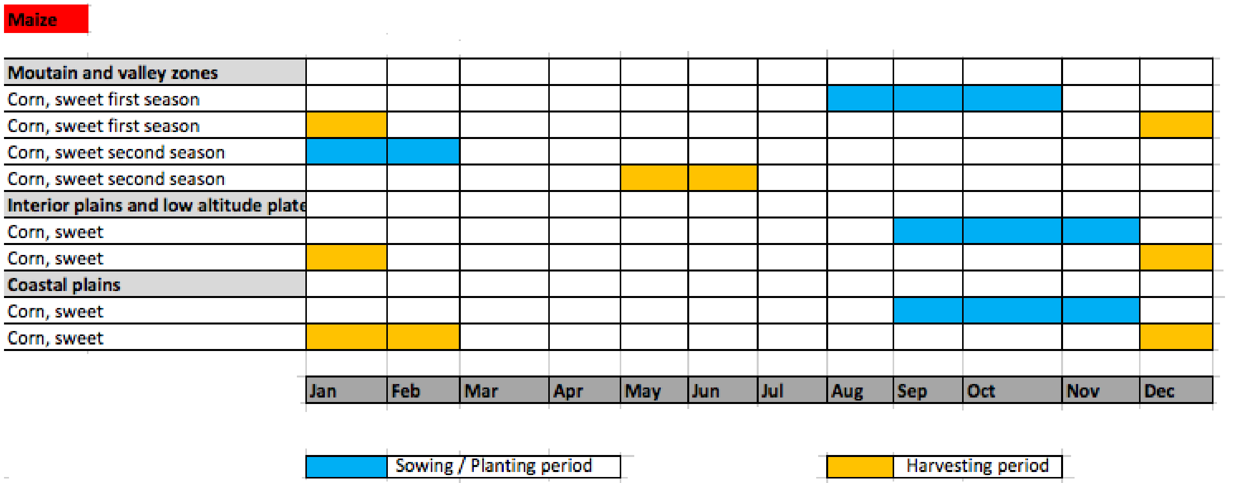
Table 3.20Agro-ecological zones in Djibouti

Agro-ecological area	**Description**	**Agricultural practices**
Coastal plains	Coastal plains, hot and humid climates, and sandy soils; Main constraints: high temperatures, one season of main crop, often salt water limiting crop.	Crops of vegetables, cereals and legumes.
Interior plains and low altitude plateaux	Continental plains: warm and dry climate, clay soils; Main constraints: high temperatures, a single main season for growing vegetables (September - May), salt water limits cultivation.	Vegetables, cereals and legumes
Mountain and valley zones	Valleys and plateaus of altitude (600 - 1700 mm); Moderate climate: favorable for growing off-season vegetables and fruit varieties, but the land area is limited.	Vegetables, cereals and legumes in season and off season.

Source: Extract from Crop Calendar proposed by FAO

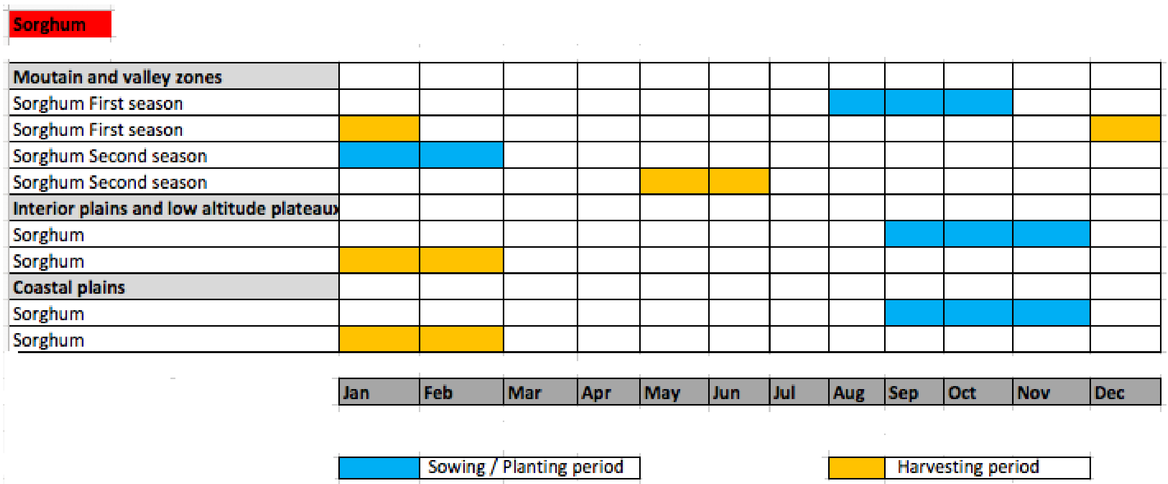
valleys, corn is grown during both seasons. This area is favorable for agriculture given its altitude and the quality of the soil.

Figure 3.30Agricultural calendar of the maize culture



Source: UN Food and Agriculture Organization

Figure 3.31Agricultural calendar of the sorghum culture



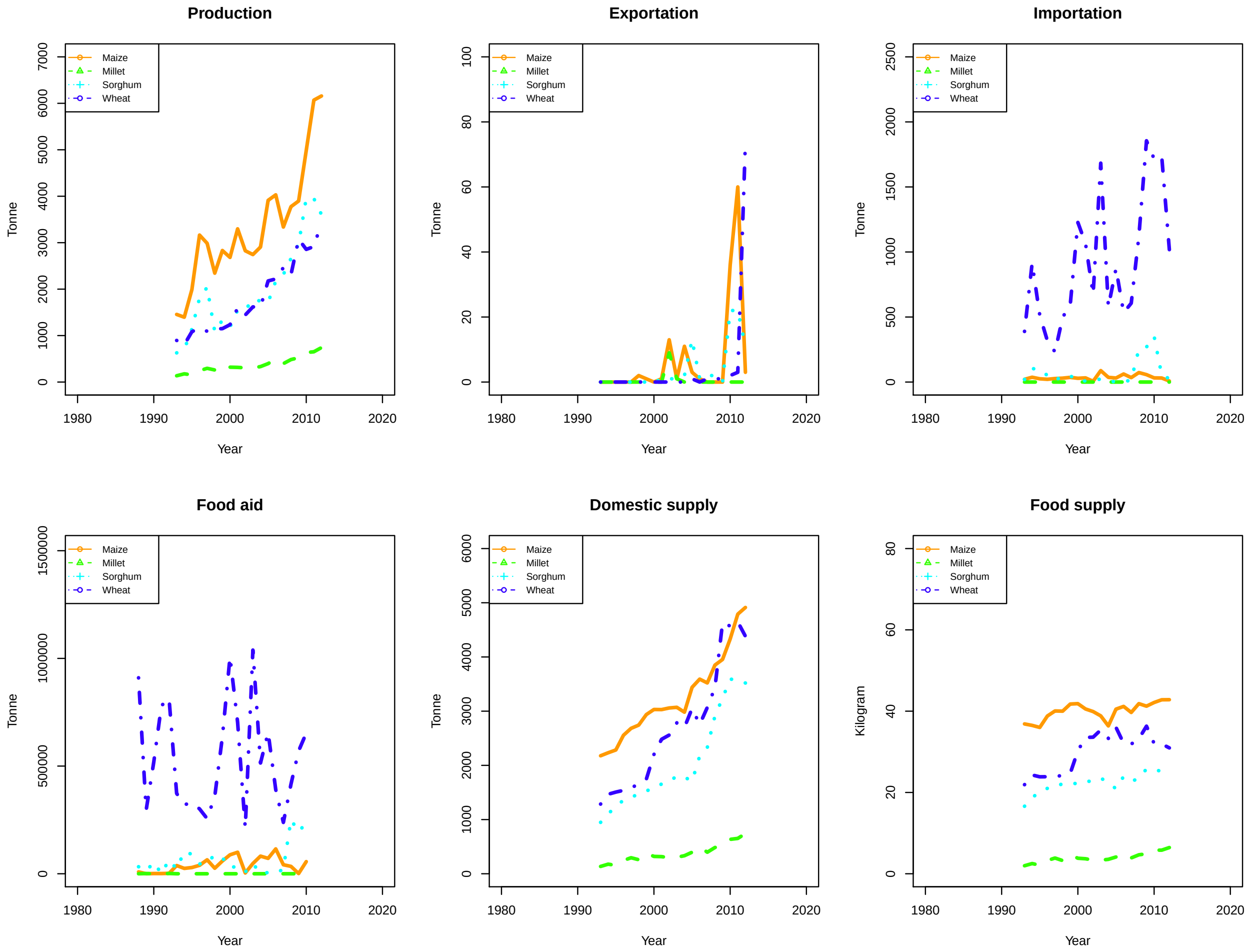
Source: UN Food and Agriculture Organization

3.9.4 Ethiopia

Flow of cereals

Ethiopia can be considered one of the countries with the highest agricultural status in comparison to the countries in our sample (Figure 3.32). In spite of its large production, the country has received substantial food aid. It should be remembered that food aid often comes into play when a country faces catastrophic situations such as drought and extreme events. Ethiopia produces a large quantity of maize, followed by sorghum, wheat and millet. The low output of wheat is offset by a large import of wheat and food aid. In terms of increasing quantity, domestic supply and food supply are for maize, wheat, sorghum and millet.

Figure 3.32Food flows in Ethiopia



Source: Realization of the author using data from the African Development Bank

Agro-ecological zones

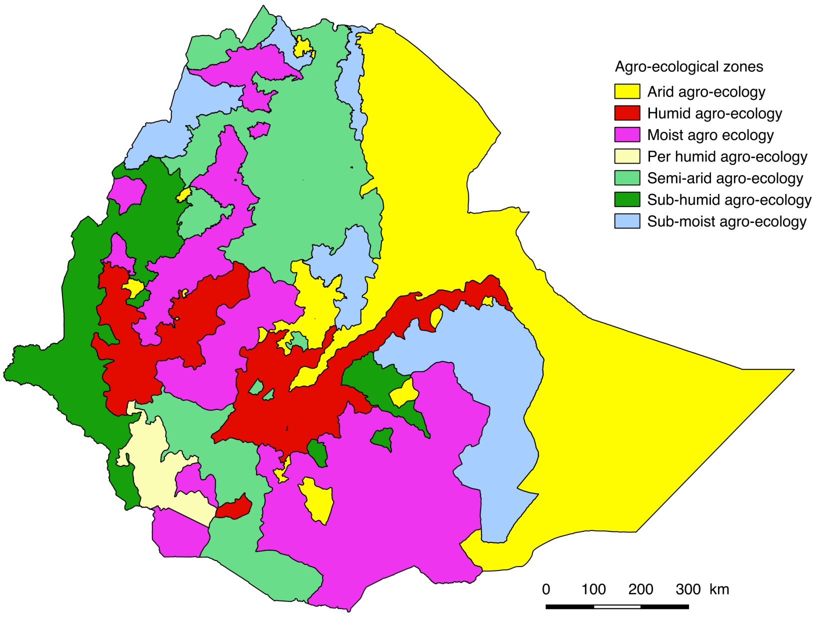
Ethiopia is the only country in our Sahel to have more agro-ecological zones (figure 3.33) spread over its entire territory.

The table 3.21 describes the seven agro-ecological zones provided by FAO and the different agricultural practices.

Crop Calendar

Available FAO data have made it possible to construct agricultural calendars for maize (Figure 3.34), sorghum (Figure 3.35), millet (Figure 3.36) and wheat (Figure 3.37). Ethiopia has favorable and diverse agro-ecological zones for agriculture. For example, the arid zone is known to be good for sorghum cultivation and the country has about 33 million hectares. Ethiopia has a significant advantage and adapted agricultural practice due to the use of the irrigated agricultural system for maize cultivation (in semi-arid and arid areas), sorghum (in the arid zone) and wheat (in the arid zone). This agricultural practice allows an agricultural economy to permanently have an agricultural rent and consumer products throughout the year while having a rainfed system highly dependent on rainfall conditions. The use of two

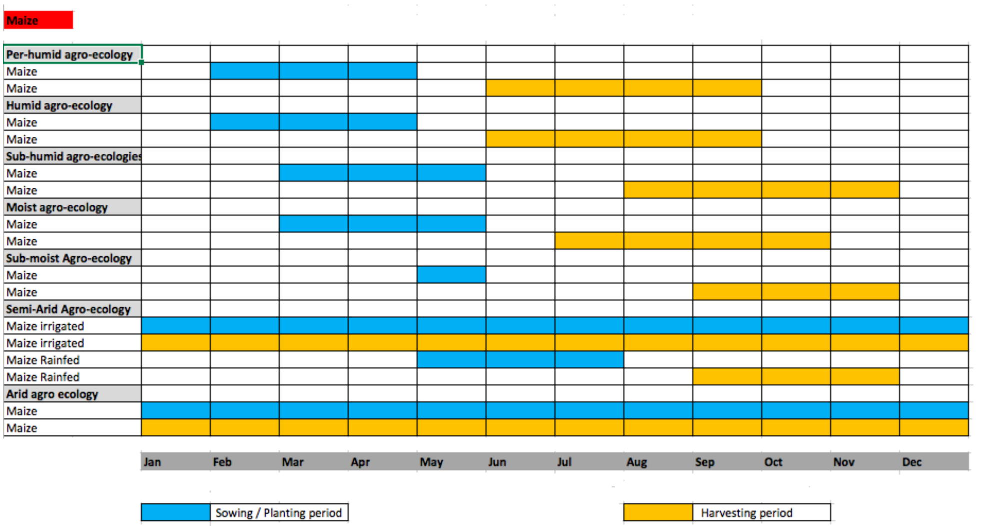
Figure 3.33Ethiopia agro-ecological map



Source: Author's production based on data from the UN Food and Agriculture Organization

or more agricultural practices allows countries to have adequate domestic food capacity to some extent.

Figure 3.34Agricultural calendar of the maize culture



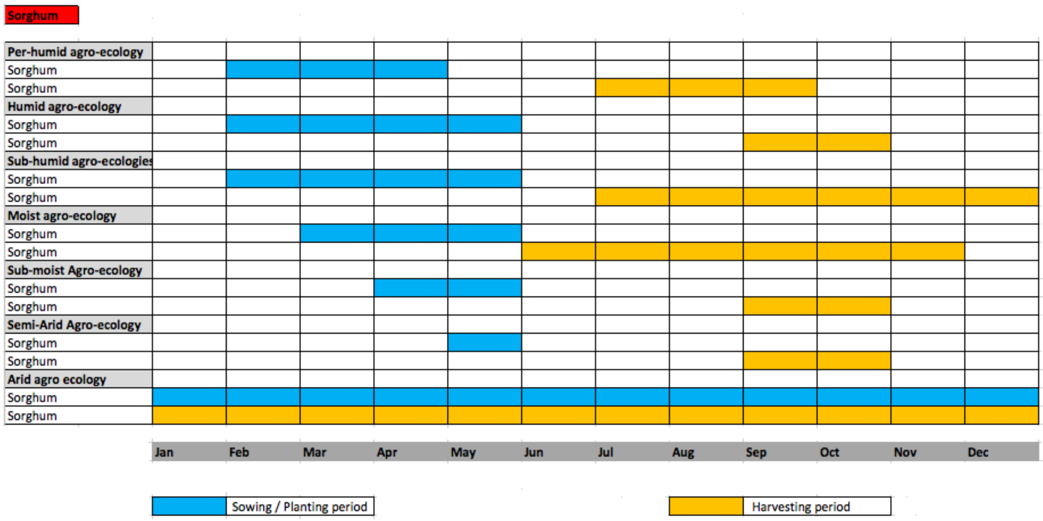
Source: UN Food and Agriculture Organization

Table 3.21Agro-ecological zones in Ethiopia

Agro-ecological area	Description	Agricultural practices
Arid agro-ecology	An area of about 35 million hectares with an average annual temperature of 16 to 28 ° C and precipitation between 100 to 800 mm. With a growth period of less than 45 days.	Cultivation of sorghum
Humid agro-ecology	The most stable area of the country with an area of about 4.4 million hectares with an average annual temperature (8-26 ° C), precipitation (500-2,200 mm) and a growing period (180-330 days).	Cultivation of cereals and animal farming
Moist agro ecology	Ethiopia's largest agricultural land with an agricultural area of about 28 million hectares, an average annual temperature (7 - 28 ° C), precipitation (250 - 2200) and a growing period (150 - 270 days).	Common practices: annual crops and perennial crops. In one part of the area, cereal crops are dominant and livestock farming is practiced as a secondary activity.
Per-humid agro-ecology	Located in southwestern Ethiopia covering an area of 0.9 million hectares, with an average annual temperature (13 - 26 ° C), average annual precipitation (1,100 - 2,200 mm) and a period of Reliable growth of 330 days.	Common practices: annual crops and perennial crops. Fruit crops are the dominant crops in the region.
Semi-arid agro-ecology	An area of about 4 million hectares with an altitude of 400-2,200 m, with an average annual temperature (16-30 ° C), precipitation (300-800 mm) and a period of growth of About 60 days.	Nomadic pastoralism and agro-pastoralism are major agricultural practices in a part of the semi-arid zone.
Sub-humid agro-ecology	The country's stable zone with an area of about 17.5 million hectares of land (15% of the country). Average annual temperature (8 - 28 ° C) and precipitation (700 - 2200mm); Growth period (180 - 330 days).	Cereal crops
Sub-moist agro-ecology	An area of about 22 million hectares (about 19.1% of the country); Average annual temperature (16 to 28 ° C) and precipitation between 200 - 2600 mm; Growth period up to 250 days;	

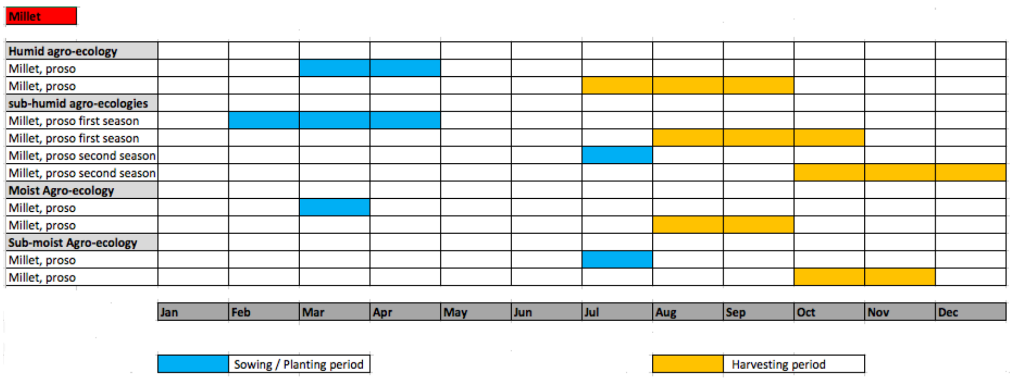
Source: Extract from Crop Calendar proposed by FAO

Figure 3.35Agricultural calendar of the sorghum culture



Source: UN Food and Agriculture Organization

Figure 3.36Agricultural calendar of the millet culture



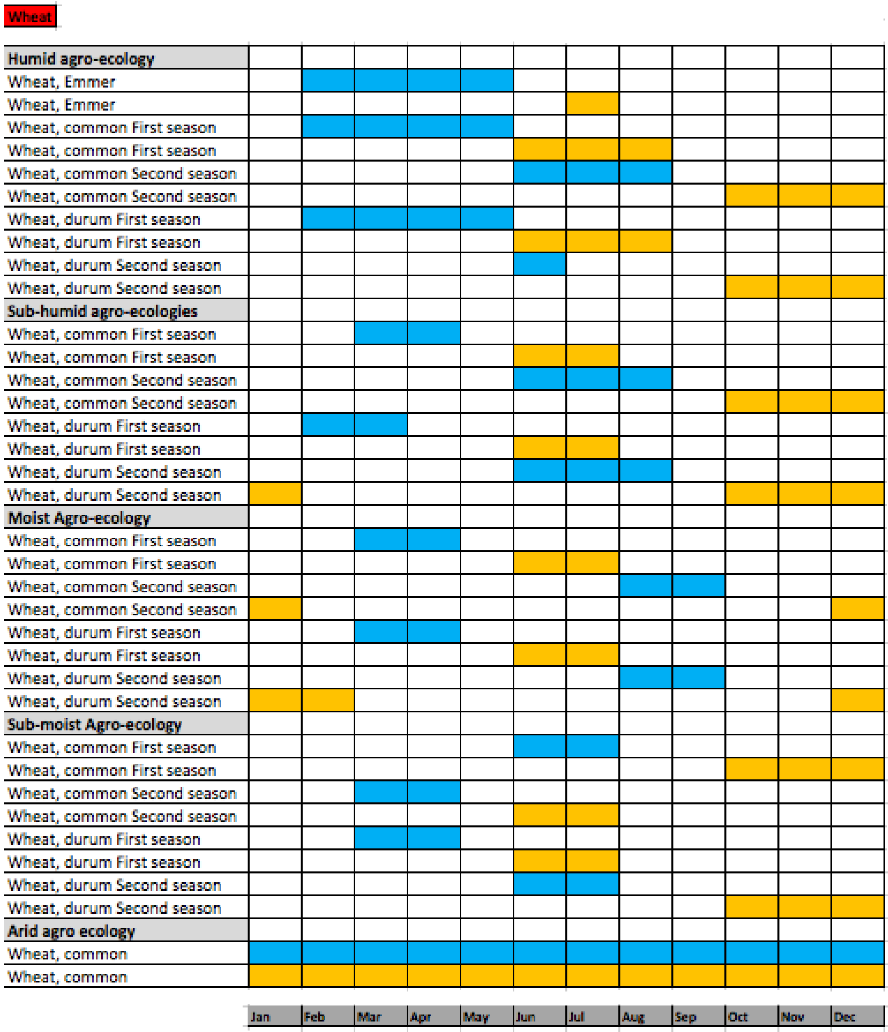
Source: UN Food and Agriculture Organization

3.9.5 Mali

Flow of cereals

Mali imports a large quantity of wheat to compensate for its low domestic production of wheat, followed by a certain amount of other food. Part of the food is destined for export, over the whole period, the country has exported a large amount of sorghum (see figure 3.38). The country also received food aid from 2007 until the end of the period. In order of increasing quantities, domestic supply and food supply include millet, sorghum, maize and wheat. Millet production in Mali has increased from 407 tonnes in 1980 to 1,462 tonnes in 2011 (see figure 3.38). The country also produces sorghum, maize and wheat. In Mali, the persistent effects of disruptions caused by recent civil conflicts have had a very negative long-term impact on household goods and economies, particularly in the north of the country. Many segments of the population still need food and non-food assistance to restore their livelihoods and enable them to have better access to food (FAO-GIEWS, 2016a).

Figure 3.37Agricultural calendar of the wheat culture

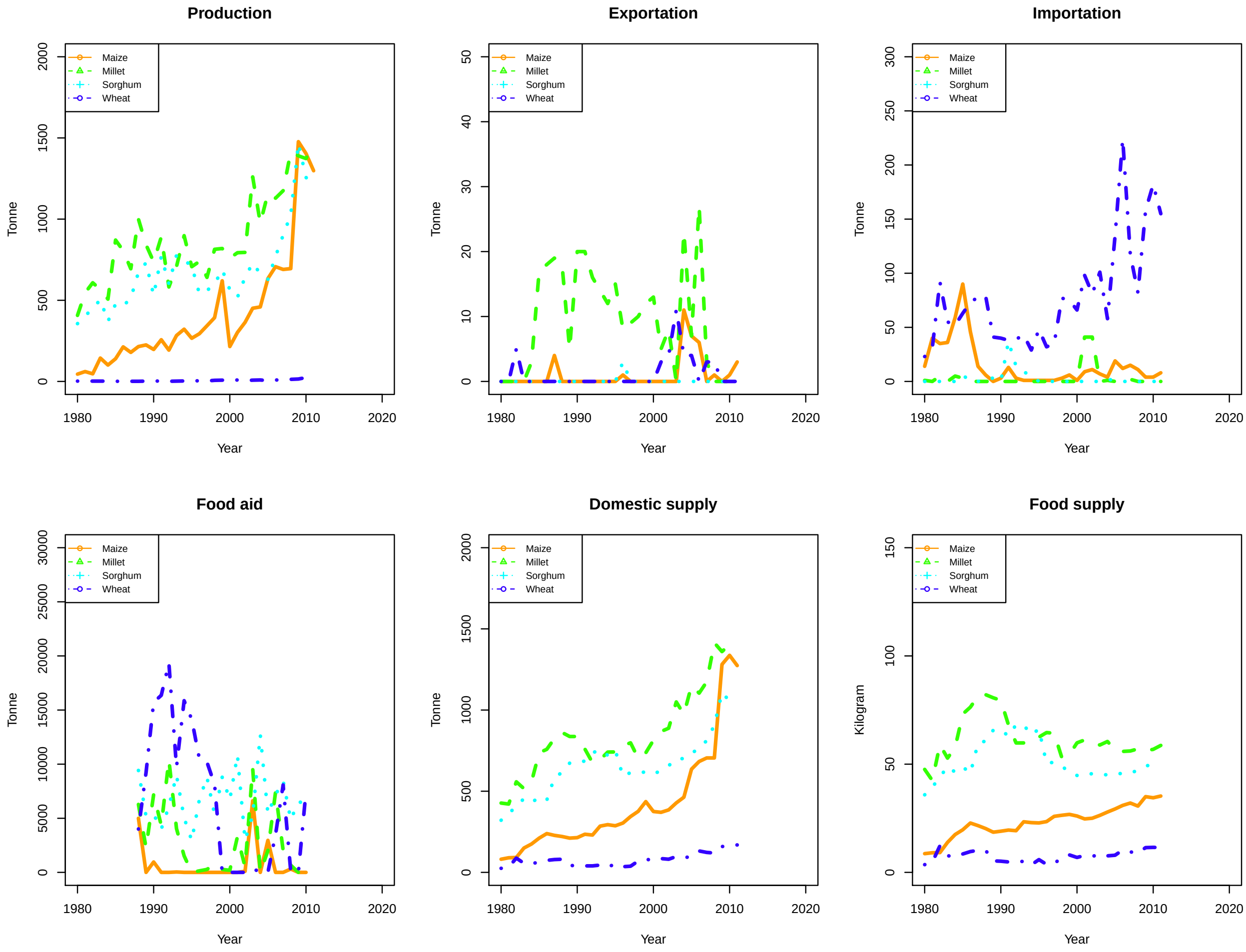


Source: UN Food and Agriculture Organization

Agro-ecological zones

Mali has four agro-ecological zones, which are shown graphically in Figure 3.39 below.

Figure 3.38Food flows in Mali



Source: Realization of the author using data from the African Development Bank

In Mali, FAO identifies 4 agro-ecological zones distributed throughout the national territory. These areas are described in the table 3.22 with their main agricultural practices.

Crop Calendar

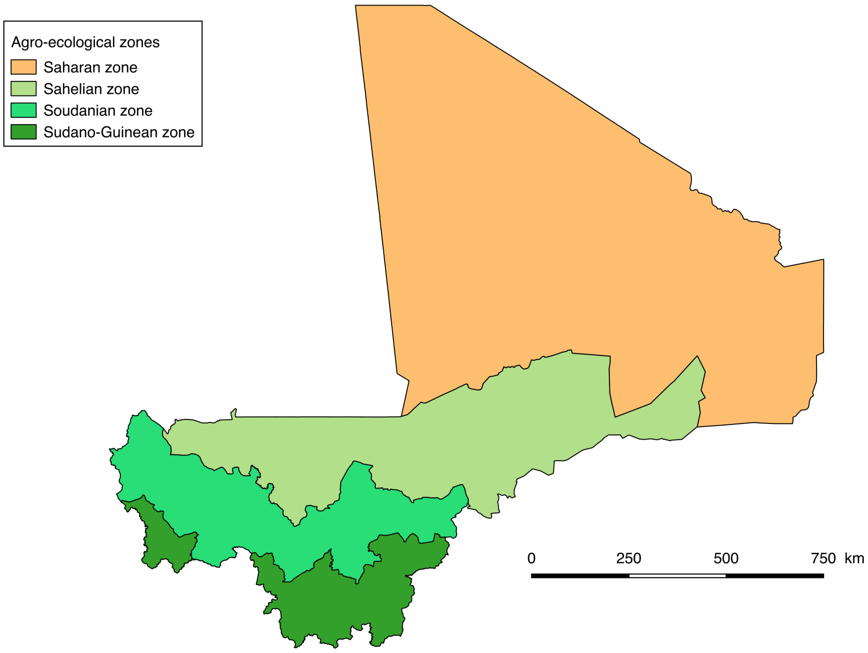
Available FAO data have made it possible to construct agricultural calendars for maize (Figure 3.40), sorghum (Figure 3.41), millet (Figure 3.42) and wheat (Figure 3.43). Like other Sahelian countries, Mali is heavily involved in rainfed agriculture, which is based on the relatively short rainy season with erratic rains. Rainfall duration as shown by crop calendars varies across different agricultural areas.

3.9.6 Mauritania

Flow of cereals

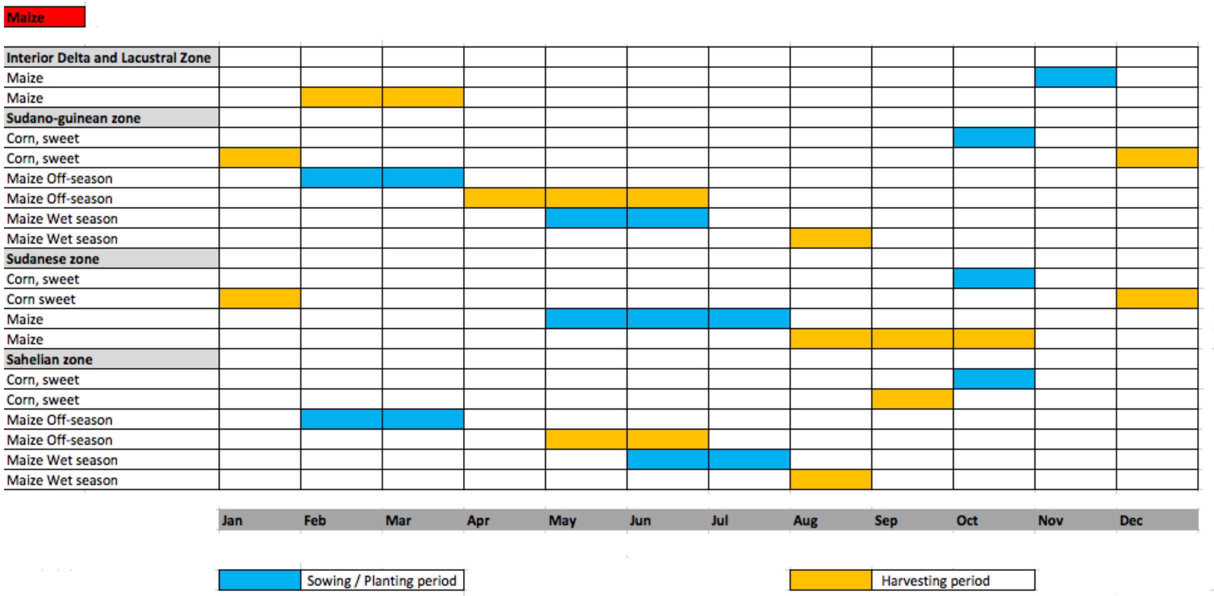
In Mauritania, Figure 3.44 shows that sorghum is the crop with much higher production than maize, sorghum, wheat and millet. No export, but Mauritania to compensate for the low domestic production of wheat imports a large amount of wheat. Wheat accounted for

Figure 3.39Mali agro-ecological map



Source: Author's production based on data from the UN Food and Agriculture Organization

Figure 3.40Agricultural calendar of the maize culture



Source: UN Food and Agriculture Organization

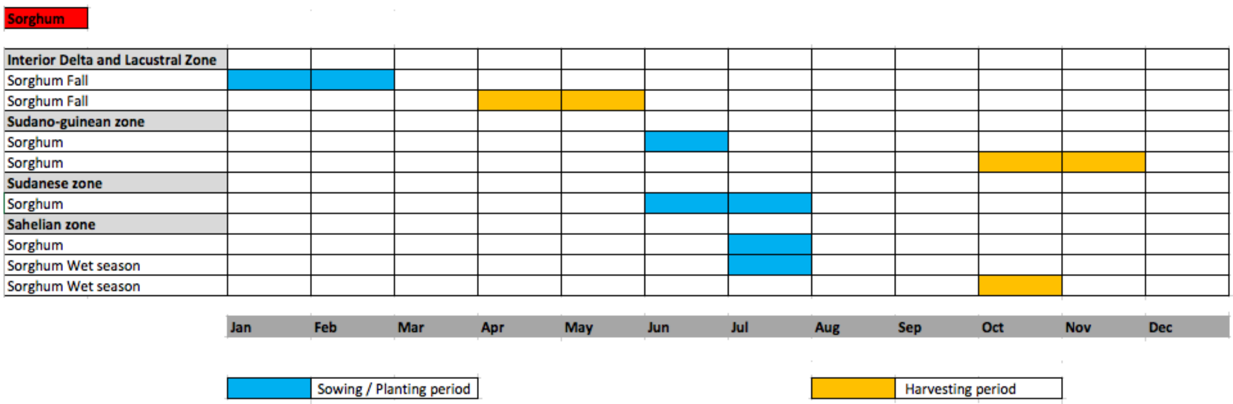
most of the food aid received by Mauritania over the entire period, followed by sorghum and maize. Domestic supply and food supply are sucessively related to wheat, sorghum, millet and maize. A large segment of the Mauritanian population relies on traditional farming and

Table 3.22Agro-ecological zones in Mali

Agro-ecological area	**Description**	**Agricultural practices**
Interior Delta and Lacustral zone	Humid zone belonging to the Sahelian zone whose area is between 30,000 to 35,000 square kilometers.	Transhumance of livestock, Recessional cultivation, Rainfed crops, Irrigated crops
Saharan zone	Covering northern Mali with an area of 632,000 square kilometers.	The population associates farm animals with subsistence farming (vegetables and date palms).
Sahelian zone	An area of 285,000 square kilometers. The humid zone is distributed in 3 and 4 months (June to September) with considerable surface water potential (Niger River, Bani River and ponds).	A system associated with rainfed crops, vegetables and palm trees.
Sudanese zone	An area of 215,000 square kilometers with precipitation distributed over 5 months ranging from 600 mm per year in the North and more than 800 mm in the South.	Agricultural practices include rainfed crops, irrigated crops, fisheries and specialized peri-urban market gardening.
Sudano-guinean zone	An area of 75 000 square kilometers located in the extreme south of Mali with precipitation ranging from 800 to more than 1 000 mm per year for a period of 6 months.	Rainfed crops alone or mixed with cotton growing; Specialized peri-urban market gardening.

Source: Extract from Crop Calendar proposed by FAO

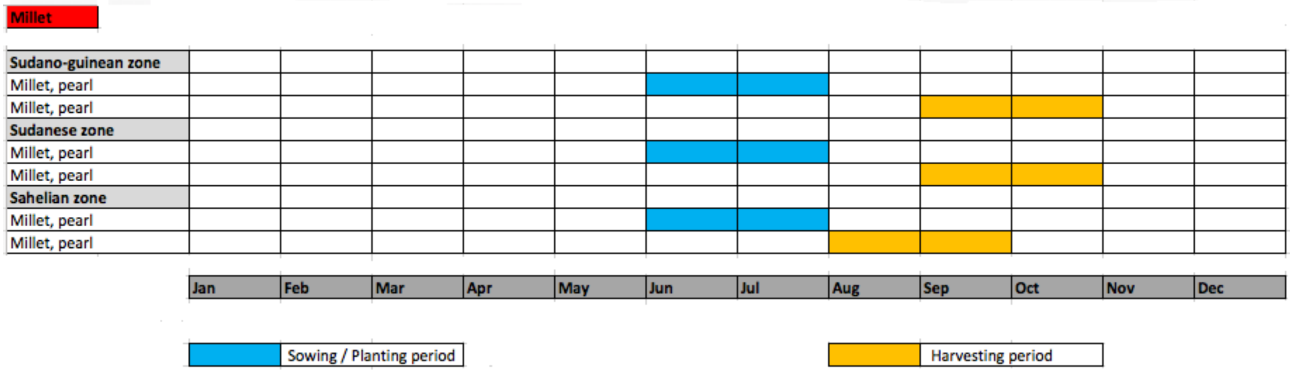
Figure 3.41Agricultural calendar of the sorghum culture



Source: UN Food and Agriculture Organization

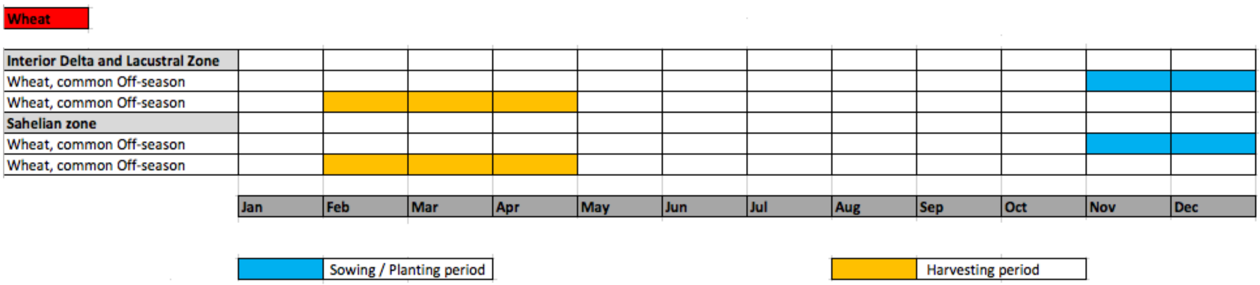
livestock activities to sustain their livelihoods and thus remain chronically vulnerable due to unpredictable seasonal rains and climatic conditions. Moreover, the high rate of import

Figure 3.42Agricultural calendar of the millet culture



Source: UN Food and Agriculture Organization

Figure 3.43Agricultural calendar of the wheat culture



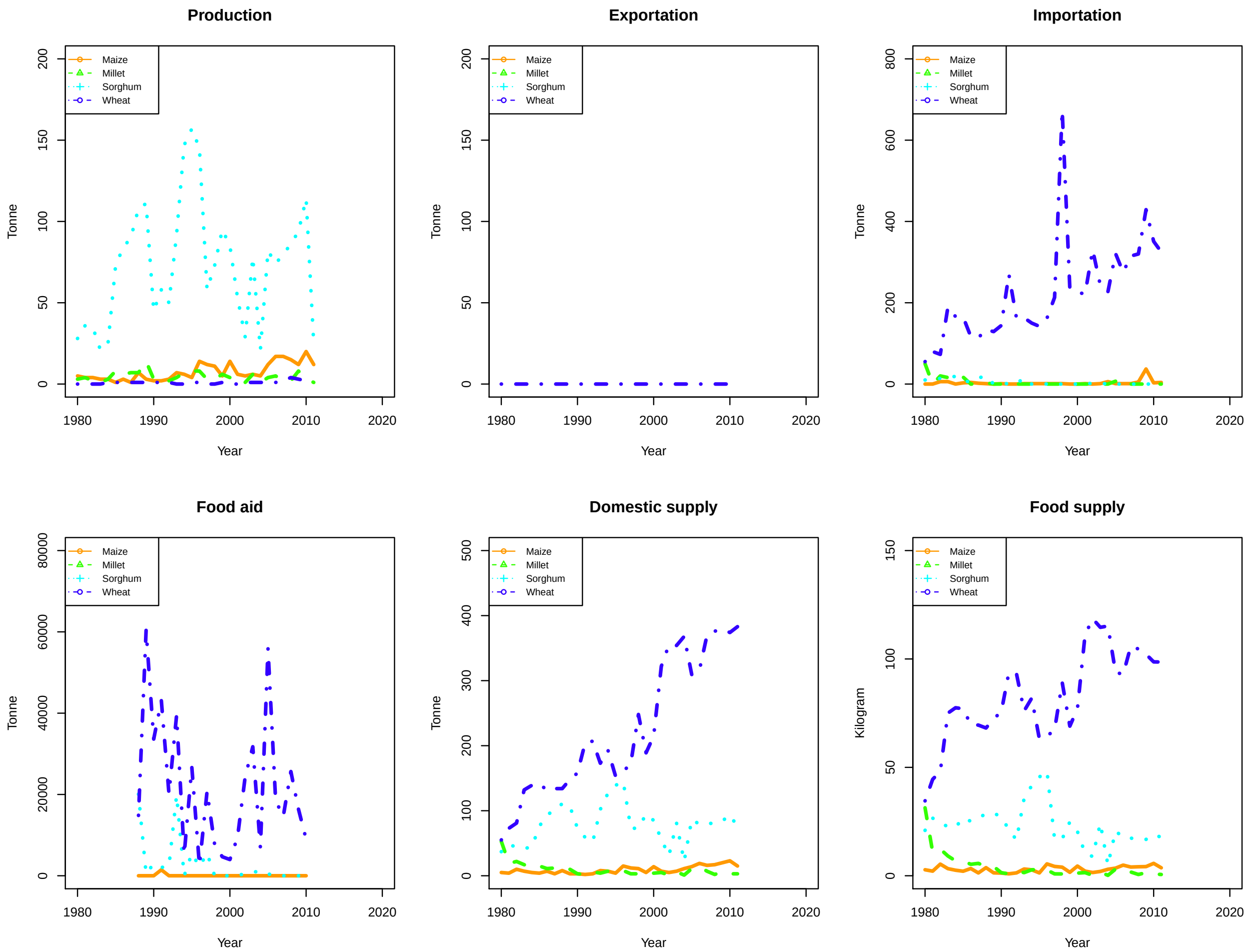
Source: UN Food and Agriculture Organization

dependence on food exposes the population to fluctuations in the world market. In addition, the armed conflict in northern Mali has forced thousands of Malians to cross the border into Mauritania. According to UNHCR, as of July 2016, some 42,000 Malian refugees were still living in Mauritania, in the Mberra camp (FAO-GIEWS, 2018).

Agro-ecological zones

Mauritania has a climate varying in the national territory and whose agroecological zones are reproduced graphically in figure 39. The big part of the country is occupied by the desert and agriculture is practiced in the Sahelian zone which has a more humid climate than the rest of the country. However, gardening and other agricultural practices are practiced in most parts of the country.

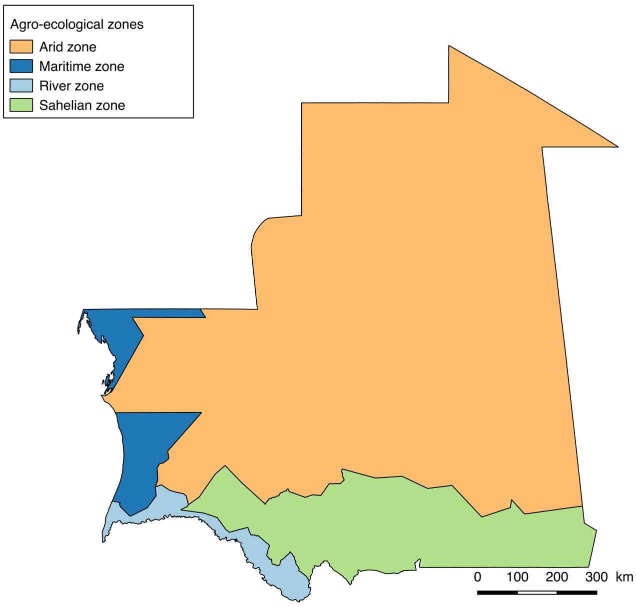
Figure 3.44Food flows in Mauritania



Source: Realization of the author using data from the African Development Bank

FAO identifies four agro-ecological zones distributed throughout Mauritania whose agricultural characteristics and practices are described in the table 3.23.

Figure 3.45Mauritania agro-ecological map

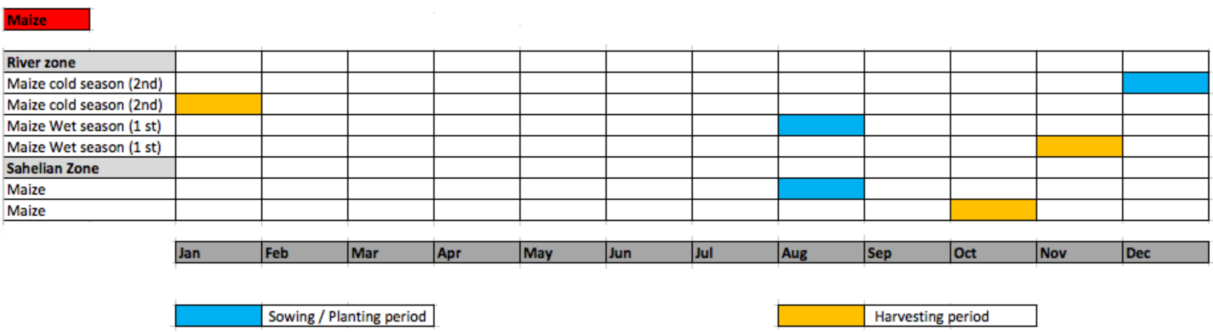


Source: Author's production based on data from the UN Food and Agriculture Organization

Crop Calendar

Available FAO data have been used to construct agricultural calendars for maize (Figure 3.46), sorghum (Figure 3.47), millet (Figure 3.48) and wheat (Figure 3.49). Mauritania has an agricultural calendar exclusively based on rainfed agriculture. Other practices are present but often less developed. The country has a short rainy season and low rainfall making rainy agricultural practice difficult in the arid part of the country.

Figure 3.46Agricultural calendar of the maize culture



Source: UN Food and Agriculture Organization

Table 3.23Agro-ecological zones in Mauritania

Agro-ecological area	Description	Agricultural practices
Arid-zone	Without maritime bands, the area covers 80% of the national territory. Precipitation is less than 100 mm per year, rarely reaching 150 mm / year in the northern part of Assaba and Hodhs and with an average annual temperature of 10-47 ° C. The wet season (July - September), the dry season (October - June) and relative humidity (28 - 43%).	Cereals (wheat, oat), vegetables (carrot, tomato, cabbage and drilling (alfalfa))
Maritime Zone	50 kilometers wide, the area covers the coastal strip extending from Nouadhibou to the banks of the Senegal River. With a humid season (August - September) and a dry season (October - July), it has a temperature ranging from 10 to 35 ° C and precipitation ranging from 0 to 50 mm rarely reaching 100 mm in the winter rain and dews (december to january).	Vegetable production is decreasing in this area due to the abandonment of irrigation by sewage, import competition (Morocco and Senegal) and domestic production of other agro-ecological zones.
River Zone	In this zone, precipitation ranges from 350 to 450 mm per year and temperature from 15 to 45 ° C. The humid season (June - September) and the dry season (October to May).	Rainfed crops (sorghum, millet, maize, cowpea, groundnut), irrigated crops (rice, maize, sorghum, vegetable crops).
Sahelian Zone	Located between the southern arid limit and the northern limit of the river, it receives precipitation ranging from 200 to 400 mm and a temperature varying from 15 to 45 ° C depending on the season: humid season (June to September) and dry season October to May).	Rainfed crops and crops grown under dam (sorghum, millet, maize); Mixed cropping is common and fertilizer use is rare.The cultivation of vegetables is developed by women's cooperatives.

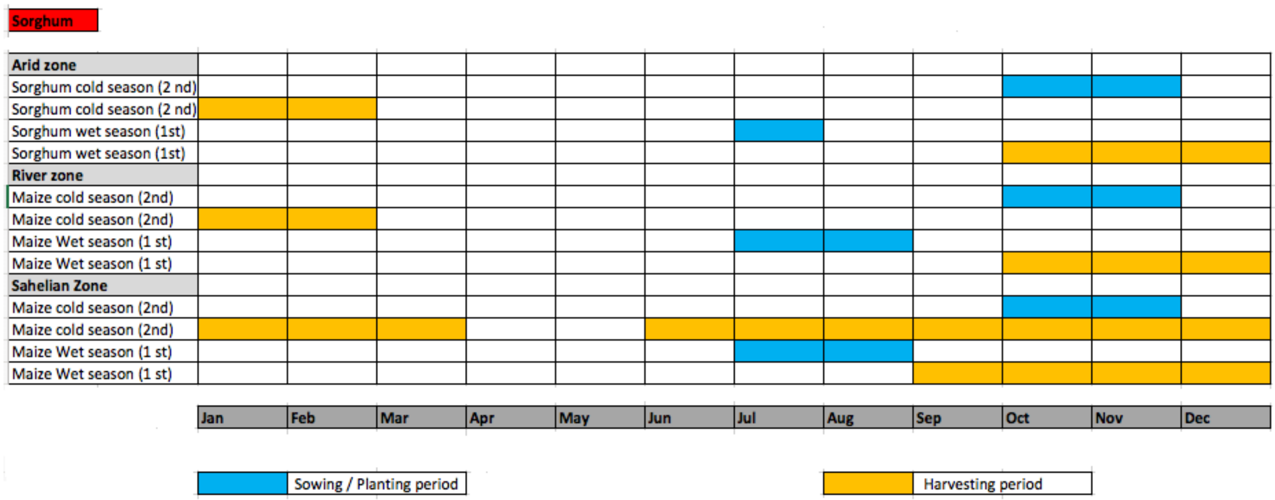
Source: Extract from Crop Calendar proposed by FAO

3.9.7 Niger

Flow of cereals

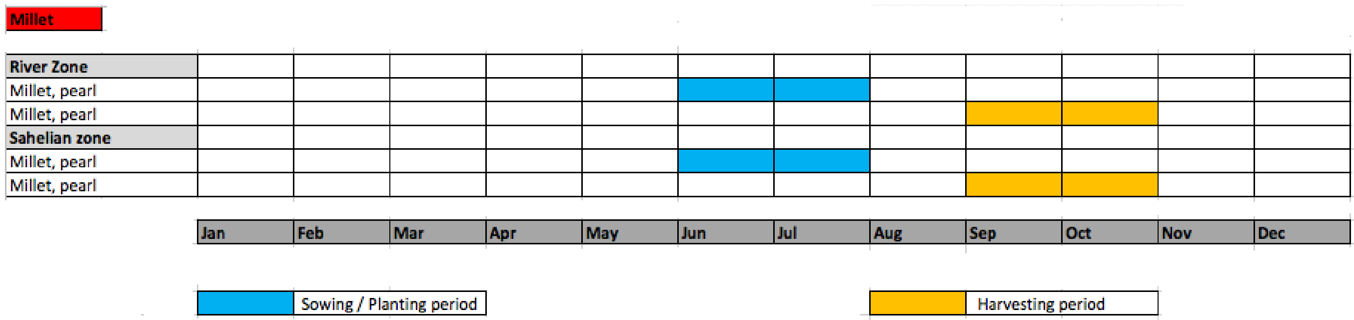
According to the for Development (2009), Niger is the second largest producer of millet after Nigeria and this crop covers more than 65% of the cultivated area and accounts for almost three-quarters of the country's cereal production. A group of scientists have shown that production and income associated with growing millet is expected to increase by up to 30% (for Development, 2011). At the beginning of the period (see Figure 3.50), the country was exporting sorghum and millet, but the export trend stagnated before recovering slightly from 2010, with the export of maize and wheat. A staple food in Africa, sorghum is

Figure 3.47Agricultural calendar of the sorghum culture



Source: UN Food and Agriculture Organization

Figure 3.48Agricultural calendar of the millet culture



Source: UN Food and Agriculture Organization

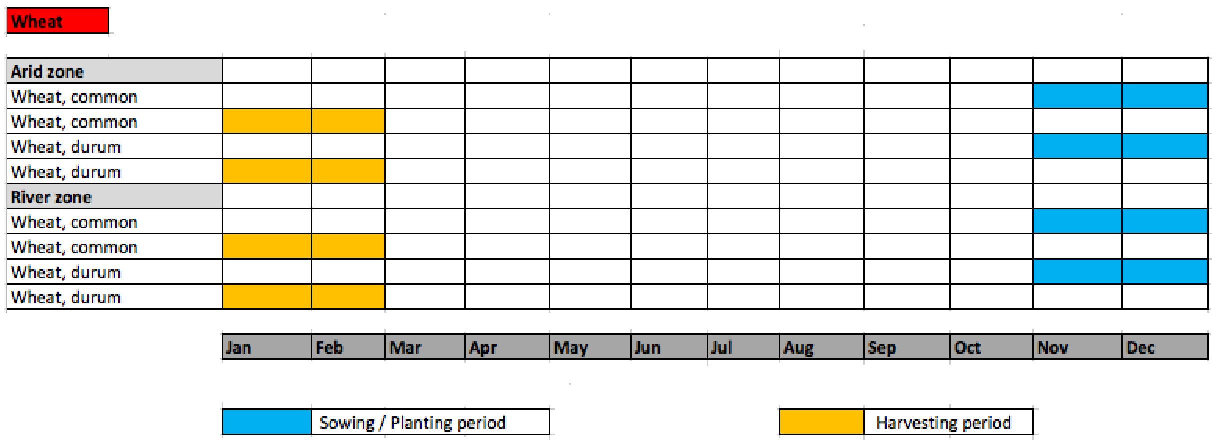
consumed in Niger in the form of flour, bread, patties or semolina (for Development, 2009). On the other hand, to satisfy its domestic demand, Niger imports food products. To cope with domestic demand, the country also receives a considerable amount of food aid. In order of increasing quantities, domestic supply and food supply include millet, sorghum, wheat and maize. Unlike other maize producing countries, Niger produces large quantities of millet, followed by sorghum production.

Agro-ecological zones

Like the majority of Sahelian countries, Niger has a highly variable climate and agroecological zones are reproduced graphically in Figure 3.51. The vast majority of the country is occupied by the desert and agriculture is practiced in the Sahelian zone which has a wetter climate than the rest of the country. However, the population uses other farming practices to provide certain food needs.

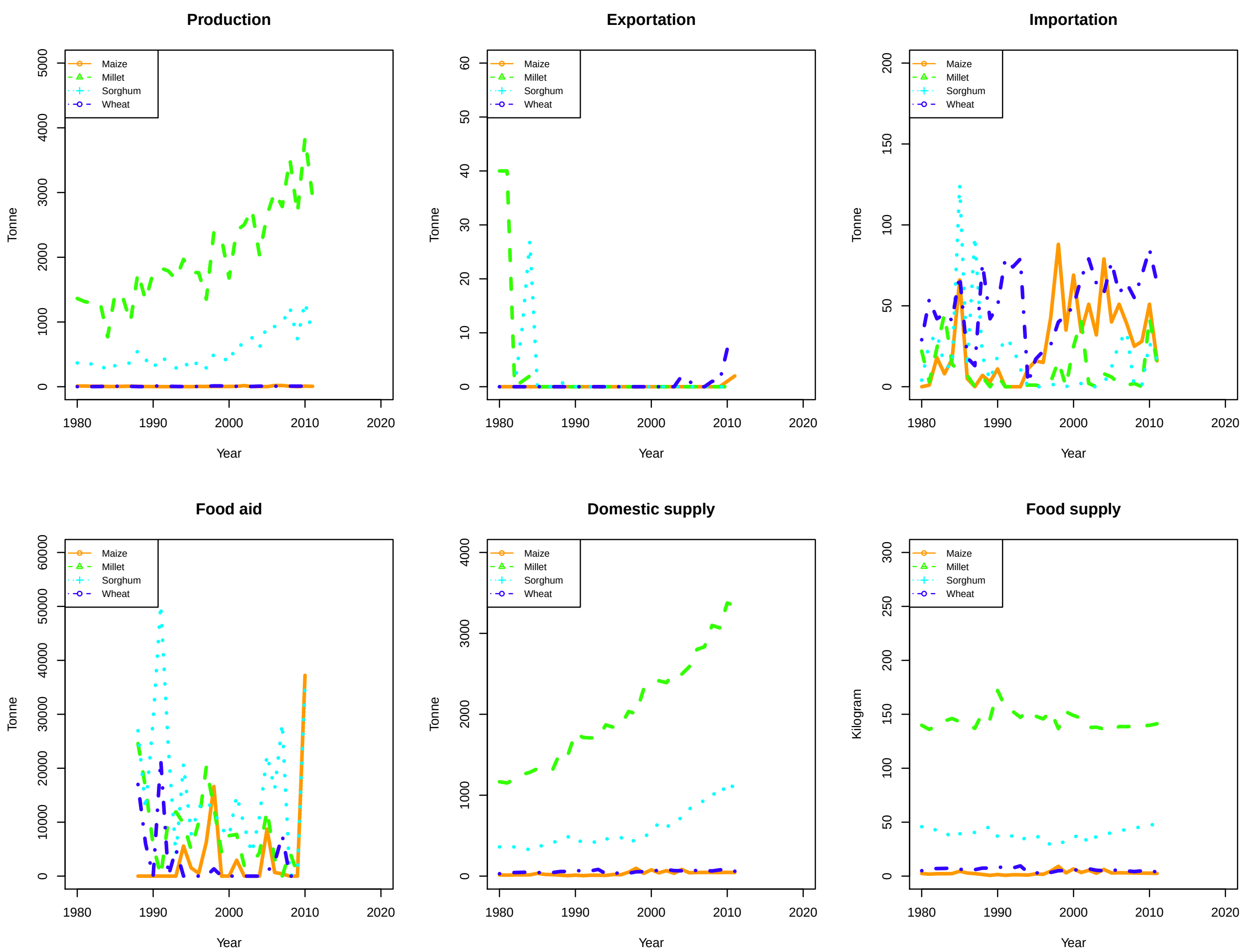
FAO identifies four agro-ecological zones whose agricultural characteristics and

Figure 3.49Agricultural calendar of the wheat culture



Source: UN Food and Agriculture Organization

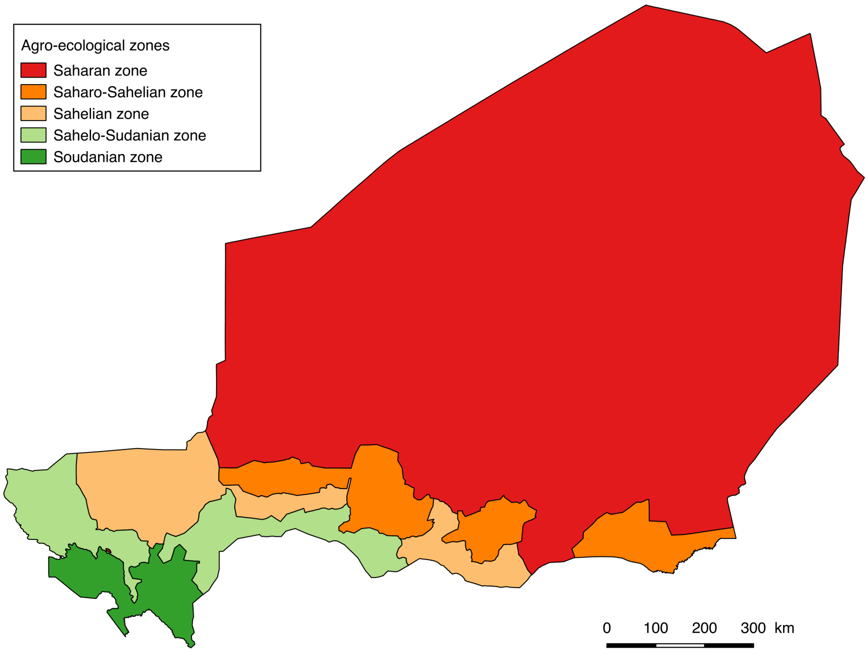
Figure 3.50Food flows in Niger



Source: Realization of the author using data from the African Development Bank

practices are described in the table 3.24.

Figure 3.51Niger agro-ecological map

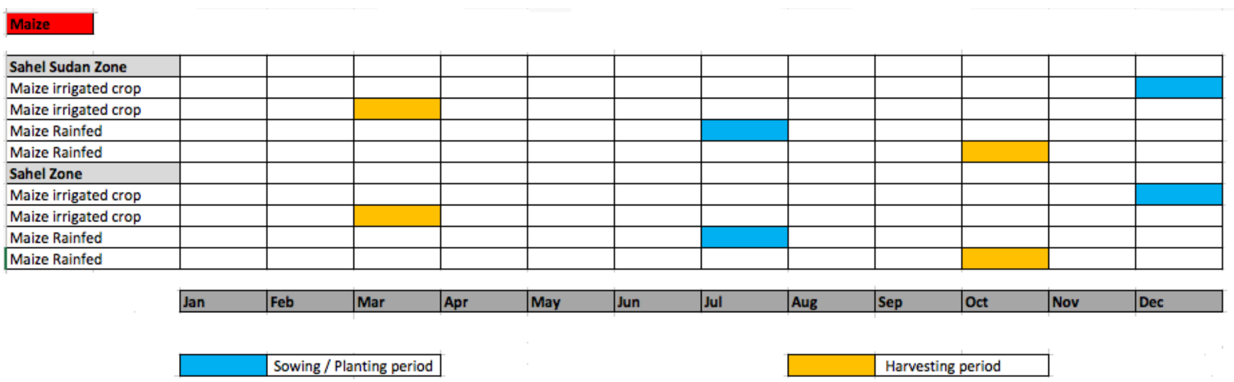


Source: Author's production based on data from the UN Food and Agriculture Organization

Crop Calendar

The calendars for maize (Figure 3.52), sorghum (Figure 3.53), millet (Figure 3.54) and wheat (Figure 3.55) are based on information from FAO. The dates of planting and harvesting are the same in the four agricultural areas. Rainy agricultural practice is the most developed in the country's zones.

Figure 3.52Agricultural calendar of the maize culture



Source: UN Food and Agriculture Organization

Table 3.24Agro-ecological zones in Niger

Agro-ecological area	**Description**	**Agricultural practices**
Desert Sahara Zone	It covers 77% of the country and receives less than 150 mm / year. No cultivation is possible except in the koris at the center where gardening is practiced, and in the oases of the Kaouar and Djado in the northeast. Extreme temperatures very hot in the day and very cold at night.	The oasis crops are crops limited to gardening and citrus crops. The water used for irrigation is drawn manually with ropes from the wells or with "Chadouf" and / or "Dalou" drawn by animals.
Sahel Sahara Zone	Covering 12% of Niger's territorial area, it receives 150 to 350 mm / year. The vegetation is composed of a shrub steppe mixed with abundant grasses for grazing.	In addition to the agricultural practices of the Desert Sahara Zone, there are rain-fed crops of cereals and vegetables.
Sahel Sudan Zone	It covers 1% of the surface of the Niger. The Sudanese zone is bounded to the north by a line running from 15 ° west latitude to less than 14 ° east latitude in the east, which is the most watered part of the country with more than 600 mm of rain per year.	The area is suitable for cereals and legumes and roots and tubers (cassava, sweet potato).
Sahel Zone	It covers 10% of the country and receives 350 to 600 mm of rain per year and includes the wooded steppe. rearing.	Rainfed crops include legumes and cereals (millet, sorghum, rice) and off-season crops (vegetables and fruit trees).

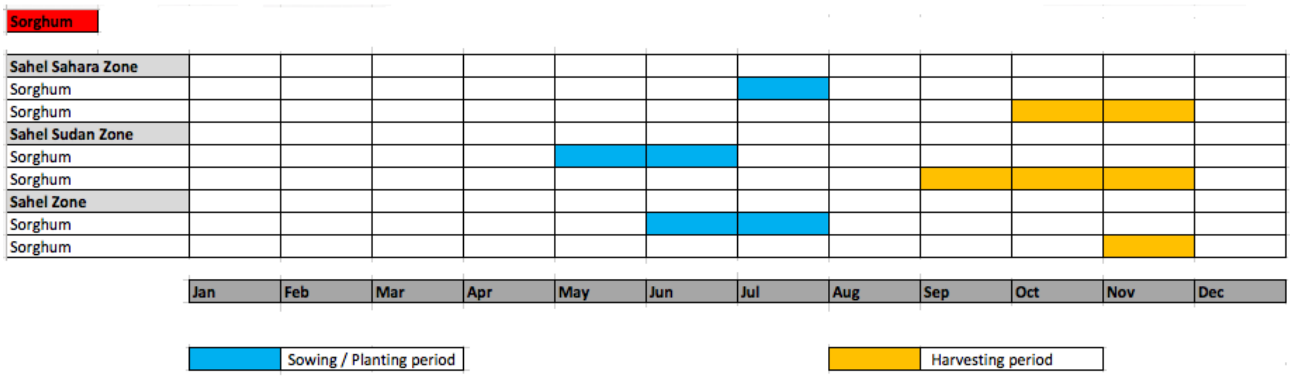
Source: Extract from Crop Calendar proposed by FAO

3.9.8 Nigeria

Flow of cereals

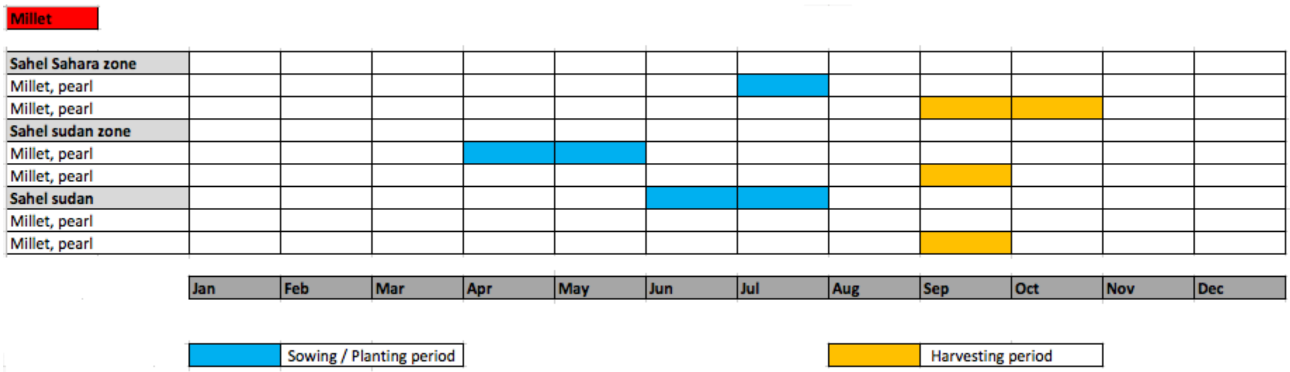
Nigeria has long produced large quantities of sorghum, millet and maize. Production of these three crops grew strongly in the early 2000s. However, low domestic wheat production was offset by a large import of wheat. Nigeria is not a major producer of wheat but it exports a large amount of wheat from its import. The country also has a large agricultural area, the area increased from 50 million hectares in 1980 to 72 million hectares in 2012. The analysis of agricultural flows (figure 3.56) indicates that the country has a certain capacity to Cover its domestic consumption because Nigeria is the only country in our sample that did not benefit from food aid. In terms of quantity, Nigeria's domestic supply and food supply concerns sorghum, maize, millet and wheat.

Figure 3.53Agricultural calendar of the sorghum culture



Source: UN Food and Agriculture Organization

Figure 3.54Agricultural calendar of the millet culture



Source: UN Food and Agriculture Organization

Agro-ecological zones

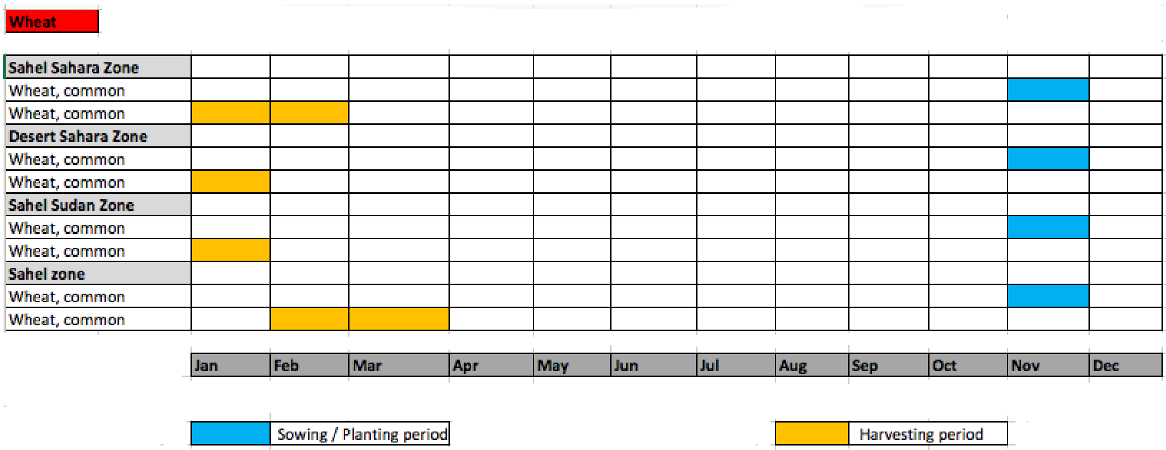
Nigeria has a contrasting and varying climate. The desert part occupies a small part located at the extreme of the country. The six agroecological zones of the country are shown graphically in Figure 3.57.

FAO identifies 6 agro-ecological zones are the characteristics and agricultural practices are described in the table 3.25.

Crop Calendar

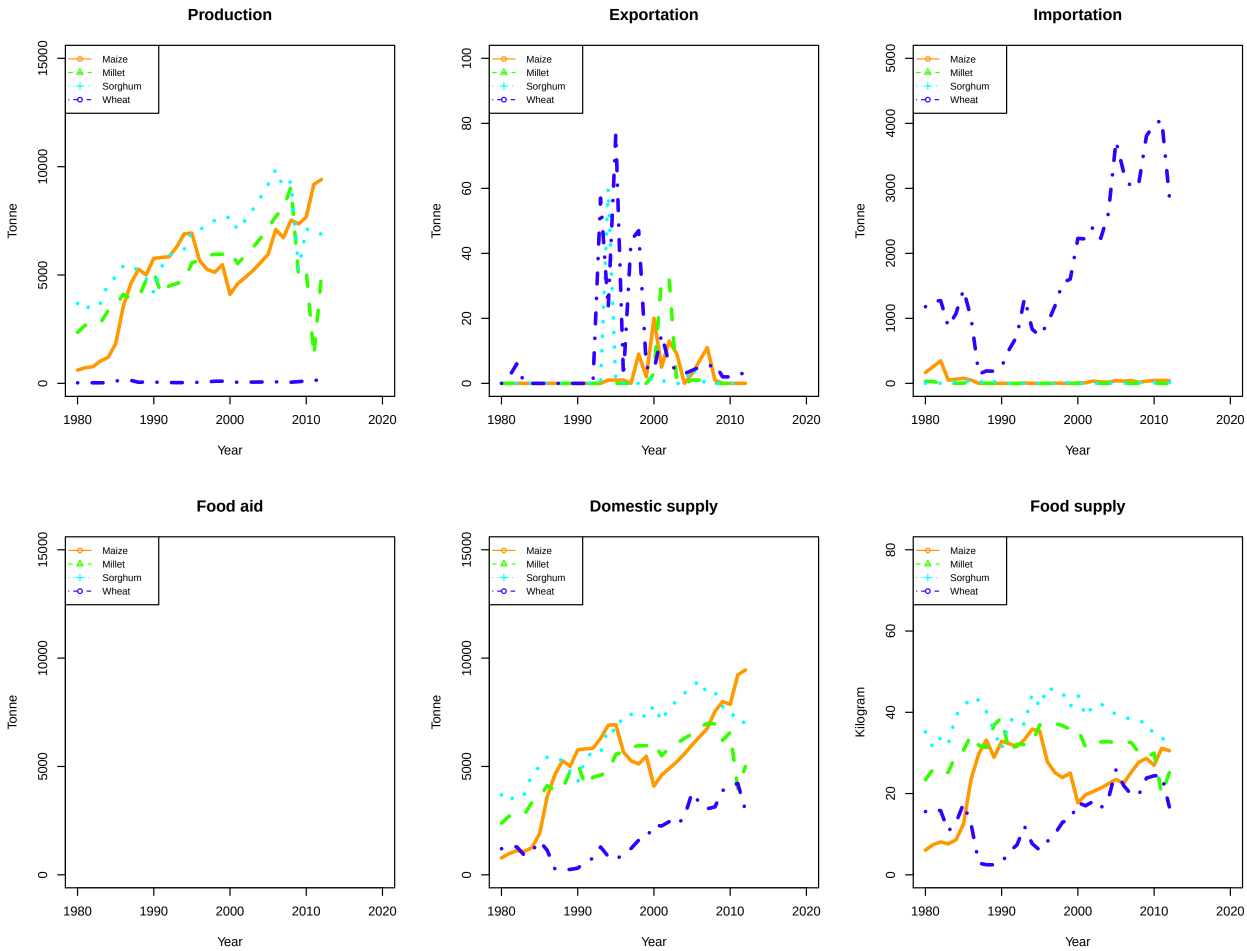
For Nigeria, the data obtained made it possible to establish the calendars for maize (Figure 3.58), sorghum (Figure 3.59) and millet (Figure 3.60). No information was provided on the date of harvest, millet sowing date is established throughout the year (during the 12 months). This is possible except in the case of an irrigated system and the presence of several rainy seasons spread over the national territory. In addition, the date of sowing of maize is established over 7 months, from March to August over a year. Sorghum is also

Figure 3.55Agricultural calendar of the wheat culture



Source: UN Food and Agriculture Organization

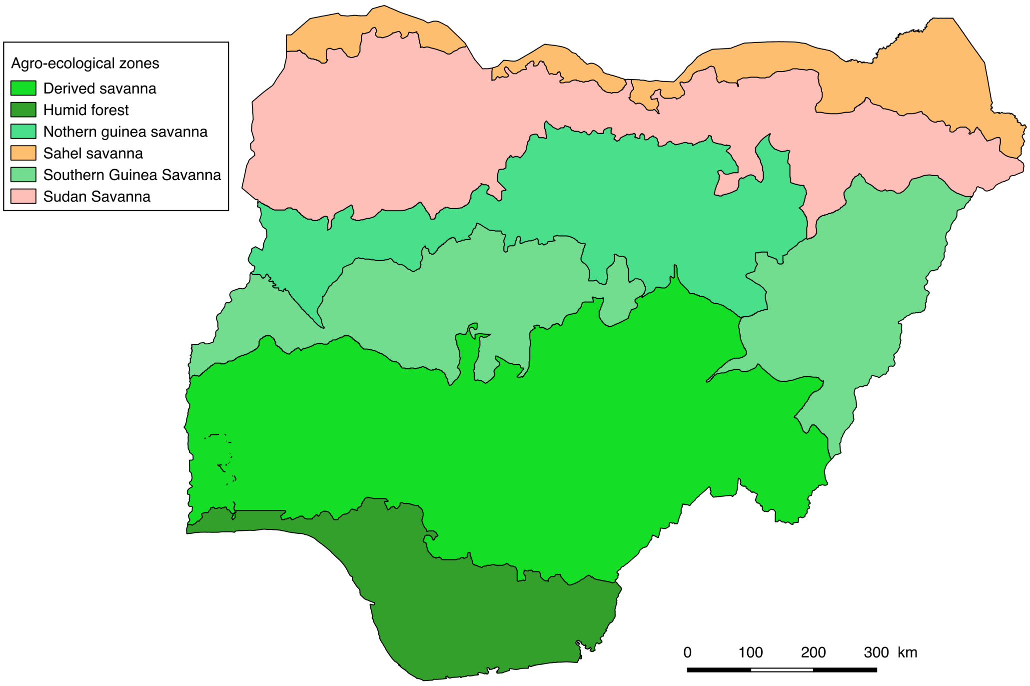
Figure 3.56Food flows in Nigeria



Source: Realization of the author using data from the African Development Bank

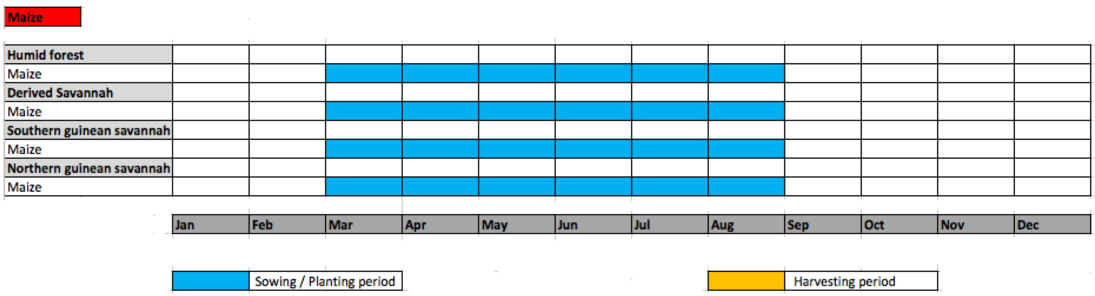
grown but on different dates between Guinean and Sudanese areas.

Figure 3.57Nigeria agro-ecological map



Source: Author's production based on data from the UN Food and Agriculture Organization

Figure 3.58Agricultural calendar of the maize culture



Source: UN Food and Agriculture Organization

3.9.9 Senegal

Flow of cereals

Senegal does not have food self-sufficiency in all four crops like the rest of the Sahel countries. Despite its production, it uses imports and food aid to offset its domestic food needs. Its wheat production is zero (see Figure 3.61) but it produces a large amount of millet, followed by maize and sorghum. The lack of wheat crop is offset by a large amount of imports (470 000 tonnes in 2011) and wheat food aid. The quantity received in wheat is used for domestic consumption and the rest is exported. Of the four commodities, maize and wheat are important crops in the Senegalese economy. However, agricultural area increased slightly from 8,841 million hectares in 1980 to 9,015 million hectares in 2012.

Table 3.25Agro-ecological zones in Nigeria

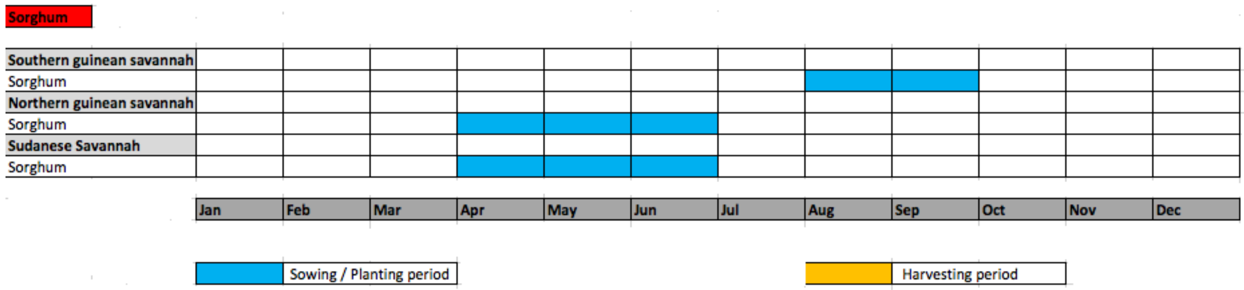
Agro-ecological area	Description	Agricultural practices
Derived Savannah	The impact of human activities has been so intense in this part of Nigeria and the vegetation has become a species of savannah type susceptible to burning.	Cultivation practices: corn, rice, sorghum, groundnut, soybean, sunflower, beans, cassava, yam, tomato, watermelon, pepper, onion ...
Humid Forest	The Humid Zone includes all areas with a relative humidity of no more than 33.28%, dry months less than 4 months with 60 mm or more precipitation, an average growing season temperature greater than 20 ° C with a range below 10 ° C.	Maize, rice, groundnut, soybean, sunflower, cassava, yam, tomato, water melon, pepper...
Northern guinean savannah	Located in central Nigeria, it is the most extensive area covering almost half of the country. It is a belt of mixed trees and tall grass to the south with grasses to the south with shorter grasses and less trees to the north.	Maize, millet, rice, sorghum, groundnut, soybean, beans, cassava, sweet potato, yam, tomato, water melon, pepper, onion, pumpkin, sweet pepper, hot pepper, melon, cucumber, eggplant, carrot.
Sahelian Savannah	Located at the fringes of the Sahara desert, it is in the far north-east of Nigeria near Lake Chad. It has one season a dry season that lasts up to 9 months and total annual precipitation reaches up to 700 mm.	Cassava, pepper, onion, cabbage, sweet pepper, hot pepper.
Southern guinean savannah	This zone has a distinctly bimodal annual rainfall of 6-8 months. Present vegetation is the by-product of years of devastation by man and fire. The annual rainfall of 1200-1500 mm.	Maize, rice, sorghum, groundnut, soybean, sunflower, beans, cassava, yam, tomato, water melon, pepper, onion, cabbage, sweet pepper, hot pepper, melon, cucumber ...
Sudanese savannah	Located in the northwest, the area receives low annual rainfall generally below 1000 mm and a long dry season (6-9 months).	Millet, sorghum, groundnut, soybean, beans, tomato, water melon, pepper, onion, pumpkin, cabbage...

Source: Extract from Crop Calendar proposed by FAO

Agro-ecological zones

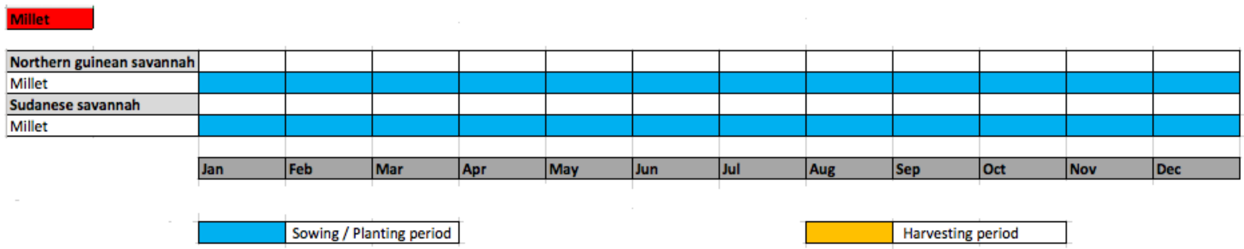
FAO identifies 6 agro-ecological zones in Senegal whose agricultural characteristics and practices are described in the table 3.26.

Figure 3.59Agricultural calendar of the sorghum culture



Source: UN Food and Agriculture Organization

Figure 3.60Agricultural calendar of the millet culture



Source: UN Food and Agriculture Organization

Crop Calendar

The calendars for maize (Figure 3.63), sorghum (Figure 3.64) and millet (Figure 3.65) are obtained from FAO information. They give information on the different dates of sowing and harvesting in different agroecological zones of Senegal. The calendar gives an overview of crops based on a rainy farming system.

3.9.10 Somalia

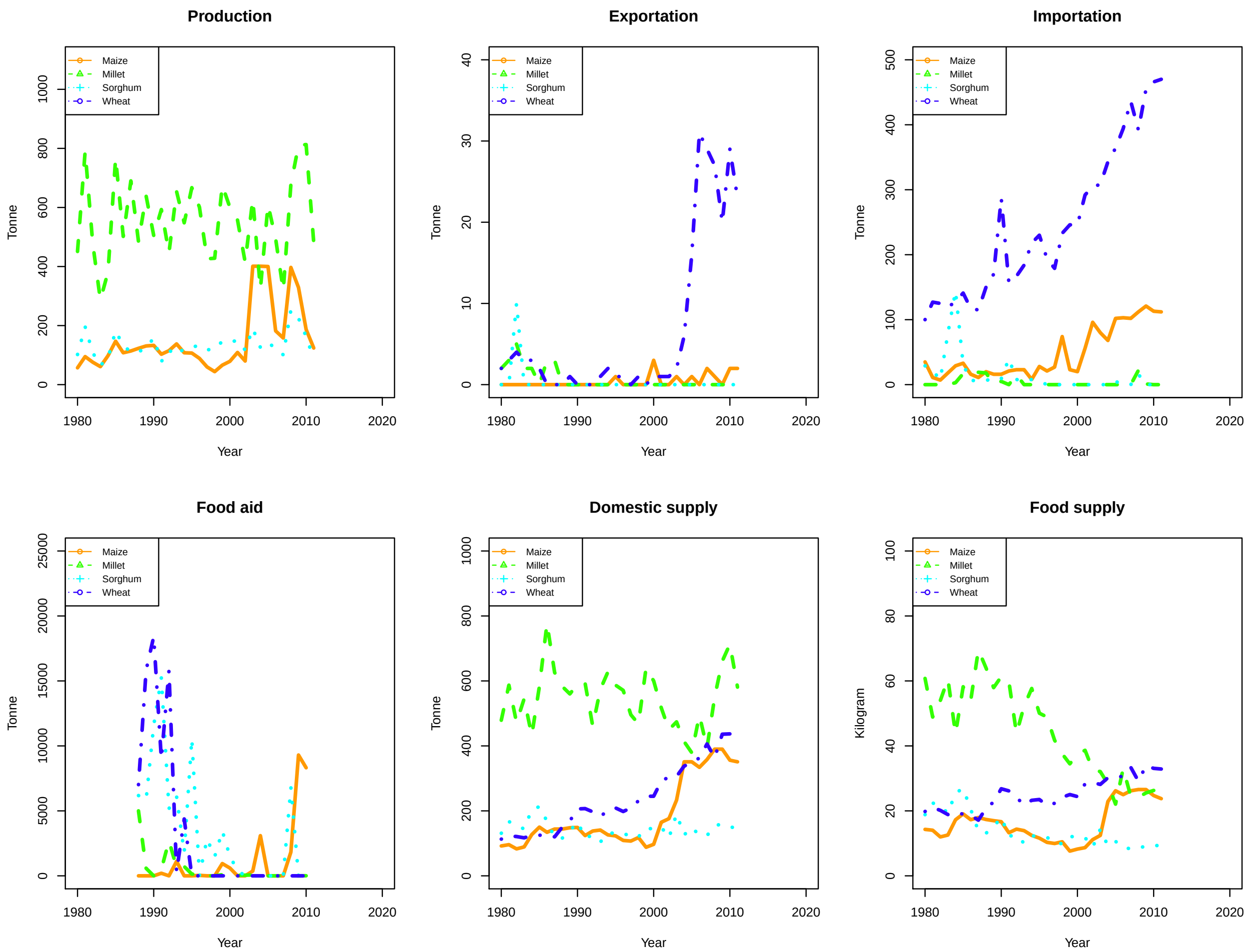
Flow of cereals

Data are missing on the different food flows (see figure 3.66) in Somalia, this can be explained by the instability that the country has faced for decades and also its administrative weakness. In addition, the country received food aid for maize, sorghum and wheat from 1987 to 2010.

Agro-ecological zones

FAO identifies five agroecological zones in Somalia (see Figure 3.67) distributed throughout the national territory, whose agricultural characteristics and practices are described in table 3.27.

Figure 3.61Food flows in Senegal



Source: Realization of the author using data from the African Development Bank

Crop Calendar

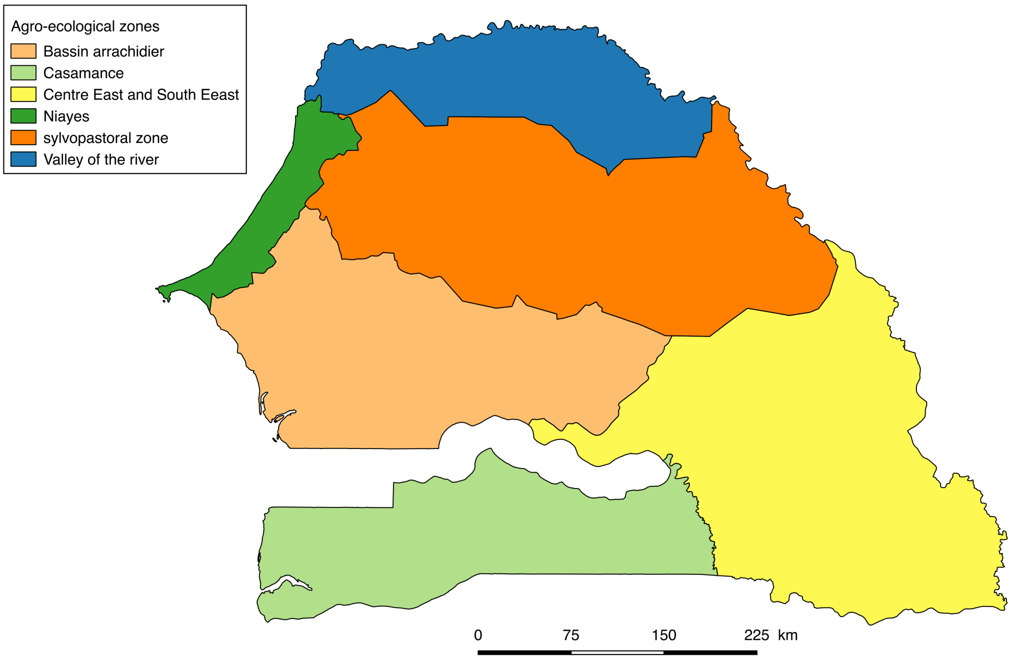
In Somalia, data have been used to establish maize and sorghum calendars. The calendars for maize (Figure 3.68) and sorghum (Figure 3.69) are obtained from FAO information. They give information on the different dates of sowing and harvesting of these two cereals in Somalia. The calendar shows that the duration of sowing seasons and harvests is short in Somalia.

3.9.11 Sudan

Flow of cereals

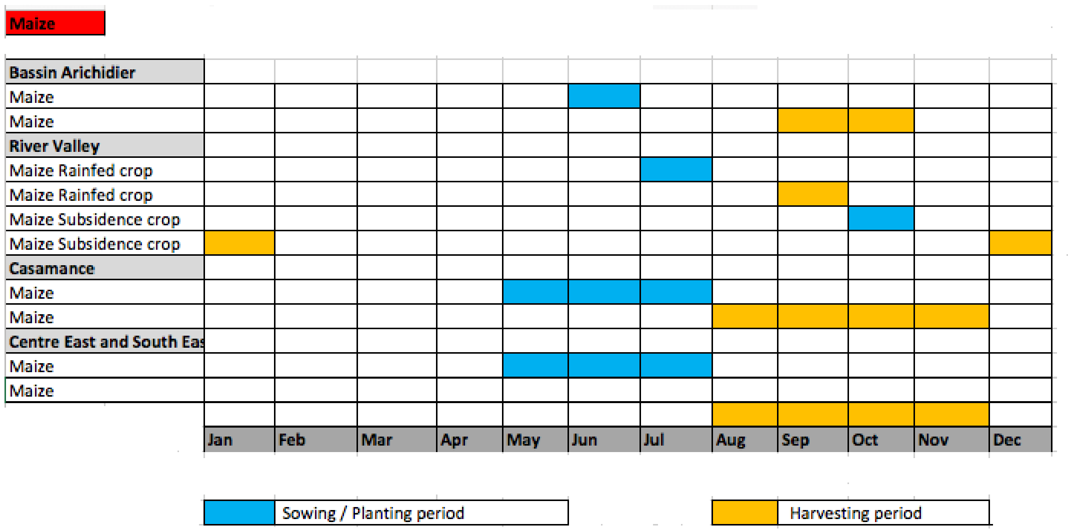
Sudan produces and exports sorghum in large quantities as well as other crops. However, sorghum exports declined slowly from 1995 to the end of 2010 (see Figure 3.70). Being a major importer of wheat, low domestic production of other crops is offset by imports and food aid. Imports and food aid in wheat are used exclusively for domestic consumption. In order of volume growth, domestic supply and food supply are higher for sorghum, followed successively by wheat, millet and maize.

Figure 3.62Senegal agro-ecological map



Source: Author's production based on data from the UN Food and Agriculture Organization

Figure 3.63Agricultural calendar of the maize culture



Source: UN Food and Agriculture Organization

Agro-ecological zones

Sudan is a country with five agro-ecological zones that give an overview of the variety of climate in this country. With the information, so we built that agroecological map based on the ancient Sudan i.e. before the division of the country in two. They are represented graphically in Figure 3.71.

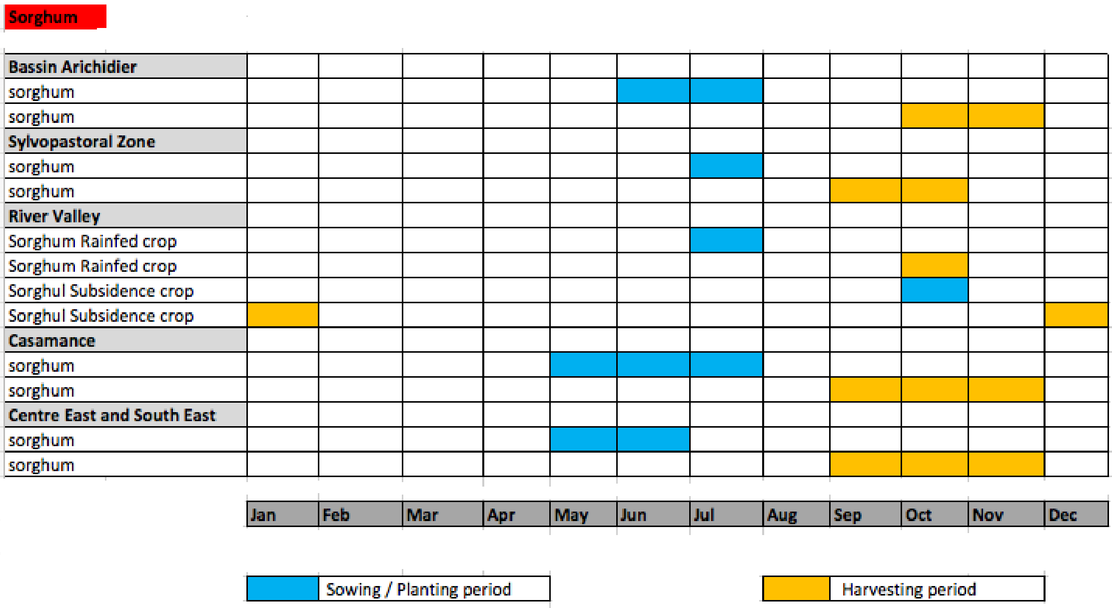
Table 3.26Agro-ecological zones in Senegal

Agro-ecological area	**Description**	**Agricultural practices**
Bassin arachidier	Situated on the Gambian border, the average temperatures vary between the minimum temperature of 20 ° C in Diourbel and 21 ° C in Kaolack and at most 37 ° C in both stations. Mean annual rainfall figures are 324.5 mm in Louga, 475.4mm in Thiès, 510.4mm in Diourbel, 557.4mm in Fatick and 609.6mm in Kaolack.	Dominated by the culture of groundnut cultivation alternating with rainfed millet (more than 1% of the land is irrigated).
Casamance	Located near the Gambia, Casamance is the rainy region of Senegal. In Zinguinchor the average temperature varies from a minimum of a minimum of 20 ° C to a maximum of 34 ° C and the average annual precipitation ranges from 1015.5 mm in Kolda to 1245.1 mm.	The main crops are the cultivation of rice and cotton.
Centre East and South East	Different from other zones by its relief and geology,the minimum average temperature is 22 ° C, the maximum temperature is 36 ° C in Tambacounda and 35 ° C in Kédougou. The mean annual precipitation is 762.7 mm (Tambacounda) and 1,192.3 mm (Kédougou).	The agricultural activities of this zone of Senegal are variable.
Niayes	It is the coastal fringe parallel to the Atlantic coast that stretches from Dakar to Saint Louis. Average annual temperatures in Dakar are 18 to 30 ° C and annual rainfall is very variable, 406.8 mm in Dakar-Yoff.	About 80% of the Senegalese agricultural population is supplied by this area, as 70% of the land is irrigated.
Valley of the river	It spreads of the Far North to the East of the territory, along the Senegal River. The mean annual temperatures range from the minimal of 18 and 23 ° C in Podors and Matams respectively, to the maximal of 37 and 38 ° C at both sites respectively. Mean rainfall varies from 214.6 mm in Podors, 360.5 mm in Matams to 522.2 mm in Bakels.	Rice cultivation, irrigated vegetable production and subsidence cropping are practiced in the Walo (zone closed to water sources). Rainfed crops such as millet, groundnut, tropical-type vegetables, etc. are cultivated Diéri.
Sylvopastoral Zone	Located immediately on the South of the River valley, the minimal and maximal temperatures vary from 21 to 37 ° C at Linguères. Average rainfall at this station is 394.8 mm.	All cultivation is rainfed and this represents a low percent land use for crop cultivation.

Source: Extract from Crop Calendar proposed by FAO

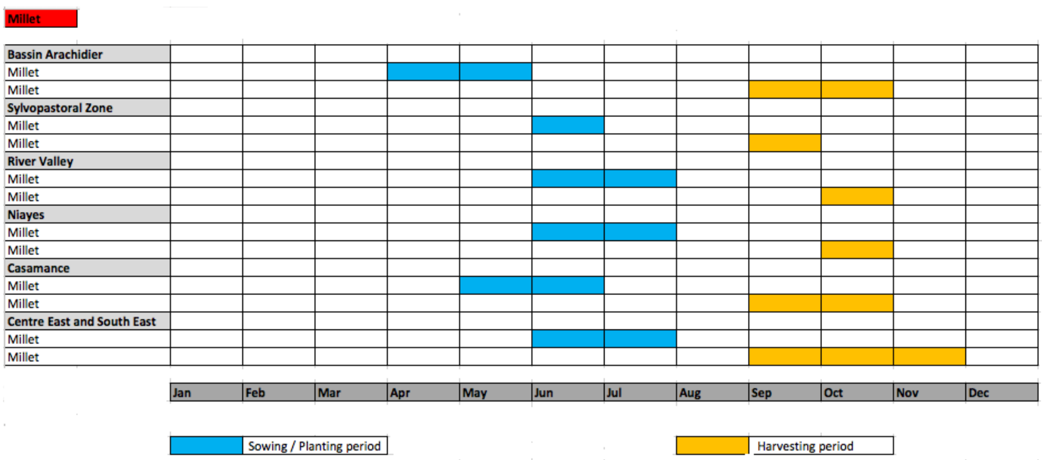
FAO identifies five agricultural areas in Sudan distributed throughout the national territory, whose agricultural characteristics and practices are described in table 3.28.

Figure 3.64Agricultural calendar of the sorghum culture



Source: UN Food and Agriculture Organization

Figure 3.65Agricultural calendar of the millet culture

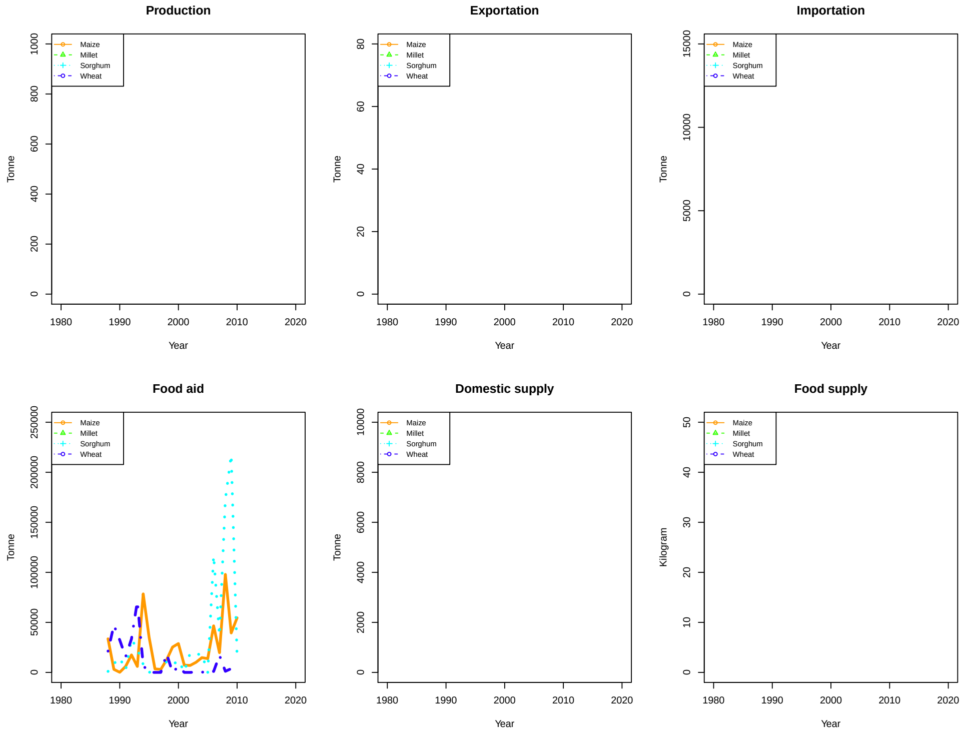


Source: UN Food and Agriculture Organization

Crop Calendar

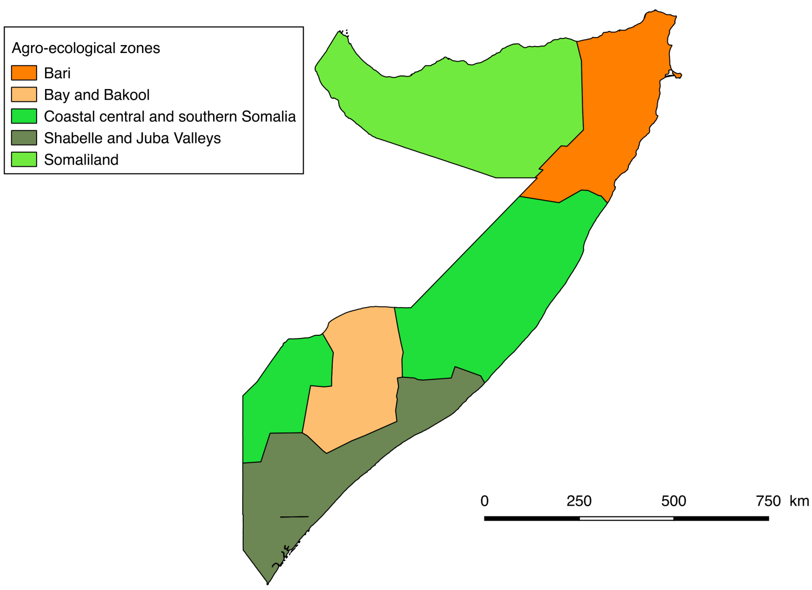
In Senegal, the data made it possible to establish the following four cereal calendars. The calendars for maize (Figure 3.72), sorghum (Figure 3.73), millet (Figure 3.74) and wheat (Figure 3.75) are obtained from FAO information. They give information on the different dates of sowing and harvesting of these two cereals in Somalia. The calendar shows that the duration of rainy seasons and practically that of sowing is short. In the Sahel, crops based on a rainy system begin after a few rains (depending on the characteristics of each crop).

Figure 3.66Food flows in Somalia



Source: Realization of the author using data from the African Development Bank

Figure 3.67Somalia agro-ecological map



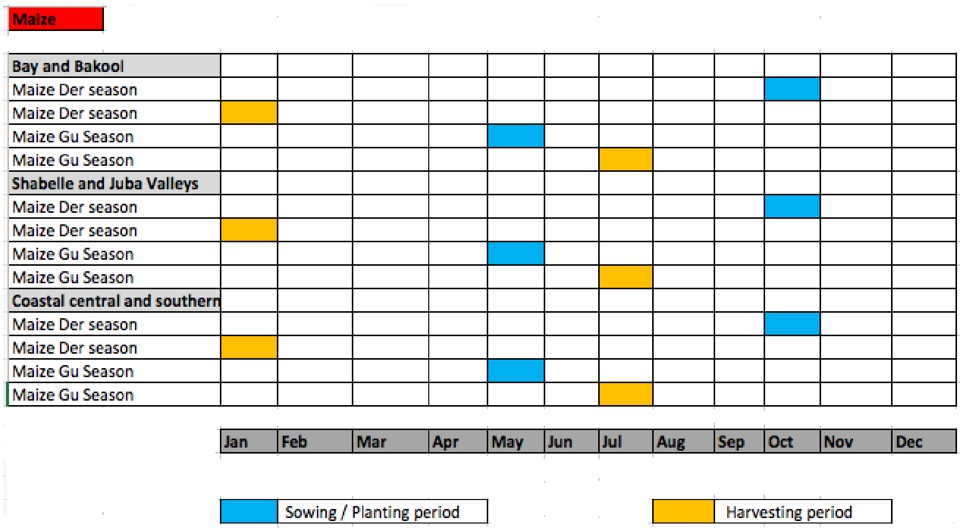
Source: Author's production based on data from the UN Food and Agriculture Organization

Table 3.27Agro-ecological zones in Somalia

Agro-ecological area	Description	Agricultural practices
Bari	An arid coastal zone in northeastern Somalia, the average annual temperature varies between 25 and 30 ° C, but it is high in coastal areas and annual precipitation ranges from 0 to 200 mm. "Gu" (Mar-June), "Hagga" (July-September), "Deyr" (Oct / Nov), "Jilaal" long dry season.	Date palm oases with small-scale horticultural production
Bay and Bakool	A semi-arid interior plateaus with a rainfall greater than 300 mm above sea level. "Gu" main rainy season (March-June), "Xagga" coastal showers (July-Sept), "Deyr" short rains (Oct/Nov), "Jilaal" long dry season (Dec-Mar). The average annual temperature is between 23 and 32 ° C and precipitation is between 300 and 600 mm.	Rainfed sorghum, maize and cowpeas
Coastal central and southern Somalia	A semi-arid and rainfed zone, the average annual temperature varies between 23 and 32 ° C and the annual precipitation ranges from 200 to 600 mm. "Gu", main rainy season (March-June), "Xagga" coastal showers - extend to 100 km inland (July -Sept), "Deyr", short rains (Oct/Nov), "Jilaal" long dry season (Dec-Mar).	Rainfed sorghum, maize, cowpea, sesame, and water melon
Shabelle and Juba Valleys	These are semi-arid lowlands, rainfall floods, irrigated and rainfed plains. The average annual temperature varies from 23 to 30 ° C and the average annual precipitation ranges from 400 to 700 mm. "Gu" main rainy season (March-June), "Xagga" coastal showers (July-Sept), "Deyr" short rains (Oct/Nov), "Jilaal" long dry season (Dec-Mar).	Rainfed and irrigated maize, sorghum, sesame, cowpeas, rice, variety of vegetables, sweetpotato, fruits and cash crops
Somaliland	Parts of Awdal, Togdheer and Galbeed, they are semi-arid and shallow irrigated highlands (> 600 mm above sea level). The average annual temperature (25 - 35 ° C) and the annual precipitation (300 - 600 mm). Gu" (March-June), "Hagga" (July-Sept), “Deyr" (Oct/Nov), "Jilaal" dry season (Dec-March). Soils generally shallow and stony.	Rainfed and spate surface flood irrigated sorghum with some small-scale horticulture

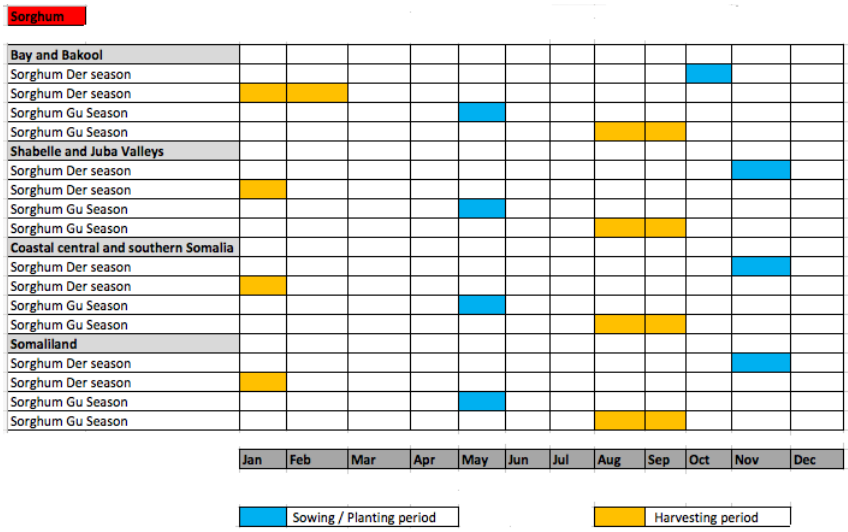
Source: Extract from Crop Calendar proposed by FAO

Figure 3.68Agricultural calendar of the maize culture



Source: UN Food and Agriculture Organization

Figure 3.69Agricultural calendar of the sorghum culture

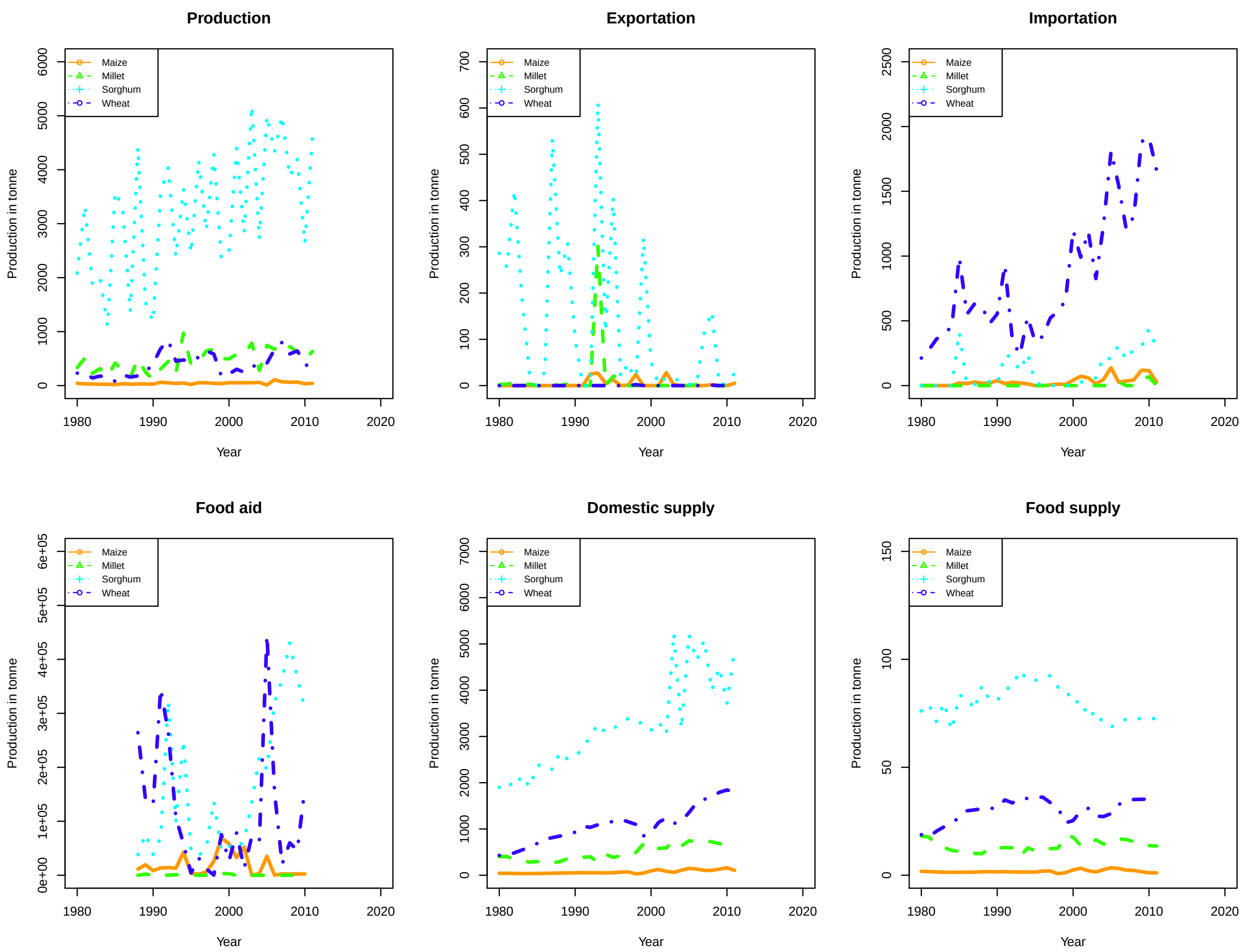


Source: UN Food and Agriculture Organization

3.10 Crop needs and stress: maize, sorghum, rice, wheat

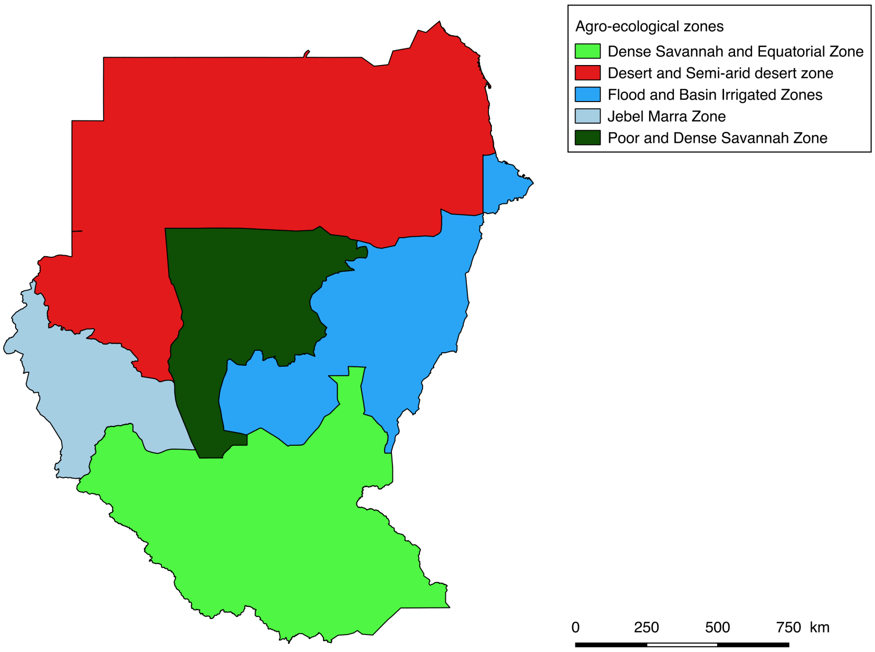
To grow cereals, conditions must be met so that these crops can grow and produce good crops. Each cereal has special characteristics. This subsection highlights the requirements and stresses of the four cereals studied (maize, millet, sorghum and wheat), summarized in the tables below: table 3.29 for corn, table 3.30 for millet, table 3.31 for wheat and table 3.32 for sorghum.

Figure 3.70Food flows in Sudan



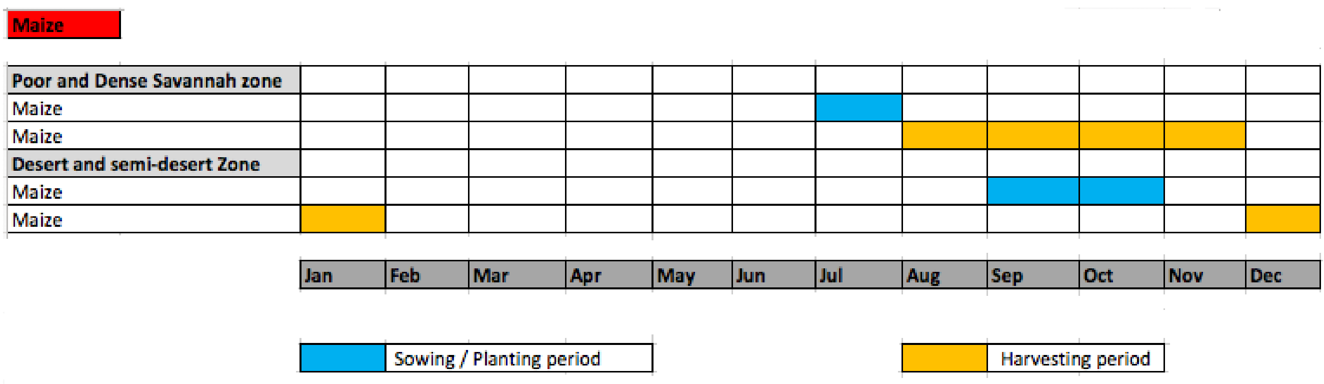
Source: Realization of the author using data from the African Development Bank

Figure 3.71Sudan agro-ecological map



Source: Author's production based on data from the UN Food and Agriculture Organization

Figure 3.72Agricultural calendar of the maize culture



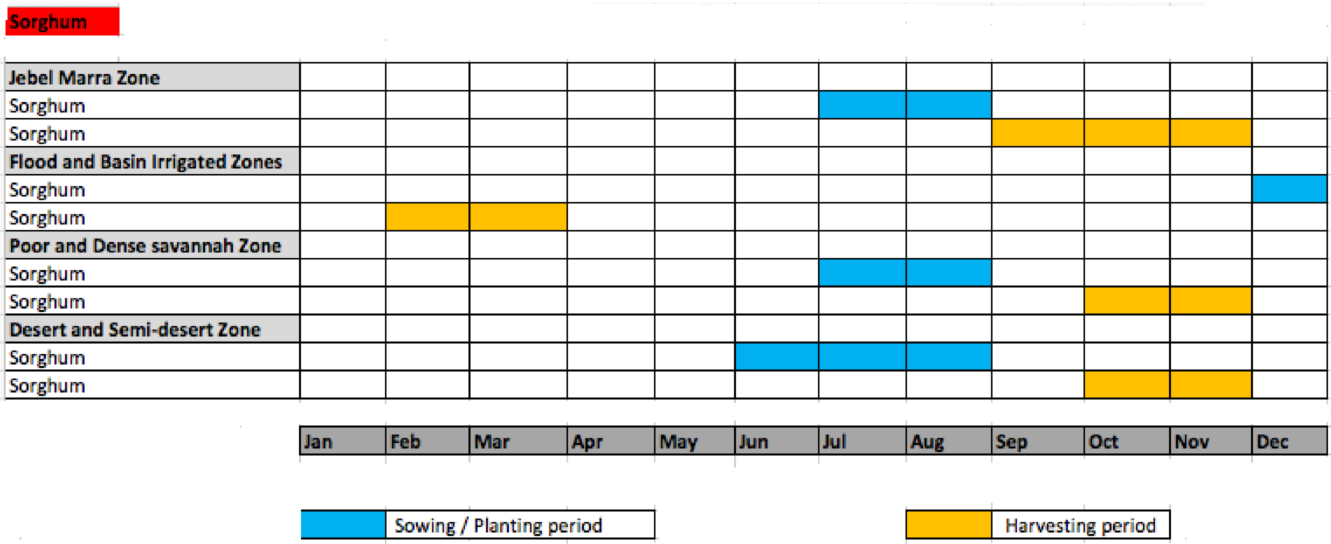
Source: UN Food and Agriculture Organization

Table 3.28Agro-ecological zones in Sudan

Agro-ecological area	Description	Agricultural practices
Dense Savannah and Equatorial Zone	most of the land is flooded and exploited for irrigated and irrigated forest agriculture. Precipitation ranges from 600 to 1500 mm.	Due to the rich forests - this zone is characterized by the existence of wild-game. Sorghum, sesame, groundnut, cassava and rice are cultivated.
Desert and Semi-desert Zone	It is composed of hills, rocks and sands; the average rainfall is less than 100 mm. There are 298,000 square kilometers semi-desert in which mean rainfall is 225 mm.	Commercial rainfed semi-mechanized farming production is practised, mainly sorghum plantation followed by sesame, groundnut and hibiscus (Karkade)
Flood and Basin Irrigated Zones	Mainly deltas Baraka (Tokar), el-Qash and Abuhabil in addition to the upper stream behind dams and Nile and other river's banks (Jirouf)	These deltas and basins harbour flood water for the wide-scope cultivation of cotton, faba bean in addition to sorghum which is at subsidiary level
Jebel Marra Zone	Equal to 29,000 square kilometers in altitude of 1000 m above sea level, with annual rainfall of 600-1000 mm and cool winter, which is favourable for apple and strawberry growing	Due to its height this zone is characterized by its different climates and obviously different crops including tobacco and forest wealth.
Poor and Dense Savannah Zone	Average precipitation ranges from 300 - 1,500 mm. The agricultural system is the traditional rainfed for growing sorghum, millet, groundnuts and gum arabic.	Irrigated Truck-Production is mainly practised in which cotton, groundnut and wheat is cultivated. Mainly Truck-Production is practised for sorghum, it is semi-mechanized, and illicit wood cut is practised affecting badly the forests.

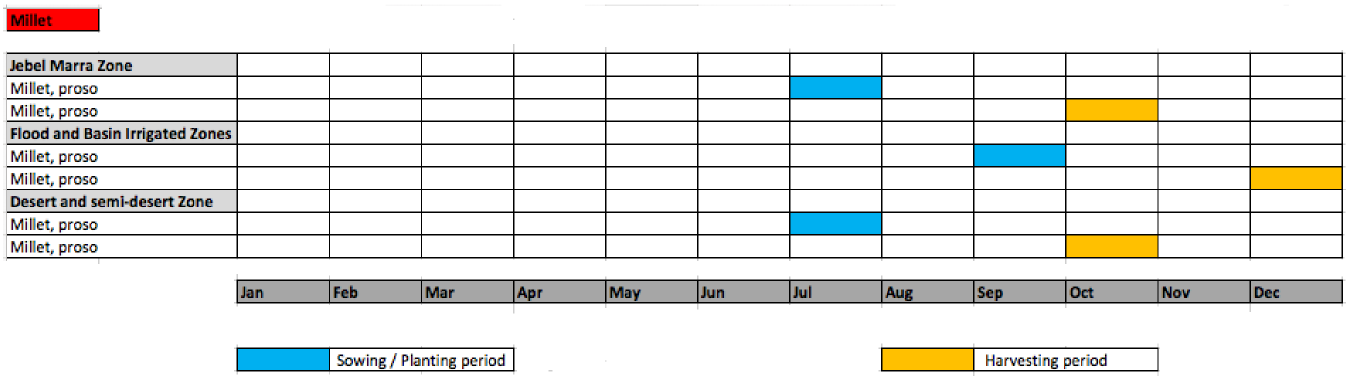
Source: Extract from Crop Calendar proposed by FAO

Figure 3.73Agricultural calendar of the sorghum culture



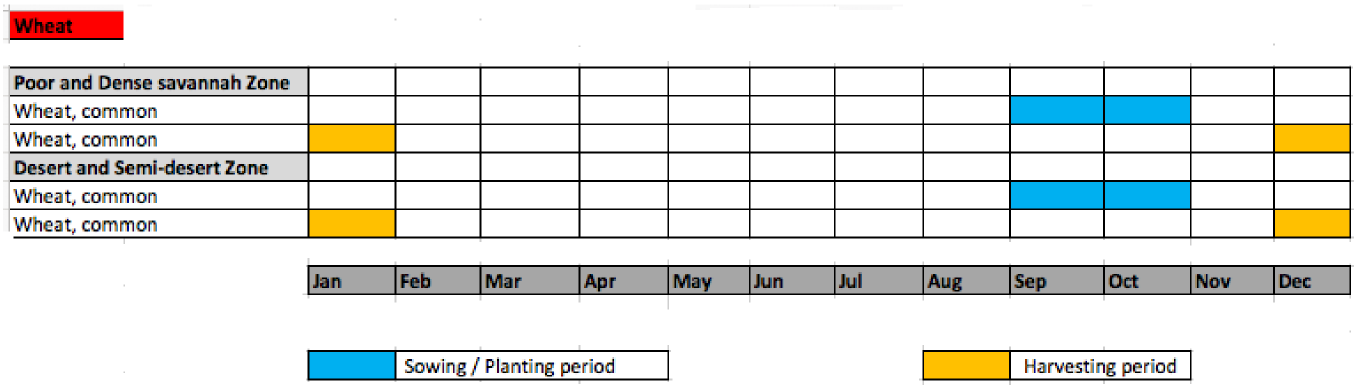
Source: UN Food and Agriculture Organization

Figure 3.74Agricultural calendar of the millet culture



Source: UN Food and Agriculture Organization

Figure 3.75Agricultural calendar of the wheat culture



Source: UN Food and Agriculture Organization

Table 3.29Needs and stress of corn

Maize requirements	
Light	The cereal makes its photosynthetic metabolism in C4 and a high temperature requirement at germination whose optimum is 25 ° C and impossible above 10 ° C.
Water	The cultivation of a 120-day maize type in the Sudanian zone requires at least 600 mm of well-distributed precipitation.
Fertility	Maize is a cereal crop that is very sensitive to deficiencies and the production reacts positively to fertilizer inputs, especially nitrogen. Corn prefers soils that are rich in organic matter and have good physical properties. She reacts positively to the farm.
Stress	
Climat	Drought at sowing causes damage to the crop and adversely affects yield during flowering.
Excess water	The flooding asphyxiates and rotates the roots. Farmers should avoid hydromorphic soils or drain poorly.
Energy	In the tropical zone, the light energy available during cultivation is limited.
Wind	Strong winds can cause lodging or breakage of stems. The best defense is to adopt a varietal resistance.
Excessive temperature	During the dry season in the Sahel, high temperatures accompanied by a dry or windy climate can cause burns on the leaves.
Soil	The yield of all types of corn is limited with acidic soils. The application of liming is possible but has no effect on profitability.
Biological factors	Maize crops are subject to frequent diseases in tropical environments, rust and helminthosporium. Indeed, the chemical treatments practiced by the farmers do not improve the yield of the cereal.

Source: This factsheet was constructed from the technical information provided by Cirad et al (2002).

Table 3.30Needs and stress of millet

Millet requirements	
Temperature	Grasses in hot semi-arid zones, penicillaries evolve at an average temperature of 28 ° C during the growing season.
Soil	Millet is grown on well-drained, light, sandy clay soils with low pH and less demanding than sorghum. It is known for its tolerance to drought, low soil fertility and high temperatures.
Stress	
Cryptogamic Diseases	Striga hermantontica is a parasitic plant which constitutes a formidable danger for millet. There are also stem borers, earburger, cantharides and cecidomylides.

Source: This factsheet was constructed from the technical information provided by Cirad et al (2002).

Table 3.31Needs and stress of wheat

Wheat Growing Cycle	
Germination	Germination begins when the grain has absorbed one quarter of its weight in water.
Tillering	This phase lasted for 45 days and was marked by the appearance of the secondary stems.
Bolting	The stems lengthen but the ears are not yet apparent.
Flowering	This phase of 30 days is marked by the appearance of the ears and the flowering of the plants. In addition, stamens appear after fertilization is complete.
Development and maturation of grains	This final phase is marked by the final formation of the grains. The grains pass from the milky to the pasty and to finish in hard grains.
Millet requirements	
Total cycle duration	In the tropics, the duration is 120 to 150 days. Generally, wheat is planted in areas with temperate climates, developing between 50 ° north latitude and south latitude.
Need fo water	Between the first two phases, the crop needs water and also during the 15 days preceding the heading. Wheat requires 100 days minimum frost-free for growth and 400-500 mm of precipitation during all five phases.
Temperature	The minimum germination temperature is 3 ° C, the optimum is set at 27 ° C. Flowering needs a temperature not exceeding 14 ° C and is optimal at 16.6 ° C. The optimum temperature for flowering is around 20 ° C.
Soils	For its growth, wheat needs deep, well-structured soils with a pH that is close to neutrality and does not support congestion. It is cultivable at high altitude and during the cold and dry season. It is irrigated and harvested at the end of the season. In the Sahel, it is grown in irrigated poles in Ethiopia, Nigeria and Sudan.

Source: This factsheet was constructed from the technical information provided by Cirad et al (2002).

Table 3.32Needs and stress of sorghum

Sorghum requirements	
Temperature	For germination, sorghum requires moist soil and average daily temperatures above 12 ° C. If the temperatures are good, i.e. above 20 ° C, the seeds rise in 3 or 4 days, the optimum temperature of the growth is about 30 ° C.
Cultivation duration	The earlier the seeding is done, the longer the length of the vegetative cycle. Depending on seeding dates, a single photoperiodic variety will have a cycle of 90 to 160 days. The particularity of sorghum is that the farmer has the assurance that his varieties will reach maturity at the end of the rainy season whatever the difficulties he has undergone during sowing.
Need fo water	Sorghum water requirements are higher than maize. The particularity of sorghum is a better ability to withstand periods of drought especially at the beginning of crops. The total water consumption depends on the variety of sorghum. For 90-day varieties, precipitation is required around 400 mm. In addition, varieties of 110-120 days require a precipitation of between 550 and 600 mm.

Source: This factsheet was constructed from the technical information provided by Cirad et al (2002).