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Changement climatique et agriculture en Afrique subsaharienne. Perception des agriculteurs et impact de l'association entre une céréale et une légumineuse sur les rendements des deux espèces et leur variabilité inter-annuelle sous climat actuel et futur. Cas du sorgho et du niébé dans l'environnement soudano-sahélien.

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A LA MÉMOIRE DE MON PÈRE,

DISPARU BEAUCOUP TROP TÔT

A MA MERE, POUR SON AMOUR ET SES PRIERES.

A mes enfants, pour leur patience durant

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RESUME

Changement climatique et agriculture en Afrique subsaharienne. Perception des agriculteurs et impact de l'association entre une céréale et une légumineuse sur les rendements des deux espèces et leur variabilité inter-annuelle sous climat actuel et futur. Cas du sorgho et du niébé dans l'environnement soudano-sahélien.

Dans la zone soudano sahélienne d'Afrique de l'Ouest, la productivité agricole est fortement affectée par la variabilité et les changements climatiques. La production agricole est dominée par la production pluviale de céréales telles que le maïs, le mil et le sorgho, pour la consommation alimentaire. Les agriculteurs ont des rendements faibles et variables, ce qui entraîne une incertitude croissante quant à leur capacité à produire davantage pour nourrir une population en forte croissance. L'objectif général de cette thèse était de concevoir des systèmes de culture plus productifs et stables, adaptés au changement climatique, en explorant les bénéfices de l'association sorgho-niébé, combiné a des choix contrastés de variété de sorgho, de fertilisation minérale et de date de semis. L'approche était basée sur un travail d'enquête, d'expérimentation au champ et de simulation à l'aide d'un modèle de culture, pour un cas d'étude au centre du Mali en Afrique de l'Ouest. Une première étape a porté sur l'identification de la perception du changement climatique par les agriculteurs et les stratégies d'adaptation agricole qu'ils considèrent pertinentes pour faire face à la variabilité et au changement climatique. En second lieu, le modèle de culture STICS a été calibré sur la base de deux années d'expérimentation (2017, 2018) de la culture associée sorgho-niébé à la station agronomique de N'Tarla. Dans ce dispositif expérimental, deux variétés de sorgho (locale et améliorée) avec une sensibilité contrastée à la photopériode ont été étudiées en culture pure et en culture associée avec le niébé. Deux dates de semis et deux niveaux de fertilisation minérale ont également été étudiés. La pertinence du modèle pour représenter les compétitions et complémentarités entre sorgho et niébé pour l'utilisation de l'eau et de l'azote a été évaluée. Enfin, la performance (productivité moyenne et stabilité de la productivité) d'une gamme d'options techniques pour la gestion intégrée de la fertilité des sols (combinant l'association sorgho-niébé au choix variétal et à l'utilisation d'engrais minéraux) a été évaluée, en climat actuel et futur, à l'aide du modèle de culture STICS. Deux cadres d'analyse ont été utilisés pour caractériser le potentiel des options techniques pour l'adaptation au changement climatique. Le premier cadre d'analyse était celui de la stratégie "sans regret" : il s'agit d'options dont la productivité moyenne (ou la stabilité de la productivité) est plus importante que la pratique actuelle, en climat actuel, et en climat futur. Le second cadre est plus contraignant et discrimine les « vraies » adaptations, i.e. les options techniques qui améliorent la productivité moyenne et/ou sa stabilité en climat actuel,

et pour lesquelles le gain de productivité et/ou de stabilité augmente en climat futur. Pour le forçage en climat futur, les simulations de température et des précipitations mensuelles de 7 modèles de circulation générale issus de la phase 6 du projet d'intercomparaison des modèles couplés (CMIP6) ont été utilisées. La majorité (>50%) des agriculteurs enquêtés ont perçu une augmentation de la température, une diminution des précipitations, un raccourcissement de la saison de croissance, un arrêt précoce des précipitations et une augmentation de la fréquence des périodes de sécheresse au début de la saison de culture. Conformément à la perception des agriculteurs, l'analyse des données climatiques a indiqué (i) une augmentation de la température annuelle moyenne et de la température minimale de la saison de culture et (ii) une diminution des précipitations totales. L'analyse des données climatiques n'a pas permis de déceler l'arrêt précoce des précipitations et à la fréquence accrue des périodes de sécheresse, tels que perçus par les agriculteurs. Pour faire face à la diminution des précipitations et au début tardif de la saison de croissance, les agriculteurs ont utilisé des variétés tolérantes à la sécheresse et ont mis en œuvre des technologies de gestion de l'eau (cordon pierreux et aménagement en courbe de niveaux). L'analyse du lien entre perception des agriculteurs et mise en œuvre des stratégies d'adaptation a révélé que la perception d'un arrêt précoce des précipitations a augmenté de manière significative la probabilité pour un agriculteur de mettre en place l'association sorgho-niébé dans ses champs. Les simulations du modèle sol culture de STICS ont été évaluées avec les données observées de l'expérimentation de la station de recherche de N'Tarla, pour la phénologie, l'indice de surface foliaire (LAI), la biomasse aérienne, le rendement en grain dur sorgho et du niébé, et l'humidité du sol. De grandes variations de la biomasse aérienne du sorgho (entre 3,5 et 9,6 t/ha) et du niébé (entre 0,4 - 2,5 t/ha) ont été observées dans l'expérience en fonction des différents traitements expérimentaux (sorgho en culture pure ou associée, date semis et application de la fumure minérale). Ces variations ont été reproduites de manière satisfaisante par le modèle, avec une efficacité de 0,81 pour le jeu de données de calibration et de 0,58 pour l'évaluation. Dans l'expérimentation, la biomasse aérienne et le rendement du sorgho et du niébé ont diminué avec l'association, en comparaison à la culture pure. Cependant, le LER observé pour la biomasse aérienne est resté supérieur à un, indépendamment du traitement expérimental (fumure minérale, date de semis et variété de sorgho). Le modèle calibré a reproduit avec précision cette tendance générale liée au LER pour la biomasse aérienne, et a rendu compte de manière satisfaisante de l'impact des apports de fumure minérale et de l'utilisation de la variété améliorée de sorgho. Cependant le modèle a simulé avec une plus faible efficacité l'indice de surface foliaire et de l'absorption de l'azote par la plante. Le modèle calibré n'a pas réussi à prédire avec précision le faible rendement du niébé dans la

culture associée, et a donc surestimé le LER de la culture associée pour le grain. Une grande disparité a été constatée entre les sept modèles climatiques utilisés pour explorer le futur du climat, en ce qui concerne l'évolution de la quantité mensuelle et annuelle des précipitations. En revanche, cinq des sept modèles climatiques se sont accordés sur une augmentation future des précipitations. Tous les modèles se sont également accordés sur une augmentation des températures. Lorsqu'on s'intéresse à l'indicateur de productivité moyenne, nos simulations sous climat historique et futur ont montré que l'association sorgho-niébé (avec la variété traditionnelle et sans apport de fertilisation minérale), n'était une adaptation pertinente au changement climatique que pour les semis tardifs. Lorsqu'on s'intéresse à l'indicateur de stabilité de la productivité énergétique, l'association sorgho-niébé avec la variété traditionnelle, et sans apport de fertilisation minérale n'était pas une adaptation pertinente, indépendamment de la date de semis (précoces ou tardifs). Pour cet indicateur de stabilité de la productivité énergétique, il faut combiner l'association sorgho-niébé avec l'utilisation de la variété améliorée de sorgho et de fumure minérale, pour que cette stratégie devienne une adaptation pertinente (i.e. une stabilité plus élevée que la pratique actuelle sous climat historique, et cet avantage qui augmente en climat futur), en semis précoce uniquement. Le chapitre final de la thèse reprend les résultats majeurs obtenus, discute les divergences entre les stratégies d'adaptation identifiées d'une part par les agriculteurs et d'autre part par les simulations du modèle de culture, confronte les résultats des simulations en climat futur aux imperfections du modèle de culture identifiées lors de la phase de calibration/évaluation, et se termine par des propositions de pistes de recherche pour le futur.

Mots clés : adaptation, précipitation, température, compétition, facilitation, intensification écologique, biomasse, culture associée, LER, modélisation.

TABLE DES MATIERES

Chapitre I : Introduction générale

En Afrique Sub-Saharienne, plusieurs pays et en particulier ceux du Sahel sont confrontés à un déséquilibre alimentaire lié à un déficit régulier de leur production agricole. Ce déficit alimentaire régulier ne permet pas d'assurer la sécurité alimentaire, défini comme l' existence pour tous les êtres humains, à tout moment, d'un accès physique et économique à une nourriture suffisante, saine et nutritive qui répond à leurs besoins et préférences alimentaires pour mener une vie saine et active (FAO, 2006). La sécurité alimentaire est donc devenue un défi majeur pour ces pays qui doivent produire davantage pour nourrir une population en forte croissance (FAO, 2016a). Les raisons qui expliquent cette insécurité alimentaire récurrente ont été largement débattues pendant des décennies et continuent de l'être. Parmi ces raisons, celles qui sont les plus souvent avancées sont l'aridification du climat, la dégradation, l'érosion et la baisse de fertilité des sols, et la faible implication des politiques publiques en faveur de l'agriculture. D'autres raisons en lien avec l'élevage et l'environnement sont aussi avancées telles que la déforestation, les feux de brousse, le surpâturage.

1.1 Dégradation des terres et durabilité des systèmes de culture

La perte de matière organique des sols constitue un lien entre désertification et perte de fertilité des sols. Au Sahel, plusieurs pratiques participent à cette baisse de matière organique des sols comme la réduction de la durée et pratique des jachères, le brûlis, et la collecte du bois mort, des pailles et chaumes. Ces pratiques s'ajoutent aux processus naturels que sont l'érosion éolienne et l'érosion hydrique des sols. Le rapport du PNUE en 2002 (UNEP, 2002) indique une augmentation rapide de la dégradation des sols et signale un risque de chaos de l'agriculture si l'Afrique ne suit pas la voie d'un développement qui respecte l'environnement. Ce rapport souligne les différentes causes de la dégradation de l'environnement depuis les indépendances nationales jusqu'à nos jours. Il met en exergue aussi bien les aspects politiques que socio-économiques et naturels, et remet en cause les méthodes d'exploitation qui sont incompatibles avec un développement durable. Niemeijer and Mazzucato (2002) montrent que la dégradation des terres et la destruction de l'environnement dans un pays du Sahel ne sont pas forcément liées aux pratiques agricoles locales. Cette tendance est aussi décrite par Breman et al. (2008) qui montrent que la dégradation des terres est un phénomène plus complexe au Sahel car les terres sont à l'origine très pauvres. En effet, une fois mis en culture, les sols tropicaux tendent à voir leur productivité diminuer suite à la chute rapide de leur teneur en matière organique combinée à l'acidification et à l'apparition de déficiences en éléments nutritifs, notamment l’azote et le phosphore (Khouma et al., 2005). Plusieurs études dont celle de Kintché et al. (2015) soulignent que l’insuffisance des apports organiques provoque une perte de la capacité du sol à supporter une production, et l’efficience de la fertilisation diminue de manière irréversible sur le long terme. Mais pour d’autres, les apports de fertilisants sont certes insuffisants pour obtenir des rendements élevés, mais les propriétés du sol évoluent peu et même après une longue période sans apports organiques, la réponse des cultures à des apports fertilisants reste la même (Pieri, 1989; A Ripoche et al., 2015). Au-delà des controverses sur l’importance relative des pratiques agricoles locales dans la dégradation des sols, le constat d’une productivité faible ou très faible est une réalité (Affholder et al., 2013). Cette situation est exacerbée par le niveau de pauvreté des populations qui s’accompagne en outre par une érosion de la biodiversité aussi bien chez les végétaux que dans le règne animal. Elle compromet la disponibilité des ressources pour les prochaines générations, donc le futur du Sahel. Les thèses avancées sur les rôles respectifs des changements climatiques ou de l'homme sur la dégradation des terres ont toujours fait l'objet de recherche. Leurs origines varient d'une étude à une autre (Bernus, 1984; Mortimore and Turner, 2005). A ces déséquilibres s’ajoutent l'impact des politiques d'ajustement structurel et les problèmes de gouvernance qui ont un impact plus négatif sur l'environnement sahélien à travers le manque de moyens alloué à l'agriculture. Pour inverser cette dynamique, plusieurs auteurs (Couty, 1991; Nacro et al., 2011) s’accordent sur la nécessité de développer des systèmes de culture durables qui, en plus d’être performants, conserveraient le potentiel de production du milieu. L’intégration culture-élevage, en particulier, est gage de durabilité des systèmes de production tropicaux (Bocquier and González-García, 2010; Lhoste, 2004). Elle permet de répondre aux objectifs sociaux et économiques de la production et d’assurer une meilleure gestion des ressources. L’intégration agriculture élevage rend aussi tout particulièrement attractives les associations culturales de légumineuses fourragères et de céréales, surtout dans les régions à faible disponibilité foncière. Les avantages potentiels qu’offrent l’association d’une légumineuse avec une céréale sont nombreux et variés : amélioration de la fertilité du sol, principalement du fait de la fixation symbiotique d’azote atmosphérique au niveau des racines de la légumineuse, lutte contre l’érosion, production de fourrage de qualité, lutte contre les mauvaises herbes et ainsi économie d’énergie par la suppression partielle ou totale du sarclage et économie en intrants (Bocquier and González-García, 2010; Chandra, 2009; Odunze, 2002).

La durabilité des systèmes agricoles est un concept qui relie les dimensions écologiques, économiques, sociales et environnementales de l'agriculture (Francis et al, 1990). Milleville and Serpantié (1994) définissent la durabilité dans sa dimension écologique en termes de maintien ou de redressement de l'état des ressources productives du milieu en fonction de la nature et de la productivité du système agricole, et en prônant des mécanismes qui peuvent être mis en œuvre par les acteurs eux-mêmes (pratiques de jachère, apports de matière organique, dispositifs anti-érosion). Or la rapide croissance de la population rurale ramenée à l'espace agricole a entraîné une baisse drastique des disponibilités en terre par habitant. La disponibilité en terres potentiellement cultivables en Afrique sahélienne diminue. Au Mali notamment, la superficie des terres cultivables estimée à 2,35 ha/habitant en 2000 ne serait plus que de 0,65 ha/habitant en 2050 (Alexandratos, 2005). Les adaptations locales pour faire face à cette saturation de l'espace ont été comme partout au Sahel, la réduction de la superficie et de la durée des jachères (Floret et al., 1993; Floret and Pontanier, 1999; Wezel and Haigis, 2002), l'utilisation des terres marginales pour l'agriculture (Raynaut, 2001), avec pour conséquence la baisse des rendements agricoles (Pieri, 1989). Les baisses de rendements enregistrées dans plusieurs pays mettent en lumière les relations étroites entre l'expansion démographique, la détérioration de l'environnement et la stagnation de l'agriculture (Milleville and Serpantié, 1994).

1.2 Intensification écologique et changement climatique

Dans les zones de savane subhumides d'Afrique de l'Ouest et du Centre, le modèle de production agricole inspiré par la révolution verte reste celui proposé le plus souvent aux agriculteurs et aux éleveurs (Dugué et al., 2012). Ce mode de production mobilise des intrants chimiques, des équipements et des races et variétés sélectionnées. Ce modèle de production est proposé par les structures de développement ou le secteur privé aux agriculteurs qui sont aussi demandeurs pour le mettre en place malgré ses limites et les risques encourus (Dugué et al., 2012). Mais ces agriculteurs sont aussi détenteurs de savoir-faire reposant sur des processus écologiques qui permettraient un fonctionnement des agroécosystèmes plus efficace et plus durable. Le défi de doubler la production agricole d'ici 2050 incite à réinventer une agriculture autre pour le Sud dont fait partie l'Afrique Subsaharienne (Dufumier, 2010; Dugué et al., 2012; Tscharntke et al., 2012). Dans le contexte du changement climatique, cette agriculture doit prendre en compte la diversité écologique des milieux, la croissance démographique des populations, l'économie de l'eau et enfin, le respect de l'environnement. Le concept d'intensification écologique a été inventé pour définir l'ensemble des principes et des moyens nécessaires pour augmenter la productivité primaire dans les principaux agro-écosystèmes céréaliers du monde (Cassman, 1999) . Selon Chevassus-au-Louis and Griffon (2008) et plusieurs autres auteurs (Affholder et al., 2008; Bommel et al., 2010; Hubert et al., 2010; Mikolasek et al., 2009), l'intensification écologique, consiste à s'appuyer sur les

processus écologiques mis naturellement à disposition par les écosystèmes pour produire en plus grande quantité et plus durablement. L'augmentation de la productivité peut être obtenue en capitalisant sur les processus écologiques dans les agro-écosystèmes (par exemple, la fixation biologique de N_2 atmosphérique), visant à réduire l'utilisation et le besoin d'intrants externes (Tittonell and Giller , 2013). Les processus écologiques de facilitation interspécifique sont basés sur les interactions exercées au niveau microbiologique, nutritionnels, physicochimique, hydrique, et plus généralement dans le partage des ressources entre êtres vivants dans l'écosystème. Un large éventail de services écologiques et écosystémiques assure une augmentation stable des rendements et la survie des plantes (Valet and Lafontaine, 2014). Les systèmes de culture innovants pour l'intensification écologique doivent être évalués avec des indicateurs agronomiques, environnementaux et économiques (Affholder et al., 2014). Cette approche qui va de pair avec la préservation de l'environnement permettra de réduire les nuisances par la baisse des intrants et du travail, de mieux valoriser les ressources rares et épuisables comme l'eau et le sol ou encore de contribuer à la conservation de la biodiversité afin de reconstituer les services écologiques que l'agriculture peut rendre à la société (Bonny 2011). La diversification des (agro)écosystèmes intégrés aux arbres et arbustes devra également permettre la diversification agricole aux différentes échelles pertinentes qui pourrait répondre aux problèmes dus à la globalisation (Tittonell, 2014).
Face aux évolutions des conditions de production notamment la raréfaction des ressources naturelles par habitant, l'augmentation du prix des matières premières nécessaires à la production agricole, les effets négatifs des systèmes de production actuels, le changement climatique, les agriculteurs et les décideurs ne peuvent pas se tenir à l'écart des recherches menées pour une intensification durable et plus agro-écologique de l'agriculture.

A l'instar de nombreuses contributions scientifiques, le rapport du Groupement Intergouvernemental d'Experts sur le Changement climatique (IPCC, 2014), indique que le changement climatique pourrait affecter de manière négative la sécurité alimentaire dans de nombreuses régions du monde et particulièrement pour les régions vulnérables telles que l'Afrique subsaharienne. D'après la littérature, l'une des raisons principales de la vulnérabilité au changement climatique observée dans les pays de l'Afrique subsaharienne est la forte dépendance de leur économie à une agriculture essentiellement pluviale (Lobell and Burke, 2010; Mendelsohn, 2008; Mohamed et al., 2002; Rosenzweig and Parry, 1994). Le changement climatique est par définition une variation statistiquement significative de l'état moyen du climat dans sa variation persistante sur une longue période de temps (décade ou plus) (Cooper et al., 2001).

Plusieurs études ont montré une augmentation attendue des températures dans l'ensemble de la zone Afrique de l'Ouest avec un réchauffement moyen de l'ordre de 2,8°C (Guan et al., 2017a; Sultan et al., 2014) . Ce changement dans la configuration du climat pourrait affecter négativement les rendements du sorgho, l'une des principales cultures vivrières de l'Afrique de l'Ouest (Sultan et al., 2014). Dans ce contexte, la perception qu'ont les agriculteurs des changements climatiques en cours pourrait déterminer dans une large mesure le type d'options techniques de gestion qu'ils choisissent d'adapter (Thomas et al., 2007). Bryan et al., (2009), mentionnent qu'il est important de mieux comprendre la perception qu'ont les agriculteurs des changements climatiques, les mesures d'adaptation actuelles et la prise de décisions afin d'éclairer les politiques visant à promouvoir des stratégies d'adaptation efficaces dans le secteur agricole. Une nouvelle forme d'agriculture permettant d'augmenter ou de stabiliser les rendements s'impose.

Pour arriver à des recommandations appropriées sur l'intensification des agrosystèmes, il est souvent nécessaire de mener des études sur plusieurs sites agroécologiques. Cependant, étudier les variations spatiales et temporelles de la productivité des systèmes de cultures à l'aide d' expérimentations s'avère chronophage et coûteux (Knörzer et al., 2011). Pour remédier à ces limites matérielles, des modèles de simulation des cultures ont été utilisés (Boote et al., 1996) pour l'évaluation de la productivité actuelle et future des systèmes de culture.

1.3 Besoins de modéliser les systèmes de culture

La figure 1 décrit le schéma général retenu pour étudier le fonctionnement de l'association sorgho-niébé. Le schéma prend en compte à la fois le partage de l'eau, l'azote et du rayonnement ainsi que la prise en compte des interactions entre ces trois processus. Ces interactions entre espèces associées sont des phénomènes complexes et dynamiques, qui comprennent à la fois des mécanismes de compétition pour les ressources (rayonnement, eau, nutriments) (Corre-Hellou et al., 2009), mais aussi des mécanismes de facilitation lorsqu'une espèce modifie l'environnement de façon positive pour l'espèce voisine (Affholder et al., 2014; Long and Nair, 1999; Malézieux et al., 2009; Zhang et al., 2008). Elles interagissent à la fois au niveau aérien pour l'interception du rayonnement et au niveau souterrain pour le prélèvement de l'eau et des éléments minéraux (Baldé, 2011). Ces interactions dépendent des espèces associées et influencent fortement les performances de l'association en rendement grain et en biomasse totale, mais aussi les conséquences sur l'environnement, en termes de flux d'eau et d'azote dans le sol (Baldé, 2011). Le choix des espèces associées est donc crucial ainsi que leur gestion. La compréhension et la quantification de ces interactions et leurs conséquences sur la productivité de chaque espèce est toutefois complexe et leur évolution dans le temps les rendent difficiles à appréhender complètement seulement par des mesures expérimentales, le recours à la modélisation est souvent nécessaire en complément à l'expérimentation (Malézieux et al., 2009).

Les modèles de cultures permettent donc sous certaines conditions une meilleure prise en compte de l'évolution des interactions au cours du temps via une quantification moins couteuse en temps et en argent de la performance des cultures associées. Les modèles peuvent servir à partir d'expérimentations virtuelles à extrapoler des résultats expérimentaux obtenus dans un nombre limité d'environnements à d'autres conditions pédoclimatiques ou de mode de gestion (Launay et al., 2009; Tsubo et al., 2005).

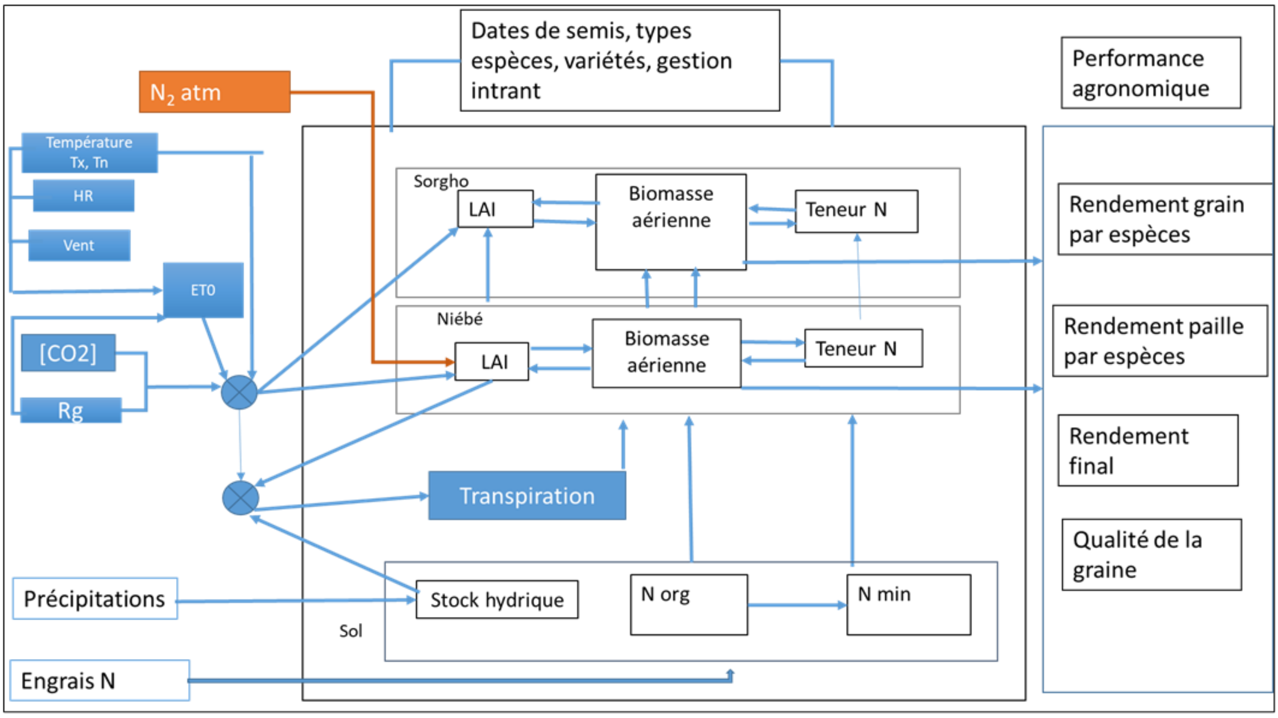
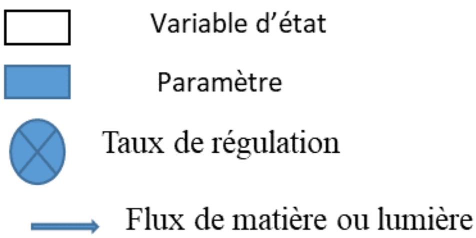


Figure 1 : Schéma conceptuel du fonctionnement de l'association sorgho-niébé. N2 atm =azote atmosphérique, Tx = température maximale, tn = température minimale, Rg = rayonnement global, ET0 = évapotranspiration de référence, N = azote.



1.4 Modélisation des cultures associées

1.4.1. Généralités sur les modèles de cultures associées

Plusieurs modèles de simulation des associations de cultures existent dans la littérature. Des modèles empiriques utilisent des relations mathématiques simples avec peu de paramètres permettant de calculer le rendement d'associations d'espèces cultivées (Vandermeer, 1989). Ces modèles ont peu de détails sur les processus écophysiologiques, et ne permettent pas de décrire une diversité des situations pédoclimatiques, car ils ne caractérisent pas les effets du milieu. L'utilisation de ces modèles dans des situations différentes de celles où ils ont été mis au point est par conséquent difficile. Les modèles mécanistes se distinguent des modèles empiriques par la prise en compte plus détaillée des processus écophysiologiques dans les systèmes simulés. Ils permettent de simuler de façon dynamique la compétition pour les ressources entre espèces en relation avec les états du milieu. Ils nécessitent donc plus de paramètres et de variables d'entrée. S'ils sont correctement paramétrés, ces modèles mécanistes sont plus précis que les modèles empiriques en termes de prédiction des performances des associations dans une large gamme de situations (Baumann et al., 2002; Tsubo et al., 2005; Whitmore and Schröder, 2007). Les modèles des associations d'espèces cultivées incluent des associations adventices/cultures, plantes fourragères-trèfles, céréales-légumineuses et arbres/cultures (Brisson et al., 2004; Tsubo et al., 2005). Ils simulent les processus de développement des cultures et leur compétition pour le partage des ressources (lumière, eau et nutriments) (Berntsen et al., 2004; Corre-Hellou et al., 2007; Tsubo et al., 2005), ainsi que leur performance en termes de biomasse et de grain (Baumann et al., 2002; Whitmore and Schröder, 2007). D'autres modèles plus écologiques intègrent en plus les relations de facilitation en communautés d'espèces (Brooker et al., 2008).

Certains modèles comme GROWIT (Lowenberg-DeBoer et al., 1991) sont des modèles de plante adaptés pour simuler une association d'espèce. GROWIT ne simule que la compétition pour la lumière et l'eau et contient peu de détails sur les processus écophysiologiques qui sont pris en compte. Les modèles ALMANAC (Kiniry et al., 1998) et Ecosys (Grant, 1992) simulent la compétition pour l'eau, l'azote, la lumière et le phosphore. La majorité des modèles de simulation des associations de cultures fonctionnent au pas de temps journalier. Le modèle Stics-Intercrop (Brisson et al., 2004) est une version de STICS (Brisson et al., 1998) adaptée pour la simulation des cultures associées, dans lequel une adaptation d'un certain nombre de modules spécifiques permet de prendre en compte l'utilisation des ressources (rayonnement, eau, et azote) par les espèces associées. Le pas de temps est journalier.

1.4.2. Le choix du modèle STICS

Le modèle sol-culture STICS (Brisson et al., 2004) a été choisi pour son caractère agro-environnemental, la généricité de la représentation des différentes espèces cultivées (permettant de simuler l'association de cultures avec le même modèle). Le modèle STICS est utilisé pour une large gamme de cultures pures (Brisson et al., 1998) et une version spécifique, Stics-Intercrop a été développée pour simuler le fonctionnement des cultures associées (Brisson et al., 2004). Il permet de simuler la compétition pour la lumière, l'eau et l'azote entre espèces avec un pas de temps journalier. Par son caractère générique, STICS peut être adapté à un grand nombre de cultures en faisant des choix de formalismes adéquats. D'autre part, le modèle STICS a fait l'objet de plusieurs travaux sur son paramétrage et son adaptation dans divers contextes de culture en zones tropicales (Baldé, 2011; Silva et al., 2019). STICS-INTERCROP v8.5 simule la dynamique quotidienne du carbone, de l'eau et de l'azote dans le système sol-culture au cours du cycle de culture. Le module bilan d'énergie et microclimat du modèle est probablement le plus complet et le plus complexe comparé aux autres modèles. Il s'appuie sur les travaux de Shuttleworth and Wallace, (1985), pour calculer la demande en eau de chaque espèce associée.

1.5 Objectif et démarche de l'étude

1.5.1 Objectif de l'étude

L'objectif général de cette thèse est de concevoir des systèmes de culture performants (productivité et stabilité de la production) qui permettent aux agriculteurs de s'adapter à la variabilité climatique, tout en effectuant une transition vers une intensification écologique adaptées au changement climatique.

Cette thèse est dès lors une contribution à :

(i) l'identification de la perceptions du changement climatique par les agriculteurs, et les stratégies d'adaptation au changement climatique qu'ils mettent en œuvre;

(ii) l'évaluation de la performance (productivité et stabilité de la production) d'une gamme d'options techniques, en climat actuel et futur, à l'aide du modèle de culture STICS.

Différentes options techniques (et leurs combinaisons) ont été évaluées, notamment :

- l'association du sorgho avec une légumineuse, le niébé
- le choix variétal pour le sorgho;
- l'application de fumure minérale

Ces options ont été évaluées pour une date de semis précoce, et une date de semis tardive.

La question de recherche est la suivante : ***les options techniques étudiées permettent – elles de mieux s'adapter au changement climatique ?***

Nous partons des hypothèses suivant lesquelles :

- les agriculteurs de la zone d'étude perçoivent un changement dans la configuration du climat et développent des stratégies plus ou moins adaptées ;

- le modèle de culture permet de rendre compte de la performance d'une adaptation potentielle candidate, i.e. l'association sorgho-niébé, au travers de la prise en compte des compétitions et complémentarités entre sorgho et niébé pour l'utilisation de l'eau et de l'azote ;

- la complémentarité entre sorgho et niébé permet une stabilisation de la production de biomasse (biomasse aérienne totale et grain) par rapport à la pratique actuelle ou de référence de la zone (la culture pure de la variété traditionnelle de sorgho, sans fertilisation minérale);

- la compétition entre sorgho et niébé dépend de la variété de sorgho, de la fertilisation, et de la date de semis ;

- la variabilité climatique a moins d'impact négatif sur les options d'intensification en terme de production par rapport à la pratique actuelle ou de référence de la zone.

1.5.2 Démarche de la recherche

La démarche générale adoptée dans le cadre de cette étude s'appuie sur des enquêtes dans les exploitations agricoles et des expérimentations en station expérimentale pour tester les hypothèses citées ci-dessus puis caler et évaluer le modèle sol-culture de STICS avec les données issues des expérimentations. Ainsi Les perceptions des agriculteurs sur le changement climatique et les options d'adaptation ont été identifiées lors de discussions de groupe, suivies d'enquêtes individuelles au niveau des exploitations pour analyser les perceptions et les stratégies d'adaptation mises en œuvre par les agriculteurs. Les données météorologiques enregistrées sur le long terme dans deux stations du Mali (N'Tarla, Koutiala) ont été analysée pour comparer le changement climatique aux perceptions des agriculteurs.

Le travail expérimental repose sur deux années de suivi (2017 et 2018) à la station expérimentale de N'tarla (12,6193°N, -5,689°W) au Mali. Les expérimentations ont été menées en saison des pluies et chaque année, les associations ont été comparées aux cultures pures correspondantes. Dans un premier temps, la démarche a consisté à calibrer le modèle sol-culture STICS à partir des données issues du dispositif expérimental de 2018 pour les deux systèmes de cultures (culture pure du sorgho et semis du niébé au sein du sorgho à différentes dates), où les observations ont été réalisées de façon poussée pour certaines variables clefs à différents moments durant le cycle de la culture (LAI, biomasse, azote dans la plante, stock d'eau). La capacité du modèle à estimer les performances des systèmes de cultures a été évaluée avec les données du dispositif expérimental de 2017 où l'effort de mesure était moindre que l'année suivante et où notamment le suivi de l'état hydrique du sol n'avait pas été réalisé. Les doses d'apport d'engrais, le contrôle des adventices et les dates de semis ont été parfaitement maitrisés.

Dans un second temps, les performances des associations ont été étudiées en relation avec la compétition pour les ressources (eau, azote et rayonnement). Les résultats obtenus ont permis de caractériser les performances de ces systèmes sur l'ensemble des expérimentations et de mettre en évidence le comportement des associations comparativement aux cultures pures. Ce couplage entre expérimentation et modélisation est indispensable pour une représentation satisfaisante du système par le modèle et pour une quantification de certains flux difficilement mesurables.

Le modèle devrait ainsi aider à définir des stratégies d'organisation et de conduite de l'agrosystème afin de maintenir la productivité du sorgho et du niébé en tenant compte des compétitions entre plante principale et plante associée et les stress induits à l'élaboration de cette biomasse (Fig. 2). L'association de culture permet d'augmenter la production totale par une meilleure valorisation de l'ensemble des ressources, voire par l'accroissement des relations de facilitation sur l'azote (fixation symbiotique de l'azote, restitution au système).

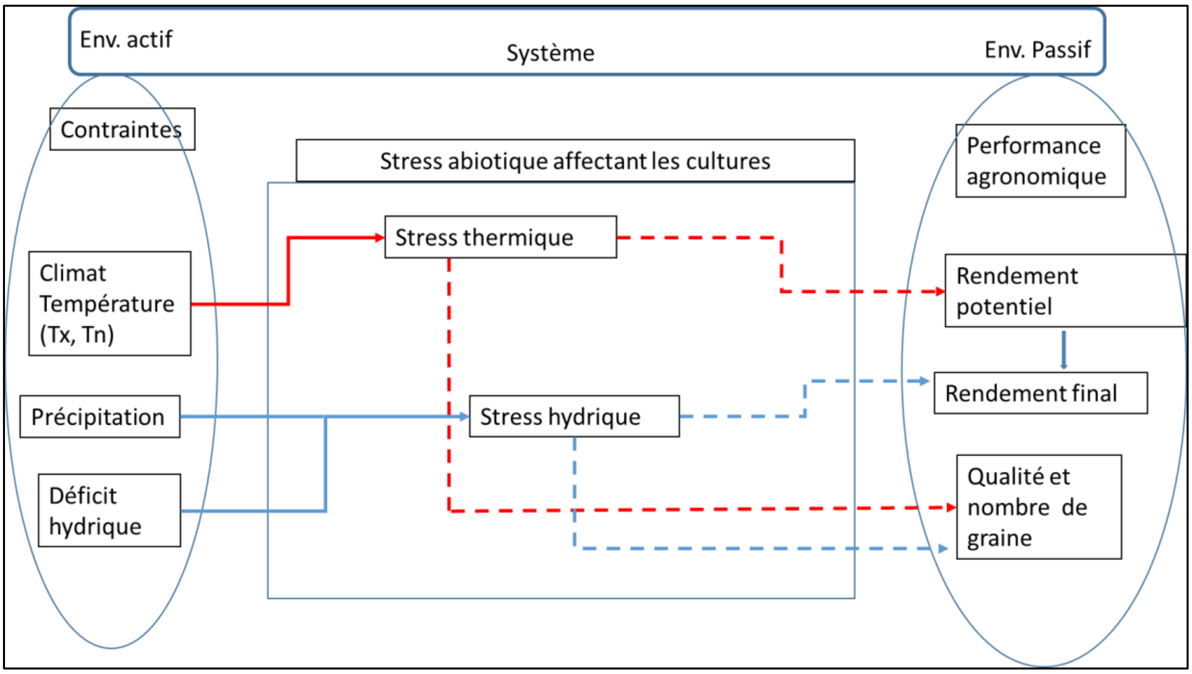
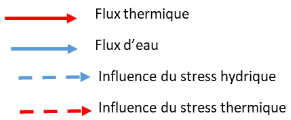


Figure2 : Schéma conceptuel du stress induits à l'élaboration de la biomasse. Tx = température maximale, tn = température minimale, Rg = rayonnement global, Env. actif = environnement actif, Env. passif = Environnement passif.



1.6 Plan de la thèse

Cette thèse se compose de cinq chapitres, dont l'introduction et la discussion générale (chapitre 1 et 5) entre lesquelles s'insèrent des chapitres rédigés sous forme d'article, dont un (chapitre 2) est été publié au journal "Weather, Climate, and Society". Les chapitres 2 à 4 contiennent les principaux résultats de cette étude. Le chapitre 2 compare les perceptions des agriculteurs sur le changement climatique avec les données météorologiques réelles enregistrées dans la zone d'étude et identifie les changements dans les pratiques agricoles mises en œuvre par les agriculteurs pour s'adapter au changement climatique. Ce chapitre analyse aussi le lien entre perception des agriculteurs et la mise en œuvre des stratégies d'adaptation. Dans le chapitre 3 nous avons adapté, calibré et évalué le modèle sol culture de STICS pour simuler la croissance et la productivité du système de culture associée sorgho-niébé, en tenant compte de la concurrence pour les ressources (eau, azote et lumière) entre les espèces dans des conditions de culture pluviale. Dans le chapitre 4, nous utilisons le modèle sol culture de STICS pour évaluer le risque climatique futur sur la productivité du système de culture associé sorgho niébé. Pour construire les scénarios de changement climatique, nous avons utilisé la moyenne mensuelle des données climatiques historiques et futures fournies par sept modèles de circulation globale issus du projet CMIP6 (Coupled Model Intercomparison Project). Les estimations représentent le changement potentiel des températures maximales et minimales et des précipitations d'ici 2065 selon le scénario ssp5-8.5 à fortes émissions de gaz à effet de serre. L'objectif était de quantifier l'effet du changement climatique sur la productivité du sorgho et du niébé en condition de culture de référence et en condition de culture intensifiée, et d'évaluer le potentiel des différentes options étudiées pour compenser la perte de rendement due au changement climatique. Dans le chapitre 5, nous faisons une discussion générale de l'étude et présentons les limites et les recommandations pour de futures recherches.

CHAPITRE II

Chapitre II: Farmers' perception and adaptation strategies to climate change in central Mali

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ABSTRACT:

Adaptation of the agricultural sector to climate change is crucial to avoid food insecurity in sub-Saharan Africa. Farmers' perception of climate change is a crucial element in adaptation process. The aim of this study was (i) to compare farmers' perception of climate change with actual weather data recorded in central Mali and (ii) to identify changes in agricultural practices implemented by farmers to adapt to climate change and iii) to investigate the link between farmers' perception of climate change and implementation of adaptation practices. Focus group discussions and individual surveys were conducted to identify climate-related changes perceived by farmers and agricultural adaptation strategies they consider relevant to cope with these changes. Majority (>50%) of farmers perceived an increase in temperature, decrease in rainfall, shortening of growing season, early cessation of rainfall and increase in the frequency of dry spells at beginning of growing season. In line with farmers' perception, analysis of climate data indicated (i) increase in mean annual temperature and minimum growing season temperature and (ii) decrease in total rainfall. Farmers' perception of early cessation of rainfall and more frequent drought periods were not detected by climate data analysis. To cope with decrease in rainfall and late start of growing season, farmers used drought-tolerant cultivars and implemented water-saving technologies. Despite a perceived warming, no specific adaptation to heat stress was mentioned by farmers. Our study highlights the need for a dialogue between farmers and researchers to develop new strategies to compensate for the expected negative impacts of heat stress on agricultural productivity.

Keywords: Climate variability and change, farmers' perception, cropping systems, focus groups, adaptation options.

2.1 INTRODUCTION

Sub-Saharan Africa staple production must increase to feed a rapidly growing population (Fao, 2006). Agricultural production in this region is strongly affected by the variability in seasonal rainfall regimes (Sultan et al., 2005). With high dependence on rainfed agriculture and limited adaptive capacity (i.e. individual and collective skills to respond to environmental and socioeconomic changes) resulting from lack of resources and technologies, sub-Saharan Africa will be one the most vulnerable regions of the world to climate change (Sultan and Gaetani, 2016a). Food security "exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO, 2006). Changes in temperature, rainfall and frequency of extreme events may negatively impact crop yield and food availability (Ouédraogo et al., 2010; Sultan et al., 2013) but also other aspects of food security such as accessibility and utilization (Hamani, 2007). These potential impacts on agriculture call for increasing efforts to reduce greenhouse gases emissions and to adapt to climate change (Ouédraogo et al., 2010).

Adaptation can occur at individual level, i.e. through a change of practice, or at community level, through collective action and knowledge sharing. At the individual/household level, adaptation can be defined as the "household level behavior that aim to avoid the physical and financial impacts imposed by climate exacerbated hazards" (Wilson et al., 2020). Understanding the drivers of a change in practice, e.g. the adoption of an innovative farm practice, has been the focus of a large body of empirical studies, e.g. Kassie et al. (2015) on the adoption of sustainable intensification practices in sub-Saharan Africa). Several factors, e.g. farm characteristics and the attribute of the innovative practice, can drive their effective implementation by farmers. However, "psychological factors", such as the perception of an environmental threat, have often been overlooked in such studies (Foguesatto et al., 2020).

Adaptation is often modelled as a two-step process that starts with the recognition of the issue at stake (i.e. perception of climate change) and is followed by the adoption (i.e. the actual implementation) of the practice that will solve that issue (Maddison, 2007). Farmers' perception of on-going climate is a critical variable to understand the adoption of climate change adaptation strategies, as it determines to a large extent the type of management options farmers choose to adapt (Thomas et al., 2007). However, the current literature on this topic does not give a clear-cut picture. In affluent countries, farmers' who perceived the potential consequences of climate change on their immediate environment showed a firmer intention to take action and get involved in adaptation programs (Arbuckle et al., 2013; Niles et al., 2013). These intentions, however, seldom translated into effective implementation (Niles et al., 2016). In developing countries, where farmers are often more hardly hit, several studies have shown the direct connection between perception of climate change and effective implementation of adaptation practices. For instance, Lalou et al. (2019) and Muller et al. (2015) showed that farmers in Senegal perceived accurately the recent recovery in rainfall and re-used an old variety of millet that was adapted to wetter climate. In the Gambia, farmers who perceived a decrease in growing season length were more likely to implement water conservation techniques (Bagagnan et al., 2019). But this link between perception and adaptation is not always systematic. For example, only half of smallholder in central America who perceived a climate change impact implemented an adaptation option (Harvey et al., 2018), pointing to constraints prevailing in smallholder systems, related to farm resource endowment e.g. land tenure and lack of financial support or working capacities. More immediate concerns (e.g. food security, financial concerns) were found to be other important predictors of adoption of adaptation practices (Waldman et al., 2019).These complex interactions call for 'place-based' insights on whether perception of climate change leads to more adaptation.

Another key dimension of the adaptation process is the analysis of the consistency between farmers' perception and measured climate trends. This investigation is crucial, as farmers' misinterpretation of climate variations can lead to maladaptation (e.g. denial of the problem) (Grothmann and Patt, 2005). Studying perception can also help building a dialogue between researchers and farmers to support co-learning of how climate is changing and how such changes are detected on the ground (Flood et al., 2018). Assessing the factors driving perception can help targeting specific groups to raise their awareness of climate change issues. For example, US ranchers' and farmers' perception of the occurrence and causes of climate change was influenced by political ideology (Liu et al., 2014). In the smallholder context of South Ethiopia, farm resource endowment mattered as farmers with larger herds and better access to extension services perceived more acutely climate change (Debela et al., 2015). Other studies suggest that age or farming experience can be an important driver of perception, as prolonged stay in a given place may facilitate recognition of environmental change, older people having in-depth knowledge of local conditions (e.g. Akerlof et al., 2013, Deressa et al., 2011). Assessing the factors driving perception can also help explain discrepancies between farmers perception and climate records. For example, in the developed context of New-Zealand, growth in irrigation facilities shaped a perceived increase in annual rainfall that was not supported by the analysis of historical weather records (Niles and Mueller, 2016).

Linking into a comprehensive assessment i) farmers' perception of climate change and observed trends in weather records, and ii) farmers' perception and implementation of adaptation, can bring crucial insights for the co-design of sound adaptation strategies that fit the needs of smallholder farmers.

Central Mali, where annual rainfall fluctuates between 700 and 900 mm (Traore et al., 2013), is representative of land-constrained sub-Saharan Africa, with high population density and limited land availability for agriculture expansion, and degradation of animal grazing areas exerting pressure on livestock systems. Majority of rural people in the region are vulnerable to climate variability and change (Sivakumar et al., 2005). In this study, we focused on this constrained region and aimed at (i) analyzing farmers' perception of on-going climate change, their drivers, and their consistency with past climate observations, (ii) identifying the adaptation strategies implemented by farmers to adapt to climate change and (iii) testing whether perception of climate change by farmers impacted the implementation of adaptation strategies. By doing so, we explored the hypothesizes that (i) farmers in the study area perceive climate change through local modification of their immediate environment, ii) farmers perception of climate change and the analysis of historical weather data align (iii) farmers who perceived climate change are more likely to implement adaptation strategies and iv) covariates like farmer age and farm resource endowment are drivers of perception of climate change and implementation of adaptation strategies. Farmers' perception of climate change and adaptation options were identified during focus groups discussions followed by individual farm-level surveys to analyze the connection between perception and adaptation strategies implemented by farmers. A long-term series of meteorological data recorded at two stations in central Mali was analyzed to compare climate change with farmers' perception.

2.2 MATERIAL AND METHODS

2.2.1 Study area

The study was conducted in the Béguéné village in central Mali (12°91' N, -5° 91' W), in the northern part of the cotton growing area (**Fig.1**). Advice on agricultural techniques is provided by extension workers of the Malian Textile Development Company (CMDT). The climate of the study area is typical of the Sudanian domain, where annual rainfall ranges between 600 and 1000 mm/year. The rainy season generally starts in June and ends in October with rain peaks in July and August. Sandy and gravelly soils prevail in the region. Farming systems integrate agriculture and livestock: cattle is used for draught power and manure production, and cereal and legume residues are used as animal feed. The region share several similar characteristics with smallholder farming systems in semi-arid regions of sub-Saharan Africa. Farmers are smallholders, i.e. they manage areas in the range 1-10 ha (http://www.fao.org/family-farming/detail/fr/c/273864/, last accessed 10/09/2021). Agriculture in the region is the main livelihood strategy. Agricultural and livestock productivity is low: cereal yield is around 30% of their potential (https://www.yieldgap.org/gygaviewer/index.html?roi_id=6), due to high cost and low use of external agricultural inputs. About half the population of sub-Saharan Africa is below the 1.9 $ day-1 poverty line (Dzanku et al., 2015), and this holds for this region of central Mali (Falconnier et al., 2018). On top of that, farmers face diverse risks and have to cope with an uncertain production context. Inter-annual rainfall variability and seasonal rainfall distribution result in great crop yield variability: short rainfall seasons and/or high number of dry spells lead to strong crop yield decrease (Traore et al., 2013). Socio-economic and institutional factors, such as the institutional support for cotton production, are also heavily fluctuating (Falconnier et al., 2015), as it is also the case in other countries of sub-Saharan Africa (see e.g. the collapse of cotton marketing institutions Ebanyat et al., (2010) and dysfunctional coffee cooperatives (Sassen et al., 2013). Africa's population is growing faster than in any other continent (Alexandratos, 2005). Mali is no exception and ranks among the ten countries with the fastest population growth rate in the world (Alexandratos, 2005). Population pressure causes cropland expansion, at the expense of grazing land (Hiernaux et al., 2009), disturbing the transfers of manure and nutrient from rangelands to cropland, hence threatening the sustainability of farming systems (Powell et al., 1996).

In central Mali, majority of farmers own at least one pair of oxen, a cultivator and a seed drill and use animal traction for soil preparation, weeding and seeding (Falconnier et al., 2015). Most of the cultivated land (70%) is used for cereal production (PASE2, 2015) . Millet (*Pennisetum glaucum (L.) R. Br.*) and maize (*Zea mays*) are the main cereals accounting for 38% and 20% of the cultivated area respectively, but sorghum cultivation (*Sorghum bicolor (L.) Moench*) is also significant with 12% (PASE2, 2015). Cereals are grown in biennial or triennial rotation with cotton (*Gossypium hirsutum L.*). Organic and mineral fertilizers, and pesticides, are mainly applied to cotton and maize. Millet and sorghum benefit from nutrient carry-overs due to fertilizer applications on cotton or maize.

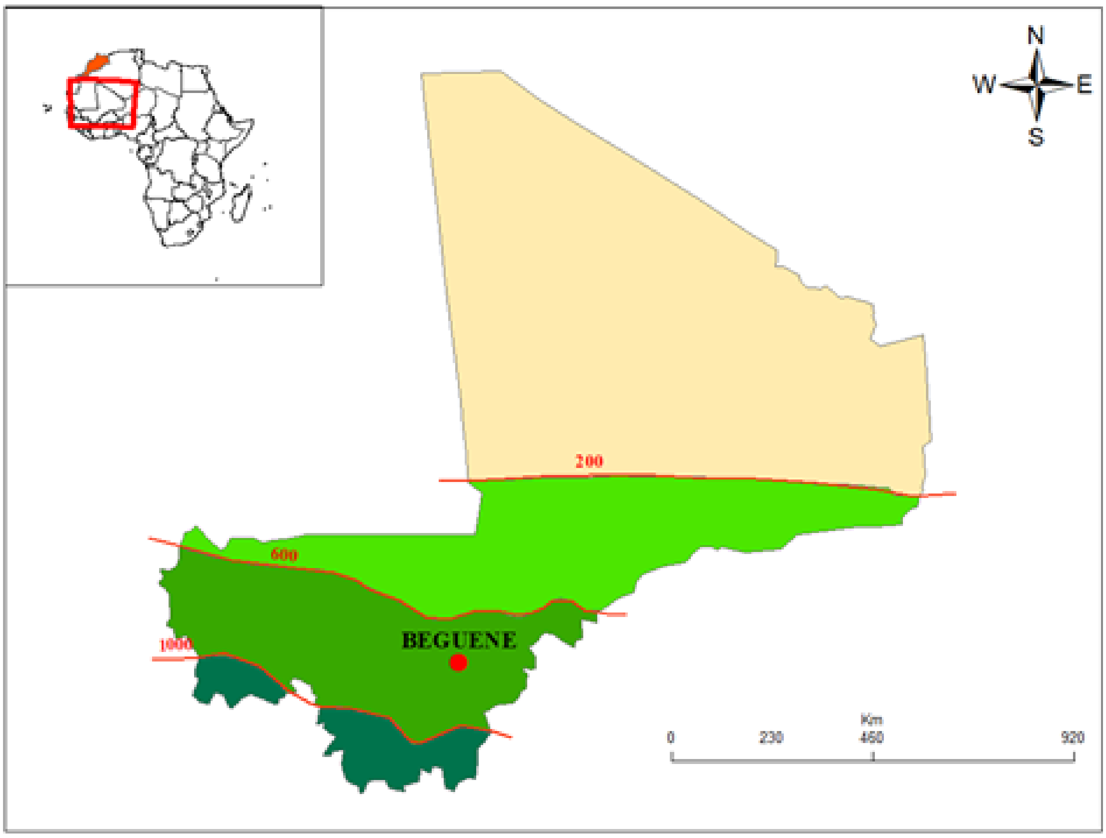


Figure 1: Location of the study area (Béguéné village) in Sudanian zone of Mali, West Africa. The red lines are the isohyets. The sudanian zone lies between the 600 and 1000mm isohyet. Map by Kader Koné.

2.2.2 Data collection on farmers' perception

A combination of focus group discussions to gather qualitative information and individual questionnaires to collect quantitative data are often used to assess farmers' perception of climate change and adaptation (Dhanya and Ramachandran, 2016; Zampaligré et al., 2014). In the present study, we used focus group discussion and individual interviews.

2.2.2.1 Focus groups

Three focus group discussions were conducted in April 2017 to gain insights on farmers' perception of on-going climate change, following the methods described in Zampaligré et al. (2014). The groups of 15-20 male farmers consisting in a mix of young (~aged 20 to 40) and old (over 50) people. These groups were formed randomly based on farmers' willingness to participate with the support of the village chief in organizing the meetings in the village. Farm managers are exclusively men in the region, so our decision to assess the representation of climate was gender-biased. Discussions at each focus group level were facilitated by a researcher or agricultural advisor in the local language *Bamanan*. Farmers were asked to elaborate on past and current climate change, focusing sequentially on rainfall, temperature and wind. When referring to past climate, no specific time horizon was indicated by the facilitator. At the level of each focus group discussion, the questions were a mix of open and close ended-questions: Have you experienced any changes in climate in your community? What do you think of the length of the growing season? What do you think about the start and end of the growing season in the past and currently? What do you think of temperature in the past and currently? What do you think about wind speed now and in the past? Farmers were also asked about the foreseen impacts of these changes on agricultural production, and the specific adaptation strategies they were implementing to cope with each of the changes in climate variables, i.e. rainfall, temperature and wind.

For questions with regard to changes in rainfall, temperature and wind, farmers' answers were noted by the researchers and development workers during the focus group discussion. The most frequent answer to these questions in each of the group was computed based on the transcript of the research assistant in each group, and an aggregated answer (i.e. the most frequent answer among the group) was considered as the final output of the discussion. For answers related to the adaptation strategies, the research team listed all adaptations mentioned in the different groups and this list was the final output.

The synthesis of the focus group discussion work on farmers' perception and endogenous coping strategies to climate variability and change was presented to the farmers two weeks later at a village meeting. Information gathered from the focus group discussions formed the basis for the survey used in the individual interviews with farm managers.

2.2.2.2 Individual surveys

Individual surveys with farm managers (63 farms out of 75 in the village) were then conducted in January 2018. The first objective was to compare the perception obtained during focus groups discussions with individual perception. A second objective was to explore whether the mentioned agricultural adaptation strategies were effectively implemented by the surveyed farmer. Lastly, we also wanted to investigate the potential connection between perception and implementation of adaptation options. The farm managers surveyed had participated (themselves or a member of their farm, e.g. the field manager) to the previous focus group discussion. Data on farm characteristics, farmers' perception of climate change (based on the list of changes mentioned during the focus group discussion) and farmers' adaptation strategies (based on the list of adaptation strategies mentioned during the focus group discussion) were collected from a structured questionnaire containing closed-ended questions (see supplementary materials, Table S3). The questions were administered in local languages by interviewers.

2.2.3 Analysis of meteorological data

The changes mentioned by farmers could not directly be translated into quantifiable indicators, therefore these perceived changes were converted by the research team into meteorological indicators that could be computed with available weather record (Table 1). Daily rainfall (1951-2017) was obtained from the station closest to the studied village (distance = 13 km), namely N'Tarla (12°35' N, 5°42' W, 302m), and the daily temperatures (1951-2010) from the Koutiala weather station (12°23′ N, -5°27′ W, 350m) located 40 km away from the study site. Land-cover is similar at Koutiala and Béguéné, with flat topography. Therefore, temperatures measured at Koutiala were assumed to be similar to the ones experienced at Béguéné. To take into account decadal variability of climate, rainfall data was analyzed by considering four 15-year historical periods (1951-1965, 1966-1980, 1981-1995, 1996-2010) and one 7-year period (2011-2017) representing the current period. Temperatures were analyzed using the same periods, but we excluded the most recent 7-year period (2011-2017) for which no record was available. The variables included in the analysis are listed and defined in **Table** 1 and **Table 2**. The effect of the factor "period" on these variables was tested with ANOVA using a probability threshold of 0.05. Visual inspections of residuals plots did not reveal deviations from normality or heteroscedasticity. When period effect was significant, pairwise comparisons of periods were performed with a Tuckey test. The statistical analysis was performed with the R software (R Development Core Team, 2021).

Table 1: Climate-related changes mentioned by farmers during three focus groups in the Beguene village in central Mali.

Changes mentioned by farmers		**Correponding meterological indicator**
Rainfall	Decreasing rainfall	Total rainfall over the season
	Shorter growing season	Length of the growing season
	Delayed rainfall	Start date of the growing season
	Early cessation of rainfall	End date of the growing season
	Increasingly intense rainfall	Frequency of daily rainfall above 30, 50 and 70mm
	More frequent dry spells at the start of the growing season	Number of dry spells between May and June
	More frequent dry spells at the end of the growing season	Number of dry spells between September and October
	More frequent dry spells in the middle of the growing season	Number of dry spells between July and August
Temperature	Increasingly hot temperature	Average maximum and minimum temperature per year
	Increased temperature during the growing season	Average maximum and minimum and mean temperature in the growing season
	Night-time temperature increase	Average minimum temperature per year
Wind	Increasingly violent winds	No corresponding observed data available in weather stations neighboring the study region

Table 2: Meteorological indicators, calculation method and data source

Meteorological indicator	Calculation method	weather database used
Total rainfall over the season	Cumulated daily rainfall over the season	N'Tarla Weather Database 1951-2018
Length of the growing season	Number of days between the start and end dates of the growing season	
Start date of the growing season	First day after May 1st when total rainfall exceeds 20 mm (adding the previous two days), without being followed for the next 30 days by a dry sequence exceeding 7 days (Stern et al., 1981; Stern and Cooper, 2011)	
End date of the growing season	Day when, after September 15, there is no rain for a consecutive decade (Traore et al., 2013).	
Number of daily rainfalls above 30, 50, 70 mm	Frequency of rainfall above 30, 50 and 70 mm	
Number of dry spells at start, end and middle of the growing season	A day was considered "dry" when daily rainfall was less than 0.1 mm. Daily observations were represented as successive sequences of dry and wet periods and the total number of dry spells of 5, 7, 10, 15, 20 days during the start (May and June), the middle (July and August) and the end (September and October) of the growing season was calculated	Koutiala Weather Database 1951-2010
Average maximum and minimum temperature per year	Maximum (*Tmax*) and minimum (*Tmin*) temperatures averaged per year	
Average maximum and minimum temperature in the growing season	Average maximum and minimum temperature averaged per growing season.	
Average temperature per year and during the growing season	Average [*Tmin*+*Tmax*/2] temperature averaged per year and per growing season	

2.2.4 Comparison of meteorological data with farmers' perception

Farmers' perception was compared with the trends in meteorological indicators computed from the climate data from the two stations mentioned above. For this analysis, farmer's perception was analyzed without considering farmer age or farm type, *i.e.* all farmers were pooled together for the analysis. When majority of farmers (i.e. at least 50% of the surveyed farmers) perceived a given change and the analysis of meteorological data indicated a significant change in the corresponding meteorological indicator, we considered that farmers' perception and weather records matched. When the change in the corresponding meteorological indicator was not significant, we considered that there was a discrepancy between farmers' perception and weather records. When only minority of farmers (i.e. less than 50% of the surveyed farmers) perceived a given change, and the analysis of meteorological data indicated a significant change in the corresponding meteorological indicator, we also considered that there was a discrepancy between farmers' perception and weather records.

2.2.5 Statistical analysis of the drivers of farmers' perception and the links between perception and implementation of adaptation

In order to better understand the drivers of farmers' perception and to investigate the potential link between perception of climate change and implementation of adaptation options, we used logit models (following Niles and Salerno, 2018) to estimate i) perception of climate change and ii) effective implementation of an adaptation, as binomial responses.

To estimate perception of climate change, the categorical covariates "farmer age" and "farm type" were included in the model. For the "farmer age" covariate, we defined four age groups: 20-39, 40-49, 50-69 and >70. It was assumed that farmers start recalling climate at 15 years of age (Kabore et al., 2019). The 15-years period division for climatic data matches the different length of farmers experience of climate change according to their age group (**Fig.2**.).For the "farm type" covariate, farms were classified in four resource endowment groups according to the typology established by the Agricultural Research Institute of Mali (IER) and the CMDT: Type A: well-equipped farm with a herd of more than 10 cattle and at least four oxen and two ploughs; Type B: equipped farm with two oxen and one plough; Type C: farm with only one oxen and or plough and Type D: farm without oxen and plough.

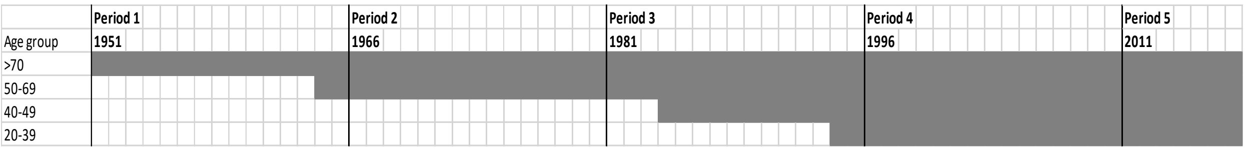


Fig. 2 Length of period (grey bars) during which farmers are assumed to have experienced the climate depending on their age group. The climate series was divided into four 15-year periods (1951-1965; 1966-1980; 1981-1995; 1996-2010) and one 7-year period for rainfall (2010-2017) and four 15-year periods for temperature (1951-1965; 1966-1980; 1981-1995; 1996-2010).

To estimate the implementation of an adaptation option, the 11 binomial (yes/no) covariates related to the perception of the 11 changes listed by farmers in Table 3 were included in the model, i.e. "PC" variables, in addition to the "farmer age" and "farm type" covariates.

The log odds of response were estimated as follows:

(Model 1) $\text{logit}(p_{\text{perception } i}) \sim a + bFT_j + cFA_k + R$

(Model 2) $\text{logit}(p_{\text{adaptation } i}) \sim a + bPC1_j + cPC2_k + \ldots + lFT_t + mFA_u + R$

In model 1, $p_{\text{perception}}$ is the probability for a farmer to perceive a given change *i* (the twelve changes mentioned in Table 3 were successively investigated), FT_j is the $_j$th level for the "farm type" covariate, and A_k is the k^{th} level of the "farmer age" covariate, R is the residual, a is the intercept, and b and c are slope coefficients.

In model 2, $p_{\text{adaptation } i}$ is the probability for a farmer to implement and adaptation option *i* (the eight adaptation options mentioned in Table 6 were successively investigated), $C1_j$ is the j^{th} level of the PC1 variable (i.e. the perception of the fist change listed in Table 3), FT is the t^{th} level for the "farm type" covariate, and A_u is the u^{th} level of the "farmer age" covariate, R is the residual, a is the intercept, and b, c,…,l,m are slope coefficients.

The logistic regression models were implemented with the glm (generalized linear model) function in R.

2.3 RESULTS

2.3.1 Climate-related changes mentioned by farmers during focus group discussion

For changes related to rainfall, farmers mentioned a decrease in rainfall, shorter growing season, delayed and early cessation of rainfall, increase in the frequency of dry spells and an increase in the intensity of rainfall events (**Table 1**). With regard to temperature, increasingly hot temperature in general, during the night, and during the growing season were reported. Increasingly violent winds were also mentioned (**Table 1**).

2.3.2 Climate-related changes perceived by individual farmers and drivers of perception

Most of the changes related to rainfall mentioned by farmers during the focus group discussions (**Table 1**) were consistent with those mentioned by the majority of individually interviewed farmers (**Table 3**). Majority (>50%) of individually interviewed farmers confirmed the listed changes related to rainfall, except the change "Increasingly intense rainfall" and "More frequent long dry spells in the middle of the growing season" that were only mentioned by minority of farmers. Changes in temperature and wind as reported during focus group discussions were also consistent with those reported by the majority of farmers during individual interviews (**Table 3**).

None of the covariates included in the logit model to determine the drivers of perception (see section 2.4) were significant: we did not find evidence of a significant impact of farmer age or farm type on the perception of the different climate change indicators.

Table 3: Share of individually interviewed farmers mentioning the changes previously listed during focus groups discussions

	Change mentioned by farmers		Number of farmers	Percent (%)
Rainfall	Decreasing rainfall	Yes	46	73
		No	17	27
	Shorter growing season	Yes	57	90
		No	6	10
	Delayed rainfall	Yes	52	83
		No	11	17
	Early cessation of rainfall	Yes	43	68
		No	20	32
	Increasingly intense rainfall	Yes	29	46
		No	34	54
	More frequent long dry spells at the start of the growing season	Yes	39	62
		No	24	38
	More frequent long dry spells at the end of the growing season	Yes	32	51
		No	31	49
	More frequent long dry spells in the middle of the growing season	Yes	24	38
		No	39	62
Temperature	Increasingly hot temperature	Yes	61	97
		No	2	3
	Increased temperature during the growing season	Yes	57	90
		No	6	10
	Night-time temperature increase	Yes	59	94
		No	4	6
Wind	Increasingly violent winds	Yes	51	81
		No	12	19

2.3.3 Analysis of measured historical climate indicators

The measured climatic indicators chosen to correspond to the changes mentioned by farmers are given in **Table 1**. Data sources and computation methods are displayed in **Table2**. Due to lack of data, we could not analyze climate indicators related to wind, despite the fact that changes in the frequency of strong winds were mentioned by farmers. Total rainfall over the season significantly differed between periods (*P<0.001*) **(Fig.3-A**, **Table S1)**. Total rainfall over the season decreased during the first three periods (1951-1965, 1966-1980, 1981-1995), rose again during the fourth period (1996-2010) and decreased during the fifth period (2011-2017). The length, start and end of growing season did not differ significantly between periods (Fig.3-B, 3-C, 3-D, **Table S1**).

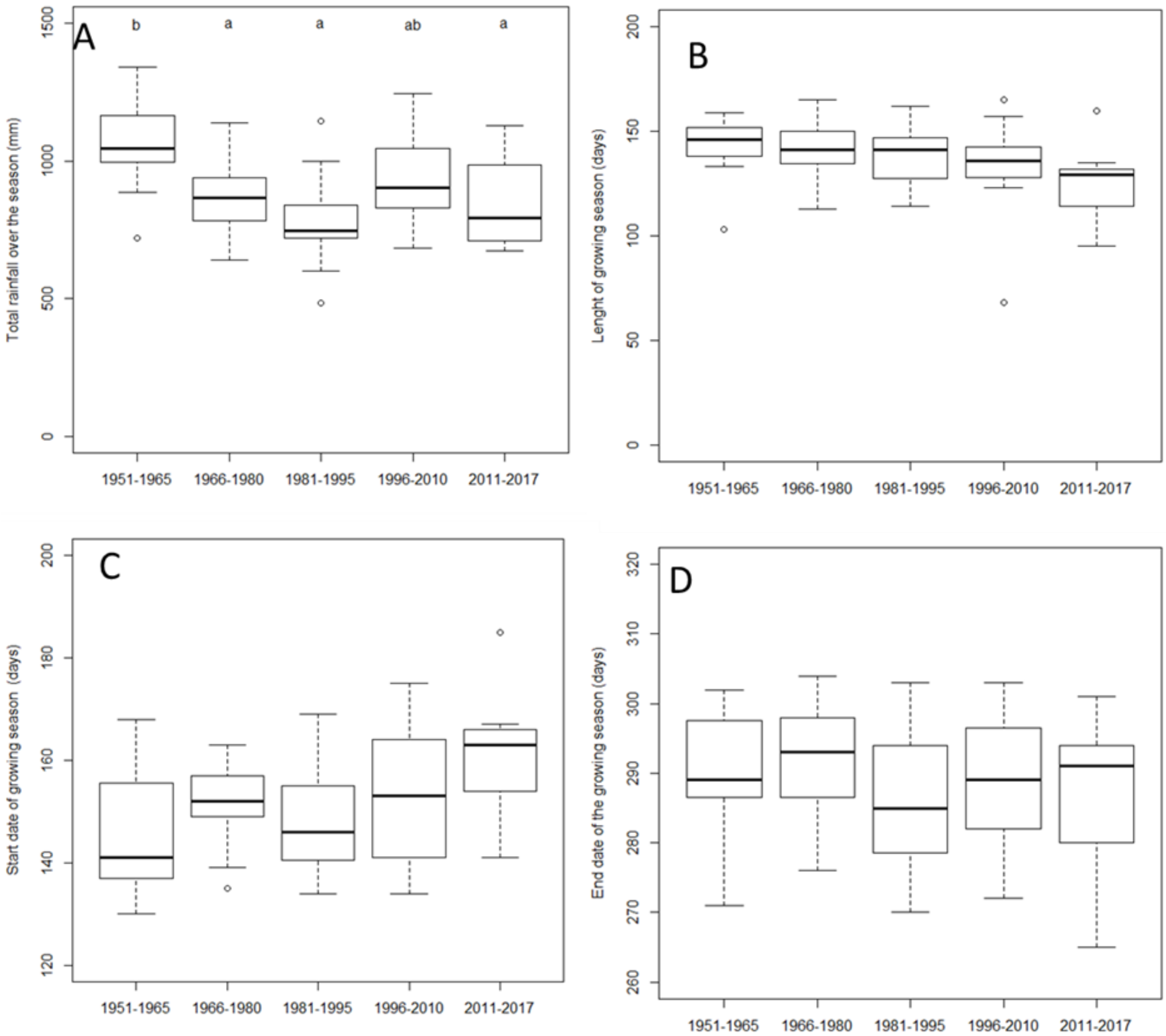


Figure 3: Boxplots of total rainfall over the season (A), length of growing season (B), start date of growing season (C) and end date of growing season (D) for five periods from 1951 to 2017 at N'tarla weather station in southern Mali. Significant (*P*<0.05) differences between periods are indicated with letters on top of boxplots. The line in the box and the width of the box are the median and the interquartile range respectively. The whiskers extend from the edge of the box to the most extreme data point below 1.5 interquartile range.

The frequency of intense rainfall (i.e. daily rainfall above 30 mm) different significantly between periods (*P = 0.002*) (**Fig.4-A**). The frequency of intense rainfall decreased from 1951 to 1995 and increased onwards: it was significantly greater in 1951-1965 than in 1981-1995. The frequency of daily rainfall above 50 mm and 70 mm was small and not significantly affected by the period (**Fig.4-B, 4-C, Table S1**).

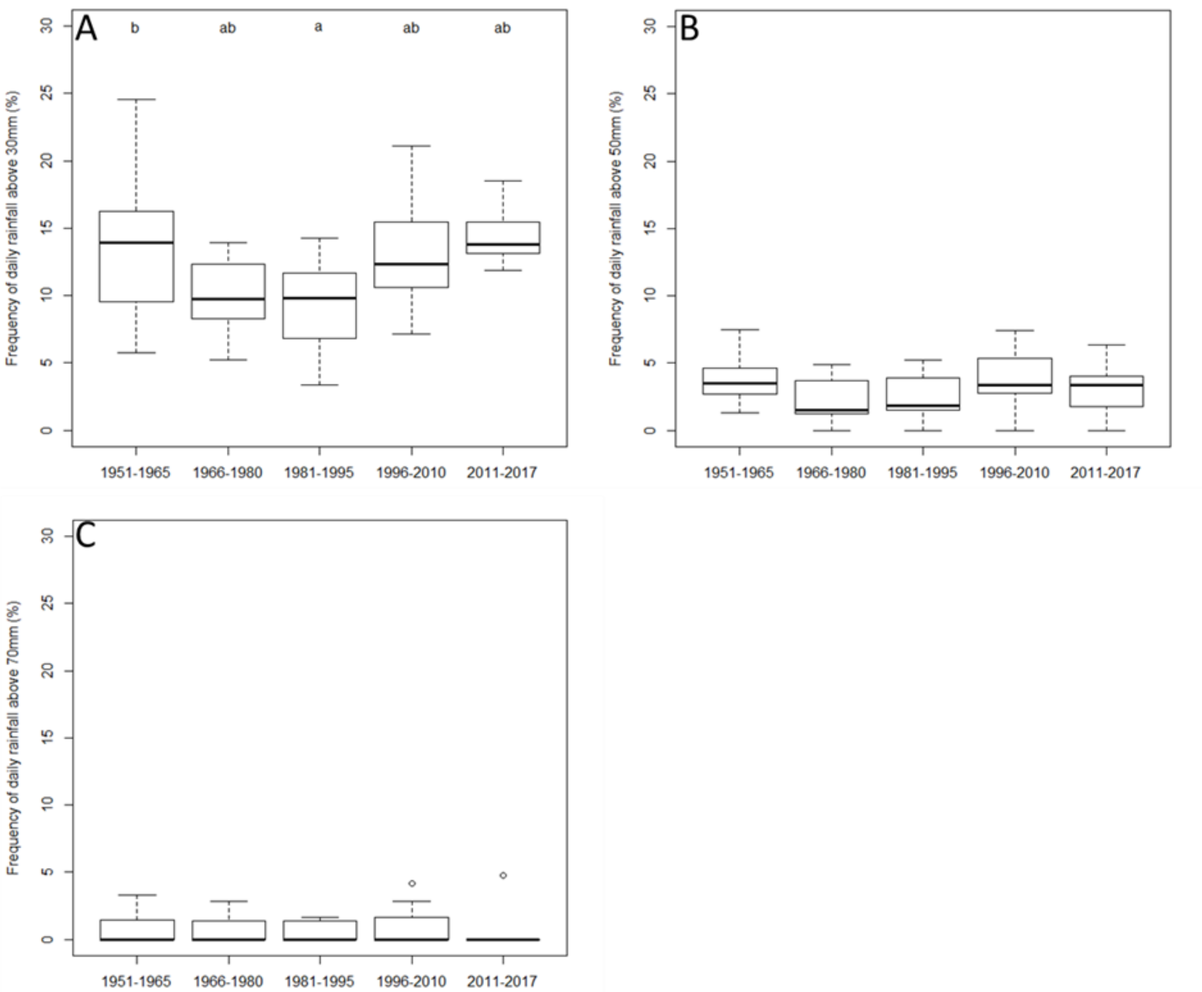


Figure 4: Frequency of intense rainfall events, >30mm (A), >50mm (B) and >70 mm (C), during the growing season for five periods from 1951 to 2017 at N'tarla weather station in Mali. Significant (*P*<0.05) differences between periods are indicated with letters on top of boxplots. The line in the box and the width of the box are the median and the interquartile range respectively. The whiskers extend from the edge of the box to the most extreme data point below 1.5 interquartile range.

The number of 5-days, 7-days, 10-days, 15-days and 20-days dry spells during the start, middle and end of the growing season did not differ significantly between periods (**Fig**. 5, 6 and **Table S1**). The average maximum temperature per year differed significantly between periods, with a clear upward trend between 1981-1995 and 1996-2010 (**Fig. 7-A, Table S2**). Average maximum temperatures during growing season did not differ significantly between periods (**Fig. 7-B, Table S2**). Average temperatures per year and during growing season significantly increased (**Fig.7-C, 7-D and Table S2).** Minimum temperatures increased significantly per year and during the growing season (**Fig 7-E, 7-F**). The greatest annual minimum temperature for 1951-1965 was 20.1°C and that of the period 1996-2010 was 22.8°C, i.e. an increase of 2.7°C. The average minimum temperature during growing season increased by 1°C between 1951 and 2010.

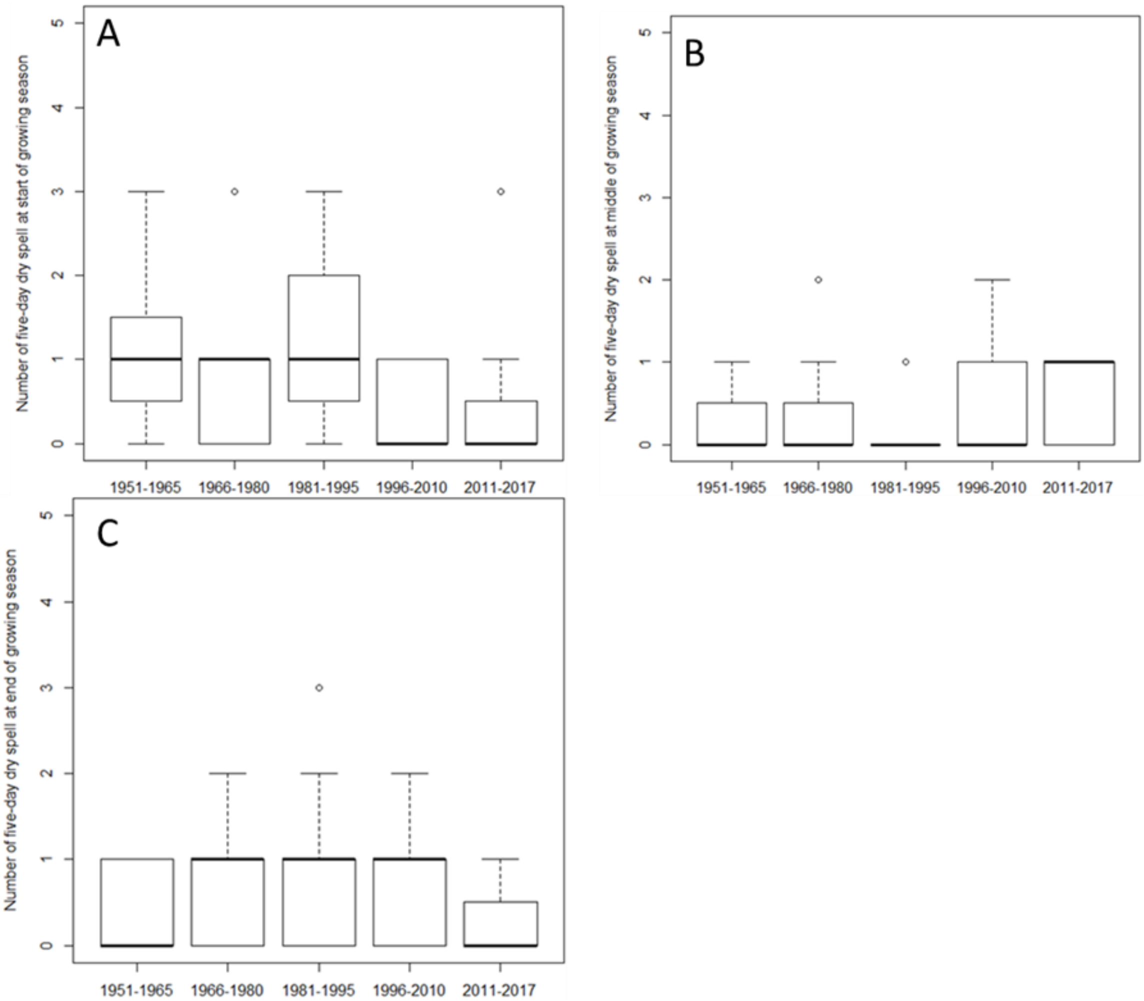


Figure 5: Number of five-day dry spells at the start (A), middle (B) and end (C) of the growing season for five periods from 1951 to 2017 at N'tarla weather station in Mali. The line in the box and the width of the box are the median and the interquartile range respectively. The whiskers extend from the edge of the box to the most extreme data point below 1.5 interquartile range.

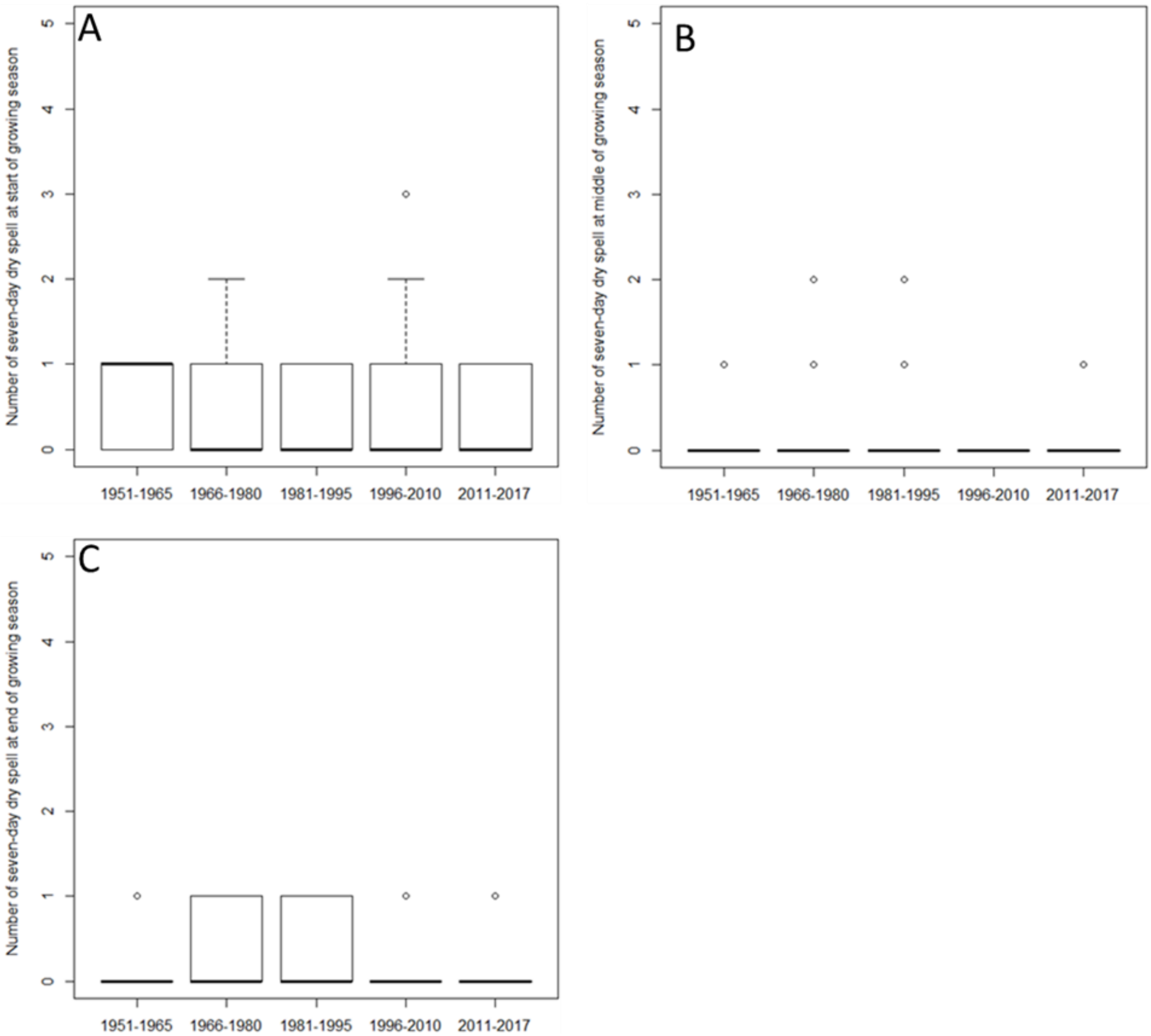


Figure 6: Number of seven-day dry spells at the start (A), middle (B) and end (C) of the growing season for five periods from 1951 to 2017 at N'tarla weather station in Mali. The line in the box and the width of the box are the median and the interquartile range respectively. The whiskers extend from the edge of the box to the most extreme data point below 1.5 interquartile range.

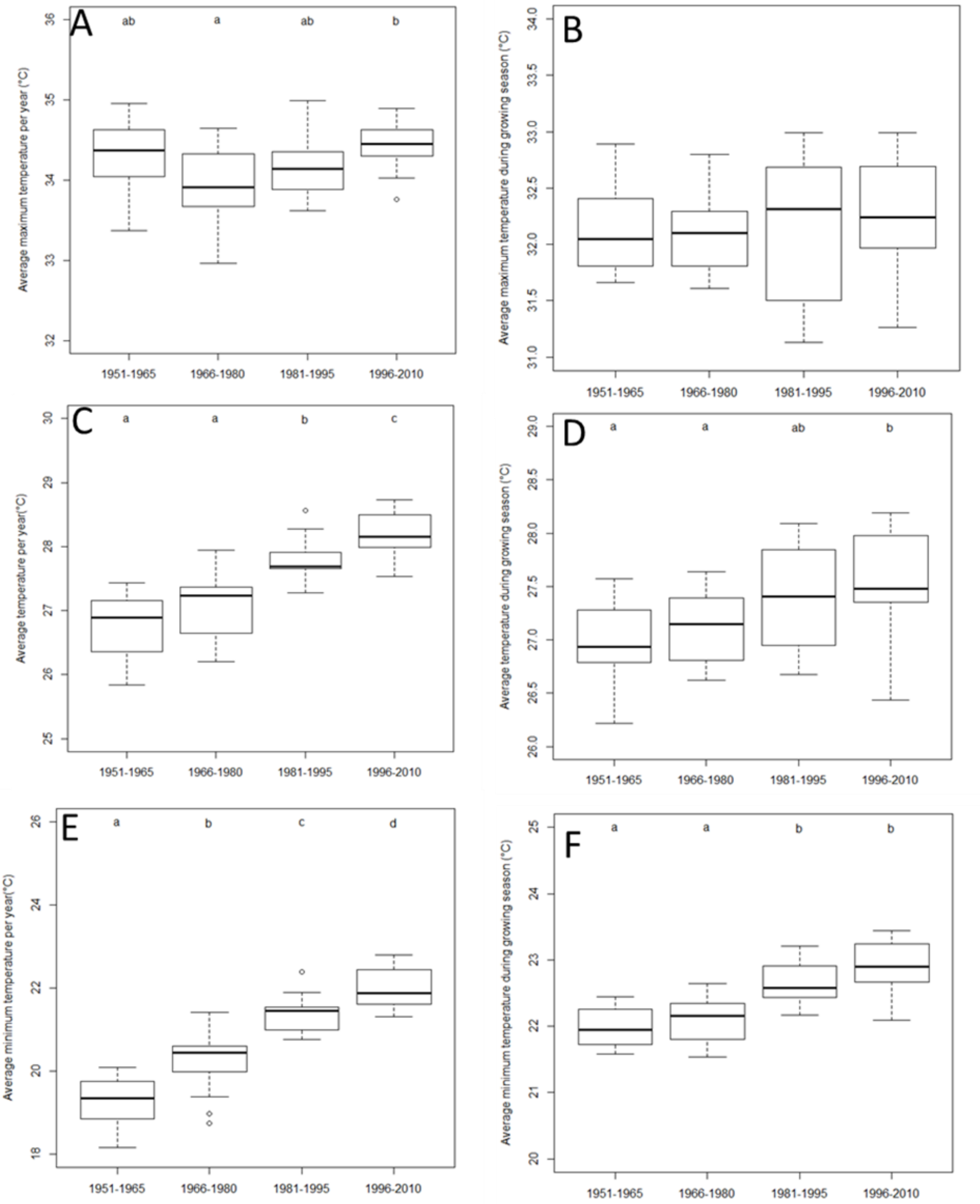


Figure 7: Average maximum temperature per year (A), average maximum temperature during growing season (B), average annual temperature per year, (C), average temperature during growing season, (D) average minimum temperature per year (E), average minimum temperature during growing season (F) four periods from 1951 to 2010 at Koutiala weather station in Mali. Significant (P<0.05) differences between periods are indicated with letters on top of boxplots. The line in the box and the width of the box are the median and the interquartile range respectively. The whiskers extend from the edge of the box to the most extreme data point below 1.5 interquartile range.

2.3.4 Comparison of meteorological data with farmers' perception.

Farmers' perception of changes in climate indicators was sometimes in agreement with the trends highlighted by the analysis of measured historical climate indicators **(Table 4).** Measured changes in total rainfall was in line with farmers' perception. Contrastingly, the analysis of past weather data did not match farmers' views with regard to length of growing season, delayed rainfall season, earlier cessation of rainfall, and more frequent dry spells (**Table 4**): though majority of farmers perceived these changes, they were not supported by the analysis of meteorological data. Also, though the analysis of meteorological data indicated an increase in the frequency of intense rainfall, only minority of farmers perceived such a change. Average temperature per year and the average minimum temperature per year significantly increased in line with farmers perception **(Table 4).**

Table 4: Comparison of farmers' perceptions of climate change and outputs of the analysis of meteorological data. Bold text in the last column indicate agreement between farmers' perception and analysis of meteorological data.

Changes mentioned by farmers during focus groups		**Perception rate of farmers (individual surveys)**	**Analysis of meteorological data**	**Agreement between farmers' perceptions and meteorological data**
Rainfall	Decreasing rainfall	>50%	Significant decrease in total rainfall between periods 1996-2010 and 2011-2017	**Yes**
	Shorter growing season	>50%	No significant change	No
	Delayed rainfall	>50%	No significant change	No
	Early cessation of rainfall	>50%	No significant change	No
	Increasingly intense rainfall	<50%	Significant effect of period on frequency of daily rainfall above 30 mm, with increasing trend from 1981-1995 to 2011-2017	No
	More frequent long dry spells at the start	>50%	No significant change	No.

Changes mentioned by farmers during focus groups		Perception rate of farmers (individual surveys)	Analysis of meteorological data	Agreement between farmers' perceptions and meteorological data
	of the growing season			
	More frequent long dry spells at the end of the growing season	>50%	No significant change	No
	More frequent long dry spells in the middle of the growing season	<50%	No significant change	**Yes**
Temperature	Increasingly hot temperature	>50%	significantly increase in average temperature per year	**Yes**
	Increased temperature during the growing season	>50%	Significant increase in average temperature during growing season	**Yes**
	Night-time temperature increase	>50%	Significant increase in average minimum temperature per year	**Yes**

2.3.5 Adaptation strategies of Béguéné farmers in response to climate change.

Farmers indicated during the focus group discussions and individual surveys that they were using adaptation measures to address the perceived climate changes (**Table 5, Fig. 8**).

The use of drought-tolerant sorghum (*i.e* early-maturing Djakoumbé and Grinka cultivars) was mentioned as a strategy for coping with decreasing rainfall and growing season length. To cope with the perceived increase in dry spell frequency, farmers also mentioned the use rock bunds and contour bunds in fields to maintain water in plots. For farmers, rising temperature favored drought stress, so that adaptation to changes in rainfall patterns also addressed the rising temperature issue. Specific adaptation to decrease in crop duration and heat stress at key plant development stages were not mentioned by farmers. Agroforestry and living and dead hedges were mentioned as means to cope with the increase in intense rainfall and violent winds. Surprisingly, rock or contour bunds were not mentioned as a response to increased erosion risk resulting from more intense rainfall events (**Table 5**).

The analysis of the individual survey showed that maize-cowpea intercropping and drought tolerant cultivar were adaptation options widely implemented by farmers, while dead hedges and living hedges were only seldom implemented.

Table 5: Adaptation strategies mentioned by Béguéne farmers in response to climate change

Climate-related change	**Foreseen impact**	**Adaptation strategy mentioned**
Decreasing rainfall	Water stress resulting in reduced crop growth and yield loss	- Drought-tolerant cultivars (Djakoumbé and Grinka, two sorghum varieties mentioned by farmers); - Rock bunds and contour bunds in fields to increase water conservation in plots - Intercropping maize or sorghum with cowpea.
Shorter growing season		
Delayed rainfall		
Early cessation of rainfall		
Increasingly intense rainfall	Soil erosion, reduced soil fertility, plant destruction	Agroforestry to reduce impact of increasingly intense rainfall on crops
More frequent dry spells at the beginning, middle and end of the growing season	Water stress resulting in the death of young plants and reduced crop growth	- Rock bunds and contour bunds in fields to increase water conservation in plots; - Drought-tolerant cultivars (Djakoumbé and Grinka, two sorghum varieties mentioned by farmers)
Increasingly hot temperature	Drought stress on crops and resulting yield loss	- Drought-tolerant cultivars;
Increased temperature during the growing season		
Night-time temperature increase	Drought stress on crops and resulting yield loss	- Drought-tolerant cultivars;
Increasingly violent winds	Soil erosion, decreasing soil fertility	- Living and dead hedges to reduce the impact of wind on crops - Agroforestry to reduce the impact of wind on crops

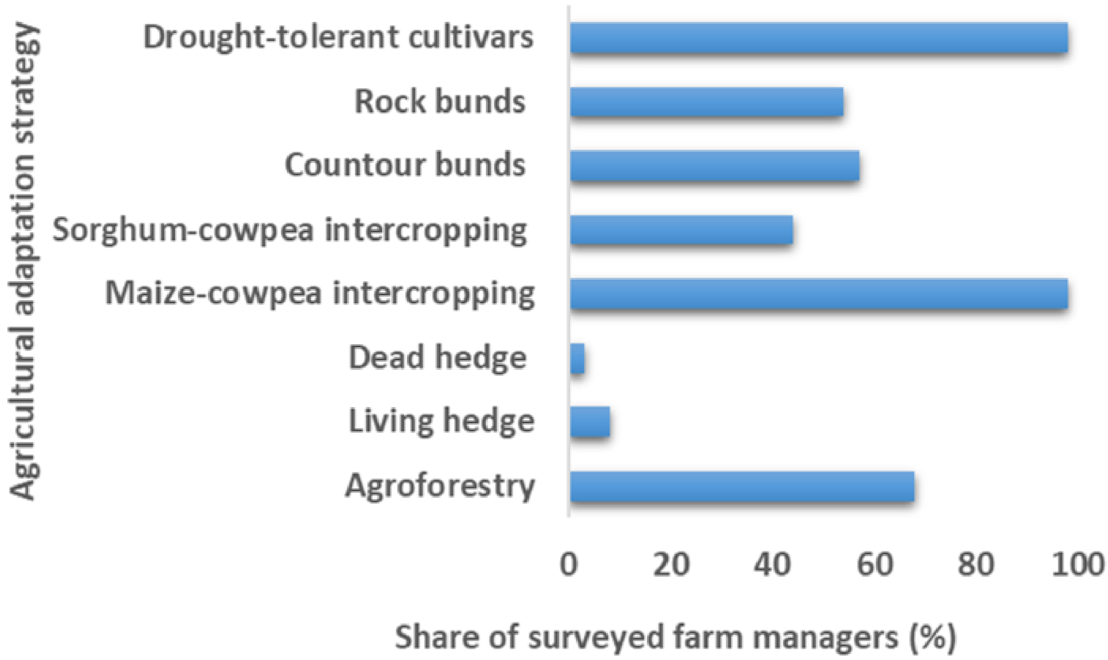


Figure 8: Share of individually surveyed farmers (%) implementing adaptation strategies to climate change.

2.3.6 Link between perception and implementation of adaptation strategies

The analysis of the connection between perception of climate change and implementation of adaptation options revealed contrasting relations, perception either increased or decreased the odds of having implemented an adaptation strategy (Table 6).

The perception of an increase in the frequency of long dry spells at the beginning of the growing season significantly increased the odds of having implemented rock bunds by a factor of 2.6 [1.7-187.7]. Similarly, the perception of an early cessation of rainfall significantly increased the odds of having implemented sorghum-cowpea intercropping by a factor of 3.1 [2 – 1477]. On the other hand, the perception of a decrease in rainfall significantly decreased the odds of having implemented contour bunds (0.0 [0.0 - 0.7]) and sorghum-cowpea intercropping (0.0 [0.0 - 0.2]). Similarly, the perception of an increase in the frequency of dry spells at the end of the growing season had a significant effect to reduce the odds of implementing rock bunds (0.2 [0.0 – 0.9]) and the perception of an increase of the frequency of dry spells at the beginning of the growing season significantly decreased the odds of having implemented agroforestry (0.1 [0.0 – 0.8]). The perception of increasingly violent winds also significantly decreased the odds of having implemented agroforestry (0.1 [0.0 -0.9]).

The farm type co-variate also mattered. Lower farm endowment (i.e. type B, C, and D as compared to type A) significantly decreased the odds of having implemented water conservation techniques (i.e. rock bunds and contour bunds). Conversely, age groups did not significantly alter the odds of implementing any of the adaptation options. For the widely implemented adaptation options “drought-tolerant cultivar” and “maize-cowpea intercropping”, no significant effect of perception, farmer age and farm type could be found. Similarly, for the very seldom implemented adaptation options “living hedge” and “dead hedge”, no significant effect of perception, farmer age and farm type could be found.

Table 6: Logit model estimates of the effect of variables related to perception of climate change, farm type, and farmer age on the implementation of adaptation strategies by farmers in one village of central Mali. Positive log odds indicate greater probability of implementation. Results that are statistically significant within a 95% confidence interval are bolded. Effect of variables for the adaptations options “drought-tolerant cultivar”, “living hedge”, “dead hedge” and “maize-cowpea intercropping was not displayed as none of the variables add a significant effect. CI=Confidence interval; LB= Lower bound, UB= Upper Bound.

Variable		Rock bunds				Contour bunds				Sorghum-cowpea intercropping				Agroforestry			
		Log Odds	Odds	95% CI - LB	95% CI - UB	Log Odds	Odds	95% CI - LB	95% CI - UB	Log Odds	Odds	95% CI - LB	95% CI - UB	Log Odds	Odds	95% CI - LB	95% CI - UB
Perception of climate change	Decreasing rainfall	-1.1	0.3	0	3.7	***-3***	***0***	***0***	***0.7***	**-4.6**	0	0	0.2	1.7	5.5	0.6	66
	Shorter growing season	0.6	1.8	0	91.2	-2.6	0.1	0	3.2	-1.1	0.3	0	20.9	0.9	2.6	0.1	64.8
	Delayed rainfall	0.3	1.3	0.1	14	0.6	1.8	0.2	23.9	0.8	2.2	0.2	30.2	0.7	2	0.2	18.7
	Early cessation of rainfall	-0.4	0.7	0.1	7.4	0.9	2.4	0.3	29.9	***3.1***	***22.3***	***1.7***	***1477.9***	-1.3	0.3	0	2
	More frequent long dry spells at the beginning of growing season	***2.6***	***14.1***	***1.7***	***187.7***	-0.2	0.8	0.1	6.6	-0.4	0.6	0.1	3.4	***-2.1***	***0.1***	***0***	***0.8***
	More frequent long dry spells at the end of growing season	***-1.7***	***0.2***	***0***	***0.9***	0.3	1.3	0.3	8	0.8	2.3	0.5	13.3	0.1	1.1	0.2	6.3
	More frequent long dry spells in the middle of growing season	1.5	4.4	0.7	38.1	0.4	1.5	0.3	9.2	0.1	1.1	0.2	5.5	0.3	1.3	0.3	6.5
	Increasingly intense rainfall	-1.7	0.2	0	1.4	-1.9	0.1	0	1.2	-1.4	0.2	0	1.6	0.9	2.4	0.4	15.8
	Increasingly hot temperature	-15.6	0	-	>10^6	15	<10^6	0	-	-2.8	0.1	0	8	2.1	8.6	0.1	1451.8
	Increased temperature during the growing season	1	2.7	0	90.9	2.1	8.1	0.3	375.1	2.2	9.1	0.2	3432.2	-1.5	0.2	0	4.6
	Increasingly violent winds	-1.7	0.2	0	3.5	0.3	1.4	0.1	15.7	1	2.8	0.4	26.3	***-2.6***	***0.1***	***0***	***0.9***
Farm type	type CMDT B	-1.7	0.2	0	1.5	***-2.3***	***0.1***	***0***	***0.7***	-0.9	0.4	0.1	2.4	0	1	0.1	7.9
	type CMDT C	***-4.2***	***0***	***0***	***0.3***	***-4.7***	***0***	***0***	***0.2***	2.9	17.6	0.8	7522.8	0.5	1.6	0.2	18.1
	type CMDT D	-2.5	0.1	0	1.1	-2.4	0.1	0	1	-0.8	0.5	0	4.1	-0.3	0.7	0.1	8.4
Farmer age	39–49-year-old	2.2	8.9	0.4	629.7	0.9	2.6	0.2	81.3	-0.7	0.5	0	15.1	-2.1	0.1	0	2.1
	49–69-year-old	2.6	13.1	0.9	664.4	1.1	3.1	0.3	79.8	0.6	1.9	0.2	48.6	-0.3	0.7	0	11.5
	Above 70-year-old	-0.3	0.8	0	47.8	0.7	2.1	0.1	107.7	1	2.8	0.1	114.5	1.3	3.6	0.1	215.4

2.4 DISCUSSION

Our comprehensive assessment of the two-step process of adaptation provides crucial insights for farmers and researchers to develop a common understanding of the impact of climate change on crops and to design site-specific strategies to offset the expected negative impacts of climate change. In what follows, we successively discuss i) farmers perception of climate change and their drivers, ii) the comparison between farmers' perception and meteorological data, iii) the relevance of farmer-identified adaptation strategies and iv) the connection between farmers' perception and implementation of adaptation strategies.

2.4.1 Farmers' perception of climate change and their drivers

Farmers perception of a delay, decrease and early cessation of rainfall revealed in our study was also found in another study in Sudanian West Africa (Zampaligré et al., 2014). Studies on individuals perception of climate change in high-income countries found an influence of age on perception (Li et al., 2011; Weber and Stern, 2011). This also held true for populations similar to the one of our study site, i.e. smallholders farmers in sub-humid and semi-arid Ethiopia (Deressa et al., 2011; Habtemariam et al., 2016), possibly because elderly farmers have experienced the relations between agriculture and their environment for a longer time and detect climate change more easily than young farmers. However, we did not find a significant link between farmers' age and farmers' perception (see section 3.2). In our study, a majority of farmers, whatever their age, perceived the changes in the other indicators mentioned during the focus group discussions, for example the increase in the frequency of violent winds. This is in line with the study of Rodríguez-Cruz et al. (2021) in Puerto Rico who found no relationship between age and farmers' perception of climate change, possibly because in places with constant climate shocks age matters less than direct experience of extreme event. However, this also contrasts with the finding that extreme climatic events usually have a stronger impact on the minds of younger people than of older people (Marx et al., 2007; Weber and Stern, 2011). Possibly, our sample of study farmers was not large enough to detect such an effect of farmer age, and future research should aim at unravelling the context-dependent contribution of age and direct experience of extreme event in explaining farmers' perception.

Farm managers being exclusively male in the region, we did not account for possible differences between men and women in the way climate change is perceived and adaptation are conceived or practiced. We assumed that adaptation of farming to climate change will impact the whole production system, with a predominant role of the farm manager in designing and implementing these adaptations. However, we acknowledge that female farm workers have a significant and sometimes specific role in decisions relative to crop and farm management in

West Africa (Lado, 1992; Ogunlela and Mukhtar, 2009), and that gender can influence the perception of climate change (Habtemariam et al., 2016). Some specific fields, crops or management practices are under women sole responsibility; women may have their own, specific perception of climate change as well as their own views on relevant adaptation. These would have to be accounted for in studies focusing on the way innovative practices emerge from the experience of farmers.

Education is also a crucial covariate than can help explain farmers' perception, better educated farmers often perceiving more acutely climate change (e.g. Roco et al., 2015). We did not investigate this factor, and this would deserve more specific attention in future studies aiming at identifying the drivers of farmers' perception to assist the design of projects and programs to enhance the understanding of climate change by farmers.

2.4.2 Comparison of farmers' perception of climate change with meteorological data

Human perception of climate is influenced by farmers expectations, and its correlation with the nature of climate as provided by data recorded with scientific instruments may be limited or non-existent (Rebetez, 1996). The most salient changes perceived by farmers in this study were related to temperature and rainfall. This is not surprising because these two variables have a direct influence on agricultural production.

Farmers' perception of an increase in temperature during growing season and at night was consistent with the significant increase in average and minimum annual and seasonal temperatures provided by the analysis of measured climate data. Kosmowski et al., (2015) also found consistency between temperature records and farmers' perception in Benin and Senegal. Farmers' perception of change in rainfall was in line with climate data analysis (see section 3.4) that showed a decrease in total rainfall.

However, some discrepancies were depicted. The increase of the intensity of intense rainfall events was only perceived by a minority of farmers, though such a change was supported by our analysis of meteorological data, and also by studies covering the broader west African region (Taylor et al., 2017). Farmers perceived an early cessation of rainfall and an increase in the frequency of dry spells during the growing season which could not be detected with the analysis of climate data (see section 3.4). Meze-Hausken (2004) and Zampaligré et al. (2014) also found that farmers often perceived long-term rainfall trends in a more negative way than indicated by weather records. An explanation of such discrepancies could possibly lie in farmers' dependence on seasonal rainfall to meet household food demand. Years when production decreases and impact household food availability will likely be considered as bad by farmers. The cause of poor performance is not necessarily related to rainfall and may include other factors, including household economic situation (Osbahr et al., 2011).

The neat perception of farmers of an increase in the frequency of violent winds, which can damage crops, is also reported by several authors in West Africa (Ouédraogo et al., 2010; Vissoh et al., 2012). Precise wind data, that were not available in our case, would be required for assessing the consistency between farmers' perception and meteorological facts with regard to this variable. A fine time resolution of wind speed recording would probably be necessary, in order to capture very short and very intense wind blasts that may severely damage crops. Unfortunately, the network of weather stations in sub-Saharan Africa is notably precarious, and when measured, wind speed is at best a daily average, in which such blasts may be completely undiscernible.

2.4.3 Relevance of the agricultural adaptation strategies mentioned by farmers

Adaptation refers to the strategies adopted by farmers to cope with climate variability and change and its adverse effects on their agricultural activities. The diversity of adaptation measures mentioned and implemented by farmers (**Table 5** and **Fig. 8**) indicated their awareness of and willingness to mitigate the impacts of climate change.

In the study area, rainfed crops are highly dependent on rainfall duration, distribution, abundance or deficit. Insufficient water supply to crops during seed filling can decrease yield by 40% (Barron et al., 2003). Farmers mentioned implementation of water conservation techniques (contour bunds and rock bunds) to cope with the decrease in rainfall and the increase in the frequency of dry spells. Water conservation techniques can improve water availability for crops thus reducing the impact of water stress (Birhanu et al., 2019; Dumanski et al., 2006; Gigou et al., 2006). Intercropping of cereals and legumes, another adaptation strategy mentioned and implemented by farmers, improves productivity per unit area through more efficient water use, which could mitigate the impact of an increase in water stress (Baldé et al., 2011; Rezig et al., 2010; Tsubo et al., 2003; Yang et al., 201). Drought-tolerant (i.e. short duration) varieties were also mentioned by farmers as an option for adapting to changes in rainfall patterns in contrast to their local long duration varieties. The modern cultivars Grinkan and Jakumbe mentioned by farmers have shorter duration, are less sensitive to photoperiods and have a greater harvest index than the traditional cultivar. They were found to be more adapted to future climate than the traditional cultivar , in addition to providing higher yields with current climate (Sultan et al., 2014). Rise in temperatures leads to greater evapotranspiration and can favor the occurrence of water stress on crops. Therefore, for farmers, adaptation to changes in rainfall patterns also addressed the rising temperature issue.

Agroforestry was mentioned by farmers as a strategy for adapting to climate variability and change. For farmers, agroforestry techniques (*i.e.* the maintenance of existing parklands, the plantation of hedges) improves soil fertility and reduce wind and water erosion of agricultural land. In line with farmers expectations, Reij et al., (2009) found that the agroforestry techniques had enabled farmers in southern Niger to regenerate and reduce soil erosion due to wind.

2.4.4 Link between farmers' perception of climate change and implementation of adaptation options

The analysis of the connection between perception of climate change and implementation of adaptation options did not fully support our initial hypothesis that perception drives the implementation of adaptation options. On the one hand, the connection held true for sorghum-cowpea and rock-bunds which were implemented more often by farmer who perceived more frequent dry spells at the beginning of rainy season, or early cessation of rainfall. Such finding is in line with other studies showing that farmers perceiving a change were more likely to implement water conservation practices (Deressa et al., 2009). Interestingly, the two perceived changes that triggered the implementation of water-conservation technique were not supported by the analysis of meteorological data. We could conclude here that mis-interpretation has been driving the implementation of adaptation option, with a risk of maladaptation that could increase the negative impacts of climate change (Grothmann and Patt, 2005). However, these water conservation techniques help address the issue of a decreasing rainfall (that was in agreement with meteorological data), and therefore the risks of 'wrong' adaptation are limited. There was also substantial evidence for the opposite connection, i.e. farmer who did perceive a change were less likely to have implemented an adaptation option. This could be understood in the light of a relation between the impact of the option on cropping systems sensitivity to climate change, *e.g.* farmers who did not implement agroforestery (i.e. who did not keep a dense and diverse tree network in their fields) were more likely to actually experience an increase in violent winds. Similarly, farmers who did not implement water conservation techniques (i.e. rock and contour bund) were more likely to perceive a decrease in total rainfall and an increase in the frequency of dry spells at the end of growing season, probably because their soil could store less water. This connection between perception and infrastructure that modify water availability in farmers' fields was also evidenced for farmers in New Zealand (Niles et al., 2016). This interaction between farm management, cropping system sensitivity, and farmers' perception (Simelton et al., 2013) could also possibly explain why some changes perceived by farmers (e.g. more frequent dry spells) could not be supported by the analysis of climate data.

Farm type was an important variable driving the adoption of water conservation techniques. Less wealthy farms of type B, C and D were less likely to have implemented water conservation techniques, thus confirming that, though perception matters, other constraints related to farm resource endowment need to be alleviated for adoption to happen (Harvey et al., 2018). Rodríguez-Cruz et al. (2021) also found that implementation of adaptation practices is explained more by structural factors (e.g. social networks, governance systems and infrastructure) than by individual farmers' perception. Possibly, constant exposure to climate-related hazards acts to lower the importance of individual perception in the adaptation process (Rodríguez-Cruz and Niles .,2021). Overall, these findings highlight the need for future research on how context influences the link between perception and implementation of adaptation (e.g. climate-change hotspots were climate-related hazards are frequent compared with less-exposed regions). Broader institutional barriers (e.g. lack of resources to implement a given adaptation option) should also be investigated.

Some of the perceived changes, and notably the "increasingly intense rainfall", were not connected to the implementation of any adaptation option. This is worrying, given the fact that the issue is real (Taylor et al., 2017). Though not mentioned directly by farmers, cereal-legume intercropping and the associated improved soil cover and denser root system could help reduce drainage and loss of nutrients when intense rainfall events occur (Walker and Ogindo, 2003; Zougmore et al., 2000). Also, farmers did not mention rock and stone bunds to prevent soil erosion associated with the increase in intense rainfall events. Rock and bunds can prevent soil loss on farmers' plots and thus preserving essential nutrients (Birhanu et al., 2019; Dumanski et al., 2006; Gigou et al., 2006). Similarly, the perceived changes in temperature, also supported by the analysis of meteorological data, was also not connected to the implementation of any adaptation options. Rising temperatures impact crop growth and yield through several processes. Above-threshold temperatures reduce radiation-use efficiency (Idso, 1991; Stockle et al., 1992). Rising temperature accelerates crop development and shortens crop cycle, which reduces the amount of solar radiation intercepted, crop biomass and grain yield (Sultan et al., 2014, 2013). Thermal stress during crop's reproductive stage can cause a drop in grain number, with negative impact on grain yield (Gérardeaux et al., 2015). For example, with night temperature increase from 22 to 28°C, Prasad and Djanaguiraman (2011) showed an increase in the sterility of sorghum spikelet. Hatfield et al. (2011) and Hatfield and Prueger (2015) showed that increases in minimum air temperature can have negative effect on maize and sorghum growth and phenology. Excessive temperature increase would significantly reduce average yields and variations in precipitation would only modulate the magnitude of this negative impact (Sultan et al., 2013). Surprisingly for the research team, specific adaptation to the decrease in crop duration and heat stress at key plant development stages were not mentioned by farmers. According to Guan et al. (2017), switching from traditional cultivar to a modern cultivar with increased tolerance to high temperatures could offset the decrease in yield associated with an increase in temperature during grain set.

These two examples of a change in climate indicator that was both supported by the analysis of meteorological data and perceived by farmers, but for which no adaptation was implemented by farmers, highlights the need for development efforts that strengthen the dialogue between farmers and researchers to develop a common understanding of the impact of climate change on crops and to design site-specific strategies to offset the expected negative impacts of climate change. Current top-down extension approaches, based on the technology transfer model, may not support the development of this shared vision. Methods related to social learning (Coudel et al., 2011), including collective diagnosis and serious games (Flood et al., 2018), will be essential to build trust and knowledge sharing between researchers and farmers. The identification and involvement of wider stakeholders (e.g. district governors and national policy makers) is necessary for such co-design to be supported by effective policy change (Totin et al., 2018). Therefore, the implementation of medium- and long-term adaptation measures must be supported by national and regional policies that provide effective technical and financial assistance to vulnerable groups.

2.5 CONCLUSION

We analyzed farmers' perception of climate change in a village of central Mali and compared their perception with an analysis of historical meteorological data. Farmers' perception of climate change was consistent with climatic data with regard to increasing temperatures and decreasing rainfall amount. Farmers' perception disagreed with climatic data with regard to the increased frequency of dry spells and the early end of growing season. Farmers mentioned a range of adaptation strategies to cope with the adverse effects of climate change on crops. Households that perceived some changes in rainfall regimes were associated with an increased likelihood of adopting adaptation practices such as stone bunds and contour bunds, compared to households that did not perceive such changes. But the inverse also held true, i.e. household that did not implement an adaptation option (e.g. water saving technologies, agroforestry) were sometimes more likely to perceive a change, possibly because their cropping systems were more sensitive to weather variations. Better-off households were also more likely to implement some adaptation measures (stone bunds, contour bunds), stressing the need to alleviate resource constraints if adaptation is to occur. Our analysis provides a rich basis for development efforts that should strengthen the dialogue between farmers and researchers in order to develop a common understanding of the impact of climate change on crops and to design site-specific strategies to compensate for the expected negative impacts of climate change.

CHAPITRE III

Chapitre III : Can STICS crop-soil model simulate the performance of rainfed sorghum-cowpea intercropping in a tropical environment of sub-Saharan Africa ?

Soumis au journal "Field Crops Research"

ABSTRACT:

Intercropping is a key entry point for sustainable intensification of cropping systems in sub-Saharan Africa where variable rainfall conditions prevail. Crop simulation models can complement field experiments to assess the agronomic and environmental performances of intercropping systems under diverse climatic conditions, including hypothetical future climate. So far, crop models that can handle intercropping, such as STICS, have not often been extensively evaluated for tropical conditions and for species grown by farmers in sub-Saharan Africa. The objective of this study was to evaluate the performance of the calibrated STICS model to simulate the growth and productivity of sorghum-cowpea cropping systems in rainfed conditions in West Africa. We used data from field experiments conducted at the N'Tarla Agronomic Station in Mali in 2017 and 2018. Two varieties of sorghum (local and improved) with contrasting photoperiod sensitivity were grown as sole crop and intercropped with cowpea (with an additive design). Two sowing dates and two levels of mineral fertilization were also investigated. Model simulations were evaluated with observed data for phenology, leaf area index (LAI), aboveground biomass, grain yield and in-season soil moisture. Large variations in aboveground biomass of sorghum and cowpea was observed in the experiment (i.e. 3.5 – 9.6 t/ha for sorghum and 0.4 - 2.5 t/ha for cowpea), owing to the experimental treatments (i.e. sole vs intercrop, early vs late sowing, no fertiliser input vs fertiliser input). Such variations were satisfactorily reproduced by the model, with EF of 0.81 in calibration and 0.58 in evaluation (with relative RMSE of 23 and 43%). The two main observed features of the intercropping was well reproduced by the model: (i) cowpea and sorghum aboveground biomass decreased with intercropping compared to sole cropping, and the decrease in cowpea biomass was greater than the decrease in sorghum biomass, and (ii) despite reduction in sorghum and cowpea yield, Land Equivalent Ratio of the intercropping for aboveground biomass was always above one. With regard to grain yield, LER was above one only in the non-fertilised treatment. The model failed at reproducing this behaviour, probably because of insufficiently accurate calibration of the process leading to grain yield formation: rRMSE for grain yield was 49% in calibration and 41% in evaluation. Based on these findings, we discuss avenues to improve model calibration

and use the model to explore options for sustainable intensification in land constrained sub-Saharan Africa.

***Keywords**:* Competition, sowing date, varieties, fertilization, contrasting seasons, aboveground biomass, Mali.

3.1 INTRODUCTION

Rainfed agriculture is the most important sector for food security in sub-Saharan Africa (Gowing and Palmer, 2008). However, the region is characterized by low yields due to limited nutrients inputs and weed pressure (Affholder et al., 2013). Rural farmers do not have access to inputs, and low levels of investment in infrastructure generates high transaction costs that lowers the profitability of agricultural activities. These constraints are exacerbated by climate change: the frequency and severity of extreme weather events such as drought and floods is predicted to increase (Connolly-Boutin and Smit, 2015; Diedhiou et al., 2018; Sultan and Gaetani, 2016a)

West Africa must produce more to feed a rapidly growing population. Sorghum is one of the main food crops in West Africa. Sorghum yield is expected to decrease by 13% due to climate change (Sultan et al., 2014). Improving soil fertility and agricultural productivity while adapting to climate change have therefore become the priority objectives of agricultural policies in West African countries (CORAF/WECARD, 2008). In land constrained areas with limited availability of arable land and pastures, intensification of agro-systems will be key. But the experience gained in developed countries indicates that excessive artificialization of the environment, as in “conventional” intensification of agriculture, causes environmental damages. A new form of agriculture to increase agricultural productivity while preserving the ecosystem services that ensure long-term environmental sustainability is needed. At cropping system level, the concept of ecological intensification was coined by to define the set of principles and means necessary to increase primary productivity in the world's major cereal agro-ecosystems (Cassman, 1999). Productivity increase can be achieved by capitalizing on the ecological processes in agro-ecosystems (e.g. biological N_2 fixation), aiming at reducing the use of and need for external inputs (Tittonell and Giller , 2013). Innovative cropping systems for ecological intensification need to be assessed with meaningful agronomic, environmental and economic indicators (Affholder et al., 2014). . Key ecological services such as carbon storage and biological diversity also need to be addressed (Bonny , 2011).

Legumes offer good prospects to increase yield in line with the principles of ecological intensification: legumes can improve soil fertility (Gbakatchetche et al.,2010), and provide crucial nutrients carry-overs for the subsequent cereal crop (Carsky et al., 2003). Intercropping is the cultivation of two or more species or varieties at the same spatial and temporal resolution (Andrews and Kassam, 1976). . In cereal-legume intercropping, inter-species complementarity and facilitation processes can lead to a production benefit of intercropping compared with sole cropping (Li et al., 2003, 1999; Vandermeer, 1989). Water use efficiency is greater in intercropping than in sole cropping (Tsubo et al., 2004, Balde et al., 2011). However, the expected benefits of intercropping cereals with legumes are not always obtained in the context of sub-Saharan Africa due to various constraints in crop establishment related to cultivar, sowing dates and fertilization levels. Intercropping benefits may be jeopardized by competitions for light, nutrients or water between the intercropped species (e.g. Baldé et al., (2011). Shifts from competition to facilitation will depend on climate, soils and crop management (Cooper et al., 2008). Appropriate and site-specific recommendations for intercropping management requires replicated experiments across contrasting sites. In order to account for climate inter-annual variations, the experiments would need to run over several years, which is challenging in terms of time, cost and technical expertise (Knörzer et al., 2011). To address such limitations, crop simulation models have been used to assess the agronomic and environmental performances of cropping systems under diverse climatic conditions, including hypothetical future climate (Boote et al., 1996). Crop models able to deal with intercropping systems are scant. So far, few studies have been conducted on cereal-legume intercropping. Chimonyo et al., (2016) evaluated the ability of the calibrated APSIM model (The Agricultural Production Systems sIMulator) to reproduce sorghum-cowpea intercropping productivity and water use efficiency in potential (i.e. fully irrigated) and water-stressed (i.e. rainfed) conditions, in South Africa. Despite overall promising simulation accuracy for partitioning of solar radiation between the dominant (sorghum) and understory crop (cowpea), the authors showed that water use efficiency of the intercrop was overestimated by the model in rainfed conditions, probably because of an inadequate simulation of water stress. The latter could be improved with soil calibration based on in-season water measurements. The experiment was set with adequate N fertilizer inputs, so that intercrop response to varying N input was not investigated. Masvaya (2019) also investigated the accuracy of APSIM model in simulating sorghum-cowpea intercropping performance in semi-arid zone in Zimbabwe. The model accurately reproduced grain yield of the two crops for contrasting seasons, soils and nitrogen inputs. However, the model could not be evaluated for intermediary variables (e.g. LAI, soil water), leaving the risk of compensation errors. The STICS model (multidisciplinary simulator for standard crops) was calibrated for wheat-pea intercrop (Corre-Hellou et al., 2009).

The model successfully simulated the interactions between the intercropped species for nitrogen uptake but failed to accurately reproduce competition for light. So far, the STICS model has not been tested for intercrops of very contrasting height, as it is the case of sorghum and cowpea for example.

This study focuses on sorghum-cowpea intercropping. The objective was to calibrate and evaluate the ability of the STICS soil-crop model to (i) simulate the growth and productivity of a sorghum-cowpea intercropping and (ii) account for possible species competition and/or facilitation for the use of light, water and nitrogen and (iii) test its ability to reproduce the impact of contrasting sorghum varieties, sowing date and fertilization on aboveground biomass and grain yield. Data from two years (2017, 2018) from an experiment conducted at the N'Tarla Agronomic Research Station in Mali were used.

3.2 MATERIAL AND METHOD

3.2.1 Study Area

This research was conducted at N'Tarla research station (12.6193°N, -5.689°W) in southern Mali. The climate is typical of the Sudano-Sahelian zone. The rainy season starts in May and ends in October. Average annual rainfall varies between 800 and 1000 mm. Seasonal average temperature is 29 ◦C (Traore et al., 2013).. Farming systems are mixed agro-sylvo-pastoral systems in which cotton (Gossypium hirsutum L.) is the main cash crop. Cotton is grown in rotation with sorghum (*Sorghum bicolor (L) Moench*), millet (Pennisetum glaucum (L.) R.Br.), maize (*Zea mays L*.) and legumes such as groundnut (*Arachis hypogaea L*.) and cowpea (*Vigna unguiculata (L) Walp*.). Mineral fertilizer are applied on cotton and maize, with nutrient carry-over benefitting the following cereals (sorghum, millet) (see e.g. Ripoche et al., (2015). Cattle, goats, and sheep are raised by farmers. Large cattle herds move during the dry season to other parts of country (*Bougouni, Kadiolo*) due to local lack of feed. The soils at the research station are classified as Lixisols (FAO, 2006). They have a silty sand texture (~10% clay) at the surface (0-35 cm), and clay content increases with soil depth (29.4% between 55 and 85 cm) (Table S1). Soil organic carbon is low (<0.1%) (Table 1), pH is about 6 and CEC is less than 3 cmol (+) kg-1 (Traore et al., 2013).

3.2.2 Experimental design

The experiment was conducted for two consecutive seasons (2017 and 2018) on the same field. Treatments were kept on the same subplots and not re-allocated from a year to another. Two sorghum varieties, namely Tiemarifing (local variety, V1) and 02-SB-F4DT "Grinka" (improved variety for grain production, V2) were cultivated as sole crops, or intercropped with dual-purpose (i.e. grain and fodder production) cowpea IT89KD-245 "Sangaraka". V1 is a photoperiod-sensitive variety (Chantereau, et al., 2013). V2 is less sensitive to photoperiod than V1 (Chantereau, et al., 2013). Sorghum variety and cropping system (sole vs intercrop) were the main treatments. The effect of two sowing dates for sorghum (D1-early sowing, D2-late sowing) was also investigated as a secondary treatment. Sorghum early sowing was done after 15 June (to limit the probability of dry spell occurring after sowing) and after a rainfall greater than 20 mm. Early sowing (D1) occurred on 24 June in 2017 and 26 June in 2018. Late sowing (D2) of sorghum occurred on 20 July in both years. Cowpea was sown two weeks after early- and late-sown sorghum. In 2017, N fertilizer application was 8 kg N/ha. Additionally, in 2018, two levels of fertilization (F0=0 kgN/ha and F1=38kgN/ha split in two applications) were investigated.

Sole and intercropped sorghum was planted at 0.80 m between sowing rows and 0.40 m along the sowing row. Two sorghum plants per hill were kept, leading to a sorghum density of 6.25 plants m^{-2} in all treatments. An additive intercropping pattern was chosen where cowpea was sown in continuous line between two sorghum plants (on the sorghum row) leading to a cowpea density of 6.25 plants m^2. Weeds were controlled using hand hoe three times for D1 and twice for D2, to keep plots free from weed pressure. Intercropped cowpea did not receive any specific fertilization other than that applied on sorghum. Sole cowpea was cultivated without nitrogen application (F0) in 2018. In 2017 there was no sole cowpea plot. Sorghum stem borer (armyworm) and cowpea pests (e.g. *aphids*, *Aphis craccivora*) were controlled with chemicals to prevent damage to crops. The combinations of year, sorghum variety, cropping system, fertilization and sowing date defined 25 cropping situations grown on as many experimental plots where plant growth and soil characteristics were monitored and used for model calibration and evaluation (Table 1). The design included replications, but we focused on the experimental plots that were better instrumented in 2018 (i.e. with soil water, LAI, plant N measurements) for calibration.

3.2.3 Measurements in experimental plots

3.2.3.1 Soil measurements

In 2017, a composite sample representing the whole experimental field was taken at a depth of 0-20 cm before the crops were planted and used to determine soil pH and soil C:N ratio. In 2018, a composite soil sample was taken in each experimental plot with semi-cylindrical augers at a depth of 0-20 cm before crop installation. Theses samples were sun-dried and sent to the laboratory for determination of total soil nitrogen using the Kjeldahl method (Bremner and Mulvaney, 1982) (Table 1).

In 2018, soil volumetric water content was measured with a Diviner 2000 probe placed in fixed vertical access PVC tubes inserted in the soil in each experimental plot. The tubes were installed two weeks before sorghum sowing. The soil-tube interface was carefully filled with fine earth to eliminate gaps at the soil-tube interface, as probe measurements are very sensitive to the quality of the contact between the access tube and the soil (Basinger et al., 2003). The soil was dry at the time of installation, so that the planned maximum depth of 155cm was not reached in some of the experimental plots (the maximum measurement depth in each plot is given in Table 1). Soil water content was measured at 10 cm intervals down to the maximum depth of the tube. Measurements were taken 2-3 times per week from the installation of the tubes to sorghum harvest. Plant-available water across soil profile (i.e. every 10 cm to the maximum depth of the tube) was calculated as the difference between soil water content measured at a given time across the profile and soil water content at wilting point. In each experimental plot, plant available water in each of the 10-cm layer was aggregated to the maximum depth to obtain a final value for each soil profile at each date.

Table 1: Description of the experimental plots at the Agronomic Research Station of N'Tarla used for model calibration and evaluation. V1 = Photoperiod-sensitive local sorghum variety, V2 = Improved sorghum variety less sensitive to the photoperiod, D1 = early sowing, D2 = late sowing, F1 = 38 kg N/ha in 2018 and f=8 kg N/ha in 2017, F0 = 0 kgN/ha. Soil water was not measured in 2017.

Dataset	Year	Cropping system	Variety	Sowing date	Fertilizer application	Maximum depth of soil water measurement (cm)	Soil organic nitrogen content in the upper layer in %	Name of simulation unit	Field capacity (%).				
									0 - 15 cm	15 – 35 cm	35- 55 cm	55-85 cm	85- maximum depth
Calibration	2018	Sole sorghum	V1	D1	F0	115	0.01	V1D1F0	13.7	19	19	19	19
					F1	145	0.02	V1D1F1	13.7	19	19	19	19
				D2	F0	155	0.01	V1D2F0	13.5	19	24	24	24
					F1	155	0.008	V1D2F1	22	25	25	28	19
			V2	D1	F0	95	0.007	V2D1F0	13.7	19	19	18	18
					F1	155	0.011	V2D1F1	13.7	19	19	19	19
				D2	F0	155	0.016	V2D2F0	13.7	19	19	19	22
					F1	155	0.018	V2D2F1	13.7	19	21	21	21
		Sorghum intercropped with cowpea	V1	D1	F0	145	0.015	V1D1F0-asso	13.7	17	17	17	19
					F1	155	0.015	V1D1F1-asso	13.7	23	23	23	23
				D2	F0	155	0.011	V1D2F0-asso	13.7	19	18	18	18
					F1	135	0.011	V1D2F1-asso	13.7	19	19	19	20
			V2	D1	F0	145	0.011	V2D1F0-asso	13.7	17	17	17	17
					F1	155	0.013	V2D1F1-asso	13.7	22	22	22	22
				D2	F0	135	0.012	V2D2F0-asso	13.7	20	20	20	20
					F1	145	0.012	V2D2F1-asso	13.7	22	22	22	22
		Sole Cowpea	Sangaraka	D1	F0	135	0.01	Niebpur	13.7	19	21	21	21**
Evaluation	2017	Sole sorghum	V1	D1	f	-	0.02*	NT17V1D1	13.7	19	19	19	19**

Dataset	Year	Cropping system	Variety	Sowing date	Fertilizer application	Maximum depth of soil water measurement (cm)	Soil organic nitrogen content in the upper layer in %	Name of simulation unit	Field capacity (%).				
									0 - 15 cm	15 – 35 cm	35- 55 cm	55-85 cm	85- maximum depth
				D2	f	-	0.007*	NT17V1D2	22	25	25	28	19**
			V2	D1	f	-	0.011*	NT17V2D1	13.7	19	19	19	19**
				D2	f	-	0.018*	NT17V2D2	13.7	19	21	21	21**
		Sorghum intercropped with cowpea	V1	D1	f	-	0.015*	NT17V1D1-asso	13.7	23	23	23	23**
				D2	f	-	0.011*	NT17SV1D2-asso	13.7	19	19	19	20**
			V2	D1	f	-	0.013*	NT17V2D1-asso	13.7	19	19	19	20**
				D2	f	-	0.012*	NT17V2D2-asso	13.7	22	22	22	22**

* Not measured in 2017, the values measured in 2018 in the experimental plot were considered. ** maximum depth of soil water measurement for 2018 was considered

3.2.3.2 Plant measurements

Date of flowering was recorded for sorghum and cowpea in sole and intercropping plots when 50% of the plants in the plot reached the stage. Physiological maturity of sorghum was observed when 100% of the plants had completed the stage of dark spots appearing at the edge of the grain attachment on the panicle. For cowpea, physiological maturity was considered when the first pods started to dry. Leaf Area Index (LAI) was measured using a Licor-LAI2000 (Licor, INC.) on four transects (covering three planting rows) with six plants per transect on each measurement date for each plot of sole or intercropped sorghum (Fig. S1). Measured LAI on the four transects was then averaged to get the experimental plot LAI for a given date. LAI measurements began on July 15 after sorghum sowing and continued until maturity with a 15-day interval between measurements. A total of seven LAI measurements were made for plots with early sowing (D1) and five for plots with late sowing (D2) of sorghum. Only five LAI measurements were taken under cowpea in sole crop condition, because cowpea senescence started before sorghum. For intercropping there were six LAI measurements in plots with D1 and four measurements in plots with D2. For the first three measurements, only sorghum LAI was measured, because cowpea was too small and we could not place the LAI meter under its canopy while avoiding direct contact of leaves with the lens. For the remaining measurements, LAI was measured (i) under cowpea canopy (to obtain total canopy LAI, i.e. sorghum and cowpea), and (ii) above cowpea canopy (to estimate sorghum LAI). The LAI of intercropped cowpea was estimated as the difference between the two measurements. Sorghum and cowpea aboveground biomass (stem, leaves and parts of the inflorescence at flowering) was sampled in three randomly selected 1 m² quadrats (corresponding to six sorghum stands and six cowpea stands) in each experimental plot every two weeks after crop installation. Fresh samples of sorghum and cowpea were weighted and oven-dried for 48h at 72°C for dry weight estimation. At harvest, yield and yield components were determined: grain yield, grain weight, number of grains, straw weight, thousand seed weight and harvest index for sorghum in 2017 and 2018. For cowpea, grain yield was measured in 2018, but the sample was unfortunately lost in 2017 before weighing. The number of grains could not be determined also in 2018 due to destruction of the sub-sample by animals during drying on a dedicated but insufficiently protected area in N'Tarla experimental station. Determination of plant nitrogen content was obtained using the Kjeldahl method (Bremner and Mulvaney, 1982) applied to plant samples taken at flowering (aboveground biomass) and at harvest (bulked stems and leaves, and grains) in all experimental plots.

3.2.3.3 Weather data

Daily climate data for the two growing seasons (2017 and 2018) were obtained from observations at the N'Tarla meteorological station located 50 m from the experimental plots. Measured variables included daily rainfall, daily minimum and maximum temperatures, duration of solar brightness, and wind speed. Global radiation (*Rg*) was calculated as a function of latitude, maximum possible sunshine duration or daylight hours and solar radiation received at the top of the Earth's atmosphere, using the following equation (usually referred to as Angstrom formula (Allen et al., 1998):

$$Rg = [a + (b \, x \frac{n}{N}] \times Ra \qquad (1)$$

Where n is the actual sunshine duration measured in hours, is N, the maximum daylight duration (Allen et al., 1998). Ra is the extra-terrestrial radiation, i.e. the solar radiation received at the top of the Earth's atmosphere. N and Ra were computed from latitude and date using astronomic formulas, and the coefficients a and b were set at the values 0.25 and 0.50 respectively, as recommended in Allen et al., 1998.

3.2.4 Assessment of sorghum cowpea intercropping system performance

Cropping system performance was evaluated by considering above-ground biomass and grain yield under sole and intercropping and using Land Equivalent Ratio (LER). LER is the land required with sole cropping to produce the yield obtained with intercropping with the same management (Willey, 1979). It is a commonly used approach to assess the land use advantage associated with intercropping (Willey and Rao, 1980):

$$LER = Ya/Sa + Yb/Sb \qquad (2)$$

Where Ya and Yb are the yields of each crop in the intercrop system, and Sa and Sb are the yields of the corresponding sole crops.

pLERa and pLERb are the partial LER values for each species:

$$pLERa = Ya/Sa \qquad (3)$$

$$pLERb = Yb/Sb \qquad (4)$$

A LER value greater than 1 indicates that there is an advantage for intercropping over sole cropping. Partial land equivalent ratio (*pLER*) values are used to assess the contribution of each crop to the final LER.

3.2.5 General description of STICS soil-crop model

STICS soil-crop model (Brisson et al., 2009) simulates carbon, water and nitrogen balances in the soil-crop-atmosphere system. The model simulates the dynamics of agricultural and environmental variables (e.g. crop yields, N content of harvested organs, soil moisture and mineral N content, nitrogen leaching and soil organic carbon) over agricultural seasons on a daily time step, taking into account the impact of weather, and soil and crop management practices (e.g. mineral and organic fertilization, irrigation, tillage and residue management). It has been designed as a generic model that can be easily adapted to different crops and environmental conditions. Crops are defined using eco-physiological options (e.g. effect of photoperiod and/or the requirements of cold on crop phenology) and plant parameters. Plant parameters include both crop specific and cultivar-dependent parameters. The version of the model used for this study is the intercropping extension of the STICS sole crop model, which considers two species grown at the same time (Brisson et al., 2004). This model, hereafter referred to as "Stics-intercrop" simulates the competition for light, water and nitrogen between associated species at the daily time step (Brisson et al., 2004). In the following section, we describe the general functioning of Stics, and detail the specific features of Stics-Intercrop.

3.2.5 Description of Stics model and intercrop version specificities

Plant development occurs in several stages associated with LAI and phenological stages (**Table 2**). The duration between stages is expressed in cumulative thermal time and is specific to species and varieties. Development is controlled by crop temperature (simulated variable). Germination and emergence are controlled by soil temperature and moisture.

Table 2: Description of the stages included in the model

Development stage	Step acronym used in model	Description
Vegetative stages	ILEV	Emergence
	AMF	Maximum acceleration of leaf growth, end of juvenile phase
	ILAX	Maximum leaf area index (LAI), end of leaf growth
Reproductive stages	Flo	Flowering
	IDRP	Start of grain filling
	IMAT	Physiological maturity

Crop height varies during growth, using a function relating height to LAI, and is limited to a maximum value for each species (*hautmax* parameter). In the intercropping version, the comparative height of the two crops determines the dominant and the understory (i.e. dominated) plant. The model is thus able to simulate possible inversions in dominance between the two species during the cycle. The sole-crop model uses Beer's law to compute radiation interception. Stics-intercrop differs on that aspect and uses a "Radiative transfer" formalism to compute radiation interception: the model estimates direct and diffuse radiation received each day for 20 points uniformly distributed along the inter-row, and the fractions intercepted by the foliage of the dominant crop and transmitted to the layer below (Brisson et al., 2009)**.** Each crop has a single extinction coefficient (*ktrou*, the same for direct and diffuse radiation). Row spacing (*interrang* parameter), row orientation (*orientrang* parameter) and canopy volume impact radiation transfers. The canopy volume is defined by (i) basic shapes (*form* parameter, either triangle or rectangle), (ii) a ratio between the height and width of the shape (*rapform* parameter), and (iii) the base height of the shape *(hautbase* parameter), considering absence of leaves between zero and base height (Brisson et al., 2004). The shape and the base height are assumed to be constant throughout crop cycle. Width varies as a function of height, distance between plant rows, LAI, leaf density distribution as a function of height, and the *rapform* parameter. For each intercropped species, daily LAI is calculated as a function of crop temperature, phenological stage, plant density, and water and nitrogen stress. The LAI growth phase follows a logistic curve as a function of thermal time. Aboveground biomass daily growth is computed by multiplying the intercepted radiation by a potential radiation use efficiency factor that depends on the species for the phenological stage considered. Root growth is decoupled from aboveground biomass growth. Root front growth and root density are computed as a function of soil temperature, soil moisture and bulk density. Roots absorb water and mineral nitrogen but allocation of biomass to root is not explicitly simulated. Water and nitrogen uptake in intercropping is calculated in STICS according to root density of each crop. Root densities above 0.5 cm/cm^{-3} of soil are not taken into account for water and nitrogen uptake since above this threshold, water and nitrogen uptake are assumed not to be limited by root density (Corre-Hellou et al., 2009). The simulated descent of root front is driven by thermal time using soil temperature with a species-specific rate. Soil moisture content below wilting point or above field capacity can reduce or stop root front growth. Separately, the model simulates root density and vertical distribution in the profile. Length growth is calculated by a logistic function similar to that of leaf growth. Roots are distributed in the profile as a function of (i) the amount of roots already present and(ii) soil constraints (drought, anoxia, penetrability). Differing with the sole crop version that uses a single crop coefficient, Stics-intercrop computes the water requirements of the two species from the sharing of radiation coupled to a resistive pattern applied at a daily time step, described in Brisson et al. (2004). The soil environment is assumed to be the same for both crops, i.e. the horizontal heterogeneity of soil is ignored (but vertical heterogeneity is not ignored). The interactions between the two root systems result from the influence of the soil on the root profile of each crop through its penetrability and water dynamics. Soil supply is determined by the balance between inputs (including possible capillary rise) and losses (soil evaporation, runoff and drainage).

Water stress and nitrogen stress that affect plant growth and grain yield are taken into account in the model using indices of reduced leaf growth and biomass accumulation under water or nutrient limiting conditions (Brisson et al., 2009). Potential transpiration is a function of Leaf Area Index (LAI) and daily potential evapotranspiration. The latter is as calculated using the approach of Shuttleworth & Walace (Brisson et al., 1998). Actual transpiration is calculated as the minimum between water soil supply and maximal crop demand. The water stress factor that affects radiation use efficiency and plant transpiration is calculated as the root transpirable fraction of soil water, which reduces growth and transpiration (Brisson et al., 2009). Daily plant nitrogen accumulation depends on biomass accumulation and soil nitrogen availability. Nitrogen uptake for each species depends on root depth, root distribution in soil layers and crop nitrogen demand. Daily nitrogen demand is the product of plant growth rate by the N amount corresponding to maximum N dilution in the plant. Soil supply is calculated per 1 cm elemental layer up to maximum root system depth. The nitrogen stress factor affects (i) LAI, (ii) radiation use efficiency and (iii) senescence. The N stress factors is calculated as the ratio between actual nitrogen concentration and critical nitrogen concentration in the crop if the former is lower than the latter, and is set to 1 otherwise. Stress factors are calculated daily and vary between 0 (complete stress) and 1 (no stress). A complete description of the equations and parameters governing stresses definition can be found in Brisson et al., (2008).

The model STICS also simulates N acquisition by N_2 fixation in the case of legume crops. Brisson et al., (2008) provide details as follows: potential symbiotic N_2 fixation by legumes is calculated by taking into account nodule life cycle, plant growth rate and physico-chemical conditions of soil that allow optimal nodule activity. Actual fixation depends on inhibitory effect of excess of nitrate in soil.

3.2.6 Model parameters, calibration and evaluation

Growing seasons and the experimental treatments (cropping system, sowing date, sorghum variety and fertilizer input) defined 25 cropping situations (8 in 2017 and 17 in 2018) corresponding to the experimental plots listed in Table 1. Each experimental plot corresponds in this study to a "simulation unit". The 17 simulation units of 2018 were used for model calibration. The remaining 8 simulations units of 2017 were used for independent model evaluation.

3.2.6.1 Setting of model parameters

Soil parameters

We defined five horizons for soil parameterization: 0-15cm, 15-35cm, 35-55cm, 55-85cm, and from 85 to maximum sampling depth (that varied per experimental plot, see Table 1). Soil analysis carried-out in the experimental plots (see section 2.3.1) informed the soil parameters "norg" (soil total Nitrogen in the topsoil) (**Table 1**). pH and soil C:N ratio were set constant across all experimental plot to 5.8 and 13, respectively, in line with the soil analysis carried out across all experimental plots in 2017. Soil moisture at field capacity and wilting point were first estimated with pedo-transfer functions (Lidon and Francis, 1983) based on the texture measured in 2017 in a soil profile in one location close to the experiment **(Table S1).**

Plant parameters

Model parameters related to crop geometry reflect the assumption that the two species in the intercrop occupy distinct rows. In our experimental design, cowpea was planted on the same row as sorghum. This issue was easily overcome by considering that the spacing between plants on a given row was the spacing between rows, and that the spacing between rows was the spacing between plants on a given row (see Fig S2). Model parameters related to grain yield formation were directly derived from the measurements made in the experimental plots (**Table 3**). The greatest experimental value of grain weight among the 16 experimental plots was considered to inform the parameter that set maximum number of grains (*nbgrmax*). Maximum height (*hautmax*) was set as measured after flowering in the experiment, i.e. 4 m for sorghum and 0.5 m for cowpea. A few other parameters were taken from the literature (e.g. temperature thresholds for development and photosynthesis) (Table 3).

3.2.6.2 Calibration procedure

STICS model has not been previously calibrated for cowpea and tropical sorghum. Initial parameter values for cowpea were obtained from the spring pea plant file (Corre-Hellou et al., 2009). For sorghum, initial parameters were taken from the STICS sorghum plant file as obtained with the 8.5 version of the model, which corresponds to temperate fodder sorghum (Constantin et al., 2015). For sorghum, we calibrated cultivar-dependent parameters for the two varieties used in the experiment.

To calibrate the thermal constants associated with development stage, the model was forced to go through the observed dates of maximum leaf area index, flowering and maturity, in order to compute the temperature sums corresponding to the intervals between the stages. We assumed that flowering coincided with the beginning of grain filling. Parameters related to photoperiod (*phobase and phosat*) for the two sorghum varieties (V1 sensitive to photoperiod and V2 less sensitive to photoperiod) were set according to Traore (2015). Phobase and phosat are daylength thresholds that define the period of crop growth during which a photoperiod slowing effect is applied to crop development. Photoperiod sensitivity Index (*sensiphot*) was obtained by trial-and-error to minimize the gap between observed and simulated flowering date (**Table 3**).

LAI is a central state variable in the model. Parameter related to leaves development (*dlaimax*) was adjusted by trial-and-error to minimize the difference between observed and simulated LAI. Similarly aboveground biomass growth parameters (*efcroijuv, efcroiveg, efrcoirepro*) were also adjusted by trial and error to minimize the difference between the observed and simulated above-ground biomass. Values for the radiative transfer parameters (*ktrou*) used for radiation transfer between sorghum and cowpea were set to 0.30 and 2 respectively. These values were obtained using a trial-and-error calibration method to minimize the differences between observed and simulated sorghum and cowpea biomass in the intercropping simulation units. Default values for shape and base height (*shape, hautbase parameters*) as well as the ratio between the thickness and width of the crop shape (*rapform parameter*) were considered.

The fraction of stable organic nitrogen in soil (*finert*) was set to zero. This appeared necessary for the model to simulate amounts of soil mineral N and plant nitrogen uptake consistent with the observed crop N uptake in the treatments without fertilization. The moisture at field capacity and at wilting point, that were first set with the help of pedo-transfer functions (see section 2.7.1) were then adjusted for each experimental plot (see final values in Table 1) to minimise the difference between observed and simulated soil water during the growing season.

For some parameters the simple trial and error approach used above would have been poorly effective and we used instead the optimization tool implemented in the software package associated with Stics model (**Table 3**). This optimizer proposes a parameter values that minimizes the gap between model simulation and observations for the variables to be explained (Buis et al., 2011), using weighted least squares (Makowski et al., 2006). Lower and upper parameters limits are set before optimization to ensure that the optimized values correspond to reasonable physiological values. Crop parameters were first calibrated using sole sorghum and cowpea simulation units. Then, these parameters were refined using intercropping simulation units. The parameters Kmabs2 (*i.e.* the affinity constant of N uptake by the roots for the low uptake system) and Vmax2 (i.e. the maximum specific N uptake rate with the high affinity transport system) were optimized to minimize the difference between observed and simulated plant N uptake. Parameters related to grain formation such as the slope of the relationship between grain number and growth rate (*cgrain*), the number of grains produced when growth rate is zero (cgrainv0) were also optimized by minimizing the difference between the simulations and the observations of the number of grains (Table 3). The rate of increase of the harvest index vs. time (*viticarbT*), it was adjusted to minimize the difference between simulations and observations for grain yield.

Table 3: Values of sorghum parameter as calibrated in the STICS crop model for experiments for the N'Tarla experiments in Mali

Parameter		Description	Target variable	Value			Source
Process	acronym			V1	V2	Cowpea	
Emergence	tdmin	basal temperature for crop development	Leaf area index	8	8	6.2	(Folliard et al., 2004) ; Fao., 2012 ; (Luo, 2011).
Crop development	sensiphot	index of photoperiod sensitivity (1=insensitive)		0.40	0.60	-	Trial and error calibration
	phobase	basal photoperiod controlling photoperiod slowing effect		14	14	-	Traroré A., 2015
	phosat	saturating photoperiod controlling photoperiod slowing effect		12,75	12.75	-	Traoré, A., 2015
	stlevamf	cumulative thermal time between emergence and end of juvenile phase		180	718	881	Test of a range of values
	stamflax	cumulative thermal time between end of juvenile phase and maximum LAI		305	314	687	Trial and error calibration
	stlevdrp	cumulative thermal time between emergence and beginning of grain filling		685	1077	1609	Trial and error calibration
Leaves	dlaimaxbrut	maximum rate of the setting up of LAI		0,0015200	0.01000	0.003500	Trial and error calibration
	durvieF	maximal lifespan of an adult leaf		480	280	240	Trial and error calibration
Shoot growth	efcroijuv	maximum radiation use efficiency during the juvenile phase	Above-ground biomass	2.1836	2.1877	1.20000	Trial and error calibration
	efcroirepro	maximum radiation use efficiency during the grain filling phase	Above-ground biomass	3.8572	2.8372	1.35590	Trial and error calibration
	efcroiveg	maximum radiation use efficiency during the vegetative stage	Above-ground biomass	3.8049	2.8414	1.746500	Trial and error calibration
	temin	basal temperature for photosynthesis	-	11	11	7.2	(Folliard et al., 2004) ; Fao., 2012 ; (Luo, 2011)
	teopt	optimal temperature for photosynthesis	-	25	25	27	(Folliard et al., 2004) ; Fao., 2012 ; (Luo, 2011)
	temax	maximal temperature for photosynthesis	-	45	45	40	(Folliard et al., 2004) ; Fao., 2012 ; (Luo, 2011)
Nitrogen fixation	fixmaxgr	maximal N symbiotic fixation rate per unit of grain growth rate	N_2 fixed*	-	-	9.50	Trial and error calibration
	fixmaxveg	maximal N symbiotic fixation rate per unit of vegetative growth rate	N_2 fixed*	-	-	30.0	Trial and error calibration

Parameter		Description	Target variable	Value			Source
Process	acronym			V1	V2	Cowpea	
Nitrogen uptake	Kmabs2	affinity constant of N uptake by roots for the low uptake system	N uptake	40000	37672.32	25000	numerical optimization
	Vmax2	maximum specific N uptake rate with the high affinity transport system	N Uptake	0.10	0.00878	0.06	numerical optimization
Yield formation	cgrain	slope of the relationship between grain number and growth rate	Number of grains	0.06	0.07	0.084	Trial and error calibration
	nbjgrain	Duration in days of the period during which the number of grains can be reduced by stresses	Number of grains	15	15	15	Traoré, A., 2015
	cgrainv0	number of grains produced during the nbjgrains before beginning of grain filling	Number of grains	0.0000	0.000	0.069	Trial and error calibration
Yield formation	vitircarbe	rate of increase of the C harvest index vs time	grain yield	0.00900	0.01500	0.01462	Trial and error calibration
	nbgrmax	maximum number of grains	grain yield	25000	60000	1200	Measurement
	pgrainmaxi	maximum weight of one grain	grain yield	0.0270	0.0247	0.25	Measurement
	Irmax	maximum harvest index	grain yield	0.30000	0.51000	0.42	Measurement

*N_2 fixed by the legume was not measured, but estimated for sole cowpea as the difference between the N uptake of sole sorghum without fertilizer and N uptake of sole cowpea.

3.2.6.3 Model evaluation

Model error was estimated the root means square error (*RMSE)*, which has the same unit as the considered variable, and the relative RMSE in % (*rRMSE*). We used these statistical criteria to assess the accuracy of STICS simulations for maximum leaf area index (*Laimax*), aboveground biomass, plant N uptake and grain yield of sole and intercropped sorghum and cowpea.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Oi - Si)^2} \quad (5)$$

$$rRMSE = \frac{RMSE}{\bar{O}} X\ 100 \quad (6)$$

With O_i et S_i are the observed and simulated values for the ith measurement, n is the number of observations and $\bar{O}$ is the average of the observed values. The lower the values, the better the model predictions. Model efficiency (*EF*) was also calculated to help compare with other model evaluation studies.

$$\mathrm{EF} = 1 - \frac{\sum_{i=1}^{n}(\mathrm{Oi} - \mathrm{Si})^2}{\sum_{i=1}^{n}(\mathrm{Oi} - \bar{\bar{O}})^2} \quad (7)$$

Model efficiency (EF) (Willmott et al., 1985) varies from infinite negative value to 1 (perfect performance). A negative value indicates that the mean of observations is a better predictor than the model, and a zero value indicates that the model does not outperform the mean of observed values. The combined analysis of these three indicators gives a comprehensive assessment of model accuracy.

3.3 RESULTS

3.3.1 Weather data

Compared to that of 2018, growing season in 2017 was cooler and wetter in terms of cumulated rainfall, but with a greater number of dry days and greater solar radiation overall. The average minimum temperature observed in 2017 (17.3°C) was 5°C lower than that observed in 2018 (22.3°C) during the growing season (**Figure 1**). Average Maximum temperature in 2017 (34.2°C) was 2.1°C lower than average maximum temperature in 2018 (36.3°C). Average temperature growing season in 2017 (27.9°C) was 1.1°C lower than in 2018 (30.0°C). Average global solar radiation during the growing season in 2017 (23.1 MJ m^{-2}) was greater than in 2018 (18.0 MJ m^2). Cumulative rainfall recorded in 2017 (808 mm) **(Fig. 1A**) was 110 mm greater than in 2018 (698 mm) (**Fig. 1B**). On the other hand, there were more dry days (i.e. days with no rainfall) in 2017 (134 days) than in 2018 (122 days).

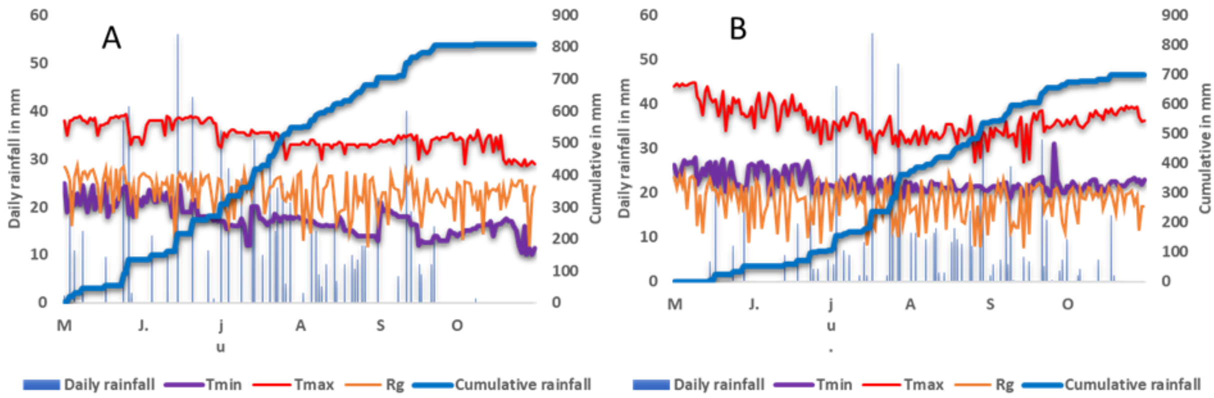


Figure 1: Daily and cumulative rainfall, daily temperature and daily global radiation (Rg) for 2017 (A) and 2018 (B) at the N'Tarla agricultural research station, southern Mali.

3.3.2 Model calibration

3.3.2.1. Sorghum and cowpea phenology

Model simulations of sorghum phenology led to a RMSE of 3.4 days for beginning of grain filling and 3.1 days for physiological maturity (**Fig. 2a, 2b**,). RMSE for cowpea phenology was 3.9 days for grain filling and 10.8 days for physiological maturity (**Fig. 2a, 2b**).

The model reproduced the relatively high sensitivity of V1 to photoperiod reasonably well: a 24-day delay in sowing (i.e. the difference between early and late sowing in the experiments) shortened the observed length of the vegetative phase (from planting to start of grain filling) by 17 days. The model simulated a 14-day decrease in the length of vegetative phase when sowing was delayed. V2 was less sensitive to photoperiod: a 24-day delay in sowing created only a 9-day observed shortening of the vegetative phase. The model simulated a 6-day decrease in the length of the vegetative phase when sowing was delayed.

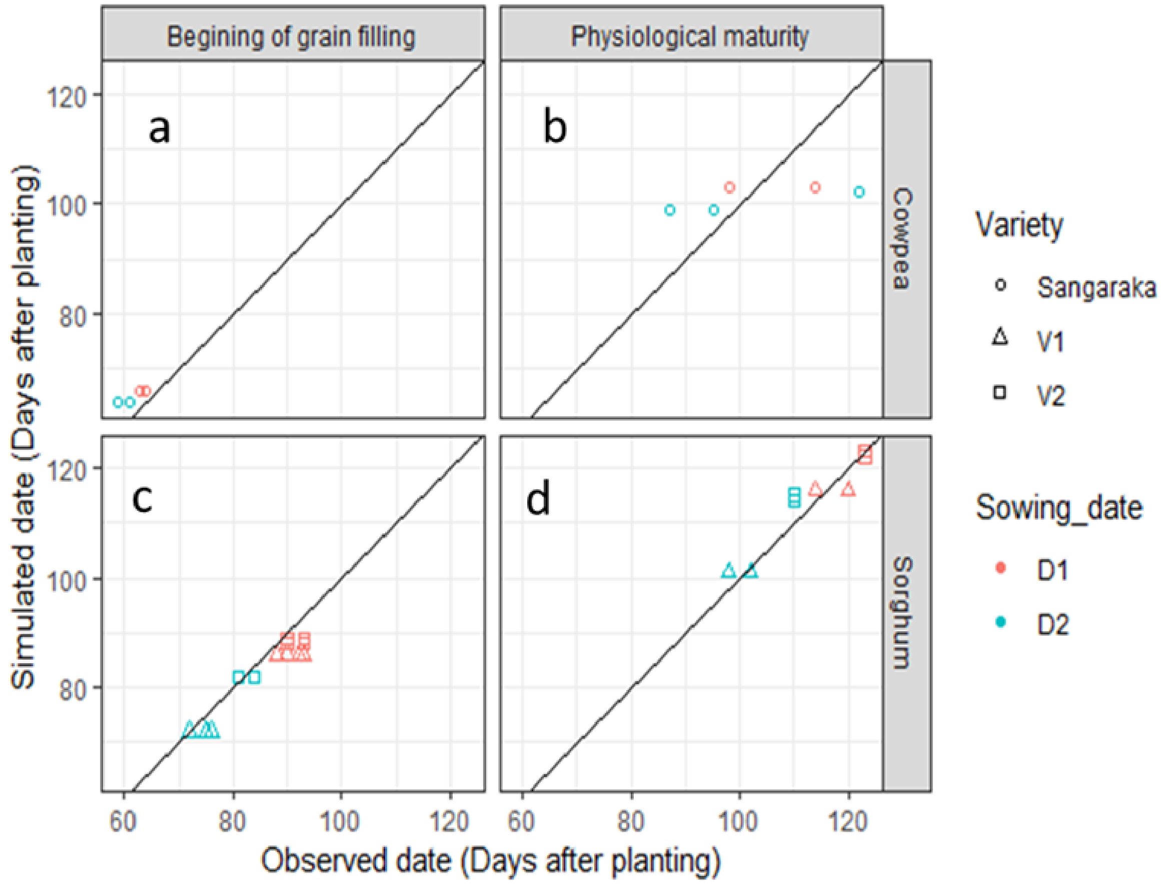


Figure: 2 Comparison between observed and simulated (STICS model) sorghum and cowpea beginning of grain filling (a and c) and physiological maturity (b and d), for sorghum local (V1) and improved (V2) variety, early sowing (D1), late sowing (D2), for sole and intercropping simulation units. Sangaraka is the name of the cowpea variety.

3.3.2.2. Simulation of in-season soil water, LAI and aboveground biomass (AGB)

Sole crops with calibration dataset

In-season soil water was well reproduced by the model, especially the increase in soil water up to field capacity during vegetative phase (**Fig. 3**). However, soil water after the end of the growth cycle (a period with low rainfall and high soil evaporation) was overestimated by the model due to the underestimation of soil evaporation by the model.

A reasonably good agreement between model and observations for the key plant growth variables was reached after calibration. However, it was not possible to calibrate LAI and biomass growth with an equally satisfactory fit for the two sowing dates treatments and the two sorghum cultivars (**Fig. 3**). More thoroughly, for sole sorghum with early sowing date (D1) and nitrogen input (F1), LAI simulated by model matched the observations for the improved variety (V2) and slightly overestimated them for the local variety (V1) (**Fig. 3a, 3c**). With late sowing (D2) and nitrogen input (F1) the model overestimated maximum LAI for both sorghum varieties (Fig. 3b, 3d). With early sowing (D1) and without nitrogen input (F0), the model overestimated observed LAI for V1 (**Fig. 3e**) but agreed with observed LAI for V2 under the same fertilization conditions (**Fig. 3g**). With late sowing (D2) and without nitrogen input (F0), the model overestimated LAI for both sorghum varieties (**Fig. 3f, Fig. 3h**). LAI simulations for cowpea in sole crop matched closely the observations (**Fig. 3i**).

AGB was underestimated (especially around flowering) in simulations for both sorghum varieties with early sowing (D1) and N input (F1) (**Fig. 3a, Fig. 3c**). With late sowing (D2) and N input (F1), AGB simulations were in closer agreement with in-season and harvest observations for V1 and V2 (**Fig. 3b, 3d**). Without nitrogen supply (F0), the same trends were observed for early sowing i.e. sorghum AGB was overestimated for both varieties (especially around flowering) (**Fig. 3e, 3g**) but underestimated at harvest for late sowing (**Fig. 3f, 3h**). The simulation of cowpea AGB closely matched the observation (**Fig. 3i**).

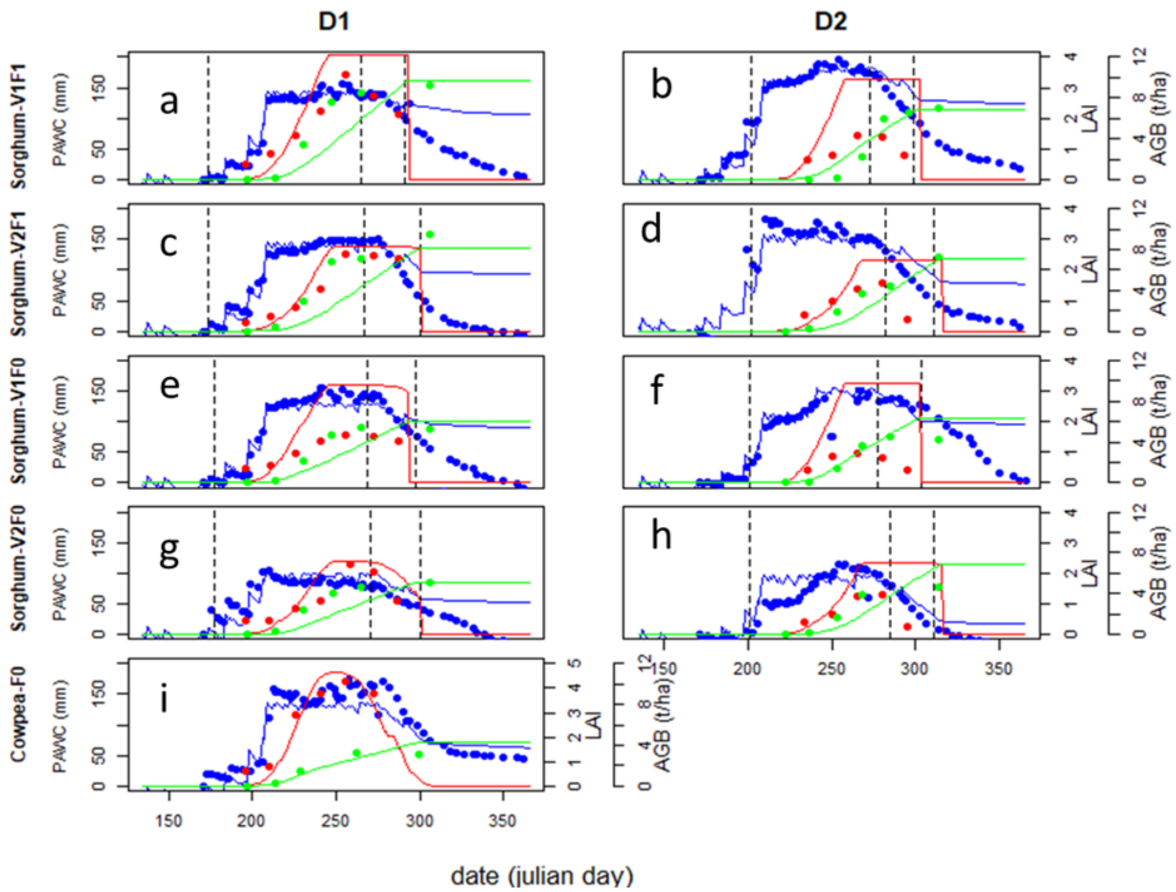


Fig. 3: Observed plant available soil water to maximum measurement depth (PAWC) (blue dots), LAI (red dots), and aboveground biomass (green dots) for the eight sole sorghum simulation units and one sole cowpea simulation unit used for model calibration. The lines are model simulations: blue for soil water to maximum measurement depth, red for LAI and green for AGB. Local variety (V1), improved variety (V2), early sowing (D1), late sowing (D2), no fertilizer (F0), 38 kgN ha-1 (F1) at Ntarla research station in 2018. Vertical dotted bars indicate from left to right sowing date, beginning of grain filling and physiological maturity.

Intercrops with calibration dataset

Simulated in-season soil water for intercrops also corresponded fairly well to the observations (**Fig.4 a, 4b, 4c, 4d, 4m, 4n, 4o, 4p**). As with sole crops, soil water at the end of the season was overestimated. Simulated LAI of (i) total canopy (sorghum plus cowpea), (ii) sorghum, and (iii) cowpea matched the observations for variety V2 (Fig. 4q) but the model simulations overestimated the observations for variety V1 (Fig. 4e) with early sowing (D1) and nitrogen input (F1). With late sowing (D2) and nitrogen input (F1), the model overestimated LAI of i) total canopy (sorghum and cowpea), (ii) sorghum, and (iii) cowpea for V1 and V2 (Fig 4f, 4r). Without N input (F0), the model also overestimated the LAI of (i) total canopy (sorghum and cowpea), (ii) sorghum, and (iii) cowpea for both varieties, both early and late sowing (Fig. 4g, 4s, 4h, 4t).

With early sowing (D1) and nitrogen input (F1), the model underestimated sorghum AGB throughout crop cycle for V1 (Fig. 4i), and matched more closely the observations for V2 (Fig 4u). With late sowing (D2) and nitrogen application (F1), AGB simulations matched the observations for both sorghum varieties (Fig. 4j, 4v).

With early sowing (D1) and without nitrogen input (F0), the model simulated accurately AGB throughout crop cycle for V1 and V2 (Fig 4k, 4w). With late sowing (D2) and without nitrogen input (F0), the model overestimated sorghum AGB at the end of crop growth (Fig. 4l, 4x).

For cowpea, the model accurately simulated AGB throughout the crop cycle whether grown with V1 or V2, with and without N inputs (Fig. 4i, 4u, 4j, 4v, 4k, 4w, 4l, 4x).

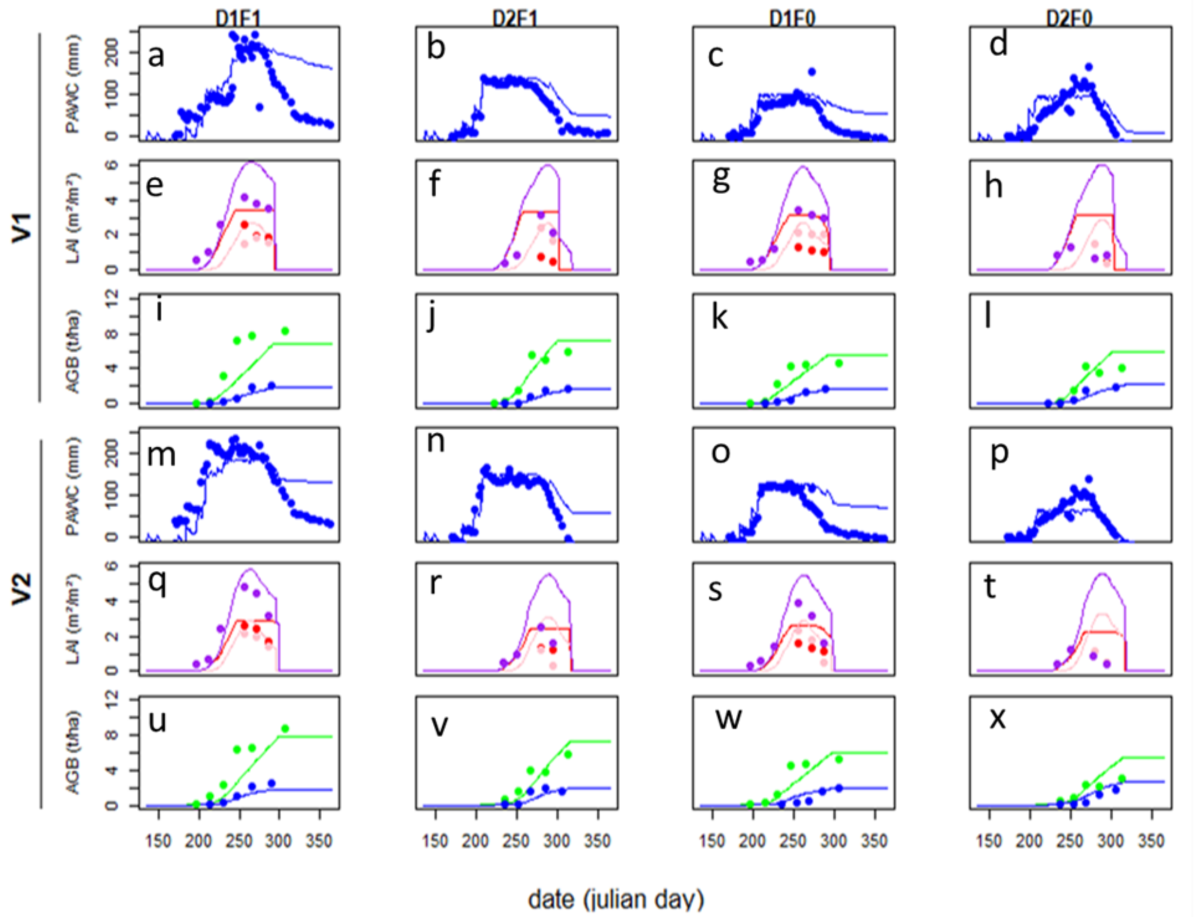


Fig. 4:Observation (blue dots) and simulation (blue line) of plant available soil water to maximum measurement depth (PAWC)(, Fig. a, b, c, d, m n, o, p); observation (purple dots for for sorghum + cowpea, red dots for sorghum in intercropping, pink and transparent dots for cowpea in intercropping) and simulations (lines) of LAI (Fig. e, f, g, h, q, r, s, t,); observation (green dots for sorghum, blue dots for cowpea) and simulations (green lines for sorghum and blue lines for cowpea) of aboveground biomass of sorghum intercropped with cowpea (Fig. i, j, k, I, u, v, w, x). Local variety (V1), improved variety (V2), early sowing (D1), late sowing (D2), 38 kgN ha^{-1} (F1), 0kgNha^{-1} (F0) at Ntarla research station in 2018.

Sole and intercrops in evaluation dataset

In sole and intercropping conditions, though the soil was filled with water during crop early growth, water stocks rapidly decreased below 50% of maximum available plant water capacity, indicating possible water stress (Figure S3 and Figure S4). For all sowing dates, for sole crop and intercrop, model simulations overestimated observed LAI (Fig. S3, Fig. S4).

In sole crop, AGB simulations were in closer agreement with the observations during the season but overestimated the observations at harvest for the local variety (V1) regardless of sowing dates (Fig. S3a, S3b). On the other hand, for improved variety (V2), the model simulations of AGB were in very good agreement with observations (Fig. S3c) for early sowing. However, with late sowing, AGB was overestimated at the end of the cycle (Fig. S3d). In intercropping, AGB simulation displayed similar trends as observed in sole cropping (Fig. S4, e, f, k, l).

3.3.2.3 Simulation of above-ground biomass, plant N, number of grains and grain yield at harvest

Sorghum and cowpea AGB at harvest varied widely in sole cropping and intercropping, due to differences in sorghum variety, sowing date and fertilizer inputs: aboveground biomass ranged from 3.5 t/ha to 9.6 t/ha for sorghum and from 0.4 t/ha to 2.5 t/ha for cowpea for the calibration dataset. The model reproduced this variability with rRMSE of 23 % and EF of 0.81 (Fig. 5a, Table 4). EF of model simulation was smaller in evaluation compared with calibration (Table 4), and rRMSE was greater, indicating a loss in the accuracy of model simulation of AGB with the independent calibration dataset.

The model underestimated plant N at harvest (Fig. 5c): rRMSE was 35% and EF was negative (-0.05). With regard to grain number per m^2 of sorghum (Fig. 5e), rRMSE was 29% (Table 4), and remained fairly stable with evaluation dataset (rRMSE = 25%). The variability in observed grain yield across crops and experimental treatments was well reproduced by the model (Fig. 5g). Although the rRMSE was large (49%), EF was 0.56 (Table 4, Fig.5). Model accuracy in simulating grain yield remained fairly stable with the evaluation dataset (rRMSE = 14% with the evaluation data set), though EF became negative (Table 4).

Table 4: Root mean square error (RMSE), relative root means square error (rRMSE), and efficiency (EF) of STICS simulation of plant variables based on the N'Tarla experiment in 2017 and 2018. See Table 1 for details on the calibration and evaluation datasets.

	EF (-)		rRMSE (%)	
Variable	**Calibration**	**Evaluation**	**Calibration**	**Evaluation**
AGB	0.81	0.58	23	43
Plant N	-0.05	-	35	-
Number of grains per m^2	-0.28	-2.17	29	25
Grain yield	0.56	-0.56	49	41

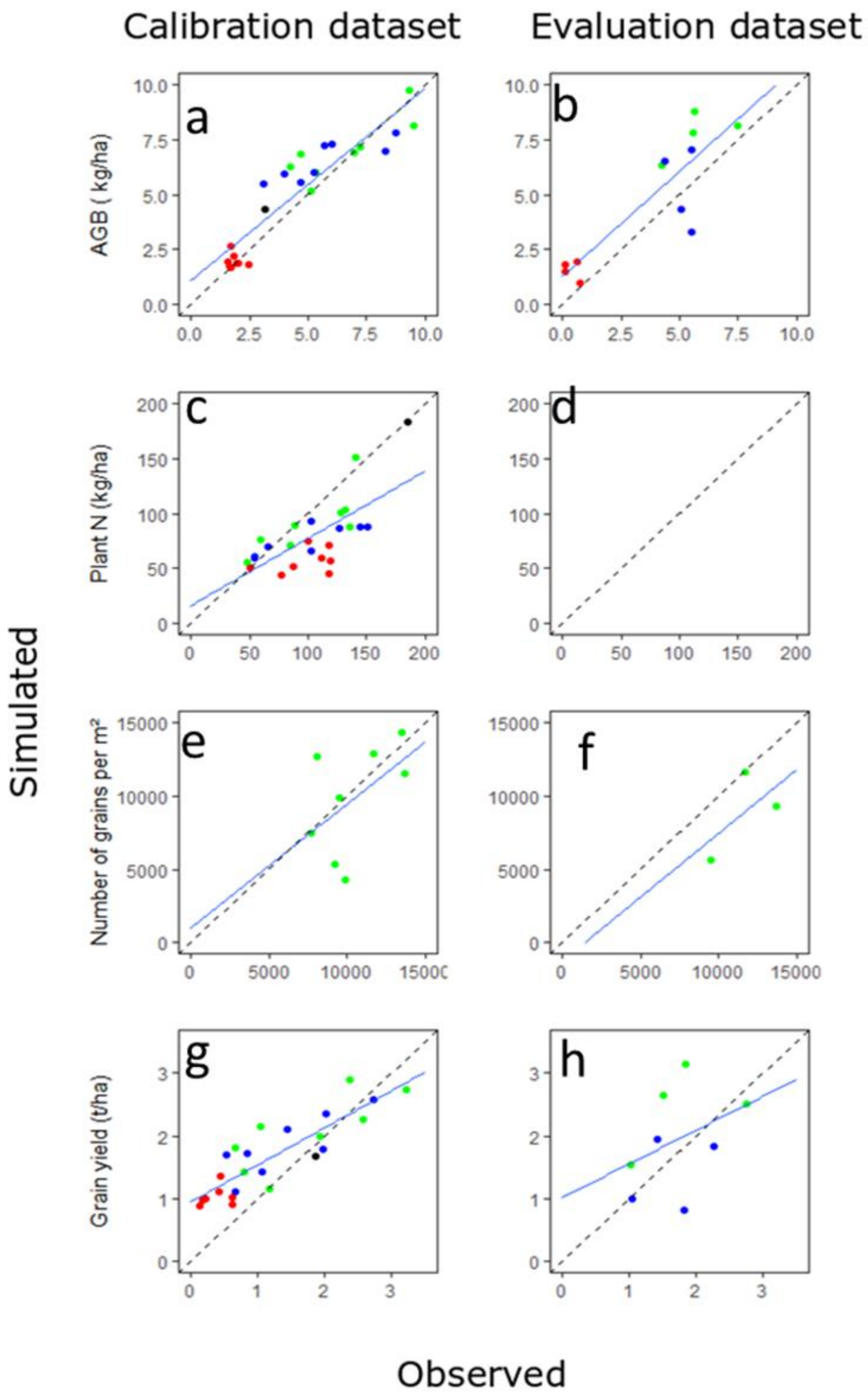


Fig. 5: Observed and STICS simulated aboveground biomass at harvest (AGB), aboveground plant N at harvest (Plant N), number of grains per m² of sorghum at harvest and grain yield for calibration and evaluation datasets (see Table1 – no data for grain yield of cowpea in 2017, no data for plant N in the evaluation dataset). The dotted black line is the 1:1 line. The blue line is the regression of simulated values against observed values. Red dots are intercropped cowpea, black dots are sole cowpea, green dots are sole sorghum, blue dots are intercropped sorghum.

3.3.3 Simulation of the impact of intercropping, fertilizer and variety on crop yield and LER

Observed sorghum and cowpea grain yield decreased when intercropped, compared with sole cropping (see figure 6a, 6c). The model accurately depicted this trend (see Figure 6b, 6d), though it underestimated the greater negative impact of intercropping that was observed for cowpea grain yield. In the experiment, the improved variety (V2) outperformed the traditional variety (**Figure 6e**) for grain yield, whereas the two varieties did not show marked differences in AGB yield (Figure S5e). The model successfully simulated this trend (Figure 6f). AGB of sorghum increased with N input, but not cowpea biomass (see Figure S5i, k), and this trend was also adequately represented by the model (Figure S5j, l). Grain yield of sorghum also increased with N input, while cowpea yield decreased with N input (Figure 6i, 6k), and this was also well depicted by the model, although the model overestimated sorghum and cowpea grain yield with no N input (Figure 6j, 6l). AGB and grain yield of sorghum and cowpea decreased with late sowing compared with early sowing (Figure 6m, 6o). The model failed to reproduce such a drop in yield with late sowing (see Figure 6n, Figure 6p). AGB and grain yield of cowpea and sorghum were smaller in 2017 than in 2018 (Figure 6q, 6s and Figure S5q, S5s). The model reproduced such behavior, although the simulated effect of year on the AGB and grain yield of cowpea and sorghum was less marked than in the reality (Fig 6r, 6t and Figure S5r, S5t).

There was an interaction between cropping system (sole vs intercropping) and growing season; in 2017, the observed negative impact of intercropping on sorghum yield was weaker than in 2018 (Fig S6). The model failed in reproducing such effect and it simulated a more pronounced detrimental effect of intercropping on sorghum yield in 2017 than in 2018. In 2018, the model attributed sorghum and cowpea yield decrease with intercropping to competition for nitrogen: while water stress was identically inexistant in sole- and intercropping, the simulated N stress for sorghum during reproductive phase was stronger (i.e. lower indicator value) in intercropping than in sole cropping (see Figure S7). In 2017, the model simulated a relatively strong water stress during reproductive stage for both intercropping and sorghum sole crop, but this did not impacted LAI as strongly as in the reality and translated into a strong simulated yield reduction only in the intercropping situation whereas the simulated yield of sole sorghum was at the same level as in 2018 where no water or nitrogen stress was simulated (Figure S6, S7).

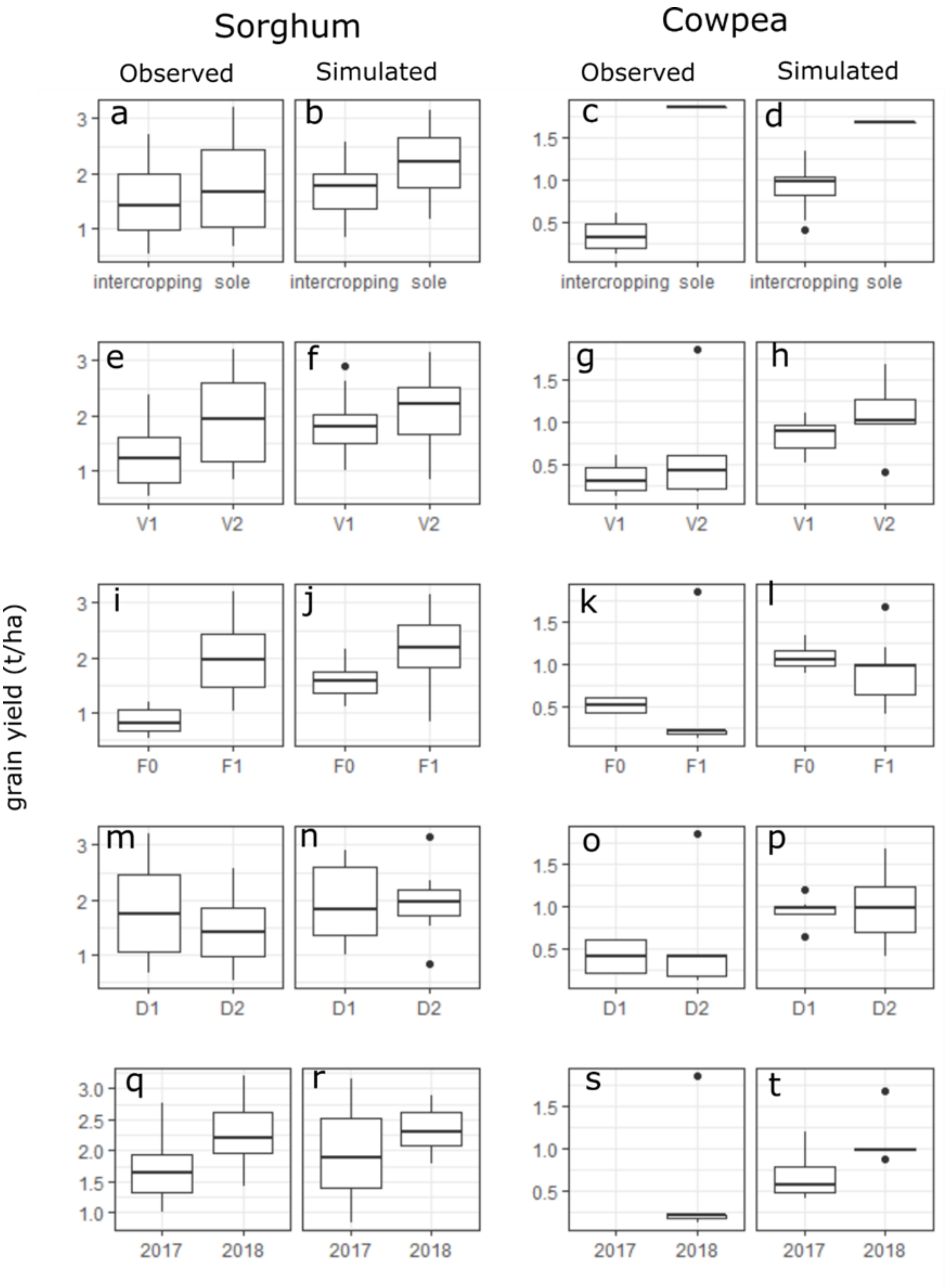


Figure 6: Boxplots of the effect of intercropping, sorghum variety (V1: local, V2: improved), N input (F0 = 0 kgN/ha^{-1}, F1 = 8 kg N/ha^{-1} in 2017 and 38 kgN/ha^{-1} in 2018) and sowing date (D1: early, D2: late) on observed and simulated grain yield. Calibration and evaluation datasets were pooled together. In 2017, there was no sole cowpea plot and no data for cowpea grain yield.

Despite the decrease in both sorghum and cowpea yield with intercropping (i.e. partial LER below one), overall observed intercropping LER was always above one, with regard to AGB (Figure 7A). The model proved accurate in simulating this behavior, as simulated LER was always above one (Figure 7B). Decrease in observed cowpea AGB with intercropping was greater than the decrease in sorghum AGB, and the model was satisfactorily depicting this trend. With regard to grain yield, LER was above one without N input, and below one with N input (due to a stronger decrease in cowpea grain yield) (Figure 7C). Because the model did not capture the stronger decrease in cowpea grain yield with N input and intercropping, the simulations could not reproduce these LER values below one (Figure 7D).

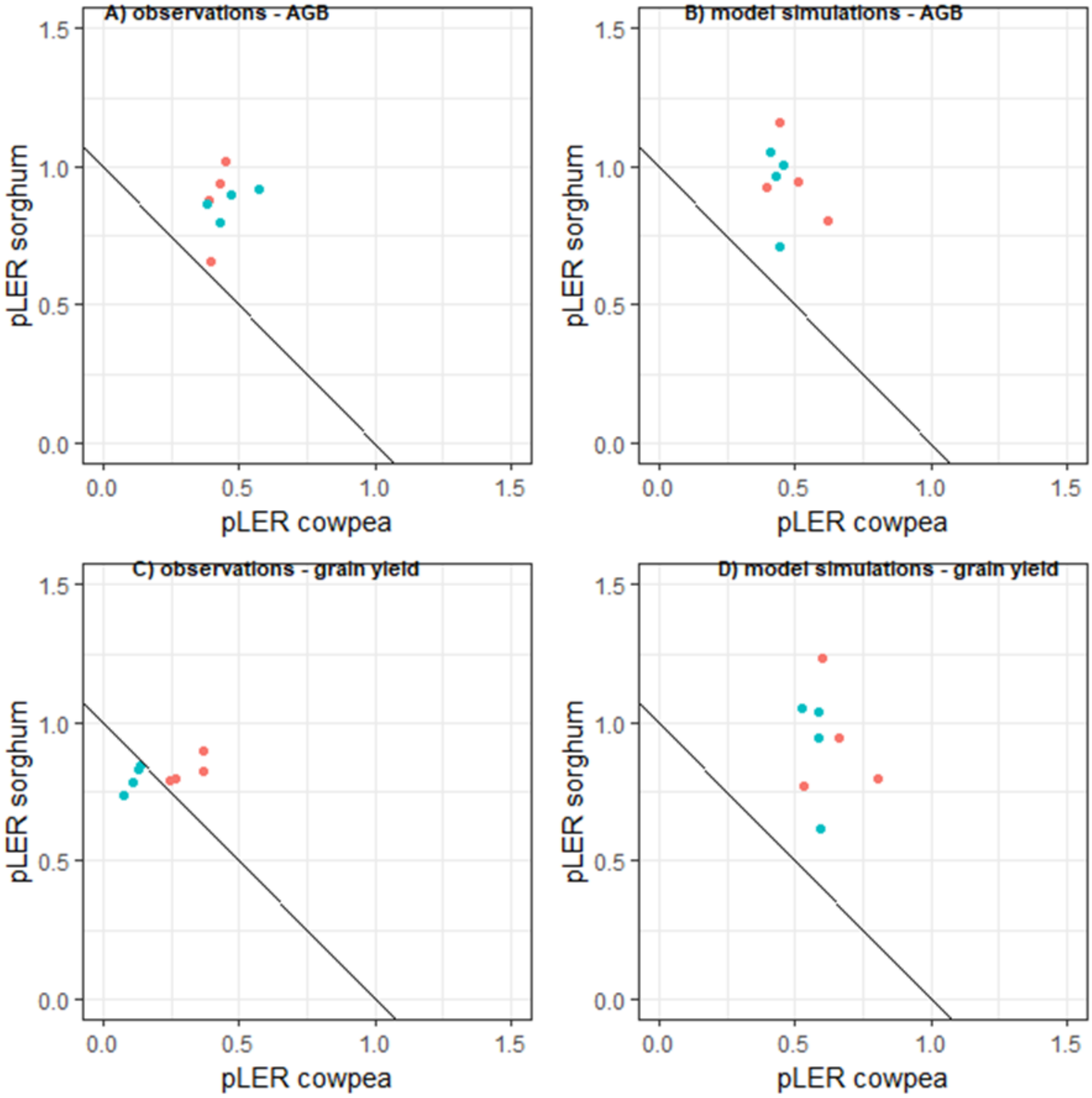


Figure 7: Cowpea and sorghum pLER as observed in the experiment (A for aboveground biomass and C for grain yield) and as simulated by the model (B for aboveground biomass and D for grain yield). Blued dots are F1 (38 kgN ha^{-1}) treatments, and red dots are F0 (0 kgN ha^{-1}) treatments. The black line indicates a LER of 1. Only 2018 experimental plots and simulation units were considered, as in 2017 pLER of cowpea could not be computed because there was no experimental plot with sole cowpea.

3.4. DISCUSSION

3.4.1 Promising features of the calibrated model

The calibrated intercrop model reproduced the key feature of the tested additive intercropping: LER for AGB was always above one, thanks to a moderate decrease in sorghum ABG and despite a more pronounced decrease in cowpea AGB. This decrease is cowpea AGB with intercropping was probably linked to the competition for solar radiation that is primarily intercepted by sorghum canopy. This gives confidence in the ability of the Stics intercrop model to predict the behaviour of intercropping based on two plant species with contrasting heights. Chimonyo et al., (2016) found a similar promising feature of the APSIM model even though the two crop models do not simulate the radiation intercepted by the two intercropped crops in the same way. With APSIM, solar radiation is governed by a crop-specific coefficient that describes the relationship between biomass and photosynthetically active radiation intercepted - the radiation use efficiency (RUE) (g MJ -1) (Sinclair and Horie, 1989). For the STICS crop model, it uses Beer's law to calculate the radiation interception for single crops. For intercrops, however, the STICS model differs in this respect and uses a "radiative transfer" formalism to calculate the radiation interception (see Section 2.6).

The grain yield advantage of the improved variety over the local variety, and the yield advantage of N input over no fertilization, were also fairly well simulated. The model simulated less accurately but reasonably well the observed differences in yield resulting from the differences in water stress occurrences between our two experimental years, under intercropping conditions. The model thus makes it possible to identify complex interactions between growing season characteristics, N inputs, and the competitions at stake in the intercropping system. While competition for water clearly prevailed in the intercropping situations of 2017, the simulations suggested that competition for nitrogen occurred in those of 2018, with clearly less water stress. Such competition for nitrogen can be surprising - because cowpea is a legume that fixes atmospheric nitrogen. Cowpea did fix nitrogen in the experiment. The observed N uptake for sole sorghum without N fertilizer was 90 kgN/ha (i.e which indicates that at least 90 kgN/ha was provided by the mineralization of soil organic matter). Sole cowpea with no fertiliser input achieved a N uptake above 200 kgN/ha. This indicates a possible N_2 fixation of at least 110 kgN ha^{-1} (on top of the 90 kg N/ha provided by the soil organic matter mineralisation). However, N competition can still occur when mineral fertilizer are applied. High level of soil mineral N can depress the amount of atmospheric N_2 that is fixed by the legume (Sprent et al., 1988). This decrease in legume N_2 fixation with mineral fertilizer input has been observed in wheat-pea and barley pea-experiments (Bedoussac and Justes, 2010;

Corre-Hellou et al., 2009), and this process is accounted for by the Stics model (Brisson et al., 2009). Detailed measurement of the amount of N_2 fixed by the legume (using ^{15}N natural abundance method), in sole and intercropping, would be required to validate this simulated competition for nitrogen in 2018.

3.4.2 Avenues to improve model calibration

Despite the promising features of the model, prediction error of crop AGB and grain yield remained rather large (in the range 29-49%), compared with other studies. Chimonyo et al. (2016) obtained rRMSE values for grain yield and aboveground biomass in the range 6-15% when simulating sorghum-cowpea intercropping in South Africa. Masvaya (2019) had rRMSE for grain yield in the range 18-29% when simulating grain yield of sorghum and cowpea in with sole and intercropping in semi-arid Zimbabwe.

In this study, the calibrated intercrop model failed to accurately predict the low yield of cowpea in the intercropping, and thus overestimated the intercropping LER for grain. In Stics, the number of grain (a key yield component) is determined by biomass growth during a short period before the beginning of grain filling (Falconnier et al., 2019). Accurately setting the length of this period, and set the parameters that define the relation between biomass growth and the final number of grain requires measurement of biomass growth during that period, along with measurement of the final number of grain, for a range of contrasting experimental conditions (e.g. with/without water and nitrogen stress) (Affholder et al., 2013). The latter was missing in our experimental setting, and more detailed measurement of biomass growth and final grain number would certainly be necessary to improve the accuracy of our calibration, and the resulting robustness of yield prediction under water stress during reproductive stage, which showed to be insufficient for the model to predict correctly the impact of water stress in some cropping situations in our experiment. Caution should therefore be taken in the interpretation of the simulated inter-annual variation in grain yield of intercropping when using historical weather records and/or future climatic series.

The model also overestimated grain yield of sorghum and cowpea with no N input. This is possibly related to the poor simulation of N uptake by both sorghum and cowpea. Measurement of initial soil mineral N prior to sowing and during crop growth would possibly help improve the calibration of the mineralization of soil organic matter and crop N uptake. These improvements in model calibration with regard to yield component and yield with no N input are required to improve our confidence in the prediction of intercropping LER for grain. This will be crucial if the model is to be used for virtual experiments where sustainable intensification pathways with intercropping are tested.

Late planting of sorghum resulted in smaller yield, and the model could not reproduce this behavior. Late sowing of photoperiodic plant decrease the length of their growing cycle, thus directly lowering the amount of radiation intercepted and the final yield (Tovignan et al., 2016). Such effect should be smaller with the less-photoperiodic variety for which late planting does not translate into shorter growing cycle. But the improved variety was also impacted by late sowing. Possibly, the late plantings were negatively impacted by excess water in the plots (anoxia), a process that can be taken into account by the Stics model, but that we did not calibrate due to lack of appropriate data on soil water conductivity under saturated conditions. Low nitrogen availability due to runoff (sowing during the period of intensive rainfall), or armyworm damage on sorghum could also possibly contribute to the discrepancy between observations and model simulations. Armyworm damage was observed on sorghum plants during the 2018 season but their impact on yield was not assessed. The Stics model does not simulate the impact of pests on the crop.

3.4.3 A calibrated intercrop model to explore options for sustainable intensification in land constrained sub-Saharan Africa

Our experimental design investigated the crucial features of sustainable intensification, namely the integration of legumes with intercropping, the use of mineral fertilizer, combined with improved varieties (Vanlauwe et al., 2014). The calibrated intercrop model was able to mimic the key main effects and interactions at play when investigating the performance of these options. Hence, it can be a crucial tool to explore pathways toward sustainable intensification of agriculture in land constrained sub-Saharan Africa. Intercropping is generally a better option with low fertilizer inputs (Bedoussac et al., 2015; Yu et al., 2015). Our experimental results also support such claim. This contrasts with the now widely acknowledged need for sustainable intensification of agriculture with more mineral fertilizer in sub-Saharan Africa (Jayne et al., 2018). The predicted increase in climate variability and climate change in sub-Saharan Africa (Sultan and Gaetani, 2016a) may alter such picture, as intercropping is also well known to stabilize yield (Weih et al., 2021a). Crop models and crop models ensembles are great tools to investigate the interactions between crop management and climate variability and change in sub-Saharan Africa (Falconnier et al., 2020). The increasing availability of promising calibrated intercrop model (e.g. this study, Chimonyo et al. (2016); Masvaya (2019)) offer the prospect of ensemble simulation of the performance of intercropping in the face of climate variability and change, in order to guide the design of adaptive cropping system involving intercropping.

3.5 CONCLUSION

Our study showed that the locally calibrated intercropping version of the STICS soil-crop model displayed some promising features to explore the performance of the sorghum-cowpea intercropping system under tropical rainfed environment. In the experiment, sorghum and cowpea aboveground biomass and yield decreased with intercropping compared with sole cropping, but observed LER for aboveground biomass remained above one, regardless of experimental treatment (fertiliser, sowing date and sorghum variety). The calibrated model accurately depicted this overall trend related to LER for aboveground biomass, and satisfactorily accounted for the impact of fertiliser and sorghum variety. It can therefore be a useful tool to understand the competitions that occur between the intercropped species in this additive cereal-legume intercropping systems in tropical rainfed environment, under the framework of sustainable intensification and integrated soil fertility management. Despite this promising feature of the model, large inaccuracies in the simulated leaf area index and N uptake were observed. The detrimental impact of late sowing on sorghum yield, possibly because of anoxia, was also poorly accounted for. Though the model can be used to explore the impact of inter-annual climate variability on intercropping performance, these limitations will constraint the ability of Stics Intercrop to accurately and meaningfully portray the interactions at stake when crop management varies strongly. We therefore advocate for increased, continuous and detailed experimental effort on cereal-legume intercropping systems (e.g. measurement of soil mineral N, N_2 fixation, and grain number for a great range of contrasted cropping situations), in order to improve the calibration of parameters related to water and N stress. This will improve model ability to deal with intercropping, a key management option for sustainable intensification of smallholder farming in the global South.

CHAPITRE IV

Chapitre IV : Is cereal legume intercropping a relevant adaptation to climate variability and climate change ?

4.1 INTRODUCTION

Food security has become a major challenge for West Africa, which must produce more to feed a rapidly growing population (FAO, 2016b). Availability of arable land is limited, so that the sustainable intensification of agro-systems has proved to be the agrarian transition to be favoured to avoid excessive artificialisation of the environment and the associated environmental and climatic risks (Affholder et al., 2014). According to the International Panel on Climate Change, climate change is a statistically significant change in the mean state of the climate in its persistent variation over a long period of time (decadal or longer) (IPCC, 2001). In the Sudano-Sahelian zone of Africa (SSA), the rainfall regime is highly dependent on the West African monsoon and shows significant variability on inter-annual and inter-decadal time scales. In addition, rainfall in the Sahel has experienced considerable variation and an overall reduction during the 20th century (Biasutti, 2013; Sanogo et al., 2015). In this region, the drought of the 1970s and 1980s was a major climatic signal in terms of rainfall (Roudier et al., 2011). According to Barrios et al., (2008), the changes observed in rainfall and temperature since the 1970s have led to significant changes in overall agricultural production. At the same time, simulations from the CMIP6 project (Couped Models Intercomparison Project stage 6) support previous assessments of an important role of anthropogenic emissions in modifying rainfall in the Sahel. The direct effect of elevated [CO2] is to strengthen the monsoon, while warmer Sea Surface Temperature (SST) induces drying over the Sahel. Historical simulations have indicated the degree of drying of the Sahel during the 20th century, and confirm that anthropogenic pressures have largely contributed to it (Ackerley et al., 2011). Also, alternation of dry and wet events has major societal consequences, and agricultural systems should therefore be strongly affected (Roudier et al., 2011). Overall, these impacts will lead to greater losses in developing countries, where populations are highly dependent on the use of natural resources. According to Roudier et al. (2011), about 80% of all cereals consumed in SSA is supplied by domestic production. And agriculture is an extremely vulnerable sector in this region, where it is essentially rainfed (96% of all cultivated land) (Wani et al., 2009). In addition, the use of crop management and intensification strategies seems to be an unavoidable path to follow in the region. While agriculture provides sinks for greenhouse gases (GHGs), it also provides sources, and it is estimated that 20% of the greenhouse effect is related to agricultural activities, such as the conversion of virgin soils into cultivated land (Reddy and Hodges, 2000). A better understanding of the impacts of climate on crop yields is needed to select more resistant crop varieties or to select cropping techniques and varieties that are more resistant to climate-induced stress. However, varietal and crop management adaptation is challenged by the uncertainties in climate change scenarios and in the response of crops to climate change. Studies carried out in West Africa show a wide dispersion of yield changes with climate change, ranging from -50% to +90%, with a median yield loss of 11% (Roudier et al., 2011). Sultan et al. (2013) simulated crop yield in 35 stations across West Africa with 35 future climate scenarios and showed that most of the 35 scenarios had a negative impact on crop yield. Climate change projections for West-Africa have indicated a temperature increase between 1.1 and 4.8°C and greater differences in rainfall between wet and dry seasons at the end of the 20th century (Stocker et al., 2013).

Faced with the uncertainty in current and future climate conditions, stabilizing crop yields is becoming a major challenge for agricultural production in West Africa to ensure sustainable food security. Diversification of cropping systems in time and space offer the prospect of stabilising crop production (Raseduzzaman and Jensen, 2017). Intercropping of two or more species in the same field is a diversification practice that can also contribute to ecological and sustainable intensification of crop production. Legumes offer good prospects to increase yield in line with the principles of ecological intensification: legumes can improve soil fertility (Gbakatchetche et al.,2010), and provide crucial nutrients carry-overs for the subsequent cereal crop (Carsky et al., 2003). Intercropping of sorghum and cowpea could help adapt to climate variability: at any level of disaster, the intercrop system usually have a much lower probability of overall yield failure than either of the individual crops (Rao and Willey, 1980). Intercropping could therefore improve stability of productivity: its yield stabilizing effect residing in inter-species facilitation (Affolder et al., 2014) or compensation i.e., the two different crops are less likely to both be lost due to e.g., disease, pest or extreme climate (Raseduzzaman and Jensen, 2017). In addition, one crop of the intercrop system can modify the microclimate of the other crop, which can be favourable for moisture conservation during drought periods or for pest and disease attacks, resulting in increased crop productivity and stability.

In this study, we used a set of crop simulation with the STICS soil-crop model to assess the impacts of climate change on the yield of sorghum, for a range of contrasting sustainable intensification options, including sorghum-cowpea intercrop. Sorghum (Soghum bicolor (L.) Moench) is one of the main food crops in West Africa (Sultan et al., 2014) and the cowpea variety that was investigated was a dual-purpose variety (seed for human consumption and fodder for animal feed). The study considered sole and intercropped sorghum for a diversity of cultural practices (fertilization, sowing dates, local and improved sorghum variety). We explored the hypothesis that (i) sorghum-cowpea intercropping help temper the often-observed negative effect of intensification practices on interannual yield variability with current climate, and (ii) this yield stability improvement thanks to intercropping is ensured with future climate.

4.2 MATERIALS AND METHODS

4.2.1. Study Area

We explored the effect of climate change on sorghum and cowpea in the old cotton basin (Koutiala region) of Mali. The soil-crop model was calibrated at the N'Tarla experimental station located in the old cotton basin (12.6193°N, -5.689°W). This region hosts about 40% of Malian total population and 50% of Mali's arable land (Traore et al., 2013). The climate of southern Mali is typical of the Sudano-Sahelian zone of West Africa. The rainy season extends from May to October. Average annual rainfall varies between 800 and 1000 mm and seasonal average temperature is 29 ◦C (Traore et al., 2013). Agricultural systems in the region are mixed agro-sylvo-pastoral systems. Cotton (Gossypium hirsutum L.) is the main cash crop, cultivated in rotation with cereals such as maize (Zea mays L.), millet (Pennisetum glaucum (L.) R.Br.), sorghum (Sorghum bicolor (L.) Moench) and legumes such as groundnut (Arachis hypogaea L.) and cowpea (Vigna unguiculata (L.) Walp.).

4.2.2 Experimental data, model calibration and model evaluation

The data for model calibration and evaluation originated from a sorghum-cowpea (sole and intercrops) experiment conducted in 2017 and 2018 at the N'Tarla experimental station. The impact of four factors was investigated: sorghum variety (a variety sensitive to photoperiod V1, and a variety less sensitive, V2), cropping system (sole cropping or intercropping), planting date (early sowing D1, late sowing D2) and fertilization (no nitrogen input F0, and 38 kg/ha nitrogen input F1). Sorghum and cowpea dates of emergence, beginning of grain filling and physiological maturity were recorded. Leaf area index (LAI) was measured during growing season (7 times for D1 sowing dates and 5 times for D2 sowing dates). In 2018 soil volumetric water content was measured with a Diviner 2000 probe placed in fixed vertical access PVC tubes inserted in the soil in each experimental plot. The tubes were installed two weeks before sorghum sowing (see details in Chapter 3). The crops were harvested after physiological maturity and total above ground biomass and grain yield were determined. The experiment was described in details in Chapter 3. Daily rainfall, minimum and maximum temperatures and insolation (converted to global radiation) were recorded at the N'Tarla meteorological station located about 100 m from the experimental field. In 2018, the combination of sorghum variety, cropping system, sowing date and fertilization defined 17 cropping situations that were used for model calibration. In 2017, there was only one fertilizer level, and treatment combinations led to 8 cropping situations that were used for model evaluation. Observations used for calibration included crop phenology, in-season soil moisture, in-season LAI, aboveground biomass and plant N, and grain yield and number of grains at harvest. Soil data used for model initialisation included pH, C/N ratio, and total topsoil nitrogen. Soil moisture at field capacity and wilting point were first estimated with pedo-transfer functions (Lidon and Francis, 1983) based on the texture measured in 2017 in a soil profile close to the experiment. To calibrate the thermal constants associated with the developmental stage, the model was forced to go through the observed dates of maximum leaf area index, flowering and maturity, in order to calculate the temperature sums corresponding to the intervals between the stages. Other soil and plant parameters were calibrated following a stepwise calibration procedure that is described in details in Chapter 3. Model performance was quantified by calculating:

- root mean square error (RMSE) with lower values indicating better agreement of the model with observed values;
- relative root mean square error (rRMSE) and model efficiency (EF) (Willmott et al., 1985), ranging from -∞ to 1 with higher values indicating better agreement between observed and simulated values.

We evaluated the performance of the STICS model to reproduce the effect of fertilization, sowing date and variety under sole and intercropping conditions with cowpea.

4.2.3 Climate scenarios

To build the scenarios, we used climate model simulations from the Coupled Model Intercomparison Project Phase 6 (CMIP6) for historical (1980-2010) and future (2035-2065) periods. The ssp5-8.5 scenario was used as the high greenhouse gas emission shared socio-economic trajectory (SSP) pathway (Meinshausen et al., 2020). In order to better understand the response of the climate system to a range of potential emission or concentration scenarios, the climate modelling community periodically undertakes large model intercomparison exercises with the latest and most sophisticated set of climate models (Meehl et al., 2007; Taylor et al., 2012). For this purpose, there are two main types of models, namely:

- Atmosphere-Ocean General Circulation Models (AOGCMs), i.e. physical climate models that can include components of biogeochemical models, such as vegetation or atmospheric chemistry. These models cannot project CO_2 concentrations from emissions due to an existing carbon cycle;

- Earth System Models (ESMs), i.e. climate models that can project CO_2 concentrations from emissions (Jones et al., 2016; Lawrence et al., 2016). These ESMs are also often run in 'CO_2 concentration-driven mode' to facilitate calculations and allow easier separation of carbon cycle feedbacks from climate responses.

To date, in the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016), AOGCMs and ESMs use concentrations of all non-CO_2 greenhouse gases to run multi-gas experiments (such as the future projections scenario) due to either missing non-CO_2 gas cycles or prohibitive computational burden.

Simulations from 21 general circulation models (GCMs) of the Coupled Model Intercomparison Project Phase 6 (CMIP6) were available. We selected seven GCMs based on availability (i.e. no missing information) of monthly values for rainfall and average, maximum and minimum surface temperatures for the study area for historical (1980-2010) and future (2035-2065) climate. These were UKESM1-0-LL, MIROC6, INM-CM5-0, INM-CM4-8, GFDL-ESM4, GFDL-CM4 and GISS-E2-1-G.

Rainfall, minimum and maximum temperatures simulated by the CMIP6 models were considered. These variables are key to determine plant response to climate change (Hatfield et al., (2011). For each climate model, monthly rainfall, minimum and maximum temperature were averaged across years for the historical (1980-2010) and future (2035-2065) periods. For the future period, simulations for ssp5-8.5 were considered. Deltas of average values of rainfall, minimum and maximum temperature between future and historical periods were calculated.

Deltas were computed as follows:

$$\Delta Tmax(i) = Future\_Tmax\ (i) - Historical\_Tmax\ (i) \qquad (1)$$

$$\Delta Tmin(i) = Future\_Tmin\ (i) - Historical\_Tmin\ (i) \qquad (2)$$

$$\Delta Rain(i) = \frac{Future\_rain(i) - Historical\_rain(i)}{Historical\_rain(i)}\ X\ 100 \qquad (3)$$

Where *ΔTmax(i), ΔTmin(i) and ΔRain(i)* are the difference between future and historical maximum temperature, minimum temperature and precipitation for month i. *Future_Tmax(i)* is average maximum temperature for future period and month i, *Historical_Tmax(i)* is maximum temperature for historical period and month i, *Future_Tmin(i)* is future minimum temperature for month i, *Historical_Tmin(i)* is historical minimum temperature for month i, *Historical_rain(i)* is the historical rain for month (i) and *Future_rain(i)* is future rain for month i.

Delta (Δ) values thus obtained were averaged across the seven models. To build the final future climate series used for crop model simulations, the average deltas were added to the daily values of Tmax, Tmin and rainfall observed at N'tarla weather station during the historical period.

Crop management options

A total of eight crop management options were considered in this study. The first option, "baseline sorghum" is the "baseline" management options, i.e. it portrays current farmers practice, see 1 in Table 1). Growing the local variety of sorghum as a sole crop without N application is indeed a common practice of farmers in the area. Though intercropping local variety of sorghum with cowpea, without N fertiliser is also practised by farmers, we wanted to be part of the basket of ISFM options for this study. ISFM crop management options (2-8 in Table 1) encompass increasing level of complexity and portray different possible steps towards "full ISFM" (Vanlauwe et al., 2014).

4.2.4 Virtual experiment: crop model simulations with historical and future climate

The STICS soil-crop model was used to (i) assess the performance of the eight-crop management option (Table 1) with current climate (1980-2010) and (ii) explore the impact of climate change on option performance and quantify their adaptation potential.

In total, 18 simulation units were constructed, corresponding to the eight cropping options of **Table 1** with two sowing dates. We used the calibrated soil parameters obtained in Chapter 3. The soil of Ntarla research station is a typical soil of the region. The calibrated STICS soil-crop model was run using historical current climate (1980-2010) observed at the N'Tarla station, and future climate (2035-2065) obtained with deltas computed from climate models projections for ssp5-8.5 (see section 2.3). In the simulations, we did not account for the effect of elavated atmospheric [CO_2] on crop growth and assumed that sorghum, as C4 plant, benefits relatively little from increased CO_2 concentrations (Taylor et al., 2014).

Table 1: Description of the actual crop management (Option 1: "baseline sorghum") and seven crop management options (2-8) tested to adapt to climate variability and change. ISFM = integrated soil fertility management, V1 = traditional variety, V2 = improved variety, D1 = early sowing date, D2 = late sowing date.

Option code number	Crop management	Innovation tested	description of the system	N fertilization	Sorghum Variety	sowing date
1	Baseline sorghum	-	Sole traditional sorghum - no fertilizer	0	V1	D1
						D2
2	ISFM intercropping	-	Intercropping traditional sorghum with cowpea - no fertilizer	0	V1	D1
						D2
3	ISFM variety	variety	Sole improved sorghum - no fertilizer	0	V2	D1
						D2
4	ISFM fertilizer	fertilizer	Sole traditional sorghum with fertilizer	150	V1	D1
						D2
5	ISFM fertilizer + intercropping	fertilizer + intercropping	Intercropping traditional sorghum with cowpea - fertilizer	150	V1	D1
						D2
6	ISFM variety + intercropping	variety + intercropping	Intercropping improved sorghum with cowpea - no fertilizer	0	V2	D1
						D2
7	ISFM variety + fertilizer	variety + fertilizer	Sole improved sorghum with fertilizer	150	V2	D2
						D2
8	ISFM variety + fertilizer + intercropping	variety + fertilizer + intercropping	Intercropping improved sorghum with cowpea - fertilizer	150	V2	D1
						D2

4.2.5 Analysis of options performance with current and future climate

To facilitate the comparison of sole and intercrop options, we determined the energy productivity (kcal/ha) of the studied options (Table 2 and 3) on the basis of grain yield of sorghum and cowpea and considering an energy content of 3290 kcal $kg^{-1}$for sorghum (FAO, 1995), and 1160 kcal kg^{-1} for cowpea (Masvaya, 2019).

For historical and future climate, we computed the 31-year average calorie productivity (Ym), its standard deviation (stdY) and coefficient of variation (CV = stdY / Ym). The coefficient of variation is widely used to quantify and compare the stability or variability of productivity from year to year, with a greater CV value indicating higher yield variability, i.e. smaller yield stability and vice versa (Smith et al., 2007; Willey and Rao, 1980).

Table 2: Effect of treatments on simulated average calorie productivity and its variability (CV in %) with historical and future climate (ssp245 = less pessimistic climate scenario, ssp585 = more pessimistic climate scenario) with early sowing with traditional variety V1 and improved variety V2, ISFM (Integrated Soil Fertility Management)

Options	**climate**	**variety**	**Average calorie productivity (kcal/ha)**	**Coefficient of variation (CV) of calorie productivity (%)**	**Calorie productivity gain (impact) (kcal/ha)**	**Relative difference in impact between future and current climate (%)**	**Relative difference in stability gains between future and current climate (%)**
Baseline sorghum	historical	V1	5334	27.13			
ISFM Variety	historical	V2	4509	25.38	-825		
Baseline sorghum	ssp585	V1	5821	30.17			
ISFM Variety	ssp585	V2	5185	30.43	-635	3.5	7.4
Baseline sorghum	historical	V1	5334	27.13			
ISFM Fertilizer	historical	V1	10459	14.39	5125		
Baseline sorghum	ssp585	V1	5821	30.17			
ISFM Fertilizer	ssp585	V1	9821	14.38	4000	-21.1	-11.2
Baseline sorghum	historical	V1	5334	27.13			
ISFM Variety Fertilizer	historical	V2	11514	16.76	6180		
Baseline sorghum	ssp585	V1	5821	30.17			
ISFM Variety Fertilizer sole crop	ssp585	V2	9516	17.03	3695	-46.6	-10.2
Baseline sorghum	historical	V1	5334	27.13			
ISFM Intercropping	historical	V1	4834	18.04	-500		
Baseline sorghum	ssp585	V1	5821	30.17			
ISFM Intercropping	ssp585	V1	5133	24.31	-688	-3.5	11.9
Baseline sorghum	historical	V1	5334	27.13			
ISFM Variety Intercropping	historical	V2	5622	18.70	288		
Baseline sorghum	ssp585	V1	5821	30.17			
ISFM Variety Intercropping	ssp585	V2	6089	25.44	268	-0.4	13.7
Baseline sorghum	historical	V1	5334	27.13			
ISFM Fertilizer Intercropping	historical	V1	6933	30.50	1600		
Baseline sorghum	ssp585	V1	5821	30.17			
ISFM Fertilizer Intercropping	ssp585	V1	5850	37.74	30	-29.4	15.5
Baseline sorghum	historical	V1	5334	27.13			
ISFM Variety Fertilizer Intercropping	historical	V2	12863	13.42	7530		
Baseline sorghum	ssp585	V1	5821	30.17			
ISFM Variety Fertilizer Intercropping	ssp585	V2	10855	13.61	5034	-46.8	-10.5

Table 3: Effect of treatments on simulated average calorie productivity and its variability (CV in %) with historical and future climate (ssp245 = less pessimistic climate scenario, ssp585 = more pessimistic climate scenario with late sowing date condition with traditional variety V1 and improved variety V2, ISFM (integrated soil fertility management).

Options	**climate**	**variety**	**Average calorie productivity (kcal/ha)**	**Coefficient of variation (CV) of calorie productivity (%)**	**Calorie productivity gain (impact) (kcal/ha)**	**Relative difference in impact between future and current climate (%)**	**Relative difference in stability gains between future and current climate (%)**
Baseline sorghum	historical	V1	5063	38.51			
ISFM Variety sole cropping	historical	V2	6409	40.15	1346		
Baseline sorghum	ssp585	V1	5146	31.79			
ISFM Variety sole cropping	ssp585	V2	6590	31.69	1444	1.9	-4.5
Baseline sorghum	historical	V1	5063	38.51			
ISFM Fertilizer sole cropping	historical	V2	10977	16.25	5914		
Baseline sorghum	ssp585	V1	5146	31.79			
ISFM Fertilizer sole cropping	ssp585	V2	8419	14.21	3273	-52.1	12.2
Baseline sorghum	historical	V1	5063	38.51			
ISFM Variety Fertilizer sole crop	historical	V1	9096	13.17	4033		
Baseline sorghum	ssp585	V1	5146	31.79			
ISFM Variety Fertilizer sole crop	ssp585	V1	7872	12.2	2726	-25.8	14.9
Baseline sorghum	historical	V1	5063	38.51			
ISFM Intercropping	historical	V1	6109	17.94	1046		
Baseline sorghum	ssp585	V1	5146	31.79			
ISFM Intercropping	ssp585	V1	6437	14.16	1291	4.8	7.7
Baseline sorghum	historical	V1	5063	38.51			
ISFM Variety Intercropping	historical	V2	5847	21.68	784		
Baseline sorghum	ssp585	V1	5146	31.79			
ISFM Variety Intercropping	ssp585	V2	6601	16.87	1455	13.2	4.9
Baseline sorghum	historical	V1	5063	38.51			
ISFM Fertilizer Intercropping	historical	V1	9294	13.49	4231		
Baseline sorghum	ssp585	V1	5146	31.79			
ISFM Fertilizer Intercropping	ssp585	V1	8814	8.91	3667	-11.1	5.5
Baseline sorghum	historical	V1	5063	38.51			
ISFM Variety Fertilizer Intercropping	historical	V2	11947	13.83	6884		
Baseline sorghum	ssp585	V1	5146	31.79			
ISFM Variety Fertilizer Intercropping	ssp585	V2	9670	9.97	4524	-46.61	7.43

4.2.6 Quantify the potential for adaptation of the crop management options

To assess the potential for adaptation of each of the technical options studied, we used two different frameworks: (i) the selection of 'no-regret' strategies (Hallegatte, 2009), and (ii) the potential for adaptation, as designed by Lobell (2014). We assessed the impact of current and future climate on average calorie productivity and its coefficient of variation (CV) for the baseline sorghum and the seven ISFM options studied as potential adaptation strategies (Table 1).

The 'no-regret' strategies are technical options that yield benefits (greater calorie productivity, less variability) even in absence of climate change (Hallegatte, 2009). Considering the high uncertainty in climate change scenarios, it consists in choosing an option that would be beneficial both in historical climate and in all possible future scenarios, an option that farmers and the society will not regret in the future. If we consider changes in mean calorie productivity and its variability, adopting a new technical management could fall into four categories **(Figure 1b**): the best option should lead to greater and more stable calorie productivity, two intermediate options which improve either stability of productivity or average productivity and the worst case where both stability and average productivity are decreasing. In order to identify the "no regret" options, we first computed changes in mean productivity and coefficient of variation between the seven intensification options (option 2 to 8, see Table 1) and the "baseline sorghum" option (Table 1). This computation was done both for the historical and future climate. We then attributed a score of +2 when an option falls into the best category (more productivity and less variability), a score of +1 when an option falls into one of the two intermediate options (less variability or more productivity), and 0 for the worst case (more variability or less productivity). We then cumulated the score for the historical and the future climate to get what we called a "no-regret" score which is ranging from 0 (the option gives smaller productivity and greater variability with current and future climate) to 4 (the option gives greater productivity and smaller variability with current and future climate) (Fig. 1b).

The framework developed by Lobell (2014) (Fig. 1a) suggests that any change that improves overall production and reduces variability can credibly be considered an adaptation to climate change, only if the benefits are greater with future climate than with current climate. We used the framework proposed by Guan et al., 2017 (Fig. 1c) to quantify the adaptation impact of an adaptation option with current climate, and the change in this impact with future climate. In Figure 1a, we assume that X is the conventional management and Y is the new counterpart in a changing climate, and then we evaluated whether the options can both benefit farmers in the current climate and reduce the impacts of climate change. For example, if A= productivity of improved sorghum variety without fertilizer (option 4 in table 1) with current climate, B= productivity of local variety without fertilizer (option 1 in Table 1) with current climate, C= productivity of option 4 with future climate and D= productivity of option 1 with future climate, then (A-B) is the absolute change in productivity attributed to option 4 with current climate and C-D is the change in productivity attributed to V2 with future climate. If (C-D) ≤ (A-B) then the gain with V2 is smaller with future climate than with current climate and therefore option 4 (varietal shift) is not a true adaptation (bottom-right quadrant in Figure 1c). On the other hand, if (C-D)>(A-B) then advantage of using V2 instead of V1 is greater with future climate and is therefore a relevant adaptation to climate change (top-right quadrant in Figure 1c). The same process can be applied for the other ISFM options of Table 1 taking the first option, i.e. "baseline sorghum" as a reference for all comparisons.

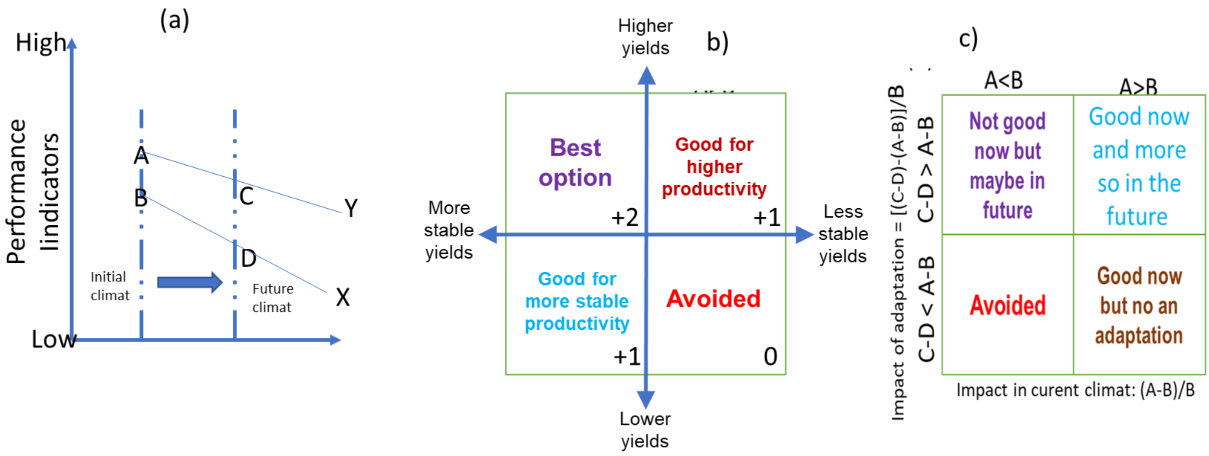


Figure 1: (a) Framework for the assessment of the impacts of crop management options. Line X refers to baseline crop management, and Y refers to the new counterpart in a changing climate (from Lobell, 2014), (b) A framework for assessing adaptation options taking based on the "no-regret" strategy: a score of 2 was attributed when an option falls into the best category (more yield and less variability), 1 when an option falls into one of the two intermediate options (less variability or more yields), and 0 for the worst case (more variability or less yield). The score with historical climate was added to the score with future climate so that the final score ranges from 0 (the option gives lower yields and higher variability with current and future climate) to 4 (the option gives higher yields and less variability with current and future climate) and, (c) A framework for assessing adaptation options taking into account the impact in the current (or historical) climate (i.e. (A - B) / B) and the impact of adaptation with future climate (i.e. [(C - D) - (A - B)] / B), adapted from Guan et al., 2017. We have called this framework " true adaptation ".

4.3 RESULTS

4.3.1 Performance of crop model with regard to experimental data

The model satisfactorily reproduced the variability of sorghum and cowpea aboveground biomass in the experiments used for model calibration with rRMSE of 23% and model efficiency (EF) of 0.81 (see Chapter 3). The variability in grain yield observed between crops and treatments was fairly well reproduced by the model. Although rRMSE was great (49%), model efficiency (EF) in reproduce the variability of yield induced by the different treatments (sole crop, intercrop, sowing date, fertilization) was 0.56. Overall, the model rightly picked-up the direction of the changes observed in the experiments: sorghum and cowpea grain yield decreased when intercropped, the improved variety outperformed the local variety for aboveground biomass, aboveground biomass of sorghum increased with N input, but not cowpea biomass, and aboveground biomass and grain yield of cowpea and sorghum were smaller in 2017 than in 2018 However, aboveground biomass and grain yield of sorghum and cowpea decreased with late sowing compared with early sowing, and the model failed to reproduce such a drop in yield. Furthermore, the negative impact of intercropping on sorghum yield was weaker than in 2018 and the model also failed in reproducing such effect as it simulated a more pronounced detrimental effect of intercropping on sorghum yield in 2017 than in 2018 (see Chapter 3 for more details).

4.3.2 Historical and future climate at Ntarla

The seven CMIP6 climate models gave a fair simulation of the characteristics of the growing season at N'Tarla with regard to rainfall, i.e. a start around May and an end in October, with a the peak in August (Figure S1a). However, there was a strong discrepancy between model simulation and observations with regard to monthly rainfall (Figure S1a) and annual rainfall (Figure S2). The climate models "GFDL-ESM4" and "GFDL-CM4" reproduced a particularly great peak of rainfall in August, much stronger than the observations and the other models. MIROC6 model was closest to the observations (Figure S1a). There was a large discrepancy between climate models with regard to simulated total rainfall in the future (Figure S1b). Total rainfall increased overall in the future compared to the historical period for all climate models except GFDL-ESM4 and UKESM1-0-LL that simulated a decrease in rainfall in the future (Figure S2). The climate model "MIROC6" that was closest to historical rainfall simulated an increase in total rainfall in the future.

On average, simulated monthly maximum temperature of the seven climate models fairly agreed with observed monthly maximum temperatures over the historical period (Figure S3a). Monthly maximum temperature increased in the future period compared to the historical period

(Fig S3a). Averaged across the seven climate models, monthly simulations of minimum temperature overestimated the historical observation (Fig. S3c). Monthly minimum temperature increased in the future period compared to the historical period (Figure S3c). Though all climate models simulated an increase in maximum and minimum temperature with future climate, they did not agree on the magnitude of this change (Fig. S3b, d). The difference in simulated average maximum temperature between future and historical climate was greatest for UKESM1-0-LL model (+3.6 °C) and between 1.5 and 2.1 °C for the other climate models (Fig. S3b). For minimum temperatures, "UKESM1-0-LL" and "GISS-E2-1-G" models simulated the greatest increase.

4.3.3 Simulated average performance of crop management options and their inter-annual variability

Average calorie productivity was greater with future climate than with current climate for the options “baseline sorghum”, “ISFM Intercropping”, “ISFM Variety” and “ISFM Variety + Intercropping” in early sowing dates (Figure 2a, b, c, f). For these options, the coefficient of variation of calorie productivity was greater with future climate than with current climate, so that an increase in calorie productivity with future climate went hand in hand with an increase in inter-annual variability of this productivity. On the contrary, average calorie productivity was smaller with future climate than with current climate for the options that included the use of fertiliser, namely "ISFM fertilizer ", "ISFM variety + fertilizer, "ISFM fertilizer + intercropping", "ISFM variety + fertilizer + intercropping" (Figure 2d, e, g, h). For these options, a decrease in average calorie productivity with future climate went hand in hand with a decrease (or similar) coefficient of variation, except for the "ISFM fertilizer + intercropping" option for which coefficient of variation of calorie production increased with future climate.

For the late sowing dates, average calorie productivity with future climate increased for the options "baseline sorghum", "ISFM Intercropping", "ISFM Variety" and "ISFM Variety + Intercropping" (Fig. 2a, b, c, f). However, the variability of calorie productivity was smaller with future climate than with current climate (Fig. 2a, b, c, f). Hence, the increase in average calorie productivity went hand in hand with a decrease in inter-annual variability for the options that did not include the use of fertiliser. For the options that included the use of fertiliser, i.e. "ISFM fertiliser", "ISFM variety + fertiliser", "ISFM fertiliser + intercropping", "ISFM variety + fertiliser + intercropping", average calorie productivity decreased with future climate, and so did inter-annual variability (Fig. 2d, e, g, f).

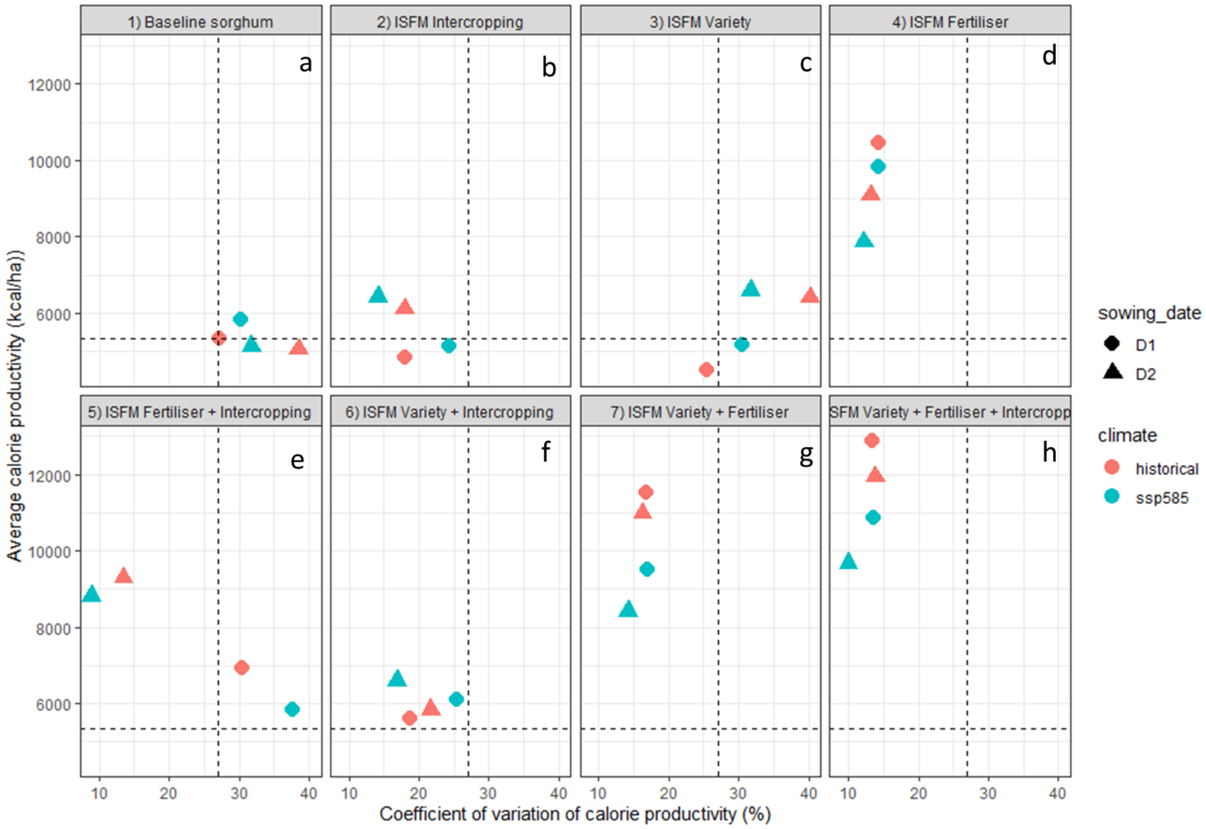


Figure 2: Average calorie productivity (kcal/ha) of seven crop management options and their interannual variability for early sowing and late sowing. ssp585 = more pessimistic climate scenario, ISFM = integrated soil fertility management. The horizontal dotted line in Figure 2 shows the average calorie productivity of the "baseline sorghum" option wit current climate, and the vertical dotted line shows the coefficient of variation of this option with current climate. D1=early sowing, D2=late sowing.

4.3.4 Assessment of adaptation potential of the crop management options

No regret strategy framework (as portrayed in figure 1b)

With early sowing, the best options, i.e. those with the greatest "no regret" score of four, included fertilisation and/or fertilisation and improved variety in sole crop or intercropping, except for the "ISFM Fertilizer Intercropping" option that had a lower score of two (Table 4). The option "ISFM Variety" in early sowing had the lowest "no regret" score of 0.

With late sowing date condition, all options had the greatest "no regret" score of 4, except the "ISFM Variety" option that had a score of three (but greater that the score of that same option with early sowing).

Table 4: Assessing the adaptive potential of crop management options under the no-regrets policy framework

Option N°	Option	Sowing date	No-regret Score	Potential for adaptation in mean calorie productivity	Potential for adaptation in variability of calorie productivity
1	Baseline sorghum	Early	2	NA	NA
2	ISFM Intercropping	Early	2	avoided	Good now but not an adaptation
3	ISFM Variety	Early	0	Not good now but may be in the future	Good now but not an adaptation
4	ISFM Fertilizer	Early	4	Good now but not an adaptation	Good now and more in the future
5	ISFM Fertilizer Intercropping	Early	2	Good now but not an adaptation	avoided
6	ISFM Variety Intercropping	Early	4	Good now and more in the future	Good now but not an adaptation
7	ISFM Variety Fertilizer	Early	4	Good now but not an adaptation	Good now and more in the future
8	ISFM Variety Fertilizer Intercropping	Early	4	Good now but not an adaptation	Good now and more in the future
1	Baseline sorghum	Late	0	NA	NA
2	ISFM Intercropping	Late	4	Good now and more in the future	Good now but not an adaptation
3	ISFM Variety	Late	3	Good now and more in the future	Not good now but maybe in the future
4	ISFM Fertilizer	Late	4	Good now but not an adaptation	Good now but not an adaptation
5	ISFM Fertilizer Intercropping	Late	4	Good now but not an adaptation	Good now but not an adaptation
6	ISFM Variety Intercropping	Late	4	Good now and more in the future	Good now but not an adaptation
7	ISFM Variety Fertilizer	Late	4	Good now but not an adaptation	Good now but not an adaptation
8	ISFM Variety Fertilizer Intercropping	Late	4	Good now but not an adaptation	Good now but not an adaptation

Adaptation potential framework (as portrayed in figure 1c)

The average calorie productivity of “baseline sorghum” option with early sowing and current climate (situation B in Figure 1a) was 5334 kcal/ha (Table 2). Intensification of sorghum cultivation with fertilizer, i.e the option "ISFM fertilizer" (situation A in Figure 1a) had smaller average calorie productivity with future climate (9821 kcal) than with historical climate (10451 kcal/ha) (Figure S4c). Therefore, the benefit of fertilization decreased with future climate: the simulated relative difference in impact between future and current climate was negative (-21%). The “ISFM fertiliser” option fell in the category “good now but not an adaptation” (Fig. 3A). Other options fell into this category, namely “ISFM Fertilizer + Intercropping", “ISFM Variety + Fertiliser” and "ISFM Variety + Fertilizer + Intercropping" (Fig. 3A). For the "ISFM

Intercropping" option (early sowing), the simulated average calorie productivity with current climate was 4834 kcal/ha, versus 5334 kcal/ha for baseline sorghum. The simulated caloric productivity with the future climate was 5133 kcal/ha with the same option versus 5821 kcal/ha for the baseline sorghum. The relative yield loss due to this option was 3.5% greater with future climate (Table 2, Figure S4a). Based on the framework of Figure 1c " true adaptation ", this option does not meet the conditions for adaptation to climate variability and change and fell into the category “avoided” (Fig. 3A). With current climate average calorie productivity of the option “ISFM variety” was smaller than the one of the baseline options “baseline sorghum”. But this loss in calorie productivity was smaller with future climate (Table 2, Figure S4b, which made this option fall into the category “not good now – but maybe in the future” (Figure 3A). With the late sowing dates and options "ISFM variety", "ISFM intercropping" and "ISFM variety + intercropping", gains in average calorie productivity were greater with future climate than with current climate, which made them fall into the category "good now and more so in the future" options (Table 3, Fig. 3A).

When looking at the coefficient of variation of calorie productivity, negative gains were the objective, i.e. decrease in inter-annual variability meaning more stability of calorie productivity. Therefore, the interpretation of the different quadrant’s changes (see Figure 3B). The options "ISFM variety + fertilizer + intercropping", "ISFM Fertiliser" and "ISFM variety + fertilizer" with early sowing were classified into the category as "good now, and more so in the future" (Fig. 3B). Interestingly, the options classified as "good now, and more so in the future" when looking at average calorie productivity ("ISFM variety", "ISFM Intercropping" and "ISFM variety + Intercropping", with late sowing) fell into the "good now - but not an adaptation" category when looking at coefficient of variation of calorie productivity (Fig. S5).

Final classification of options

With early sowing, though many options had a strong “no-regret potential” (greatest score of 4), only the " ISFM Variety Intercropping" option was “good now, and more so in the future” when looking at average productivity (Table 4). The three ISFM options with fertiliser were “no regret options” and also “good now, and more so in the future” when looking at variability of calorie productivity (Table 4). No option combined the advantage of being a “no regret” option, and “good now, and more so in the future” for both average calorie productivity and variability productivity. With late sowing, most options had the maximum "no regrets" score of 4, and only three options were “good now, and more so in the future” with regard to average calorie productivity (ISFM Intercropping, ISFM Variety, ISFM Variety Intercropping). No options were true adaptation (good now, and more so in the future) with regard to variability of calorie productivity.

Overall, intercropping does not seem to be a panacea to adapt current sorghum cropping systems to climate change. The relevance of intercropping depends on the sorghum variety, the level of mineral fertiliser, and the sowing date. The full combination of ISFM options (i.e. improved sorghum variety with increased use of mineral fertiliser and integration of a legume with intercropping) did not offer the maximum benefits in terms of adaptation.

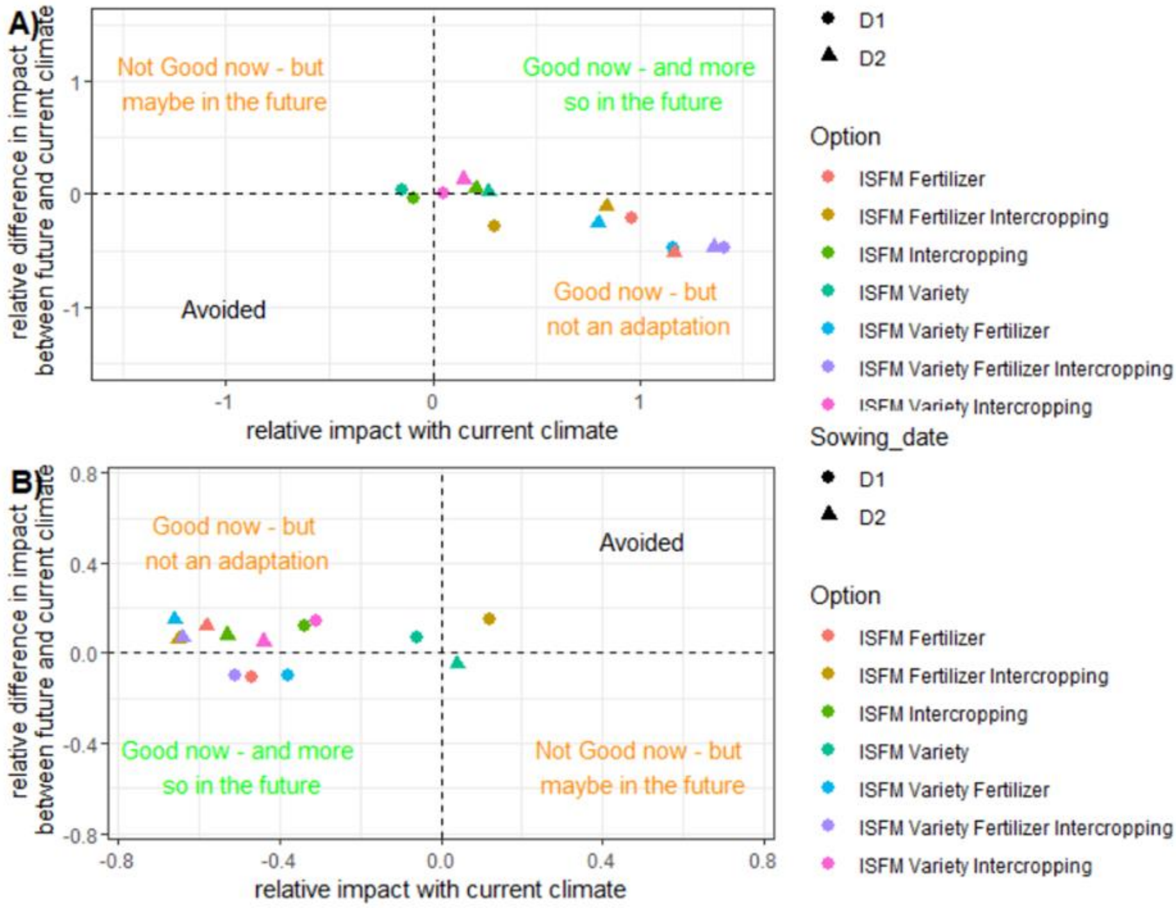


Figure 3: Relative impact of seven options on average calorie productivity (A) and coefficient of variation of calorie yield (B) for current climate (x axis) and future climate (y axis). D1: early sowing; D2: late sowing. The vertical and horizontal dotted line delimit for areas as described in Figure 1c.

4. 4 DISCUSSIONS

4. 4.1 Simulation of climate models

There was great disparity between the seven climate models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) with regard to the changes in monthly amount of rainfall. Roudier et al. (2011) have also highlighted the uncertainties of climate models for the simulation of future precipitation. All climate models except one agreed on a future increase in rainfall, in line with the findings of Muller et al. (2015) in a similar area to the one of this study. All models agreed with an increase in temperature in the future, in line with the expected increase in temperatures across West Africa with an average warming of around 2.8°C (Guan et al., 2017a; Sultan et al., 2014).

4.4.2 Average calorie productivity and its coefficient of variation for the different crop management options

Early sowing

The simulated average calorie productivity of sole crop sorghum was greater with future climate than with current climate. Though we did not take into account the increase in atmospheric [CO_2], it is possible that this increase was related to the increase in rainfall simulated by the average of the seven CMIP6 climate models for future climate. The average rainfall simulated by the seven CMIP6 models was 824 mm in the future scenario (ssp5-8.5) and 774 mm with the current climate (Table S1). To our knowledge, CMIP6 climate simulations have not been used to assess the impact of climate change on sorghum in West Africa so far, so that we cannot compare our simulation results to other studies.

The inter-annual variability of calorie productivity was greater with future climate than with current climate for options such as "ISFM intercropping", "ISFM variety", "ISFM fertilizer + intercropping" and "ISFM variety + intercropping". This increase in the variability of calorie productivity is in agreement with the study of Sultan et al. (2014) who also found variability in the average yield of crops such as sorghum and millet with future climate. In contrast, inter-annual variability was lower in the future climate with options such as those that included fertilisation and variety, "ISFM fertilizer", "ISFM variety + fertiliser" and "ISFM variety + fertiliser + intercropping". Nitrogen input combined with the use of the improved variety (the " ISFM Variety + Fertilizer" option) increased average calorie productivity compared with the sorghum baseline option regardless of the climate (future or current). The coefficient of variation was smaller with this option, i.e. below 20% in both future and current climates. The same trend was observed with the intensification of sorghum cropping system with improved variety, nitrogen input, and intercropping (ISFM variety + fertilizer + intercropping). According to Vanlauwe et al. (2010), the first step towards integrated soil fertility management (ISFM) is the recognition of the need for fertilisers and improved varieties. In rainfed agriculture in semi-arid environments, increases in yield with fertilisation can lead to overconsumption of water resources by the crops, which can deplete the reserves more quickly if a drought episode occurs, leading to stronger inter-annual yield variability of intensified cropping systems (Affholder, 1997, 1995). Contrastingly, our results showed that with early sowing, the intensification options including fertilizer had lower inter-annual yield variability compared with the no-fertiliser baseline sorghum. Our study focused on the coefficient of variation (CV in %) to compare the stability or variability of calorie productivity. The coefficient of variation has been widely used to quantify and compare the stability or variability of yields from year to year of crops, with a greater CV value indicating greater yield variability, i.e. smaller yield stability and vice versa (Smith et al., 2007; Willey and Rao, 1980). However, other indicators such as yield failure rate (Guan et al., 2017) can also be used to compare the stability or variability of crop yields from one year to another.

Late sowing

With late sowing, the simulated average calorie productivity was smaller than with early sowing, in line with the study of Traore et al., (2017) who simulated a 70% decrease in maize and millet yield with late planting compared to early planting in southern Mali. Other studies (Kamara et al., 2009) have also shown the importance of planting date for improving crop productivity. On the other hand, we found greater inter-annual variability in calorie productivity with late sowing than with early sowing for the baseline sorghum crop indicating greater stability in calorie productivity with early sowing compared to late sowing. Inter-annual variability was also more pronounced with current climate than with future climate. With late sowing, adaptation options including the variety, "ISFM variety", "ISFM variety + intercropping" and intercropping "ISFM intercropping" also had smaller variability of calorie productivity with future climate in contrast to what was observed with the early sowing dates. Our simulations with the STICS soil crop model are in agreement with those of Guan et al. (2017) who simulated an increase in yield variability with late sowing dates using the APSIM model. With the SARRA model, these authors found a reduced variability for late sowing dates, which contrast with our simulations. The options including variety and fertilizer "ISFM variety + fertilizer" and "ISFM variety + fertilizer + intercropping" displayed similar behaviour in late and early sowing, i.e. a slightly smaller inter-annual variability with future climate than with current climate indicating a greater stability of calorie productivity when combining variety and fertiliser for the intensification of sorghum cropping systems.

4.4.3 Impact of adapting different options to climate variability and change

When looking at average calorie productivity, two options that involve the use of variety, namely « ISFM variety » and « ISFM Variety Intercropping » fell within the category of relevant adaptation that are « good now, and more so in the future » But this held true only for late sowing. This means that the advantage of improved variety as an adaptation option only holds for late sowing. Regardless of sowing date, Sultan et al., (2019, 2014) found that the negative impacts of climate change on average yield and yield variability were lower for photoperiod insensitive cultivars.

The benefit of intensification with nitrogen input, i.e. the “ISFM fertiliser” option, was smaller in the future climate than in the current climate. This result is consistent with the findings of the studies of Guan et al. (2017) and Sultan and Gaetani (2016). Plants that are better fertilised are more sensitive to the adverse effects of climate (water and heat stress): climate change reduces the potential for intensification with more nutrients. The options combining variety with fertiliser and intercropping ("ISFM variety + fertiliser", "ISFM variety + fertiliser + intercropping") fell into the “good now, and more so in the future" category when looking at the coefficient of variation: our study shows that these options are relevant adaptation to increase yield stability in the future compared with baseline sorghum. This contrast with the general finding that the use of fertilisation as an intensification option increases the climatic risks in the case of drought periods (Affholder, 1997, 1995).

The list of relevant adaptations (options that are "good now - and more so in the future") changed according to the indicator considered for evaluation. When aiming at increasing average calorie productivity, adaptation options that proved to be relevant were those that included the improved variety with late sowing. When aiming at decreasing inter-annual yield variability, the options with fertiliser were relevant, i.e. "ISFM fertilizer", "ISFM variety + fertilizer", "ISFM variety + fertilizer + intercropping" with early sowing.

In smallholder agriculture, farmers practise intercropping to produce and sell grains for food security and as a livelihood basis (Raseduzzaman and Jensen, 2017). The stability of food production is considered an important factor for food security in tropical regions (FAO, 2013). The main reasons for variability in cereal crop yields in tropical conditions are year-to-year climatic variations caused by high temperatures and low and erratic rainfall, as well as the incidence of crop pests and diseases. It has been suggested that if the current trend of climate change continues, food production in the tropics will be challenging in the future, but this problem can be solved by promoting intercropping in arable crop production (Altieri et al., 2015). Our study shows that ISFM options including variety and intercropping "ISFM variety

+ intercropping" and "ISFM variety + fertilizer + intercropping" with early sowing date conditions can be considered as adaptation options because calorie productivity of these options is more stable than the calorie productivity of baseline sorghum, and because this gain in stability increases with climate change. In smallholder farms in southern Mali, the combination of different options (fertiliser, variety, intercropping) can be a way to achieve the objective of stabilising yields.

The evaluation of adaptation options using 'no-regret' strategies resulted in the identification of more adaptation options with early sowing, compared with the identification made with the "true adaptation" framework (Figure 1c). Also, with the "no regrets" method, almost all adaptation options produced benefits in terms of either productivity and/or productivitiy stability for the late sowing dates. Adaptation options identified with the no-regrets method can produce benefits even in the absence of climate change (Hallegatte, 2009).

4.4.4 Limitations of the study

In the simulations, we did not consider the effects of elevated [CO_2] on the efficiency of photosynthesis and plant transpiration. Plants that grow in an environment with greater [CO2] increase their rate of photosynthesis, leading to an increase in yield, that is stronger for temperate crops than for C4 drought-resistant crops characteristic of tropical and hot arid regions (e.g. maize, sorghum and millet) (Rosenzweig and Parry, 1994; Sage et al., 2011). We assumed that sorghum as a C4 plant benefits relatively little from increasing atmospheric [CO_2] (Taylor et al., 2014). But cowpea is a C3 plant and may benefit more from elevated [CO_2]. However, the effects of increased temperature coupled with changes in soil moisture usually outweigh the countervailing effects of increased [CO_2] on crop yield (Rosenzweig and Parry, 1994). Seven out of the 21 available climate models were used. Hence, we may not have explored the full span of possible future climate. Eventually, the delta method used to build future climate does not take into account changes in the distribution of rainfall events such as intense rainfall, dry spells and shifting of the rainy season pattern. Such changes have a strong impact on crop inter-annual variability and should be taken into account in future studies to grasp better the potential of the tested options.

4.5 CONCLUSION

Agricultural intensification on smallholder farms in sub-Saharan Africa is challenging because of the heterogeneous nature of the smallholder farming environment in terms of socio-technical conditions, farmer typologies and production objectives. Our approach provides an analytical framework that can assist farmers or future land use research in the comparison of adaptation strategies including varietal improvement, nitrogen application, and intercropping. By disentangling the effects of variety and fertilisation, and the specific contribution of intercropping and sowing dates on productivity, we propose an approach that breaks down the advantages and limitations of each of the intensification strategies studied. We show that there are trade-offs between increase in productivity and decrease in variability when combining variety, fertilisation and intercropping for integrated soil fertility management. Due to the instability of cereal yields in the Sudanian zone of West Africa, adaptation options with a great potential to stabilise productivity ("ISFM variety + intercropping", "ISFM variety + fertilizer" and "ISFM variety + fertilizer + intercropping") are likely to be the ones that will contribute to improving future food security.

CHAPITRE V

CHAPITRE V : DISCUSSION GENERALE

L'agriculture pluviale est le secteur le plus important pour la sécurité alimentaire en Afrique subsaharienne. Cependant, la région est caractérisée par de faibles rendements dus à des apports limités en nutriments et à la pression des adventices (Affholder et al., 2013). Les agriculteurs ruraux ont un accès limité aux intrants agricole et les faibles niveaux d'investissement dans les infrastructures génèrent des coûts de transaction élevés qui réduisent ou compromettent la rentabilité des activités agricoles. Ces contraintes sont exacerbées par le changement climatique : la fréquence et la gravité des événements météorologiques extrêmes tels que les sécheresses et les inondations devraient augmenter (Connolly-Boutin and Smit, 2015; Diedhiou et al., 2018; Sultan and Gaetani, 2016). La recherche sur le changement et la variabilité climatiques et leurs impacts sur l'agriculture joue un rôle clé dans le développement de moyens tactiques et stratégiques pour minimiser ces impacts. Les tentatives visant à résoudre le problème de la faible productivité agricole des petites exploitations ayant une faible capacité d'adaptation au climat futur, doivent combiner la connaissance locale du fonctionnement des systèmes agricoles concernés et la quantification des effets possibles des options d'adaptation par l'expérimentation et la modélisation.

L'objectif général de cette thèse était de concevoir des systèmes de culture productifs et stables, adaptés au changement climatique, en explorant les bénéfices de l'association sorgho-niébé, combiné a des choix contrastés de variété de sorgho, de fertilisation minérale et de date de semis.

Nous avons d'abord analysé la perception du changement climatique par les agriculteurs et comparé cette perception avec une analyse des données météorologiques historiques. Ensuite nous avons identifié les changements dans les pratiques agricoles mises en œuvre par les agriculteurs pour s'adapter au changement climatique. Les liens entre la perception du changement climatique par les agriculteurs et la mise en œuvre de pratiques d'adaptation ont ensuite été analysés, au regard de l'hypothèse suivant laquelle les agriculteurs percevant un changement sont plus susceptibles de mettre en œuvre des pratiques d'adaptation (Deressa et al., 2009).

Dans un second temps, nous avons exploré le potentiel pour l'intensification écologique de l'association sorgho-niébé, dans un environnement à risque typique de la zone soudano-sahélienne. Cette technologie est censée avoir le potentiel d'augmenter durablement la productivité et les revenus agricoles tout en garantissant la possibilité de s'adapter à la variabilité et au changement climatique. L'intensification écologique vise à augmenter la productivité primaire dans les principaux agro écosystèmes céréaliers du monde (Cassman, 1999). Elle vise aussi à augmenter la production alimentaire à partir des terres cultivées existantes de manière à avoir un faible impact sur l'environnement, à ne pas compromettre la capacité de continuer à produire des aliments à l'avenir, et à augmenter en même temps les contributions au capital naturel (Campbell et al., 2014; Pretty et al., 2011). Les arguments avancés pour cette technologie ont été testés, en quantifiant la productivité des cultures et la dynamique de l'eau et de l'azote du sol dans le sud du Mali, en utilisant des approches de terrain et de modélisation, et en tenant compte de l'effet de diverses pratiques de gestion (dates de semis, variétés de sorgho, fertilisation minérale).

Dans cette discussion, les principaux résultats et enseignements des chapitres précédents sont résumés (section 5.1). Ensuite, la pertinence des simulations pour reproduire la performance de l'association sorgho-niébé sous climat futur est discutée (Chapitre 4), au regard des limites du modèle identifiée au Chapitre 3 (section 5.2). Les résultats sur la performance de l'association sorgho-niébé et de son adaptation à la variabilité et au changement climatique obtenus par simulation sont ensuite comparés (Chapitre 4) aux résultats de la littérature et aux perceptions des agriculteurs (Chapitre 2). L'intérêt de nos résultats pour les agriculteurs et les décideurs est discuté dans une dernière section (section 5.3). Le chapitre est conclu par des suggestions pour des recherches ultérieures.

5.1 Principaux résultats et enseignements

Les conclusions de cette étude peuvent s'appliquer aux petites exploitations agricoles des zones semi-arides d'Afrique sub-Saharienne où la disponibilité des terres arables est une contrainte majeure.

Dans le chapitre 2, il a été établi que la perception du changement climatique par les agriculteurs était cohérente avec les données climatiques en ce qui concerne l'augmentation des températures et la diminution des précipitations mais en désaccord en ce qui concerne la fréquence accrue des périodes de sécheresse et la fin précoce de la saison de culture. Les ménages qui percevaient certains changements dans les régimes pluviaux étaient associés à une probabilité accrue d'adopter des pratiques d'adaptation telles que la mise en place des cordons pierreux ou des digues en courbe de niveau, par rapport aux ménages qui ne percevaient pas de tels changements. Mais l'inverse était également vrai, c'est-à-dire que les ménages qui ne mettaient pas en œuvre une option d'adaptation (par exemple, des technologies d'économie d'eau, l'agroforesterie) étaient parfois plus susceptibles de percevoir un changement, peut-être parce que leurs systèmes de culture étaient plus sensibles aux variations météorologiques. Les agriculteurs ont mentionné les associations céréales-légumineuses telles que sorgho-niébé et maïs-niébé pour la grande majorité comme étant des stratégies pour s'adapter à d'éventuels stress hydriques qui entrainent une réduction de la croissance des cultures et une perte de rendement. Notre analyse sur le lien entre perception des agriculteurs et mise en œuvre des stratégies d'adaptation a révélé que la perception d'un arrêt précoce des précipitations a augmenté de manière significative la probabilité pour un agriculteur de mettre en place l'association sorgho-niébé dans ses champs. Ce chapitre a fourni une base solide pour des efforts de développement qui devraient renforcer le dialogue entre les agriculteurs et les chercheurs afin de développer une compréhension commune de l'impact du changement climatique sur les cultures et de concevoir des stratégies spécifiques à chaque zone pour compenser les impacts négatifs attendus du changement climatique.

Dans le chapitre 3, nous avons constaté par expérimentation que la biomasse aérienne et le rendement du sorgho et du niébé ont diminué avec la culture associée par rapport à la culture pure. Cependant, le LER observé pour la biomasse aérienne est resté supérieur à un, indépendamment du traitement expérimental (fumure minérale, date de semis et variété de sorgho). Le modèle calibré a décrit avec précision cette tendance générale liée au LER pour la biomasse aérienne, et a rendu compte de manière satisfaisante de l'impact des apports de fumure minérale et de l'utilisation de la variété améliorée de sorgho. De ce point de vue le modèle sol-culture STICS peut donc être un outil utile pour comprendre les compétitions qui se produisent entre les espèces dans ces systèmes de cultures associées céréales-légumineuses dans un environnement tropical pluvial, dans le cadre d'une intensification durable et d'une gestion intégrée de la fertilité des sols. Malgré cette caractéristique prometteuse du modèle, nous avons observé de substantielles inexactitudes dans les simulations de l'indice de surface foliaire et de l'absorption de l'azote par la plante. Le modèle calibré n'a pas réussi à prédire avec précision le faible rendement du niébé dans la culture associée, et a donc surestimé le LER de la culture associée pour le grain. Des mesures plus détaillées de la croissance de la biomasse et du nombre final de grains sont nécessaires pour améliorer la précision de notre calibration. Le modèle a également surestimé le rendement en grain du sorgho et du niébé dans les traitements sans apport de fertilisation minérale. Cela est peut-être lié à la mauvaise simulation de l'absorption de l'azote par le sorgho et le niébé. La mesure de l'azote minéral initial du sol avant le semis et pendant la croissance de la culture permettrait d'améliorer la calibration de la minéralisation de la matière organique du sol et par conséquent de l'absorption de l'azote par la culture. Ces améliorations dans la calibration du modèle concernant les composantes du rendement et le rendement sans apport d'azote sont nécessaires pour améliorer la prédiction du rendement des cultures associées céréales-légumineuses. En outre, le semis tardif du sorgho a entraîné un rendement plus faible que le modèle n'a pas pu reproduire. Il est possible que les semis tardifs aient été négativement affectés par un excès d'eau dans les parcelles (anoxie), un processus qui peut être pris en compte par le modèle STICS, mais que nous n'avons pas calibré en raison du manque de données appropriées sur la conductivité de l'eau du sol en conditions saturées pour notre site expérimental.

Dans le chapitre 4, nous avons constaté que les prédictions des modèles CMIP6 prévoient une augmentation des pluies avec le climat futur. Ce changement de régime pluviométrique contraste avec la perception des agriculteurs d'une diminution des pluies au cours des décennies passées. Nous avons également constaté que l'intensification de la culture du sorgho avec la variété améliorée en culture pure et en culture associée avec le niébé étaient la meilleure options technique (en termes de productivité calorique moyenne par rapport à la pratique de culture actuelle pour le sorgho) pour s'adapter au climat futur. Mais cela n'était vrai que pour des semis tardifs. En revanche, les options d'intensification avec les cultures associées sorgho-niébé incluant la variété améliorée et/ou l'apport de fumure minérale et la culture pure du sorgho incluant la variété et l'apport de fumure minérale ont eu une production énergétique plus stable sous climat actuel et futur que les autres options en condition de semis précoce.

5.2 Pertinence des simulations sur la performance de l'association sorgho-niébé en climat historique et futur

Dans nos expérimentations sur l'association sorgho-niébé, le "Land Equivalent Ratio" (LER) pour la production de biomasse était toujours supérieur à un, grâce à une diminution modérée de la biomasse du sorgho et malgré une diminution plus prononcée de celle du niébé. Le modèle une fois calibré a pu reproduire cette caractéristique de la culture associée. La diminution de la biomasse du niébé avec la culture associée était probablement liée à la compétition pour le rayonnement solaire qui est principalement intercepté par le couvert du sorgho. Cette compétition pour le rayonnement intercepté entre espèces en association a été signalée par des études antérieures telles que Carof et al. (2007) et Akanvou et al. (2002).

Pour les semis précoces, nos simulations sous climat historique et futur ont montré que l'association sorgho-niébé avec la variété traditionnelle, et sans apport d'azote (ISFM intercropping) n'était pas une adaptation pertinente au changement climatique si on s'intéresse à l'indicateur de productivité ou de stabilité de la production énergétique. En revanche, cette option est devenue une adaptation pertinente (au regard du critère de productivité moyenne) lorsqu' on la combine avec la variété améliorée (ISFM intercropping variety). Il a été démontré que la performance d'un mélange d'espèce était plus liée à l'inclusion d'espèce à forte productivité que d'espèce moins productive (Elhakeem et al., 2019). Avec un apport accru de fumure minérale (ISFM intercropping variety fertiliser), l'association sorgho niébé devient également une adaptation pertinente au regard du critère de stabilité, i.e. sa stabilité est accrue par rapport à la pratique actuelle et ce gain de stabilité augmente en climat futur. Cela signifie que les cultures associées peuvent être plus efficaces du point de vue de la stabilité de la production que les cultures pures à condition d'inclure des espèces performantes et un apport de fumure minérale.

Pour les semis tardifs, les meilleures options d'adaptation (au regard du critère de productivité moyenne) ont été celles incluant la variété améliorée de sorgho, en culture pure ou en association avec le niébé. La date de semis (précoce vs tardif) a donc eu un impact fort sur le classement des options concernant leur pertinence pour l'adaptation au changement climatique. Or l'effet de la date de semis a été mal simulé par le modèle sol culture de STICS (Chapitre 3). Le semis tardif du sorgho a entraîné une diminution de rendement que le modèle n'a pas pu reproduire. Cette diminution de rendement des semis tardifs a été surtout constaté pour l'année 2018, qui a été globalement humide (la teneur en eau du sol était toujours à la capacité au champs). Il est possible que les semis tardifs aient été négativement affectés par un excès d'eau dans les parcelles donc à l'anoxie du sol. Or les prédictions des modèles CMIP6 prévoient globalement plus de pluie en climat futur qu'en climat historique (Chapitre 4). Ce phénomène d'anoxie du sol va sans doute s'intensifier dans le futur et bouleverser le classement des options pertinentes, d'où la nécessité de bien le prendre en compte. De ce point de vue, nos résultats de simulation obtenus avec le modèle sol-culture STICS sur l'impact des options d'adaptation à la variabilité et au changement climatique doivent être interprétés avec précaution.

L'apport de fumure minérale (option "ISFM fertiliser") apparait comme une adaptation pertinente pour stabiliser les rendements, en raison d'un plus faible coefficient de variation que la pratique actuelle (sorgho sans engrais), avec une diminution de CV plus marquée sous climat futur que sous climat historique. Habituellement, les systèmes de culture intensifiés sont les plus sensibles au stress hydrique en raison d'une consommation accrue des ressources en eau par la plante qui épuise les réserves du sol plus rapidement en cas de sécheresse, entraînant une plus forte variabilité interannuelle du rendement (Affholder, 1997, 1995). Or dans nos simulations les traitements sans apport de fumure minérale étaient plus variables que les traitements avec fumure minérale. La calibration du modèle sol culture STICS a été faite avec les données issues de l'expérimentation de 2018 où le stress hydrique était nettement moindre comparativement à 2017 où des périodes de sécheresse accrues ont été observées. Il se peut que la simulation du rendement du sorgho en cas de stress hydrique se soit avérée insuffisante pour représenter avec précision l'impact du stress hydrique dans des années les plus sèches.

5.3 Comparaisons des résultats de simulation sur la performance de l'association sorgho-niébé avec la littérature et les perceptions des agriculteurs

5.3.1 Caractéristiques des petits exploitants agricoles au sud du Mali

Les agriculteurs soudano-sahéliens en particulier ceux d'Afrique de l'Ouest produisent principalement du mil, du sorgho et du maïs comme cultures de base avec un minimum d'intrants et d'équipements, ce qui se traduit le plus souvent par un faible rendement. Les cultures mineures comprennent le niébé (Vigna unguiculata (L) Walp.), l'arachide (Arachis hypogaea L.). Les agriculteurs de cette région combinent des activités agricoles et non agricoles pour assurer leur sécurité alimentaire et maintenir ou améliorer leurs moyens de subsistance (Homann-Kee Tui et al., 2015; Ncube et al., 2009). La productivité varie fortement en raison d'une grande diversité d'activités et d'actifs entre les agriculteurs d'une même zone agro-écologique (Sanogo, 2010). Il est important de reconnaître que les agriculteurs soudanais et sahéliens ne sont pas tous pauvres de manière homogène et ne sont pas non plus vulnérables de manière homogène au changement climatique. Certains agriculteurs qui sont engagés dans de nombreuses autres activités qui peuvent fournir une grande partie de leurs revenus (Bryceson, 2019; Nielsen and Reenberg, 2010) sont moins vulnérables et ont une meilleure capacité à faire face aux impacts climatiques négatifs.

5.3.2 Adaptation de l'association sorgho niébé à la variabilité et au changement climatique pour les petites exploitations agricoles

Les résultats de notre analyse ont montré que l'association sorgho niébé avec la variété traditionnelle de sorgho sans apport d'azote "ISFM intercropping" n'était pas une option d'adaptation pertinente du point de vue de la productivité moyenne ou de la stabilité de la production du système de culture. Des résultats similaires ont été signalé par Weih et al. (2021) qui ont trouvé peu de preuve d'une plus forte stabilisation du rendement des cultures associées par rapport aux cultures pures. En revanche, nos résultats ont montré que les options d'intensification incluant la culture associée, avec la variété améliorée et la fertilisation, i.e. les options "ISFM variety + fertiliser" ; "ISFM variety + intercropping" et "ISFM variety + fertiliser + intercropping", dans des conditions de date de semis précoce, peuvent être considérées comme des options d'adaptation en raison (i) d'un fort potentiel de stabilisation de la productivité (en comparaison de la culture du sorgho en culture pure avec la variété locale sans apport de fumure minérale) et (ii) d'une augmentation de ce potentiel de stabilisation en climat futur. Nos simulations ont également montré que pour les semis tardifs, les options d'intensification incluant la variété, c'est-à-dire "ISFM variety + intercropping", "ISFM variety" et l'association sorgho-niébé "ISFM intercropping", ont une productivité moyenne plus élevée que la pratique actuelle sous climat historique, et cet avantage augmente en climat futur. Ce résultat dénote l'intérêt de modéliser les systèmes de culture multi-espèces pour identifier les options techniques les plus pertinentes lorsque l'on combine différentes espèces, variétés et fertilisations. L'intérêt de modéliser les systèmes de culture multi-espèces ont été mentionnées dans les études précédentes (Brisson et al., 2004; Corre-Hellou et al., 2009; Launay et al., 2009). Les agriculteurs avaient précédemment mentionné dans le chapitre 2, la pratique de l'association céréales légumineuses et l'utilisation des variétés tolérantes à la sécheresse (c'est-à-dire à cycle plus court que leurs variétés locales) comme des options pertinentes pour s'adapter aux changements dans les régimes pluviométriques. Nos résultats de simulation ont montré que l'association sorgho niébé est une adaptation pertinente à condition d'utiliser une variété améliorée adaptée et d'apport de fumure minérale ce qui est en partie cohérent aux stratégies d'adaptation mentionnées par les agriculteurs. L'avantage d'utiliser des variétés de sorgho tolérantes à la sécheresse dans les agricultures familiales des zones semi arides et subhumides de l'Afrique peut être considéré comme une pratique d'intensification où le sorgho joue un rôle de culture alimentaire de subsistance. Traore et al. (2017) ont mentionné que l'adaptation de la gestion des cultures par des semis précoces, des niveaux d'engrais plus élevés et des variétés de cultures adaptées est essentielle pour faire face au changement climatique.

Enfin les changements climatiques simulés par les modèles de climat CMIP6 ont montré en moyenne une augmentation des pluies en climat futur par rapport au climat historique. Ce changement prédit à long terme contraste avec les changements perçus par les agriculteurs au cours des décennies passées et révélés par l'analyse des séries historique de climat (voir chapitre 2). Les stratégies d'adaptation mentionnées par les agriculteurs ont été en majorité celles qui permettent de s'adapter à l'augmentation des stress hydriques, entraînant une réduction de la croissance des cultures et une perte de rendement. Dans des études antérieures non loin de la zone d'étude, Lalou et al. (2019) et Muller et al. (2015) ont montré que les agriculteurs du Sénégal percevaient avec précision la récente reprise des précipitations et réutilisaient une ancienne variété de mil adaptée à un climat plus humide. Nos résultats montrent la nécessité d'un dialogue avec les agriculteurs et les acteurs de développement agricole. Cela peut se faire par la restitution de leur perception du changement climatique couplée à nos résultats de modélisation sur les options d'adaptation et les changements climatiques simulés par les modèles CMIP6 pour une meilleure prise en compte des stratégies d'adaptation à la variabilité et au changement climatique.

5.4 Recommandations de la thèse pour de futures recherches

A la suite de cette thèse, nous formulons quelques recommandations pour des futures recherches notamment la nécessité :

- d'explorer les bénéfices de l'association pour la diversité des contextes des agriculteurs (par exemple faire des expérimentations chez les agriculteurs) ;
- d'explorer d'autres motifs d'association (substitutif plutôt qu'additifs) ou le niébé serait plus favorisé ;
- de prendre en compte la rotation pour permettre à la culture céréalière de bénéficier de la fixation biologique de l'azote atmosphérique que peut offrir la culture légumineuse.

Dans cette étude, nous n'avons pas analysé en détails les mécanismes par lesquels se manifeste l'impact du changement climatique sur les cultures (e.g. stress hydrique, stress thermique, réduction de la durée de cycle) (Fig. 2). Ces analyses, déjà en partie possibles sans produire de nouvelles simulations, pourraient permettre de mieux comprendre les processus simulés qui conduisent à une adaptation pertinente.

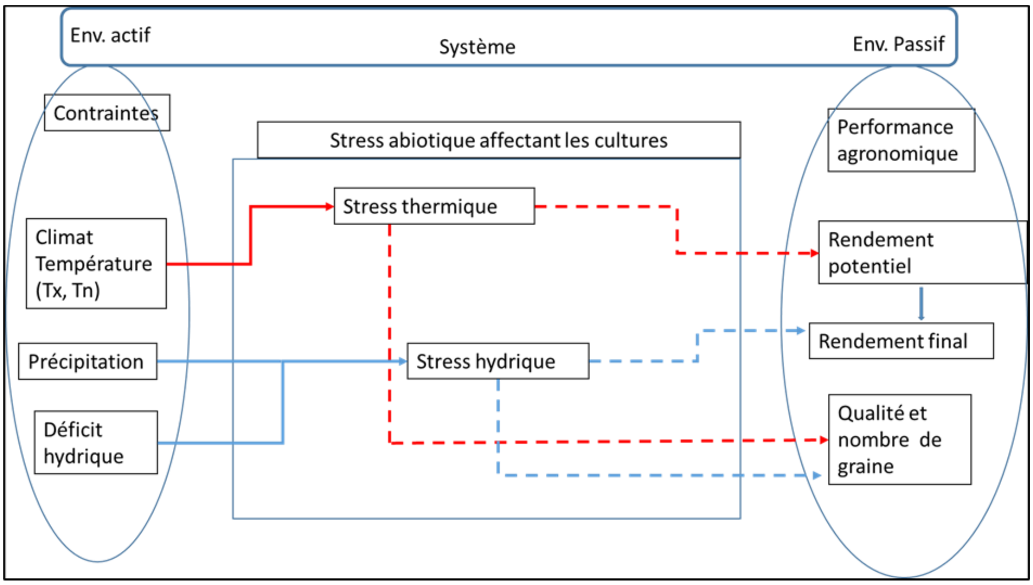
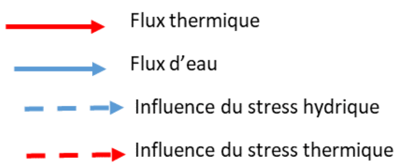


Figure2 : Schéma conceptuel du stress induits à l'élaboration de la biomasse. Tx = température maximale, tn = température minimale, Rg = rayonnement global, Env. actif = environnement actif, Env. passif = Environnement passif.



Nos résultats ont également montré la nécessité de renforcer le dialogue entre les agriculteurs et les chercheurs afin de développer une compréhension commune de l'impact du changement climatique sur les cultures et de concevoir des stratégies spécifiques pour la diversité d’acteur afin de compenser les impacts négatifs attendus du changement climatique. L'implication de parties prenantes plus larges (par exemple, les gouverneurs de district et les décideurs politiques nationaux) sont nécessaires pour que cette co-conception soit soutenue par un changement de politique agricole efficace. Par conséquent, la mise en œuvre de mesures d'adaptation à moyen et long terme doit être soutenue par des politiques nationales et régionales qui fournissent une assistance technique et financière efficace aux groupes vulnérables.

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ANNEXE

Supplementary materials

Chapitre 1

Table S1: Results of analysis of rainfall-related indicators. mean = average ; sd = standard deviation ; min = minimum ; max = maximum ; median = median value of the variable ; q25 = first quantile or 25% of the variable ; q75 = third quantile or 75% of the variable ; Significant (*P*<0.05) differences between periods are indicated with letters on the right of the reported mean.

Variables	Periods of time	Number of years	mean	sd	min	q25	median	q75	max
Total rainfall over the season	1951-1965	15	1065 b	158	721	996	1045	1165	1340
	1966-1980	15	863 a	124	640	783	866	938	1140
	1981-1995	15	779 a	166	482	719	746	840	1144
	1996-2010	15	926 ab	163	684	828	901	1044	1246
	2011-2017	7	837 a	176	672	706	763	952	1127
F Test probability	**0.0001**								
Length of the growing season	1951-1965	15	143	14	103	138	146	152	159
	1966-1980	15	141	13	113	135	141	150	165
	1981-1995	15	138	14	114	128	141	147	162
	1996-2010	15	134	22	68	128	136	143	165
	2011-2017	7	124	20	95	114	129	131	160
F Test probability	**0.1111**								
Start date of the growing season									
	1951-1965	15	146	12.34	130	137	141	156	168
	1966-1980	15	157	25.50	135	149	152	157	245
	1981-1995	15	148	11.14	134	141	146	155	169
	1996-2010	15	153	13.26	134	141	153	164	175
	2011-2017	7	163	13.52	141	155	164	169	185
F Test probability	**0.196**								
End date of the growing season									
	1951-1965	15	289	9.76	271	287	289	298	302
	1966-1980	15	292	8.47	276	287	293	298	304
	1981-1995	15	286	10.03	270	279	285	294	303
	1996-2010	15	287	15.35	243	282	289	297	303
	2011-2017	7	287	11.49	265	280	291.5	293	301
F Test probability	**0.5510**								
rainfall frequency above 30 mm	1951-1965	15	14 b	5.11	6	10	14	16	25
	1966-1980	15	10 ab	2.79	5	8	10	12	14
	1981-1995	15	10 a	3.27	3	7	10	12	14
	1996-2010	15	13 ab	4.04	7	11	12	15	21
	2011-2017	7	14 ab	2.34	12	13	14	15	19
F Test probability	**0.0022**								
frequency of daily rainfall above 50 mm	1951-1965	15	4	1.76	1	3	3	5	7

Variables	Periods of time	Number of years	mean	sd	min	q25	median	q75	max
	1966-1980	15	2	1.55	0	1	1	4	5
	1981-1995	15	3	1.60	0	2	2	4	5
	1996-2010	15	4	2.19	0	3	3	5	7
	2011-2017	7	3	2.06	0	2	3	4	6
F Test probability	**0.0590**								
Frequency of daily rainfall above 70 mm	1951-1965	15	1	1.09	0	0	0	1	3
	1966-1980	15	1	0.97	0	0	0	1	3
	1981-1995	15	1	0.73	0	0	0	1	2
	1996-2010	15	1	1.33	0	0	0	2	4
	2011-2017	7	1	1.80	0	0	0	0	5
F Test probability	**0.3360**								
Number dry spells of five days start season	1951-1965	15	1	0.88	0	1	2	1	3
	1966-1980	15	1	0.77	0	0	1	1	3
	1981-1995	15	1	0.92	0	1	2	1	3
	1996-2010	15	0	0.51	0	0	1	0	1
	2011-2017	7	1	1.13	0	0	1	0	3
F Test probability	**0.1050**								
Number dry spells of five days end season	1951-1965	15	0	0.51	0	0	1	0	1
	1966-1980	15	1	0.72	0	0	1	1	2
	1981-1995	15	1	0.86	0	0	1	1	3
	1996-2010	15	1	0.72	0	0	1	1	2
	2011-2017	7	0	0.49	0	0	1	0	1
F Test probability	**0.3920**								
Number dry spells of five days in the middle season	1951-1965	15	0	0.46	0	0	1	0	1
	1966-1980	15	0	0.74	0	0	1	0	2
	1981-1995	15	0	0.41	0	0	0	0	1
	1996-2010	15	0	0.64	0	0	1	0	2
	2011-2017	7	1	0.53	0	0	1	1	1
F Test probability	**0.5442**								
Number of seven-day dry spells start season									
	1951-1965	15	1	0.52	0	0	1	1	1
	1966-1980	15	1	0.74	0	0	1	0	2
	1981-1995	15	0	0.49	0	0	1	0	1
	1996-2010	15	1	0.92	0	0	1	0	3
	2011-2017	7	0	0.53	0	0	1	0	1
F Test probability	**0.8441**								
Number of seven-day dry spells end season									
	1951-1965	15	0	0.41	0	0	0	0	1
	1966-1980	15	0	0.49	0	0	1	0	1
	1981-1995	15	0	0.52	0	0	1	0	1
	1996-2010	15	0	0.41	0	0	0	0	1
	2011-2017	7	0	0.38	0	0	0	0	1

Variables	Periods of time	Number of years	mean	sd	min	q25	median	q75	max
F Test probability	**0.3733**								
Number of seven-day dry spells in the middle season									
	1951-1965	15	0	0.35	0	0	0	0	1
	1966-1980	15	0	0.56	0	0	0	0	2
	1981-1995	15	0	0.59	0	0	0	0	2
	1996-2010	15	0	0.00	0	0	0	0	0
	2011-2017	7	0	0.38	0	0	0	0	1
F Test probability	**0.5560**								

Table S2: Results of analysis of temperature-related indicators. mean = average; sd = standard deviation ; min = minimum ; max = maximum ; median = median value of the variable ; q25 = first quantile or 25% of the variable ; q75 = third quantile or 75% of the variable ; Significant (*P*<0.05) differences between periods are indicated with letters on the right of the reported mean.

Variables	Periods of time	Number of years	mean	sd	min	q25	median	q75	max
F Test probability	1951-1965	15	34.2 ab	0.49	33	34	34	35	35
Average maximum temperature per year	1966-1980	15	33.9 a	0.46	33	34	34	34	35
	1981-1995	15	34.1 ab	0.38	34	34	34	34	35
	1996-2010	15	34.4 a	0.30	34	34	34	35	35
F Test probability	**0.013**								
Average minimum temperature per year	1951-1965	15	19 a	0.60	18	19	19	20	20
	1966-1980	15	20 b	0.75	19	20	20	21	21
	1981-1995	15	21 c	0.43	21	21	21	22	22
	1996-2010	15	22 d	0.48	21	22	22	22	23
F Test probability	**0.0010**								
Average annual temperature	1951-1965	15	27 a	0.50	26	26	27	27	27
	1966-1980	15	27 a	0.50	26	27	27	27	28
	1981-1995	15	29 b	0.34	27	28	28	28	29
	1996-2010	15	28 c	0.36	28	28	28	28	29
F Test probability	**0.0012**								
Average maximum temperature in the growing season	1951-1965	15	32	0.49	33	34	34	35	35
	1966-1980	15	32	0.46	33	34	34	34	35
	1981-1995	15	32	0.38	34	34	34	34	35
	1996-2010	15	32	0.30	34	34	34	35	35
F Test probability	**0.9430**								
Average minimum temperature in the growing season	1951-1965	15	19.2 a	0.60	18	19	19	20	20
	1966-1980	15	20.3 a	0.75	19	20	20	21	21
	1981-1995	15	21.4 ab	0.43	21	21	21	22	22
	1996-2010	15	22.0 b	0.48	21	22	22	22	23
F Test probability	**0.0010**								

Variables	Periods of time	Number of years	mean	sd	min	q25	median	q75	max
Average temperature in the growing season									
	1951-1965	15	26.8 a	0.50	26	26	27	27	27
	1966-1980	15	27.1 a	0.50	26	27	27	27	28
	1981-1995	15	27.8 b	0.34	27	28	28	28	29
	1996-2010	15	28.2 b	0.36	28	28	28	28	29
F Test probability	**0.0010**								

Table S3: Close-ended questions and their possible answers, as asked to farmers during the individual surveys. For Q1, farmers answering "wetter" and "no change" were pooled together in the "no" category for the change "decreasing rainfall". For Q2, farmers answering "longer" and "no change" were pooled together in the "no" category for the change "shorter growing seasons". For Q3, farmers answering "earlier" and "no change" were pooled together in the "no" category for the change "delayed rainfall". For Q4, farmers answering "later" and "no change" were pooled in the "no "category for the change "early cessation of rainfall" (see Table 3 in manuscript).

Questions		**Possible answers**
Q 1	Are the rainy seasons becoming increasingly	1=wetter; 2=drier; 3=no change
Q2	Are the rainy seasons becoming increasingly	1=longer; 2=shorter; 3=no change
Q3	Is the onset of the rainy season increasingly	1=later; 2; earlier; 3=no change
Q4	Is the end of rainy season increasingly	1=later; 2; earlier; 3=no change
Q5	Are rainfall events increasingly intense?	1=yes; 2=no
Q6	Are dry spells longer during the growing season?	1= yes; 2=no
Q7	When do these longer dry spell occur?	1=at the start; 2=at the middle, 3= at the end
Q8	Are temperatures getting increasingly hotter?	1=yes; 2=no
Q9	Are temperature getting increasingly hotter during the rainy season in particular	1=yes; 2=no
Q10	Are nights getting increasingly hotter?	1=yes; 2=no

Table S1: Table S1: Soil characteristics, soil moisture content at field capacity, wilting point and maximum plant available soil water capacity at the experimental site of the N'tarla Agronomic Research Station. Soil texture analysis was carried out at the Laboratory Soil-Water-Plant of Institut d'Economie Rurale (IER) in Mali in 2017.

Upper and lower depth of soil layer (cm)	Bulk density	Texture		Gravimetric field capacity (%)	Gravimetric wilting point (%)	Maximum Plant Available Water Content (mm)
		Clay (%)	Fine silt (%)			
0-15	1.16	3.8	25.4	13.7	4.6	15
15-35	1.29	15.7	27.4	20.7	7.9	33
35-55	1.15	17	30.4	21.6	8.6	29
55-85	1.15	29.4	23.4	24.5	10.8	47
85-155	1.2	29.4	23.4	24.5	10.8	115

Values of hcc and hmin were obtained using pedo-transfer function as in (Lidon and Francis, 1983)

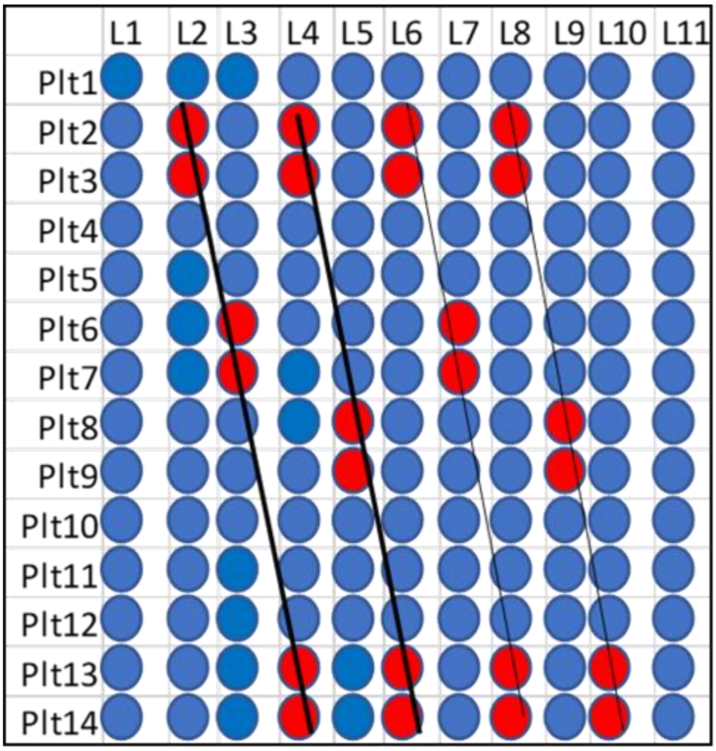


Figure S1 Methodological design for the measurement of leaf area index. L1 to L11 are the sowing rows of the experimental plot, Plt 1 to plt 14 are sorghum plant (rounds). For each transect (black solid line), LAI measurements were made under the sorghum plants highlighted in red.

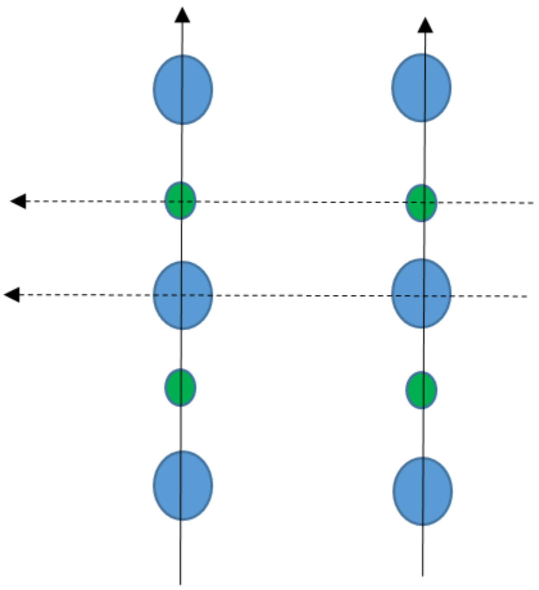


Figure S2: Real-life sowing lines (plain arrows) and model-simulation sowing lines (dotted arrows). Blue dots: sorghum plants, green dots: cowpea plants

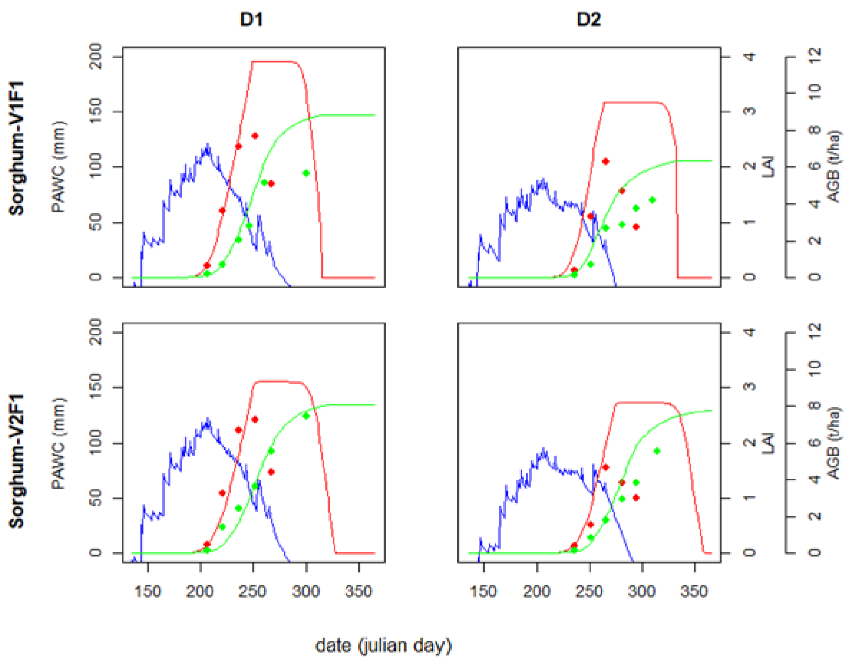


Figure S3: Observation of LAI (red dots) and aboveground biomass (green dots) for the four sole sorghum simulation units at the Ntarla research station in 2017, used for model evaluation. Lines are model simulations: blue for plant available soil water capacity (PAWC), red for LAI and green for AGB. Local variety (V1), improved variety (V2), early sowing (D1), late sowing (D2).

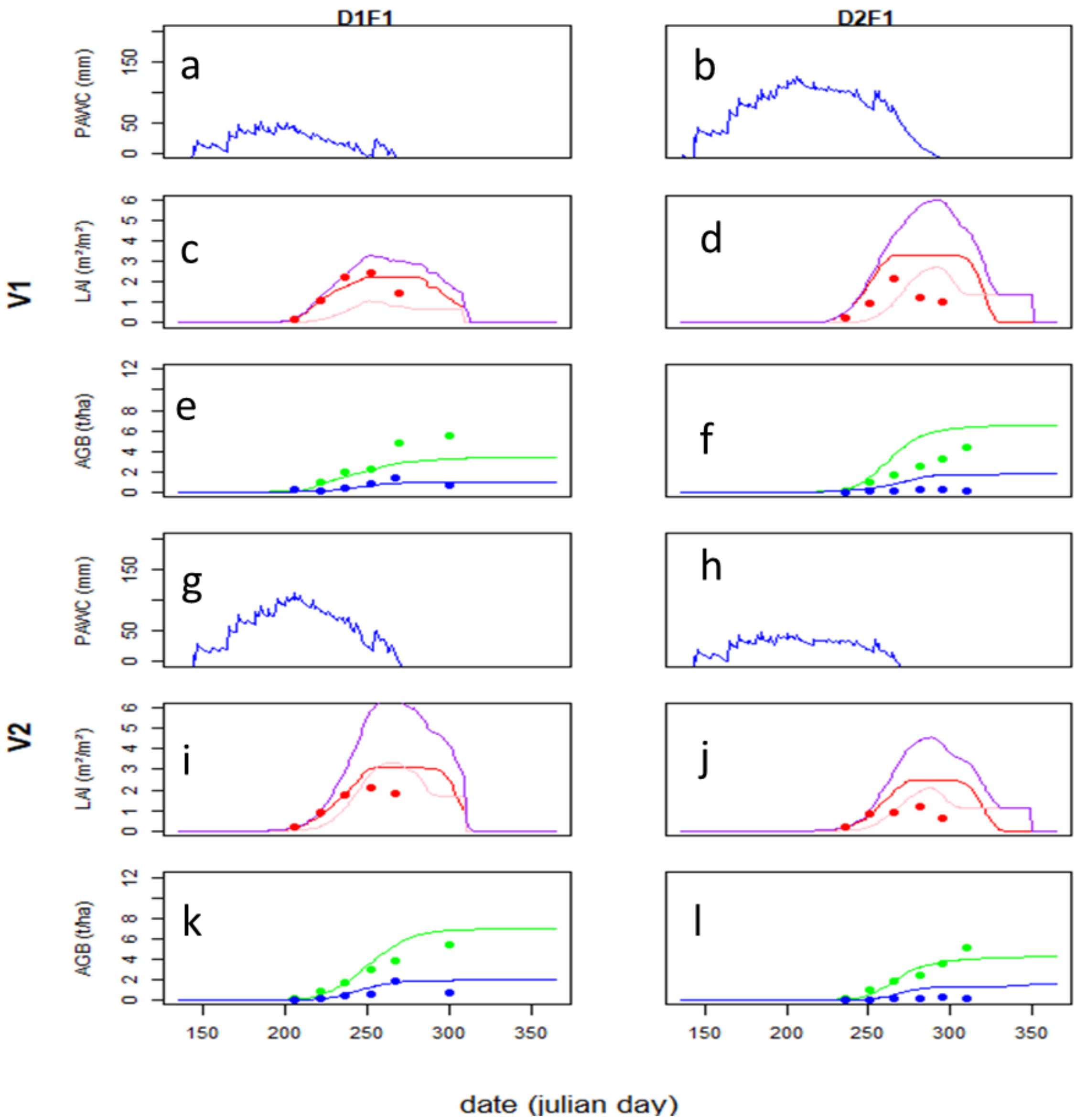


Figure S4: Simulation (blue line) of plant available soil water to maximum measurement depth (PAWC)(, Fig. a, b, g, h); observation (red dots for sorghum in intercropping) and simulations (lines) of LAI (Fig. c, d, i, j); observation (green dots for sorghum, blue dots for cowpea) and simulations (green lines for sorghum and blue lines for cowpea) of aboveground biomass of sorghum intercropped with cowpea (Fig. e,f,k,l). Local variety (V1), improved variety (V2), early sowing (D1), late sowing (D2), 38 kgN ha^{-1} (F1) at Ntarla research station in 2017. In 2017, there was no measure of Lai sorghum + cowpea as there was in 2018.

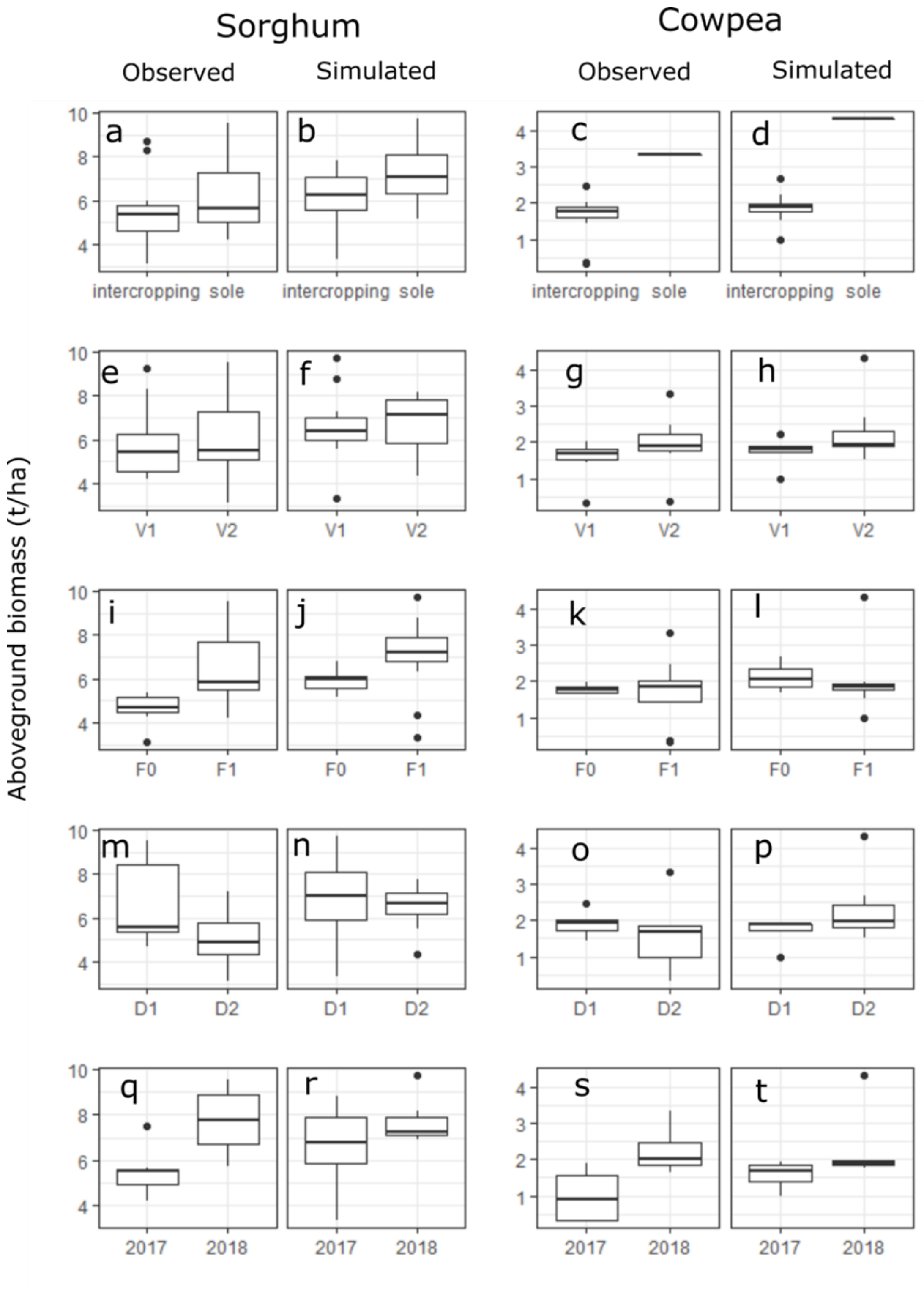


Figure S5: Boxplots of the effect of intercropping, sorghum variety (V1: local, V2: improved), N input (F0 = 0 kgN/ha^{-1}, F1 = 8 kg N/ha^{-1} in 2017 and 38 kgN/ha^{-1} in 2018) and sowing date (D1: early, D2: late) on observed and simulated aboveground biomass. Calibration and evaluation datasets were pooled together.

Figure S6: Boxplots of the effect of interaction between cropping system (i.e. sole vs intercrop) and year on observed (a) and simulated (b) Sorghum grain yield. Calibration and evaluation datasets were pooled together. Only the F1 treatment was considered (f1 = 8 kg N/ha^{-1} in 2017 and F1 = 38 kgN/ha^{-1} in 2018).

Figure S6: Boxplots of the effect of interaction between cropping system (i.e. sole vs intercrop) and year on observed (a) and simulated (b) Sorghum grain yield. Calibration and evaluation datasets were pooled together. Only the F1 treatment was considered (f1 = 8 kg N/ha^{-1} in 2017 and F1 = 38 kgN/ha^{-1} in 2018).

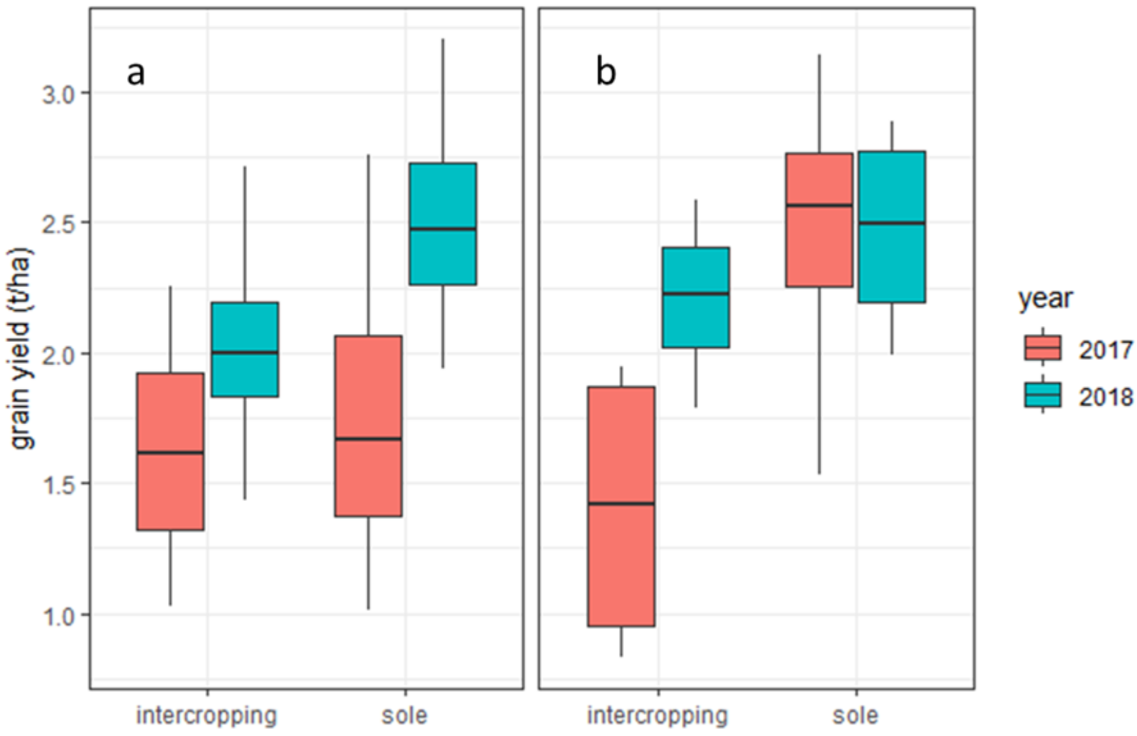


Figure S6: Boxplots of the effect of interaction between cropping system (i.e. sole vs intercrop) and year on observed (a) and simulated (b) Sorghum grain yield. Calibration and evaluation datasets were pooled together. Only the F1 treatment was considered (f1 = 8 kg N/ha^{-1} in 2017 and F1 = 38 kgN/ha^{-1} in 2018).

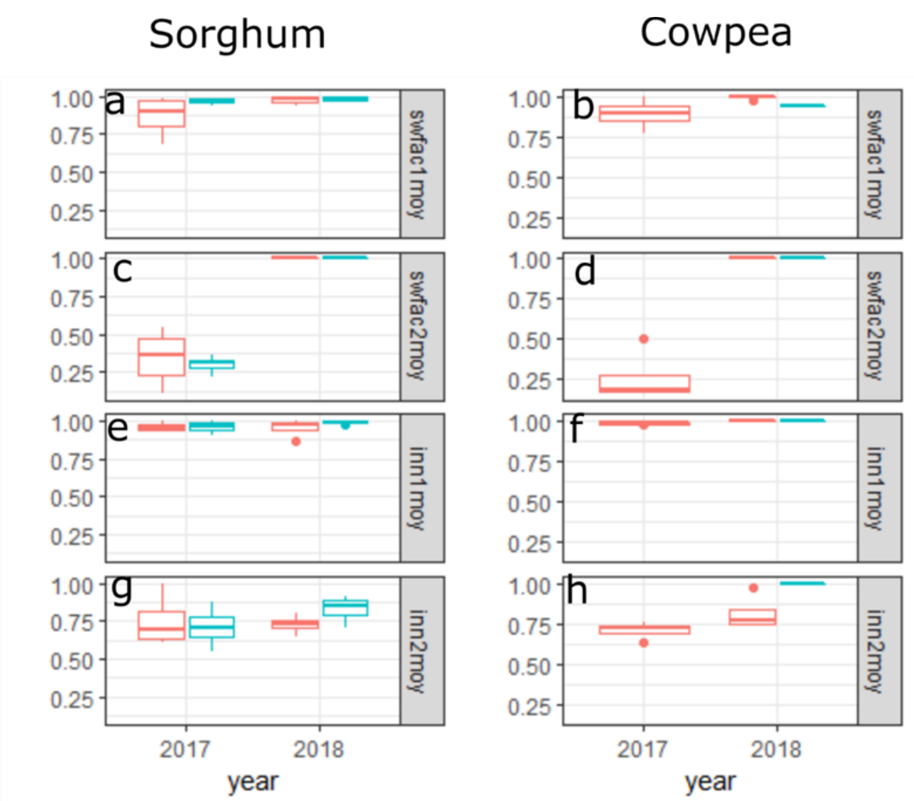
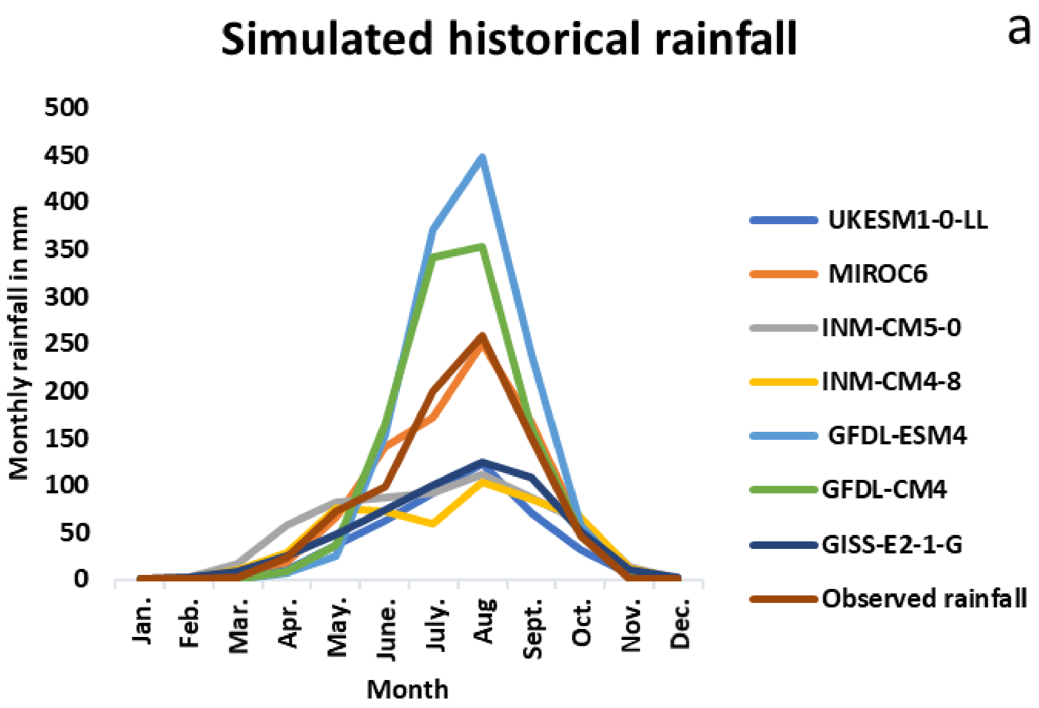
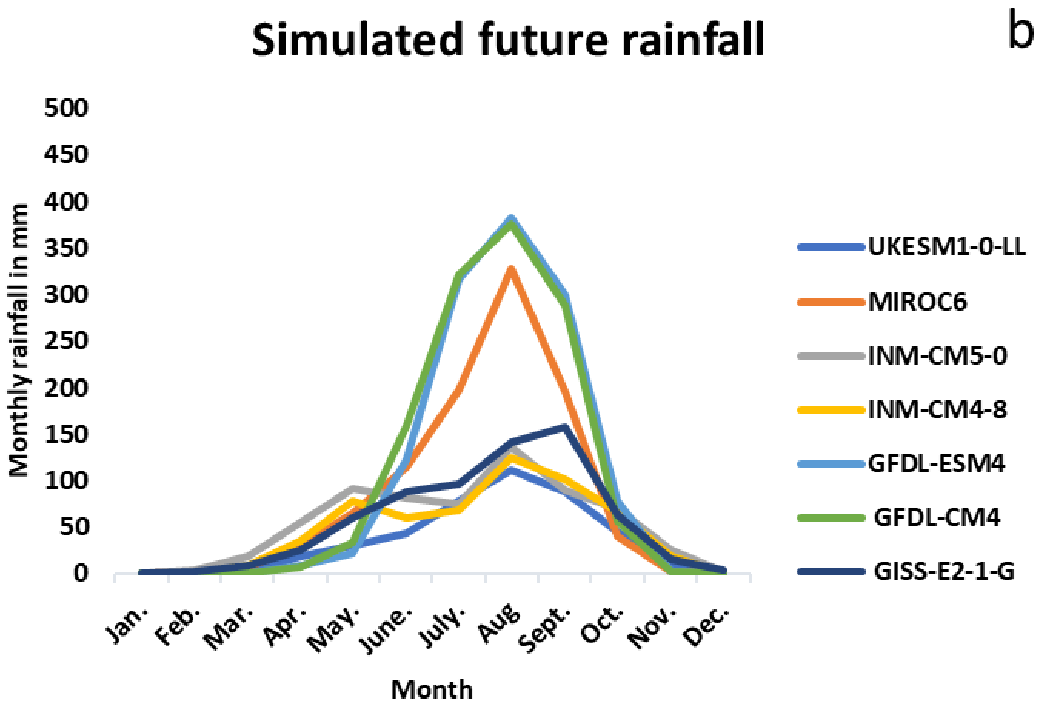


Figure S7: Boxplots water stress indicator during vegetative phase (a,b) and reproductive phase (c,d) ; and values of nitrogen stress indicator during vegetative phase (e, f) and reproductive phase (g,h), in 2017 and 2018 for intercropping simulation units (red) and sole cropping simulation units (blue).

Chapitre 4





Figures S1: Average of observed (Ntarla weather station) and simulated (seven CMIP6 climate model) monthly rainfall (a) over the historical (1980-2010) and (b) future (2035-2065) periods

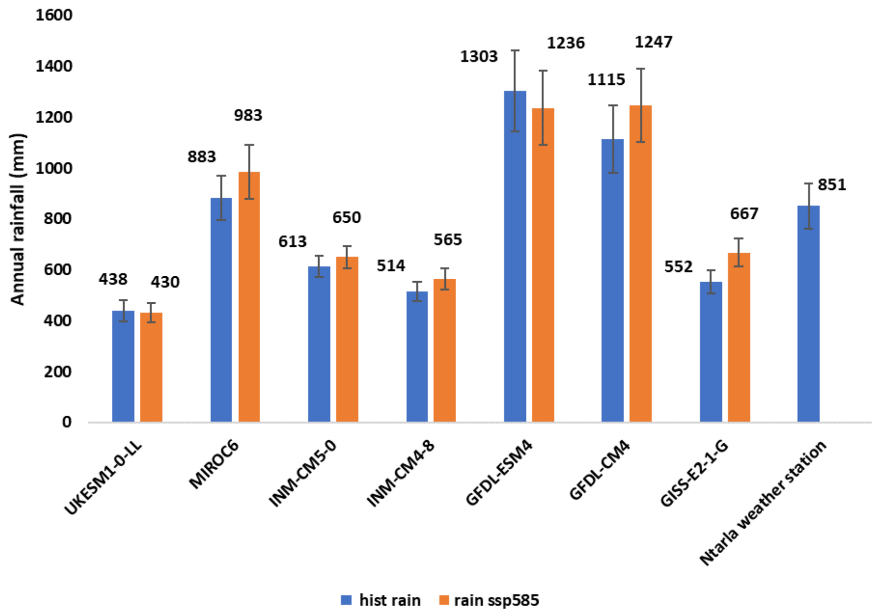


Figure S2: Observed (Ntarla weather station) and simulated (seven CMIP6 climate models) average annual rainfall for historical (1980-2010) and future (2035-2065) period. The bars represent the standard deviation of the average.

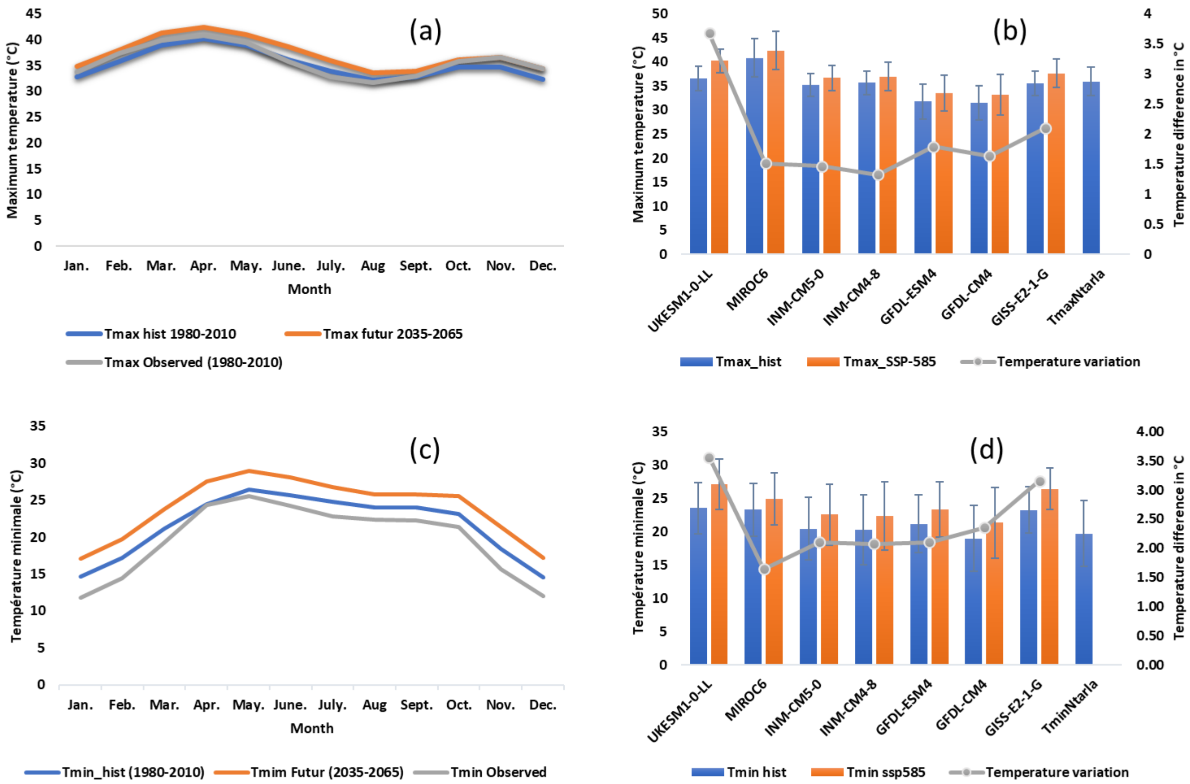


Figure S3: Average of observed (Ntarla weather station) and simulated (seven CMIP 6 climate models) monthly temperature for historical (1980-2010) and future (2035-2065) periods; (a) maximum temperature, (b) minimum temperature; and historical and future average annual temperature simulated by the seven CMIP6 climate models; (c) maximum temperature, (d) minimum temperature. The bars are the standard deviation of the average annual mean and the grey dots and line is the annual average temperature difference between historical and future climate.

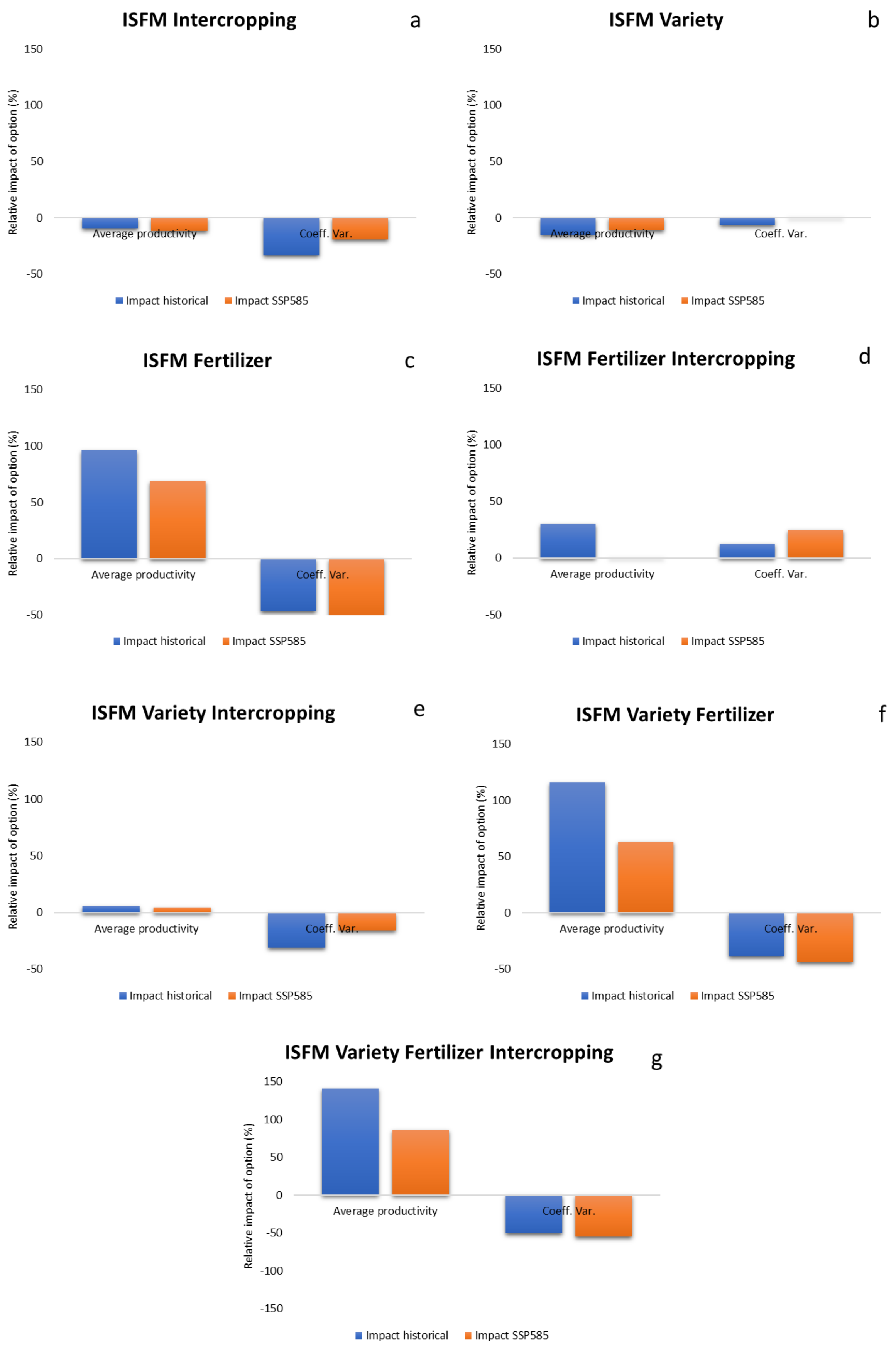


Figure S4: Relative impact (compared with the "baseline sorghum" option) of seven options on average calorie productivity and its coefficient of variation (Coeff. Var) for historical and future climate in early sowing date.

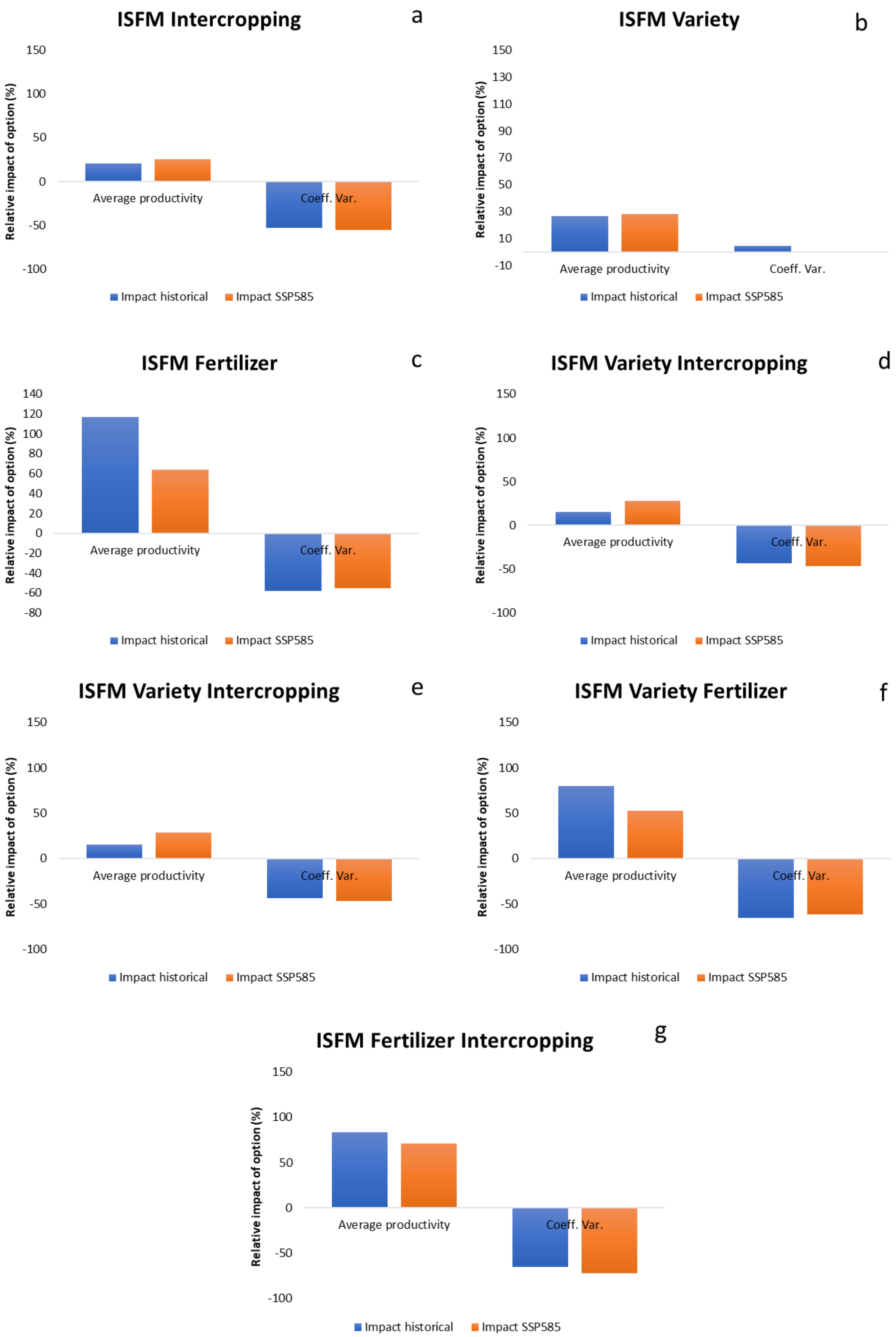


Figure S5: Relative impact (compared with the "baseline sorghum" option) of seven options on average calorie productivity and its coefficient of variation (Coeff. Var) for historical and future climate in late sowing date.

Table S1: Average simulated rainfall (mm) by 7 models from phase 6 of the Coupled Model Interoperation project (CMIP6)

Climate scenarios	UKESM1-0-LL	MIROC6	INM-CM5-0	INM-CM4-8	GFDL-ESM4	GFDL-CM4	GISS-E2-1-G	Average rainfall in mm
Current climate	438	883	613	514	1303	1115	552	774
ssp585	430	983	650	565	1236	1247	667	825
% Increase compared to current climate	**-2**	**11**	**6**	**10**	**-5**	**12**	**21**	8