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THREE ESSAYS ON CHALLENGES FACING AGRICULTURE IN DEVELOPING COUNTRIES

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A mes chers parents...

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Résumé

L'agriculture occupe une place prépondérante dans l'économie des pays en développement où la majeure partie de la population réside en milieu rural et dépend de l'agriculture et des systèmes alimentaires pour leur subsistance. Cette population est par ailleurs confrontée à de nombreux défis tels que le changement climatique, la pauvreté, la dégradation de l'environnement ou l'insécurité alimentaire. L'objectif de la thèse est d'apporter un nouvel éclairage sur les enjeux liés à l'agriculture afin d'en déduire des recommandations de politiques économiques. La thèse comprend trois chapitres. Le chapitre 2 analyse les effets de l'irrigation sur les scores de diversité alimentaires des femmes et des ménages agricoles. L'étude se concentre sur les pays d'Afrique Sub-Saharienne (ASS), en particulier les pays de l'Union Economique et Monétaire Ouest Africaine (UEMOA) où la part de la population souffrant d'insécurité alimentaire modérée à grave est très élevée. Notre stratégie d'identification est basée sur la méthode d'équilibrage de l'entropie développé par Hainmueller 2012. Les résultats obtenus montrent que les ménages ayant recours à l'irrigation présentent des scores de diversité alimentaire plus élevés que ceux n'ayant pas utilisé l'irrigation. De plus, les résultats révèlent également que les femmes au sein des ménages utilisant l'irrigation affichent des scores de diversité alimentaire plus élevés que ceux des femmes des ménages non-irrigants. Par ailleurs, ces conclusions mettent en évidence que l'autonomisation des femmes, l'augmentation du revenu agricole, de la production et l'accès à l'eau représentent les mécanismes potentiels par lesquels l'irrigation contribue à améliorer les scores de diversité alimentaire.

Le chapitre 3 se focalise sur la relation entre la prévalence du paludisme et le travail agricole dans un contexte d'irrigation et d'agriculture familiale en ASS. L'objectif de cette étude est d'évaluer l'impact du paludisme sur le travail agricole (quantité et productivité) en mettant en lumière certains mécanismes sous-jacents expliquant la relation entre le paludisme et le travail dans l'agriculture familiale africaine. Plus précisément, nous nous sommes concentrée sur l'irrigation et la taille

des ménages en tant que deux variables potentielles de modération de l'impact du paludisme sur le travail. D'une part, les résultats obtenus montrent que le paludisme a un impact négatif sur la quantité de travail. Cet effet est l'impact direct de la santé dû à la perte de journées de travail en raison de la maladie. Cependant, une fois que le paludisme interagit avec l'irrigation ou la taille du ménage, son effet s'avère insignifiant. D'autre part, les résultats révèlent que le paludisme augmente la productivité du travail. Nous expliquons ce résultat dans le contexte de l'inefficacité productive de l'agriculture familiale africaine. En ce qui concerne l'effet modérateur de l'irrigation, nous constatons un impact négatif de l'interaction du paludisme avec l'irrigation, bien que peu de résultats soient robustes. Dans l'ensemble, nos résultats mettent en évidence que le paludisme demeure une contrainte dans l'agriculture familiale en Afrique.

Le chapitre 4 se penche sur la question de l'industrialisation des zones rurales. Plus explicitement, il analyse l'impact de la pollution industrielle de l'eau sur la production de riz dans la province du Jiangsu, en Chine. Cette étude vise à démêler cette relation complexe en utilisant un modèle de fonction de production translog. Ce modèle nous permet de séparer les effets directs de la pollution industrielle de l'eau sur la riziculture de ses effets d'adaptation. Les résultats obtenus confirment que les rendements du riz sont négativement affectés par la pollution de l'eau industrielle, en raison d'un effet biologique direct. Cet effet préjudiciable est le plus significatif dans un rayon de 5 kilomètres du centre du comté. En réponse, les agriculteurs utilisent davantage d'intrants tels que les engrais et les pesticides pour atténuer l'impact négatif de la pollution de l'eau industrielle. Le changement dans les comportements de production aide les agriculteurs à mieux faire face au développement industriel et à s'adapter à l'évolution de l'environnement rural. Les résultats de ce chapitre permettent d'apporter un éclairage afin de mieux comprendre le lien entre le développement de l'industrie et l'agriculture au niveau local.

Mots-clés : Irrigation · Diversité alimentaire · Travail agricole · Paludisme · Pollution d'eau industrielle · Afrique Sub-Saharienne · Chine

Codes JEL : D13 · H31 · I1 · I12 · I19 · L66 · O13 · O55 · Q1 · Q12 · Q15

Abstract

Agriculture plays a major role in the economy of developing countries where the majority of the population lives in rural areas and depends on agriculture and food systems for their livelihoods. This population is also faced with numerous challenges such as climate change, poverty, environmental degradation or food insecurity. The objective of the thesis is to shed new light on the issues related to agriculture in order to derive economic policy recommendations. The thesis consists of three chapters. Chapter 2 assesses the impact of adopting irrigation on household and women's dietary diversity. The study focuses on Sub-Saharan African (SSA) countries, particularly countries of the West African Economic and Monetary Union (WAEMU) where the share of the population suffering from moderate to severe food insecurity is very high. Our identification strategy is based on the entropy balancing method developed by Hainmueller 2012. The results show that irrigating households have higher dietary diversity scores compared to non-irrigating households. In addition, the results also reveal that women in irrigating households have higher dietary diversity scores than women in non-irrigating households. Furthermore, these findings highlight that women's empowerment, increased agricultural income, production, and water supply are potential mechanisms through which irrigation contributes to improving dietary diversity.

Chapter 3 focuses on the relationship between malaria prevalence and agricultural labor in the context of irrigation and family farming in SSA. The goal of this study is to analyse the impact of malaria on agricultural labor (quantity and productivity) by highlighting some underlying mechanisms that explain the relationship between malaria and labor in African family farming. More precisely, we focused on irrigation and household size as two potential moderator variables of the impact of malaria on labor. On the one hand, the results show that malaria has a negative impact on labor quantity. This effect is a direct health impact through the loss of workday due to the disease. However, once malaria interacts with irrigation or household size, its effect turns out to be insignificant. We explain these results by the presence of a moderating effect of irrigation and household size. On the other hand, the baseline and robustness results reveal that malaria increases labor productivity. We explain this result in the context of the productive inefficiency of African family farming. Regarding the moderating effect of irrigation, we do find a negative impact of the interaction of malaria with irrigation while few are robust. Overall, our results highlight that malaria remains a constraint in family farming in Africa.

Chapter 4 examines the issue of industrialization in rural areas. More specifically, it analyzes the impact of industrial water pollution from manufacturing firms on rice production in Jiangsu, China. This study aims to disentangle this complex relationship by using a translog production function model. This model allows us to separate the direct effects of industrial water pollution on rice cultivation from its adaptation effects. Our results confirm that rice yields are negatively impacted by industrial water pollution through a direct biological effect. This detrimental effect is the most significant within a radius of 5 kilometers from the county center. In response, farmers use more operating costs to mitigate the negative impact of industrial water pollution. The change in production behaviors helps farmers to better cope with industrial development and adapt to the changing rural environment. Our study highlights the need to better understand the nexus between industry and agriculture at the local level.

Keywords: Irrigation · Dietary diversity · Agricultural labor · Malaria · Water pollution · Sub-Saharan African · China

JEL Codes: D13 · H31 · I1 · I12 · I19 · L66 · O13 · O55 · Q1 · Q12 · Q15

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Chapter 1

Introduction

1.1 Contexte : les défis de la population rurale dans les pays en développement

L'agriculture occupe une place prépondérante dans l'économie des pays en développement. Environ 3,4 milliards de personnes résident dans les zones rurales de ces pays et la plupart d'entre elles dépendent de l'agriculture et des systèmes alimentaires pour leur subsistance (UNDESA, 2021). Selon le rapport "Perspectives agricoles de l'OCDE et de la FAO", le secteur contribue à 10% du PIB en 2023 et emploie plus de 70% de la population active de ces pays (OCDE and FAO, 2023). Les ménages ruraux sont confrontés à de nombreux défis tels que le changement climatique, la pauvreté, la dégradation de l'environnement ou l'insécurité alimentaire.

L'insécurité alimentaire est l'un des défis les plus pressants de ces pays. Selon l'Organisation des Nations unies pour l'alimentation et l'agriculture, environ 42,7% de la population rurale de ces pays souffraient d'insécurité alimentaire modérée ou grave en 2022 (FAO et al., 2023). Face à cette insécurité alimentaire élevée dans ces zones où la production agricole reste principalement pluviale, l'irrigation est fortement encouragée afin de garantir la sécurité alimentaire, de préserver les moyens de subsistance des agriculteurs et de réduire leur vulnérabilité face aux aléas pluviométriques (Okyere and Usman, 2021; Passarelli et al., 2018; Mekonnen et al., 2022). Cependant, en dépit des avantages de l'irrigation qui permet d'augmenter les rendements agricoles, l'irrigation engendre également des externalités négatives, en particulier sur l'environnement et la santé des communautés rurales. En effet, l'irrigation est un facteur de risque de propagation des maladies comme le paludisme qui reste un problème de santé mondial dans les pays en développement où elle est la sixième cause de décès (WHO, 2022).

En plus, il est important de noter que l'industrialisation rurale est un phénomène

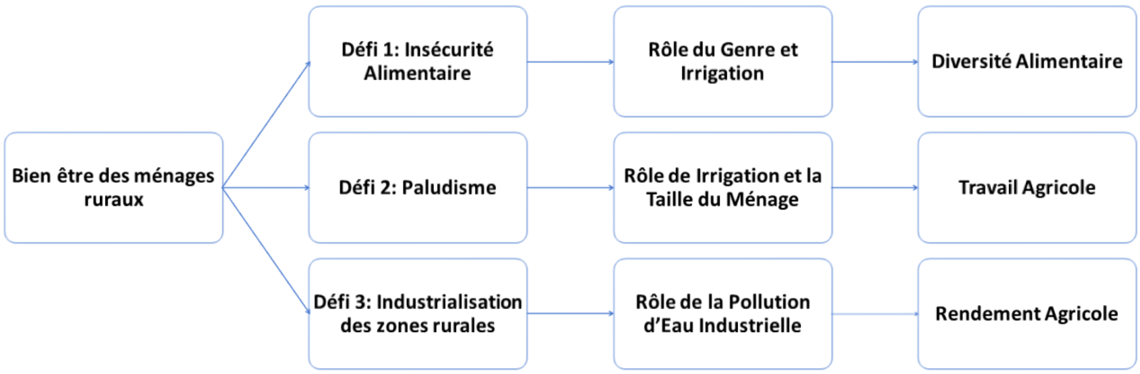


Figure 1.1: Cadre conceptuel pour analyser les impacts des défis sur le bien être de la population rurale

en expansion dans ces pays. Elle englobe l'introduction de technologies et de pratiques industrielles dans les régions rurales. Cependant, cette transition vers une économie plus industrielle suscite des préoccupations, notamment en ce qui concerne la pollution de l'eau, qui peut avoir des répercussions significatives sur la préservation de l'environnement rural et le développement agricole durable.

Ces défis s'inscrivent en complémentarité avec d'autres enjeux tels que le réchauffement climatique, les sécheresses et les inondations, dans un contexte de pauvreté au sein de la population locale.

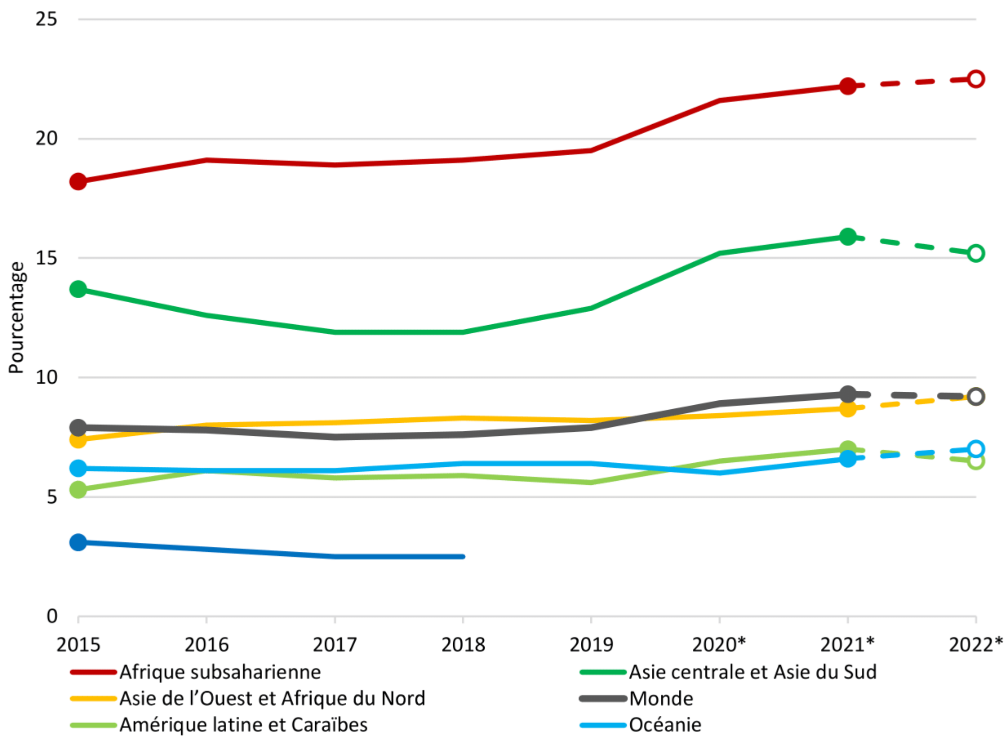
Cette thèse porte sur la compréhension des conséquences de certains de ces défis sur des aspects importants contribuant au bien-être de la population rurale tels que la diversité alimentaire, le travail agricole et les rendements agricoles. La Figure 1.1 illustre schématiquement l'approche analytique de notre travail. Dans la section suivante, nous presenterons les différents défis liés à l'agriculture que nous étudions.

1.1.1 L'insécurité alimentaire

La sécurité alimentaire est considérée comme l'un des enjeux majeurs du monde actuel. L'expression "sécurité alimentaire" a été introduite en 1974 lors de la Conférence mondiale de l'alimentation en réponse aux famines au Sahel et au Darfour, et était largement considérée comme un problème de production alimentaire insuffisante et instable (Maxwell, 1996). En 1996, lors du Sommet Mondial de l'Alimentation, la définition de la sécurité alimentaire s'affine : "la sécurité alimentaire existe lorsque toutes les personnes, à tout moment, ont un accès physique et économique à une nourriture suffisante, sûre et nutritive qui répond à leurs besoins et à leurs préférences alimentaires pour mener une vie active et saine". La part de la population mondiale n'ayant pas cet accès se trouve en insécurité alimentaire.

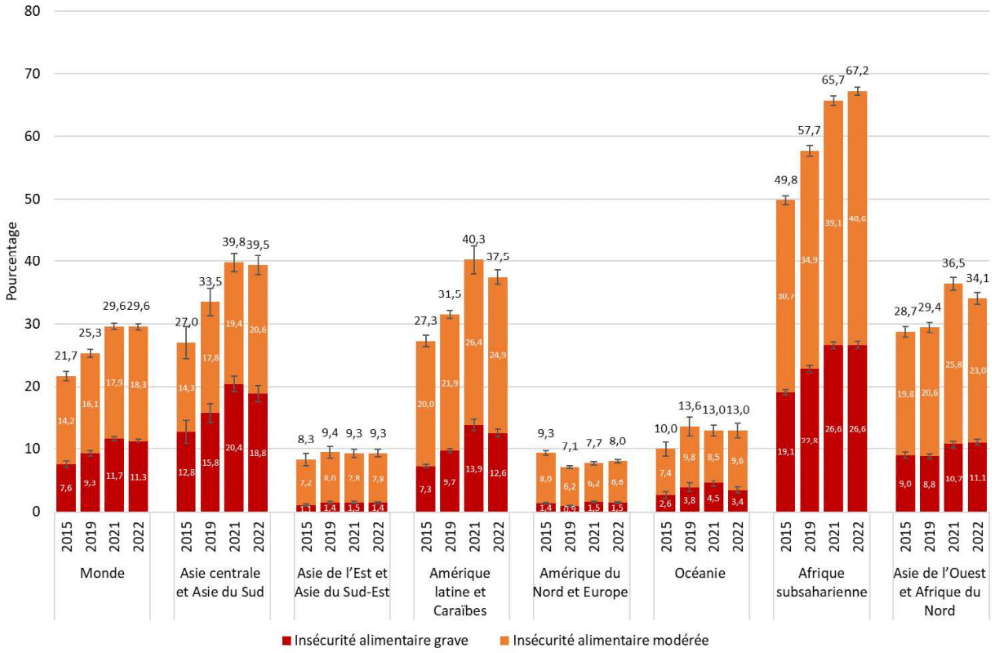
Au cours de ces dernières décennies la faim et l'insécurité alimentaire ont continué à être au centre de la plupart des débats à l'échelle mondiale. Ainsi, plusieurs sommets des Nations Unies sur les objectifs mondiaux de développement visent à améliorer la vie des personnes dans le monde entier en mettant un fort accent sur l'élimination de la faim, l'assurance de la sécurité alimentaire, l'amélioration de la nutrition et la promotion d'une agriculture durable. Lors de la dernière conférence de l'ONU pour l'alimentation et l'agriculture qui s'est déroulée à New York en 2023, les dirigeants mondiaux et les organisations internationales ont réaffirmé qu'il leur faut amplifier et mieux cibler leurs actions, faute de quoi l'objectif d'éliminer la faim, l'insécurité alimentaire et la malnutrition sous toutes ses formes d'ici à 2030 restera hors de portée.

Or, malgré les récents efforts déployés pour améliorer la sécurité alimentaire, la sous-alimentation et l'insécurité alimentaire persistent et touchent encore des milliards de personnes dans le monde, en particulier les femmes et les personnes vivant en zone rurale des pays en développement. En 2022, le rapport de l'ONU pour l'alimentation et l'agriculture a révélé que 9,2% de la population mondiale était confrontée à la faim chronique contre 7,9% en 2019, soit une augmentation de plus de 1,3% (FAO et al., 2023). De plus, environ 2,4 milliards de personnes, soit 29,6% de la population mondiale (dont 42,7% vivent dans les zones rurales des pays en développement), ont connu une insécurité alimentaire modérée à grave, ce qui signifie qu'elles n'avaient pas un accès régulier à une alimentation adéquate. Cette hausse peut être attribuée à la pandémie de covid-19, aux conflits, aux changements climatiques et aux inégalités croissantes qui ont eu des effets négatifs sur la sécurité alimentaire dans le monde.



Source: FAO. 2023. FAOSTAT: Données de la sécurité alimentaire

Figure 1.2: Prévalence de la sous-alimentation dans le monde et par région (% de la population)



Source: FAO. 2023. FAOSTAT: Données de la sécurité alimentaire

Figure 1.3: Prévalence de l'insécurité alimentaire modérée ou grave (% de la population)

Les Figures 1.2 et 1.3 donnent un aperçu de l'évolution de la prévalence de la sous-alimentation et de l'insécurité alimentaire par région au cours de ces dernières années. Nous constatons que la sous-alimentation et l'insécurité alimentaire restent l'un des problèmes majeurs principalement en Afrique subsaharienne (ASS) qui compte la plus grande part de population souffrant de la faim (22,5% de la population) et d'insécurité alimentaire modérée ou grave (67,2% de la population) en 2022. Ainsi, la recherche autour de la sécurité alimentaire est indispensable pour que tous les individus puissent être en bonne santé et développer leur plein potentiel. L'objet d'une partie de cette thèse est de contribuer à ce débat en mettant en avant le rôle de l'irrigation et du genre.

1.1.2 Le paludisme

Le paludisme demeure l'un des principaux défis en matière de santé publique à l'échelle mondiale, provoquant un nombre significatif de décès et d'invalidité, en particulier parmi les ménages ruraux des pays en développement où l'agriculture est la principale source de revenus. Selon un rapport récent de l'Organisation mondiale de la Santé sur le paludisme, environ 247 millions de cas de paludisme et 619 000 décès ont été attribués à cette maladie en 2021 (WHO, 2022). Le risque de contracter le paludisme demeure élevé dans les pays à faible revenu où il figure en sixième position parmi les principales causes de décès. L'Afrique subsaharienne (ASS) est particulièrement touchée, représentant environ 95 % des cas de paludisme et 96 % des décès liés à cette maladie dans le monde en 2020 (WHO, 2021). Au fil des décennies, les pays d'ASS ont mis en œuvre divers outils et stratégies de prévention, notamment une lutte efficace contre les vecteurs du paludisme et l'utilisation de médicaments antipaludiques préventifs. Ces mesures ont entraîné une réduction significative du nombre de décès liés au paludisme comme indiqué dans l'étude de Bhatt et al. 2015. Cependant, le nombre de cas de paludisme reste important comme évoqué précédemment dans ces pays où l'agriculture joue un rôle central dans leur développement économique. La relation entre le paludisme et l'agriculture a en effet suscité une attention considérable dans la littérature. D'une part, plusieurs études ont montré qu'un mauvais état de santé des ménages agricoles liée au paludisme réduit les rendements agricoles et les revenus en diminuant la productivité du travail et en faisant perdre des journées de travail à cause de la maladie (Strauss and Thomas, 1998; Audibert et al., 2003; Asenso-Okyere et al., 2011; Iheke and Ukaegbu, 2015). D'autre part, certains auteurs trouvent que certains projets et pratiques de développement agricole peuvent avoir des effets négatifs sur la santé. L'agriculture intensive, due aux systèmes d'irrigation, peut provoquer, par exemple, des maladies d'origine hydrique, telles que le paludisme. En effet, une augmentation de l'eau stagnante associée à l'irrigation, en particulier lorsque les systèmes sont mal gérés, peut servir de terrain de reproduction aux vecteurs de maladies, notamment les moustiques anopheles, et contribuer à une augmentation du paludisme et d'autres maladies. Cependant, certaines études ont montré que l'irrigation n'était pas ou peu associée à une prévalence accrue du paludisme (Audibert et al., 2007; Assi et al., 2013). Ainsi, l'un des objectifs de cette thèse est d'apporter une contribution à ce débat en mettant en lumière certains mécanismes sous-jacents expliquant la relation entre le paludisme et le travail dans l'agriculture familiale africaine.

1.1.3 L'industrialisation des zones rurales

L'essor de l'industrialisation rurale dans les pays en développement est un phénomène en rapide expansion et est souvent considéré comme une phase inévitable de leur développement économique. Alors que ces pays s'efforcent de diversifier leur économie et d'améliorer les conditions de vie de la population rurale, la croissance des industries et des activités non agricoles dans les zones rurales est devenue une priorité. L'industrialisation rurale est un processus qui consiste à introduire des technologies et des pratiques industrielles dans les zones rurales. Néanmoins, cette transition vers une économie plus industrielle soulève des questions et des préoccupations légitimes, en particulier en ce qui concerne la pollution de l'eau.

L'expansion industrielle dans les regions rurales peut entraîner une augmentation de la demande en eau à des fins industrielles et provoquer des rejets de polluants industriels dans les systèmes d'eau locaux. Cette réalité a un impact direct sur la qualité de l'eau utilisée pour l'irrigation agricole, ce qui a des répercussions sur les rendements des cultures. Malheureusement, l'industrialisation se produit souvent en l'absence de réglementations environnementales strictes et correctement appliquées, exposant ainsi les sources d'eau à une contamination potentiellement dévastatrice. Cette contamination peut avoir des effets significatifs sur la préservation de l'environnement rural et le développement agricole durable.

La pollution de l'eau résultant de ces activités industrielles peut contenir des produits chimiques toxiques, des métaux lourds et des contaminants organiques, autant de composants susceptibles de nuire aux cultures et de rendre les sols moins propices à la production. De plus, les polluants présents dans l'eau industrielle peuvent compromettre la santé des plantes, entraînant ainsi une réduction des rendements agricoles. Cette situation met en évidence l'urgence de la mise en place de réglementations environnementales rigoureuses dans les zones rurales afin de concilier la croissance durable de l'industrie et le secteur agricole, tout en préservant les ressources en eau essentielles à l'agriculture.

Diverses études et recherches menées dans des pays en développement ont mis en lumière les conséquences néfastes de l'industrialisation rurale sur l'agriculture. Par exemple, une étude menée en Inde a révélé que la pollution industrielle de l'eau a des impacts négatifs et significatifs sur les rendements agricoles, les terres cultivées, le bétail (en raison de l'eau contaminée), l'emploi rural et la santé humaine des résidents du village touché (Reddy and Behera, 2006). De même, des recherches menées par Yongguan et al. 2001 ont évalué l'impact de la pollution industrielle sur l'agriculture, la santé humaine et les activités industrielles à Chongqing, l'une des mégalopoles les plus polluées de Chine. Ils ont estimé que les coûts totaux de la pollution industrielle représentaient 1,2% du produit brut de Chongqing. Sur ce montant, 56 % concernent le secteur agricole, tandis que les dommages causés au capital humain et au secteur industriel représentent respectivement 20 % et 18 %. Ces études révèlent que la pollution industrielle impose des coûts importants aux autres secteurs connexes d'une économie.

L'industrialisation rapide dans les pays en développement, bien qu'ayant contribué au développement économique, a eu des conséquences significatives sur le bien-être économique. Ces répercussions se manifestent à travers les effets néfastes qu'elle a générés sur les activités agricoles, la santé humaine et l'écosystème dans son ensemble, y compris les problèmes de pollution de l'air et de l'eau. En particulier, la pollution de l'eau représente un défi majeur en raison de son impact sur un large éventail d'activités économiques.

La question de la pollution de l'eau revêt une importance accrue dans le contexte d'une économie largement axée sur l'agriculture, en particulier dans les zones rurales des pays en développement. C'est dans ce contexte que cette thèse se penche sur l'analyse des impacts de la pollution de l'eau d'origine industrielle émanant des entreprises manufacturière sur la production agricole. Cette analyse vise à mieux comprendre comment cette pollution affecte la production agricole et, par conséquent, le bien-être économique des communautés rurales.

1.2 Contribution de la thèse

Cette thèse se concentre sur les enjeux liés à l'agriculture et apporte une contribution significative au débat politique concernant la compréhension globale des défis complexes auxquels sont confrontés les ménages ruraux. En combinant des perspectives géographiquement et thématiquement diverses, elle examine tout d'abord l'impact de l'accès à l'irrigation sur la diversité alimentaire et propose des solutions visant à favoriser à la fois la production de cultures diversifiées et la sécurité alimentaire. Puis, elle examine la relation entre le paludisme et le travail agricole dans un contexte d'irrigation. Enfin, elle se penche sur l'impact de la pollution des eaux industrielles sur la production de riz. Ce faisant, cette thèse se situe à la croisée de l'économie de la famille, l'économie de la santé et l'économie agricole.

Plus spécifiquement, le chapitre 2 analyse les effets de l'irrigation sur le scores de diversité alimentaires des femmes et des ménages agricoles. L'analyse porte sur les pays d'ASS, en particulier les pays de l'Union Economique et Monétaire Ouest Africaine (UEMOA) où la part de la population souffrant d'insécurité alimentaire modérée à grave est très élevée. Notre stratégie d'identification est basée sur la méthode d'équilibrage de l'entropie développé par Hainmueller 2012. Cette analyse met en évidence comment les pratiques d'irrigation peuvent influencer la disponibilité de divers types de cultures, en utilisant une base de données récente sur l'enquête harmonisée sur les conditions de vie des ménages dans plusieurs pays d'ASS. Ce chapitre enrichit la littérature en mettant en lumière l'importance de la diversité alimentaire pour les femmes, ce qui peut contribuer à la réduction de la malnutrition et à la prévention de carences nutritionnelles avec des effets bénéfiques sur la santé maternelle et infantile. Les résultats démontrent que les ménages ayant recours à l'irrigation présentent des scores de diversité alimentaire plus élevés que ceux n'ayant pas utilisé l'irrigation. De plus, les résultats révèlent également que les femmes au sein des ménages utilisant l'irrigation affichent des scores de diversité alimentaire plus élevés que ceux des femmes des ménages non-irrigants. Ces résultats s'expliquent par le fait que l'irrigation favorise la culture d'une plus grande variété de cultures, y compris des légumes, des fruits et d'autres cultures riches en nutriments. Cela contribue à la diversification de l'alimentation des ménages ruraux, ce qui est essentiel pour garantir un apport varié en nutriments essentiels dans l'alimentation des femmes et de leurs familles. Par ailleurs, l'irrigation permet d'accroître la production agricole en permettant de cultiver en dehors de la saison des pluies et d'obtenir deux à trois récoltes par an. Cela permet ainsi d'améliorer la sécurité alimentaire en assurant un accès plus constant à une variété d'aliments tout au long de l'année. L'irrigation réduit également la dépendance à l'égard des précipitations pluviales, rendant la production agricole moins vulnérable aux sécheresses et aux variations climatiques, ce qui renforce la sécurité alimentaire et la résilience face aux changements climatiques. Ainsi, ce chapitre met en évidence comment l'irrigation a un impact significatif sur la diversité alimentaire

Le chapitre 3 se focalise sur la relation entre la prévalence du paludisme et le travail agricole dans un contexte d'irrigation et d'agriculture familiale en ASS. Dans ce chapitre, nous explorons l'impact du paludisme sur le travail agricole en utilisant deux mesures distinctes. Plus précisément, nous examinons la quantité de travail mesurée en jour-personne par hectare et la productivité mesurée en production récoltée en kilogrammes par jour-personne. Ce chapitre contribue à la littérature existante sur la relation entre les maladies endémiques et l'agriculture de plusieurs manières. Tout d'abord, notre étude évalue l'impact du paludisme sur le travail agricole en mettant en lumière certains mécanismes sous-jacents expliquant la relation entre le paludisme et le travail dans l'agriculture familiale africaine. Plus spécifiquement, nous nous sommes concentrés sur l'irrigation et la taille des ménages en tant que deux variables modératrices potentielles de l'impact du paludisme sur le travail. En effet, nous nous penchons sur l'irrigation car elle constitue un facteur contextuel important dans la propagation du paludisme mais elle peut également aider les agriculteurs à accroître leur production, à augmenter leurs revenus et à acquérir des outils de prévention et de contrôle du paludisme. Ainsi, les systèmes d'irrigation peuvent jouer un rôle de variable modératrice à la fois positif et négatif dans l'effet du paludisme sur le travail. En outre, les ménages de notre enquête sont principalement engagés dans l'agriculture familiale et rencontrent des difficultés d'accès aux marchés des intrants agricoles ou aux services de vulgarisation. Pour ces ménages, le travail familial est souvent le meilleur moyen de compenser les chocs tels que la maladie. L'allocation intra-ménage de la main-d'œuvre peut ainsi contribuer à faire face à la maladie affectant les membres de la famille. Les ménages de grande taille devraient mieux pouvoir compenser l'absence de travailleurs malades que les ménages de petite taille. Deuxièmement, alors que la plupart des études se limitent à analyser l'effet du paludisme dans un pays, cette étude complète ces études spécifiques à chaque pays en fournissant des preuves de l'effet causal du paludisme sur le travail agricole à partir de données récentes sur l'enquête harmonisée sur les conditions de vie des ménages dans les huit pays de l'UEMOA. Pour ce faire, nous utilisons la methode des variables instrumentales en utilisant les moustiquaires imprégnées d'insecticide et l'utilisation d'insecticides et de spirales en tant qu'instruments externes. Les résultats montrent que le paludisme a un impact négatif sur la quantité de travail. Cet effet est un impact direct sur la santé dû à la perte de journées de travail en raison de la maladie. Cependant, une fois que le paludisme interagit avec l'irrigation ou la taille du ménage, son effet s'avère insignifiant. Nous expliquons ces résultats par la présence d'un effet modérateur de l'irrigation et de la taille du ménage. En ce qui concerne l'irrigation, nous affirmons qu'il s'agit d'un effet modérateur de richesse. Les parcelles irriguées ont des rendements plus élevés, ce qui peut augmenter les revenus des agriculteurs et leur capacité à acheter des moyens de prévention contre le paludisme. En ce qui concerne la taille du ménage, nous expliquons son effet modérateur comme un effet de compensation grâce à une allocation intra-ménage de la main-d'œuvre. D'autre part, les résultats révèlent que le paludisme augmente la productivité du travail. Nous expliquons ce résultat dans le contexte de l'inefficacité productive de l'agriculture familiale africaine. Il y a de la marge pour augmenter la productivité du travail de telle sorte que les travailleurs en bonne santé peuvent augmenter leur productivité pour compenser l'absence de travailleurs malades. En ce qui concerne l'effet modérateur de l'irrigation, nous constatons un impact négatif (peu robuste) de l'interaction du paludisme avec l'irrigation. Nous expliquons ce résultat par un effet d'exposition car les ménages possédant des parcelles irriguées sont plus exposés au paludisme que ceux n'ayant pas de parcelles irriguées. Dans l'ensemble, nos résultats mettent en évidence que le paludisme demeure un problème dans l'agriculture familiale en Afrique. Plus intéressant encore, son impact sur le travail agricole est complexe et dépend des types de travail, des pratiques agricoles et de la composition des ménages. Il est important de garder à l'esprit que la promotion des systèmes d'irrigation doit s'accompagner de mesures de contrôle appropriées (comme la maintenance systématique des canaux d'irrigation) et, en même temps, de la promotion du contrôle du paludisme, de l'information sur la prévention et du système de prestation de services de santé.

Le chapitre 4 se penche sur la question de l'industrialisation des zones rurales. Plus explicitement, il analyse l'impact de la pollution industrielle de l'eau sur la production de riz dans la province du Jiangsu en Chine. Jiangsu est classée comme la troisième province chinoise ayant les rejets d'effluents d'eaux usées les plus élevés en 2015 selon Chen et al. 2019. Pour estimer l'impact de la pollution de l'eau industrielle sur la culture du riz, nous utilisons les données agricoles de l'enquête sur les points fixes ruraux en Chine (CRFPS) que nous combinons avec la base de données administratives complète des statistiques environnementales chinoises (CES) pour construire une base de données associant entreprises industrielles et ménages ruraux. Notre recherche se concentre spécifiquement sur la demande chimique en oxygène (DCO) et l'azote ammoniacal (NH3-N) car ces deux polluants sont couramment utilisés comme indicateurs de la pollution des eaux de surface et sont strictement surveillés par le gouvernement chinois dans le cadre de sa réglementation sur l'environnement aquatique. L'exposition des agriculteurs à la pollution de l'eau industrielle est ensuite calculée en utilisant la moyenne de la pollution de l'eau provenant des entreprises polluantes, pondérée en fonction de la distance de l'entreprise par rapport au centre du comté. L'objectif de cette étude est d'enrichir la littérature sur la relation entre la pollution industrielle de l'eau et l'agriculture dans les pays en développement. Alors que la plupart des études dans la littérature se concentrent sur la manière dont la pollution de l'air affecte les activités agricoles, la problématique de la pollution de l'eau est rarement examinée. Notre étude vise à démêler cette relation complexe en utilisant un modèle de fonction de production translog. Ce modèle nous permet de séparer les effets directs de la pollution industrielle de l'eau sur la riziculture de ses effets d'adaptation. Nos résultats confirment que les rendements du riz sont négativement affectés par la pollution de l'eau industrielle, en raison d'un effet biologique direct. Cet effet préjudiciable est le plus significatif dans un rayon de 5 kilomètres du centre du comté. En réponse, les agriculteurs utilisent davantage d'intrants tels que les engrais et les pesticides pour atténuer l'impact négatif de la pollution de l'eau industrielle. Le changement dans les comportements de production aide ainsi les agriculteurs à mieux faire face au développement industriel et à s'adapter à l'évolution de l'environnement rural. Ainsi, notre étude met en évidence la nécessité de mieux comprendre le lien entre le développement de l'industrie et l'agriculture au niveau local.

Chapter 2

Water for the best: Access to irrigated land and dietary diversity scores in Sub-Saharan Africa

This chapter is joint work with Mohamed Boly (The World Bank).

In this study, we assess the impact of adopting irrigation in West African countries on household and women's dietary diversity using entropy balancing with household data from Harmonized Survey on Household Living Conditions collected in 2018 and 2019. Our results show irrigating households have higher household dietary diversity scores (HDDS) compared to non-irrigating households. In addition, women in irrigating households have higher women's dietary diversity scores (WDDS) compared to non-irrigators. After checking the robustness of these results, we explore the pathways through which nutrition outcomes can be achieved and, identify food production, agricultural income, water supply, and women's empowerment as the potential pathways through which irrigation increases dietary diversity scores. The findings highlight the need to expand and develop access to irrigation, which is a key factor driving agricultural intensification in Sub-Saharan Africa, especially for areas prone to recurring and severe drought.

Keywords: Irrigation · Dietary diversity · Entropy balancing · Sub-Saharan Africa

2.1 Introduction

Despite recent momentum towards improving nutrition and reducing poverty globally, undernutrition still affects billions of people worldwide. According to the 2022 Global Food Policy Report (FAO et al., 2022), around 2.3 billion people in the world were moderately or severely food insecure in 2021, 11.7% of the global population faced food insecurity at severe levels and more than 3 billion people worldwide could not afford a healthy diet. The highest burden of undernutrition is found in low- and middle-income countries (Unicef-WHO-WB, 2020). Sub-Saharan Africa (SSA) including the eight West African Economic and Monetary Union (WAEMU) countries investigated in this study (Benin, Burkina Faso, Côte d'Ivoire, Guinea-Bissau, Mali, Niger, Senegal, and Togo) is particularly concerned and accounted for 40% of the global prevalence of hunger and different forms of malnutrition (FAO et al., 2022). Poor diets, both in quantity and quality, along with diseases are key underlying proximal causes of malnutrition (Webb et al., 2018). Women of reproductive age in low- and middle-income countries are particularly vulnerable (Darnton-Hill and Mkparu, 2015; USAID, 2012). This is the case because of increased nutrient needs for women during pregnancy and lactation, and when these needs are not met, mothers may experience wasting and fatigue that may limit their ability to fully satisfy infant needs (USAID, 2012). This may result in infants who are small for gestational age and children with stunted growth and slowed cognitive development, which may persist into adulthood and transmit to the next generation (USAID, 2012). Thus, the consequences of micronutrient malnutrition do not only affect the health and survival of women but also their offspring. It is estimated that 2 billion people around the world were affected by one of more forms of micronutrient deficiency, including 32 million pregnant or lactating women (FAO et al., 2022).

Furthermore, the prevalence of undernutrition is often higher in SSA rural where agricultural production remains predominantly rainfed with only few smallholder farmers resorting to irrigation (Kemeze, 2020). The high dependence on rainfed agriculture is a source of worry to feed a growing and increasingly prosperous population in a situation of decreasing availability of natural resources, declining soil fertility, and against a backdrop of erratic rainfall patterns and extreme weather conditions, which render farmers vulnerable[1]. However, irrigation is

[1] Note that only 4% of the cultivated area in sub-Saharan Africa is currently irrigated (Giordano et al., 2012).

highly promoted to reduce the farmers' vulnerability to rainfall patterns and to ensure food and livelihood security in the agricultural policy space of many SSA countries (Okyere and Usman, 2021). Then, the relationship between irrigation and nutritional outcomes has received considerable attention from economists and other researchers over the past decade (Ruel et al., 2018). Many studies have explored both positive and negative effects of agriculture on nutrition and health (Mekonnen et al., 2022; Marquis et al., 2018; Pandey et al., 2016; Domènech, 2015; Herforth and Harris, 2014). However, while irrigation is an important component of agricultural intensification, particularly in Sub-Saharan Africa, the impact on nutrition remain an area that requires further investigation.

There are several potential pathways through which irrigation can influence food security, nutrition, and health outcomes including (i) food production, (ii) agricultural income, (iii) women's empowerment and (iv) water supply (Domènech, 2015; Passarelli et al., 2018). The first one describes how irrigation can influence the production pathway through increased agricultural productivity, shifting crop types to more nutrient-rich crops, such as fruits and vegetables, and extending the production season to the dry season, all of which could contribute to improved food security, dietary diversity, and nutritional status. For instance, Du et al. (2018) and Zheng et al. (2019) found that irrigation can increase crop yield by 19.3 and 30.5%, respectively. Moreover, by enabling dry-season cultivation, irrigation can increase the availability of food throughout the year as a result of being able to plant during this season (Domènech, 2015). Irrigation also is most often used to grow horticultural crops like fruits and vegetables which generally provide both greater economic and nutritional benefits (see for instance in Malawi (Jones et al., 2014), Burkina Faso (Olney et al., 2015), Benin (Alaofè et al., 2016), and Ethiopia and Tanzania (Passarelli et al., 2018)). The second pathway, agricultural income, is justified by market sales and employment generation. An increase in agricultural productivity due to irrigation adoption can lead to increased food availability for own consumption or marketing and income generation purposes. Irrigation can therefore be an important source of income since it is frequently used to grow vegetables, fruits, and other cash crops that are usually marketable and highly profitable (Ogutu et al., 2020). As a result of increased agricultural productivity, demand for labor within the household and in neighboring communities may also increase, which is particularly significant during the dry season because job opportunities are less abundant. Irrigation can therefore increase the purchasing power of seasonal workers and members of low-income households, who may decide to use the additional income to purchase nutritious foods and improve dietary diversity (Gebregziabher et al., 2009; Burney and Naylor, 2012; Passarelli et al., 2018; Balana et al., 2020). The third pathway, women's empowerment, including decision-making authority and access to and control over resources, is also an important pathway. Studies of irrigated agricultural interventions targeted towards women have found that women's control over decisions regarding which technologies are adopted and how they are used, are associated with better diet quality and nutrition outcomes (Sraboni et al., 2014; Malapit et al., 2015). Furthermore, women tend to invest more in household nutrition, education, and health and are usually responsible for food preparation and childcare (Quisumbing et al., 2003; Yoong et al., 2012; Meinzen-Dick et al., 2012). Finally, there is a substantial body of literature highlighting the significant role of water, sanitation and hygiene (WASH) in improving nutrition (Humphrey, 2009; Spears, 2013). Thus, reliable access to clean water for irrigation has the potential to improve nutrition through an improved WASH environment as the systems are designed to meet the needs of both agricultural production and domestic uses.

In this study, we assess the impact of adopting irrigation in SSA countries on women's and household dietary diversity using entropy balancing with household data from Harmonized Survey on Household Living Conditions (HSHLC) collected in 2018 and 2019[2]. Specifially, it explores the potential for irrigation to impact dietary as an indicator of the access dimension to food security[3]. Our paper aims to contribute to the literature in different ways. First, our paper provides micro-evidence of the impact of irrigation on dietary diversity from recent and high-quality data across eight different Sub-Saharan African countries. This complements country-specific studies which are often limited in scope. Second, our study highlights the critical importance of dietary diversity, particularly for women. This can contribute to reducing malnutrition and preventing nutritional

[2]Note that the Harmonized Survey on Household Living Conditions (HSHLC) database is EHCVM database named Enquête Harmonisée sur les Conditions de Vie des Ménages on World bank website.

[3]According to FAO 1996, food security exists when all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life. Expanding on this, Barrett 2002 defines food security as a multifaceted concept with four dimensions: availability (referring to the physical existence of food in sufficient quantities to meet the needs of the population); access (pertaining to people's ability to acquire sufficient food to meet their dietary needs); utilization (addressing the ability of people to consume the food they have access to in a way that meets their nutritional needs) ; and stability (highlighting the ability of people to have access to food on a regular basis, even in times of stress or crisis).

deficiencies, with beneficial effects on maternal and child health. Third, we use a novel identification strategy, the entropy balancing method developed by Hainmueller 2012, to empirically quantify the effect of adopting irrigation on dietary diversity scores[4]. Fourth, we explore the pathways through which irrigation affects dietary diversity. We empirically demonstrate that factors such as women's education, access to clean water, income, and agricultural production positively influence dietary diversity. Notably, our study shows that the adoption of irrigation has a positive impact on these different channels, underscoring the crucial role of women in enhancing diet quality and, ultimately, nutrition outcomes.

Regarding the effect of irrigation on nutrition outcomes, our results show that irrigation is an important component of agricultural intensification that contributes to improved nutrition in SSA. This result remains robust to various tests, including alternative specifications, alternative dietary diversity measures, and alternative estimation methods. To explain this result, we highlight various transmission pathways. We demonstrate that food production, agricultural income, water supply and women's empowerment could serve as potential pathways by which irrigation positively enhances dietary diversity. Subsequently, the heterogeneity test shows that the effect of irrigation may depend on idiosyncratic shocks affecting the households including natural shocks, idiosyncratic demographic and price shocks.

The rest of the paper is organized as follows. Section 2.2 presents the empirical methodology. Section 2.3 shows the data and descriptive statistics. Section 2.4 gives the results. Sections 2.5 to 2.7 present respectively the robustness, the transmission channels, the heterogeneity analysis, and Section 2.8 concludes.

2.2 Empirical Methodology

This study assesses the impact of adopting irrigation in SSA countries on Household Dietary Diversity Score (HDDS) and Women's Dietary Diversity Score (WDDS) in irrigating households (treatment group) compared to non-irrigating household (control group). Indeed, as stressed by Passarelli et al. 2018, farmers who choose to irrigate may be inherently different from farmers who do not, based on levels of motivation, knowledge, access to information, and resources. Though we can control

[4] One reason for the superiority of this method over traditional program evaluation approaches such as propensity score matching methods is that entropy balancing combines both matching and linear regression allowing to control for country and time-fixed effects in the second stage. See Section 2.2 for more information on the methodology.

for certain measured variables, like education, income and farm characteristics, we cannot address the unobservable factors that differ between irrigating and non-irrigating households. Since these factors can also influence dietary diversity, irrigation adoption becomes endogenous due to the selection bias. To circumvent this problem and identify the impact of irrigation, we use an impact assessment method, namely entropy balancing developed by Hainmueller 2012. A similar strategy is also used by Pék et al. 2019 to study the effect of farmers' participation in irrigation management on farm productivity and profitability in the Mubuku irrigation scheme, by Morais et al. 2021 to assess the effect of irrigation on farm technical efficiency in Brazil, and by Afesorgbor 2021 to assess the effect of economic sanctions on food security in targeted states.

Our assessment approach in this study is based on the idea that irrigation adoption is the treatment and women's and household dietary diversity scores is the outcome variable. The units of observation are household observations. The observations with irrigation are the treatment group and those without irrigation are the control group. The treatment effect on the treated (ATT) is defined as follows:

$$\text{ATT} = \text{E}[Y_{(1)}|T = 1] - E[Y_{(0)}|T = 1] \tag{2.1}$$

Where $Y_{(.)}$ is the outcome variable measuring the women's and household dietary diversity scores. T indicates if the unit observation is subject to irrigation adoption (T=1) or not (T=0). Consequently, $E[Y_{(1)}|T = 1]$ is the women's and household dietary diversity during the irrigation period and $E[Y_{(0)}|T = 1]$ is the counterfactual outcome for households that had adopted irrigation, i.e the dietary diversity in households that had adopted irrigation if they had not.

The problem lies in the fact that $E[Y_{(0)}|T = 1]$ is not observable due to the non-random nature of irrigation adoption. If it were observable, the ATT could easily be identified by comparing he dietary diversity in irrigating households non-irrgating households. Hence, the identification of ATT requires a good proxy for $E[Y_{(0)}|T = 1]$. To do so, we match irrigation units with non-irrigation units (after purging for some specific factors) that are as close as possible on observable characteristics that meet the following two conditions: correlated with irrigation adoption and women's and household dietary diversity. Under the condition that the non-irrigation household units are fairly close to the irrigation units, any difference in dietary diversity is attributable to irrigation adoption. Based on these different elements, the equation can be rewritten as:

$$\text{ATT} = \text{E}[Y_{(1)}|T = 1, X = x] - E[Y_{(0)}|T = 0, X = x] \tag{2.2}$$

Where $X = x$ is a vector of observable covariates that may affect both the decision to practice irrigation and the dietary diversity scores, $E[Y_{(1)}|T = 1, X = x]$ is the dietary diversity of irrigation units, and $E[Y_{(0)}|T = 0, X = x]$ is the expected dietary diversity for the synthetic control units.

In this study, we use the entropy balancing approach, a generalization of conventional matching methods proposed by Hainmueller 2012, to match treated units with their untreated counterfactuals. In implementing the entropy balancing method, we follow two consecutive steps. The first is to compute weights for the non-treated group (control group). These weights may satisfy pre-specified balanced constraints involving sample moments of observable characteristics (X). Following Neuenkirch and Neumeier 2016, we choose balance constraints that impose equal covariates means between the treatment and control groups. By doing so, we want to ensure that the control group, on average, has non-treatment units that are as similar as possible to the treated units[5]. The second use the weights obtained from the first step in a regression analysis where women's and household dietary diversity scores is the dependent variable. In the second step, we additionally control for the covariates employed in the first step. This is equivalent to including control variables in a randomized experiment and increases estimation efficiency. In addition, time- and department-specific effects are included in the second step to respectively account for time-specific effects such as climatic varia-

[5]This procedure ensures that once the weights are generated, irrigating and non-irrigating households exhibit similar trends in their outcome variable over the pre-treatment period (Ogrokhina and Rodriguez, 2019).

tions and department-specific heterogeneity arising from, for instance, differences between various geographic regions or administrative units, considering factors like soil quality, climate, or local agricultural practices.

Entropy balancing allows us to identify the effect of irrigation by comparing irrigating and non-irrigating households (or units) that are similar on observable characteristics. By combining both matching (in its first step) and regression (in its second step), this method has some advantages over other treatment effect estimators as listed by Hainmueller 2012; Neuenkirch and Neumeier 2016. A particularly important advantage compared to simple regression-based approaches (namely difference-in-difference estimations) as well as matching methods relying on propensity scores is that entropy balancing is nonparametric in the sense that no empirical model for either the outcome variable or selection into treatment needs to be specified. Hence, potential types of misspecification like those, for instance, regarding the functional form of the empirical model, which likely leads to biased estimates, are ruled out. A second advantage is that in contrast to regression-based analyses, treatment effects estimates based on entropy balancing do not suffer from multicollinearity, as the reweighting scheme orthogonalizes the covariates with respect to the treatment indicator. Also in contrast to other matching methods, entropy balancing ensures a high covariate balance between the treatment and control group even in small samples. With "conventional" matching methods such as, for instance, nearest neighbor matching or propensity score matching, each treated unit—in the simplest case—is matched with the one untreated unit that is closest in terms of a metric balancing score. Accordingly, the control group is comprised of only a subset of the units that are not subject to treatment (Hainmueller, 2012; Diamond and Sekhon, 2013). To put it differently, with conventional matching methods, each untreated unit either receives a weight equal to 0, in the event it does not represent the best match for a treated unit or equal to 1, in the event, it does represent the best match for one treated unit[6]. However, when the number of untreated units is limited, and the number of pretreatment characteristics is large, this procedure does not guarantee a sufficient balance of pretreatment characteristics across the treatment and control groups.

[6]Note that conventional matching approaches typically allow for replacement, meaning that an untreated unit can be used multiple times as a match. Thus, in general, conventional matching approaches allow for weights equal to any non-negative integer. However, while matching with replacement improves the quality of the matching in terms of covariate balance, it comes at the expense of efficiency, as the number of observations used to estimate the ATT decreases (see also (Caliendo and Kopeinig, 2008).

This is a serious problem, as a low covariate balance may lead to biased treatment effect estimates. In contrast, with entropy balancing, the vector of weights assigned to the units not exposed to treatment is allowed to contain any non-negative values. Thus, a synthetic control group is designed that represents a virtually perfect image of the treatment group. Entropy balancing thus can be interpreted as a generalization of conventional matching approaches[7]. Another advantage is that compared to conventional matchings such as bias-corrected matching or nearest neighbor matching where control units are either discarded or matched, entropy balancing uses a more flexible reweighting scheme. It reweights units with the goal of achieving balance while keeping at the same time the weights as close as possible to the base weights to avoid a loss of information. Finally, while conventional matching methods rely on the conditional independence assumption, using entropy balancing allows considering the panel dimension of the data.

2.3 Data and descriptive statistics

2.3.1 Data

The data used in this study are derived from the Harmonized Survey on Household Living Conditions (HSHLC) with the support of the World Bank collected in WAEMU countries. Through this survey, the World Bank supports the WAEMU Commission to improve the availability, quality, and comparability of indicators for monitoring poverty and household living conditions in its member states. HSHLC was organized in 2 waves, each counting half of the sample, and took place simultaneously in the eight-member States of the Union over the period from September to December 2018 for the first wave and from April to July 2019 for the second. We have in total a representative sample varying from 5,300 to 13,000 households depending on the country located in eight states of WAEMU.

These data were collected by administering a questionnaire through face-to-face interviews. The survey questionnaire included modules on agricultural production activities, health conditions, dietary diversity, shocks experienced, and socio-demographic characteristics. On the one hand, we have a questionnaire administered at the household level. It collects data on sociodemographic characteristics of

[7] Hainmueller 2012 using Monte Carlo simulations as well as empirical applications, demonstrates that entropy balancing outperforms other matching techniques, such as propensity score matching, nearest neighbor matching, and genetic matching, in terms of estimation bias and mean square error.

individuals within a household (level of education, age, sex, religion...). Moreover, for each household, we have information on their use consumption, and different sources of income (agricultural, non-agricultural, services,...). Through this questionnaire, we also have information on the occurrence of extreme events by category (drought, floods, crop damage from pests and disease...). On the other hand, information related to agriculture production in each household were captured at the plot level.

In this study, we are focused on households living in rural areas as the adoption of irrigation is specific to them. In other words, this study provides evidence to support the positive influence of irrigation on nutrition outcomes in rural areas of developing countries, where rainfed agriculture is the main source of livelihood, and climatic shocks are among the main risks to agricultural production and well-being.

Measuring dietary diversity

Our outcome variable is dietary diversity[8]. Using household-level food consumption data, dietary diversity was measured using FANTA II Project's Household Dietary Diversity Score (HDDS) (FAO, 2011; Swindale and Bilinsky, 2006). HDDS measures a household's economic access to food and is the count of the number of food groups consumed by the household over a certain period of time (Swindale and Bilinsky, 2006). Dietary data were collected using a qualitative, 7-day dietary recall. FAO 2011 suggests that a more robust approach is to use a 24-hour recall period, but this was not available in the HSHLC dataset. Therefore, we employed a HDDS based on food consumption over the preceding 7 days. It's essential to note that various recall timeframes, such as 3 days or, in some cases, the previous month, are valid (FAO, 2011). For instance, Turner et al. 2018 argues that a 24-hour recall period does not accurately measure diets in contexts with varied diets and where seasonality of consumption exists as in SSA countries. Additionally, according to Koppmair et al. 2017 the bias introduced by use of seven-day recall does not significantly affect dietary diversity scores.

A score of 1–12 was then constructed based on the following food groups: (1) cereals, (2) roots and tubers, (3) vegetables, (4) fruits, (5) meat, poultry, offal, (6) eggs, (7) fish and seafood, (8) pulses, legumes, seeds, and nuts, (9) milk and milk products, (10) oils/fats, (11) sugar/honey, and (12) miscellaneous (FAO, 2011; Swindale and Bilinsky, 2006).

[8]We refer to women's and household dietary diversity defined below.

Women's dietary diversity was also calculated using the Women's Dietary Diversity Score (WDDS) (FAO, 2011). It reflects the probability of micronutrient adequacy of the diet, putting more emphasis on micronutrient intake than on economic access according to (FAO, 2011). Dietary data were collected using a qualitative 7-day recall, similar to the HDDS. According to (FAO, 2011) for the measuring of WDDS, 9 food groups were suggested: (1) starchy staples, (2) dark green leafy vegetables, (3) other vitamin-A rich fruit and vegetables, (4) other fruits and vegetables, (5) organ meat, (6) meat and fish, (7) eggs, (8) legumes, nuts and seeds, and (9) milk and milk products. It is the sum of consumed food groups with the reference period (previous 7 days). 1 to 9 food groups have been used to measure the WDDS, with the potential score range being 1-9. In this study, we focus on women of reproductive age (15-49 years) responsible for food preparation for the household[9]. We are interested in women for two reasons. First, focusing on women's diets is important because they are particularly vulnerable to nutritional deficiencies and are more likely to be in charge of smaller purchases including daily staple food expenditures within the household. Second, adequate nutrition, a fundamental cornerstone of any individual's health, is especially critical for women because inadequate nutrition wreaks havoc not only on women's own health but also on the health of their children. Children of malnourished women are more likely to face cognitive impairments, short stature, lower resistance to infections, and a higher risk of disease and death throughout their lives.

[9]As in our study, we focus on the role of women in dietary diversity, only households with a woman aged 15-45 were included in the sample. In female-headed households, we consider that the female respondent was seen as the primary decision maker.

Measuring irrigation

In this study, irrigation is our treatment variable. Based on the plot-level agricultural production information, we construct a measure of irrigation. In fact, in the survey questionnaire, the survey asked each household to mention the main sources of water used on their plot. The respondents reported the following various sources of water: irrigation, own well, canal irrigation, stream irrigation, rainfed, marshes/wetland, and others. We utilized the information above to construct a measure of irrigation as a binary variable which equals 1 if the household practices irrigation and 0 otherwise. Using this recent database, we found that more than 14% of land is equipped for irrigation in WAEMU.

For the control variables, we select the control group of units with non-irrigating that is on average as similar as possible to the treatment group of irrigating units in terms of relevant pretreatment characteristics. Following previous literature on the determinants of irrigation and dietary diversity, we select the following control variables: agricultural land size, agricultural yield, agricultural production, soil fertility, household size, household wealth and household head education (Passarelli et al., 2018; Mekonnen et al., 2022). Since sound farm and household characteristics and agricultural activities may increase households' decision to participate in irrigation, we expect all these variables to be positively correlated with irrigation practice.

2.3.2 Descriptive statistics

Tables 2.1 and 2.2 present descriptive statistics obtained before and after weighting used to estimate the treatment effect of irrigation adoption using entropy balancing. Table 2.1 shows in columns (1) and (2) respectively the sample mean before weighting for the treatment group (irrigators) and the control group (non-irrigators). Columns (3), (4), and (5) of this table report the difference in means between the two groups, and the corresponding t-test statistics and p-values respectively. The results reveal a difference between these two groups. Indeed, households' decisions to practice irrigation farming are determined by high yield, production, education, low fertility, small total area, household size and wealth. These differences across irrigating and non-irrigating households demonstrate the importance of selecting an appropriate control group when computing the treatment effect of irrigation to avoid incorrectly estimated treatment effects.

In Table 2.2, we also report in columns (1) and (2), the sample mean after weighting between the treatment group and the synthetic group obtained from entropy balancing. Columns (3), (4), and (5) show the difference in means, the t-test statistics, and the associated p-values[10]. The analysis of the two groups in this table reveals the effectiveness of entropy balancing as the difference shown in the previous table seems to disappear. It appears clearly that all covariates are perfectly balanced between the two groups and no significant difference remains after weighting. Consequently, entropy balancing allows the construction of a perfect control group that is closely similar to irrigating households in terms of the mean values of the pretreatment covariates.

[10]It is worth noting that time-fixed effects are included in the first step model to control for time-varying local conditions.

Table 2.1: Descriptive statistics before weighting

	(1) Irrigators	(2) Nonirrigators	(3)=(2)-(1) Diff	(4) t-Test	(5) p-Value
Log(total area)	1.096	1.44	0.344	15.975	0.000
Log(yield)	6.648	5.107	-1.541	-23.419	0.000
Log(production)	6.87	6.055	-0.815	-14.691	0.000
Fertility	1.731	1.867	0.136	1.825	0.068
HH size	8.94	9.432	0.492	8.447	0.000
Wealth	1.763	1.778	0.015	-5.415	0.000
Education	1.393	1.262	-0.131	-3.009	0.003
Observations	2772	14890			

Note: This table presents the sample mean before weighting for the treatment group (irrigators) in column (1) and the control group (nonirrigators) in column (2). Columns (3), (4), and (5) show the differences in means between the two groups, and the corresponding t test statistics and p-values.

Table 2.2: Descriptive statistics after weighting

	(1)	(2)	(3)=(2)-(1)	(4)	(5)
	Irrigators	Nonirrigators	Diff	t-Test	p-Value
Log(total area)	1.096	1.096	0.000	0.000	1.000
Log(yield)	6.648	6.647	-0.001	-0.009	0.993
Log(production)	6.87	6.87	0.000	-0.011	0.991
Fertility	1.731	1.731	0.000	-0.007	0.995
HH size	8.94	8.939	-0.001	-0.004	0.997
Wealth	1.763	1.763	0.000	-0.012	0.990
Education	1.393	1.393	0.000	-0.004	0.997
Observations	2772	14890			
Total of weights	2772	2772			

Note: This table presents the sample means matching covariates after weighting across the treated group in column (1) and the synthetic control group obtained from entropy balancing in column (2). Columns (3), (4), and (5) show the differences in means, and the corresponding t-test statistics and p-values.

Next, we compare women's and household dietary diversity scores in the treated and control groups. We explore this comparison in two ways. First, we examine graphically some key statistics presented in Figure 2.1. This figure presents the average percentages of women's and household dietary diversity between irrigators and non-irrigators. Indeed, it shows that irrigating households have, on average, recorded a much higher more diverse food than non-irrigators, with a difference of about 6.2 percent. In addition, women in irrigating households have, on average, more diverse food than non-irrigators, with a difference of 2.5 percent[11]. While this figure exhibits a difference between irrigators and non-irrigators, it cannot assess its magnitude or significance. Thus, to judge the significance of the difference between these two groups of households, we then rely on statistics from tests of difference in means. The results presented in Table 2.3 show these statistics by comparing the average women's and household dietary diversity scores in the two

[11]Note that our outcomes indicators ranged from 1 to 12 for HDDS and from 1 to 9 for WDDS. So, to represent this figure, we convert these values into their corresponding percentages. Thus, for the rest of our study, we will use these measures in %.

groups and reveals that access to irrigation seems to increase dietary diversity. This relationship, while not causal, provides a picture of the treatment effect of irrigation adoption.

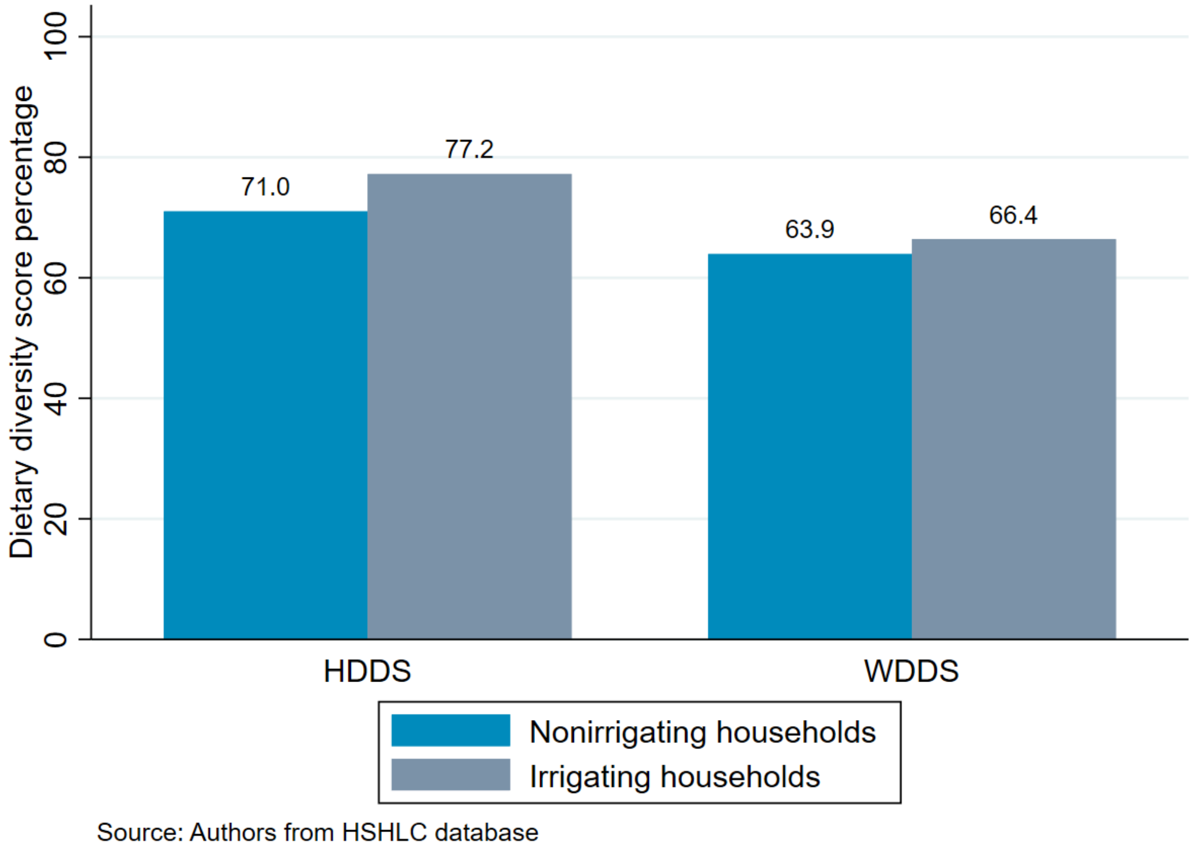


Figure 2.1: Women's and Household dietary diversity scores by irrigation access

Table 2.3: Women's and household dietary diversity score by irrigation: mean-comparison tests

	(1)	(2)	(3)=(2)-(1)	(4)	(5)
	Irrigators	Nonirrigators	Diff	T-test	P-value
HDDS	77.207	69.056	-8.150	-25.785	0.000
WDDS	66.932	62.813	-4.119	-13.358	0.000

Note: This table presents the statistics by comparing the average women's and household dietary diversity scores for the treatment group (irrigators) in column (1) and the control group (non-irrigators) in column (2). Column (3) reports the differences in means between the two groups. (4), and (5) show the differences in means, and the corresponding t-test statistics and p-values.

2.4 Results

2.4.1 Irrigation and household dietary diversity score

With the synthetic controls in Table 2.2, we estimate the impact of access to irrigation on household dietary diversity score (ATT) using a fractional logit. This method is specifically chosen over alternatives, such as weighted least squares, because it is more appropriate for cases where the dependent variable is a proportion or percentage (Papke and Wooldridge, 1996, 2008). Our choice of the fractional logit model over weighted least squares is further justified by the nature of our outcome variable, which is originally expressed as a score. To align with the requirements of the fractional logit model, we transform our outcome variable, namely dietary diversity scores into a percentage relative to the maximum score. The fractional logit model is preferred over weighted least squares, as it is better suited for capturing the nonlinearities and constraints associated with variables that have a bounded distribution between 0 and 1. This choice enhances the model's appropriateness for our specific study context, contributing to a more accurate representation of the impact of irrigation on household dietary diversity.

The findings are provided in Table 2.4 using different specifications. Columns 1 to 4 report the second-step results with no addition of the covariates used in the first stage in constructing the synthetic group. Column 1 excludes month, year and department fixed effects. Columns 2 and 3 include respectively month, year and department fixed effects while column 4 includes these two effects jointly. Finally, columns 5 to 8 repeat the exercise of columns 1 to 4 except for adding in each second stage regression the covariates used in the first stage, namely agricultural land size, agricultural yield, agricultural production, soil fertility, household size, education and wealth. It is worth noting including matching covariates in the second stage of entropy balancing increases the quality of the matching (as in a randomized experiment) while controlling for department, month and year fixed effects eliminates any department- or month and year-specific effects.

Independent of the specification, the estimated effect of access to irrigation is positive and statistically significant at 1%. The magnitude of the effect ranges from 0.20 percentage points (col. 4) to 0.33 percentage points (col. 5) a robust result given the relative stability of the coefficients in the eight specifications of the table with an average effect of 0.27 percentage points. In other words, irrigation access increases on average household dietary diversity by 0.27 percentage points in irrigating households compared to households non-irrigating.

This result is economically high given the average household dietary diversity percentage score of 0.71% in the sample. By adopting irrigation, a household with a percentage average dietary diversity score of 0.71% can expect to increase its dietary diversity from 29.84% to 46.39%, or an average of 38.05%.

Table 2.4: Irrigation and household dietary diversity score (HDDS)

HDDS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Irrigation	0.325***	0.325***	0.211***	0.201***	0.328***	0.327***	0.223***	0.214***
	(0.0264)	(0.0266)	(0.0384)	(0.0380)	(0.0257)	(0.0257)	(0.0373)	(0.0373)
Covariates in the second step	No	No	No	No	Yes	Yes	Yes	Yes
Month fixed effects in the second step	No	Yes	No	Yes	No	Yes	No	Yes
Year fixed effects in the second step	No	Yes	No	Yes	No	Yes	No	Yes
Department*Month fixed effects in the second step	No	No	Yes	Yes	No	No	Yes	Yes
Observations	17,632	17,632	17,632	17,632	17,632	17,632	17,632	17,632

Notes: This table presents the effect of access to irrigation on household dietary diversity score (HDDS) using a fractional logit model with weight. The treatment variable is irrigation. The outcome variable is HDDS. The control variable not reported are total area, yield, production, fertility, household size, wealth and head education. Robust standard errors are in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%.

2.4.2 Irrigation and women's dietary diversity score

In this section, we present the results of women's dietary diversity scores. As explained above, with the synthetic controls, we estimate the effect of irrigation on women's dietary diversity score (WDDS) using fractional logit model. The results are reported in Table 2.5. The same approach is followed for results in Table 2.4. Taken together (cols. 1 to 8), our results show a positive and significant effect at 1%, suggesting that women in irrigating households have more diversified diets compared to women in non-irrigating households. More precisely, the magnitude of the effect ranges from 0.09 percentage points (col. 4) to 0.11 percentage points (col.7) with an average effect of 0.11 percentage points. In other words, irrigation access increases on average women's dietary diversity score by 0.11 percentage points in women in irrigating households compared to non-irrigating households.

Economically, this result is high, considering the average dietary diversity percentage of women in non-irrigating households, which is 0.63%. In households adopting irrigation, women would see their dietary diversity increase from 14.93% to 17.19%, or an average of 16.88%.

Table 2.5: Irrigation and women's dietary diversity score (WDDS)

WDDS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Irrigation	0.109***	0.109***	0.104***	0.095***	0.110***	0.109***	0.113***	0.105***
	(0.0219)	(0.0215)	(0.0340)	(0.0335)	(0.0230)	(0.0222)	(0.0328)	(0.0327)
Covariates in the second step	No	No	No	No	Yes	Yes	Yes	Yes
Month fixed effects in the second step	No	Yes	No	Yes	No	Yes	No	Yes
Year fixed effects in the second step	No	Yes	No	Yes	No	Yes	No	Yes
Department*Month fixed effects in the second step	No	No	Yes	Yes	No	No	Yes	Yes
Observations	15,678	15,678	15,678	15,678	15,678	15,678	15,678	15,678

Notes: This table presents the effect of access to irrigation on women's dietary diversity score (WDDS) using a fractional logit model with weight. The treatment variable is irrigation. The outcome variable is WDDS. The control variable not reported are total area, yield, production, fertility, household size, wealth and head education. Robust standard errors are in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%.

2.5 Robustness checks

While the previous findings show that access to irrigation significantly increases dietary diversity, in this section, we perform a battery of robustness checks to ensure that these findings are not sensitive to alternative specifications. To do this, several variables are used for this exercise. First, based on the irrigation and dietary diversity literature, we test the robustness of our results using a set of additional control variables. Then, an alternative definition of the dependent variable is used to test the robustness of our findings. We test the sensitivity of our results by using food consumption scores (FCS).

2.5.1 Alternative specifications

Using additional controls

Our first alternative specification is to use a set of additional control variables. Based on the irrigation and dietary diversity literature, we then test the robustness of our results using a set of additional covariates such as livestock (number of cows, goats or sheep, poultry, pigs, rabbits), production diversity, household head age, and income-related variables (whether a household received remittances in the previous 12 months and whether a household received income in the form of a gift). For this purpose, we first include these variables in the second stage of entropy balancing. Columns 1 to 8 of Table 2.9 in Appendix, which report the results of these specifications, show their consistency with our baseline findings. In other words, adding these additional covariates does not change our results. In addition, given that any characteristics able to predict irrigation can be a source of endogeneity, we augment the variables used in the baseline first-stage model by adding these additional control variables to construct the new synthetic controls. The new results are reported in columns 1 to 8 of Table 2.10 in Appendix and show that adding these variables in the first stage only does not change our results. In the same vein, by adding these additional control variables in both the second and first stages presented in Table 2.11, the results remain similar to the baseline case.

Alternative measure of the outcome variable: food consumption score

In this section, we use an alternative measure of dietary diversity, namely food consumption score (FCS) to test the robustness of our results. The food consumption score (FCS) was measured using a core indicator by the World Food Programme (WFP) (WFP, 2008). It measures dietary quality. It is calculated by adding the number of days each food group was consumed. Then, we multiply those frequencies by a predetermined set of weights designed to reflect the heterogeneous dietary quality for each of the food groups consumed by the households. Note that FCS information was collected using a list of nineteen items. The FCS ranges in value from 0 to 100, and a higher score would imply a better heterogeneous dietary quality[12]). Armed with this new measure, we evaluate the stabilizing effect of irrigation using entropy balancing. Table 2.12 replicates Table 2.4 using FCS[13].

Table 2.12 in Appendix shows that independent of the specification, the adoption of irrigation significantly increases the food consumption score. This result ranges from 0.14 percentage points (column 3) to 0.21 percentage points (column 6), a robust result given the relative stability of the coefficients in the 8 specifications of the table, with an average effect of 0.18 percentage points. In other words, irrigation access increases on average food consumption by 0.18 percentage points in irrigating households compared to households non-irrigating.

Taken together, our results support that alternative measure of dietary diversity does not alter our conclusions.

2.5.2 Alternative estimation methods

While previous findings of our entropy balancing tell a very consistent story. We use two methods to test the robustness of our results. This exercise aims to check if our results are influenced by the choice of estimation method. To do this, we use the Ordinary Least square (OLS) method and the propensity score method (PSM) developed by Rosenbaum and Rubin 1983.

Our first method consists of using Ordinary Least squares (OLS). The results are reported in Table 2.13 in the Appendix. Columns 1 to 4 present the results with HDDS and columns 5 to 8 show the results with WDDS. With regards to HDDS results, column 1 excludes department- and (month) time-fixed effects. Columns 2 to 3 include respectively month(year)- and department-fixed effects while column 4 includes these two effects jointly. Regarding WDDS results, columns 5 to 8 repeat the same exercise as columns 1 to 4. The results in columns 1 to 8 show that similar to the entropy balancing approach, access to irrigation increases women's and household dietary diversity scores independently of the specification. However,

[12]FCS has been used as a measure of dietary quality in other African countries (e.g., (Hoddinott et al., 2018)

[13]As we use the fractional logit model, we convert our variables between 0 and 1.

the relationship identified in the previous table may suffer from omitted variables bias. To mitigate this problem, we test the robustness of this link by extending our baseline specification with a set of control variables drawn from irrigation and dietary diversity literature. To do so, we add the previous additional control variables used in section 2.5.1. The results are provided in Table 2.14. We find that the estimated effect of irrigation is still positive and statistically significant.

Next, we test the robustness of our results using the propensity score method, which is part of an impact analysis method. This method allows us to correct for endogeneity problems, particularly selection bias. The results in Tables 2.15 and 2.16 in Appendix compile the estimation of irrigation effect (ATT) using four matching methods: Nearest-Neighbor Matching, Radius Matching, Kernel Matching, and Local Linear Regression Matching. They allow us to conclude the consistency of our findings to the choice of the alternative method since the ATTs are independent of the matching method used positively and statistically significant.

Taken together, based on these different estimations, we can conclude that our results are robust to the choice of estimation method since changing the method does not qualitatively modify our conclusions.

2.6 Channels

Our findings suggest that irrigation contributes to enhanced dietary diversity in Sub-Saharan Africa. This section aims to shed light on the mechanisms underlying this result. Drawing on the discussion in the introduction, we test the relevance of our four potential transmission channels. These channels include women's education, agricultural income, agricultural total production, and water supply access. They serve as indicators of women's empowerment, agricultural income, food production, and water supply, respectively, addressing these pathways in our model[14]. As it is well known, the literature does not provide explicit methods for evaluating transmission channels. In this study, we adopt a simple two-step approach.

First, before testing our channels, we evaluate their relevance to women's and household dietary diversity scores using the OLS estimator. The aim of this

[14] Following Passarelli et al. 2018, we control for proxy of women's empowerment using women's education due to data limitations

approach is to see if the four identified pathways are each correlated with dietary diversity. Second, we re-estimate our baseline model using OLS regressions and replace our dependent variable with the potential channel.

In Columns (1)-(4) of Model A in Table 2.6, we estimate a univariate regression of women's education, agricultural income and production and water supply on women's and household dietary diversity scores. Consistent with economic theory, the results show that these pathways are highly correlated with dietary diversity, representing potentially important transmission channels through which irrigation can positively affect dietary diversity in SSA. Finally, the findings reported in Model B indicate a significant correlation between irrigation and substantial enhancements in women's education, agricultural income, production, and access to water supply. In summary, irrigation can play a pivotal role in improving dietary diversity by increasing household incomes, influencing production dynamics, promoting women's education, and facilitating greater access to clean water.

Table 2.6: Validity of transmission channels

Model A	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	HDDS	HDDS	HDDS	HDDS	WDDS	WDDS	WDDS	WDDS
Women's education	0.0167***				0.0115***			
	(0.00131)				(0.00122)			
Log(income)		0.00791***				0.00528***		
		(0.000920)				(0.000894)		
Log(production)			0.00703***				0.00485***	
			(0.000791)				(0.000784)	
Water supply				0.0223***				0.0201***
				(0.00205)				(0.00202)
Model B	(1)	(2)	(3)	(4)				
	Women's education	Log(income)	Log(production)	Water supply				
Irrigation	0.0974***	0.189**	0.116*	0.0406***				
	(0.0224)	(0.0847)	(0.0631)	(0.0157)				

*** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%..

2.7 Heterogeneity of results

Despite having some common characteristics, irrigation may have different impacts during shocks such as storms, drought, and floods, crop damage from pests and disease, and idiosyncratic shocks, such as death and illness of a household member.

The adoption of practices can also be explained by internal factors, i.e., factors directly linked to the farm characteristics such as area size. Consequently, this section explores some potential heterogeneity features of the treatment effect. On the one hand, the aim of this exercise is to test the hypothesis that access to irrigation tends to increase household and women's resilience to climate and idiosyncratic shocks. On the other hand, we test whether irrigation adoption has a persistent effect by estimating the effect of irrigation according to the area of irrigated land.

First, we analyze the effectiveness of irrigation according to climate and idiosyncratic shocks (demographic shock, price shock, and natural shock). Climate and idiosyncratic shocks are shown to have a negative impact on dietary diversity and child nutrition, and access to irrigation tends to increase household and women's resilience to these shocks (Mekonnen et al., 2022). We test this hypothesis by constructing a dummy variable that captures the access to irrigation under shocks such as demographic shocks, price shocks, and natural shocks. We then estimate the effect of irrigation on women's and household dietary diversity scores. The results reported in Table 2.7 in columns 1 to 8 support our hypothesis. We find the estimated effects of irrigation are positive and statistically significant in all specifications.

Second, we analyze the sensitivity of our results according to the area of irrigated land. To test this hypothesis, we define a treatment variable equal to 1 if irrigation for small farmers (total land irrigated less than 2 ha), and 0 otherwise[15]. We then estimate the effect of irrigation on women's and household dietary diversity scores using the new treatment variable, and after excluding households with an irrigated area greater than 2 ha. The results based on the entropy balancing are reported in Table 2.8. We find that the estimated coefficient is positive and statistically significant. It suggests that the adoption of irrigation practices on small farms (less than 2 hectares) is associated with an improvement in dietary diversity. This could

[15]Note that we use this measure according to the 2019 report of Food and Agriculture Organization, which defines a threshold of less than 2 ha to define small farms (Lowder et al., 2019).

imply that small-scale irrigation positively influences, for example, food production or income, contributing to dietary diversity.

Table 2.7: Irrigation, women's and household dietary diversity scores: climate and idiosyncratic shocks effects using entropy balancing

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable	HDDS	HDDS	HDDS	HDDS	WDDS	WDDS	WDDS	WDDS
Irrigation	0.320***	0.319***	0.215***	0.205***	0.103***	0.102***	0.101***	0.0912***
	(0.0291)	(0.0290)	(0.0399)	(0.0398)	(0.0258)	(0.0248)	(0.0350)	(0.0346)
Covariates in the second step	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Month FE in 2nd. step	No	Yes	No	Yes	No	Yes	No	Yes
Year FE in 2nd. step	No	Yes	No	Yes	No	Yes	No	Yes
Dpt*Month FE in 2nd. step	No	No	Yes	Yes	No	No	Yes	Yes
Observations	14,461	14,461	14,461	14,461	12,880	12,880	12,880	12,880

Notes: This table presents the heterogeneities of the effect of access to irrigation on women's and household dietary diversity scores using a fractional logit model. Columns 1 to 4 and columns 5 to 8 report the results of HDDS and WDDS respectively. Robust standard errors are in parentheses. level. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%..

Table 2.8: Irrigation, women's and household dietary diversity scores: farm size effect using entropy balancing

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable	HDDS	HDDS	HDDS	HDDS	WDDS	WDDS	WDDS	WDDS
Irrigation	0.367***	0.369***	0.317***	0.289***	0.158***	0.159***	0.218***	0.191***
	(0.0339)	(0.0326)	(0.0567)	(0.0557)	(0.0285)	(0.0274)	(0.0475)	(0.0455)
Covariates in the second. step	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Month fixed effects in the second. step	No	Yes	No	Yes	No	Yes	No	Yes
Year fixed effects in the second step	No	Yes	No	Yes	No	Yes	No	Yes
Dpt*Month fixed effects in the second step	No	No	Yes	Yes	No	No	Yes	Yes
Observations	9,171	9,171	9,171	9,171	7,872	7,872	7,872	7,872

Notes: This table presents the sensitivity of the effect of access to irrigation on women's and household dietary diversity scores using a fractional logit model. The treatment variable takes 1 if irrigation for small farmers (total land irrigated less than 2 ha), and 0 otherwise. Columns 1 to 4 and columns 5 to 8 report the results of HDDS and WDDS respectively. Robust standard errors are in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%.

2.8 Conclusion

This paper analyses the effect of access to irrigation on women's and households dietary diversity scores in Sub-Saharan African countries. Using recent household data from HSHLC collected in 2018 and 2019 and relying on entropy balancing, we show that households using irrigation have a higher dietary diversity scores. This result is robust to various tests, including alternative specifications, alternative dietary diversity measure such as food consumption scores, and alternative estimation methods. Transmission pathway analysis indicates that women's empowerment and agricultural income are the potential pathways through which irrigation increases dietary diversity. However, results reveal some heterogeneity of irrigation according to structural factors such as climate and idiosyncratic shocks, and farm size. Additional results highlighted in this paper show that irrigation not only improves nutrition outcomes in SSA countries but also contributes to increasing households' resilience to climate and idiosyncratic shocks in a manner that can counteract the negative effects of these shocks on the nutritional status of households.

This study contributes to the debate on the effect of irrigation which is a key factor driving agricultural intensification in SSA and its impacts on nutrition. Speciffialy, it highlights the importance of dietary diversity for women, which can contribute to reducing malnutrition and preventing nutritional deficiencies, with beneficial effects on maternal and child health.

Taken together, these results highlight the need to the importance of promoting the adoption of irrigation to strengthen food security in rural areas of developing countries, particularly in SSA. As such, irrigation should be promoted on its merit to improve nutrition, in addition to its potential for higher yields, incomes, and employment. It would be advantageous to consider financial incentives, such as subsidies or preferential loans, to support farmers' investments in irrigation infrastructure. Additionally, providing technical training to farmers on effective irrigation practices, including water management, crop planning, and irrigation system maintenance, would be essential. The results also suggest that it is essential to highlight women's empowerment as a central objective of this policy because it plays a crucial role in improving dietary diversity scores. This could be achieved through programs aimed at strengthening women's participation in decision-making related to agriculture and granting them better access to agricultural resources. Such an approach could enhance the resilience of rural communities to climate shocks and contribute to improving the overall quality of their nutrition. This is especially important for areas prone to recurring and severe drought and considering expected climatic changes that will increase the frequency, intensity, and duration of the climatic shock. However, despite the positive impact of irrigation, we contend that other sustainable irrigation sources, such as rainwater harvesting should be used. Moreover, rained agriculture can be improved with other farming techniques such as agroforestry and soil and water conservation practices.

2.9 Appendices of Chapter 2

Table 2.9: Irrigation, women's and household dietary diversity scores: additional control in the second stage

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dept. var.	HDDS	HDDS	HDDS	HDDS	WDDS	WDDS	WDDS	WDDS
Irrigation	0.378***	0.376***	0.223***	0.213***	0.148***	0.148***	0.141***	0.132***
	(0.0298)	(0.0299)	(0.0464)	(0.0455)	(0.0251)	(0.0246)	(0.0400)	(0.0393)
Log(total area)	0.102***	0.106***	0.0910***	0.0849***	0.0368	0.0501*	0.0456**	0.0395*
	(0.0357)	(0.0355)	(0.0264)	(0.0265)	(0.0280)	(0.0278)	(0.0211)	(0.0210)
Log(yield)	0.0560***	0.0577***	0.0385***	0.0338**	0.0286*	0.0355**	0.0230**	0.0185
	(0.0195)	(0.0193)	(0.0147)	(0.0143)	(0.0158)	(0.0158)	(0.0116)	(0.0114)
Log(production)	0.0386*	0.0335*	0.0173	0.0187	0.0248	0.0160	0.0181	0.0211
	(0.0205)	(0.0203)	(0.0172)	(0.0168)	(0.0171)	(0.0170)	(0.0142)	(0.0141)
Fertility	-0.123***	-0.125***	-0.0710***	-0.0689***	-0.0846***	-0.0854***	-0.0538***	-0.0509***
	(0.0206)	(0.0206)	(0.0193)	(0.0191)	(0.0188)	(0.0186)	(0.0164)	(0.0163)
Household size	0.00904***	0.00930***	0.00268	0.00264	0.00838***	0.00807***	0.000513	0.000210
	(0.00288)	(0.00285)	(0.00264)	(0.00260)	(0.00252)	(0.00249)	(0.00234)	(0.00233)
Wealth	-0.133***	-0.138***	-0.176***	-0.176***	-0.0761***	-0.0860***	-0.130***	-0.129***
	(0.0324)	(0.0324)	(0.0251)	(0.0250)	(0.0280)	(0.0275)	(0.0214)	(0.0214)
HH head education	0.137***	0.134***	0.0925***	0.0899***	0.0904***	0.0863***	0.0609***	0.0600***
	(0.0168)	(0.0166)	(0.0145)	(0.0143)	(0.0128)	(0.0129)	(0.0114)	(0.0113)
Production diversity	-0.00916***	-0.00925***	-0.00572**	-0.00569**	-0.00856***	-0.00843***	-0.00484**	-0.00480**
	(0.00287)	(0.00285)	(0.00227)	(0.00222)	(0.00253)	(0.00250)	(0.00206)	(0.00204)
Number of cows	-3.29e-05	4.68e-05	-0.000231	-0.000252	0.000589	0.000754	-0.000148	-0.000139
	(0.000824)	(0.000810)	(0.000650)	(0.000650)	(0.000628)	(0.000605)	(0.000568)	(0.000568)
Number of goats or sheep	-0.000186	-0.000217	0.000649	0.000719	0.000854	0.000726	0.000901	0.000941
	(0.000559)	(0.000569)	(0.000721)	(0.000727)	(0.000565)	(0.000546)	(0.000720)	(0.000731)
Number of pig	-0.0110***	-0.0114***	-0.00645***	-0.00716***	-0.00739*	-0.00823**	-0.00436**	-0.00478**
	(0.00319)	(0.00333)	(0.00222)	(0.00231)	(0.00385)	(0.00373)	(0.00205)	(0.00213)
Number of rabbit	0.0364*	0.0376**	0.0250	0.0249	0.0147	0.0164	0.0177	0.0179
	(0.0187)	(0.0185)	(0.0158)	(0.0163)	(0.0152)	(0.0151)	(0.0149)	(0.0148)
Number of poultry	0.000847*	0.000922*	0.00120***	0.00125***	0.00132***	0.00145***	0.000947***	0.000992***
	(0.000506)	(0.000499)	(0.000461)	(0.000466)	(0.000423)	(0.000421)	(0.000362)	(0.000364)
HH head age	0.00121	0.00112	-7.29e-05	-0.000236	0.00130*	0.00138*	0.000802	0.000738
	(0.000815)	(0.000811)	(0.000711)	(0.000701)	(0.000764)	(0.000760)	(0.000684)	(0.000679)
Remittances	-0.139***	-0.139***	-0.0837***	-0.0799***	-0.0743***	-0.0747***	-0.0373*	-0.0360*
	(0.0298)	(0.0300)	(0.0249)	(0.0247)	(0.0251)	(0.0250)	(0.0216)	(0.0215)
Gifts	-0.104***	-0.107***	-0.145***	-0.149***	-0.120***	-0.115***	-0.122***	-0.123***
	(0.0352)	(0.0350)	(0.0289)	(0.0290)	(0.0307)	(0.0302)	(0.0258)	(0.0258)
Month FE in 2nd. step	No	Yes	No	Yes	No	Yes	No	Yes
Year FE in 2nd. step	No	Yes	No	Yes	No	Yes	No	Yes
Dpt*Month FE in 2nd. step	No	No	Yes	Yes	No	No	Yes	Yes
Observations	12,701	12,701	12,701	12,701	11,564	11,564	11,564	11,564

Notes: This table presents the effect of access to irrigation on women's and household dietary diversity scores using a fractional logit model with weight. The treatment variable is irrigation. The outcome variable is HDDS (col.1-4) and WDDS (col.5-8). Columns 1 to 4 and columns 5 to 8 report the results of HDDS and WDDS respectively. Robust standard errors are in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%.

Table 2.10: Irrigation, women's and household dietary diversity scores: additional controls in the first stage only

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dept. var.	HDDS	HDDS	HDDS	HDDS	WDDS	WDDS	WDDS	WDDS
Irrigation	0.376***	0.376***	0.221***	0.208***	0.143***	0.144***	0.132***	0.123***
	(0.0315)	(0.0317)	(0.0515)	(0.0499)	(0.0261)	(0.0258)	(0.0443)	(0.0431)
Covariates in the second step	No	No	No	No	No	No	No	No
Month fixed effects in the second step	No	No	Yes	Yes	No	No	Yes	Yes
Year fixed effects in the second step	No	No	Yes	Yes	No	No	Yes	Yes
Dpt*Month fixed effects in the second step	No	Yes	No	Yes	No	Yes	No	Yes
Observations	12,701	12,701	12,701	12,701	11,564	11,564	11,564	11,564

Notes: This table presents the effect of access to irrigation on women's and household dietary diversity scores using a fractional logit model with new synthetic controls. It presents the results with additional control covariates in the first stage only used to construct this new synthetic control. These additional control variables are total area, yield, production, fertility, household size, production diversity, number of cows, number of poultry, number of goats and sheep, number of pigs, number of rabbits, household head age, household head education, remittances, and gifts. Columns 1 to 4 and columns 5 to 8 report the results of HDDS and WDDS respectively. Robust standard errors are in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%.

Table 2.11: Irrigation, women's and household dietary diversity scores: additional control in both second and first stage

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dept. var.	HDDS	HDDS	HDDS	HDDS	WDDS	WDDS	WDDS	WDDS
Irrigation	0.380***	0.379***	0.220***	0.209***	0.143***	0.143***	0.132***	0.123***
	(0.0297)	(0.0298)	(0.0475)	(0.0468)	(0.0252)	(0.0247)	(0.0410)	(0.0403)
Log(total area)	0.105***	0.108***	0.0891***	0.0836***	0.0311	0.0414	0.0345*	0.0289
	(0.0376)	(0.0371)	(0.0254)	(0.0259)	(0.0296)	(0.0298)	(0.0209)	(0.0208)
Log(yield)	0.0478**	0.0491***	0.0324**	0.0280**	0.0220	0.0270*	0.0151	0.0108
	(0.0190)	(0.0187)	(0.0133)	(0.0132)	(0.0161)	(0.0164)	(0.0111)	(0.0110)
Log(production)	0.0505**	0.0459**	0.0250	0.0256	0.0363**	0.0300	0.0275*	0.0298**
	(0.0208)	(0.0204)	(0.0167)	(0.0162)	(0.0182)	(0.0183)	(0.0142)	(0.0138)
Fertility	-0.119***	-0.121***	-0.0599***	-0.0552***	-0.0805***	-0.0819***	-0.0406**	-0.0366**
	(0.0218)	(0.0218)	(0.0199)	(0.0196)	(0.0196)	(0.0196)	(0.0169)	(0.0166)
Household size	0.00709**	0.00776**	0.00119	0.00107	0.00767**	0.00783***	-0.000441	-0.000803
	(0.00325)	(0.00319)	(0.00280)	(0.00276)	(0.00298)	(0.00292)	(0.00255)	(0.00253)
Wealth	-0.142***	-0.148***	-0.182***	-0.184***	-0.0784***	-0.0885***	-0.132***	-0.131***
	(0.0345)	(0.0342)	(0.0255)	(0.0254)	(0.0294)	(0.0289)	(0.0215)	(0.0215)
HH head education	0.134***	0.130***	0.0827***	0.0797***	0.0867***	0.0829***	0.0543***	0.0529***
	(0.0178)	(0.0175)	(0.0150)	(0.0149)	(0.0136)	(0.0138)	(0.0118)	(0.0117)
Production diversity	-0.00908***	-0.00936***	-0.00506**	-0.00518**	-0.00852***	-0.00852***	-0.00469**	-0.00473**
	(0.00302)	(0.00298)	(0.00229)	(0.00225)	(0.00267)	(0.00263)	(0.00210)	(0.00208)
Number of cows	9.35e-05	6.51e-05	-0.000266	-0.000245	0.000317	0.000311	-0.000331	-0.000298
	(0.000720)	(0.000701)	(0.000568)	(0.000576)	(0.000554)	(0.000544)	(0.000479)	(0.000480)
Number of goats or sheep	-0.000169	-0.000193	0.00126*	0.00132*	0.00140*	0.00128*	0.00179***	0.00183***
	(0.000840)	(0.000844)	(0.000696)	(0.000699)	(0.000733)	(0.000704)	(0.000653)	(0.000655)
Number of pigs	-0.0114**	-0.0119**	-0.00271	-0.00343	-0.00925**	-0.00984**	-0.00309	-0.00356
	(0.00446)	(0.00476)	(0.00331)	(0.00341)	(0.00403)	(0.00401)	(0.00267)	(0.00273)
Number of rabbits	0.0457**	0.0463**	0.0360**	0.0398**	0.0190	0.0182	0.0160	0.0174
	(0.0201)	(0.0198)	(0.0173)	(0.0185)	(0.0225)	(0.0210)	(0.0173)	(0.0172)
Number of poultry	0.000338	0.000435	0.000809*	0.000850*	0.00108*	0.00125**	0.000806**	0.000853**
	(0.000644)	(0.000654)	(0.000456)	(0.000458)	(0.000568)	(0.000592)	(0.000389)	(0.000391)
HH head age	0.00113	0.000939	0.000130	-4.11e-05	0.00128	0.00124	0.000879	0.000805
	(0.000853)	(0.000847)	(0.000727)	(0.000718)	(0.000803)	(0.000798)	(0.000696)	(0.000691)
Remittances	-0.156***	-0.154***	-0.0754***	-0.0706***	-0.0775***	-0.0764***	-0.0305	-0.0284
	(0.0339)	(0.0343)	(0.0263)	(0.0260)	(0.0280)	(0.0280)	(0.0225)	(0.0225)
Gifts	-0.125***	-0.128***	-0.154***	-0.158***	-0.133***	-0.128***	-0.122***	-0.124***
	(0.0455)	(0.0453)	(0.0325)	(0.0326)	(0.0386)	(0.0371)	(0.0278)	(0.0279)
Month FE in 2nd. step	No	Yes	No	Yes	No	Yes	No	Yes
Year FE in 2nd. step	No	Yes	No	Yes	No	Yes	No	Yes
Dpt*Month FE in 2nd. step	No	No	Yes	Yes	No	No	Yes	Yes
Observations	12,701	12,701	12,701	12,701	11,564	11,564	11,564	11,564

Notes: This table presents the effect of access to irrigation on women's and household dietary diversity scores using a fractional logit model with new synthetic controls. It presents the results with additional control covariates in both the second and first stages. Columns 1 to 4 and columns 5 to 8 report the results of HDDS and WDDS respectively. Robust standard errors in parentheses are clustered at department level. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%.

Table 2.12: Irrigation and food consumption score (FCS)

FCS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Irrigation	0.206***	0.206***	0.135***	0.137***	0.208***	0.209***	0.148***	0.151***
	(0.0223)	(0.0223)	(0.0299)	(0.0294)	(0.0216)	(0.0213)	(0.0286)	(0.0284)
Covariates in the second step	No	No	No	No	Yes	Yes	Yes	Yes
Month fixed effects in the second step	No	Yes	No	Yes	No	Yes	No	Yes
Year fixed effects in the second step	No	Yes	No	Yes	No	Yes	No	Yes
Department*Month fixed effects in the second step	No	No	Yes	Yes	No	No	Yes	Yes
Observations	17,632	17,632	17,632	17,632	17,632	17,632	17,632	17,632

Notes: This table presents the effect of access to irrigation on food consumption score (FCS) using a fractional logit model. The treatment variable is irrigation. The outcome variable is FCS. The control variables not reported are total area, yield, income, production, fertility, household size, and women's education. Robust standard errors are in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%.

Table 2.13: Irrigation, women's and household dietary diversity scores using OLS

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dept var.	HDDS	HDDS	HDDS	HDDS	WDDS	WDDS	WDDS	WDDS
Irrigation	0.979***	1.005***	0.796***	0.781***	0.370***	0.388***	0.378***	0.364***
	(0.0355)	(0.0356)	(0.0560)	(0.0561)	(0.0284)	(0.0280)	(0.0438)	(0.0437)
Logtotal(area)	0.134***	0.136***	0.0759***	0.0791***	0.0786***	0.0812***	0.0554***	0.0586***
	(0.0300)	(0.0299)	(0.0283)	(0.0283)	(0.0226)	(0.0223)	(0.0214)	(0.0213)
Log(yield)	0.00425	0.00429	-0.0187	-0.0162	0.0173	0.0172	0.00203	0.00315
	(0.0152)	(0.0151)	(0.0146)	(0.0147)	(0.0118)	(0.0116)	(0.0111)	(0.0112)
Log(production)	0.129***	0.121***	0.0916***	0.0876***	0.0636***	0.0570***	0.0410***	0.0376***
	(0.0174)	(0.0173)	(0.0174)	(0.0174)	(0.0134)	(0.0132)	(0.0130)	(0.0131)
Fertility	-0.366***	-0.365***	-0.187***	-0.192***	-0.187***	-0.186***	-0.0964***	-0.106***
	(0.0221)	(0.0221)	(0.0239)	(0.0239)	(0.0164)	(0.0164)	(0.0178)	(0.0179)
Household size	0.0365***	0.0361***	0.0299***	0.0296***	0.0321***	0.0319***	0.0190***	0.0187***
	(0.00293)	(0.00292)	(0.00306)	(0.00306)	(0.00211)	(0.00210)	(0.00218)	(0.00217)
Wealth	-0.449***	-0.460***	-0.429***	-0.435***	-0.228***	-0.239***	-0.241***	-0.251***
	(0.0322)	(0.0322)	(0.0308)	(0.0308)	(0.0237)	(0.0236)	(0.0231)	(0.0231)
HH head education	0.230***	0.220***	0.158***	0.156***	0.129***	0.121***	0.0823***	0.0802***
	(0.0179)	(0.0179)	(0.0177)	(0.0177)	(0.0133)	(0.0132)	(0.0135)	(0.0134)
Month fixed effects in the second step	No	Yes	No	Yes	No	Yes	No	Yes
Year fixed effects in the second step	No	Yes	No	Yes	No	Yes	No	Yes
Dpt*Month fixed effects in the second step	No	No	Yes	Yes	No	No	Yes	Yes
Observations	17,632	17,632	17,632	17,632	15,678	15,678	15,678	15,678

Notes: This table presents the effect of access to irrigation on women's and household dietary diversity scores using OLS model. Robust standard errors in parentheses are clustered at department level. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%.

Table 2.14: Irrigation, women's and household dietary diversity scores using OLS: using additional covariates

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dept var.	HDDS	HDDS	HDDS	HDDS	WDDS	WDDS	WDDS	WDDS
Irrigation	1.089***	1.122***	0.780***	0.765***	0.421***	0.443***	0.389***	0.373***
	(0.0407)	(0.0411)	(0.0688)	(0.0696)	(0.0321)	(0.0318)	(0.0531)	(0.0533)
Logtotal(area)	0.249***	0.246***	0.150***	0.141***	0.126***	0.125***	0.0871***	0.0815***
	(0.0361)	(0.0357)	(0.0341)	(0.0343)	(0.0274)	(0.0270)	(0.0264)	(0.0265)
Log(yield)	0.0935***	0.0890***	0.0439**	0.0398**	0.0601***	0.0571***	0.0277*	0.0240
	(0.0191)	(0.0188)	(0.0186)	(0.0188)	(0.0151)	(0.0149)	(0.0146)	(0.0148)
Log(production)	0.0329	0.0288	0.0252	0.0276	0.0156	0.0123	0.0116	0.0141
	(0.0214)	(0.0213)	(0.0216)	(0.0217)	(0.0165)	(0.0163)	(0.0165)	(0.0166)
Fertility	-0.322***	-0.321***	-0.187***	-0.191***	-0.183***	-0.181***	-0.103***	-0.107***
	(0.0253)	(0.0254)	(0.0279)	(0.0280)	(0.0188)	(0.0188)	(0.0210)	(0.0211)
Household size	0.0370***	0.0362***	0.0239***	0.0236***	0.0282***	0.0276***	0.0140***	0.0138***
	(0.00330)	(0.00329)	(0.00347)	(0.00347)	(0.00241)	(0.00239)	(0.00249)	(0.00249)
Wealth	-0.417***	-0.429***	-0.428***	-0.433***	-0.241***	-0.250***	-0.269***	-0.274***
	(0.0364)	(0.0363)	(0.0354)	(0.0354)	(0.0268)	(0.0268)	(0.0267)	(0.0266)
HH head education	0.244***	0.233***	0.134***	0.133***	0.147***	0.139***	0.0873***	0.0865***
	(0.0218)	(0.0218)	(0.0221)	(0.0220)	(0.0161)	(0.0161)	(0.0166)	(0.0166)
Production diversity	-0.0193***	-0.0191***	-0.0136***	-0.0134***	-0.0144***	-0.0140***	-0.00988***	-0.00975***
	(0.00363)	(0.00361)	(0.00334)	(0.00333)	(0.00269)	(0.00268)	(0.00253)	(0.00253)
Number of cows	0.00121	0.00125	-5.46e-05	-3.31e-05	0.00107	0.00109	-0.000267	-0.000271
	(0.00102)	(0.00102)	(0.000997)	(0.00100)	(0.000702)	(0.000700)	(0.000686)	(0.000686)
Number of goats or sheep	0.000574	0.000656	0.00172	0.00167	0.00100*	0.000975*	0.00115	0.00112
	(0.000819)	(0.000808)	(0.00107)	(0.00106)	(0.000601)	(0.000559)	(0.000785)	(0.000776)
Number of pigs	-0.0177***	-0.0202***	-0.0103**	-0.0111**	-0.00950***	-0.0113***	-0.00725**	-0.00814***
	(0.00460)	(0.00461)	(0.00432)	(0.00434)	(0.00311)	(0.00308)	(0.00305)	(0.00304)
Number of rabbits	0.0655**	0.0670**	0.0548**	0.0557**	0.0193	0.0217	0.0247	0.0262
	(0.0309)	(0.0293)	(0.0236)	(0.0242)	(0.0295)	(0.0285)	(0.0252)	(0.0252)
Number of poultry	0.00307***	0.00348***	0.00426***	0.00429***	0.00231***	0.00259***	0.00213***	0.00215***
	(0.000652)	(0.000661)	(0.000943)	(0.000949)	(0.000726)	(0.000749)	(0.000811)	(0.000815)
age	-0.00144	-0.00133	-0.00248**	-0.00263**	0.000891	0.00110	0.000465	0.000366
	(0.00112)	(0.00112)	(0.00106)	(0.00106)	(0.000853)	(0.000851)	(0.000826)	(0.000826)
Remittances	-0.291***	-0.282***	-0.182***	-0.173***	-0.162***	-0.155***	-0.0796***	-0.0749***
	(0.0360)	(0.0359)	(0.0346)	(0.0346)	(0.0267)	(0.0266)	(0.0262)	(0.0262)
Gifts	-0.277***	-0.296***	-0.243***	-0.250***	-0.213***	-0.224***	-0.183***	-0.188***
	(0.0496)	(0.0493)	(0.0477)	(0.0477)	(0.0367)	(0.0364)	(0.0360)	(0.0361)
Month FE in the 2nd. step	No	Yes	No	Yes	No	Yes	No	Yes
Year FE in the 2nd. step	No	Yes	No	Yes	No	Yes	No	Yes
Dpt*Month FE in the 2nd. step	No	No	Yes	Yes	No	No	Yes	Yes
Observations	12,701	12,701	12,701	12,701	11,564	11,564	11,564	11,564
R-squared	0.139	0.148	0.371	0.375	0.093	0.103	0.319	0.322

Notes: This table presents the effect of access to irrigation on women's and household dietary diversity scores using OLS model. The treatment variable is irrigation. The observations in this table are different from those in Table 2.13 due to differences in observations of additional covariates. Robust standard errors are in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%.

Table 2.15: Irrigation and household dietary diversity scores using PSM

Dependent variable	Nearest-Neighbor Matching			Radius Matching			Kernel Matching	Local Linear Regression Matching
HDDS	N=1	N=2	N=3	r=0.005	r=0.01	r=0.05		
				Irrigation on HDDS				
ATT	0.887***	0.934***	0.939***	0.936***	0.933***	0.953***	0.951***	0.899***
	(0.0645)	(0.0592)	(0.0577)	(0.0408)	(0.0411)	(0.0355)	(0.0355)	(0.0383)
Number of Treated obs.	2772	2772	2772	2772	2772	2772	2772	2772
Number of Controls Obs.	14890	14890	14890	10895	14890	14890	14890	14890
Observations	17,632	17,632	17,632	17,632	17,632	17,632	17,632	17,632

Notes: This table presents the effect of access to irrigation on household dietary diversity score using propensity score matching. Robust standard errors are in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%.

Table 2.16: Irrigation and women dietary diversity scores using PSM

Dependent variable	Nearest-Neighbor Matching			Radius Matching			Kernel Matching	Local Linear Regression Matching
WDDS	N=1	N=2	N=3	r=0.005	r=0.01	r=0.05		
				Irrigation on WDDS				
ATT	0.291***	0.304***	0.339***	0.340***	0.341***	0.355***	0.354***	0.330***
	(0.0492)	(0.0425)	(0.0401)	(0.0295)	(0.0357)	(0.0314)	(0.0305)	(0.0291)
Number of Treated obs.	2772	2772	2772	2772	2772	2772	2772	2772
Number of Controls Obs.	14890	14890	14890	10895	14890	14890	14890	14890
Observations	17,632	17,632	17,632	17,632	17,632	17,632	17,632	17,632

Notes: This table presents the effect of access to irrigation on women's dietary diversity score using propensity score matching. Robust standard errors in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%.

Table 2.17: Descriptive statistics

Variables	Mean	Std. Dev.	Min	Max
Household dietary diversity score	0.707	0.154	0.083	1
Women dietary diversity score	0.634	0.142	0.111	1
Food consumption score	0.281	0.131	0	0.965
Irrigation	0.110	0.313	0	1
Total area (log)	1.370	0.826	0	10.822
Yield (log)	5.287	1.914	-8.367	21.416
Income(log)	11.354	1.589	2.708	21.277
Production (log)	6.150	1.579	0.405	13.997
Production diversity	6.541	4.252	1	12
Fertility	1.806	0.594	1	3
Number of cows	5.184	13.503	0	512
Number of goats or sheep	9.586	21.691	0	1150
Number of pigs	0.419	2.519	0	76
Number of rabbits	0.033	0.726	0	30
Number of poultry	11.513	20.685	0	997
Remittances	1.683	0.465	1	2
Gifts	1.860	0.346	1	2
Household size	9.403	6.008	1	67
Wealth	1.761	0.426	1	2
Household education	1.308	0.681	1	4
Household head age	47.736	14.024	15	105
Shock	0.821	0.383	0	1

Notes: Descriptive statistics have been computed using household sampling weights. See Table 2.18 for definitions of variables.

Table 2.18: Definition and description of variables

Variables	Definition and description
Dietary diversity variables	
HDDS	Household Dietary Diversity Score
WDDS	Women's Dietary Diversity Score
FCS	Food Consumption Score
Agriculture variables	
Irrigation	1 if the household adopts irrigation and 0 otherwise
Agricultural land area	The area of agricultural land in hectares
Yield	Agricultural yields in kg per ha
Income	Agricultural income in FCFA
Production	Total crop production in kg
Fertility	The average soil characteristic of the plots is defined as good fertility, medium fertility, and low fertility
Number of cows	The number of cows owned by the household
Number of goats and sheep	The number of goats and sheep owned by the household
Number of pigs	The number of pigs owned by the household
Number of rabbits	The number of rabbits owned by the household
Number of poultry	The number of poultry owned by the household
Socioeconomic variables	
Household size	Number of persons living together in one house
Women's education	The education level of women from 1 (no education) to 4 (post-secondary education)
Education	The education level of the household head from 1 (no education) to 4 (post-secondary education)
Age	Age of the household head in years.
Household wealth (dummy)	0 if the household declared to consider itself as rich or middle class and 1, as poor or very poor
Remittances	1 whether a household received remittances in the previous 12 months
Gifts	1 whether a household received income in the form of a gift
Shock	1 if a household experienced shocks such as demographic shocks, price shocks, and natural shocks, and 0 otherwise

Notes: All these variables come from Harmonized Survey on Household Living Conditions.

Chapter 3

Understanding the links between malaria, irrigation and agriculture in Sub-Saharan Africa

This chapter is joint work with Martine Audibert (CERDI-CNRS-UCA) and Sebastien Marchand (CERDI-UCA).

This chapter aims to revisit malaria's impact on agricultural labor in an irrigation context in the eight West African Economic Monetary Union countries. We deal with the endogeneity concerns of malaria using the instrumental variables method. Our identification strategy is implemented with household data from Harmonized Survey on Household Living Conditions collected in 2018 and 2019. Results show that malaria prevalence in a household reduces significantly labor quantity while increasing labor productivity. Our results also suggest that the magnitude and significance of these links depend on irrigation on the one hand and household size on the other hand. The findings highlight the need to strengthen access to malaria control, prevention information, and health service delivery system to enhance human health and agricultural productivity.

Keywords: Malaria · Irrigation · Agricultural labor · Sub-Saharan Africa

3.1 Introduction

Malaria remains a significant global health problem with an estimated 247 million cases and 619,000 deaths in 2021 according to the 2022 World Malaria Report of the World Health Organization (WHO, 2022)[1]. The risk of the disease is still high in low-income countries where malaria is the sixth leading cause of death[2]. Sub-Saharan Africa (SSA) including the eight West African Economic and Monetary Union (WAEMU) countries investigated in this study (Benin, Burkina Faso, Côte d'Ivoire, Guinea-Bissau, Mali, Niger, Senegal, and Togo) is particularly concerned and accounted, in 2020, for about 95% (17% for the WAEMU countries) of malaria cases and 96% (16% for the WAEMU countries) of deaths globally, and 80% of all deaths are among children aged under 5 years (WHO, 2021). In the past decade, in the WAEMU countries, prevention tools and strategies – including effective vector control and the use of preventive antimalarial drugs, has resulted in a substantial reduction in the number of death (Bhatt et al., 2015) while the number of cases has remained the same (about 40 million cases) (WHO, 2021). As a consequence, the eight WAEMU countries remain high-burden countries with endemic malaria transmission risk (Thuilliez et al., 2017).

Malaria risk and disease burden depend mainly on the agroecological environment and the coverage and use of control measures. Regarding the agroecological environment, the characteristics of the farming practices such as irrigation affect both heterogeneity in mosquito abundance and malaria risk. The development of crop irrigation produces habitat characteristics that contribute to increased human exposure to malaria-carrying mosquitoes, resulting in an upsurge in malaria transmission. However, irrigation is called to be one of the solutions to help agriculture to cope with its numerous current and upcoming challenges. The agricultural sector is indeed confronted with the major challenge of increasing production to feed a growing and increasingly prosperous population in a situation of decreasing availability of natural resources, declining soil fertility, and increasing weather variability (rain and temperature) (Asafu-Adjaye, 2014). Helping the world's farmers to achieve this target is challenging in itself, but beyond providing

[1]According to WHO (2022), globally in 2019, there were an estimated 229 million malaria cases in the world. In 2020, one year after the COVID-19 pandemic and service disruptions, the estimated number of malaria cases rose to 241 million cases, an additional 12 million cases compared with 2019.

[2]Source: https://www.who.int/news-room/fact-sheets/detail/the-top-10-causes-of-death.

food, agriculture also sustains the economies of most countries in significant ways, especially in the SSA. While in most countries of SSA agricultural production remains predominantly rain-fed (Kemeze, 2020), irrigation is highly promoted to reduce the farmers' vulnerability to rainfall patterns (Okyere and Usman, 2021) and to increase agricultural yield. Then, the effect of irrigation on malaria risk is ambiguous. While irrigation practices can increase malaria risk by expanding the exposure of humans to malaria-carrying mosquitoes, irrigation improves crop yield and farmers' income which helps them to buy preventive tools. The negative and direct biological (exposure) effect of irrigation can thus be canceled out by a positive and indirect economic (wealth) effect.

This study aims at revisiting the relationships between malaria and labor in an irrigation context using instrumental variable methods in the eight WAEMU countries from household data taken from the Harmonized Survey on Household Living Conditions (HSHLC) collected in 2018 and 2019[3]. By answering this issue, this study is in line with the literature on the assessment of malaria transmission dynamics in irrigated agro-systems. Our paper aims to contribute to the existing literature on endemic diseases-agriculture nexus (Audibert, 2010) in different ways. First, our study estimates the impact of malaria on crop labor defined both by labor productivity (in kg of harvested crops per person-days) and labor quantity (in person-days per hectare)[4]. We assume that malaria has a different impact on these two measures regarding the context of countries investigated in this study where agricultural households are primarily engaged in family farming and faced with income, financial, and input constraints with strong market failures (Dillon and Barrett, 2017). Sub-section 3.2.3 presents the theoretical explanations of these opposite effects of malaria on labor productivity and labor quantity. Second, this study investigates the role of irrigation systems and household size as moderating variables on the effect of malaria on labor. The choice of these two moderating variables relies on the specific context of sub-Saharan African family farming. We discuss the underlying explanations of the moderating roles of these two variables in Sub-section 3.2.3. Third, while most studies are limited to analyzing the effect of malaria in one country (e.g Audibert et al. (2003); Mangani et al. (2021); Okyere et al. (2021)), this study augments these country-specific studies by providing

[3]Note that the Harmonized Survey on Household Living Conditions (HSHLC) database is EHCVM database named Enquête Harmonisée sur les Conditions de Vie des Ménages on the World Bank website.

[4]We also take into account the different steps of crop labor according to the cropping season: land preparation and sowing, field management, and harvesting stage.

micro-evidence of the causal effect of malaria on labor in agriculture from recent and high-quality data from eight different sub-Saharan African countries.

On one hand, regarding the effect of malaria on labor, our main findings suggest that malaria reduces significantly labor quantity measured in terms of person-days per ha on a farm. Increasing malaria by one percentage point is associated with a decrease between 2.23 percent and 7.47 percent of labor quantity in our baseline model. This result suggests that malaria can push family members to increase their labor force to compensate for the negative impact of malaria due to the workday loss of infected individuals. We attribute this effect to a compensation effect which is more obvious in households engaged in family farming where intra-allocation of the labor force is important in a case of health shock. Moreover, we do find a moderating effect of irrigation and household size. More precisely, the effect of malaria turns out to be null once irrigation and household size increase. Regarding irrigation, we assume that the wealth effect is at stake rather than the exposure effect. Irrigation can help to increase income and in turn the consumption of prevention and control tools against malaria. The household size plays a moderating role through a compensation effect and intra-household labor allocation which are more feasible in large households.

On the other hand, malaria is found to increase labor productivity. Increasing malaria by one percentage point is associated with an increase in labor productivity between 7.45% and 14.08%. These results suggest that malaria can push wealthy members of a household to compensate for the lack of work of sick workers. Again, this is relevant in the case of family farming where there is room to increase global labor productivity. Regarding the moderating effect of irrigation, while few are robust, we do find a negative impact of the interaction of malaria with irrigation. It seems that an exposure effect rather than a wealth effect of irrigation is at stake because households owning irrigated plots are more exposed to malaria. Taken together, these findings highlight that malaria still has an impact on rural households. The need to keep strengthening access to malaria control, prevention information, and health service delivery system is still accurate in sub-Saharan African family farming.

The rest of the paper is organized as follows. Section 3.2 presents the literature related to the link between malaria, agricultural labor, and irrigation. Section 3.3 provides the data and descriptive statistics. Sections 3.4-3.5 present respectively the econometric framework and main results, and Section 3.6 concludes.

3.2 Literature review

In this section, we first present the literature on the link between irrigation and malaria. This will allow us to understand the different channels by which irrigated agricultural systems could impact the health of households. Then, we highlight the literature on the link between malaria and agricultural labor. Finally, the theoretical links between malaria and agricultural labor tested in this study are highlighted.

3.2.1 Irrigation and Malaria

The relationship between irrigation and malaria has received considerable attention in the literature and is more broadly connected to the endemic diseases-agriculture nexus (Audibert, 2010). The effects of irrigation on malaria rely on two strands: the first strand finds negative effects through increased health risk and the second strand finds positive effects on health through higher income, increased productivity, increased food supply, and availability of water for domestic use.

There are many studies on the impact of irrigated agricultural systems and malaria transmission. First, several papers (WHO et al., 1986; Coosemans and Mouchet, 1990; Singh et al., 1999; Ghebreyesus et al., 1999) conclude that an increase in standing water associated with irrigation, especially when systems are poorly managed, can serve as a breeding ground for disease vectors including Anopheles mosquitos, and contribute to an increase in malaria and other diseases. For instance, Ghebreyesus et al. (1999) look at the relationship between irrigation and malaria prevalence in Ethiopia and find that villages closer to the small-scale dams experienced a seven-fold rise in malaria prevalence after the introduction of the dams. Guthmann et al. (2002), from a comparison between two villages (those closer to irrigation systems and the others in non-irrigated areas) located in Peru, find that malaria prevalence was five times higher in villages closer to irrigation systems than villages in a non-irrigated area. Using the same methodology (comparison between irrigated areas and non-irrigated areas), Ersado (2005); Asayehegn (2012); Jaleta et al. (2013) in Ethiopia, Mutero et al. (2004) in Kenya, and Marrama et al. (2004) in Madagascar also conclude that malaria incidence was higher in villages closer to irrigation systems than villages in non-irrigated areas. Moreover, other studies on sub-Saharan Africa (Hunter et al., 1993; Kibret et al., 2015, 2016, 2019) also reach the same conclusion of negative consequences of irrigated land on malaria transmission or prevalence.

Other studies focus on the impact of irrigated agroecosystems using mixed-effects logistic regression analysis. For instance, increased malaria risk was associated with rice irrigation schemes in Tanzania (Mboera et al., 2011; Mazigo et al., 2017; Rumisha et al., 2019), a cotton irrigation scheme in Sudan Oomen et al. (1988), irrigated vegetable production in Ghana Klinkenberg et al. (2005), and irrigation schemes in Kenya Muriuki et al. (2016) and Ethiopia (Kibret et al., 2010, 2014). Moreover, while Mangani et al. (2022) also find increased malaria risk with the proximity of human dwellings to the irrigation scheme, they differ from other studies by focusing on the distance of human residence to irrigated agricultural areas and on how the socioeconomic gains provided by enhanced crop production might balance malaria risk.

Some studies have shown that irrigation was not or less associated with higher malaria prevalence (Faye et al., 1995; Assi et al., 2013; Mboera et al., 2010). For instance, in Sri Lanka, Klinkenberg et al. (2004) find that rice-growing areas with irrigation canals had a lower risk of malaria than areas irrigated by natural streams. Mutero et al. (2006); Ijumba and Lindsay (2001) have also shown a lower malaria prevalence in villages located near irrigated areas compared with villages near non-irrigated areas. In the same vein De Plaen et al. (2004); Audibert et al. (2003, 2007) conclude that irrigation systems both in Savannah and forest areas in Cote d'Ivoire had no effect on malaria transmission. A plausible explanation for these results by these authors is the potential wealth generated by irrigation that allowed farm households to increase investment in malaria prevention such as the purchase of insecticide-treated nets, the use of chemical measures for mosquito control (insecticides, spirals, and indoor residual spraying).

3.2.2 Malaria and agricultural labor

The economic impacts of malaria on agriculture have been studied in many theoretical and empirical papers[5]. Basically, malaria-related morbidity is found to reduce agricultural yield and income through decreased labor productivity and lost workdays due to the disease.

Several empirical studies have investigated the theoretical negative relationship between malaria and agricultural labor through lost workdays to the disease. For instance, in Ghana, Afrane et al. (2004) find that the number of reported malaria episodes and days lost due to illness was significantly higher in urban areas with

[5] See Asenso-Okyere et al. (2011) for a review of the economic impacts of malaria on agriculture.

irrigated agriculture in both seasons (rainy and dry) for all age groups. Also, Iheke and Ukaegbu (2015) highlight this negative effect of malaria but conclude that small farmers are significantly more impacted than large farmers. Other studies reach the same conclusion that malaria contributes significantly to worker absenteeism (see for example Oladepo et al. (2010); Asenso-Okyere et al. (2009) in Nigeria, Lukwa et al. (2019) in Zimbabwe, Fink and Masiye (2015) in Zambia).

Several other papers have investigated the impact of malaria on crop production through limited labor supply. In Cote d'Ivoire, from a comparison of farmers classified according to the number of days prescribed sick due to malaria, Girardin et al. (2004) find a negative correlation between total yield and the number of days described sick due to malaria. In Ghana, Asiamah et al. (2014) find that during periods of malaria disability, 90.2% of affected farmers did not work which resulted in a reduction in agricultural income.

Other studies have explored the impact of malaria on technical efficiency. Using a production frontier model, Audibert et al. (2003) assessed the effect of malaria on cotton-crop development in the Savannah zone in Côte d'Ivoire and find that malaria had a negative effect on technical efficiency in the cotton crop. In Nigeria, Madaki (2017) uses the same methodology and shows that the crop output of malaria-uninfected households is higher by 20 percent than the crop output of the infected household.

To conclude, these impacts on labor production are found to be conditional to the quality of the maintenance of the irrigation system (Boelee, 2003), the investment in prevention tools such as bednets (Fink and Masiye, 2015) or the presence of agricultural extension program (Pan and Singhal, 2019).

3.2.3 Theoretical links between malaria and agricultural labor

Regarding the context of countries investigated in this study where agricultural households are primarily engaged in family farming and faced with income, financial, and inputs constraints (Dillon and Barrett, 2017), we assume that malaria should affect agricultural labor, and this effect should be conditioned to the measure of labor (quantity *versus* productivity), the presence of an irrigation scheme, and the household size (the number of individuals of working age (aged 14 and over)).

More precisely, we consider both labor quantity (measured in person-days per ha) and productivity (measured in harvested production in kg per person-days).

The effect of malaria on agricultural labor should be different according to the measure of labor. In the case of labor quantity, malaria has to reduce the number of person-days per ha because of the workday loss. This is the direct health effect of the disease. However, in the context of weak labor productivity that faces the households of our sample, we assume that there is room to increase labor productivity so that health workers can increase their productivity to compensate for the absence of sick workers within a household. Put differently, we assume that even if the denominator (the number of workers) decreases because of malaria, the numerator (the harvested production) stays stable because health workers can increase their productivity.

Also, as highlighted in the previous subsection, an irrigation system is an important contextual factor in the spread of malaria but can also help farmers to produce more, earn more money and buy preventive and control tools. Irrigation systems can play a twofold moderator variable in the effect of malaria on labor. Moreover, households in our survey are primarily engaged in family farming with difficult access to input markets or extension services so family labor is often the better way to compensate for shocks such as disease. Intra-household allocation of the labor force can thus help to cope with the health condition of members of the family. Put differently, households with large sizes should compensate more easily for the absence of sick workers than small households.

With this in mind, we want to test the impact of malaria on labor by testing the following hypotheses:

- H1: malaria reduces the quantity of labor (due to the loss of workday) but increases labor productivity (due to the context of productive inefficiency).
- H2: there is a twofold moderating effect of irrigation. On one hand, farmers owing irrigation plots are both more exposed to the disease but also are more efficient (thanks to irrigation). Accordingly, malaria reduces labor quantity (H1 is amplified - there are more sick workers) but also productivity (H1 is reduced). Regarding labor productivity, farmers using irrigation should be more productive so there is no or less room to increase productivity. Health workers cannot increase their productivity to compensate for the absence of sick workers. In this case, malaria should have a negative effect on productivity by reducing both the quantity of labor (denominator) and the output (numerator). This is the *exposure effect*. On the other hand, irrigated plots can help to produce more and in return increase the income of

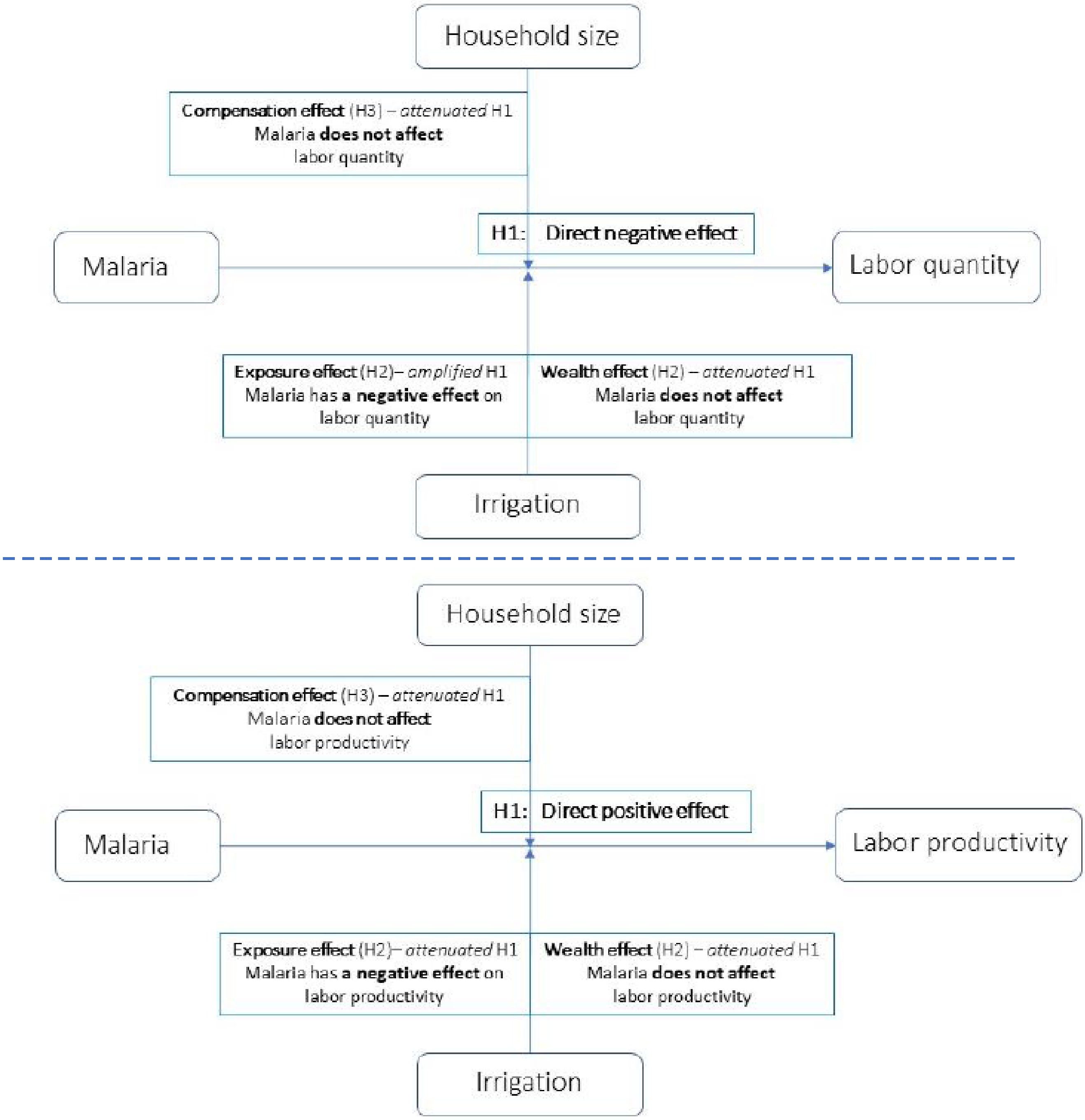
farmers and their capacity to buy prevention tools against malaria. This is a *wealth effect*. In the case of labor quantity, this effect means that malaria should have no impact on labor quantity because farmers can use prevention and control tools against the disease (H1 is attenuated - there are fewer sick workers). In the case of labor productivity, the wealth effect means that malaria has no effect on labor quantity (denominator). Accordingly, it is possible to assume that there is no impact of malaria on labor productivity if the wealth effect is at stake.

- H3: there is a moderating effect of household size. We assume that in large households, it is more likely to find healthy workers who can compensate for sick workers. This moderating effect of household size can be seen as a *compensation effect* thanks to an intra-household allocation of the labor force. In this case, malaria should have no impact on labor quantity when household size increases. So, we assume that the moderated effect of malaria by household size on labor quantity is non-significant (H1 is attenuated - the absence of sick workers is less detrimental). Regarding productivity, if there is a compensation effect, malaria does not reduce labor quantity (denominator) and there is no effect on labor productivity. So, the moderated effect of malaria by household size on labor productivity is non-significant (H1 is attenuated - the absence of sick workers is less detrimental).
- H4: we combine H2 and H3 to investigate the combined moderator roles of irrigation and household size.

These hypotheses are represented in the path diagram of Figure 3.1. The impact of malaria on labor quantity and labor productivity (H1) is moderated by irrigation (H2) and household size (H3). Lastly, in order to study all these hypotheses, we propose an econometric framework, presented in Section 3.4.

3.3 Data and descriptive statistics

Our data is derived from Harmonized Survey on Household Living Conditions (HSHLC) with the support of the World Bank and covers the WAEMU countries. Through this survey, the World Bank supports the WAEMU Commission to improve the availability, quality, and comparability of indicators for monitoring poverty and household living conditions in its member states. The HSHLC used in this study was organized in 2 waves that took place simultaneously in the eight WAEMU countries from September to December 2018 for the first wave and from April



Source: Authors

Figure 3.1: Path diagram representations of the moderating role of irrigation and household size

to July 2019 for the second wave. It should be noted that each household was only interviewed once, so we are unable to exploit the panel dimensions in our analysis. We have in total a representative sample varying from 5,300 to 13,000 households by country. These data were collected by administering a questionnaire through face-to-face interviews. The survey questionnaire included modules on health conditions, agricultural production activities, access to services, and socio-demographic characteristics. Information related to agriculture production in each household was captured at the plot level. The questionnaire also captured individual-level data on general health and our measure of malaria is deduced from this module. In this study, we focus only on households living in rural areas. The total final sample used is about 12,600 rural households located not equally in the eight WAEMU countries (from 541 households in Côte d'Ivoire to 2,654 households in Niger).

Tables 3.3 and 3.4 respectively present the definition and descriptive statistics of all variables used in the study.

Regarding health variables, we note that the prevalence of malaria defined as the proportion of household members with malaria was about 18% in a household. In addition, 24% of households use insecticide-treated nets (bednets), and 83% use insecticide and spirals.

Concerning agricultural labor, we focus on all crop productions (maize, rice, millet, and sorghum are the most important crops). We consider two measures of labor: the quantity of labor measured in person-days per ha and labor productivity measured in kg (of the harvested crop) per person-days. Note that in the survey questionnaire, the cropping season was divided into three steps: land preparation and sowing, field management, and harvesting. Analyzing all three steps separately could give misleading results, so all three steps were combined to construct our measure of farm labor. This measure is then normalized by the area allocated to production to determine the quantity of farm labor used in person-days per ha. Concerning labor productivity, we use the quantity of production harvested divided by the quantity of farm labor per person-days. Since we have this information at the plot level, we then average the two labor measures at the household level. The mean value of the quantity of farm labor on one plot was about 4.4 person-days per ha with a standard deviation of 1.818 and labor productivity was about 1.3 kg per person-days with a standard deviation of 1.5.

With regard to irrigation, we use three measures derived from the survey questionnaire. The survey asked each household to mention the main sources of water used on each plot. The respondents reported the following various sources of water: irrigation, own well, canal irrigation, stream irrigation, rainfed, marshes/wetland, and others. From this information, we consider three measures of irrigation including the share of irrigated plots among all plots owned by a household (1 if the household practices irrigation on all plots), the total irrigated area in ha (the sum of the surface area of all plots with irrigation scheme), and the share of irrigated land in % (calculated by dividing the total irrigated area by the total area devoted to crop production). In our sample, about 13.9% of plots are irrigated on average, and, per household, the irrigated land surface is estimated at 0.13 ha with a standard deviation of 0.40 ha, and the percentage of irrigated land was about 14.4% at the mean.

In addition, at mean, the number of individuals of working age (aged 14 and over) in a household is about six persons with a standard deviation of 4.80. This may have important implications for the effect of malaria on labor. As mentioned above, the intra-household allocation of the labor force can help to cope with the shock produced by the disease.

3.4 Econometric model

3.4.1 Labor model

As mentioned in Subsection 3.2.3, we aim to estimate the causal impact of malaria on agricultural labor by assuming that this impact is different according to the measure of labor (quantity *versus* productivity). Also, we assume that the presence of an irrigation scheme on plots and the size of the household can be moderator variables of the effect of malaria on labor. To do this, we start with the following baseline model:

$$ln(labor_{i,c,t}) = \beta_0 + \beta_1 malaria_{i,c,t} + \beta_2 irrig_{i,c,t} + + \beta_3 hhsize_{i,c,t} + + \sum_k \beta_k Z_{k,i,c,t} + \eta_i + \tau_t + \epsilon_{i,c,t}, \quad (3.1)$$

where $i = 1, \ldots, N$ are the household unit observations at time t ($t = 1, 2$ because the first wave occurred in 2018 and the second wave in 2019) in the country c ($c = 1, 2, \ldots, 8$); $ln(labor_{i,c,t})$ is the logarithm of each measure of labor: the quantity of farm labor and labor productivity for household i at year t and located in the country c; $malaria_{i,c,t}$ is the proportion of household members with malaria; $irrig_{i,c,t}$ is irrigation measured by the share of irrigated plots, $hhsize_{i,c,t}$ is the household size; $Z_{i,c,t}$ is the vector of control variables such as level of education, age, gender, household wealth, house wall and roof quality, household activities, soil type, and the duration between the household residence and irrigated agricultural area; η_i is country fixed effects; τ_t is the time fixed effects capturing wave-specific variables; $\epsilon_{i,c,t}$ is the error term; β_0, β_1, β_2, ..., β_k are parameters to be estimated. According to H1.a, we assume that β_1 is negative if the dependent variable is labor quantity and positive if it is labor productivity.

The baseline Model 3.1 is extended to introduce the moderated effect of malaria according to irrigation (H2) and household size (H3). We first test the role of irrigation with an interaction term of malaria with irrigation and Model 3.1 becomes:

$$\begin{aligned} ln(labor_{i,c,t}) = \beta_0 + \beta_1 malaria_{i,c,t} + \beta_2 irrig_{i,c,t} + \beta_3 hhsize_{i,c,t} + \beta_4 malaria.irrig_{i,c,t} \\ + \sum_k \beta_k Z_{k,i,c,t} + \eta_i + \tau_t + \epsilon_{i,c,t}, \end{aligned} \tag{3.2}$$

where β_4 is the effect of malaria moderated by irrigation that has to be estimated. According to H2, we assume that β_4 is either an *exposure effect* or a wealth effect. β_4 is negative (H1 is amplified in the labor quantity model or attenuated in the labor productivity model) if it is an *exposure effect*. If β_4 is a *wealth effect*, it should be non-significant (H1 is attenuated both in the labor quantity model and in the labor productivity model).

We then test the role of household size with an interaction term of malaria with this variable and Model 3.1 becomes:

$$\begin{aligned} ln(labor_{i,c,t}) = \beta_0 + \beta_1 malaria_{i,c,t} + \beta_2 irrig_{i,c,t} + \beta_3 hhsize_{i,c,t} + \beta_4 malaria.hhsize_{i,c,t} \\ + \sum_k \beta_k Z_{k,i,c,t} + \eta_i + \tau_t + \epsilon_{i,c,t}, \end{aligned} \tag{3.3}$$

where β_4 is the effect of malaria moderated by the household size that has to be estimated. According to H3, we assume that β_4 is a *compensation effect*. β_4 should be non-significant (H1 is attenuated both in the labor quantity model and in the labor productivity model).

Finally, we add both the interaction effects of malaria with household size and irrigation to test H4, and Model 3.1 becomes:

$$\begin{aligned} ln(labor_{i,c,t}) = \beta_0 + \beta_1 malaria_{i,c,t} + \beta_2 irrig_{i,c,t} + \beta_3 hhsize_{i,c,t} + \beta_4 malaria.irrig_{i,c,t} \\ + \beta_5 malaria.hhsize_{i,c,t} + \beta_6 malaria.hhsize.irrig_{i,c,t} \\ + \sum_k \beta_k Z_{k,i,c,t} + \eta_i + \tau_t + \epsilon_{i,c,t}, \end{aligned} \tag{3.4}$$

where the sign of β_6 is the effect of malaria which is moderated both by household size and irrigation.

3.4.2 Endogeneity issues

Three sources of endogeneity can plague the causal impact of malaria on labor. First, endogeneity may be due to unobservable factors such as health care inputs of households that may affect household production decisions. The second cause of endogeneity is that it may result from potential reverse effects between malaria prevalence and agricultural labor. On the one hand, malaria incidence might reduce farm productivity through its debilitating effects on family workers participating in farming activities. On the other hand, the potential wealth generated by agriculture may be used to improve household health through investment in measures to prevent the disease. So, income from agriculture can be used to hire labor to compensate for the family labor lost. The third source of endogeneity occurs when estimations of the impact of malaria on labor are biased due to measurement errors arising from self-reported data on the main health problem[6].

Our identification strategy consists in using the instrumental variable approach and estimating previous models with the two-stage least square (2SLS) estimator. To do this, we use two external instruments related to malaria disease control efforts: the use of insecticide-treated nets (z1) and the use of insecticides and spirals (z2). Malaria risk is found to be negatively related to the use of insecticide-treated nets and the use of preventive measures to control mosquitoes in the literature (Bhatt et al., 2015; Steketee and Campbell, 2010; Gansey, 2020). Beyond the economical

[6]See for example Schultz and Tansel (1997) who explained that self-reported illnesses due to malaria might well be wrong because people reporting might simply be suffering from fevers or pains from other diseases, under-reporting or over-reporting malaria episodes, thus biasing the estimated effect of the disease upwards or downwards.

validity of bednet and the use of insecticides and spirals as instruments of malaria, the statistical validity of these external instruments is measured by two tests. The Hansen test is used as a test of overidentifying restrictions (H0: instruments are valid instruments, i.e., uncorrelated with the error term). The Kleibergen-Paap test is used as an under-identification test (H0: the excluded instruments are not correlated with the endogenous regressors). Table 3.5 available in Appendice gives the list of endogenous variables and instruments used.

3.5 Results

3.5.1 Impact of malaria on agricultural labor

Tables 3.1 and 3.2 present the results of the 2SLS estimation of the impact of malaria on labor (H1) in column 1 and the conditional impact of malaria according to irrigation (H2) in column 2, household size (H3) in column 3 and both (H4) in column 4[7]. Table 3.1 reports the results with labor quantity as the dependent variable and Table 3.2 reports the results with labor productivity as the dependent variable. In both tables, irrigation is measured by the share of irrigated plots.

Also, to control for the endogeneity of malaria, we use two external instruments (the use of insecticide-treated nets (bednet) and the use of insecticides and spirals)[8]. In each model, instrumental variables are found to have joint significance on malaria. Moreover, in Tables 3.1 and 3.2, a look at statistical tests of the validity of instruments shows that the Hansen test accepts the null hypothesis that our set of instruments is valid. Also, the Kleibergen-Paap under-identification test always rejects the null hypothesis that the excluded instruments are not correlated with the endogenous variables.

In Table 3.1, we notice four worthwhile results. First, our results show that increasing the prevalence of malaria in a household significantly reduces the quantity of labor as expected in H1. Increasing malaria by one percentage point is associated

[7]Tables 3.1 and 3.2 present estimation results of interest variables (malaria, irrigation and household size). Complete results are available in Tables 3.6 and 3.7 as supplementary materials in Appendice.

[8]Table 3.5 available in Appendice as supplementary materials gives both the list of endogenous variables and instruments and reports the joint significance of all instrumental variables on malaria calculated from the instrumentation equation of each column of Tables 3.1 and 3.2. Note that there are as many instrumentation equations as there are endogenous variables. For reading convenience, we present only the joint significance of instrumental variables on malaria (for the other endogenous variables, i.e., malaria and its interaction with irrigation and household size). Results are available upon request).

with a decrease of 2.23 percent (column 1 - no interaction), 2.7 percent (column 2 - interaction with irrigation), 7.47 percent (column 3 - interaction with household size), and 3.34 (column 4 - interaction both with irrigation and household size) of labor quantity. Also, a 50% increase away from the mean (17.9%) in malaria prevalence reduces the quantity of labor by 19.96 percent (column 1), 23.17 percent (column 2), 66.86 percent (column 3), and 29.89 percents (column 4)[9]. A plausible explanation for this result is related to a reduction in the number of days spent on the farm. Moreover, given that we focus on labor quantity at the household level when an individual falls ill due to malaria, one or two family members engage in seeking medical aid, which exerts a significantly negative effect on time spent on farming activities. Thus, family labor days can decrease because they have to look after sick family members.

Second, regarding the moderating effect of irrigation, we find that the impact of malaria on labor quantity is insignificant when households use an irrigation scheme. This result suggests that the wealth effect is at stake rather than the exposure effect. Irrigation can help to increase income and in turn the consumption of prevention and control tools against malaria. In this context, there are fewer sick workers, and labor quantity is not influenced by malaria. Third, we do find a moderator role of the household size through a compensation effect as expected in H3. The moderated effect of malaria on labor due to household size is non-significant. This result suggests that the negative effect of malaria on labor quantity is compensated by intra-household labor allocation. Fourth, malaria is found to have a non-significant impact on labor once its effect is moderated by irrigation and household size in column 4.Both the compensation and the wealth effect are at stake.

[9]Note that the dependent variable is the quantity of labor in logarithm. A 50% increase in the prevalence of malaria, given the average ratio of 0.179 for all members (see Table 3.4), corresponds to a 0.0895 increase in the ratio. For instance, given the coefficient of malaria prevalence in column 1 of Table 3.1, the quantity of labor loss is about 2.23*0.0895*100 = 24.75%. We multiply by 100 because the dependent variable is in logarithm.

Table 3.1: Impact of malaria on labor quantity

Dpt. var.: *labor* in person-days per ha	(1)	(2)	(3)	(4)
Malaria	-2.226*	-2.696*	-7.474*	-3.341**
	(1.161)	(1.429)	(3.870)	(1.539)
Malaria*irrigation		2.548		1.025
		(2.057)		(1.494)
Malaria*hh size			0.815	0.152
			(0.518)	(0.102)
Malaria*irrigation*hh size				-0.0305
				(0.0729)
Irrigation	0.0408	-0.374	-0.00779	-0.106
	(0.0829)	(0.350)	(0.0973)	(0.304)
HH size	0.0667***	0.0668***	-0.0508	0.0456***
	(0.00468)	(0.00471)	(0.0759)	(0.0147)
Constant	5.624***	5.427***	6.777***	5.747***
	(0.382)	(0.330)	(0.941)	(0.355)
Observations	18,796	18,796	18,796	18,796
R-squared	0.442	0.429	0.131	0.420
Covariates	YES	YES	YES	YES
Year*Country FE	YES	YES	YES	YES
Hansen test	0.938	1.351	0.646	3.948
Hansen p-value	0.333	0.509	0.422	0.267
Kleibergen-Paap test	26.93	21.72	6.512	35.95
Kleibergen-Paap p-value	0.000	0.00007	0.0385	0.000

Notes: The dependent variable is the quantity of farm labor in logarithm measured in person-days per ha. Columns 1-4 report the results using the 2SLS model. Robust standard errors are in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. Covariates are the level of education, age, gender, and the main activities of the household head, an index of household wealth, the quality of house wall and roof, soil type of plots, total area, and the duration between the household residence and the plot. The Hansen test is a test of overidentifying restrictions (H0: instruments are valid instruments, i.e., uncorrelated with the error term). The Kleibergen-Paap test is an under-identification test (H0: the excluded instruments are not correlated with the endogenous regressors).

In Table 3.2, four results are also worth noting with regard to labor productivity (harvested production in kg per person-days). First, our results show that malaria increases labor productivity (columns 1 to 4) as expected in H1. Increasing malaria by one percentage point is associated with an increase in labor productivity between 7.45% (column 3) and 14.08% (column 4). These results suggest that malaria can push wealthy members of a household to compensate for the lack of work of sick workers. Given that there is room to increase productivity, health workers can increase their contribution to production and compensate for the negative contribution of sick workers. Second, malaria is found to affect negatively labor productivity through irrigation in column 4 but not in column 2. So, the wealth effect is at stake if the moderating effect of household size is not controlled for (column 2) whereas the exposure effect plays once the moderating effect of household size is taken into account (column 4). The exposure effect is quite important in magnitude. A one percent increase in malaria is associated with a reduction of 20.24 percent in labor productivity (column 4). Third, our results show that malaria is found to not influence labor productivity through household size (column 4) as expected in H3. This result also suggests the presence of a compensation effect within the household between sick workers and wealthy workers. Moreover, malaria stimulates productivity when household size increases in column

3. This positive effect of the interaction term between malaria and household size can also be explained by a compensation effect. Indeed, sick workers can be easily compensated by health workers in large households and, given that there is room to increase productivity, the health workers contribute more to production. The positive effect of malaria (H1) is amplified by large household sizes.

Table 3.2: Impact of malaria on labor productivity

Dpt. var.: *labor* in kg per person-days	(1)	(2)	(3)	(4)
Malaria	9.113***	7.956***	7.454***	14.08***
	(2.302)	(2.820)	(2.468)	(5.336)
Malaria*irrigation		4.107		-20.24***
		(6.312)		(6.983)
Malaria*HH size			0.273	0.162
			(0.204)	(0.289)
Malaria*irrigation*hh size				0.206
				(0.182)
Irrigation	0.973***	0.283	0.959***	4.171***
	(0.126)	(1.069)	(0.124)	(1.229)
HH size	-0.0156*	-0.0167*	-0.0556*	-0.0375
	(0.00929)	(0.00924)	(0.0300)	(0.0422)
Constant	-0.956	-1.167	-0.593	0.180
	(0.793)	(0.864)	(0.797)	(0.929)
Observations	16,790	16,790	16,790	16,790
R-squared	-1.532	-1.465	-1.386	-3.550
Covariates	YES	YES	YES	YES
Year*Country FE	YES	YES	YES	YES
Hansen test	1.298	1.555	0.718	0.187
Hansen p-value	0.255	0.212	0.397	0.911
kleibergen-Paap test	23.14	14.92	21.92	11.35
kleibergen-Paap p-value	0.000	0.0006	0.00001	0.009

Notes: The dependent variable is labor productivity in logarithm measured in kg per person-days. Columns 1-4 report the results using the 2SLS model. Robust standard errors are in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. Covariates are the level of education, age, gender, and the main activities of the household head, an index of household wealth, the quality of house wall and roof, soil type of plots, and the duration between the household residence and the plot. The Hansen test is a test of overidentifying restrictions (H0: instruments are valid instruments, i.e., uncorrelated with the error term). The Kleibergen-Paap test is an under-identification test (H0: the excluded instruments are not correlated with the endogenous regressors).

3.5.2 Robustness checks

In this section, we present several robustness tests of our baseline results. First, we use two alternative definitions of the dependent variable. We begin by investigating crop production stages. To do so, we recalculate both labor quantity and labor productivity by separating the soil preparation and field management stages from the harvesting step. Then, we focus on agricultural income as the dependent variable. Second, following the approaches of Tables 3.1 and 3.2, we augment our baseline model by adding climate variables that can plague the impact of malaria. Third, we use an alternative measure of malaria by focusing on household members who have reported that they have consulted a health worker for this disease. Lastly, we alter the definition of irrigation variable using either the share or the surface of irrigated land.

Alternative dependent variables

In this section, we test the robustness of our findings using alternative dependent variables. More precisely, we investigate the sensitivity of our results by considering the type of labor. Based on agricultural production activities information, we construct new labor measures using the three steps of cropping season: land preparation and sowing, field management, and harvesting. We first combine field management and land preparation steps and separate them from the harvesting step. We thus have the number of person-days for each of the two steps. Next, we normalized by the area allocated to production to determine the quantity of labor used in person-days per ha. Concerning labor productivity, we use the quantity of harvested production (output) divided by the quantity of labor per person-days.

Results obtained using these new dependent variables are reported in Appendice. Tables 3.8 and 3.9 present the results of labor quantity while Tables 3.10 and 3.11 concern labor productivity. Taken together, our results suggest that the baseline results are confirmed.

We still do find the negative effect of malaria on labor quantity and the positive effect on labor productivity (with the same magnitude as in the baseline results) as expected in H1. Second, regarding the moderating effects of irrigation and household size in the labor quantity model, we have the same results as in the baseline results for land preparation and field management labor 3.8. Here, we found that there is a positive effect of the interaction term between malaria and irrigation in columns 2 and 4. This effect is difficult to explain. It may be related to the specificity of irrigated crops that needs more labor for land preparation and management than rain-fed crops. Moreover, interestingly, the additive effect of irrigation is significantly positive when the interaction with malaria is not taken into account (columns 1) and turns out to be insignificant when the interaction term with malaria is at stake (columns 2 and 4). This means that irrigation plots need more labor for field preparation and management but this need is amplified in malaria-infected households because wealthy members must compensate sick workers. However, the moderating effect of irrigation is different for harvesting labor Table 3.9. Here, malaria turns out to have null effects on labor quantity when it interacts with irrigation or household size suggesting that both a wealth effect and a compensation effect are at stake.

Third, for labor productivity, we find an exposure effect of irrigation both for land preparation/management and harvesting but only in column 2 (when the moderating effect of household size is not taken into account). Moreover, our results show that malaria has no impact on labor productivity through household size (columns 3 and 4 in the case of field preparation and management and for harvesting labor) as in the baseline results.

Alternative specification: adding climate variables

Following the approaches of Tables 3.1 and 3.2, we add climate variables in the baseline model. To do this, we use precipitation and evapotranspiration variables. They come from the University of East Angelia's Climate Research Unit (CRU) database and are at the department level (ADM2)[10]. Evapotranspiration and precipitation are meteorological features that influence both malaria (Cairncross et al., 2010) and irrigation. They are good proxies for water requirements on an irrigated farm but also for the conditions suitable for the development, reproduction, and survival of mosquito vectors and parasites. The evapotranspiration variable is defined as the loss of water from both plants and the soil due to sunlight, wind, humidity, and temperature. We use the standard deviation for monthly evapotranspiration in 2018 or 2019 depending on the survey wave in which the household is interviewed. We also use the mean of monthly precipitation calculated between the previous month and the month when a household was interviewed[11].

The results presented in Tables 3.12 and 3.13 available in Appendice support those previously reported in Tables 3.1 and 3.2. The baseline estimate results are not driven by the meteorological conditions of the cropping activities. Malaria still has a negative effect on labor quantity and a positive effect on labor productivity but these effects turn out to be null when malaria is interacting with irrigation or household size.

Alternative malaria variable

Moreover, we use an alternative measure of malaria by focusing on household members who have reported that they have consulted a health worker for this disease. Tables 3.14 and 3.15 available in appendix present respectively the

[10]CRU TS (Climatic Research Unit gridded Time Series) is a widely used climate dataset on a 0.5° latitude by 0.5° longitude grid over all land domains of the world except Antarctica. See Harris et al. (2020) for more information.

[11]There were two waves: wave 1 between September to December 2018 and wave 2 between April to July 2019. If a household was interviewed in September 2018, we used (1) the standard deviation for monthly evapotranspiration and precipitation in 2018 and (2) the monthly precipitation in August and September.

estimation results for labor quantity and labor productivity. These findings reveal that using an alternative measure of malaria does not modify our conclusions. These results remain similar to those presented in Tables 3.1 and 3.2.

Alternative measure of irrigation

Finally, we re-estimate the baseline model using alternatively the share of irrigated lands and the surface of irrigated land in place of the share of irrigated plots. Tables 3.16 and 3.17 available in Appendice present respectively the estimation results for labor quantity and labor productivity. Columns 1-4 report the results with the share of irrigated land and columns 5-8 with the surface of irrigated land. Overall, the results remain close to those presented in Tables 3.1 and 3.2. In the case of labor quantity, malaria still has a negative effect that turns out to be null once the moderating wealth effect of irrigation is at stake. Regarding labor productivity, we still find a positive impact of malaria. However, the moderating exposure effect of irrigation is only found in column 2 (share of irrigation). In all other regressions, the interaction effect between malaria and irrigation is non-significant.

3.6 Conclusion

The aim of the study was to disentangle the interrelationships between malaria prevalence and agricultural labor in the context of irrigation and family farming in eight sub-Saharan countries. Despite a recent declining trend, malaria is still a significant cause of global morbidity and mortality in rural areas of sub-Saharan countries. While the impact of malaria on agriculture, and the role of agroecological conditions on malaria are particularly well studied, the goal of this study is to update the literature and highlights some underlying mechanisms explaining the relationship between malaria and labor in African family farming.

More precisely, we focused on irrigation and household size as two potential moderator variables of the impact of malaria on labor. We decided to focus on irrigation because it is an important contextual factor in the spread of malaria but can also help farmers to produce more, earn more money and buy preventive and control tools. So irrigation systems can play a positive or negative moderator variable in the effect of malaria on labor. Moreover, households in our survey are primarily engaged in family farming with difficult access to input markets or extension services. For these households, family labor is often the better way to compensate for shocks such as disease. Intra-household allocation of the labor force can thus help to cope with the disease of members of the family. Households with large sizes should compensate more easily for the absence of sick workers than small households.

Moreover, above the role of these two potential moderator variables, we extend the literature by focusing on two types of labor. We deal both with the quantity measured as person-day per hectare and the productivity measured as harvested quantity per person-day. We assume that the effect of malaria on labor quantity is negative while positive on labor productivity given the African family farming.

With this in mind, we propose to estimate the causal impact of malaria by using an instrumental variable approach with the use of insecticide-treated nets and the use of insecticides and spirals as external instruments.

On one hand, our results from the baseline model and robustness checks confirm that malaria has a negative impact on labor quantity. This effect is a direct health impact through the loss of workday due to the disease. However, once malaria interacts with irrigation or household size, its effect turns out to be insignificant. We explain these results by the presence of a moderating effect of irrigation and household size. In the case of irrigation, we assert that this is a moderating wealth effect of irrigation. Irrigated plots are higher yields which can increase the income of farmers and their capacity to buy prevention tools against malaria. Regarding household size, we explain its moderating effect as a compensation effect thanks to an intra-household allocation of the labor force.

On the other hand, the baseline and robustness results reveal that malaria increases labor productivity. We explain this result in the context of the productive inefficiency of African family farming. There is room to increase labor productivity so that health workers can increase their productivity to compensate for the absence of sick workers. Regarding the moderating effect of irrigation, we do find a negative impact of the interaction of malaria with irrigation while few are robust. We explain this result by an exposure effect because households owning irrigated plots are more exposed to malaria.

Taken together, our results highlight that malaria is still an issue in family farming in Africa. More interestingly, its impact on agricultural labor is complex and depends on types of labor, agricultural practices, and household composition. It is important to have in mind that the promotion of irrigation systems has to be done with appropriate control measures (such as systematic maintenance of irrigation canals) and, in the meantime, by promoting malaria control, prevention information, and health service delivery system. Agricultural productivity, crop income, and farmers' health have to be promoted hand in hand.

3.7 Appendices of Chapter 3

Table 3.3: Definition and description of variables

Variables	**Definition and description**
Agriculture variables at household level	
Labor quantity	Quantity of labor for crop production in person-days per ha.
Labor productivity	Total crop production in kg per person-days.
Irrigation (main measure)	The ratio between the number of irrigated plots and the number of all plots (%).
Irrigation (area)	The average area of irrigated land on one plot (in hectares).
Irrigation (share)	The ratio between the surface of irrigated land (in hectares) and the surface of all croplands (in hectares) (%).
Agricultural land area	The average area of agricultural land in hectares.
Time	The average duration between plots and household residence (in minutes).
Soil	The average soil characteristic of plots defined as 1 for sandy soil and 2 for silty, clay, or other types of soil.
Health variables at household level	
Malaria (share)	The proportion of household members with malaria.
Bednet (dummy)	1 if the household uses bednet and 0, otherwise.
Measures (dummy)	1 if the household uses chemical measures (insecticides or spirals) and 0, otherwise.
Socioeconomic variables at household level	
Education	The education level of the household head from 1 (no education) to 4 (post-secondary education).
Age	Age of the household head.
Gender (dummy)	Gender of the household head (0: male and 1: female).
Household wealth (dummy)	0 if the household declared to consider itself as rich or middle class and 1, as poor or very poor.
House quality	2 if the household answered to have both sound walls and an adequate roof, 1 if sound walls or an adequate roof, and 0, otherwise.
Household activities	Main activities of the household head (1: others, 2: agriculture, and 3: livestock).
Household size	Number of working-age persons living together in one household.
Climatic variables at ADM2 level	
Evapotranspiration (in mm)	The standard deviation for monthly evapotranspiration in the entire 2018 or 2019 depending on the survey wave in which the household is interviewed (CRU dataset).
Precipitation (in mm)	The mean of monthly precipitation calculated between the previous month and the month when a household was interviewed (CRU dataset).

Table 3.4: Descriptive statistics

Variables	Mean	Std. Dev.	Min	Max
Malaria prevalence	0.179	0.224	0	1
Log labor quantity (person-day per ha)	4.378	1.818	-2.708	15.032
Log labor productivity (kg per person-day)	1.296	1.489	-5.449	9.698
Share of irrigated plots	0.139	0.336	0	1
Share of irrigated land	14.385	34.407	0	100
Total irrigated land (ha)	0.130	0.404	0	3.932
Total agricultural area (ha)	1.109	0.781	0	3.931
Time (minutes)	3.149	1.047	0	5.707
Household size (persons)	5.611	4.795	1	67
Soil	1.404	.453	1	2
Household uses chemical measures (dummy)	0.236	0.425	0	1
Household uses bednet (dummy)	0.828	0.377	0	1
Education	1.428	0.775	1	4
Age (years)	45.731	14.658	15	105
Gender (dummy)	1.129	0.335	0	1
Household wealth (dummy)	1.768	0.422	0	1
House quality	1.103	0.815	0	2
Household activities	1.860	0.445	1	3
Evapotranspiration (in mm)	0.381	0.275	0.005	1.496
Precipitation (in mm)	93.287	86.396	0	573.4

Notes: See Table 3.3 for definitions of variables.

Table 3.5: Impact of malaria on agricultural labor: First stage (IV) regressions

Col. of Tables 3.1 and 3.2	(1)	(2)	(3)	(4)
List of endog. variables	$malaria$	$malaria$ $malaria * irrig.$	$malaria$ $malaria * hhsize$	$malaria$ $malaria * irrig.$ $malaria * hhsize$ $mal. * irrig. * hhsize$
List of instrument. var.	$z1$ $z2$	$z1$ $z2$ $z1 * irrig.$ $z2 * irrig.$	$z1$ $z2$ $z1 * hhsize$ $z2 * hhsize$	$z1$ $z2$ $z1 * irrig.$ $z2 * irrig.$ $z1 * irrig. * hhsize$ $z2 * irrig. * hhsize$
Col. No. of Table 3.1	(1)	(2)	(3)	(4)
Observations	18,796	18,796	18,796	18,796
F-stat intsrum. var.	13.52***	8.65***	9.18***	5.81***
Col. No. of Table 3.2	(1)	(2)	(3)	(4)
Observations	16,790	16,790	16,790	16,790
F-stat intsrum. var.	11.61***	7.79***	7.86***	6.66***

Notes: Columns 1-4 report the results of irrigation as the ratio between the number of irrigated plots and the number of all plots (%) in Tables 3.1 and 3.2. The observations in these tables are different because the dependent variables in the two tables are different. While Table 3.1 uses labor quantity as dependent variable, Table 3.2 uses labor productivity. Number of observations and F-stat come from the instrumentation equation (first stage) in which the dependent (endogenous) variable is *malaria*. F-stat reports the joint significance of all *instrumental* variables on variable *malaria*. These external instruments are z1 or the use of insecticide-treated net and z2 or the use of preventive measures to control mosquitoes. We do not report the results for all other endogenous variables (*malaria* and its interactions with irrigation and household size) but there are available upon request. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%.

Table 3.6: Impact of malaria on labor quantity – complete table results

Dpt. var.: *labor* in person-days per ha	(1)	(2)	(3)	(4)
Malaria	-2.226*	-2.696*	-7.474*	-3.341**
	(1.161)	(1.429)	(3.870)	(1.539)
Malaria*irrigation		2.548		1.025
		(2.057)		(1.494)
Malaria*hh size			0.815	0.152
			(0.518)	(0.102)
Malaria*irrigation*hh size				-0.0305
				(0.0729)
Irrigation	0.0408	-0.374	-0.00779	-0.106
	(0.0829)	(0.350)	(0.0973)	(0.304)
HH size	0.0667***	0.0668***	-0.0508	0.0456***
	(0.00468)	(0.00471)	(0.0759)	(0.0147)
Total area	-1.422***	-1.418***	-1.437***	-1.423***
	(0.0175)	(0.0182)	(0.0221)	(0.0181)
Time	0.0174	0.0153	0.0201	0.0173
	(0.0106)	(0.0113)	(0.0134)	(0.0113)
Soil	0.0329	0.0275	0.0278	0.0297
	(0.0254)	(0.0250)	(0.0316)	(0.0252)
Primary education	-0.133***	-0.144***	-0.141***	-0.139***
	(0.0270)	(0.0279)	(0.0336)	(0.0277)
Secondary education	-0.180***	-0.185***	-0.178***	-0.182***
	(0.0410)	(0.0412)	(0.0521)	(0.0418)
Superior education	-0.275***	-0.288***	-0.254***	-0.277***
	(0.0702)	(0.0716)	(0.0879)	(0.0717)
Age	0.00441***	0.00461***	0.00154	0.00398***
	(0.00110)	(0.00105)	(0.00242)	(0.00112)
Gender	-0.178***	-0.178***	-0.0526	-0.157***
	(0.0474)	(0.0477)	(0.107)	(0.0508)
Household wealth	0.0599**	0.0653**	0.0526*	0.0606**
	(0.0249)	(0.0259)	(0.0301)	(0.0257)
House (quality wall or roof)	-0.00666	-0.0120	-0.0143	-0.0103
	(0.0270)	(0.0283)	(0.0339)	(0.0282)
House (quality wall and roof)	-0.00988	0.000866	-0.0367	-0.0109
	(0.0289)	(0.0301)	(0.0393)	(0.0299)
Agriculture (main activity)	0.228***	0.244***	0.233***	0.235***
	(0.0286)	(0.0311)	(0.0342)	(0.0305)
Livestock(main activity)	-0.0682	-0.0496	-0.0317	-0.0543
	(0.0545)	(0.0557)	(0.0675)	(0.0559)
Constant	5.624***	5.427***	6.777***	5.747***
	(0.382)	(0.330)	(0.941)	(0.355)
Observations	18,796	18,796	18,796	18,796
R-squared	0.442	0.429	0.131	0.420
Covariates	YES	YES	YES	YES
Country*Year FE	YES	YES	YES	YES
Hansen test	0.938	1.351	0.646	3.948
Hansen p-value	0.333	0.509	0.422	0.267
Kleibergen-Paap test	26.93	21.72	6.512	35.95
Kleibergen-Paap p-value	0.000	0.00007	0.0385	0.000

Notes: The dependent variable is the quantity of farm labor in logarithm measured in person-days per ha. Columns 1-4 report the results using the 2SLS model. Robust standard errors are in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. The Hansen test is a test of overidentifying restrictions (H0: instruments are valid instruments, i.e., uncorrelated with the error term). The Kleibergen-Paap test is an under-identification test (H0: the excluded instruments are not correlated with the endogenous regressors).

Table 3.7: Impact of malaria on labor productivity – complete table results

Dpt. var.: *labor* in kg per person-days	(1)	(2)	(3)	(4)
Malaria	9.113***	7.956***	7.454***	14.08***
	(2.302)	(2.820)	(2.468)	(5.336)
Malaria*irrigation		4.107		-20.24***
		(6.312)		(6.983)
Malaria*HH size			0.273	0.162
			(0.204)	(0.289)
Malaria*irrigation*hh size				0.206
				(0.182)
Irrigation	0.973***	0.283	0.959***	4.171***
	(0.126)	(1.069)	(0.124)	(1.229)
HH size	-0.0156*	-0.0167*	-0.0556*	-0.0375
	(0.00929)	(0.00924)	(0.0300)	(0.0422)
Total area	-0.0633**	-0.0589**	-0.0676**	-0.0893**
	(0.0288)	(0.0288)	(0.0288)	(0.0405)
Time	0.0608***	0.0530**	0.0621***	0.0993***
	(0.0210)	(0.0235)	(0.0203)	(0.0359)
Soil	0.0686	0.0551	0.0679	0.128**
	(0.0513)	(0.0552)	(0.0496)	(0.0634)
Primary education	-0.0292	-0.0377	-0.0337	0.00526
	(0.0518)	(0.0527)	(0.0501)	(0.0688)
Secondary education	0.0608	0.0643	0.0554	0.0438
	(0.0765)	(0.0763)	(0.0738)	(0.102)
Superior education	0.192	0.179	0.206	0.275
	(0.132)	(0.138)	(0.126)	(0.168)
Age	-0.00119	-0.00104	-0.00208	-0.00211
	(0.00220)	(0.00220)	(0.00220)	(0.00305)
Gender	-0.403***	-0.390***	-0.363***	-0.448***
	(0.0920)	(0.0920)	(0.0910)	(0.147)
Household wealth	-0.294***	-0.285***	-0.296***	-0.340***
	(0.0457)	(0.0466)	(0.0451)	(0.0634)
House (quality wall or roof)	0.209***	0.198***	0.207***	0.266***
	(0.0556)	(0.0564)	(0.0539)	(0.0832)
House (quality wall and roof)	0.164***	0.187***	0.155***	0.0539
	(0.0574)	(0.0666)	(0.0561)	(0.0806)
Agriculture (main activity)	-0.111**	-0.0827	-0.110**	-0.241***
	(0.0520)	(0.0676)	(0.0506)	(0.0779)
Livestock (main activity)	0.110	0.141	0.120	-0.0298
	(0.101)	(0.110)	(0.0984)	(0.136)
Constant	-0.956	-1.167	-0.593	0.180
	(0.793)	(0.864)	(0.797)	(0.929)
Observations	16,790	16,790	16,790	16,790
R-squared	-1.532	-1.465	-1.386	-3.550
Covariates	YES	YES	YES	YES
Country*Year FE	YES	YES	YES	YES
Hansen test	1.298	1.555	0.718	0.187
Hansen p-value	0.255	0.212	0.397	0.911
kleibergen-Paap test	23.14	14.92	21.92	11.35
kleibergen-Paap p-value	0.000	0.0006	0.00001	0.009

Notes: The dependent variable is labor productivity in logarithm measured in kg per person-days. Columns 1-4 report the results using the 2SLS model. Robust standard errors are in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. The Hansen test is a test of overidentifying restrictions (H0: instruments are valid instruments, i.e., uncorrelated with the error term). The Kleibergen-Paap test is an under-identification test (H0: the excluded instruments are not correlated with the endogenous regressors).

Table 3.8: Impact of malaria on labor quantity: using land prepa. and field manag. steps

Dpt. var.: *labor* in person-days per ha	(1)	(2)	(3)	(4)
Malaria	-1.764	-2.753*	-8.029*	-3.311**
	(1.191)	(1.463)	(4.303)	(1.597)
Malaria*irrigation		4.330		4.365
		(3.107)		(3.044)
Malaria*hh size			0.963*	0.0881
			(0.579)	(0.109)
Malaria*irrig*hh size				-0.0286
				(0.0953)
Irrigation	0.171**	-0.541	0.110	-0.513
	(0.0847)	(0.513)	(0.103)	(0.621)
HH size	0.0659***	0.0653***	-0.0732	0.0518***
	(0.00482)	(0.00508)	(0.0849)	(0.0156)
Total area	-1.496***	-1.489***	-1.514***	-1.488***
	(0.0180)	(0.0193)	(0.0238)	(0.0192)
Time	0.0365***	0.0324***	0.0392***	0.0326***
	(0.0109)	(0.0119)	(0.0143)	(0.0120)
Soil	0.0809***	0.0758***	0.0724**	0.0747***
	(0.0255)	(0.0269)	(0.0331)	(0.0264)
Primary education	-0.144***	-0.161***	-0.151***	-0.162***
	(0.0280)	(0.0317)	(0.0359)	(0.0320)
Secondary education	-0.172***	-0.177***	-0.169***	-0.178***
	(0.0421)	(0.0441)	(0.0563)	(0.0444)
Superior education	-0.289***	-0.317***	-0.265***	-0.316***
	(0.0719)	(0.0784)	(0.0923)	(0.0782)
Age	0.00536***	0.00556***	0.00183	0.00533***
	(0.00112)	(0.00117)	(0.00272)	(0.00126)
Gender	-0.203***	-0.191***	-0.0533	-0.181***
	(0.0488)	(0.0519)	(0.118)	(0.0550)
Household wealth	0.0998***	0.109***	0.0924***	0.108***
	(0.0256)	(0.0276)	(0.0323)	(0.0275)
House (quality wall or roof)	-0.0752***	-0.0850***	-0.0870**	-0.0850***
	(0.0276)	(0.0297)	(0.0364)	(0.0298)
House (quality wall and roof)	-0.104***	-0.0866***	-0.133***	-0.0876***
	(0.0292)	(0.0334)	(0.0412)	(0.0339)
Agriculture (main activity)	0.211***	0.238***	0.215***	0.237***
	(0.0296)	(0.0358)	(0.0366)	(0.0371)
Livestock(main activity)	-0.0767	-0.0464	-0.0414	-0.0449
	(0.0577)	(0.0627)	(0.0723)	(0.0640)
Constant	4.845***	4.555***	6.247***	4.671***
	(0.398)	(0.459)	(1.056)	(0.458)
Observations	18,524	18,524	18,524	18,524
R-squared	0.426	0.374	0.032	0.366
Year*Country FE	YES	YES	YES	YES
Hansen test	1.525	2.309	0.511	1.914
Hansen p-value	0.217	0.129	0.475	0.166
Kleibergen-Paap test	25.73	23.12	6.294	14.52
Kleibergen-Paap p-value	0.000	0.000	0.0430	0.0007

Notes: The dependent variable is the quantity of farm labor in logarithm measured in person-days per ha computed by combining land preparation and field management steps in one step. Columns 1-4 report using 2SLS model. Robust standard errors in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. Hansen test is a test of overidentifying restrictions (H0: instruments are valid instruments, i.e., uncorrelated with the error term). Kleibergen-Paap test is an underidentification test (H0: the excluded instruments are not correlated with the endogenous regressors).

Table 3.9: Impact of malaria on labor quantity: using harvesting step

Dpt. var.: *labor* in person-days per ha	(1)	(2)	(3)	(4)
Malaria	-0.862	-0.686	-2.456*	-2.854*
	(1.185)	(1.337)	(1.351)	(1.477)
Malaria*irrigation		-0.937		-0.885
		(3.404)		(1.786)
Malaria*hh size			0.297***	0.337***
			(0.0988)	(0.113)
Malaria*irrig*hh size				-0.110
				(0.105)
Irrigation	-0.0952	0.0555	-0.104	0.169
	(0.0869)	(0.550)	(0.0872)	(0.411)
HH size	0.0732***	0.0731***	0.0316**	0.0260*
	(0.00483)	(0.00485)	(0.0149)	(0.0153)
Total area	-1.286***	-1.288***	-1.292***	-1.289***
	(0.0185)	(0.0191)	(0.0186)	(0.0195)
Time	-0.000635	0.000309	0.00156	0.00162
	(0.0103)	(0.0109)	(0.0105)	(0.0112)
Soil	-0.0264	-0.0241	-0.0316	-0.0279
	(0.0254)	(0.0270)	(0.0259)	(0.0260)
Primary education	-0.164***	-0.161***	-0.169***	-0.164***
	(0.0276)	(0.0297)	(0.0279)	(0.0289)
Secondary education	-0.196***	-0.195***	-0.199***	-0.199***
	(0.0407)	(0.0411)	(0.0415)	(0.0428)
Superior education	-0.249***	-0.245***	-0.239***	-0.238***
	(0.0704)	(0.0726)	(0.0718)	(0.0746)
Age	0.00508***	0.00503***	0.00426***	0.00387***
	(0.00114)	(0.00116)	(0.00120)	(0.00119)
Gender	-0.213***	-0.214***	-0.176***	-0.167***
	(0.0453)	(0.0453)	(0.0486)	(0.0494)
Household wealth	-0.0179	-0.0201	-0.0217	-0.0226
	(0.0252)	(0.0265)	(0.0254)	(0.0264)
House (quality wall or roof)	0.0769***	0.0780***	0.0752***	0.0728**
	(0.0285)	(0.0287)	(0.0289)	(0.0296)
House (quality wall and roof)	0.102***	0.0976***	0.0924***	0.0842***
	(0.0297)	(0.0344)	(0.0304)	(0.0323)
Agriculture (main activity)	0.196***	0.190***	0.200***	0.188***
	(0.0294)	(0.0371)	(0.0297)	(0.0334)
Livestock(main activity)	-0.115**	-0.122**	-0.0954*	-0.107*
	(0.0558)	(0.0611)	(0.0566)	(0.0595)
Constant	4.507***	4.588***	4.832***	5.055***
	(0.410)	(0.510)	(0.438)	(0.393)
Observations	18,140	18,140	18,140	18,140
R-squared	0.502	0.501	0.485	0.460
Year*Country FE	YES	YES	YES	YES
Hansen test	2.184	2.038	2.766	0.667
Hansen p-value	0.139	0.153	0.251	0.716
Kleibergen-Paap test	25.01	11.04	23.51	22.70
Kleibergen-Paap p-value	0.000	0.004	0.00003	0.00004

Notes: The dependent variable is the quantity of farm labor in logarithm measured in person-days per ha using only harvesting activity. Columns 1-4 report using 2SLS model. Robust standard errors in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. Hansen test is a test of overidentifying restrictions (H0: instruments are valid instruments, i.e., uncorrelated with the error term). Kleibergen-Paap test is an underidentification test (H0: the excluded instruments are not correlated with the endogenous regressors).

Table 3.10: Impact of malaria on labor prod.: using land prepa. and field manag. steps

Dpt. var.: *labor* in kg per person-days	(1)	(2)	(3)	(4)
Malaria	8.915***	14.98***	6.447***	7.115**
	(2.378)	(4.884)	(2.343)	(2.939)
Malaria*irrigation		-21.31***		-0.714
		(7.168)		(3.228)
Malaria*hh size			0.299	0.202
			(0.194)	(0.209)
Malaria*irrig*hh size				0.277
				(0.187)
Irrigation	0.840***	4.440***	0.814***	0.338
	(0.130)	(1.255)	(0.124)	(0.754)
HH size	-0.0136	-0.00734	-0.0598**	-0.0515*
	(0.00960)	(0.0144)	(0.0288)	(0.0296)
Total area	0.00467	-0.0195	0.00231	-0.0135
	(0.0294)	(0.0418)	(0.0279)	(0.0293)
Time	0.0456**	0.0841**	0.0441**	0.0460**
	(0.0216)	(0.0367)	(0.0197)	(0.0225)
Soil	0.0202	0.0772	0.0252	0.0387
	(0.0512)	(0.0653)	(0.0468)	(0.0469)
Primary education	-0.0169	0.0216	-0.0183	-0.0180
	(0.0528)	(0.0712)	(0.0486)	(0.0498)
Secondary education	0.0356	0.00856	0.0314	0.0399
	(0.0778)	(0.106)	(0.0712)	(0.0733)
Superior education	0.230*	0.307*	0.238**	0.247**
	(0.133)	(0.176)	(0.120)	(0.124)
Age	-0.00184	-0.00242	-0.00333	-0.00289
	(0.00225)	(0.00298)	(0.00210)	(0.00217)
Gender	-0.382***	-0.483***	-0.320***	-0.333***
	(0.0947)	(0.149)	(0.0870)	(0.0958)
Household wealth	-0.328***	-0.373***	-0.331***	-0.337***
	(0.0466)	(0.0651)	(0.0440)	(0.0450)
House (quality wall or roof)	0.272***	0.327***	0.264***	0.263***
	(0.0560)	(0.0844)	(0.0513)	(0.0543)
House (quality wall and roof)	0.252***	0.137	0.241***	0.239***
	(0.0576)	(0.0843)	(0.0536)	(0.0574)
Agriculture (main activity)	-0.0934*	-0.244***	-0.0972*	-0.0871
	(0.0537)	(0.0804)	(0.0498)	(0.0565)
Livestock(main activity)	0.151	-0.0145	0.152	0.161
	(0.107)	(0.141)	(0.0997)	(0.104)
Constant	-0.244	0.904	0.379	0.603
	(0.829)	(0.900)	(0.766)	(0.724)
Observations	16,564	16,564	16,564	16,564
R-squared	-1.291	-3.273	-0.960	-1.045
Year*Country FE	YES	YES	YES	YES
Hansen test	0.539	0.0124	0.838	0.286
Hansen p-value	0.463	0.911	0.658	0.867
Kleibergen-Paap test	21.84	12.47	21.13	16.82
Kleibergen-Paap p-value	0.00001	0.002	0.00009	0.0008

Notes: The dependent variable is labor productivity in (ln (kg per person-days)) computed by combining land preparation and field management steps in one step. Columns 1-4 report using 2SLS model. Robust standard errors in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. Hansen test is a test of overidentifying restrictions (H0: instruments are valid instruments, i.e., uncorrelated with the error term). Kleibergen-Paap test is an underidentification test (H0: the excluded instruments are not correlated with the endogenous regressors).

Table 3.11: Impact of malaria on labor productivity: harvesting step

Dpt. var.: *labor* in kg per person-days	(1)	(2)	(3)	(4)
Malaria	8.529***	12.61***	7.564***	4.990**
	(2.262)	(3.850)	(2.332)	(2.291)
Malaria*irrigation		-16.65***		11.30
		(5.609)		(9.192)
Malaria*hh size			0.0914	-0.0452
			(0.170)	(0.186)
Malaria*irrig*hh size				0.454
				(0.295)
Irrigation	1.144***	3.914***	1.133***	-1.705
	(0.125)	(0.973)	(0.120)	(1.965)
HH size	-0.0208**	-0.0188*	-0.0356	-0.0284
	(0.00898)	(0.0114)	(0.0259)	(0.0271)
Total area	-0.186***	-0.207***	-0.185***	-0.193***
	(0.0282)	(0.0366)	(0.0273)	(0.0289)
Time	0.0699***	0.101***	0.0688***	0.0454*
	(0.0199)	(0.0300)	(0.0190)	(0.0236)
Soil	0.144***	0.206***	0.148***	0.128**
	(0.0486)	(0.0560)	(0.0463)	(0.0613)
Primary education	0.00260	0.0265	0.00176	-0.0124
	(0.0497)	(0.0608)	(0.0477)	(0.0532)
Secondary education	0.0751	0.0505	0.0721	0.104
	(0.0744)	(0.0908)	(0.0713)	(0.0832)
Superior education	0.193	0.230	0.196	0.179
	(0.129)	(0.151)	(0.123)	(0.154)
Age	-0.00107	-0.00188	-0.00171	-0.000822
	(0.00223)	(0.00258)	(0.00216)	(0.00264)
Gender	-0.384***	-0.420***	-0.360***	-0.335***
	(0.0870)	(0.114)	(0.0849)	(0.0855)
Household wealth	-0.246***	-0.288***	-0.246***	-0.225***
	(0.0446)	(0.0573)	(0.0431)	(0.0476)
House (quality wall or roof)	0.112**	0.151**	0.108**	0.0737
	(0.0545)	(0.0722)	(0.0520)	(0.0537)
House (quality wall and roof)	0.0372	-0.0518	0.0318	0.0958
	(0.0558)	(0.0712)	(0.0539)	(0.0820)
Agriculture (main activity)	-0.0785	-0.196***	-0.0799	0.0219
	(0.0508)	(0.0682)	(0.0488)	(0.0968)
Livestock(main activity)	0.162*	0.0377	0.163*	0.267**
	(0.0974)	(0.121)	(0.0938)	(0.126)
Constant	-0.0185	1.082	0.242	-0.0522
	(0.790)	(0.748)	(0.766)	(1.123)
Observations	16,494	16,494	16,494	16,494
R-squared	-1.204	-2.339	-1.026	-1.352
Year*Country FE	YES	YES	YES	YES
Hansen test	0.532	0.000711	0.794	1.002
Hansen p-value	0.466	0.979	0.672	0.606
Kleibergen-Paap test	21.96	14.79	21.59	14.39
Kleibergen-Paap p-value	0.00001	0.0006	0.00007	0.002

Notes: The dependent variable is labor productivity in (ln (kg per person-days)) using only harvesting activity. Columns 1-4 report using 2SLS model. Robust standard errors in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. Hansen test is a test of overidentifying restrictions (H0: instruments are valid instruments, i.e., uncorrelated with the error term). Kleibergen-Paap test is an underidentification test (H0: the excluded instruments are not correlated with the endogenous regressors).

Table 3.12: Impact of malaria on labor quantity: adding climate variables

Dpt. var.: *labor* in person-days per ha	(1)	(2)	(3)	(4)
Malaria	-1.097*	-3.250***	-1.737**	-2.031**
	(0.657)	(1.142)	(0.816)	(0.967)
Malaria*irrigation		6.084*		-0.532
		(3.179)		(1.693)
Malaria*hh size			0.166*	0.190*
			(0.0893)	(0.107)
Malaria*irrig*hh size				-0.0830
				(0.0820)
Irrigation	0.0446	-0.00389	0.0381	0.200
	(0.0791)	(0.533)	(0.0790)	(0.346)
HH size	0.0706***	0.0201***	0.0480***	0.0456***
	(0.00303)	(0.00397)	(0.0129)	(0.0140)
Precipitation	-0.00204***	-0.00266***	-0.00211***	-0.00206***
	(0.000225)	(0.000502)	(0.000232)	(0.000322)
Evapotranspiration	-0.119***	-0.295***	-0.112***	-0.110***
	(0.0422)	(0.0572)	(0.0420)	(0.0427)
Constant	5.430***	2.700***	5.541***	5.705***
	(0.227)	(0.363)	(0.250)	(0.270)
Observations	17,576	17,576	17,576	17,576
R-squared	0.511	0.079	0.513	0.495
Covariates	YES	YES	YES	YES
Month FE	YES	YES	YES	YES
Country FE	YES	YES	YES	YES
Hansen test	0.154	0.0180	4.150	1.214
Hansen p-value	0.695	0.893	0.126	0.545
Kleibergen-Paap test	66.31	17.21	63.95	45.56
Kleibergen-Paap p-value	0.000	0.0002	0	0.000

Notes: The dependent variable is the quantity of farm labor in logarithm measured in person-days per ha. Columns 1-4 report the results using 2SLS model. Robust standard errors in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. Hansen test is a test of overidentifying restrictions (H0: instruments are valid instruments, i.e., uncorrelated with the error term). Kleibergen-Paap test is an underidentification test (H0: the excluded instruments are not correlated with the endogenous regressors).

Table 3.13: Impact of malaria on labor productivity: adding climate variables

Dpt. var.: *labor* in kg person-days	(1)	(2)	(3)	(4)
Malaria	11.12***	9.382***	10.31***	12.43**
	(2.857)	(3.631)	(3.246)	(6.335)
Malaria*irrigation		3.939		-1.836
		(5.555)		(3.977)
Malaria*hh size			0.103	-0.312
			(0.210)	(0.570)
Malaria*irrig*hh size				0.360
				(0.267)
Irrigation	0.641***	-0.430	0.654***	0.658
	(0.146)	(1.167)	(0.145)	(0.762)
HH size	-0.00185	-0.00566	-0.0177	0.0323
	(0.0130)	(0.0136)	(0.0345)	(0.0858)
Precipitation	-0.00306***	-0.00287***	-0.00299***	-0.00280***
	(0.000848)	(0.000834)	(0.000838)	(0.000910)
Evapotranspiration	-0.259**	-0.210**	-0.247**	-0.270**
	(0.102)	(0.0945)	(0.103)	(0.120)
Constant	-1.548	-1.220	-1.391	-1.678
	(0.953)	(0.945)	(0.984)	(1.332)
Observations	15,689	15,689	15,689	15,689
R-squared	-2.390	-2.049	-2.235	-2.326
Covariates	YES	YES	YES	YES
Month*Country FE	YES	YES	YES	YES
Hansen test	1.071	1.267	1.476	1.685
Hansen p-value	0.301	0.260	0.224	0.431
Kleibergen-Paap test	20.23	10.68	17.96	13.07
Kleibergen-Paap p-value	4.05e-05	0.00480	0.000126	0.00448

Notes: The dependent variable is labor productivity in (ln(kg per person days)). Columns 1-4 report the results using 2SLS model. Robust standard errors in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. Hansen test is a test of overidentifying restrictions (H0: instruments are valid instruments, i.e., uncorrelated with the error term). Kleibergen-Paap test is an underidentification test (H0: the excluded instruments are not correlated with the endogenous regressors).

Table 3.14: Impact of malaria on labor quantity: alternative measure of malaria

Dpt. var.: *labor* in person-days per ha	(1)	(2)	(3)	(4)
Malaria	-2.198*	-2.604*	-3.061**	-3.445**
	(1.201)	(1.469)	(1.431)	(1.633)
Malaria*irrigation		2.547		-0.310
		(2.118)		(1.913)
Malaria*hh size			0.128	0.222**
			(0.0935)	(0.104)
Malaria*irrig*hh size				-0.0979
				(0.0859)
Irrigation	0.0378	-0.376	0.0299	0.169
	(0.0833)	(0.360)	(0.0843)	(0.383)
HH size	0.0672***	0.0676***	0.0486***	0.0376**
	(0.00484)	(0.00483)	(0.0148)	(0.0154)
Total area	-1.421***	-1.418***	-1.423***	-1.425***
	(0.0177)	(0.0183)	(0.0178)	(0.0183)
Time	0.0184*	0.0168	0.0185*	0.0198*
	(0.0108)	(0.0114)	(0.0110)	(0.0116)
Soil	0.0349	0.0294	0.0346	0.0344
	(0.0258)	(0.0252)	(0.0263)	(0.0267)
Primary education	-0.133***	-0.144***	-0.134***	-0.132***
	(0.0271)	(0.0280)	(0.0277)	(0.0293)
Secondary education	-0.185***	-0.189***	-0.184***	-0.185***
	(0.0408)	(0.0409)	(0.0419)	(0.0426)
Superior education	-0.267***	-0.276***	-0.263***	-0.262***
	(0.0709)	(0.0716)	(0.0724)	(0.0740)
Age	0.00443***	0.00468***	0.00396***	0.00369***
	(0.00111)	(0.00106)	(0.00121)	(0.00122)
Gender	-0.178***	-0.180***	-0.157***	-0.147***
	(0.0485)	(0.0484)	(0.0533)	(0.0546)
Household wealth	0.0581**	0.0632**	0.0574**	0.0557**
	(0.0251)	(0.0261)	(0.0254)	(0.0261)
House (quality wall or roof)	-0.00907	-0.0144	-0.0103	-0.0106
	(0.0272)	(0.0285)	(0.0277)	(0.0286)
House (quality wall and roof)	-0.0104	0.000624	-0.0147	-0.0205
	(0.0291)	(0.0302)	(0.0298)	(0.0316)
Agriculture (main activity)	0.229***	0.245***	0.230***	0.226***
	(0.0288)	(0.0310)	(0.0292)	(0.0321)
Livestock(main activity)	-0.0655	-0.0466	-0.0601	-0.0593
	(0.0548)	(0.0557)	(0.0558)	(0.0574)
Constant	5.603***	5.385***	5.795***	5.913***
	(0.392)	(0.332)	(0.436)	(0.432)
Observations	18,622	18,622	18,622	18,622
R-squared	0.443	0.434	0.420	0.404
Year*Country FE	YES	YES	YES	YES
Hansen test	0.951	1.454	0.524	5.741
Hansen p-value	0.329	0.483	0.469	0.125
Kleibergen-Paap test	25.17	20.57	22.29	21.44
Kleibergen-Paap p-value	0.000	0.0001	0.00001	0.0003

Notes: The dependent variable is the quantity of farm labor in logarithm measured in person-days per ha. Columns 1-4 report using 2SLS model. Robust standard errors in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. Hansen test is a test of overidentifying restrictions (H0: instruments are valid instruments, i.e., uncorrelated with the error term). Kleibergen-Paap test is an underidentification test (H0: the excluded instruments are not correlated with the endogenous regressors).

Table 3.15: Impact of malaria on labor productivity: alternative measure of malaria

Dpt. var.: *labor* in kg per person-days	(1)	(2)	(3)	(4)
Malaria	9.197***	15.62***	7.575***	6.894**
	(2.367)	(5.131)	(2.569)	(2.892)
Malaria*irrigation		-20.85***		-0.156
		(7.255)		(3.220)
Malaria*hh size			0.263	0.204
			(0.208)	(0.210)
Malaria*irrig*hh size				0.257
				(0.188)
Irrigation	0.941***	4.441***	0.928***	0.393
	(0.128)	(1.263)	(0.126)	(0.745)
HH size	-0.0153	-0.00758	-0.0541*	-0.0546*
	(0.00958)	(0.0150)	(0.0312)	(0.0299)
Total area	-0.0670**	-0.0904**	-0.0707**	-0.0818***
	(0.0293)	(0.0426)	(0.0291)	(0.0283)
Time	0.0614***	0.101***	0.0625***	0.0591***
	(0.0215)	(0.0377)	(0.0207)	(0.0218)
Soil	0.0673	0.126*	0.0673	0.0887*
	(0.0524)	(0.0664)	(0.0507)	(0.0464)
Primary education	-0.0255	0.0202	-0.0299	-0.0273
	(0.0522)	(0.0720)	(0.0505)	(0.0479)
Secondary education	0.0763	0.0608	0.0715	0.0790
	(0.0768)	(0.106)	(0.0738)	(0.0698)
Superior education	0.209	0.247	0.223*	0.226*
	(0.133)	(0.176)	(0.127)	(0.120)
Age	-0.00104	-0.00141	-0.00191	-0.00231
	(0.00224)	(0.00301)	(0.00225)	(0.00208)
Gender	-0.400***	-0.480***	-0.361***	-0.340***
	(0.0943)	(0.147)	(0.0940)	(0.0912)
Household wealth	-0.304***	-0.351***	-0.305***	-0.310***
	(0.0462)	(0.0667)	(0.0455)	(0.0434)
House (quality wall or roof)	0.205***	0.268***	0.204***	0.192***
	(0.0565)	(0.0883)	(0.0547)	(0.0532)
House (quality wall and roof)	0.161***	0.0504	0.152***	0.149***
	(0.0581)	(0.0842)	(0.0569)	(0.0560)
Agriculture (main activity)	-0.104**	-0.241***	-0.103**	-0.0958*
	(0.0529)	(0.0792)	(0.0515)	(0.0543)
Livestock(main activity)	0.116	-0.0320	0.126	0.129
	(0.103)	(0.141)	(0.0998)	(0.0973)
Constant	-0.939	-0.0269	-0.581	-0.0396
	(0.811)	(0.889)	(0.822)	(0.687)
Observations	16,632	16,632	16,632	16,632
R-squared	-1.566	-3.947	-1.413	-1.145
Year*Country FE	YES	YES	YES	YES
Hansen test	1.329	0.178	0.781	2.907
Hansen p-value	0.249	0.673	0.377	0.406
Kleibergen-Paap test	22.19	11.69	20.72	18.58
Kleibergen-Paap p-value	0.00001	0.003	0.00003	0.001

Notes: The dependent variable is labor productivity in (ln (kg per person-days)). Columns 1-4 report using 2SLS model. Robust standard errors in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. Hansen test is a test of overidentifying restrictions (H0: instruments are valid instruments, i.e., uncorrelated with the error term). Kleibergen-Paap test is an underidentification test (H0: the excluded instruments are not correlated with the endogenous regressors).

Table 3.16: Impact of malaria on labor quantity: alternative measure of irrigation

Type of irrigation	Irrigation in %				Irrigation in ha			
Dpt. var.: *labor* in person-days per ha	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Malaria	-2.227*	-2.647*	-7.470*	-3.666**	-2.066*	-2.023*	-3.060**	-9.850**
	(1.161)	(1.446)	(3.865)	(1.614)	(1.157)	(1.167)	(1.379)	(4.471)
Malaria*irrigation		0.0171		0.0229		0.0910		3.677*
		(0.0324)		(0.0272)		(1.506)		(2.229)
Malaria*hh size			0.814	0.198*			0.147	0.513**
			(0.517)	(0.103)			(0.0912)	(0.233)
Malaria*irrig*hh size				-0.00100				-0.0625
				(0.000879)				(0.0600)
Irrigation	0.000370	-0.00211	-0.000180	-0.00218	-0.879***	-0.898***	-0.897***	-1.785***
	(0.000879)	(0.00598)	(0.00104)	(0.00560)	(0.0862)	(0.347)	(0.0890)	(0.595)
Irrigation sq.					0.462***	0.462***	0.460***	0.466***
					(0.0391)	(0.0385)	(0.0396)	(0.0408)
HH size	0.0667***	0.0664***	-0.0507	0.0412***	0.0683***	0.0685***	0.0468***	-0.0174
	(0.00468)	(0.00481)	(0.0758)	(0.0150)	(0.00469)	(0.00450)	(0.0143)	(0.0413)
Total area	-1.422***	-1.418***	-1.437***	-1.421***	-1.481***	-1.481***	-1.479***	-1.464***
	(0.0175)	(0.0182)	(0.0222)	(0.0182)	(0.0192)	(0.0197)	(0.0195)	(0.0285)
Time	0.0174*	0.0154	0.0202	0.0172	0.0208**	0.0208*	0.0212**	0.000463
	(0.0106)	(0.0112)	(0.0134)	(0.0115)	(0.0104)	(0.0109)	(0.0106)	(0.0211)
Soil	0.0332	0.0289	0.0282	0.0245	0.0397	0.0394	0.0394	0.0774*
	(0.0254)	(0.0254)	(0.0315)	(0.0255)	(0.0248)	(0.0250)	(0.0254)	(0.0446)
Primary education	-0.133***	-0.141***	-0.141***	-0.144***	-0.129***	-0.129***	-0.131***	-0.121***
	(0.0270)	(0.0304)	(0.0336)	(0.0301)	(0.0265)	(0.0264)	(0.0271)	(0.0413)
Secondary education	-0.180***	-0.183***	-0.178***	-0.187***	-0.182***	-0.182***	-0.181***	-0.159**
	(0.0410)	(0.0418)	(0.0521)	(0.0422)	(0.0404)	(0.0403)	(0.0417)	(0.0649)
Superior education	-0.274***	-0.285***	-0.254***	-0.285***	-0.271***	-0.271***	-0.268***	-0.249**
	(0.0701)	(0.0732)	(0.0879)	(0.0731)	(0.0688)	(0.0687)	(0.0706)	(0.106)
Age	0.00441***	0.00445***	0.00154	0.00402***	0.00443***	0.00449***	0.00387***	0.000264
	(0.00110)	(0.00111)	(0.00242)	(0.00119)	(0.00110)	(0.00107)	(0.00119)	(0.00281)
Gender	-0.178***	-0.176***	-0.0528	-0.156***	-0.193***	-0.194***	-0.169***	0.0128
	(0.0474)	(0.0481)	(0.107)	(0.0527)	(0.0463)	(0.0470)	(0.0508)	(0.133)
Household wealth	0.0599**	0.0646**	0.0524*	0.0632**	0.0516**	0.0518**	0.0502**	0.0632*
	(0.0249)	(0.0261)	(0.0301)	(0.0260)	(0.0243)	(0.0248)	(0.0247)	(0.0368)
House (quality wall or roof)	-0.00678	-0.0112	-0.0144	-0.0132	-0.00651	-0.00615	-0.00853	-0.0410
	(0.0270)	(0.0291)	(0.0339)	(0.0289)	(0.0268)	(0.0267)	(0.0274)	(0.0455)
House (quality wall and roof)	-0.00990	-0.00319	-0.0368	-0.00811	-0.0144	-0.0142	-0.0191	-0.0392
	(0.0289)	(0.0316)	(0.0393)	(0.0317)	(0.0285)	(0.0284)	(0.0292)	(0.0447)
Agriculture (main activity)	0.228***	0.237***	0.234***	0.240***	0.242***	0.242***	0.243***	0.246***
	(0.0286)	(0.0346)	(0.0342)	(0.0337)	(0.0282)	(0.0283)	(0.0286)	(0.0409)
Livestock (main activity)	-0.0679	-0.0552	-0.0317	-0.0415	-0.0592	-0.0584	-0.0522	-0.0491
	(0.0545)	(0.0603)	(0.0675)	(0.0594)	(0.0536)	(0.0537)	(0.0548)	(0.0785)
Constant	5.627***	5.497***	6.786***	5.634***	5.848***	5.828***	6.079***	7.742***
	(0.385)	(0.380)	(0.946)	(0.408)	(0.375)	(0.358)	(0.420)	(1.168)
Observations	18,796	18,796	18,796	18,796	18,796	18,796	18,796	18,796
R-squared	0.442	0.429	0.132	0.417	0.461	0.465	0.435	-0.309
Year*Country FE	YES	YES	YES	YES	YES	YES	YES	YES
Hansen test	0.935	1.167	0.648	3.288	1.002	1.033	0.476	0.516
Hansen p-value	0.334	0.280	0.421	0.193	0.317	0.309	0.490	0.772
Kleibergen-Paap test	26.93	14.59	6.525	22.92	26.28	28.13	23.40	8.601
Kleibergen-Paap p-value	0.000	0.000	0.0383	0.00004	0.000	0.000	0.000	0.0351

Notes: This table indicates coefficients estimated from two-stage least squares (2SLS) using the instrumental variables method. The dependent variable is the quantity of farm labor in logarithm measured in person-days per ha. Columns 1-4 and 5-8 report the results of the percentage of irrigated land and the irrigated area in hectares respectively. Robust standard errors in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. Hansen test is a test of overidentifying restrictions (H0: instruments are valid instruments, i.e., uncorrelated with the error term). Kleibergen-Paap test is an underidentification test (H0: the excluded instruments are not correlated with the endogenous regressors).

Table 3.17: Impact of malaria on labor productivity: alternative measure of irrigation

Type of *irrigation*	Irrigation in %				Irrigation in ha			
Dpt. var.: *labor* in kg per person-days	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Malaria	8.941***	14.65***	7.295***	7.100**	8.983***	9.430***	9.849***	7.048***
	(2.276)	(4.723)	(2.435)	(2.861)	(2.280)	(2.470)	(3.707)	(2.476)
Malaria*irrigation		-0.187***		-0.00978		-2.289		-0.517
		(0.0666)		(0.0308)		(2.208)		(1.791)
HH size*malaria			0.268	0.202			0.244	0.211
			(0.199)	(0.204)			(0.231)	(0.195)
Malaria*irrig*hh				0.00232				0.0361
				(0.00176)				(0.134)
Irrigation	0.0123***	0.0434***	0.0121***	0.00853	1.126***	1.597***	1.164***	1.152**
	(0.00133)	(0.0117)	(0.00131)	(0.00709)	(0.168)	(0.505)	(0.203)	(0.499)
Irrigation sq.					-0.279***	-0.244***	-0.294***	-0.278***
					(0.0659)	(0.0564)	(0.0762)	(0.0730)
HH size	-0.0172*	-0.0105	-0.0564*	-0.0541*	-0.0155*	-0.0158*	-0.0426	-0.0501*
	(0.00906)	(0.0137)	(0.0293)	(0.0288)	(0.00923)	(0.00909)	(0.0370)	(0.0286)
Total area	-0.0545*	-0.0770*	-0.0585**	-0.0698**	-0.151***	-0.145***	-0.164***	-0.143***
	(0.0290)	(0.0409)	(0.0288)	(0.0286)	(0.0309)	(0.0310)	(0.0381)	(0.0287)
Time	0.0587***	0.0954***	0.0598***	0.0592***	0.0628***	0.0691***	0.0741***	0.0617***
	(0.0203)	(0.0345)	(0.0195)	(0.0211)	(0.0208)	(0.0230)	(0.0251)	(0.0209)
Soil	0.0609	0.122*	0.0603	0.0813*	0.0905*	0.0904*	0.0647	0.0985**
	(0.0509)	(0.0627)	(0.0492)	(0.0457)	(0.0508)	(0.0509)	(0.0615)	(0.0465)
Primary education	-0.0248	0.0159	-0.0294	-0.0260	-0.0163	-0.0158	-0.0296	-0.0184
	(0.0513)	(0.0684)	(0.0496)	(0.0478)	(0.0511)	(0.0515)	(0.0591)	(0.0472)
Secondary education	0.0709	0.0647	0.0652	0.0714	0.0751	0.0698	0.0693	0.0701
	(0.0756)	(0.101)	(0.0729)	(0.0701)	(0.0758)	(0.0765)	(0.0873)	(0.0697)
Superior education	0.190	0.265	0.202	0.207*	0.209	0.197	0.232	0.213*
	(0.131)	(0.167)	(0.124)	(0.120)	(0.130)	(0.130)	(0.148)	(0.118)
Age	-0.00108	-0.00103	-0.00197	-0.00229	-0.000814	-0.00113	0.000159	-0.00214
	(0.00219)	(0.00294)	(0.00218)	(0.00209)	(0.00220)	(0.00212)	(0.00310)	(0.00201)
Gender	-0.395***	-0.462***	-0.356***	-0.344***	-0.378***	-0.395***	-0.407***	-0.332***
	(0.0915)	(0.136)	(0.0903)	(0.0903)	(0.0898)	(0.0965)	(0.122)	(0.0889)
Household wealth	-0.282***	-0.319***	-0.284***	-0.292***	-0.297***	-0.305***	-0.298***	-0.300***
	(0.0452)	(0.0622)	(0.0445)	(0.0430)	(0.0452)	(0.0463)	(0.0524)	(0.0431)
House (quality wall or roof)	0.215***	0.272***	0.213***	0.206***	0.202***	0.203***	0.223***	0.194***
	(0.0549)	(0.0828)	(0.0532)	(0.0530)	(0.0553)	(0.0560)	(0.0663)	(0.0508)
House (quality wall and roof)	0.182***	0.0900	0.173***	0.165***	0.148***	0.144**	0.150**	0.138***
	(0.0568)	(0.0788)	(0.0555)	(0.0549)	(0.0567)	(0.0572)	(0.0666)	(0.0529)
Agriculture (main activity)	-0.122**	-0.236***	-0.121**	-0.120**	-0.133***	-0.139***	-0.121**	-0.134***
	(0.0512)	(0.0742)	(0.0498)	(0.0522)	(0.0512)	(0.0520)	(0.0593)	(0.0478)
Livestock (main activity)	0.143	-0.0256	0.152	0.145	0.104	0.0926	0.132	0.104
	(0.0994)	(0.138)	(0.0964)	(0.0967)	(0.0999)	(0.102)	(0.114)	(0.0933)
Constant	-1.183	-0.403	-0.816	-0.321	-0.637	-0.588	-1.086	-0.0759
	(0.790)	(0.862)	(0.794)	(0.684)	(0.790)	(0.767)	(1.202)	(0.735)
Observations	16,700	16,700	16,700	16,700	16,790	16,790	16,790	16,790
R-squared	-1.459	-3.454	-1.312	-1.137	-1.482	-1.528	-2.298	-1.123
Year*Country FE	YES	YES	YES	YES	YES	YES	YES	YES
Hansen test	1.164	0.307	0.609	2.371	1.372	1.155	1.314	5.859
Hansen p-value	0.281	0.579	0.435	0.499	0.241	0.283	0.252	0.119
kleibergen-Paap test	23.12	12.36	21.86	20.68	23.17	22.59	12.59	21.06
kleibergen-Paap p-value	0.000	0.0021	0.00001	0.0004	0.000	0.00001	0.0019	0.00031

Notes: This table indicates coefficients estimated from two-stage least square (2SLS) using instrumental variables method. The dependent variable is labor productivity in (ln (kg per person-days)). Columns 1-4 and 5-8 report the results of the percentage of irrigated land and the irrigated area in hectares respectively. Robust standard errors in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. Hansen test is a test of overidentifying restrictions (H0: instruments are valid instruments, i.e., uncorrelated with the error term). Kleibergen-Paap test is an underidentification test (H0: the excluded instruments are not correlated with the endogenous regressors).

Chapter 4

Industrial water pollution and farmer adaptation: evidence from rice farming in Jiangsu China

This chapter is joint work with Sebastien Marchand (CERDI-UCA) and Huanxiu Guo (Institute of Economics and Finance, Nanjing Audit University, China) and has been submitted in Journal of Cleaner Production

This study examines the impact of industrial water pollution from manufacturing firms on rice production in Jiangsu, China. After compiling the China Rural Fixed Point Survey with the China Environmental Statistics Database, we apply an extended translog production function to separate the impact of industrial water pollution from farmers' adaptation behavior. Our empirical results show that industrial water pollution has a direct biological effect on the growth process of paddy rice, reducing rice yields by 0.06 to 17.41 percent. Moreover, farmers would increase their operating costs to mitigate the detrimental effects of industrial water pollution. The results highlight the importance of strict environmental regulations in rural areas to coordinate the sustainable growth of the manufacturing industry and agriculture in developing countries.

Keywords: Water pollution ·Rice farming · Rural environment · China

4.1 Introduction

Relocation of manufacturing industries from urban to rural areas is a global phenomenon in the wake of rapid industrialization (Liu et al., 2016). Despite lower infrastructure services and higher transportation costs than in urban areas, rural areas are attractive to polluting firms in developing countries (Ma, 2010). First, because of the vastness of rural areas, environmental regulations tend to be more complex and permissive. As a result, polluting firms may prefer to locate in rural areas to reduce their environmental costs (Wang et al., 2008). Second, because rural areas have lower population density, government-designed industrial parks where polluting firms are more likely to be located in rural areas, potentially avoiding serious public health damage (Zheng et al., 2017). As a result of the relocation of polluting manufacturing industries, rural areas are exposed to severe industrial pollution. In this context, the quantitative assessment of the impact of industrial pollution in rural areas has important implications for rural environmental protection and sustainable agricultural development.

As an illustration, this paper attempts to estimate the impact of industrial wastewater, the largest contributor of toxic pollutants (Chen et al., 2019) and the third-largest contributor of nutrients in bodies of water in China (Huang et al., 2020), on rice farming in Jiangsu Province, China. Jiangsu is located on the east coast of China, in the heart of the Yangtze River Delta. With a population of about 80 million people and an output of 19.5 million tons of rice in 2019 (9.38% of the national output), Jiangsu was the fourth largest rice-producing province in China. In addition, Jiangsu was the second largest economy in the country with an average GDP per capita of 124.1 thousand yuan (about 18,000 US dollars) in 2019 (NBS, 2020). However, rapid industrialization and economic growth in the province have been accompanied by serious environmental problems caused by polluting industries such as chemicals, paper, textiles, and dyeing. According to Chen et al. (2019), Jiangsu is the third province with the highest wastewater effluent fluxes in China in 2015 preceded by Guangdong and Shandong. Also, according to China's Ministry of Ecology and Environment (MEE), in 2015, polluting industries discharged 5.75 billion tons of industrial wastewater, 0.74 million tons of chemical oxygen demand (hereafter COD), and 101 thousand tons of ammonia nitrogen (hereafter NH3-N) (MEE, 2019). As a result, more than half of the 83 nationally controlled water sections listed in China's national surface water environmental quality monitoring network had degraded water quality of class IV-V or worse than class V (i.e., the water quality is poor and cannot be used as a drinking water source) (EPD, 2015). Massive water pollution caused abnormal algae growth in water reserves, resulting in the eutrophication of rivers and lakes. This problem was particularly severe in the Tai Lake watershed in Jiangsu. For example, satellite remote sensing in 2015 detected 91 cyanobacterial blooms in the Lake Tai watershed (EPD, 2015). Similar problems occurred in tributaries and canals, affecting water supply and irrigation systems in urban and rural areas. At that time, industrial water pollution and water eutrophication were identified as two of the major challenges to environmental sustainability and economic growth in Jiangsu.

Beyond the significance of the case study in Jiangsu, this research aims to expand the body of knowledge on the relationship between industrial water pollution and agriculture in developing countries (Metaxoglou and Smith, 2020). While most studies in the literature focus on how air pollution affects agricultural activities, the problem of water pollution is rarely examined[1]. In reality, industrial water pollution may have a greater impact on agricultural production via water runoff[2]. On the one hand, water pollution would directly affect the biological growth of crops by weakening the growth of roots, seedlings, and plantlets, resulting in lower yields (World Bank, 2007). On the other hand, industrial water pollution may have an indirect effect on agricultural production as farmers adapt to it through input adjustment and technological advances[3]. To shed light on the complicated relationship between industrial water pollution and agriculture, we model an extended translog production function that accounts for the interactions between industrial water pollution and farmers' input use and non-neutral technical change. This model allows us to separate the direct and adaptation effects of industrial wastewater on rice farming.

For the empirical studies, we combine the agricultural data from the China Rural Fixed Point Survey (CRFPS) with the comprehensive administrative database of Chinese Environmental Statistics (CES) to construct a unique firm-household level database for Jiangsu between 2011 and 2015. The comprehensive information on

[1] See Section 4.2 for a discussion of the literature.

[2] Note that industrial water pollution can also have an impact on agriculture via exchange of intermediate industrial products but this issue is beyond the scope of this paper (Li et al., 2017).

[3] For instance, water pollution is highly associated with health problems in China (Wang and Yang, 2016) and can influence rice farming through labor and day lost due to illness. Section 4.2.2 provides an overview of the theoretical relationships between water pollution and rice yield, and Section 4.3 provides the econometric framework to separate the direct effect from the adaptation effects.

pollution emissions at the firm level allows us to accurately quantify industrial water pollution in the form of chemical oxygen demand (COD) and ammonia nitrogen (NH3-N)[4]. Farmers' exposure to industrial water pollution is then calculated using the average water pollution from polluting firms, weighted by the distance of the firm to the county centre[5]. Finally, we estimate the impact of farmers' exposure to industrial water pollution on their rice yields in the translog production function.

We highlight three important results. First, we prove that industrial water pollution directly and negatively impacts rice farming. The effects are robust to different indicators of water pollution and the use of instrumental variables (IV) to mitigate the endogeneity of water pollution. More specifically, a 1 percent increase in COD (NH3-N) results in a 3.76 (6.82) to 4.17 (6.97) percent loss in rice yields, depending on the model specification. Second, the adverse effects of industrial water pollution are most pronounced within a five-kilometer radius of the center of counties. Third, we find consistent evidence that farmers spent more on operating costs to mitigate the adverse effects of industrial water pollution on rice production. Overall, our results show that industrial water pollution directly affects rice production and indirectly affects farmers' adaptive behavior, highlighting the need for strong and targeted environmental control to coordinate rapid industrialization and agricultural expansion in rural China.

The remainder of the paper is organized as follows. Section 2 presents the literature related to the impact of industrial pollution on agriculture and highlights the theoretical links between wastewater and rice farming expected in this study. Section 3 introduces the econometric framework. Section 4 presents the data and descriptive statistics. Section 5 discusses the econometric results and Section 6 provides concluding remarks.

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[4]These two pollutants (COD and NH3-N) are commonly used as markers of surface water pollution in environmental chemistry and are monitored by the Chinese government as part of its water environment monitoring.

[5]Because we lack the coordinates of each farmer, our measurement is weighted by the distance between each firm and the center of the county where the farmers are located. For a detailed explanation of how we construct the measure, see section 4.4.

4.2 Literature and theoretical hypothesis

4.2.1 Literature review

In the literature, most studies on the relationship between industrial pollution and agriculture focus on analyzing the effects of air pollution on agricultural activities. Therefore, we first review the literature on air pollution before discussing the literature on water pollution, which is rarely studied.

Air pollution and agriculture

There have been numerous studies on the effects of air pollution (e.g., particulate matter (PM), surface ozone (O3), and sulfur dioxide (SO2)) on agriculture. Several papers concluded that air pollution, especially surface O3, and SO2, leads to a reduction in crop yields in China. For example, an earlier work by Cao (1989) examined the relationship between SO2 and its effects on crops and found that airborne SO2 concentration reduces growth and crop yields by 5-25%. As for surface O3 levels, recent studies have found a negative impact of O3 on crop yields. Aunan et al. (2000) used exposure-response functions to show that O3 at the surface results in significant but variable crop yield losses depending on the coincidence of peak O3 levels and crop growing season. Feng et al. (2003) also used open chambers to show that increases in O3 concentrations lead to greater losses in winter wheat and rice. Similarly, Wang and Mauzerall (2004), Feng et al. (2015), Zhu et al. (2015), and Miao et al. (2017) concluded that O3 pollution leads to reduced crop yields. In addition, while Yi et al. (2016) also found a significant and negative effect of aboveground O3 pollution on winter wheat productivity, it differed from other studies by using an econometric approach instead of natural science methods. Outside China, many other studies also concluded that air pollution negatively affects crop yields. Among others, Avnery et al. (2011) presented evidence on a global scale, Emberson et al. (2001) in several developing countries, Wahid et al. (1995); Maggs et al. (1995) in Pakistan, Tai and Martin (2017) in the U.S. and Europe, and Benton et al. (2000) in Europe.

While most studies focused on the biological effects of air pollution on agriculture, some papers examined the effects of air pollution on agriculture through worker health and productivity. For example, Miao et al. (2017) examined the effects of pollutants such as PM2.5 and surface O3 on human health and crop yield loss. Using model-based results and concentration-response functions for human health and crops, combined with population and crop yield data, their results showed that outdoor PM2.5 leads to 1.70-1.99 million deaths and crop yield losses estimated at 9, 4.6, 0.44, and 0.34 million tons for wheat, rice, corn, and soybeans, respectively. Using an econometric model with daily labor and ozone pollution data, Graff Zivin and Neidell (2012) concluded that 10 parts per billion change in O3 concentration lead to a significant and robust 5.5 percent change in farm worker productivity in the Central Valley of California in the United States. Similarly, Hanna and Oliva (2015) used an econometric model and took advantage of exogenous variations in SO2 levels resulting from the closure of a large oil refinery in Mexico City. They found that SO2 levels in neighborhoods near the refinery decreased by an average of eight percent and hours worked increased by about five percent compared to other neighborhoods.

Water pollution and agriculture

Compared to studies on air pollution, there is little evidence of the effects of industrial water pollution on agricultural production. Among other studies, Reddy and Behera (2006) compared two villages (a pollution-affected village and an unaffected control village) in southern India and found that industrial water pollution has significant negative impacts on agricultural yields, cropland, livestock (due to contaminated water), rural employment, and human health of residents of the affected village. Similarly, Khai and Yabe (2012) found that irrigation with wastewater increases production costs and leads to yield and profit losses in rice production in Vietnam.

In China, a report by World Bank (2007) showed that land used for wastewater irrigation has expanded rapidly in China since the 1980s. The report estimated the economic cost of wastewater irrigation to agricultural yield and quality (rice, wheat, vegetables, and corn) at 7 billion yuan. In addition, Lindhjem et al. (2007) compared areas irrigated with wastewater and areas irrigated with clean water in four villages in Hebei Province to estimate the value of reduced crop quantity and quality due to wastewater irrigation. Yongguan et al. (2001) provided a global estimate of the cost of industrial water pollution in Chongqing, China. Using an analysis of resource costs (i.e., resources expended to mitigate the effects of pollution and the potential loss of GDP due to pollution), they found that the damage of water pollution was greater to crop production (e.g., grains and vegetables) than to industry (e.g., water scarcity), human health (e.g., medical costs, premature death or water treatment measures), and livestock (e.g., livestock, poultry, and fish).

4.2.2 Theoretical hypothesis

Based on the previous literature review, the manufacturing industry could discharge water pollution into the rural environment and affect agricultural production. We hypothesize that industrial water pollution affects rice yields through both direct biological effects and indirect adaptation effects in farmers' inputs use and technical changes.

First, industrial water pollution may have a direct and detrimental biological impact on the rice-growing process[6]. According to the report from World Bank (2007), water pollution can have a significant impact on the height, leaf area, and dry matter of the rice plant. The theory holds that the development of rice plants and the growth of roots can both be hampered by industrial wastewater. Therefore, the first hypothesis for an empirical test is derived:

H1: Rice yields are negatively impacted by industrial water pollution through a biological effect.

Second, farmers can adapt to industrial water pollution by altering the inputs they use (e.g., the combination of labor, capital, and other operating costs). To offset the negative effects of industrial water pollution on rice yields, it is hypothesized that farmers will use more inputs, which will indirectly affect rice yields. However, the significance of the indirect effects of water pollution is unclear and depends on farmers' awareness and capacity for adaptation. For example, farmers may employ more workdays to make up for the decreased rice yields. However, the importance of these initiatives might be jeopardized by the health risks of farmers associated with water pollution, which could ultimately result in a reduction in labor productivity and rice yields. To counteract the yield losses due to industrial water pollution, farmers could instead apply more fertilizer. We derive the second hypothesis to empirically test farmers' adaptation behavior:

H2: Rice yields are impacted by industrial water pollution through farmers' inputs use.

Third, industrial water pollution can affect rice yields through technical changes. In this context, industrial water pollution can be considered as a technology

[6]Note that this biological effect may affect the quality of rice as well. The impact of water pollution on rice quality is not examined in this study due to a lack of data.

"disruptor". Due to substantial changes in the rural environment, farmers might switch their production technology from traditional family farming to modern agricultural production. Specifically, the effects of technical change can be divided into effects due to pure technical change (i.e., the effect of technology upgrade) and biased technical change (i.e., caused by farmers' long-term misuse of inputs). Instead of presuming that industrial water pollution has an impact on technological changes, we simply hypothesize about the role of technological changes in farmers' adaptation to industrial water pollution:

H3: Rice yields are impacted by industrial water pollution through changes in agricultural production technology.

4.3 Econometric analysis

The econometric analysis aims to estimate the impact of industrial water pollution on rice yield. We aim to identify the causal relationship between industrial water pollution and rice yields by separating the direct biological effects of industrial water pollution from their indirect effects on farmers' adaptation behaviors. To achieve this, we employ an extended translog production function that accounts for all interactions between industrial water pollution, and farmers' input use and technical changes.

4.3.1 The Translog production function model

We start by assuming the following rice production function with a translog form that accommodates non-neutral technical change (TC hereafter) as follows:

$$\begin{aligned} ln(y_{i,c,t}) = \beta_0 + \sum_{j=1}^{5} \beta_j ln(x_{ji,c,t}) + 0.5 \sum_{j=1}^{5} \sum_{k=1}^{5} \beta_{jk} ln(x_{ji,c,t}).ln(x_{ki,c,t}) \\ + \beta_t t + 0.5\beta_{tt} t^2 + \sum_{j=1}^{5} \beta_{jt} ln(x_{ji,c,t}) t + \mu_i + \nu_{i,c,t}, \end{aligned} \tag{4.1}$$

where $i = 1, \ldots, N$ are the farmer unit observations at time t ($t = 1, \ldots, 5$) in county c ($c = 1, 2, \ldots, 6$) ; $ln(y_{i,t})$ is the logarithm of rice yield (in kg/mu) of farmer i at time t ; $x_{j,k} = 1, \ldots, 5$ are the three following inputs: labor (l: number of working days (both family labor and hired labor)), the value of fixed assets (c) and operating costs (e.g., irrigation, fertilizers, insecticides, seed, agricultural plastic etc.) (rc) and $ln(x_{ji,c,t})$ is the logarithm of the jth input ; t (time trend),

t^2 and $ln(x_{i,c,t})t$ are used to take into account non-neutral TC where the measure of TC is the elasticity of output with respect to time that is both time and farm specific and varies with inputs ; μ_i are time-invariant farmer-specific effects and $\nu_{i,c,t}$ is idiosyncratic factors uncorrelated with input decisions. β_0, β_j, β_{jk}, β_t, β_{tt} and β_{jt} are parameters to be estimated. Output and inputs are normalized to land devoted to rice farming[7].

We then assume that rice farming may be influenced by farm-specific exposure to industrial water pollution emitted by manufacturing firms (P). As highlighted in Section 4.2.2, P may affect rice farming through three different channels: a direct biological effect, interaction effects with input uses, and interaction effects with TC. We present three models to test these effects.

First, P is added to Model 4.1 that becomes[8]:

$$
\begin{aligned}
ln(y) = \beta_0 + \sum_{j=1}^{5} \beta_j ln(x_j) + 0.5 \sum_{j=1}^{5}\sum_{k=1}^{5} \beta_{jk} ln(x_j).ln(x_k) \\
+ \beta_t t + 0.5\beta_{tt}t^2 + \sum_{j=1}^{5} \beta_{jt} ln(x_j).t + \beta_p ln(P) + \mu_i + \nu,
\end{aligned}
\tag{4.2}
$$

where β_p is the effect of industrial water pollution to be estimated. This model does not allow us to disentangle the direct and indirect effects of P on y. Thus, to isolate the direct biological effect of P, we first add interaction effects of P with input uses. Model 4.2 becomes:

$$
\begin{aligned}
ln(y) = \beta_0 + \sum_{j=1}^{5} \beta_j ln(x_j) + 0.5 \sum_{j=1}^{5}\sum_{k=1}^{5} \beta_{jk} ln(x_j).ln(x_k) + \beta_t t + 0.5\beta_{tt}t^2 + \sum_{j=1}^{5} \beta_{jt} ln(x_j).t \\
+ \beta_p ln(P) + \sum_{j=1}^{5} \beta_{pj} ln(P).ln(x_j) + \beta_{pjk} ln(P).0.5(\sum_{j=1}^{5}\sum_{k=1}^{5} ln(x_j).ln(x_k)) + \mu_i + \nu,
\end{aligned}
\tag{4.3}
$$

where β_{pj} and β_{pjk} are the effect of industrial water pollution associated with

[7]More information on all variables can be found in Section 4.4 and Table 4.8 in the Appendix.

[8]Recall that all variables are defined at the farmer level (i) and each farmer is located in a county c at time t.

farmers' input uses. We study the interaction effects of P with each input j as: $\beta_{pj} + \sum_{j=1}^{5}\sum_{k=1}^{5}\beta_{pjk}$. The overall effect of industrial water pollution is $\beta_p + \sum_{j=1}^{5}\beta_{pj} + \sum_{j=1}^{5}\sum_{k=1}^{5}\beta_{pjk}$.

Third, P is assumed to influence rice yields as a "technology disruptor". Model 4.3 becomes:

$$
\begin{aligned}
ln(y) = {} & \beta_0 + \sum_{j=1}^{5}\beta_j ln(x_j) + 0.5\sum_{j=1}^{5}\sum_{k=1}^{5}\beta_{jk} ln(x_j).ln(x_k) + \beta_t t + 0.5\beta_{tt}t^2 + \sum_{j=1}^{5}\beta_{jt} ln(x_j).t \\
& + \beta_p ln(P) + \sum_{j=1}^{5}\beta_{pj} ln(P).ln(x_j) + \beta_{pjk} ln(P).0.5(\sum_{j=1}^{5}\sum_{k=1}^{5} ln(x_j).ln(x_k)) \\
& + \beta_{pt} ln(P)t + \beta_{ptt} ln(P)t^2 + \sum_{j=1}^{5}\beta_{pjt} ln(P).ln(x_j).t + \mu_i + \nu,
\end{aligned}
\tag{4.4}
$$

where β_{pt}, β_{ptt} and β_{pjt} are the effects of industrial water pollution associated with TC. We investigate three types of interactions with TC. First, we compute the interaction effects of P with total TC as: $\beta_{pt} + \beta_{ptt} + \sum_{j=1}^{5}\beta_{pjt}$. Second, we calculate the interaction effects of P with pure technical change as $\beta_{pt} + \beta_{ptt}$. Third, we calculate the interaction effects of P with biased technical change as: $\sum_{j=1}^{5}\beta_{pjt}$. The overall effect of industrial water pollution is $\beta_p + \beta_{pt} + \beta_{ptt} + \sum_{j=1}^{5}\beta_{pjt}$. Finally, β_p is the direct biological effect of P since all other indirect effects of P interacted with the production process are controlled for.

For the estimation, Models 4.2, 4.3 and 4.4 are estimated using the *within* estimator that allows us to control for μ_i. Moreover, if farmers producing within a county experience similar unobservable market conditions or agro-climatic shocks, the random error may be spatially correlated. We address this issue by clustering the errors at the county level.

4.3.2 Farm exposure to industrial water pollution

The farm-specific exposure to industrial water pollution P is our variable of interest. We need first to determine how much a farm is exposed to industrial water pollution. For an accurate measure of industrial water pollution, we follow the literature to focus on two major water pollutants of COD and NH3-N, which have caused severe water pollution in Jiangsu and are under strict monitoring and regulation by the local environmental agency. To calculate the location-specific exposure to water pollution, we first determine water pollution discharged by all polluting firms in the sample county where the farm is located. Specifically, we obtain the longitude and latitude of each polluting firm in the county via the Baidu Map API. The geographical coordinates are used to calculate the shortest distance (d_i) between each polluting firm and the farm[9]. The farm's exposure to industrial water pollution is then calculated as the average water pollution emission (p_i) weighted by the reciprocal distance (w_i) of each firm to the farm.

$$P = \sum_{1}^{n} \frac{p_i}{d_i}, i \in (1, 2, 3 \ldots, n) \tag{4.5}$$

Second, we measure the farm's exposure to industrial water pollution by the total water pollution discharged by all the polluting firms within a radius of distance. Specifically, we selected polluting firms within 10km, 10-20km, 20-30km, and 30-40km from the county center and calculated the total amount of water pollution emitted by the polluting firms within each distance radius (r). It is recorded as $P10, P20, P30$ and $P40$, respectively.

$$P\_r = \sum_{1}^{n} p_i, n \in \{r\} \tag{4.6}$$

4.3.3 The endogeneity of industrial water pollution

The identification of the causal effect of P can be challenged by its endogeneity. P is also a result of industrial activities surrounding rice farming and local environmental regulation. Therefore, P can capture either a negative competition effect between industry and agriculture to attract labor and capital or a positive agglomeration effect due to the presence of industry (e.g., more industry implies more consumers or more infrastructure which also benefits agriculture). We firstly deal with this problem by introducing two control variables of industrial production (i.e., output (I_1) and work hours (I_2)) in Models 4.2, 4.3 and 4.4[10]. These two variables could capture the effects of industry activities on rice farming except for the water pollution effect. In addition, we also control for several farmers' socio-economic

[9] Given the small size of our sample counties, we assume that all farms are located in the center of the sample county

[10] More information on these two variables can be found in Section 4.4 and Table 4.8 in the Appendix.

characteristics, such as the number of plots on the farm, farmer's age, health status, household size, non-agricultural work, and agricultural training. With all these additional controls, we expect to partially address the problem of confounding factors.

Additionally, we use the amount of firm-generated water pollution ($z1$) as the external instrument (IV) for P to eliminate any potential bias resulting from local environmental regulations. It is reasonable to assume that water pollution generated by polluting firms and water pollution released by polluting firms are closely related. While a local environmental agency may have the authority to regulate a firm's water pollution emissions, it is less likely to regulate the process by which water pollution is generated. Thus, the relevance and exclusion restriction requirements of the IV validity should be met in our context.

Finally, the set of IVs used is different according to the model estimated. In Model 4.2, only P is endogenous so we use only $z1$ as the instrument. In Model 4.3, all interaction terms of P with inputs are also assumed to be endogenous so we use $z1$ and their interactions with inputs as instruments. In Model 4.4, all interaction terms of P with TC terms are added and we assume them endogenous. We add $z1$ and their interactions with TC terms in the set of instruments. Table 4.1 gives the list of endogenous variables and their instrumental variables for each model.

Table 4.1: List of endogeneous variables and instrumental variables

	Model 4.2	Model 4.3	Model 4.4
Endogenous variables	P	P $P.\sum_{j=1}^{3} x_j$ $P.(0.5\sum_{j=1}^{3}\sum_{k=1}^{3} x_j x_k)$	P $P.\sum_{j=1}^{3} x_j$ $P.(0.5\sum_{j=1}^{3}\sum_{k=1}^{3} x_j x_k)$ $P.t$ $P.t^2$ $P.t.\sum_{j=1}^{3} x_j$
List of Z variables	$z1$	$z1$ $z1.\sum_{j=1}^{3} x_j$ $z1.0.5(\sum_{j,k=1}^{3} x_j x_k)$	$z1$ $z1.\sum_{j=1}^{3} x_j$ $z1.0.5(\sum_{j,k=1}^{3} x_j x_k)$ $z1.t$ $z1.t^2$ $z1.\sum_{j=1} 3x_j.t$

Note: p: weighted average of industrial water pollution. $z1$: weighted average of water pollution generated by industrial firms. x: the three inputs of rice production (l = labor, c = capital, rc = operating costs), t: time trend.

4.4 Data and descriptive statistics

For the empirical analysis, we combine the agricultural data from the China Rural Fixed Point Survey (CRFPS) with the administrative pollution database of Chinese Environmental Statistics (CES) to create a distinct firm-household level database for Jiangsu between 2011 and 2015. Table 4.8 in the Appendix gives the definitions of the variables used in the study.

4.4.1 Rice farming data

The data on rice farming is derived from the China Rural Fixed Point Survey (CRFPS). The survey is carried out by the Ministry of Agriculture and Rural Affairs (MOARA) of China to gather information on agricultural production (inputs and outputs), non-agricultural activities, and sociodemographic characteristics of households in rural China. For our analysis, only households that participated in rice farming and were surveyed at least twice between 2011 and 2015 (five waves) are retained for analysis. In total, We have about 1,600 observations for 366 households across six sample counties.

Table 4.9 provides descriptive statistics for the rice farming-related variables used in this study. It is worth noting that all input and output variables are normalized by the area devoted to rice farming. On average, the rice farming area is about 3.66 mu (the unit of area used in China; 1 mu = 1/15 ha). Moreover, each household owns 4.29 plots which make each plot even smaller. Regarding the output, we focus on the quantity of rice. The average output of rice farming is about 580 kilograms per mu with a standard deviation of 81.

Inputs for rice farming are in three categories, i.e., labor, capital costs, and expenditures for operating costs [11]. For labor input, farmers in the sample spent roughly 13 working days (both hired labor and family members) per mu, with a standard deviation of 3.74. For the capital costs, fixed assets are estimated at 3,621 yuan per mu with a standard deviation of 14,848 yuan per mu. For the operating costs, farmers spent about 433 yuan per mu for rice farming with a standard deviation of 87 yuan. All variables in monetary value are deflated with the 2011 Consumer Price Index. Regarding household socio-demographic variables, the average age of the household head is 57 years, with a standard deviation of about 10 years. The average level of education is about 7 years, with a standard deviation of 3 years. The average household size is 3.8 people, with a standard deviation of 1.65.

[11] Labor and all operating costs are specifically related to the farm's rice farming but capital costs are related to all agricultural production activities of farmers. In the questionnaire, there is no question related to the possession of fixed assets specifically related to rice farming. Thus if the farmer is engaged in another agricultural activity (e.g., other grain production, cash crops, garden crops, or animal husbandry), capital costs for rice farming may be overestimated.

4.4.2 Industrial water pollution data

Industrial water pollution data are derived from the administrative database of China Environmental Statistics (CES), collected by the Ministry of Ecology and Environment (MEE) of China. The CES database covered major polluting firms in China, which emit approximately 85 percent of the total pollution in China, i.e., Chemical Oxygen Demand (COD), ammonia nitrogen (NH3-N), sulfur dioxide (SO2), industrial smoke and dust, and solid waste. For our study, we focus on COD and NH3-N because these two pollutants are commonly used as indicators of surface water pollution and are strictly monitored by the Chinese government as part of its water environmental regulation. In this study, we weigh each pollutant emitted by a firm by the distance between this firm and the center of the county.

Maps 4.2 and 4.3 in the Appendix present the spatial distribution of industrial water pollution in the six counties. It is worth noting that there is significant heterogeneity in different indicators of industrial water pollution between counties. Finally, Table 4.9 gives descriptive statistics. On average, the emissions of COD (NH3) in a county is 16.58 tons (349.18 kg), with a standard deviation of 13.73 (252.33 kg).

4.5 Econometric results

4.5.1 Effects of industrial water pollution on rice yields

We first present the preliminary graphical evidence of the correlation between industrial water pollution and rice yields. Figure 4.1 provides insights into this relationship. This figure gives the resulting line, along with a confidence interval, of the prediction for rice yields (y) from a linear regression of y on COD and NH3-N respectively. More industrial water pollution is associated with lesser rice yields. Although the relationships displayed cannot be interpreted as a causal link between industrial water pollution and rice yields, they do confirm a negative pattern between industrial water pollution and rice yields.

To estimate the causal relationship between industrial water pollution and rice yield, we run the Translog production function models depicted in Section 4.3. Table 4.2 reports the estimation results. To facilitate the reading, a short version of the results is presented in these tables (without interaction terms). The complete results are presented in Table 4.11 in the Appendix. We implement a step-by-step approach. Column 1 of Table 4.2 reports the estimation of Model 4.2, i.e., only

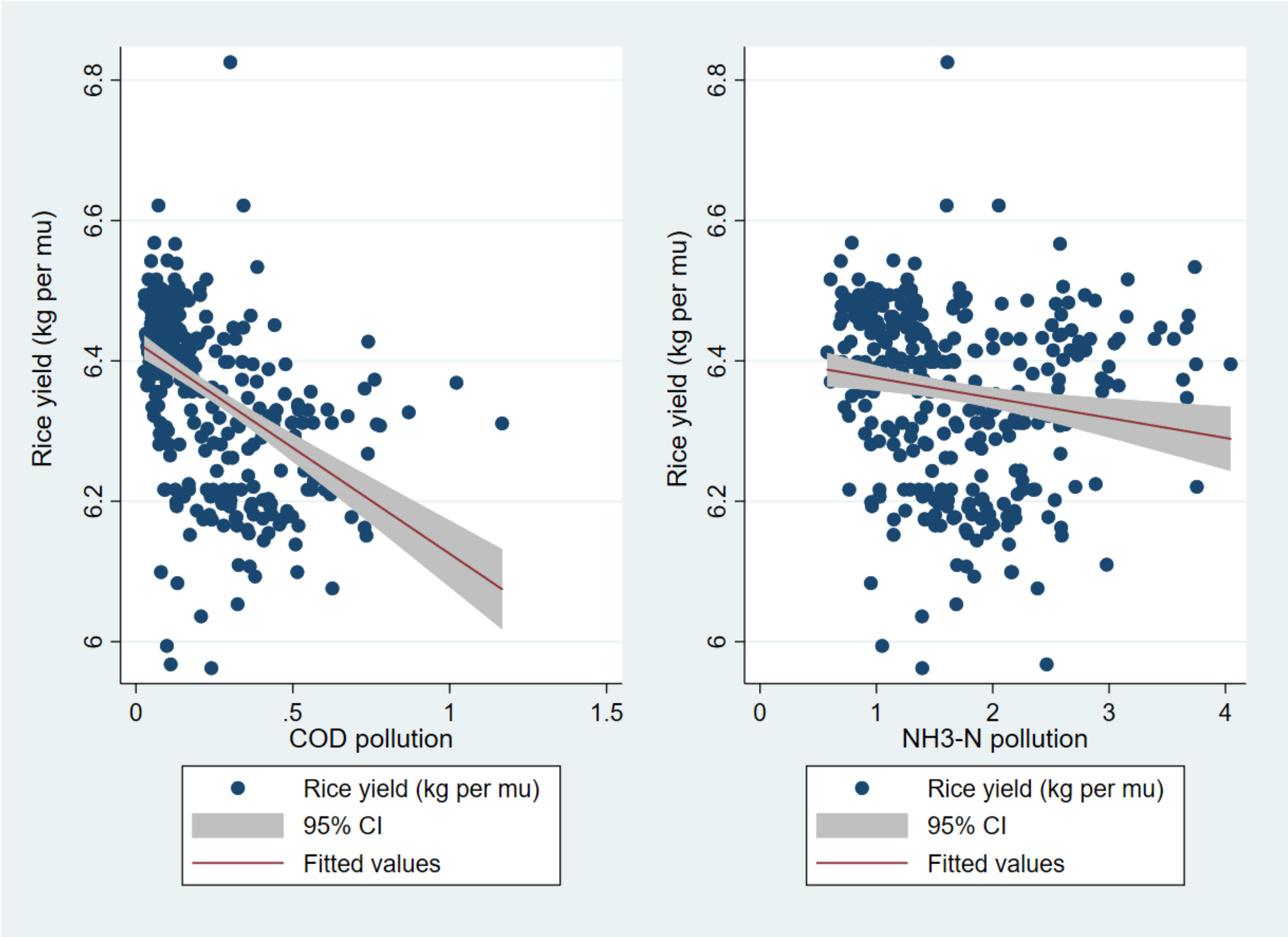


Figure 4.1: COD and NH3-N pollution and rice yield

the additive effect of water pollution without controlling for interactions of water pollution with input uses or technical change (TC) terms. Column 2 reports the estimation of Model 4.3, i.e., Model 4.2 plus interaction effects between water pollution and inputs. The total effect of water pollution through each input is calculated as $\sum_{j=1}^{3} \beta_{pj} + \sum_{j=1}^{3} \sum_{k=1}^{3} \beta_{pjk}$[12]. Column 3 reports the estimation of Model 4.4, i.e., Model 4.3 plus interaction effects between industrial water pollution and technical change (TC) terms. The effect of industrial water pollution through total TC is calculated as $\beta_{pt} + \beta_{ptt} + \sum_{j=1}^{3} \beta_{pjt}$, pure TC as $\beta_{pt} + \beta_{ptt}$ and biased TC as $\sum_{j=1}^{3} \beta_{pjt}$.

In Table 4.2, three results are worth noting. First, COD is found to have a

[12]For instance, the effect of COD associated with labor is the sum of the coefficients associated with variables $p.l$, $p.l^2$, $p.l.c$ and $p.l.rc$.

significant and negative biological effect on rice yield when the interaction effects are controlled for (columns 2 and 3). A one percent increase in COD exposure reduces rice yields by 3.8 (column 3) and 4.2 (column 2) percent. The magnitude of the direct biological effect is substantial and confirms our theoretical hypothesis 1. Second, the effect of industrial water pollution is significantly mitigated through farmers' use of operating costs (columns 2 and 3). In other words, farmers adapt to industrial water pollution by using more operating inputs such as fertilizers and pesticides in rice farming. This result confirms our theoretical hypothesis 2. Third, industrial water pollution also reduces rice yield through farmers' technical change (column 3). This effect suggests that industrial water pollution may discourage farmers to adopt more efficient technology and further reduces rice yield. Therefore, our theoretical hypothesis 3 is confirmed.

Table 4.2: The impact of COD on rice yields

	(1)	(2)	(3)
Dependent variable		Rice yield	
Estimated model	Model 4.2	Model 4.3	Model 4.4
Labor	0.662	3.539	4.106
	(0.595)	(2.505)	(2.313)
Capital	-0.187**	-0.220	-0.489*
	(0.0761)	(0.280)	(0.236)
Operating Costs	3.555***	-1.876	-1.590
	(0.577)	(1.631)	(1.607)
t	0.209**	0.142	1.004*
	(0.0623)	(0.0863)	(0.449)
t2	0.00768	0.00629	0.0560
	(0.00784)	(0.00908)	(0.0514)
COD	0.152	-4.171**	-3.757*
	(0.0861)	(1.647)	(1.692)
Constant	-3.621**	9.239	9.219
	(1.377)	(5.957)	(7.192)
Effect of COD through			
All inputs		0.756	0.654
Labor (l)		-0.821	-0.963
Capital (c)		0.0312	0.116
Operating costs (rc)		1.916**	1.876**
Technical change (TC)			-0.311*
Observations	1,573	1,573	1,573
R-squared	0.391	0.396	0.402
Number of ID	421	421	421
Translog terms	YES	YES	YES
Time*inputs	YES	YES	YES
Pollution*inputs	NO	YES	YES
Pollution*TC	NO	NO	YES
Household FE	YES	YES	YES
Controls	YES	YES	YES

Note: The estimation method is the within regression estimator. The dependent variable is rice production (quantities) per mu. All variables are in logarithms (except t and $t2$). Standard errors in parentheses are clustered at the county level. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. Translog terms not reported are: l^2, c^2, rc^2, l×c, l×rc, c×rc. Technical change (TC) terms not reported are t×l, t×c, and t×rc. Other control variables are industrial output, industrial production, number of plots, the health of the household head, non-agricultural work (days), Out-of-Town Work (days), household size, household head age, and agricultural training.

4.5.2 Farmers' adaptation behaviors

We next estimate the effects of industrial water pollution on farmers' use of inputs to provide direct evidence of farmers' adaptation behaviors. Precisely, we check the effects of industrial water pollution on farmers' use of labor, capital, and operating costs respectively, conditional on the use of other inputs. The estimation results using within estimator are reported in Table 4.3.

As noted in the table, the effects of industrial water pollution on farmers' use of labor and capital are negative but statistically non-significant. In contrast, the effect on the use of operating costs is positive and significant. The results suggest that farmers may adjust their farming behaviors by using more operating inputs such as fertilizer and pesticides to mitigate the negative impact of industrial water pollution on rice yield. By doing so, farmers adapt to the industrial water pollution and the changing rural environment, to maintain the profitability of rice farming.

Table 4.3: Industrial water pollution and farmer inputs use

Dependent variable	(1) Labor	(2) Capital	(3) Operating costs
COD	-0.276	-0.0777	0.340**
	(0.196)	(0.122)	(0.136)
Labor		-0.130	0.722***
		(0.0865)	(0.109)
Capital	-0.0169**		0.0264***
	(0.00541)		(0.00466)
Operating costs	0.748***	0.211	
	(0.0616)	(0.117)	
t	-0.0347	0.123**	0.0986
	(0.0625)	(0.0492)	(0.0552)
t2	0.0182	-0.0286*	-0.0394**
	(0.0150)	(0.0121)	(0.0157)
Constant	-5.080***	8.183**	6.775***
	(0.885)	(2.496)	(1.268)
Observations	1,573	1,573	1,573
R-squared	0.644	0.055	0.659
Number of ID	421	421	421
Household FE	YES	YES	YES
Controls	YES	YES	YES

Note: The estimation method is the within regression estimator. The dependent variable is labor (lnl) in column 1, capital (lnc) in column 2, and operating costs (lnrc) in column 3. All variables are in logarithms. Standard errors in parentheses are clustered at the county level. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. Other controls not reported are industrial output, industrial production, number of plots, the health of the household head, non-agricultural work (days), Out-of-Town work (days), household size, household head age, and agricultural training.

4.5.3 The scope of industrial water pollution

Assuming that the effects of industrial water pollution should decrease by distance, we would like to estimate a distance decay function to shed light on the influence scope of industrial water pollution. Therefore, we calculate the industrial water pollution by the total COD emissions by all industrial firms within a given radius from the center of the county and re-estimate the effects of industrial water pollution in different distances ranging from 5 kilometers to 40 kilometers.

We estimate the Model 4.4 using within estimator and the results are reported in Table 4.4. It is noted that the direct biological effect of industrial water pollution is the most pronounced within 5 kilometers of the county center. As the distance increases, the effect may even turn to be positive, while it becomes non-significant beyond 20 kilometers. However, the indirect effects of industrial water pollution through farmers' use of operating costs remain significant in a much larger distance of up to 30 kilometers. These results have important policy implications. First, industrial firms located within 5 kilometers of agricultural land should be strictly regulated to protect agricultural production from potential industrial pollution. Designation of a protection red line or automatic monitoring of industrial pollution is a possible way to regulate industrial pollution near agricultural land. Second, more environmental education and agricultural extension services should be provided to help farmers to better cope with industrial development nearby and adapt to the changing rural environment.

Table 4.4: The effects of industrial water pollution on rice yield by distance

	(1)	(2)	(3)	(4)	(5)
Dependent variable			Rice yield		
Estimated model	Model 4.4	Model 4.4	Model 4.4	Model 4.4	Model 4.4
Distance radius	5km	5-10km	10-20km	20-30km	30-40km
Labor	0.871	8.031	19.56	6.686	1.419
	(0.942)	(4.158)	(12.19)	(3.560)	(3.924)
Capital	-0.107	-0.725*	-0.953	0.303	0.167
	(0.199)	(0.301)	(1.453)	(0.413)	(0.349)
Operating costs	-1.494	4.164	-8.769*	-3.997	1.218
	(1.001)	(3.117)	(3.982)	(3.014)	(1.575)
t	0.246	1.137	2.530**	1.217*	0.757**
	(0.371)	(0.687)	(0.871)	(0.625)	(0.194)
t2	-0.0150	0.0506	0.0390	-0.0699	0.0385
	(0.0152)	(0.0318)	(0.0489)	(0.0659)	(0.0337)
COD	-7.755***	4.190**	-2.278	-1.886	0.464
	(1.014)	(1.421)	(2.530)	(1.407)	(2.179)
Constant	9.998**	-14.51*	8.148	-3.967	-5.714
	(2.196)	(6.860)	(15.61)	(22.95)	(4.004)
Effect of COD through					
All inputs	1.883***	-1.854**	-0.400	0.227	-0.184
Labor (l)	-0.468	-1.377	-2.016	-0.682	-0.128
Capital (c	0.0805	0.0663	0.0227	-0.0688	-0.0289
Operating costs (rc)	2.440**	0.0363	2.557**	1.362**	0.0460
Technical change (TC)	-0.0731	-0.182	-0.306**	-0.151	-0.160*
Observations	1,236	1,573	1,573	1,573	1,064
R-squared	0.671	0.394	0.412	0.399	0.149
Number of ID	331	421	421	421	275
Translog terms	YES	YES	YES	YES	YES
Time*inputs	YES	YES	YES	YES	YES
Pollution*inputs	YES	YES	YES	YES	YES
Pollution*TC	YES	YES	YES	YES	YES
Household FE	YES	YES	YES	YES	YES
Controls	YES	YES	YES	YES	YES

Note: The estimation method is the within regression estimator. The dependent variable is rice production (quantities) per mu. All variables are in logarithms (except t and $t2$). Standard errors in parentheses are clustered at the county level. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. Translog terms not reported are: l^2, c^2, rc^2, l×c, l×rc, c×rc. Technical change (TC) terms not reported are t×l, t×c, and t×rc. Other controls not reported are industrial output, industrial production, number of plots, the health of the household head, non-agricultural work (days), Out-of-Town work (days), household size, household head age, and agricultural training.

4.5.4 Robustness checks

To ensure the robustness of our results, we implement a battery of robustness checks. First, we re-estimate the models using an alternative measure of industrial water pollution, i.e., NH3-N. The estimation results are reported in Table 4.5.

We still find a strong biological effect of industrial water pollution on rice yields (columns 2 and 3). The effect is even stronger, a one percent increase of NH3-N leads to a reduced rice yield of 6.8 (column 2) and 7.0 (column 3) percent. Similarly, the detrimental effect is mitigated by farmers' operating costs. Taken together, the robust results in Table 4.2 and Table 4.5 highlight that industrial water pollution affects rice yields mainly through the direct biological effect and its interactions with farmers' operation of rice farming.

Table 4.5: The impact of NH3-N on rice yields

	(1)	(2)	(3)
Dependent variable		Rice yield	
Estimated model	Model 4.2	Model 4.3	Model 4.4
Labor	0.451	1.262	2.493
	(0.592)	(6.261)	(5.207)
Capital	-0.190*	2.077**	2.208*
	(0.0844)	(0.677)	(0.940)
Operating costs	3.704***	-12.55*	-12.99*
	(0.585)	(5.924)	(5.356)
t	0.235***	0.128	-1.029
	(0.0594)	(0.0969)	(2.417)
t2	0.00364	0.00231	-0.0916
	(0.00863)	(0.00919)	(0.113)
NH3-N	-0.0412	-6.824**	-6.965**
	(0.104)	(2.175)	(2.236)
Constant	-3.558**	36.33**	36.27**
	(1.318)	(12.74)	(12.90)
Effect of NH3-N through			
All inputs		1.736***	1.662**
Labor (l)		-0.183	-0.301
Capital (c		-0.230**	-0.223*
Operating costs (rc)		2.384*	2.546**
Technical change (TC)			0.166
Observations	1,573	1,573	1,573
R-squared	0.386	0.401	0.408
Number of ID	421	421	421
Translog terms	YES	YES	YES
Time*inputs	YES	YES	YES
Pollution*inputs	NO	YES	YES
Pollution*TC	NO	NO	YES
Household FE	YES	YES	YES
Controls	YES	YES	YES

Note: The estimation method is the within regression estimator. The dependent variable is rice production (quantities) per mu. All variables are in logarithms (except t and $t2$). Standard errors in parentheses are clustered at the county level. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. Translog terms not reported are: l^2, c^2, rc^2, l×c, l×rc, c×rc. Technical change (TC) terms not reported are t×l, t×c, and t×rc. Other control variables are industrial output, industrial production, number of plots, the health of the household head, non-agricultural work (days), Out-of-Town works (days), household size, household head age, and agricultural training.

Next, we address the potential endogeneity of industrial water pollution by implementing the IV estimation. We use COD generation as one external instrument ($z1$) and its interactions with input uses and TC terms to deal with the endogeneity of COD emission as well as for its interactions with input uses and TC terms. Table 4.6 reports the results of the IV estimation. Table 4.10 in the Appendix provides statistical tests of the joint significance of all instruments for each column of Tables 4.6[13].

The robust IV estimation results confirm our previous findings. First, the direct

[13]Note that there are as many instrumentation equations as endogenous variables. For reading convenience, we do not report the estimation results of all the instrumentation equations. They are available upon request.

biological effect of COD emission remains negative and significant while the magnitude is smaller (a reduction of 3.8 percent (col. 2) and 3.5 percent (col. 3)). Second, the farmers' adaptation effects through running costs remain positive and significant. Third, the indirect effects of technical change remain negative and significant. Taken together, the IV estimation results confirm the nexus between industrial water pollution and rice yields. We need to take into account the direct and indirect effects, as well as farmers' adaptation behaviors while estimating the impacts of industrial water pollution on rice farming. Our study highlights the complex relationships between industrial water pollution and rice farming, which deserve more attention and thorough investigations for future studies.

Table 4.6: The impact of COD on rice yields (an IV approach)

	(1)	(2)	(3)
Dependent variable		Rice yield	
Estimated model	Model 4.2	Model 4.3	Model 4.4
Labor	0.710	3.364	4.011*
	(0.512)	(2.216)	(2.093)
Capital	-0.187**	0.0978	-0.178
	(0.0761)	(0.364)	(0.374)
Operating costs	3.523***	-1.750	-1.382
	(0.419)	(2.104)	(1.652)
t	0.203***	0.167***	0.662**
	(0.0729)	(0.0572)	(0.261)
t2	0.00866	0.00493	0.0937**
	(0.00650)	(0.00845)	(0.0421)
COD	0.189	-3.809*	-3.462**
	(0.232)	(2.308)	(1.685)
Effect of COD through			
All inputs		.684	.535
Labor (l)		-.748*	-.824*
Capital (c		-.0832	.00569
Operating costs (rc)		1.905***	1.709***
Technical change (TC)			-.184**
Observations	1,520	1,520	1,520
R-squared	0.391	0.394	0.399
Number of ID	368	368	368
Translog terms	YES	YES	YES
Time*inputs	YES	YES	YES
Pollution*inputs	YES	YES	YES
Pollution*TC	NO	NO	YES
Household FE	YES	YES	YES
Controls	YES	YES	YES
Endogeneity test of COD	0.0237	0.0405	3.740**
Kleibergen-Paap test	20.85***	17.42***	52.64***

Note: The estimation method is the IV within regression estimator. The dependent variable is rice production (quantities) per mu. All variables are in logarithms (except t and t2). Robust standard errors are in parentheses. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. Translog terms not reported are: l^2, c^2, rc^2, l×c, l×rc, c×rc. Technical change (TC) terms not reported are t×l, t×c, and t×rc. Other controls not reported are industrial output, industrial production, number of plots, the health of the household head, non-agricultural work (days), Out-of-Town work(days), household size, household head age, and agricultural training. The endogeneity test is a GMM distance test statistic (H0: COD is exogenous). Kleibergen-Paap test is an under-identification test (H0: the excluded instruments are not correlated with the endogenous regressors).

Finally, to rule out other economic factors confounded with industrial water pollution, we implement a placebo test with wheat yield as an alternative dependent variable. Being different from rice farming, the production of wheat requires much less water in Jiangsu Province. As a result, the effects of industrial water pollution on wheat yield should be minimum or negligible. Any significant effects should be interpreted as confounding effects. We re-estimate the models and report the results in Table 4.7.

As noted in the table, in column 1, the effect of industrial water pollution is significant but positive without accounting for the indirect effects. While taking into account the indirect effects in columns 2 and 3, the effects of industrial water pollution become non-significant. These results confirm the causal effect of industrial water pollution on rice farming and highlight again the importance of accounting for both the direct and indirect effects while estimating the relationship between industrial water pollution and agricultural production.

Table 4.7: The impact of COD on wheat yields

	(1)	(2)	(3)
Dependent variable		Wheat yield	
Estimated model	Model 4.2	Model 4.3	Model 4.4
Labor	2.253***	2.619	4.992**
	(0.299)	(1.772)	(1.524)
Capital	0.208*	0.578	0.508
	(0.0934)	(0.420)	(0.598)
Operating costs	0.302	-0.498	-0.571
	(0.263)	(0.779)	(1.467)
t	-0.0200	-0.0470	-0.851
	(0.110)	(0.0736)	(0.720)
t2	0.0731***	0.0781***	0.277**
	(0.0181)	(0.0176)	(0.113)
COD	0.280**	0.391	1.221
	(0.109)	(1.613)	(2.518)
Constant	-0.966	-1.665	1.132
	(1.259)	(2.753)	(5.974)
Effect of COD through			
All inputs		0.140	-0.662
Labor (l)		0.0296	-0.639*
Capital (c		-0.165	-0.183
Operating costs (rc)		0.137	0.303
Technical change (TC)			0.261
Observations	1,697	1,697	1,697
R-squared	0.339	0.358	0.385
Number of ID	434	434	434
Translog terms	YES	YES	YES
Time*inputs	YES	YES	YES
Pollution*inputs	NO	YES	YES
Pollution*TC	NO	NO	YES
Household FE	YES	YES	YES
Controls	YES	YES	YES

Note: The estimation method is within regression estimator. The dependent variable is wheat production (quantities) per mu. All variables are in logarithms (except t and $t2$). Standard errors in parentheses are clustered at the county level. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%. Translog terms not reported are: l^2, c^2, rc^2, l×c, l×rc, c×rc. Technical change (TC) terms not reported are t×l, t×c, and t×rc. Other controls not reported are industrial output, industrial production, number of plots, the health of the household head, non-agricultural work (days), Out-of-Town work (days), household size, household head age, and agricultural training.

4.6 Conclusion

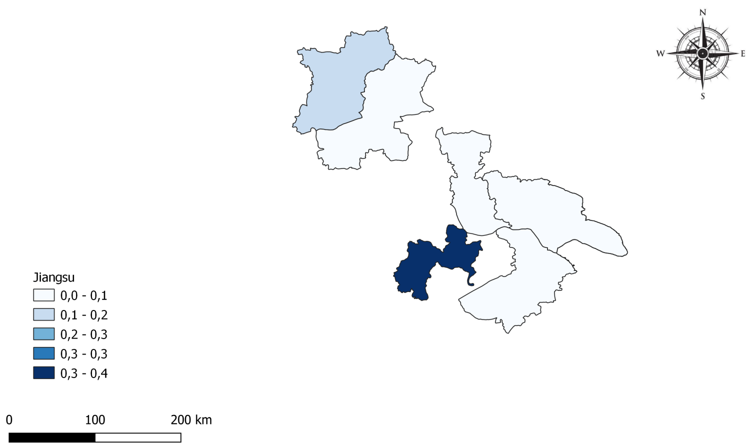
In the past decades, the rapid industrialization of the Chinese economy was accompanied by the relocation of manufacturing industries from urban areas to rural areas, which has caused severe industrial water pollution in rural areas. In this paper, we aim to estimate the impact of industrial water pollution on rice farming in Jiangsu province of China. Using data from the Chinese Environmental Statistics (CES) and the China Rural Fixed Point Survey (CRFPS), we compile the data sets of firm-level industrial water pollution and rice farming at the household level between 2011 and 2015 in Jiangsu province.

We model a Translog production function to isolate the direct effect of industrial water pollution on rice yields from other indirect effects through farmers' inputs use and technical change. In addition, we estimate a distance decay function to determine the influence scope of industrial water pollution. We also implement the IV estimation to address the potential endogeneity problem of industrial water pollution.

Our results confirm that rice yields are negatively impacted by industrial water pollution through a direct biological effect. This detrimental effect is the most significant within a radius of 5 kilometers from the county center. In response, farmers use more operating costs to mitigate the negative impact of industrial water pollution. The change in production behaviors helps farmers to better cope with industrial development and adapt to the changing rural environment.

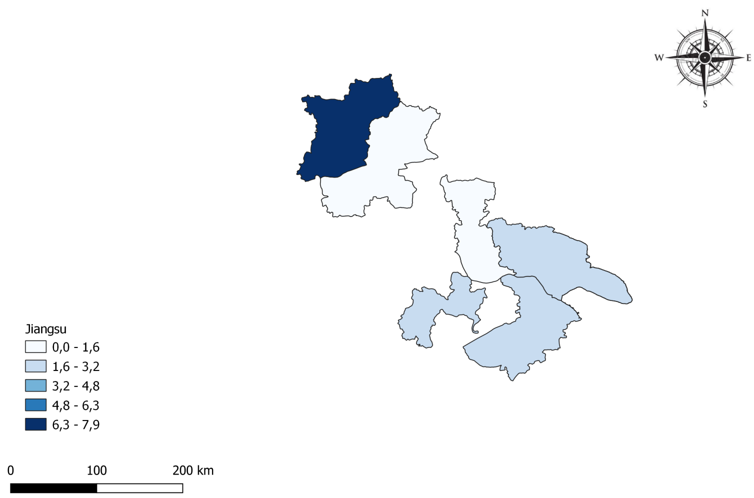
Our study highlights the need to better understand the nexus between industry and agriculture at the local level. While there are positive economic spillover effects of industry on agriculture, negative environmental spillovers such as industrial water pollution should also be taken into account by social planners.

4.7 Appendices of Chapter 4



Source: Authors from database of Chinese Environmental Statistics

Figure 4.2: Exposure to COD emissions of the six counties (in ton per mu)



Source: Authors from database of Chinese Environmental Statistics

Figure 4.3: Exposure to NH3-N emissions of the six counties (in kg per mu)

Table 4.8: Definition and description of variables

Variables	**Definition and description**
Household level rice production variables	
Rice yield (y)	Total rice production over the past 12 months (in kg per mu).
Wheat yield (y)	Total wheat production over the past 12 months (in kg per mu).
Labor (l)	Number of working days (family and hired labor) per mu.
Capital (c)	Original value of fixed assets owned for production (yuan per mu).
Operating costs (rc)	Running costs for rice farming such as seeds, fertilizers, irrigation, pesticides, agricultural plastics, etc.) (yuan per mu).
Plot	Number of plots per household.
Household size	Number of individuals per household.
Age	Age of the household head
Health	Health status of the household head.
Training	If the household head has received any agricultural training.
Non-farm	Number of days in non-farm activities.
Out-of-Town	Number of days for Out-of-Town works.
Village level variables of industrial production	
Industrial output (I_1)	Output in yuan of all industrial firms located in one village.
Industrial production (I_2)	Production in hours of all industrial firms located in one village.
Industrial water pollution (p)	
COD	Chemical Oxygen Demand discharged by firms weighted by the distance between each firm and the center of the village (in tons).
NH3-N	Ammonia nitrogen discharged by firms weighted by the distance between each firm and the center of the village (in kg).

Table 4.9: Descriptive statistics

Variables	Mean	Std. Dev.	Min	Max	Obs.
Rice farming data					
Rice yield (kg/mu)	579.84	81.25	51.67	920	1,573
Wheat yield (kg/mu)	392.82	68.24	18	1166.66	1,573
Labor (in days per mu)	12.73	3.74	0.83	35	1,573
Capital costs (yuan per mu)	3,621.82	14,848.88	0	210,523.73	1,573
Operating costs (yuan per mu)	433	87.18	34.43	1,203.781	1,573
Rice area (in mu, 1 mu = 1/15 ha)	3.66	3.3	0.3	30	1,573
Number of plot	4.29	3.19	1	31	1,573
Health	1.64	1.02	1	5	1,573
Non-farm activities (days)	84.97	127.44	0	355	1,573
Out-of-Town works (days)	54.56	101.53	0	350	1,573
Household size	3.81	1.66	1	9	1,573
Age	56.93	9.39	19	87	1,573
Training	0.06	0.25	0	1	1,573
Industry data					
Industrial output (yuan)	886,994.61	1,533,648.49	13,407	4,288,787	1,573
Industrial production (hours)	60,307.21	23,606.27	22,772	87,482	1,573
COD (tons)	16.58	13.73	4.978	43.143	1,573
NH3 (kg)	349.18	252.33	123.54	1,717.05	1,573

Note: Authors' calculation. Rice farming data comes from the China Household Living Standard Survey. Industry-related pollution data comes from the Chinese Environmental Statistics. See Table 4.8 for definitions of variables.

Table 4.10: First stage of IV regressions

Col. of Tables 4.6	(1)	(2)	(3)
List of endog. variables	P	P $P.\sum_{j=1}^{3} x_j$ $P.(0.5\sum_{j=1}^{3}\sum_{k=1}^{3} x_j x_k)$	P $P.\sum_{j=1}^{3} x_j$ $P.(0.5\sum_{j=1}^{3}\sum_{k=1}^{3} x_j x_k)$ $P.t$ $P.t^2$ $P.t.\sum_{j=1}^{5} x_j$
List of Z variables	$z1$	$z1$ $z1\sum_{j=1}^{3} Z_z.x_j$ $z1.0.5(\sum_{j,k=1}^{3} x_j x_k)$	$z1$ $z1\sum_{j=1}^{3} Z_z.x_j$ $z1.0.5(\sum_{j,k=1}^{3} x_j x_k)$ $z1.t$ $z1.t^2$ $z1.\sum_{j=1}^{3} .x_j.t$
Observations	1,514	1,514	1,514
R-squared	0.404	0.563	0.539
Number of ID	366	366	366
F-stat Z variables	14.96***	8.120***	7.720***

Note: P: COD. $z1$: industrial COD generation. x: the three inputs of rice production (l, c, rc), t: time trend. Number of observations and ID, R-squared and F-stat come from the instrumentation equation (first stage) in which the dependent (endogeneous) variable is P. F-stat reports the joint significance of all Z variables on endogeneous variables p . *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%.

Table 4.11: COD and rice yields - complete results of Table 4.2

	(1)	(2)	(3)
Dependent variable		Rice yield	
Estimated model	Model 4.2	Model 4.3	Model 4.4
l	0.662	3.539	4.106
	(0.595)	(2.505)	(2.313)
c	-0.187**	-0.220	-0.489*
	(0.0761)	(0.280)	(0.236)
rc	3.555***	-1.876	-1.590
	(0.577)	(1.631)	(1.607)
lsq	-0.128**	-0.219	-0.245
	(0.0463)	(0.234)	(0.190)
rcsq	-0.548**	0.563	0.575
	(0.149)	(0.374)	(0.344)
csq	-0.00258	0.00946	0.0129
	(0.00195)	(0.0110)	(0.0128)
l*rc	-0.168	-1.095	-1.217
	(0.224)	(0.883)	(0.803)
l*c	0.0447	0.0994	0.0926
	(0.0275)	(0.115)	(0.0888)
rc*c	0.0506*	0.0208	0.0996
	(0.0214)	(0.119)	(0.0956)
t	0.209**	0.142	1.004*
	(0.0623)	(0.0863)	(0.449)
t2	0.00768	0.00629	0.0560
	(0.00784)	(0.00908)	(0.0514)
l*t	-0.0124	-0.0129	-0.0716
	(0.0169)	(0.0140)	(0.0636)
c*t	-0.00150	-0.00168	0.00385
	(0.00193)	(0.00242)	(0.00726)
rc*t	-0.0271*	-0.0153	-0.155*
	(0.0137)	(0.0172)	(0.0689)
I1	-0.0144	-0.0129	-0.00887
	(0.0138)	(0.0149)	(0.0217)
I2	-0.167**	-0.183**	-0.349
	(0.0549)	(0.0558)	(0.205)
Health	-0.00460	-0.00514	-0.00331
	(0.00724)	(0.00601)	(0.00502)
Plot	-0.00207	-0.00275	-0.00226
	(0.00232)	(0.00188)	(0.00194)
Non-farm	-7.43e-05	-9.18e-05	-0.000113*
	(5.00e-05)	(4.78e-05)	(4.61e-05)
Out-of-Town (income)	7.69e-05	8.47e-05	7.76e-05
	(0.000120)	(0.000121)	(0.000120)
Household size	0.00184	0.00121	0.00417
	(0.00252)	(0.00235)	(0.00287)
Age	0.000395	0.000725	0.000425
	(0.00108)	(0.00112)	(0.00109)
Training	-0.0323	-0.0305	-0.0271
	(0.0224)	(0.0210)	(0.0208)
COD	0.152	-4.171**	-3.757*
	(0.0861)	(1.647)	(1.692)
COD*l		-1.239	-1.434
		(0.791)	(0.795)
COD*c		0.0579	0.179
		(0.138)	(0.119)
COD*rc		1.933**	1.906**
		(0.589)	(0.548)
COD*lsq		0.0469	0.0590
		(0.0724)	(0.0596)
COD*rcsq		-0.406**	-0.424**
		(0.147)	(0.131)
COD*csq		-0.00591	-0.00738
		(0.00492)	(0.00635)
COD*l*rc		0.391	0.430
		(0.277)	(0.269)
COD*l*c		-0.0194	-0.0185
		(0.0407)	(0.0321)
COD*rc*c		-0.00148	-0.0368
		(0.0567)	(0.0456)
COD*t			-0.370
			(0.191)
COD*t2			-0.0225
			(0.0253)
COD*l*t			0.0225
			(0.0198)
COD*c*t			-0.00219
			(0.00267)
COD*rc*t			0.0609*
			(0.0265)
Constant	-3.621**	9.239	9.219

	(1.377)	(5.957)	(7.192)
Effect of COD through ...			
All inputs		0.756	0.654
Labor (l)		-0.821	-0.963
Capital (c)		0.0312	0.116
Operating costs (rc)		1.916**	1.876**
Technical change (TC)			-0.311*
Pure TC (t, t^2)			-0.392*
Biased TC ($t\times$inputs)			0.0812**
Observations	1,573	1,573	1,573
R-squared	0.391	0.396	0.402
Number of ID	421	421	421
Translog terms	YES	YES	YES
Time*inputs	YES	YES	YES
Pollution*inputs	NO	YES	YES
Pollution*TC	NO	NO	YES
Household FE	YES	YES	YES

Note: The estimation method is within regression estimator. The dependent variable is rice production (quantities) per mu. l: labor ; c: capital ; rc: running costs ; I_1 and I_2 : industrial production in yuan and hours. All variables are in logarithm (except t and $t2$). Standard errors in parentheses are clustered at village level. *** statistical significance at 1%, ** statistical significance at 5%, * statistical significance at 10%.

Chapter 5

Conclusion

L'agriculture joue un rôle essentiel dans l'économie des pays en développement où la majeure partie de la population réside en milieu rural et dépend de l'agriculture et des systèmes alimentaires pour leur subsistance. Cette population est par ailleurs confrontée à de nombreux défis.

L'objectif de cette thèse était d'apporter des preuves empiriques sur l'impact de certains grands défis de l'agriculture dans ces pays sur le bien être de la population locale. Pour ce faire, trois études empiriques ont été menées. La conclusion de la thèse revient sur les principaux résultats de ces études puis discute les implications politiques et les limites de celles-ci.

5.1 Résultats principaux

Dans le chapitre 2, notre étude s'est penchée sur l'effet de l'irrigation sur les scores de diversité alimentaires des femmes et des ménages agricoles. L'objectif de cette étude était d'analyser l'impact de l'adoption de l'irrigation sur l'accès à la nourriture dans les zones rurales des pays d'ASS. Pour ce faire, nous avons mis en œuvre une stratégie d'identification basée sur la méthode d'équilibrage de l'entropie. Les résultats obtenus montrent que les ménages ayant recours à l'irrigation présentent des scores de diversité alimentaire plus élevés que ceux n'ayant pas utilisé l'irrigation. De plus, les résultats révèlent également que les femmes au sein des ménages utilisant l'irrigation affichent des scores de diversité alimentaire plus élevés que celles des ménages non-irrigants. Ces résultats s'expliquent par le fait que l'irrigation favorise la culture d'une plus grande variété de cultures, y compris des légumes, des fruits et d'autres cultures riches en nutriments. Par ailleurs, ces conclusions mettent en évidence que l'autonomisation des femmes, l'augmentation du revenu agricole, de la production et l'accès à l'eau représentent les mécanismes potentiels par lesquels l'irrigation contribue à améliorer les scores de diversité alimentaire.

Dans le chapitre 3, nous avons analysé la relation entre la prévalence du paludisme et le travail agricole dans un contexte d'irrigation et d'agriculture familiale en ASS. Dans ce chapitre, nous explorons l'impact du paludisme sur la quantité de travail mesurée en jour-personne par hectare et la productivité mesurée en production récoltée en kilogrammes par jour-personne. L'objectif de cette étude était d'évaluer l'impact du paludisme sur le travail agricole en mettant en lumière certains mécanismes sous-jacents expliquant la relation entre le paludisme et le travail dans l'agriculture familiale africaine. Plus précisément, nous nous sommes concentrée sur l'irrigation et la taille des ménages en tant que deux variables potentielles de modération de l'impact du paludisme sur le travail. D'une part, les résultats obtenus montrent que le paludisme a un impact négatif sur la quantité de travail. Cet effet est un impact direct de la santé dû à la perte de journées de travail en raison de la maladie. Cependant, une fois que le paludisme interagit avec l'irrigation ou la taille du ménage, son effet s'avère insignifiant. Nous expliquons ces résultats par la présence d'un effet modérateur de l'irrigation et de la taille du ménage. En ce qui concerne l'irrigation, nous affirmons qu'il s'agit d'un effet modérateur de richesse liée à l'irrigation. Les parcelles irriguées ont des rendements plus élevés, ce qui peut augmenter les revenus des agriculteurs et leur capacité à acheter des moyens de prévention contre le paludisme. En ce qui concerne la taille du ménage, nous expliquons son effet modérateur comme un effet de compensation grâce à une allocation intra-ménage de la main-d'œuvre. D'autre part, les résultats révèlent que le paludisme augmente la productivité du travail. Nous expliquons ce résultat dans le contexte de l'inefficacité productive de l'agriculture familiale africaine. Il y a de la marge pour augmenter la productivité du travail de telle sorte que les travailleurs en bonne santé peuvent augmenter leur productivité pour compenser l'absence de travailleurs malades. En ce qui concerne l'effet modérateur de l'irrigation, nous constatons un impact négatif de l'interaction du paludisme avec l'irrigation, bien que peu de résultats soient robustes. Nous expliquons ce résultat par un effet d'exposition car les ménages possédant des parcelles irriguées sont plus exposés au paludisme. Dans l'ensemble, nos résultats mettent en évidence que le paludisme demeure une contrainte dans l'agriculture familiale en Afrique. Plus intéressant encore, son impact sur le travail agricole est complexe et dépend des types de travail (familial, salarié), des pratiques agricoles et de la composition des ménages.

Dans le chapitre 4 nous avons étudié l'impact de la pollution industrielle de l'eau sur la production de riz dans la province du Jiangsu, en Chine. Plus précisement, cette étude visait à démêler cette relation complexe en utilisant un modèle de fonction de production translog. Ce modèle nous permet de séparer les effets directs de la pollution industrielle de l'eau sur la riziculture de ses effets d'adaptation. Les résultats obtenus confirment que les rendements du riz sont négativement affectés par la pollution de l'eau industrielle, en raison d'un effet biologique direct. Cet effet préjudiciable est le plus significatif dans un rayon de 5 kilomètres du centre du comté. En réponse, les agriculteurs utilisent davantage d'intrants tels que les engrais et les pesticides pour atténuer l'impact négatif de la pollution de l'eau industrielle. Le changement dans les comportements de production aide les agriculteurs à mieux faire face au développement industriel et à s'adapter à l'évolution de l'environnement rural.

5.2 Les implications politiques

Les résultats de cette thèse offrent plusieurs recommandations politiques. Ces recommandations ont pour objectif d'orienter les décideurs politiques, les praticiens et les acteurs du développement dans la mise en œuvre des mesures pratiques pour résoudre les défis complexes auxquels sont confrontés les ménages ruraux.

Tout d'abord, les résultats mettent en évidence l'importance de promouvoir l'adoption de l'irrigation pour renforcer la sécurité alimentaire dans les zones rurales des pays en développement. Il serait avantageux d'envisager des incitations financières, telles que des subventions ou des prêts à taux préférentiels, pour soutenir les investissements des agriculteurs dans des infrastructures d'irrigation. De plus, la formation technique des agriculteurs sur les pratiques d'irrigation efficaces, y compris la gestion de l'eau, la planification des cultures et l'entretien des systèmes d'irrigation, serait essentielle.

Ensuite, les résultats soulignent l'importance cruciale du rôle des femmes dans la sécurité alimentaire. Les politiques doivent mettre l'accent sur l'autonomisation des femmes dans le processus d'adoption de l'irrigation. Cela pourrait être réalisé grâce à des programmes visant à renforcer la participation des femmes dans les prises de décisions liées à l'agriculture et et à leur accorder un meilleur accès aux ressources agricoles. Cette approche contribuerait à renforcer la sécurité alimentaire.

Par ailleurs, étant donné que le paludisme est l'une des principales causes de morbidité et de mortalité dans les régions rurales des pays d'ASS, entravant ainsi le développement du secteur agricole, il est impératif que les décideurs politiques intensifient leurs investissements dans ce secteur. Ces investissements pourraient inclure la mise en place de programmes de distribution de moustiquaires imprégnées d'insecticide, le déploiement de campagnes de sensibilisation sur la prévention du paludisme, et le renforcement des systèmes de soins de santé dans les zones agricoles. De plus, des fonds spécifiques pourraient être alloués au développement des infrastructures d'irrigation, accompagnés de mesures de contrôle appropriées telles que la maintenance régulière des systèmes d'irrigation, la formation des agriculteurs aux pratiques agricoles durables et la création de coopératives agricoles. Cette approche intégrée vise à garantir un fonctionnement efficace des systèmes d'irrigation et permettrait de réduire considérablement le risque de paludisme, tout en augmentant la productivité agricole.

Enfin, la transition vers une économie plus industrielle dans les pays en développement suscite des questions et des préoccupations légitimes, en particulier en ce qui concerne la pollution de l'eau. Les résultats soulignent ainsi la nécessité de mieux comprendre le lien entre l'industrie et l'agriculture au niveau local. Il serait bénéfique que les autorités locales intensifient leurs actions pour renforcer les réglementations environnementales strictes en vue de réduire la pollution de l'eau. Cette mesure contribuera à la préservation des ressources hydriques essentielles à l'agriculture et au maintien de la productivité agricole.

5.3 Limites de nos recherches et perspectives

Les différentes analyses effectuées dans cette thèse, comme toute étude, présentent certaines limites. Tout d'abord, ces travaux de recherche pourraient être étendus en utilisant les données d'enquête sur une période plus longue, si disponibles, pour examiner les tendances au fil du temps. Par exemple les chapitres utilisent des données sur une période rélativement courte. Dans les chapitres 2 et 3, nous avons réalisé des études en nous concentrant sur huit pays d'ASS. Il serait peut-être intéressant de mener des analyses spécifiques pour chaque pays, ce qui permettrait d'obtenir des recommandations politiques plus ciblées.

Le chapitre 2 aborde la question de la sécurité alimentaire en utilisant les scores de diversité alimentaire comme indicateur de l'accès à la nourriture. Cependant, la sécurité alimentaire est un concept multidimensionnel, et nos analyses pourraient être approfondies en utilisant d'autres indicateurs que ceux que nous avons utilisés comme variables dépendantes. Par exemple, la création d'un indice synthétique de sécurité alimentaire prenant en compte toutes ses dimensions pourrait être envisagée. De plus, étant donné les répercussions négatives de la pandémie de COVID-19 sur la sécurité alimentaire, en particulier dans les pays en développement, il serait pertinent que des recherches futures intègrent cette pandémie en tant que variable de contrôle lorsque les données seront plus accessibles

Le chapitre 4 se concentre sur la province du Jiangsu en Chine. Les résultats obtenus peuvent ne pas être directement généralisables à d'autres régions, en raison des variations considérables dans les conditions environnementales et économiques. Ainsi, des travaux futurs pourraient élargir cette analyse en examinant plusieurs régions de la Chine ou d'autres pays. De plus, des études ultérieures pourraient se pencher sur les solutions d'atténuation de la pollution de l'eau industrielle et évaluer leur efficacité pour préserver la productivité agricole.

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Chapter 6

RÉSUMÉ EXTENSIF EN FRANÇAIS

6.1 Contexte : les défis de la population rurale dans les pays en développement

L'agriculture occupe une place prépondérante dans l'économie des pays en développement. Environ 3,4 milliards de personnes résident dans les zones rurales de ces pays et la plupart d'entre elles dépendent de l'agriculture et des systèmes alimentaires pour leur subsistance (UNDESA, 2021). Selon le rapport "Perspectives agricoles de l'OCDE et de la FAO", le secteur contribue à 10% du PIB en 2023 et emploie plus de 70% de la population active de ces pays (OCDE and FAO, 2023). Les ménages ruraux sont confrontés à de nombreux défis tels que le changement climatique, la pauvreté, la dégradation de l'environnement ou l'insécurité alimentaire.

L'insécurité alimentaire est l'un des défis les plus pressants de ces pays. Selon l'Organisation des Nations unies pour l'alimentation et l'agriculture, environ 42,7% de la population rurale de ces pays souffraient d'insécurité alimentaire modérée ou grave en 2022 (FAO et al., 2023). Face à cette insécurité alimentaire élevée dans ces zones où la production agricole reste principalement pluviale, l'irrigation est fortement encouragée afin de garantir la sécurité alimentaire, de préserver les moyens de subsistance des agriculteurs et de réduire leur vulnérabilité face aux aléas pluviométriques (Okyere and Usman, 2021; Passarelli et al., 2018; Mekonnen et al., 2022). Cependant, en dépit des avantages de l'irrigation qui permet d'augmenter les rendements agricoles, l'irrigation engendre également des externalités négatives, en particulier sur l'environnement et la santé des communautés rurales. En effet, l'irrigation est un facteur de risque de propagation des maladies comme le paludisme qui reste un problème de santé mondial dans les pays en développement où elle est la sixième cause de décès (WHO, 2022).

En plus, il est important de noter que l'industrialisation rurale est un phénomène en expansion dans ces pays. Elle englobe l'introduction de technologies et de

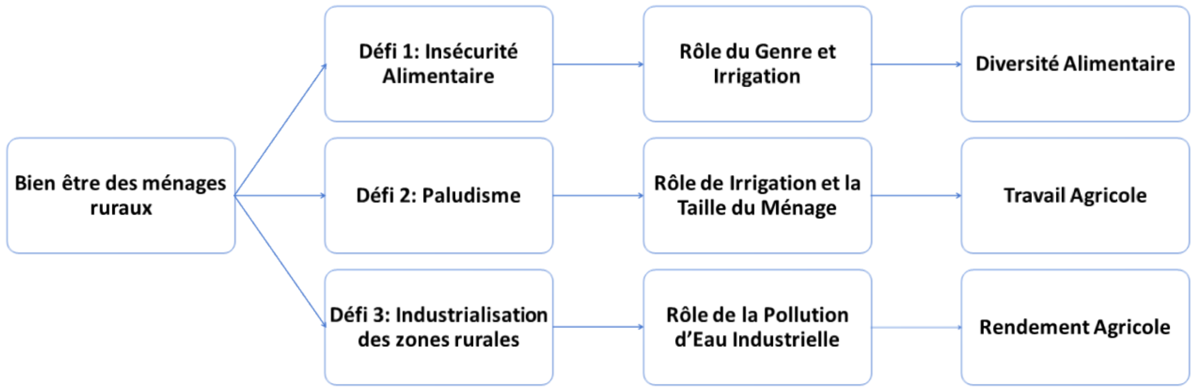

Figure 6.1: Cadre conceptuel pour analyser les impacts des défis sur le bien être de la population rurale

pratiques industrielles dans les régions rurales. Cependant, cette transition vers une économie plus industrielle suscite des préoccupations, notamment en ce qui concerne la pollution de l'eau, qui peut avoir des répercussions significatives sur la préservation de l'environnement rural et le développement agricole durable.

Ces défis s'inscrivent en complémentarité avec d'autres enjeux tels que le réchauffement climatique, les sécheresses et les inondations, dans un contexte de pauvreté au sein de la population locale.

Cette thèse porte sur la compréhension des conséquences de certains de ces défis sur des aspects importants contribuant au bien-être de la population rurale tels que la diversité alimentaire, le travail agricole et les rendements agricoles. La Figure 6.1 illustre schématiquement l'approche analytique de notre travail. Dans la section suivante, nous presenterons les différents défis liés à l'agriculture que nous étudions.

6.1.1 L'insécurité alimentaire

La sécurité alimentaire est considérée comme l'un des enjeux majeurs du monde actuel. L'expression "sécurité alimentaire" a été introduite en 1974 lors de la Conférence mondiale de l'alimentation, en réponse aux famines au Sahel et au Darfour, et était largement considérée comme un problème de production alimentaire insuffisante et instable (Maxwell, 1996). En 1996, lors du Sommet Mondial de l'Alimentation, la définition de la sécurité alimentaire s'affine : "la sécurité alimentaire existe lorsque toutes les personnes, à tout moment, ont un accès physique et économique à une nourriture suffisante, sûre et nutritive qui répond à leurs besoins et à leurs préférences alimentaires pour mener une vie active et saine". La part de la population mondiale n'ayant pas cet accès se trouve en insécurité alimentaire.

Au cours de ces dernières décennies la faim et l'insécurité alimentaire ont continué à être au centre de la plupart des débats à l'échelle mondiale. Ainsi, plusieurs sommets des Nations Unies sur les objectifs mondiaux de développement visent à améliorer la vie des personnes dans le monde entier en mettant un fort accent sur l'élimination de la faim, l'assurance de la sécurité alimentaire, l'amélioration de la nutrition et la promotion d'une agriculture durable. Lors de la dernière conférence de l'ONU pour l'alimentation et l'agriculture qui s'est déroulée à New York en 2023, les dirigeants mondiaux et les organisations internationales ont réaffirmé, qu'il leur faut amplifier et mieux cibler leurs actions, faute de quoi l'objectif d'éliminer la faim, l'insécurité alimentaire et la malnutrition sous toutes ses formes d'ici à 2030 restera hors de portée.

Or, malgré les récents efforts déployés pour améliorer la sécurité alimentaire, la sous-alimentation et l'insécurité alimentaire persistent et touchent encore des milliards de personnes dans le monde, en particulier les femmes et les personnes vivant en zone rurale des pays en développement. En 2022, le rapport de l'ONU pour l'alimentation et l'agriculture a révélé que 9,2% de la population mondiale était confrontée à la faim chronique contre 7,9% en 2019, soit une augmentation de plus de 1,3% (FAO et al., 2023). De plus, environ 2,4 milliards de personnes, soit 29,6% de la population mondiale (dont 42,7% vivent dans les zones rurales des pays en développement), ont connu une insécurité alimentaire modérée à grave, ce qui signifie qu'elles n'avaient pas un accès régulier à une alimentation adéquate. Cette hausse peut être attribuée à la pandémie de covid-19, aux conflits, aux changements climatiques et aux inégalités croissantes qui ont eu des effets négatifs sur la sécurité alimentaire dans le monde.

Selon le dernier rapport de la FAO, la sous-alimentation et l'insécurité alimentaire restent l'un des problèmes majeurs principalement en Afrique subsaharienne (ASS) qui compte la plus grande part de population souffrant de la faim (22,5% de la population) et d'insécurité alimentaire modérée ou grave (67,2% de la population) en 2022 (FAO et al., 2023). Ainsi, la recherche autour de la sécurité alimentaire est indispensable pour que tous les individus puissent être en bonne santé et développer leur plein potentiel. L'objet d'une partie de cette thèse est de contribuer à ce débat en mettant en avant le rôle de l'irrigation et du genre.

6.1.2 Le paludisme

Le paludisme demeure l'un des principaux défis en matière de santé publique à l'échelle mondiale, provoquant un nombre significatif de décès et d'invalidité, en particulier parmi les ménages ruraux des pays en développement où l'agriculture est la principale source de revenus. Selon un rapport récent de l'Organisation mondiale de la Santé sur le paludisme, environ 247 millions de cas de paludisme et 619 000 décès ont été attribués à cette maladie en 2021 (WHO, 2022). Le risque de contracter le paludisme demeure élevé dans les pays à faible revenu où il figure en sixième position parmi les principales causes de décès. L'Afrique subsaharienne (ASS) est particulièrement touchée, représentant environ 95 % des cas de paludisme et 96 % des décès liés à cette maladie dans le monde en 2020 (WHO, 2021). Au fil des décennies, les pays d'ASS ont mis en œuvre divers outils et stratégies de prévention, notamment une lutte efficace contre les vecteurs du paludisme et l'utilisation de médicaments antipaludiques préventifs. Ces mesures ont entraîné une réduction significative du nombre de décès liés au paludisme comme indiqué dans l'étude de Bhatt et al. 2015. Cependant, le nombre de cas de paludisme reste important comme évoqué précédemment dans ces pays où l'agriculture joue un rôle central dans leur développement économique. La relation entre le paludisme et l'agriculture a en effet suscité une attention considérable dans la littérature. D'une part, plusieurs études ont montré qu'un mauvais état de santé des ménages agricoles liée au paludisme réduit les rendements agricoles et les revenus en diminuant la productivité du travail et en faisant perdre des journées de travail à cause de la maladie (Strauss and Thomas, 1998; Audibert et al., 2003; Asenso-Okyere et al., 2011; Iheke and Ukaegbu, 2015). D'autre part, certains auteurs trouvent que certains projets et pratiques de développement agricole peuvent avoir des effets négatifs sur la santé. L'agriculture intensive, due aux systèmes d'irrigation, peut provoquer, par exemple, des maladies d'origine hydrique, telles que le paludisme. En effet, une augmentation de l'eau stagnante associée à l'irrigation, en particulier lorsque les systèmes sont mal gérés, peut servir de terrain de reproduction aux vecteurs de maladies, notamment les moustiques anopheles, et contribuer à une augmentation du paludisme et d'autres maladies. Cependant, certaines études ont montré que l'irrigation n'était pas ou peu associée à une prévalence accrue du paludisme (Audibert et al., 2007; Assi et al., 2013). Ainsi, l'un des objectifs de cette thèse est d'apporter une contribution à ce débat en mettant en lumière certains mécanismes sous-jacents expliquant la relation entre le paludisme et le travail dans l'agriculture familiale africaine.

6.1.3 L'industrialisation des zones rurales

L'essor de l'industrialisation rurale dans les pays en développement est un phénomène en rapide expansion et est souvent considéré comme une phase inévitable de leur développement économique. Alors que ces pays s'efforcent de diversifier leur économie et d'améliorer les conditions de vie de la population rurale, la croissance des industries et des activités non agricoles dans les zones rurales est devenue une priorité. L'industrialisation rurale est un processus qui consiste à introduire des technologies et des pratiques industrielles dans les zones rurales. Néanmoins, cette transition vers une économie plus industrielle soulève des questions et des préoccupations légitimes, en particulier en ce qui concerne la pollution de l'eau.

L'expansion industrielle dans les regions rurales peut entraîner une augmentation de la demande en eau à des fins industrielles et provoquer des rejets de polluants industriels dans les systèmes d'eau locaux. Cette réalité a un impact direct sur la qualité de l'eau utilisée pour l'irrigation agricole, ce qui a des répercussions sur les rendements des cultures. Malheureusement, l'industrialisation se produit souvent en l'absence de réglementations environnementales strictes et correctement appliquées, exposant ainsi les sources d'eau à une contamination potentiellement dévastatrice. Cette contamination peut avoir des effets significatifs sur la préservation de l'environnement rural et le développement agricole durable.

La pollution de l'eau résultant de ces activités industrielles peut contenir des produits chimiques toxiques, des métaux lourds et des contaminants organiques, autant de composants susceptibles de nuire aux cultures et de rendre les sols moins propices à la production. De plus, les polluants présents dans l'eau industrielle peuvent compromettre la santé des plantes, entraînant ainsi une réduction des rendements agricoles. Cette situation met en évidence l'urgence de la mise en place de réglementations environnementales rigoureuses dans les zones rurales afin de concilier la croissance durable de l'industrie et le secteur agricole, tout en préservant les ressources en eau essentielles à l'agriculture.

Diverses études et recherches menées dans des pays en développement ont mis en lumière les conséquences néfastes de l'industrialisation rurale sur l'agriculture. Par exemple, une étude menée en Inde a révélé que la pollution industrielle de l'eau a des impacts négatifs et significatifs sur les rendements agricoles, les terres cultivées, le bétail (en raison de l'eau contaminée), l'emploi rural et la santé humaine des résidents du village touché (Reddy and Behera, 2006). De même, des recherches menées par Yongguan et al. 2001 ont évalué l'impact de la pollution industrielle sur l'agriculture, la santé humaine et les activités industrielles à Chongqing, l'une des mégalopoles les plus polluées de Chine. Ils ont estimé que les coûts totaux de la pollution industrielle représentaient 1,2% du produit brut de Chongqing. Sur ce montant, 56 % concernent le secteur agricole, tandis que les dommages causés au capital humain et au secteur industriel représentent respectivement 20 % et 18 %. Ces études révèlent que la pollution industrielle impose des coûts importants aux autres secteurs connexes d'une économie.

L'industrialisation rapide dans les pays en développement, bien qu'ayant contribué au développement économique, a eu des conséquences significatives sur le bien-être économique. Ces répercussions se manifestent à travers les effets néfastes qu'elle a générés sur les activités agricoles, la santé humaine et l'écosystème dans son ensemble, y compris les problèmes de pollution de l'air et de l'eau. En particulier, la pollution de l'eau représente un défi majeur en raison de son impact sur un large éventail d'activités économiques.

La question de la pollution de l'eau revêt une importance accrue dans le contexte d'une économie largement axée sur l'agriculture, en particulier dans les zones rurales des pays en développement. C'est dans ce contexte que cette thèse se penche sur l'analyse des impacts de la pollution de l'eau d'origine industrielle émanant des entreprises manufacturière sur la production agricole. Cette analyse vise à mieux comprendre comment cette pollution affecte la production agricole et, par conséquent, le bien-être économique des communautés rurales.

6.2 Contribution de la thèse

Cette thèse se concentre sur les enjeux liés à l'agriculture et apporte une contribution significative au débat politique concernant la compréhension globale des défis complexes auxquels sont confrontés les ménages ruraux. En combinant des perspectives géographiquement et thématiquement diverses, elle examine tout d'abord l'impact de l'accès à l'irrigation sur la diversité alimentaire et propose des solutions visant à favoriser à la fois la production de cultures diversifiées et la sécurité alimentaire. Puis, elle examine la relation entre le paludisme et le travail agricole dans un contexte d'irrigation. Enfin, elle se penche sur l'impact de la pollution des eaux industrielles sur la production de riz. Ce faisant, cette thèse se situe à la croisée de l'économie de la famille, l'économie de la santé et l'économie agricole.

Plus spécifiquement, le chapitre 2 analyse les effets de l'irrigation sur le scores de diversité alimentaires des femmes et des ménages agricoles. L'analyse porte sur les pays d'ASS, en particulier les pays de l'Union Economique et Monétaire Ouest Africaine (UEMOA) où la part de la population souffrant d'insécurité alimentaire modérée à grave est très élevée. Notre stratégie d'identification est basée sur la méthode d'équilibrage de l'entropie développé par Hainmueller 2012. Cette analyse met en évidence comment les pratiques d'irrigation peuvent influencer la disponibilité de divers types de cultures, en utilisant une base de données récente sur l'enquête harmonisée sur les conditions de vie des ménages dans plusieurs pays d'ASS. Ce chapitre enrichit la littérature en mettant en lumière l'importance de la diversité alimentaire pour les femmes, ce qui peut contribuer à la réduction de la malnutrition et à la prévention de carences nutritionnelles, avec des effets bénéfiques sur la santé maternelle et infantile. Les résultats démontrent que les ménages ayant recours à l'irrigation présentent des scores de diversité alimentaire plus élevés que ceux n'ayant pas utilisé l'irrigation. De plus, les résultats révèlent également que les femmes au sein des ménages utilisant l'irrigation affichent des scores de diversité alimentaire plus élevés que ceux des femmes des ménages non-irrigants. Ces résultats s'expliquent par le fait que l'irrigation favorise la culture d'une plus grande variété de cultures, y compris des légumes, des fruits et d'autres cultures riches en nutriments. Cela contribue à la diversification de l'alimentation des ménages ruraux, ce qui est essentiel pour garantir un apport varié en nutriments essentiels dans l'alimentation des femmes et de leurs familles. Par ailleurs, l'irrigation permet d'accroître la production agricole en permettant de cultiver en dehors de la saison des pluies et d'obtenir deux à trois récoltes par an. Cela permet ainsi d'améliorer la sécurité alimentaire en assurant un accès plus constant à une variété d'aliments tout au long de l'année. L'irrigation réduit également la dépendance à l'égard des précipitations pluviales, rendant la production agricole moins vulnérable aux sécheresses et aux variations climatiques, ce qui renforce la sécurité alimentaire et la résilience face aux changements climatiques. Ainsi, ce chapitre met en évidence comment l'irrigation a un impact significatif sur la diversité alimentaire

Le chapitre 3 se focalise sur la relation entre la prévalence du paludisme et le travail agricole dans un contexte d'irrigation et d'agriculture familiale en ASS. Dans ce chapitre, nous explorons l'impact du paludisme sur le travail agricole en utilisant deux mesures distinctes. Plus précisément, nous examinons la quantité de travail mesurée en jour-personne par hectare et la productivité mesurée en production récoltée en kilogrammes par jour-personne. Ce chapitre contribue à la littérature existante sur la relation entre les maladies endémiques et l'agriculture de plusieurs manières. Tout d'abord, notre étude évalue l'impact du paludisme sur le travail agricole en mettant en lumière certains mécanismes sous-jacents expliquant la relation entre le paludisme et le travail dans l'agriculture familiale africaine. Plus spécifiquement, nous nous sommes concentrés sur l'irrigation et la taille des ménages en tant que deux variables modératrices potentielles de l'impact du paludisme sur le travail. En effet, nous nous penchons sur l'irrigation car elle constitue un facteur contextuel important dans la propagation du paludisme, mais elle peut également aider les agriculteurs à accroître leur production, à augmenter leurs revenus et à acquérir des outils de prévention et de contrôle du paludisme. Ainsi, les systèmes d'irrigation peuvent jouer un rôle de variable modératrice à la fois positif et négatif dans l'effet du paludisme sur le travail. En outre, les ménages de notre enquête sont principalement engagés dans l'agriculture familiale et rencontrent des difficultés d'accès aux marchés des intrants agricoles ou aux services de vulgarisation. Pour ces ménages, le travail familial est souvent le meilleur moyen de compenser les chocs tels que la maladie. L'allocation intra-ménage de la main-d'œuvre peut ainsi contribuer à faire face à la maladie affectant les membres de la famille. Les ménages de grande taille devraient mieux pouvoir compenser l'absence de travailleurs malades que les ménages de petite taille. Deuxièmement, alors que la plupart des études se limitent à analyser l'effet du paludisme dans un pays, cette étude complète ces études spécifiques à chaque pays en fournissant des preuves de l'effet causal du paludisme sur le travail agricole à partir de données récentes sur l'enquête harmonisée sur les conditions de vie des ménages dans les huit pays de l'UEMOA. Pour ce faire, nous utilisons la methode des variables instrumentales en utilisant les moustiquaires imprégnées d'insecticide et l'utilisation d'insecticides et de spirales en tant qu'instruments externes. Les résultats montrent que le paludisme a un impact négatif sur la quantité de travail. Cet effet est un impact direct sur la santé dû à la perte de journées de travail en raison de la maladie. Cependant, une fois que le paludisme interagit avec l'irrigation ou la taille du ménage, son effet s'avère insignifiant. Nous expliquons ces résultats par la présence d'un effet modérateur de l'irrigation et de la taille du ménage. En ce qui concerne l'irrigation, nous affirmons qu'il s'agit d'un effet modérateur de richesse. Les parcelles irriguées ont des rendements plus élevés, ce qui peut augmenter les revenus des agriculteurs et leur capacité à acheter des moyens de prévention contre le paludisme. En ce qui concerne la taille du ménage, nous expliquons son effet modérateur comme un effet de compensation grâce à une allocation intra-ménage de la main-d'œuvre. D'autre part, les résultats révèlent que le paludisme augmente la productivité du travail. Nous expliquons ce résultat dans le contexte de l'inefficacité productive de l'agriculture familiale africaine. Il y a de la marge pour augmenter la productivité du travail de telle sorte que les travailleurs en bonne santé peuvent augmenter leur productivité pour compenser l'absence de travailleurs malades. En ce qui concerne l'effet modérateur de l'irrigation, nous constatons un impact négatif (peu robuste) de l'interaction du paludisme avec l'irrigation. Nous expliquons ce résultat par un effet d'exposition car les ménages possédant des parcelles irriguées sont plus exposés au paludisme que ceux n'ayant pas de parcelles irriguées. Dans l'ensemble, nos résultats mettent en évidence que le paludisme demeure un problème dans l'agriculture familiale en Afrique. Plus intéressant encore, son impact sur le travail agricole est complexe et dépend des types de travail, des pratiques agricoles et de la composition des ménages. Il est important de garder à l'esprit que la promotion des systèmes d'irrigation doit s'accompagner de mesures de contrôle appropriées (comme la maintenance systématique des canaux d'irrigation) et, en même temps, de la promotion du contrôle du paludisme, de l'information sur la prévention et du système de prestation de services de santé.

Le chapitre 4 se penche sur la question de l'industrialisation des zones rurales. Plus explicitement, il analyse l'impact de la pollution industrielle de l'eau sur la production de riz dans la province du Jiangsu, en Chine. Jiangsu est classée comme la troisième province chinoise ayant les rejets d'effluents d'eaux usées les plus élevés en 2015 selon Chen et al. 2019. Pour estimer l'impact de la pollution de l'eau industrielle sur la culture du riz, nous utilisons les données agricoles de l'enquête sur les points fixes ruraux en Chine (CRFPS) que nous combinons avec la base de données administratives complète des statistiques environnementales chinoises (CES) pour construire une base de données associant entreprises industrielles et ménages ruraux. Notre recherche se concentre spécifiquement sur la demande chimique en oxygène (DCO) et l'azote ammoniacal (NH3-N) car ces deux polluants sont couramment utilisés comme indicateurs de la pollution des eaux de surface et sont strictement surveillés par le gouvernement chinois dans le cadre de sa réglementation sur l'environnement aquatique. L'exposition des agriculteurs à la pollution de l'eau industrielle est ensuite calculée en utilisant la moyenne de la pollution de l'eau provenant des entreprises polluantes, pondérée en fonction de la distance de l'entreprise par rapport au centre du comté. L'objectif de cette étude est d'enrichir la littérature sur la relation entre la pollution industrielle de l'eau et l'agriculture dans les pays en développement. Alors que la plupart des études dans la littérature se concentrent sur la manière dont la pollution de l'air affecte les activités agricoles, la problématique de la pollution de l'eau est rarement examinée. Notre étude vise à démêler cette relation complexe en utilisant un modèle de fonction de production translog. Ce modèle nous permet de séparer les effets directs de la pollution industrielle de l'eau sur la riziculture de ses effets d'adaptation. Nos résultats confirment que les rendements du riz sont négativement affectés par la pollution de l'eau industrielle, en raison d'un effet biologique direct. Cet effet préjudiciable est le plus significatif dans un rayon de 5 kilomètres du centre du comté. En réponse, les agriculteurs utilisent davantage d'intrants tels que les engrais et les pesticides pour atténuer l'impact négatif de la pollution de l'eau industrielle. Le changement dans les comportements de production aide ainsi les agriculteurs à mieux faire face au développement industriel et à s'adapter à l'évolution de l'environnement rural. Ainsi, notre étude met en évidence la nécessité de mieux comprendre le lien entre le développement de l'industrie et l'agriculture au niveau local.

6.3 Les implications politiques

Les résultats de cette thèse offrent plusieurs recommandations politiques. Ces recommandations ont pour objectif d'orienter les décideurs politiques, les praticiens et les acteurs du développement dans la mise en œuvre des mesures pratiques pour résoudre les défis complexes auxquels sont confrontés les ménages ruraux.

Tout d'abord, les résultats mettent en évidence l'importance de promouvoir l'adoption de l'irrigation pour renforcer la sécurité alimentaire dans les zones rurales des pays en développement. Il serait avantageux d'envisager des incitations financières, telles que des subventions ou des prêts à taux préférentiels, pour soutenir les investissements des agriculteurs dans des infrastructures d'irrigation. De plus, la formation technique des agriculteurs sur les pratiques d'irrigation efficaces, y compris la gestion de l'eau, la planification des cultures et l'entretien des systèmes d'irrigation, serait essentielle.

Ensuite, les résultats soulignent l'importance cruciale du rôle des femmes dans la sécurité alimentaire. Les politiques doivent mettre l'accent sur l'autonomisation des femmes dans le processus d'adoption de l'irrigation. Cela pourrait être réalisé grâce à des programmes visant à renforcer la participation des femmes dans les prises de décisions liées à l'agriculture et et à leur accorder un meilleur accès aux ressources agricoles. Cette approche contribuerait à renforcer la sécurité alimentaire.

Par ailleurs, étant donné que le paludisme est l'une des principales causes de morbidité et de mortalité dans les régions rurales des pays d'ASS, entravant ainsi le développement du secteur agricole, il est impératif que les décideurs politiques intensifient leurs investissements dans ce secteur. Cela garantira un fonctionnement efficace des systèmes d'irrigation et permettrait de réduire considérablement le risque de paludisme, tout en augmentant la productivité agricole.

Enfin, la transition vers une économie plus industrielle dans les pays en développement suscite des questions et des préoccupations légitimes, en particulier en ce qui concerne la pollution de l'eau. Les résultats soulignent ainsi la nécessité de mieux comprendre le lien entre l'industrie et l'agriculture au niveau local. Il serait bénéfique que les autorités locales intensifient leurs actions pour renforcer les réglementations environnementales strictes en vue de réduire la pollution de l'eau. Cette mesure contribuera à la préservation des ressources hydriques essentielles à l'agriculture et au maintien de la productivité agricole.

6.4 Limites de nos recherches et perspectives

Les différentes analyses effectuées dans cette thèse, comme toute étude, présentent certaines limites. Tout d'abord, ces travaux de recherche pourraient être étendus en utilisant les données d'enquête sur une période plus longue, si disponibles, pour examiner les tendances au fil du temps. Par exemple les chapitres utilisent des données sur une période rélativement courte. Dans les chapitres 2 et 3, nous avons réalisé des études en nous concentrant sur huit pays d'ASS. Il serait peut-être intéressant de mener des analyses spécifiques pour chaque pays, ce qui permettrait d'obtenir des recommandations politiques plus ciblées.

Le chapitre 3 aborde la question de la sécurité alimentaire en utilisant les scores de diversité alimentaire comme indicateur de l'accès à la nourriture. Cependant, la sécurité alimentaire est un concept multidimensionnel, et nos analyses pourraient être approfondies en utilisant d'autres indicateurs que ceux que nous avons utilisés comme variables dépendantes. Par exemple, la création d'un indice synthétique de sécurité alimentaire prenant en compte toutes ses dimensions pourrait être envisagée. De plus, étant donné les répercussions négatives de la pandémie de COVID-19 sur la sécurité alimentaire, en particulier dans les pays en développement, il serait pertinent que des recherches futures intègrent cette pandémie en tant que variable de contrôle lorsque les données seront plus accessibles

Le chapitre 4 se concentre sur la province du Jiangsu en Chine. Les résultats obtenus peuvent ne pas être directement généralisables à d'autres régions, en raison des variations considérables dans les conditions environnementales et économiques.

Ainsi, des travaux futurs pourraient élargir cette analyse en examinant plusieurs régions de la Chine ou d'autres pays. De plus, des études ultérieures pourraient se pencher sur les solutions d'atténuation de la pollution de l'eau industrielle et évaluer leur efficacité pour préserver la productivité agricole.

Contributions pour les co-écritures

Les recherches que j'ai menées pour ma thèse m'ont offert l'opportunité de travailler en collaboration avec d'autres chercheurs. De façon plus détaillée, mes contributions sont les suivantes pour les différents chapitres co-écrits :

Chapitre 2 a été coécrit avec Mohamed Boly[1]. Ma contribution se situe à plusieurs niveaux :

- La revue de littérature
- Apurement de la base de donnée
- Construction de la base de donnée
- Régression économétrique
- Rédaction

Chapitre 3 a été coécrit avec Martine Audibert[2] et Sébastien Marchand[3]. Ma contribution s'étend sur divers niveaux :

- La revue de littérature
- Apurement de la base de donnée
- Construction de la base de donnée
- Régression économétrique
- Rédaction

Chapitre 4 a été coécrit avec Sébastien Marchand et Huanxiu Guo[4]. Ma contribution se situe à plusieurs niveaux :

- La revue de littérature
- Apurement de la base de donnée
- Régression économétrique
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Enfin, j'ai collaboré avec Olivier Santoni (géomaticien au CERDI) pour l'extraction et la préparation des bases de données climatiques qui ont été utilisées dans le **chapitre 3**.