

Achieving water security through cooperation and food trade

Esther Delbourg

▶ **To cite this version:**

Esther Delbourg. Achieving water security through cooperation and food trade. Economics and Finance. Université Paris Saclay (COmUE), 2016. English. NNT : 2016SACLX077 . tel-01494749

HAL Id: tel-01494749
https://pastel.hal.science/tel-01494749

Submitted on 23 Mar 2017

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NNT: 2016SACLX077

THÈSE
pour l'obtention du grade de
DOCTEUR DE L'UNIVERSITÉ PARIS SACLAY
préparée à l' ÉCOLE POLYTECHNIQUE

École doctorale n°578 (Sciences de l'Homme et de la Société)
Spécialité: Sciences Économiques

Par
ESTHER DELBOURG

ACHIEVING WATER SECURITY THROUGH COOPERATION AND FOOD TRADE

ASSURER L'AVENIR DE NOS RÉSERVES EN EAU À TRAVERS LA COOPÉRATION ET LE COMMERCE INTERNATIONAL

December 7th, 2016

AX, Paris

Thèse rédigée en Anglais

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Acknowledgements

I would like to express my sincere gratitude to my advisor Eric Strobl, Professor at the Ecole Polytechnique and at the Aix-Marseille School of Economics, for his precious guidance, patience and immense knowledge. Eric always left me free to explore the literature and the topics that I was passionate about, all the while keeping me on a straight path and providing essential advice on rigorous econometrics, analysis and writing. He guided me both through my masters' thesis and my Ph.D. and I am incredibly grateful to him.

Along with my advisor, I would like to thank my thesis committee: Professor Robert Elliott, Professor Görg and Professor Perez-Barahona. Their time and contributions have been invaluable for my thesis. They gave insightful comments, offered encouraging suggestions and also posed the hard questions which drove me to widen my research from various perspectives.

I wish to thank the Axa Research Fund who generously funded my thesis and gave me complete freedom to pursue my research and explore its many tempting topics. The ARF is an exceptionally dynamic, fascinating and major actor within the world of research thanks to its wonderful team led (at the time) by Godefroy de Beauvallet with Isabelle Delaporte, Isabelle Jubelin, Raphaëlle Lalo and Isabelle Bergeron.

It was a wonderful experience to co-write my second chapter with Professor Shlomi Dinar, Professor of International Relations at Florida International University. Water management is all about pooling academic disciplines and I was lucky to benefit from his knowledge and experience. Thanks to our passionate discussions and exchanges, we wrote an article which I am very proud of.

My most and warm thank you to Professor Ezra Suleiman, a mentor, who gave me the most invaluable academic and career advice.

I am also proud to have written my Ph.D. within the prestigious Ecole Polytechnique and benefited from top researchers and facilities. Particular thanks to Professor Yukio Koriyama, Isabelle Méjean, Raicho Bolijov and Guy Meunier who helped me throughout the thesis, took the time to read my research and provide precious recommendations. My warmest thoughts to the staff at Polytechnique, Lyza Racon, Eliane Nitiga-Madelaine and Chantal Poujouly who always took care of us, Ph.D. students, supported and helped us through all the important steps, even the ones we could not see back at the time.

Those years at Polytechnique would not have been the same without my teammates to discuss research, drink coffee at the Bobar and beers at the Academy de la Bière. I wish them all the best for their academic career: Dr. Robert Somogyi, Dr. Raphaël Treibich, Dr. Antonin Macé, Dr. Gwenaël Roudaut, Dr. Mathias André, Dr. Alena Kotelnikova and Dr. Guilhem Lecouteux

and soon to be Doctors Jeanne Commault, Sebastian Franco, Alexis Louaas, Reda Aboutajdine, Margot Hovsepian, Anaïs Goburdhun, Anasuya Raj, Aymeric Guidoux and Christine Lavaur. Very special thanks to Dr. Arnaud Goussebaïle, an amazing researcher and friend as he helped me get through the thesis since the beginning and who I cannot thank enough.

I also owe a great deal to the researchers at the School of International and Public Affairs and the Earth Institute at Columbia University. In particular, I wish to thank Professors John Mutter and Scott Barrett who invited me to visit Columbia University. This exchange would not have been the same without my frequent discussions with Professor Upmanu Lall, Director of the Water Centre. My stay in New York was a perfect stay thanks to many hours spent at Butler and the Avery libraries with Dr. Anna Ray and Dr. Clément Feger.

My thesis has also been influenced by influential researchers I met throughout the years: Professor Tony Allan from King's College who introduced me to the main topic of virtual water. Professor Ariel Dinar, who took the time to discuss my research; Kaitlin Cordes from Columbia Law School with whom we discussed the topics of water economic rights vs rights to water and trusted me to teach several times at Columbia.

Last but not the least, and not without great emotion, I would like to thank my wonderful parents, Therese and Denis. They are outstanding people, parents, mentors and (sometimes) friends who have always been supportive of my dreams, from being a violinist and a wine maker to writing a Ph.D. thesis. I owe them all the extraordinary things I've experienced up to now and I hope they know how much I love them. They were also brilliant when suggesting I should get advice from other people such as Catherine Fahri, who convinced me that I should do a Ph.D.

An incredible thank you to my close friends and family who supported me throughout: Esther and Antoine, Julien, Marie-Anne, Victor, Jean, Timothy, Anne and to those who know what it's like to write a thesis or support someone who is: Elodie, soon to be Dr. Charles, Dr. Sarah, Dr. Clarisse, William and my aunt Anne-Claude. To my inspirational cousins, both researchers, Dr. Pierre and soon to be Dr. Marianne. And my last thank you goes to Jean-Yves (Faff). He experienced the thesis on a daily basis, discussed the results and kept me going through the end all the while building our future home with his bare hands. I owe him a wonderful and unexpected last year of thesis, and years of more amazing unexpectedness to come.

Contents

Introduction **1**

1 Water conflicts and cooperation up and down African rivers **13**
1.1 Introduction . . . 1
1.2 Data and Summary Statistics . . . 4
1.2.1 Region and Unit of Analysis . . . 4
1.2.2 The Basins At Risk scale . . . 4
1.2.3 Upstream vs downstream relationships . . . 5
1.2.4 Streamflow/Runoff . . . 7
1.2.5 Evapotranspiration . . . 8
1.2.6 Population, GDP, Dams, Bilateral Trade and Lagged Values . . . 8
1.2.7 Summary Statistics . . . 9
1.3 Methodology . . . 14
1.3.1 Modeling interaction . . . 14
1.3.2 Modeling the outcome of interaction: cooperation or conflict . . . 15
1.3.3 Extension to the baseline setting . . . 16
1.4 Regression results . . . 17
1.4.1 Results for interaction . . . 17
1.4.2 Results for the outcome of interaction: conflict or cooperation . . . 18
1.5 Conclusion . . . 21
1.6 Appendix . . . 23
1.6.1 BARscale as described in Wolf's database . . . 23
1.6.2 Description of the African basins studied in this paper . . . 25
1.6.3 Extract from a query for the Nile basin in the Barscale database . . . 26
1.6.4 The Pfafstetter numbering system . . . 26

2 The Globalization of Virtual Water Flows: Explaining Trade Patterns of a Scarce Resource **27**
2.1 Introduction . . . 28
2.2 Explaining Virtual Water Flows: Water Endowments versus Water Productivity 29
2.3 Data . . . 31
2.3.1 Bilateral trade flows . . . 31
2.3.2 Relative water endowments and footprints . . . 32
2.3.3 Gravity and control data . . . 33
2.3.4 Summary Statistics . . . 34
2.4 Econometric Methodology . . . 37
2.5 Results . . . 39

2.6 Sectoral Analysis 48
2.7 Conclusion 53
2.8 Appendices 55
2.8.1 World Customs Organization - HS Nomenclature 2012 55

3 Food production and cursed water resources: challenging trade diversification mechanisms 57
3.1 Introduction 58
3.2 Virtual Water flows and concentrated exports 60
3.3 Export concentration, agricultural dependence and water resources 62
3.3.1 Data 62
3.3.2 The Theil and Water Theil index 63
3.3.3 Descriptive statistics 64
3.4 Regression results 68
3.4.1 Theil, Water Theil and water-dependence 68
3.4.2 Food export diversification and water efficiency 73
3.5 Conclusion 77
3.6 Appendices 79
3.6.1 World Customs Organization - HS Nomenclature 2012 79
3.6.2 Additional regression results 79
3.6.3 The Oil Seeds and Sugars sector in Ethiopia 80

Conclusion 83
References 85

Introduction

L'eau pour l'agriculture est un bien économique comme les autres

Il y a deux catégories de ressources en eau: la première désigne l'eau essentielle à la vie et qui répond à nos besoins domestiques (boire, hygiène, cuisine). L'accès à l'eau domestique a été reconnu en 2010 par l'ONU comme un droit fondamental alors que 40% de la population était alors en situation de stress hydrique (World Water Development, Rapport 4, 2012). Ce chiffre n'a pas baissé aujourd'hui car cette situation de grande précarité n'est pas le résultat d'une rareté des ressources mais d'une mauvaise allocation des investissements. En effet, l'eau domestique ne représente que 10% de nos prélèvements en eau et c'est donc l'absence d'infrastructures d'assainissements, d'acheminement et de services en eau qui pénalise les populations les plus pauvres.

La deuxième catégorie des ressources en eau est aujourd'hui la plus menacée et désigne l'eau que nous utilisons pour l'agriculture. A l'échelle de la planète, 80% de l'eau que nous prélevons sert à produire des biens alimentaires et la disponibilité de cette eau est menacée par le changement climatique, l'accroissement de la population et une demande toujours plus forte pour des biens diversifiés et peu chers. Les pays moins riches en eau sont d'autant plus vulnérables aux variations du climat et des prix du marché car ils n'ont généralement aucune gestion efficace et économe de l'eau pour garantir leur sécurité alimentaire.

Bien que les deux types d'eau aient exactement les mêmes caractéristiques physiques, l'eau pour la production alimentaire ne devrait pas avoir le même statut. Les économistes avancent que c'est précisément ce manque de distinction avec l'eau domestique qui empêche l'eau agricole d'être reconnue comme un bien économique et fait ainsi obstacle à une logique de gestion au coût marginal, au même titre que la main d'œuvre ou le capital. Pourquoi cette distinction est-elle si importante? Tout simplement parce que l'inégalité des ressources en eau n'est jamais reflétée dans le coût de la production ou dans le prix final du bien. L'eau étant considérée comme un droit humain fondamental, nous ne pouvons nous résoudre à y attacher un prix, ainsi nous ne payons que les infrastructures permettant d'y accéder. Cependant le coût d'opportunité d'un litre d'eau dans une région sèche est bien plus élevé que s'il provenait d'une région abondante et c'est pourquoi la gestion de l'eau agricole ne peut reposer sur l'hypothèse d'un bien commun. De fait, les pays et leurs agriculteurs sont inégaux face à la ressource et c'est précisément cette asymétrie qui peut, à terme, être source de tensions.

Comment assurer la sécurité de l'eau pour assurer la sécurité alimentaire?

L'eau est donc un facteur de production, au même titre que la main d'œuvre ou le capital. Il nous est désormais possible de comptabiliser précisément la productivité-eau d'un bien en

mesurant la quantité nécessaire à la production de ce bien: c'est le concept de *l'eau virtuelle*, ainsi nommé par Tony Allan en 1991. Ce concept permet de mesurer l'empreinte eau de chaque bien, dans chaque pays, en $m^3/tonne$; c'est aussi l'inverse de la productivité de l'eau qui se mesure en tonne produite par m^3 d'eau utilisé. Grâce à ces données, nous pouvons envisager deux façons d'assurer notre sécurité en eau.

La première est d'augmenter notre productivité en eau (ou de diminuer notre empreinte). Grâce aux technologies de l'eau, au suivi de consommation (smart-metering) et à des stratégies de production sensibles au sol et au climat, nous pouvons désormais produire les biens les plus adaptés, au bon endroit et au bon moment. Nous avons des moyens toujours plus efficaces pour améliorer notre productivité en eau - et donc d'en utiliser moins pour produire autant, voire plus. Parce que cette productivité dépend de facteurs endogènes (le capital, le savoir-faire, la technologie) mais aussi exogènes (climat, sol, géographie), la productivité de l'eau sera différente entre fermiers, entre régions, entre pays. En France, un kilo de bœuf coûtera, en moyenne, près de 16 000 litres d'eau, soit l'équivalent de 3,5 mois de consommation d'eau en France ou de 2 mois aux Etats-Unis. La sécurité de l'eau pour l'agriculture est donc cruciale pour la sécurité alimentaire et les pays ayant réussi à améliorer leur productivité-eau ont même une sorte d'avantage comparatif dans la ressource.

C'est ainsi que la discipline économique a progressivement formulé l'argument selon lequel le commerce international alimentaire peut, à terme, permettre aux pays pauvres en eau d'économiser leurs ressources en important des biens plutôt qu'en les produisant localement (Allan, 1993). Le commerce international est donc la deuxième option, complémentaire, pour assurer notre sécurité en eau.

Le graphe en Figure 1 présente la quantité d'eau que nous aurions pu épargner en 2007, à l'échelle du monde, si l'ensemble des pays avaient produit exactement la même quantité de biens agricoles avec la meilleure productivité-eau existante. Nous utilisons les données Comtrade de l'ONU sur les biens alimentaires entre 1994 et 2007 ainsi que les données sur l'empreinte eau issues du Water Footprint Network (Hœkstra et Hung, 2002 et Chapagain et Hœkstra en 2004) et trouvons que 37 à 40% de l'eau aurait pu être économisée. Le deuxième graphe détaille ces économies d'eau par secteurs: plus de 60% de toute l'eau utilisée pour l'industrie animale aurait pu être économisée à travers une meilleure gestion de la ressource. Plus de 40% aurait pu être épargnée dans l'industrie laitière, le café, le thé et les épices.

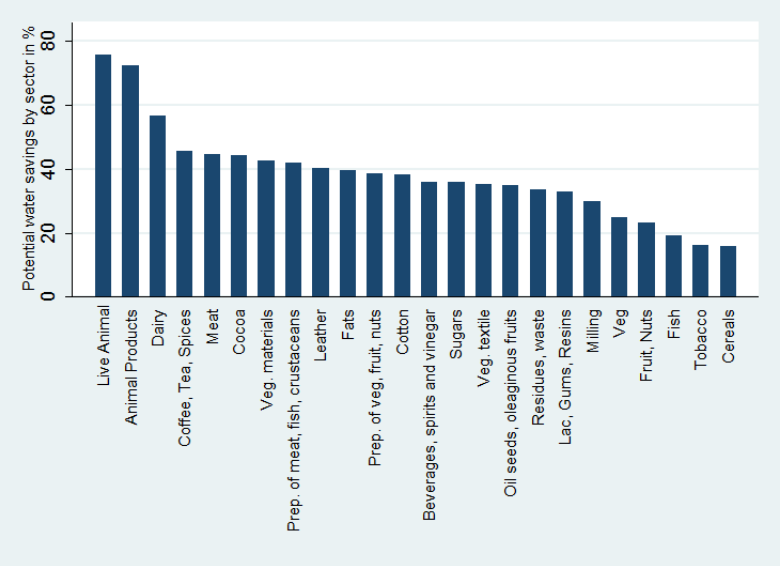
Il se trouve que la plupart de ces produits proviennent de pays en voie de développement, certains riches en eau (Brésil, Chine, Inde) et d'autres en situation de stress hydrique (Pérou, Chili, Mexique et Kenya). Mais ils ont tous en commun une gestion encore sous-optimale de l'eau, voire une gestion qui menace l'accès à l'eau potable dans un futur proche. Qui plus est, le monde produit plus de nourriture que nécessaire aujourd'hui, seulement la distribution des produits est inefficace et les déficiences du marché et le commerce internationale dirigent les flux alimentaires dans le "mauvais sens". Les pays riches en eau reçoivent bien plus de nourriture alors que les pays pauvres en eau ont parfois du mal à accéder aux marchés internationaux. Il semblerait donc souhaitable de repenser notre stratégies de production et d'import-export en fonction de nos disponibilités en eau.

Malheureusement, l'eau n'est pas encore un critère de décision stratégique (Wichelns, 2010). La production et l'échange de bien alimentaires sont le fruits de bien d'autres facteurs économiques, tels le capital, la disponibilité de la main d'œuvre et les opportunités commerciales. Ces facteurs appartiennent à des marchés qui sont eux-mêmes régulés, ce qui n'est pas le cas de l'eau. En

Figure 1: Potentiel d'économie de l'eau dans la production alimentaire mondiale en 2007



Figure 2: Potentiel d'économie de l'eau par secteurs en 2007



effet, pour l'instant il n'y a pas de consensus général sur la régulation des ressources ou sur l'accès à l'eau. Dans la plupart des pays, le fermier est propriétaire des ressources qui coulent le long ou sous ses terres: la propriété de la terre implique donc la propriété de l'eau. Il existe des exceptions notables en Afrique du Sud, en Californie et en Australie notamment. L'eau y a été dissociée de la terre et peut ainsi être vendue à différents agents, même à des kilomètres de là. Ces "marchés de l'eau" sont déjà de véritables laboratoires pour une solution plus globale mais ils peuvent avoir leur défauts, comme lorsqu'ils incitent les fermiers à utiliser le maximum de leurs quotas, faute de quoi ils en auront moins l'année suivante. Les systèmes de marchés de l'eau ne sont encore que peu adaptés aux aléas climatiques, de plus en plus fréquents. Beaucoup de temps et d'eau ont été perdus lors des récentes sécheresses en Californie notamment à cause des négociations sur les règles d'allocation pour hiérarchiser et équilibrer l'approvisionnement en eau. Les pertes sont donc largement dues à une absence de règles et de droits sur l'accès et l'utilisation des ressources en eau.

Malgré cette absence de règles, les débats sur l'utilisation des biens communs ne sont pas récents, comme le montre la Tragédie des biens communs d'Hardin en 1969. Les mécanismes institutionnels font également l'objet de grandes études et la première femme à recevoir le prix Nobel d'économie en 2006, Elinor Ostrom, a même défini une nouvelle approche de la gestion des ressources. Elle propose une alternative entre la privatisation des ressources - considérée par l'économie comme le meilleur moyen d'assurer une gestion optimale sans free-riding - et une gestion par l'Etat, parfois perçu comme seul garant d'une ressource aussi fondamentale que l'eau. Ostrom propose une gestion locale des ressources, où les parties prenantes ainsi que leur pouvoir seraient déterminés par le contexte géographique, économique et social. Comme évoqué précédemment, la rareté de l'eau est une notion relative. Les meilleurs méthodes de gestion seront celles qui s'adaptent au contexte, et non celles qui cherchent à s'appliquer de force. Ostrom a légitimé cette approche et ainsi ouvert une voie peut-être plus durable pour la gestion des ressources en eau. Alors que la discipline économique joue un rôle dans notre compréhension des mécanismes d'allocation et de gestion grâce aux méthodes quantitatives, elle doit également prendre en compte le contexte local.

Cette thèse de doctorat en économie s'inscrit dans le grand débat sur la rareté des ressources en eau et des impacts potentiels sur nos économies et notre sécurité alimentaire. Avec l'usage d'outils quantitatifs et économétriques, elle étudie les mécanismes de répartition de l'eau d'abord lorsqu'elle doit être partagée par plusieurs pays et ensuite lorsqu'elle est utilisée par l'agriculture et expédiée à travers les aliments sous forme virtuelle par le commerce international alimentaire. Les chapitres sont présentés dans l'ordre chronologique de leur écriture.

Chapitre I

Le premier chapitre, co-écrit avec Prof. Eric Strobl, s'intitule "Coopérations et Conflits le long des basins Africains". Il étudie les conflits de l'eau entre pays Africains situés en amont-aval d'un fleuve et contraints de partager la ressource entre 1949 et 2007. Cet article contribue de deux façons à la littérature existante: d'abord par l'étude d'une variable jusqu'ici inutilisée, à savoir le flux annuel d'eau traversant les pays et mesuré en $m^3/seconde$. Ensuite, par le calcul des positions amont-aval entre pays grâce à l'utilisation des bases de données Hydro1K (USGS) et du système de chiffrage Pfaffstetter (1989).

Notre premier modèle de regression s'intéresse à l'existence ou l'absence d'interaction entre deux pays sur des sujets liés à l'eau. Le deuxième modèle regarde ensuite l'intensité de cette

interaction selon une variable dépendante ordonnée allant de -6 (conflit) à +6 (coopération). Entre 1949 et 2007 nous trouvons peu de traces de conflits, même si la paix est souvent contingente à une situation égalitaire en termes d'accès à l'eau. En effet, les pays qui interagissent et coopèrent le plus sont ceux qui connaissent peu d'asymétrie en termes d'accès à l'eau. Le pays en aval, défavorisé par sa position, est clairement à l'origine des interactions, et préfère interagir lorsqu'il est en position de force. S'il est en position de faiblesse, le peu d'interactions sera conflictuel. Le pays en aval arrive souvent à contre-carrer ce désavantage par une pression économique (comme dans le cas de l'Egypte, en aval, face à l'Ethiopie). Nos analyses montrent également que les barrages sont plutôt un facteur de coopération que de conflit, étant donné le grand nombre d'avantages qu'ils apportent dans la maÃőtrise et le stockage des flux amont-aval. Par ailleurs l'absence de coopération ne présage en rien des coopérations futures, un résultat encourageant pour les basins transfrontaliers où l'entente est encore difficile.

Ce premier article a également dévoilé le peu d'interactions des pays sur les problèmes d'accès à l'eau domestique. La plupart des coopérations s'appliquent à la gestion de l'eau pour des communautés de fermiers. C'est à la suite de nombreuses conversations avec les Professeurs Tony Allan et Shlomi Dinar que le deuxième article de cette thèse s'est tourné vers la gestion de l'eau pour l'agriculture et les relais du commerce international alimentaire.

Chapitre II

Le deuxième chapitre est co-écrit avec Prof. Shlomi Dinar et s'intitule "La mondialisation des flux d'eau virtuelle". Il s'intéresse à la théorie des avantages comparatifs liés à l'eau dans le commerce international alimentaire entre 1994 et 2007, à une échelle globale et à travers l'ensemble des secteurs alimentaires. L'analyse porte sur deux types d'avantages entre des pays exportateurs et importateurs: ceux à la "Hecksher-Ohlin", à savoir la quantité relative des ressources en eau et ceux à la "Ricardo", soit la productivité relative en eau entre deux pays. L'objectif est de comprendre si les pays échangent des biens alimentaires en accord avec leurs deux avantages comparatifs en utilisant les données de BACI (Gaulier et Zignago, 2010).

Les résultats montrent que les pays les plus pauvres en eau sont obligés d'importer les produits qu'ils ne peuvent eux-mêmes produire sur place, faute d'eau. Il y a un bien un avantage comparatif à la ressource. En revanche, nous montrons qu'en termes de productivité-eau (la quantité produite par litre d'eau utilisé), les pays s'échangent des biens pour lesquels ils n'ont pas nécessairement d'avantage, voire bien le contraire. L'eau est donc négligée dans l'équation lorsqu'il s'agit des stratégies de production et d'exports. Nous recommandons deux types d'actions: la réallocation des flux commerciaux dans le cas de biens alimentaires produits dans des pays pauvres en eau uniquement pour des raisons de main d'œuvre; l'augmentation de la productivité eau pour les biens nécessitant un contexte géo-climatique bien particulier dans des pays souvent secs.

Ce deuxième chapitre éclaire donc la position des ressources en eau dans la théorie du commerce international et des avantages comparatifs. Le troisième chapitre vient compléter cette analyse en s'intéressant aux paniers de biens produits par chaque pays en relation avec leurs avantages en eau.

Chapitre III

Le dernier article de cette thèse s'intitule "Les mécanismes de diversification dans l'agriculture

en relation aux ressources en eau". Il se penche sur ces pays pauvres en eau et pourtant souvent dépendants du secteur agricole. En particulier, il s'inspire des théories qui prédisent que le développement économique va de pair avec la diversification de la production et des exportations. Or un manque d'eau contraint nécessairement les pays dans leur stratégie de diversification. Nous analysons les paniers de biens exportés par les pays à l'échelle du monde entre 1994 et 2007 et utilisons une mesure transformée de l'index Theil qui incorpore les flux d'eau virtuelle contenus dans les aliments exportés.

Contrairement à la littérature qui montre que la diversification des exportations est corrélée au développement, nous trouvons que la concentration dans le secteur agricole a tendance à nourrir la croissance. En effet, les pays les plus riches se sont concentrés sur un petit nombre de produits avant de se diversifier. Ce résultat vient conforter l'hypothèse selon laquelle les avantages comparatifs en eau sont importants pour le développement de l'activité agricole. Nous trouvons également que les produits exigeant le plus d'eau survivent moins longtemps dans les paniers d'exportations des pays les plus pauvres ou les moins productifs en eau. Le manque d'eau semble donc être un obstacle à la diversification et donc, à terme, au développement.

Les pays avec une eau rare et une productivité-eau faible ne peuvent donc se développer par l'agriculture, à moins de se concentrer sur un petit nombre de produits. Investir dans des technologies de l'eau pour un nombre restreint de produits permet d'intensifier la production et d'avoir des externalités positives sur d'autres cultures potentielles. La concentration est donc souhaitable avant la diversification. Une meilleure gestion de l'eau (dans sa quantité et sa productivité) peut ainsi, à terme, être bénéfique pour le développement économique.

Water resources for agriculture should be treated as an economic good

There are two kinds of water resources: the first one, water for drinking and sanitation, responds to a vital human need. Domestic water has been explicitly recognized by the UN as a human right since 2010 to tackle the challenge of 40% of world population currently undergoing water stress (World Water Development, Report 4, 2012). However, failure to access safe water is rather the result of inefficient or inexistent water infrastructures than that of absolute scarcity. Indeed, domestic water only accounts for 10% of total water withdrawn and we should less be concerned about water availability, as there is plenty, but rather about the lack of equipment to treat, sanitize and carry the resource to people in need.

The second kind, water for food production, is the one facing the most imminent threats. Water for agriculture accounts for over 80% of global consumption and population growth coupled with climate change and exploding demand for diversified and cheap food is increasing water scarcity. Water-scarce nations are relatively more vulnerable to variations in climate and in market prices than their water-abundant counterparts and as such, water management will be crucial to achieve food security. Efficient allocation methods, production and water-productivity strategies are key to alleviating the pressure of water scarcity and using water wisely.

Although not physically distinguishable from the first, water for food production is a completely different good. Economists even argue that the lack of distinction with the first kind is precisely what prevents it from being recognized as an economic good, thus hampering all efforts towards efficient allocation and sustainable use. Why is that? To start with, every country needs water to produce food and every nation has water - except that some have more than others. This would not be a problem if the relative scarcity of water resources was reflected in the final price of food products. Yet precisely because water is a human right, there is still no consensus on whether it should be priced. As such, we are only billed for the infrastructures required to access it - but a liter of water will carry the same value in a water-scarce or abundant region, although the opportunity cost of the latter is much lower. Water scarcity thus creates asymmetries between farmers, consumers and countries in their ability to produce, trade and consume food. This is what politicians are implicitly referring to when making statements about "water wars" as tensions over water rarely occur over domestic consumption but often arise in situations with competing uses for food production.

Without a water price, how can we achieve secure supply of water for agriculture?

We have established that water is main factor of production for the food we eat. Through different transformation or consumption processes, water is embedded within our food, hence the term "Virtual Water"coined by Tony Allan (1991) which allows us to keep track of our water footprint (the amount of water consumed in m3). Tracking the amount of water used for food is what enables us to measure their water footprint, measured in m^3 per ton produced, which is the inverse of water productivity, measured in ton per m^3 of water. It provides us with two interesting solutions to help achieve water security.

The first solution is to improve water productivity. This is done through the use of water-saving technologies, monitoring and wiser crop strategies by planting the right crop at the right time in the right place, taking local climatic and soil conditions into account. Improved water productivity will provide at least as much food all the while saving water. Because it depends both on exogenous (climate, soil) and endogenous (knowledge, capital, technology) factors, farm-

Figure 3: Potential water savings in global food production, 2007



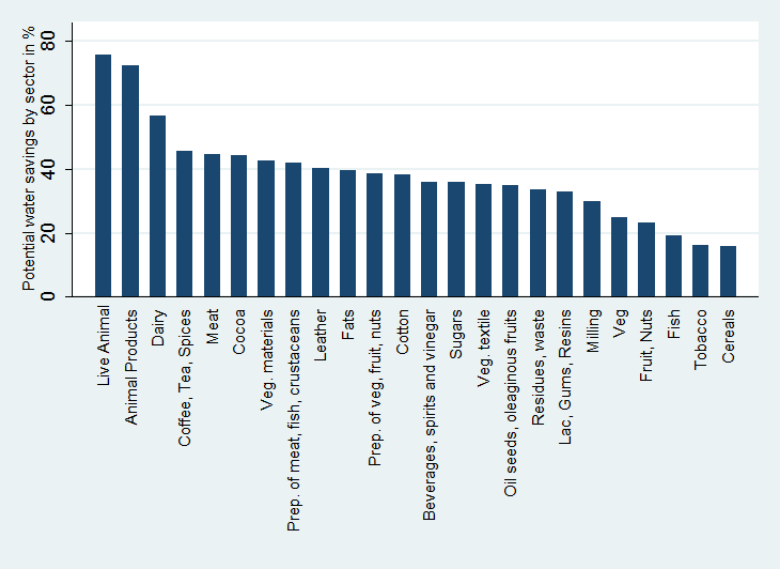
ers, regions and countries will have different water footprints for the same products. In France, a kilo of beef will cost you, on average, about 16 000L of water, that is about 3,5 months' worth of domestic water (drinking, sanitation, cooking, toilets) or 2 months' worth in the United States. As such, countries with water-saving technologies have succeeded in increasing their water productivity even obtaining a sort of comparative advantage in the production of food.

The idea of comparative advantage gradually brought the idea that by importing food, water-scarce countries could be relieved from using the little resource they have (Allan, 1993). As such, international trade is the second, complementary option to save water globally by re-reallocating flows of agricultural goods - and thus flows of virtual water from water abundant to water scarce countries. Figure 1 shows how much water, in percentage, could have been saved globally in 2007 if countries had produced and exported the same amounts of food using the optimum level of water currently achieved through technologies. Using the UN Comtrade data on food trade between 1994 and 2007 and data on water productivity provided by the Water Footprint Network (Hoekstra and Hung, 2002 and further elaborated by Chapagain and Hoekstra, 2004), 37-40% of our water resources could have been saved each year. Figure 2 details all water savings by sector: over 60% of water consumed specifically for animals products can be saved through enhanced water management. Over 40% could have been saved for diary, coffee, tea spices and meat products.

Most of these products are produced in developing nations, a majority of which are either water abundant (Brazil, China, India) or water scarce (Peru, Chile, Mexico, Kenya) but a common feature among these countries is that water use is largely inefficient and threatening future supplies. What is more, the amount of food being produced globally is largely enough to feed the world, but inefficient allocation of production, market discrepancies and international trade are directing trade flows in the wrong way: too much food goes to wealthy and water-abundant nations while the rest of the world is struggling to access subsistence crops at affordable prices. It would seem natural to rethink our production and export-import mechanisms by taking water availability into account.

Although the theory of thinking production strategies in relation to water availability seems

Figure 4: Potential water savings per sector, 2007



intuitive, in practice, water scarcity has yet to become a relevant criterion for production and export strategies (Wichelns, 2010). Indeed, food production and trade are determined by many other types of economics factors (capital, labor, trade opportunities). These other factors have the power to affect trade because they are generally regulated. Unfortunately, there is no consensus over regulation and rights to water for agriculture. In most countries, farmers own the water beneath the land; in South Africa, California or Australia, water has been de-bundled from land and can be sold separately. These so-called "water markets" are an improvement, although they have their flaws, such as the "use it or lose it" rule, giving farmers incentives to excessively use the water so they do not lose their rights the following year. The system is also not designed to adapt to increasingly frequent climate change events and in the case of droughts, such as California, time and water are lost in the process of deciding on new allocation mechanisms. Inefficient or inexistent allocation rights and rules are thus largely responsible for water depletion around the world.

Despite our lack of immediate solutions, the debate over common pool resources is far from recent, as pointed in the Tragedy of the Common by Hardin in 1969. Institutional mechanisms are still being heavily debated and the first female Nobel laureate in economics in 2006, Elinor Ostrom (Governing the commons, 1990), redefined our approach of resource management, suggesting an alternative way between state control and privatization of resources. While liberal economics would advocate that private property is the best incentive to avoid free-riding and degradation of goods, other theories state that only the welfare state can be trusted to own and manage common resources. Ostrom's work has legitimated new and different ways to govern our resources and her contribution is especially important for water resources, which should be analyzed from a local perspective. Water scarcity is indeed relative to its surroundings and people's ability to access it hence our slow adjustments towards better water practice at a global level. Management methods and techniques are not easily transferable from one region to the other and

international institutions have limited power over local management of water. Water economics can play a role in enhancing our understanding of the mechanisms behind international trade, water availability and food security through the use of quantitative methods and empirical analysis. While economists should be cautious in making global recommendations, results of such analysis should be used to make thought-out decisions on the sustainable allocation of water within local frameworks.

This thesis sets out to contribute to these pressing issues with quantitative and econometric analyses. It will deal with two major issues in water economics: water conflicts when resources are shared between countries, and food production and security when water is scarce. The chapters are presented in the order that they were written and I briefly provide explanations on how each chapter led to the next.

First chapter

The first chapter of this thesis, co-authored with Dr. Eric Strobl, is entitled "Water conflicts and cooperation up and down African rivers" and investigates the impact of water availability over cooperation and conflict from 1949 to 2007 between African transboundary countries sharing a common water basin. Our first contribution is to explicitly take account of relative water scarcity within a basin, as measured in $m^3/second$ by historical river flow between nations and computed by Blanc and Strobl (2013). Our second innovation is the computation of upstream/downstream relations using the Hydro1K (USGS) dataset and the Pfaffstetter number system (1989).

Our first model explains what triggered countries interact in the first place; the second model features an ordered dependent variable (range from -6 to +6) representing the outcome of that interaction (cooperative or negative). We find that interaction and cooperation are mostly the doing of the strategically weaker country, namely the downstream one. Transboundary water management is successful when there is little asymmetry between both countries and when the downstream country is at least as well off as the year before in terms of water availability. Furthermore, cooperation occurs when downstream nations are relatively wealthier, suggesting that relative economic strength can offset geographical disadvantage. We also find that the building of dams upstream has been a factor of cooperation rather than conflict and that the likeliness of cooperation between countries does not suffer from past conflicts, giving hope to many African nations with conflictive history.

In analyzing the treaties from the Basins at Risk dataset, a simple observation quickly came up: cooperation or conflict over water almost never occurred over domestic consumption. Most treaties concerned water access for small farm-holders to grow crops or breed their cattle. A coincidental meeting with Pr. Tony Allan and a summer school with Pr. Shlomi Dinar were decisive in taking the next step of this thesis by tackling water resources from a pure economic perspective within the scope of international trade.

Second chapter

Pursuing on the empirical path, the second chapter of this thesis, co-authored with Prof. Shlomi Dinar, is entitled "The Globalization of Virtual Water Flows: Explaining Trade Patterns of a Scarce Resource". The paper addresses the determinants of bilateral trade of virtual water, namely the water embedded in food and virtually traded between countries. We investigate

whether countries trade according to their comparative advantage in water, proxied by water endowments (in $m^3/capita$) and water productivity (in $tons/m^3$ used) between 1994 and 2007 using the BACI dataset (Gaulier and Zignago, 2010).

We show that there is a positive correlation between exports and relative exporter-importer water endowments, suggesting that the driest countries use trade as a means to alleviate water scarcity. We also find that relative water productivity and food trade display an inverted u-shape, suggesting a threshold effect in demand in developed countries and a disregard for water resources relative to the lack of other inputs (such as capital, technology or qualified labor) in relatively water-scarce countries. In fact, for very water-inefficient exporting countries, we recommend two types of action: reallocating trade flows for products that only benefit from cheaper labor and enhancing water productivity for products that do require a specific climate-land context and cannot be produced elsewhere.

This second chapter provided an in-depth study into bilateral trade strategies and relative water endowments and productivity between exporters and importers. The third chapter completes this study by investigating the basket of goods available for each country and the products that they chose to produce and export in relation to their water footprint and water endowments.

Third chapter

The last chapter of this thesis is entitled "Food production and cursed water resources: challenging trade diversification mechanisms" and deals with diversification of food exports in relation to water endowments and productivity. Building on the abundant literature relating trade diversification, resource curse and growth, we analyze food exports from 1994 to 2007 at a global level. We compute an adapted measure of the Theil index to incorporate flows of embedded (virtual) water instead of quantities of food.

Contrary to traditional results in the literature that export diversification goes hand in hand with development, we find that the food sector goes in the opposite way. Food exports concentrate in countries as they grow richer; on the other hand, they diversify along with water availability. Because food is mostly constrained by land and water, countries do focus on products for which they have some sort of water comparative advantage.

Furthermore, we find that water-intensive goods display lower subsistence in time when countries are water-scarce and have lower water efficiency than world average. In fact, water-scarce countries have unstable diversifying trade patterns with water-intensive goods disappearing and re-appearing throughout our period of study, revealing that the inefficient use of water resources is a main obstacle to trade diversification. We conclude that inefficient water management and insufficient investments in water efficiency are an obstacle to exiting water dependency by inducing similar economic impacts as those caused by "traditional" cursed resources such as oil, natural gas or minerals. We recommend that water-scarce countries focus on improving the water footprint of a small number of goods in order to trigger positive spillovers to other crops and other sectors of the economy before attempting to diversify.

Chapter 1

Water conflicts and cooperation up and down African rivers

Esther Delbourg & Eric Strobl

"Why go to war over water? For the price of one week's fighting, you could build five desalination plants. No loss of life, no international pressure and a reliable supply you don't have to defend in hostile territory".

Israeli Defence Forces analyst in Wolf, 1995b

Abstract

This study investigates the impact of water endowments over cooperation and conflict between African transboundary countries from 1949 to 2007. Using the Basins at Risk database (Wolf, Yoffe and Giordano, 2003), we make two contributions to the literature: first, we take account of an aspect largely ignored which is relative water scarcity within transboundary river basins, namely streamflow. Second, we concentrate our study on upstream-downstream country pairs to understand how exogenous power asymmetries over water can affect the mechanisms of water cooperation and/or conflict. Our results show that over the last 50 years, downstream nations have played a decisive role in triggering interaction and cooperation with their upstream counterpart, often allowing geographical asymmetries to be offset by economic leverage over the region. In particular, the availability of water seems to increase cooperation (or conflict) only when the downstream nation is at least as well (worse) off than in the previous years. Results indicate that dams are a factor of cooperation rather than conflict and that cooperation is correlated with past interaction, meaning that transboundary basins with a history of cooperation over water are likely to keep cooperating in the near future. On the other hand, past conflicts do not affect likeliness of cooperation today.

JEL classification: C10, O13, Q17, Q34, Q54

Keywords:Transboundary water, conflict, cooperation, climate, Africa

1.1 Introduction

Over half of the African population lives along major river basins shared with at least one or two countries, making transboundary water management a key policy issue for water security. Sharing a common river basin implies that any use of the resource will affect, in some way, any possible use by others. As major rivers such as the Congo/Zaire, the Nile or the Niger are shared by more than ten riparian countries, it becomes inevitable for them to interact and find common grounds regarding the management of their resource (Yoffe et al., 2004; Uitto and Duda, 2002; Yoffe et al., 2003; Kameri-Mbote, 2005; Lindemann, 2005; Turton, 2005; Dinar, 2008, 2009).

A major obstacle to smooth cooperation over water is the fact that countries are not equal in accessing the resource and their ability to use it. Countries are first and foremost constrained by their geographical features, such as relative position within a basin, soil and climatic conditions. Second, economic and political leverage can overturn those geographical advantages, enabling less advantaged countries to enforce their own rules of water allocation. For instance, the 1959 bilateral sharing agreement between downstream Egypt and Sudan over the Nile waters was enforced because of the economic and military force they could exert on upstream nations. As upstream Ethiopia is now growing stronger and gaining international support, a new power balance is settling in the region. In 1992, Zimbabwe avoided serious economic drawbacks when the RDC (former Zaire) accepted to forgo part of its hydroelectricity share to offset power shortages due to important droughts. In this case, Zaire was undoubtedly advantaged by its upstream position within the basin and higher potential for hydroelectricity production. Recent allegations of downstream Mozambique cutting hydroelectric supplies to Zimbabwe over unpaid debts in 2008 is, on the other hand, a case of economic leverage overtaking geographical asymmetries.

All three examples, taken from many cases in Africa, show that the very nature of transboundary management is affected by exogenous and endogenous asymmetries between countries. Understanding what drives countries to interact and determines whether the outcome is cooperative or conflictive thus requires to disentangle these various mechanisms. This article addresses the determinants of water interactions and their outcome, by building upon an important literature in the disciplines of economics, geography and international relations.

Starting with the popular mindset that water will become a source of conflict in the coming century (Starr, 1991; Gleick, 1993; Lowi, 1993; Homer-Dixon, 1994; Ismail Serageldin, World Bank, 1995; Klare, 2001), the international relations and economic literature agree that the very nature of transboundary water management provides higher incentives for states to enter into a cooperative mode. They also argue that the history of water politics is one of cooperation rather than one of confrontation (Allan, 1997; Wolf, 1998; Yoffe et al., 2003 and Turton, 2005). Yet this does not imply that water agreements are fully cooperative or that tensions have not occurred before giving way to efficient collaboration.

To understand such cooperative outcomes, the literature first turned to politics and the absence of relevant and efficient institutions (Kameri-Mbote, 2005; Bhaduri and Babier, 2008; Dinar, 2008; Brochmann, 2012) and how they shaped the very perception of potential economic and political gains from cooperating instead of acting unilaterally (Sadoff and Grey, 2002, 2005; Whittington et al., 2005, 2006; Ambec and Ehlers, 2008). In particular, Sadoff and Grey (2002) argue that identifying the inter-related benefits of cooperation beforehand[1] is central to succesful

[1]There are four types of benefits: benefits to and from the river, cost reducations and benefits beyond the river.

transboundary management schemes[2].

Recent models even started to account for hydro-geographic variables and how they would affect hydropower and irrigation potentials. The Nile Economic Optimization Model (NEOM) computed by Whittington, Wu and Sadoff (2005) and Wu and Whittington (2006) determines the annual pattern of water use that will maximize the sum of economic benefits from irrigated agriculture and hydropower. Their results suggest that Egypt would gain tremendous value in outsourcing hydroelectricity to upstream Ethiopia where production potential is higher given its position in the basin. This would, in turn, increase Ethiopia's share of the Nile waters with positive externalities for domestic, agricultural and industrial consumption of water. Nevertheless such a recommendation, based on hydro-geographical and cost-benefit analysis, was until recently incompatible with Egyptian economic and political considerations.

The previous results directly stem from the upstream-downstream asymmetry between Egypt and Ethiopia, giving an economically weaker country (Ethiopia) an undeniable advantage over a more economically powerful one (Egypt). Upstream-downstream configurations are particularly challenging because of the unidirectional (Rogers, 1997; Dombrowski, 2007) and/or reciprocal externalities (Barrett, 1994) they induce. Negative externalities in an upstream/downstream configuration can derive from upstream storage, through the use of dams or water pollution. Positive externalities can include upstream wastewater treatment or provision of retention area. Although Turton (2005) explains how availability of water has dictated economic development and induced positive externalities within the Orange basin in the last 50 years, no study has proved it empirically.

Indeed, these externalities heavily rely on the issues that countries are willing to address together. For instance, it is initially more complicated to get countries to act upon water allocation issues than in the area of environmental protection, an area which easily obtains consensus (OECD/CSAO, 2009). The Basins at Risk project (Wolf et al., 2003), which we use in this study, finds that treaties over water quantity, quality, joint management and hydropower tend to be highly cooperative while conflictive relations tend to center around quantity and infrastructure concerns. Yet they still conclude that no single indicator can clearly explain conflict or cooperation (among climatic, water stress, government type, dependence variables), arguing that willingness and ability to cooperate are relative to a historical context where different types of leverages are at work[3].

The complexity of isolating causes of cooperation drove researchers towards another set of explanations, the first pertaining to the types of country pairs and river configurations likelier to interact and cooperate. Song and Whittington (2004) show that transboundary rivers that cross riparian countries with countervailing powers, population and economic hegemon are more likely to cooperate. They also find that river types appear more important in determining cooperative treaties than do country pair types, suggesting that cooperation is easier to achieve when there is little history of it[4]. Based on Shlomi Dinar's finding (2009) of an inverted U-shape relationship

[2]In doing so, they assume that countries can anticipate the finality of cooperative or conflictive agreements but do not address what can actually trigger them.

[3]The patterns they find are partly issued from summary statistics of their data, partly from linear regressions models to test the level of international conflict/cooperation over water to a set of quantifiable independent variables (GDP, population density, overall relations, rate of population growth, number of dams, dam density, basin area, water stress, HDI, agriculture as % of GDP and hydropower).

[4]By using the same database as this article - the Basins At Risk project conducted by Aaron T. Wolf at the Oregon University in 2003 described later on - they develop a typology of rivers according to different criteria, mainly civilization, size of population and GDP with different combinations of the three. Their study is at the global level and they only consider the existence of treaties and not their intensity.

between water scarcity and cooperation, Dinar, Dinar and Kurukulasuriya (2011) study three cooperation variables for the whole of each basin (interaction, number of treaties signed and share of water-allocation issues) and show that more developed states use economic incentives to stir cooperation when they need it.

Lastly, a growing literature has also sought to relate climate change to conflicts, mainly by exploring the rivalry induced by the degradation of available resources, forcing populations to migrate internally or to cross borders (Homer-Dixon, 1994; Hauge and Ellingsen, 1998; de Soysa, 2002; Miguel et al., 2009; Dinar et al., 2014).

Although the literature has addressed geographical and economic asymmetries, surprisingly little attention has been given to the decisive exogenous features of geography, climate and water availability together, arguably constituting an important gap in the literature. First of all, the upstream-downstream feature has never been specifically exploited when analyzing water events. Second, a most relevant variable that is directly affected by upstream/downstream relative positions - the quantity of water running through countries, namely streamflow - has not been studied within the scope of water agreements.

Our paper contributes to the literature on the determinants of water cooperation by empirically investigating how streamflow and evapotranspiration - a measure of plant transpiration and a main climatic parameter - can trigger water cooperation or conflict between African nations that specifically display an upstream-downstream relationship. Using the Basins At Risk data (Wolf et al., 2003) which lists and grades all the water events according to their cooperative or conflictive nature, we build our dataset to determine relative position of countries within basins and use it to understand how economic asymmetries are at play when interacting with geographical features.

Our first innovation in this approach is to explicitly take account of actual relative water scarcity within a basin, as measured by historical river flow between nations. Streamflow is computed on an annual basis by Blanc and Strobl (2013) from 1949 to 2007 and contains information on land cover type, soil characteristics, daily precipitation and network coverage. Our second contribution is the computation of upstream/downstream relations coupling the Hydro1K (USGS), a dataset containing topographically derived data sets of streams and drainage basins with the Pfaffstetter numbering system (1989) for watershed identification which describes the regional anatomy and enables us to identify the direction of streams. Combined with geographical, spatial and climatic data, this water event database offers a resource for a qualitative and quantitative exploration of African water issues.

Our results show that the likeliness of interaction over transboundary waters and the cooperative outcome of such water agreements are greatly the doing of downstream nations. Their relatively weaker position provides incentives to interact when they need to and agreements turn out to be more cooperative when they are relatively better off in terms of streamflow than the previous year. In particular, the availability of water seems to increase cooperation when there is little asymmetry between upstream and downstream availability of water. Furthermore, water interaction and cooperation are likelier to occur when the downstream nation is relatively wealthier, suggesting that they use their relative economic strength to initiate interaction and influence the outcome of the agreement. We also find that the building of upstream dams has been a factor of cooperation rather than conflict and that the history of cooperation between two nations does trigger further interaction, providing hope for many African nations and basins for which transboundary water management is fairly recent.

We begin with a brief review of the determinants of water cooperation according to the recent

literature. We then discuss the complex nature of our different data base and out variables before explaining our identification strategy and displaying our results.

1.2 Data and Summary Statistics

1.2.1 Region and Unit of Analysis

This study will focus on 16 river basins in the African continent, namely: the Awash, the Congo/Zaire, the Gambia, the Incomati, the Juba-Shibeli, the Kunene, the Lake Chad, the Limpopo, the Niger, the Nile, the Okavango, the Orange, the Ruvuma, the Senegal, the Volta and the Zambezi. The basins are represented in Figure 1.1 and Appendix 1.6.2 provides further economic and demographic details.

We choose our unit of study to be country pairs to specifically observe the upstream vs downstream unilateral relationship and enquire into bilateral mechanisms of cooperation and conflict. Our database thus comprises every possible country pair for each basin of study, regardless of whether countries share a common border or not.

Figure 1.1: International River Basins of Africa - Copyright Transboundary Freshwater Dispute Database, 2000



1.2.2 The Basins At Risk scale

The Transboundary Freshwater Dispute Databse (TFDD, Wolf et al., 2003) and the BAR scale, taken from the Basins At Risk project, covers historical incidents of international water cooperation and conflict from 1950 to 2008. The events are ranked by intensity from -6 to +6 using precise definitions of conflict and cooperation as defined in Appendix A. Formal water events

can occur between two or more countries and the dataset attributes the same BAR scale to each of the countries involved in a specific water-related event (see Appendix C for an example of a query for the Nile basin). As such, water treaties can include countries that do not share a river basin but we limit ourselves to country interactions within river basins and not between them. Studying such interactions goes beyond the scope of this paper because countries are no longer constrained by their relative positions within a specific basin.

The difficulty of assessing the intensity of water events lies in the very complexity of defining conflict and cooperation. In the database, water conflicts can be understood as a series of tensions or specific non-cooperative acts perpetrated by one of the countries regarding the others. On the other hand, cooperation will designate a series of agreements and events fostering bilateral or multilateral action for the sake of the common resource. A main issue is that the popular approach that conflict ends when cooperation begins is limited as both of them can co-exist at the same time (Allan, 2012). Also, conflict and cooperation are not to be understood locally in time but rather widespread over several periods which are difficult to identify. The 1959 bilateral agreement between Egypt and Sudan over the Nile waters was still being informally enforced until recently even though this conflictive event was never officially renewed and does not appear again in the database. The dataset does not take into account such a time effect, as it lists agreements or events in the year they took place and will consider years to follow as empty of such events, almost as if the interaction had ceased existing. This aspect will play a role in interpreting our results.

Also, we might be tempted to acknowledge the absence of conflict rather than the existence of cooperation. This was described by Johan Galtung (1969) as "negative peace", namely the absence of violence without further constructive collaboration. In fact, when nothing is happening on a formal basis - that is the absence of cooperation or conflict for a given year or basin - it does not imply that countries are not interacting. It may mean that countries are currently satisfied with the status quo, working on future regulations or following previous treaties; it can also mean that certain forms of cooperation do not require formal agreements.

We use the BAR scale in two different ways: first, by observing whether an event has occurred or not in a given year for a specific country pair, with a dependent binary variable. Second, by taking its value (from -6 to +6) when country pairs have interacted at least once, according to Wolf's terms, over the years 1949 to 2006. We built our database in order for each water event to appear once in the database if it only involved two countries and as many times as there are country-pairs if it involved more than two countries.

1.2.3 Upstream vs downstream relationships

Given the complexity of basin and river configurations, there is no international database available that precisely determines upstream-downstream relationships for country pairs with complex configurations. Figures 1.2 and 1.3 illustrate the difficulty of determining the type of hydro-geographic relation that exists between two countries, in the whole of the African continent, and in the specific case of the Congo/Zaire river basin. Indeed, a great number of riparian countries do not feature a clear downstream/upstream relationship: rivers can form a perfect border between both countries or flow from country A to country B, with part of it being fed by a tributary source that comes from country B and flows itself into country A.

A main contribution of this article is that we built our upstream-downstream variable through the comprehensive use of Geographic Information Systems (GIS) and exploitation of the Hydro1K database from the U.S. Geographical Survey (USGS)[5]. Making extensive use of Arcgis,

[5]The Hydro1K database provides a consistent global coverage of topographically derived data sets of streams

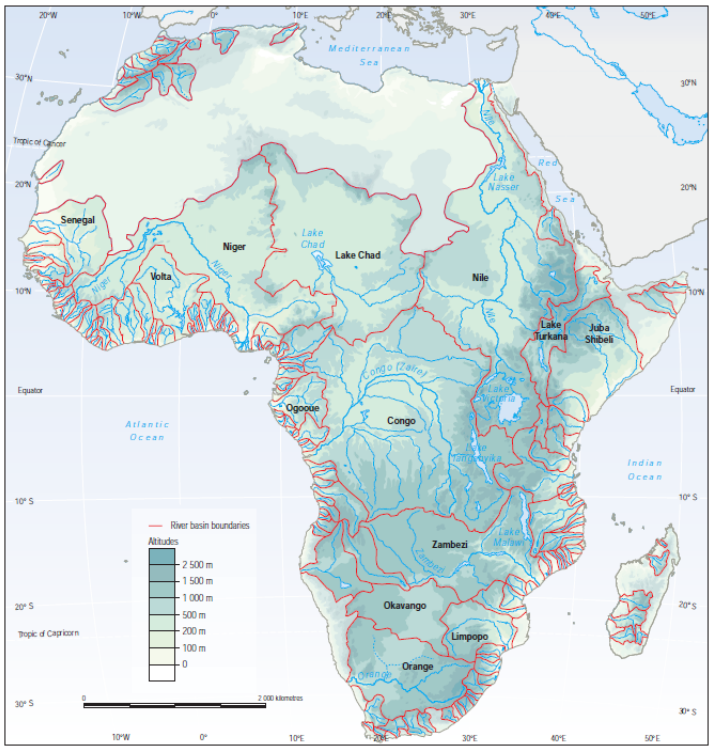


Figure 1.2: Africa's major river basins cross political borders - Source: UNEP 2002



Figure 1.3: The Congo/Zaire river basin - a multitude of river flow configurations

a geographic information system (GIS) for working with maps and geographic information, we overlaid African river maps with basins and countries, thus disaggregating our maps into the smallest units of basins possible as defined by the Pfafstetter numbering system. The Pfafstetter numbering system, as developed by the Brazilian engineer Otto Pfafstetter in 1989, describes the regional anatomy of stream networks using a hierarchical arrangement of decimal digits. Watersheds are distinguished between basins, interbasins and internal basins. Basins are the headwater of rivers and do not receive any inflow from other water areas; interbasins receives flow from upstream watersheds and internal basins are closed. The Pfafstetter system attributes levels of classification from 1 to 5 which help identify the direction of inflows and outflows. We provide complete details of our methodology in Appendix D.

Level 1 classification is the highest one and is attributed to major river basins, level 5 being the lowest and attributed to minor rivers or streams. At each level, the four largest basins are identified and assigned Pfafstetter digits 2, 3, 6 and 8 in a clockwise direction. The five largest interbasins are assigned digits 1, 3, 5, 7 and 9, clockwise. Internal basins are assigned the number 0. Basins continue to be subdivided and numbered as before at levels 2 to 5. Interbasins continue to be divided into the 4 largest basins at levels 2 to 5 but instead of numbering the resulting basins in a clockwise direction, the basins are numbered from the most downstream basin to the most upstream. We use this method to determine whether each watershed, at the smallest level, is upstream or downstream from its nearest neighbor.

1.2.4 Streamflow/Runoff

Our second main innovation comes from using a measure of the water resources over which cooperative/conflictive events occurs and proxying this by a measure of streamflow. More precisely, streamflow is a component of the water runoff and the main mechanism by which water moves from the land to the oceans. It is measured in $m^3.s^{-1}$ and is mainly formed by precipitation runoff in the watershed and the contribution of other tributary rivers or water bodies. As such, streamflow is shared by countries and crosses borders. It has the particularity of changing from day to day, mostly because of natural[6] or human-induced mechanisms and increases as it flows further downstream[7]. It is a mostly relevant and useful indicator for our study as streamflow will determine both the amount of water available to a country but then also its leverage on or its dependency regarding the whole of the basin.

We use the streamflow computed by Blanc and Strobl (2013) where they compute streamflow data per year and per country using the GeoSFM model (Geospatial Stream Flow Model) built by the USGS (U.S. Geographical Survey). It is a semidistributed physically based hydrological model, with particular relevance for Africa's hydrology (Asante et al., 2007a; Asante et al., 2007b). It stimulates the dynamics of runoff processes using spatial information on river basin and network coverage, land cover type, soil characteristics and daily precipitation and evapotranspiration data. Blanc and Strobl then use the HYDRO1k data to delineate basins and river network.

and drainage basins derived from the USGS30 arc-second digital elevation model (DEM) of the world (GTOPO30). It allows scale modeling and analyses of African rivers.

[6]Runoff from rainfall and snowmelt, evaporation from soil and surface-water bodies, evapotranspiration, ground-water discharge from aquifers, sedimentation of lakes and wetlands, etc.

[7]Surface-water withdrawals and transbasin diversions (through dams), construction, removal, and sedimentation of reservoirs, irrigation through stream channelization, etc.

1.2.5 Evapotranspiration

Evapotranspiration combines normal evaporation and plant transpiration from land surface to atmosphere and is measured in millimetres (mm) per unit of time. It represents an evaporative demand of the air within a basin. Because plants will transpire more as soils are liquid, such a measure is important in order to manage catchments for water supply and irrigation. Contrary to streamflow which flows from country A to country B, evapotranspiration is a purely local variable. It is also a comprehensive weather indicator as it is a combination of solar radiation and temperature.

We use the data computed by Blanc and Strobl (2013)[8] where they follow the computation in Hargreaves and Samani (1985):

$$ET = 0.0023(Tavg + 17.8)(Tmax - Tmin)0.5Ra \tag{1.1}$$

where Tavg, Tmax and Tmin are mean, maximum and minimum temperature, respectively and Ra is the extraterrestrial radiation calculated following Allen et al. (1998) [9].

1.2.6 Population, GDP, Dams, Bilateral Trade and Lagged Values

We control for country-specific features that are likely to play a role in whether countries interact over water management and whether the outcome is cooperative or conflictive. We introduce three variables: population, gdp per capita from the Penn World Table (PWT) 7.0[10] and number of dams per country.

Countries that build dams over the years are more likely to be involved in water events although this information cannot help predict the intensity of such events. Investments in dams will show concern for water management and water access as they affect the shared resource as a whole. It fosters discussion over water issues and increases the likelihood of interaction. On the other hand, an increase in the number of dams also increases the likeliness of non-compatible projects upstream vs downstream. Controlling for the number of dams enables to understand interaction ahead of time. These issues will be further discussed along with the results. The number of dams per country and per year is provided by Strobl and Strobl (2010) where they use the FAO's African Dams Database, a georeferenced database of large dams[11].

Because we assume that the number of dams will affect water events, we also have to assume that formal water agreements will arise with those changes. Taking the lagged values of both those variables will enable us to incorporate their effects over time. Indeed, building a dam upstream or downstream requires public concern for water-related issues and so perhaps a higher

[8] Evapotranspiration data is obtained from the CRU TS 2.1 dataset (Mitchell and Jones, 2005) compiled by the Climatic Research Unit (CRU) at the University of East Anglia. Strobl and Blanc (2009) use monthly data on mm of precipitation and degrees of average, minimum and maximum temperature, all of which were given at the 0.5 degree resolution globally for land surface areas over the period 1901-2002, to calculate annual river basin level measures of these weather factors.

[9] The rate expresses the amount of water lost from a cropped surface in units of water depth. The time unit here is year. As one hectare has a surface of 10000 m^2 and 1 mm is equal to 0.001 m, a loss of 1 mm of water corresponds to a loss of 10m^3 of water per hectare. In other words, 1 mm.day^{-1} is equivalent to 10 m^3 .ha^{-1}.day^{-1}.

[10] It is provided by Alan Heston, Robert Summers and Bettina Aten, Penn World Table Version 7.0, Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania, May 2011. It is derived from growth rates at 2005 constant prices.

[11] It contains information about the date of construction and was completed using updated data from the International Commission on Large Dams (ICOLD), internet searches and a list of dams and their characteristics provided by the South African Department of Water and Forestry.

and compelled commitment to transboundary management. Building a dam will also affect the shared basin and foster cooperation or tensions.

We follow the same reasoning for real gdp. As a control variable for economic development, it can be highly correlated with unobserved factors influencing the intensity of water events. African economies rely heavily on farming and irrigation, and are thus easily affected by lack of water, harsh climatic conditions and poor water infrastructures. Enhanced climatic conditions may steer local economy and increase real gdp per capita, making the country either less or more cooperative according to the benefits it can reap out of a formal water agreement. Taking the lag value of real gdp per capita enables us to get round this contemporary correlation.

We will also be using a lagged historical variable representing the lagged sum of events a country pair has been involved in since 1949. This is helpful in analyzing the frequency of a country pair in water events, moreover as water events between two countries generally follow each other closely in time, thus supposedly increasing the likeliness of having an event occur as the years go by.

1.2.7 Summary Statistics

Our dataset comprises 33 countries that display an upstream-downstream relationship over a span of 58 years. Table 1.1 shows the main summary statistics of our variables of interest. "Et" stands for evapotranspiration. The letters "U" and "D" at the end of the variables stand for "upstream" and "downstream". Note that upstream streamflow has a slightly lower average value than downstream streamflow. As mentioned earlier, the size of rivers and their streamflow increase naturally as it moves downstream given the construction of the streamflow variable.

Table 1.1: Summary statistics

Variable	Mean	Std. Dev.	Min.	Max.
BAR scale	0.204	0.959	-5	6
StreamflowU	1200.049	1951.627	5.698	16079.916
StreamflowD	1497.713	2409.28	5.698	16079.916
etU	11.433	1.801	7.497	15.169
etD	11.408	1.744	8.539	15.169
DAMU	14.032	50.144	0	433
DAMD	13.397	50.133	0	433
rgdpU	1423.18	1812.781	151.18	22956.973
rgdpD	1580.052	2300.41	151.18	22956.973
popU	10427.293	12898.722	415.767	140397.766
popD	12583.563	16982.324	271.369	140397.766

Source: Author computations

Table 1.2 displays some statistics on formal water events according to geographical configurations. Together they show that from 1949 to 2006, upstream-downstream country pairs have interacted, on average, 3.5 times vs 1.9 for other types of country pair configurations.

Likeliness of interaction

Figure 1.4 shows the likeliness of a country interacting with its upstream or downstream counterpart, according to its income group (LI: Low-income, LMI: Low-Middle income, UMI:

Table 1.2: **Statistics over different geographical configurations, 1949-2006**

	All config	UpS/DwS config	Other
Basins	16	/	/
Country pairs	296	91	172
Countries	38	33	33
Interactions	766	435	331
Interactions/year	13,2	7,5	5,7
Interactions/country	20,2	13,2	10
Interactions/CP	2,6	3,5	1.9
%interaction/CP	4,5%	6 %	3,3%

Source: Author computations

Upper Middle Income, HI: Income)[12]. In our data, 60% of countries are low income, 30% are low-middle income and the rest are equally divided between upper-middle and high income. The left side of the graph does not consider relative position within a basin, and shows that the likeliness of interacting is higher for upper-middle income countries, although they only represent 5% of our total sample of countries. This trend is emphasized if the country interacting is downstream from its counterpart and lowered if it is upstream.

We now look at the impact of upstream/downstream income asymmetry on cooperation mechanisms. Figure 1.5 shows the likeliness of interaction depending on relative income groups, and we observe that country pairs have a higher chance of interacting when the downstream nation is wealthier than its upstream counterpart. One of the explanations for such an observation is that water agreements are the result of negotiations where different leverages are at play. Because upstream nations have the upper hand on the resource, it would seem that formally agreeing on water management is in the downstream nation's first interest. A wealthier downstream country is bound to have a certain economic leverage over upstream users, enhancing the likeliness of negotiations amounting to a formal agreement. It also seems that being upstream and having economic strength over downstream users is less decisive for interaction.

The BAR scale

Figure 1.6 displays the distribution of the BAR scale, from -6 to +6, for water events by basin from 1949 to 2006. Each dot represents a water event, involving at least two countries. Red dots have negative BAR scales (tensions/conflicts over water) while green events have positive ones (cooperation). Remember that filtering for upstream/downstream country-pairs has reduced the number of events considered throughout history. One can easily see that the Nile basin is the one with the most widespread distribution across the scale. Historically, the Nile basin has been known to host important political and economic tensions, which happen to have been materialized through formal agreements or declarations. The Zambezi, on the other hand, has been known to be quite an example of joint cooperation in the last 20 years (World Bank, 2010). Lake Chad and Congo/Zaire offer a smaller number of agreements proportionally to the popular issues involved and the number of riparians involved (respectively 8 and 13 countries). This is because filtering for clear upstream-downstream relationships has reduced the number of

[12]World Bank Atlas method: LI countries: GNI per capita < $1005; LMI countries: GNI per capita ∈ ($1006, $3975); UMI countries: GNI per capita ∈ ($3976, $12275); HI countries: GNI per capita> $12276

Figure 1.4: Likeliness of country interaction according to income and position, 1949-2006

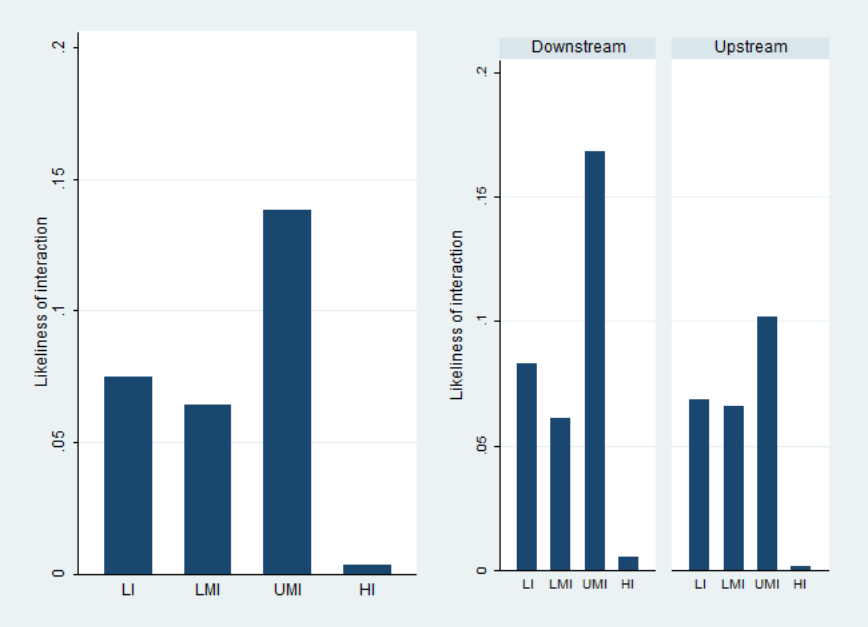
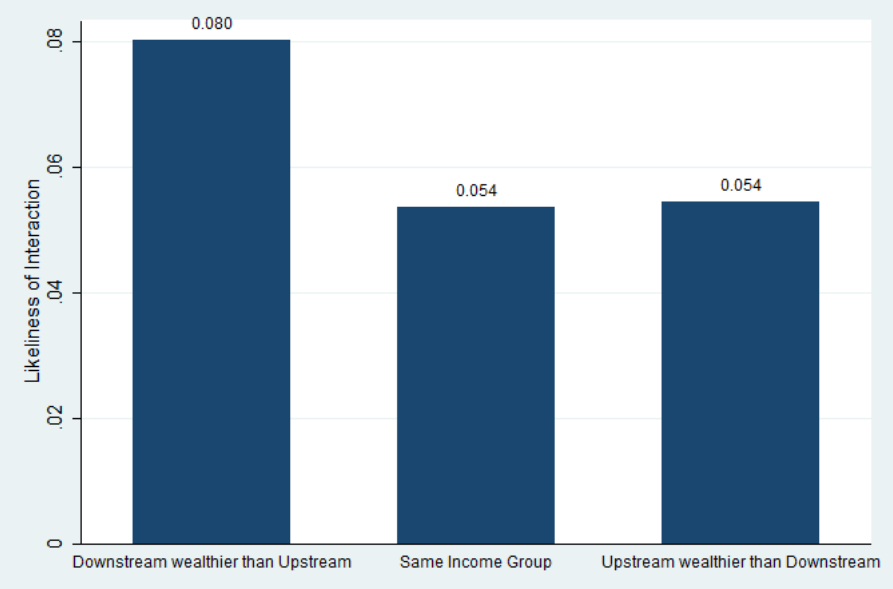


Figure 1.5: Likeliness of Interaction depending on relative wealth, 1949-2007



events for this particular basin.

Figure 1.6: Distribution of the BAR scale by basin, 1949-2006

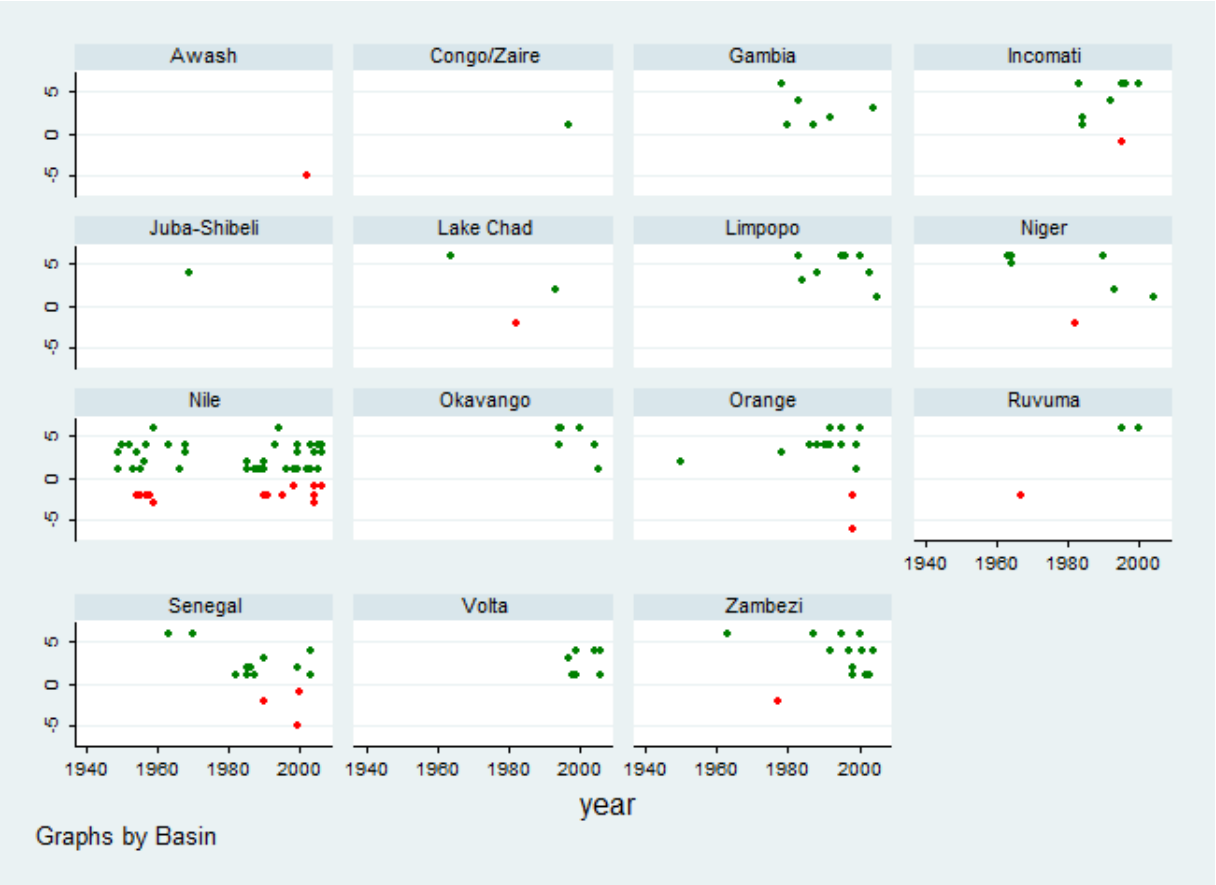
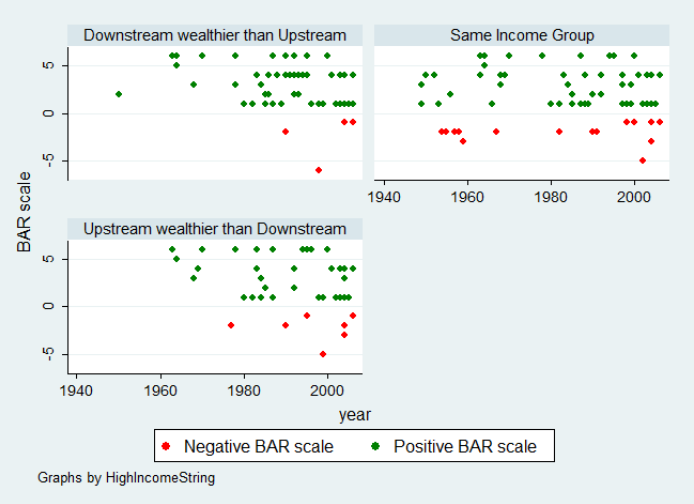


Figure 1.7 shows the distribution of the BAR scale according to upstream downstream income groups. There are a total of 192 water events in the case where country pairs are in the same income group, versus 140 when downstream nations are wealthier and 103 in the opposite case. In terms of qualitative interpretation, the number of conflictive events (red dots) is slightly lower when the downstream country is wealthier, strengthening the intuition that downstream nations are an essential component of cooperation. Not only does a strong downstream nation correlate with a higher frequency of events, it also does with more positive outcomes.

Figure 1.7: Distribution of the BAR scale according to relative wealth

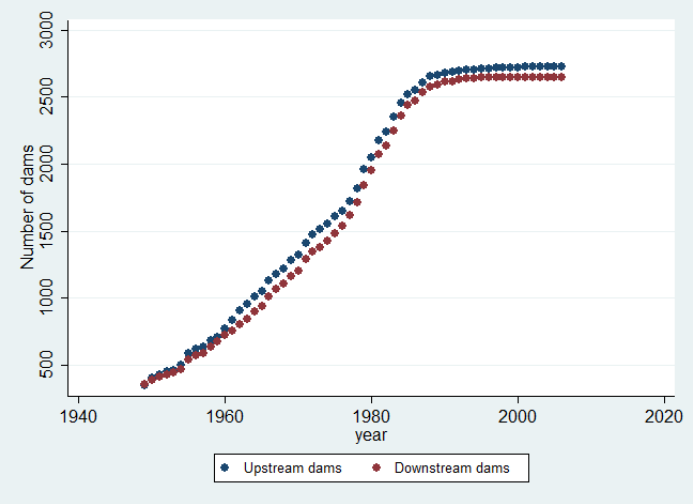


Dams

The issue of dams along a transboundary river is an essential trigger for interaction, as dams may bring positive and negative externalities to downstream users. Dams hold potential for hydropower, water storage (thus preventing flooding) or insurance against drought, but it may also modify downstream ecosystems and water availability. At a certain level of aggregation, it is difficult to know how downstream users are affected by upstream dams, especially when upstream users are also downstream to others. Taking the number of dams proxies for the importance of water investments within the river basin; it does not, in itself, provide information on whether externalities are positive or negative. This can only be observed on a case to case basis in the TFDD.

Figure 1.8 shows the number of dams according to relative position within the basin. Dams can appear several times in the graphs when they are both downstream and upstream from another dam which is why they are fairly equal in numbers. There is a steep increase in the number of dams starting in the 1960s until 1990 (a 500% increase). During that period, many transboundary water management institutions were created to accompany important investments such as dams (Nile Basin Authority, Niger Basin Authority, Zambezi Action Plan, etc.). But these institutions were, at the time, unexperienced and had difficulties enforcing the agreements. As such many dams were built with variable efficiency until a point where environmental protection and ecosystem preservation became an important point and the rate of new dams slowed down in the beginning of 2000.

Figure 1.8: Number of Dams according to relative position within the basin



Our data shows that from 1949 to 2007, 200 water interactions occurred in a configuration where the downstream dams outnumbered upstream ones. 177 events happened in the reverse situation, but only 58 occurred where there was an equivalent number of dams upstream and downstream.

1.3 Methodology

1.3.1 Modeling interaction

We start with explaining the likeliness of interaction. Our first model displays a time varying dichotomous indicator as our dependent variable, equal to 1 when a country-pair interacted in that specific year and 0 otherwise. We regress our dependent variable on our streamflow values using a fixed effects model to account for all the yearly changes that are the same for our country pairs. Our streamflow variables are built to reflect specific asymmetries between upstream and downstream values.

Our first regression with no controls is the following, where the ratio of streamflows is lagged for one year[13].

$$Event^{*}_{it} = \beta_0 + \beta_1 \frac{StreamflowU_{i,t-1}}{StreamflowD_{i,t-1}} + \beta_2 \frac{etU_{i,t-1}}{etD_{i,t-1}} + \lambda.Controls_{i,t} + \epsilon_{it} \tag{1.2}$$

for country-pair i $\in$ [1, 124], year t $\in$ [1949, 2006].

Our controls are lagged values of population, gdp, number of dams and past historical events.

Lagging for one year enables to take into account the laps of time needed for countries to account of a potential asymmetry upstream and downstream, and perhaps trigger an interaction. We made several attempts to lag our ratios up to five years ahead: the streamflow ratios kept the same sign but its significancy decreased.

[13] "et" stands for evapotranspiration; "U" is for usptream; "D" is for downstream

1.3.2 Modeling the outcome of interaction: cooperation or conflict

Our second model will focus on the Barscale as our dependent variable and now takes an integer value from -6 to +6. In order to exploit our hydrological and climatic country-pair data, we need to build a specification that allows one to control for country-pair specific traits.

First of all, the need to account for the ordered structure of our dependent variable (from -6 to 6) leads us to use an ordered probit model. Furthermore, given the strong heterogeneity of country-pairs, exacerbated by unobserved factors such as political affinities, history, culture, etc., the econometric analysis needs to account for unobservable country-pair effects and potential heteroskedaticity.

Therefore we specify a heteroskedaticity pooled panel ordered probit, which is augmented to account for unobserved time-invariant country-pair effects. We control for these unobserved effects, which are neither considered as parameters to be estimated nor as having a certain distribution and being independent from all covariates, accommodating the model by Mundlak (1978). In this way we control for fixed effects, where the modified random coefficients model leads to an estimator identical to the fixed effect estimator where unobserved effects are assumed to be normally distributed conditional on the covariates.

Baseline Setting

We first use a basic pooled panel ordered probit model. Our first regression will only include our measure of streamflow asymmetries upstream and downstream, while the second will control for asymmetries in evapotranspiration, lagged values of gdp, population, number of dams and number of events the country pair has been involved in the past.

The ordered categorical outcome for Barscale is coded in a rank preserving manner:

$$Barscale_{it} \in \{-6, ..., j, ..., 6\}$$

where $Barscale_{it}$ is attributed to country pair i for year t (t from 1949 to 2006). The vector of covariates X represents upstream and downstream streamflow as followed:

$$Barscale_{it} = \beta_0 + \beta_1 \frac{StreamflowU_{i,t-1}}{StreamflowD_{i,t-1}} + \epsilon_{it} \tag{1.3}$$

The explanatory variable corresponds to the lag ratio of upstream relative to downstream streamflow values. This regression does not include controls; our results will add the same controls as for the specification of interaction.

The cumulative probabilities of the outcome are linked to a single index of independent variables as follows:

$$P(Barscale_{it} \leq j|X_{it}) = \Phi(\alpha_j - X_{it}\beta) \tag{1.4}$$

where α_j and β_j are unknown parameters and Φ is the standard normal cumulative density function.

Well-defined probabilities are ensured if $\alpha_j > \alpha_{j-1}$ with $\alpha_j = \infty$ such that $\Phi(\infty) = 1$ and $\alpha_0 = -\infty$ such that $\Phi(-\infty) = 0$. Ordered response models are expressed by means of an underlying continuous latent process $Barscale^*_{it}$ and a response scheme:

$$Barscale^*_{it} = X_{it}\beta + \epsilon_{it} \tag{1.5}$$

$$Barscale_{it} = j \leftrightarrow \alpha_{j-1} < Barscale^{*}_{it} = X_{it}\beta < \alpha_j, j \ \in \ -6, ..., 6 \tag{1.6}$$

where $BARscale^{*}_{it}$ represents the real line that is discretized in 13 categories by the threshold parameters α_j and is in linear relation with observables and unobservables, the latter assumed to be distributed as a standard normal, $\Phi(\epsilon_{it})$.

The estimated parameters are to be interpreted as indicative of the sign but not the economic significance of the effect. Indeed, conditional probabilities are crucial in this kind of analysis and read as follows:

$$P(Barscale = j/X = x) = \Phi(\alpha_j - X_{it}\beta) - \Phi(\alpha_{j-1} - X_{it}\beta) \tag{1.7}$$

We are interested in understanding how a partial variation in one covariate (streamflow or evapotranspiration) produces a change in the cumulative distribution of the BARscale, thus a variation in all the outcome probabilities. So we need to compute average partial effects:

$$Partial \ effects : \theta_j(X, q) = \frac{partialE(Barscale/X, q)}{partialX_j} \tag{1.8}$$

where q is an unobserved random variable the unobserved heterogeneity.

And then Average Partial Effects of say X_1 is:

$$\delta_j(X_1) \equiv E_q(\theta(X_1, q)) \tag{1.9}$$

Given that the calculation of the average partial effects involves a two-step procedure where one first obtains the coefficients from the ordered probit estimation and then adjusts these, the standard errors in the second stage should be adjusted for the first stage estimation. We here follow Papke and Woolridge (2008) and bootstrap standard errors sampling from the country pairs using 500 replications. We include fixed times effects to capture yearly changes that are the same for all riparian countries. The most relevant in this context are common climatic trends, such as drought or heavy rainfall.

1.3.3 Extension to the baseline setting

It is not unfeasible to at least hypothesize that there are some unobserved (to the researcher) time invariant factors that could be correlated with our country pair cooperation and our explanatory variables. In other words, while shocks to river flow are clearly exogenous, depending on local conditions and weather, there may be geographic features that are correlated with the average river flow across country pairs and their tendency to cooperate. For example, the nature of the soil might determine the degree of transfer of water resources from upstream to downstream countries. But it could also be possible that soil quality might determine whether countries are both mainly agricultural producers and, perhaps, countries with similar economies of production are on average more likely to cooperate. It is thus desirable to at least determine whether allowing for such time invariant unobservables might influence results. Assuming that such unobserved country pair specific effects exist, the specification of the model changes as follows:

$$BARscale^{*}_{it} = \xi_i + X_{it}\beta + \epsilon_{it} \tag{1.10}$$

with t=1949,.., 2006 and i varying according to which country pair geographical configurations we are taking into account.

In a linear model ξ_i could be eliminated by a first difference estimation or by a within-transformation. The ordered probit, instead, given its non-linear form, does not permit similar methods. One option might be to use a random effects ordered probit model. However, this would assume that the unobserved time varying determinants of cooperation are not serially correlated. But it is easy to imagine that there might be some persistence in the unobserved time-varying determinants of cooperation. What we do instead is use a Mundlak transformation, i.e., we model the conditional distribution of such a term with respect to the covariates as:

$$\xi_i = \bar{X}_i\gamma + \phi_{it} \tag{1.11}$$

where $\bar{X}_i$ is the average over time of the time varying exogenous variables X_i and ϕ_{it} is a random error term with $\phi_{it}/X_i \ N(0, \sigma^2_{phi})$. In essence the Mundlak transformation entails including the average values of the time varying explanatory variables in our main specification. One should note that as long as the time varying explanatory variables are strictly exogenous, this is equivalent to fixed effects estimator. A test of $\gamma = 0$ constitutes a test that the individual country pair effects are uncorrelated with the observables.

1.4 Regression results

1.4.1 Results for interaction

Table 1.3 presents the results of our fixed effects logit regression explaining whether interaction has taken place or not. We add a binary variable "$StrD > StrU$" for whether downstream streamflow is higher than upstream (binary variable is equal to 1) or lower (binary variable is 0). The first column shows that the log-odds of interaction are significant (5% level) and negatively correlated coefficients for the lag streamflow ratio. This means that as the ratio increases (decreases) by one unit, the log-odds of interaction decrease (increase) by 0.34. In this case, the direction of the asymmetry (whether in favor of the upstream or the downstream nation) is not significant. In other words, it is a situation of asymmetry between both countries that decreases the likeliness of interaction.

In the second column, the direction of the asymmetry becomes significant. The coefficient on lag streamflow ratio is even more significant as well, at the 1% level. This means that if ratio is higher than 1 (downstream higher than upstream), giving the downstream country the advantage, interaction is less likely to occur if the asymmetry decreases the next year. On the other hand, if the asymmetry continues to grow, there is a higher log-odd of an interaction occurring.

On the other hand, if our dummy variable is equal to 0, meaning that the asymmetry is in disfavor of the downstream country, interaction is likelier if the asymmetry decreases the year after. If it continues to grow, the likeliness of events falls.

The coefficient on upstream dams is positive and significantly correlated with our dependent variable. For very additional dam upstream, log-odds of interaction are increased by 0.003. This is a fairly intuitive results as dams will likely affect the quantity or the quality of shared waters. As such they naturally lead countries to interact, whether cooperatively or in a conflictive way.

The history of cooperation between both countries is significantly and positively correlated with the dependent variable, suggesting that countries are likelier to interact if they have done so in the past. This is easily seen in figure 1.6 where we can see that interaction points generally display a close distribution in time, even when they start later than historical interacting basins such as the Nile.

Table 1.3: Logit regression results on event likeliness

	(1) Event		(2) Event	
$l.StrU/StrD$	-0.336**	(0.102)	-0.302***	(0.0893)
$StrD > StrU$	-0.426	(0.291)	-0.520*	(0.261)
$l.EtU/EtD$			-1.490	(0.969)
Dam_Ups			0.00306*	(0.00154)
Dam_DwnS			0.00278	(0.00160)
GDP_Ups			-0.0000981	(0.0000543)
GDP_DwnS			0.0000686	(0.0000458)
Pop_Ups			0.00000434	(0.00000650)
Pop_DwnS			0.00000396	(0.00000477)
lag_history			0.0843***	(0.0223)
_cons	0.462*	(0.223)	-0.152	(0.286)
N	5475		5475	
df_m	58		66	

Standard errors in parentheses

Unit of study is at the bilateral level

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

1.4.2 Results for the outcome of interaction: conflict or cooperation

Table 1.4 displays our results for the ordered probit regression on the Barscale. We also performed a logit model on our BAR scale transformed into two binary variable: "Cooperation" equal to 1 if cooperation took place (BAR scale higher than 0) or "Conflict" equal to 1 if conflict took place.

All in all, we see that the sign and statistical significance of the coefficients for our variable of interests are maintained and even increased in the logit regression on the binary variable "Cooperation" (columns 3 and 4).

The coefficients on the lag streamflow ratio are negatively correlated and significant at the 5% level in column 1 and at the 10% level when adding controls. In columns 1, 2 and 3, we learn that an increased asymmetry in upstream vs downstream flows brings higher likeliness of conflictive interaction the year after. In both cases (ordered probit and logit), the economic significance of this result decreases when controlling for our climatic and economic variables. The dummy variable for whether downstream streamflow is higher or lower than its upstream counterpart is not significant in column 2, but is in column 3 (logit regression adding controls). It is thus the asymmetry between both countries that counts, whether in favor of one or the other.

The second column show that the number of dams upstream and downstream are relevant for the outcome of cooperation; an additional dam upstream or downstream, keeping other factors constant, increases the BAR scale by 0.001. An in-depth reading of the transboundary freshwater dispute database show that countries are generally more inclined to agree on the use of dams along the river basin. Dams are seen as collaborative projects and their construction is the result of a consensus, even when feared by downstream nations. There are many benefits related to flood control, hydropower production, evening out flow for downstream agriculture or even enhancing water transportation for the benefit of both riparians. Wolf (1995b) even goes to saying that destroying an existing dam would bring disastrous consequences for the quality

Table 1.4: Ordered probit regression results on Barscale including Mundlak terms and logit results on binary variable Cooperation/Conflict

	Ordered probit		Logit regression		Logit regression	
	(1)	(2)	(3)	(4)	(5)	(6)
	BAR scale	BAR scale	Coop	Coop	Conflict	Conflict
$l.StrU/StrD$	-0.00921**	-0.00749*	-0.323**	-0.299***	-0.157	-0.0134
	(0.00287)	(0.00310)	(0.100)	(0.0893)	(0.304)	(0.154)
$StrD > StrU$		-0.0180	-0.459	-0.545*	0.259	-0.193
		(0.0603)	(0.288)	(0.264)	(0.844)	(0.796)
$l.EtU/EtD$		-0.362		-1.288		-8.290*
		(0.251)		(0.983)		(3.414)
Dam_Ups		0.00177***		0.00333*		-0.115
		(0.000410)		(0.00155)		(0.0950)
Dam_DwnS		0.00117**		0.00267		0.0183**
		(0.000409)		(0.00161)		(0.00665)
GDP_Ups		-0.0000238		-0.0000972		0.0000273
		(0.0000162)		(0.0000548)		(0.000298)
GDP_DwnS		-0.00000363		0.0000721		-0.00143*
		(0.0000125)		(0.0000461)		(0.000598)
Pop_Ups		-0.00000269		0.00000317		0.0000346
		(0.00000195)		(0.00000662)		(0.0000201)
Pop_DwnS		-0.000000306		0.00000371		0.0000163
		(0.00000149)		(0.00000492)		(0.0000122)
lag_history		0.0298***		0.0715**		0.178***
		(0.00571)		(0.0218)		(0.0521)
_cons			-1.117**	-0.455	-4.263***	2.831
			(0.391)	(1.127)	(1.240)	(3.609)
N	5475	5475	5475	5475	5475	5475
df_m	57	66	58	66	58	66

Standard errors in parentheses

Unit of study is at the bilateral level

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

and quantity of water running down the watershed. Our results thus are in line with the general intuition that the building of dams has favored cooperative interaction rather than conflict.

The history of cooperation between upstream and downstream country-pairs is significant at the 5% level and positively correlated with the BAR scale in both cases. This suggests that history of interaction between countries increases the likeliness that the outcome of interaction will be cooperative.

In order to simplify the interpretation of our results for interaction and its outcome, we summarized them in table 1.5:

Table 1.5: Interpretation of results according to direction of streamflow asymmetry

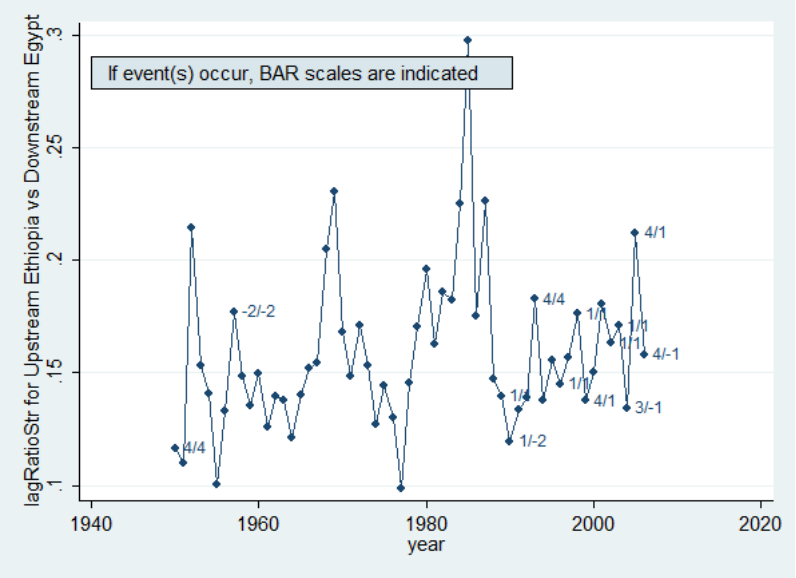
	Asymmetry at $t+1$	
Status quo at t	$\frac{StrU}{StrD} \nearrow$	$\frac{StrU}{StrD} \searrow$
$StrU > StrD$	Divergence (disf D)	Convergence (favor D)
$StrU < StrD$	Converge (U+)	Divergence (D+)
Result	Event $\searrow$ Conflict $\nearrow$	Event $\nearrow$ Cooperation $\nearrow$

Source: Author computations

We see here that events are cooperation are more likely when the downstream country is at least as well off as the previous year (right column). Indeed, in both cases, the asymmetry, creating whether convergence or divergence of streamflow, is in favor of the downstream country. In the first column, we see that an increase in the streamflow ratio can only bring divergence or convergence in favor of the upstream nation, and thus lower occurrence of interaction and higher likeliness of conflict. As such, given that the upstream nation has a natural advantage over the resource, we deduce that the downstream country needs to feel in a comfortable position water-wise to interact with a positive outcome.

This result is easily seen in the Nile basin where downstream Egypt has always threatened upstream Ethiopia to attack if its water availability were to be affected. Figure 1.9 plots the streamflow ratio along the years between both countries and displays the BAR scale values when event occurred. In this case, dowstream flows are higher than upstream, meaning that likeliness of events occurring increases as the streamflow ratio increases but that streamflow ratio has little impact on the BAR scale itself. Most events have been cooperative as years go by, given international pressure and authority within the Nile basin. Recently, Egypt has accepted the building of the Renaissance dam in Ethiopia, mostly because all the conditions to protect its water supply had been met.

Figure 1.9: Lag streamflow ratios for upstream Ethiopia vs downstream Egypt: BAR scales are indicated when events occur



1.5 Conclusion

The complexity of understanding what leads two upstream/downstream countries to cooperate or enter conflict over water lies in multidisciplinary approaches. Political and economic incentives will respond to each other as they interact with climate, geography, culture and history. Isolating the effects of these features becomes difficult, as country pairs display specific features which need to be accounted for. The analysis should also chose carefully the type of data to apply and the right unit of study for it to provide results of interest.

In this study, we attempt to determine if streamflow asymmetries and variations have facilitated bilateral interaction between African riparian countries between 1950 and 2006 and whether they influenced the outcomes of such interactions. Our results are summarized below.

First of all, downstream nations play a determinant role in triggering interaction and shaping their cooperative outcome. Their relatively weaker geographical position within the basin provides incentives to engage into formal cooperation and foster positive outcomes.

Second, downstream vulnerability differs between river basins. When upstream water availability is greater than downstream, high asymmetry will decrease the likeliness of formal interaction and the probability of it being cooperative. Country pairs with little water asymmetry thus tend to cooperate more. On the other hand, if downstream water availability is relatively higher than upstream, it is only when the downstream country is at least as well off as the previous year that interaction - and cooperation - occurs. This suggests that downstream variations of streamflow are likelier to trigger formal water agreements than upstream changes in water availability.

Fourth, the building of dams upstream has been a factor of cooperation rather than conflict. Although this may sound counter-intuitive, dams have always been the result of intense (and sometimes conflictive) talks but always providing some good to all parties. Given the different economic externalities (flood control, irrigiation for agriculture, etc.), downstream nations are bound to find common grounds with their upstream counterparts.

Lastly, recent history of cooperation matters: nations are more likely to interact and cooperate if they have done so in the past. On the other hand, conflict does not affect likeliness of conflict or cooperation, giving hope to many transboundary basins where little interaction has happened in the past.

All in all, the upstream-downstream relationship tremendously complexifies the understanding of transboundary water negotiations. There are several implications to this study which concern data availability and trustworthiness, the qualification of conflictive vs cooperative relations, the interpretation of water events and the importance of interdisciplinary approach.

1.6 Appendix

1.6.1 BARscale as described in Wolf's database

BARscale	Event Description
-6	**Extensive War Acts** causing deaths, dislocation or high strategic cost: Use of nuclear weapons; full scale air, naval, or land battles; invasion of territory; occupation of territory; massive bombing of civilian areas; capturing of soldiers in battle; large scale bombing of military installations; chemical or biological warfare.
-5	**Small scale military acts**: Limited air, sea, or border skirmishes; border police acts; annexing territory already occupied; seizing material of target country; imposing blockades; assassinating leaders of target country; material support of subversive activities against target country.
-4	**Political-military hostile actions**: Inciting riots or rebellions (training or financial aid for rebellions); encouraging guerilla activities against target country; limited and sporadic terrorist actions; kidnapping or torturing foreign citizens or prisoners of war; giving sanctuary to terrorists; breaking diplomatic relations; attacking diplomats or embassies; expelling military advisors; executing alleged spies; nationalizing companies without compensation.
-3	**Diplomatic-economic hostile actions**: Increasing troop mobilization; boycotts; imposing economic sanctions; hindering movement on land, waterways, or in the air; embargoing goods; refusing mutual trade rights; closing borders and blocking free communication; manipulating trade or currency to cause economic problems; halting aid; granting sanctuary to opposition leaders; mobilizing hostile demonstrations against target country; refusing to support foreign military allies; recalling ambassador for emergency consultations regarding target country; refusing visas to other nationals or restricting movement in country; expelling or arresting nationals or press; spying on foreign government officials; terminating major agreements. Unilateral construction of water projects against another countryï£¡s protests; reducing flow of water to another country, abrogation of a water agreement.
-2	**Strong verbal expressions displaying hostility in interaction**: Warning retaliation for acts; making threatening demands and accusations; condemning strongly specific actions or policies; denouncing leaders, system, or ideology; postponing heads of state visits; refusing participation in meetings or summits; leveling strong propaganda attacks; denying support; blocking or vetoing policy or proposals in the UN or other international bodies. Official interactions only.
-1	**Mild verbal expressions displaying discord in interaction:**Low key objection to policies or behavior; communicating dissatisfaction through third party; failing to reach an agreement; refusing protest note; denying accusations; objecting to explanation of goals, position, etc.; requesting change in policy. Both unofficial and official, including diplomatic notes of protest.
0	**Neutral or non-significant acts for the inter-nation situation**: Rhetorical policy statements; non-consequential news items; non-governmental visitors; indifference statements; compensating for nationalized enterprises or private property; no comment statements.

1	**Minor official exchanges, talks or policy expressions– mild verbal support**: Meeting of high officials; conferring on problems of mutual interest; visit by lower officials for talks; issuing joint communiques; appointing ambassadors; announcing cease-fires; non-governmental exchanges; proposing talks; public non-governmental support of regime; exchanging prisoners of war; requesting support for policy; stating or explaining policy.
2	**Official verbal support of goals, values, or regime**: Official support of policy; raising legation to embassy; reaffirming friendship; asking for help against third party; apologizing for unfavorable actions or statements; allowing entry of press correspondents; thanking or asking for aid; resuming broken diplomatic or other relations.
3	**Cultural or scientific agreement or support (non- strategic)**: Starting diplomatic relations; establishing technological or scientific communication; proposing or offering economic or military aid; recognizing government; visit by head of state; opening borders; conducting or enacting friendship agreements; conducting cultural or academic agreements or exchanges. Agreements to set up cooperative working groups.
4	**Non-military economic, technological or industrial agreement**: Making economic loans, grants; agreeing to economic pacts; giving industrial, cultural, or educational assistance; conducting trade agreements or granting most favored nation status; establishing common transportation or communication networks; selling industrial- technological surplus supplies; providing technical expertise; ceasing economic restrictions; repaying debts; selling non-military goods; giving disaster relief. Legal, cooperative actions between nations that are not treaties; cooperative projects for watershed management, irrigation, poverty-alleviation.
5	**Military economic or strategic support**: Selling nuclear power plants or materials; providing air, naval, or land facilities for bases; giving technical or advisory military assistance; granting military aid; sharing highly advanced technology; intervening with military support at request of government; concluding military agreements; training military personnel; joint programs and plans to initiate and pursue disarmament.
6	**International Freshwater Treaty**; Major strategic alliance (regional or international): Fighting a war jointly; establishing a joint military command or alliance; conducting joint military maneuvers; establishing economic common market; joining or organizing international alliances; establishing joint program to raise the global quality of life.

1.6.2 Description of the African basins studied in this paper

Basin	Nber of riparian countries	Riparian countries	Total area of basin (km^2)	Population	Population Density (pers./km^2)
Awash	2	Ethiopia, Somalia	154,352	16,406,800	22.15
Congo/Zaire	13	Angola, Burundi, Central African Republic, Cameroon, Democratic Republic of Congo, Gabon, Malawi, Rwanda, Sudan, Tanzania, Uganda, DRC, Zambia	3,674,844	81,395,310	22.15
Incomati	3	Mozambique, Swaziland, South Africa			
Juba-Shibeli	3	Ethiopia, Kenya, Somalia	799,773	18,361,000	22.96
Lake Chad	8	Central African Republic, Cameroon, Algeria, Libya, Niger, Nigeria, Sudan, Chad	2,380,489	41,249,002	17.33
Limpopo	4	Bostwana, Mozambique, South Africa, Zimbabwe	413,552	14,569,200	35.23
Niger	11	Sierra Leone, Benin, Burkina Faso, Ivory Coast, Cameroon, Algeria, Guinea, Mali, Niger, Nigeria, Chad	2,105,196	88,602,900	42.09
Nile	11	Burundi, Central African Republic, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, Sudan, Tanzania, Uganda, DRC	3,020,100	184,079,360	60.95
Okavango	4	Angola, Botswana, Namibia, Zimbabwe	704,935	1,482,700	2.10
Orange	4	Botswana, Lesotho, Namibia, South Africa	944,051	13,002,500	13.77
Ruvuma	3	Malawi, Mozambique, Tanzania	151,241	2,196,600	14.50
Senegal	4	Guinea, Mali, Mauritania, Senegal	434,518	5,597,600	12.88
Volta	6	Benin, Burkina Faso, Ivory Coast, Ghana, Mali, Togo	411,203	22,794,500	55.43
Zambezi	9	Angola, Botswana, Mozambique, Malawi, Namibia, Tanzania, Congo, Zambia, Zimbabwe	1,380,197	33,714,700	24.43

1.6.3 Extract from a query for the Nile basin in the Barscale database

Name	Signatories	Issue Area	Date	Barscale
Agreement between the government of the United Arab Republic and the government of Sudan for full utilization of the Nile waters	Egypt, Sudan	Water quantity, Flood control/relief	1959-11-08	6
Musa, Suduan minister of irrigation and hydraulic resources, today opened regular meeting of permanent joint technical board for Nile waters at board's headquarters	Ethiopia, Sudan, United Republic of Egypt, Uganda	Joint Management	1989-09-25	1
Rival ethnic groups, the Afar (Ethiopia) and Issas (Somali), are clashing over scarce water due to a devastating drought with large impact on the pastoralists. Issas are moving into Afar territory for use of their watering holes.	Ethiopia, Somalia	Water quantity	2002-07-29	-5
A two-day shared vision meeting between Niger's Minister of Water, Bank Group, and the Niger Basin Commission to discuss protection of the Niger River and sustainable dev. in the basin.	Benin, Burkina Faso, Cameroon, CÃ‡te d'Ivoire, Guinea, Mali, Niger, Nigeria, Chad	Joint Management	2008-01-24	1

1.6.4 The Pfafstetter numbering system

The Pfafstetter numbering system, as developed by the Brazilian engineer Otto Pfafstetter in 1989, uses different levels of classification according to the type of watershed. Those are divided into 3 types: basins, interbasins and internal basins. A Pfafstetter basin is an area that does not receive drainage from any other drainage area; it actually contains the headwater of the river reach for which the watershed is defined. A Pfafstetter interbasin is a watershed that receives flow from upstream watersheds. An internal basin is a drainage area that does not contribute flow to another watershed or to a waterbody, it is closed.

Level 1 classification is the highest one and is attributed to major river basins, level 5 being the lowest and attributed to minor rivers or streams. At each level, the four largest basins are identified and assigned Pfafstetter digits 2, 3, 6 and 8 in a clockwise direction. The five largest interbasins are assigned digits 1, 3, 5, 7 and 9, clockwise. Internal basins are assigned the number 0. Basins continue to be subdivided and numbered as before at levels 2 to 5. Interbasins continue to be divided into the 4 largest basins at levels 2 to 5 but instead of numbering the resulting basins in a clockwise direction, the basins are numbered from the most downstream basin to the most upstream.

For example, a Pfafstetter number of 8673 indicates that the basin drains through basin number 8 at level 1, basin number 6 at level 2, interbasin number 7 at level 3 and interbasin number 3 at level 4.

Because certain identification numbers corresponded to two countries at the same time, we had to look at the 5 digit number identification (the first smallest basin identification after the 6 digit number one) in order to look where that part of the basin was located in majority. Once each of our 6-digit basin identification number was assigned to a unique country, the Pfafstetter system enabled us to derive a downstream/upstream relationship between all of our 6 digit basin identification number, thus deriving a downstream/upstream relationship between African countries.

Chapter 2

The Globalization of Virtual Water Flows: Explaining Trade Patterns of a Scarce Resource

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Abstract

Although 80% of global water withdrawals are for agriculture, the burgeoning literature on virtual water has not reached a consensus on the applicability of the comparative advantage theory in water resources for food production and trade. Using panel data of bilateral virtual water trade flows, we first demonstrate that the driest countries resort to trade as a means to alleviate water scarcity (Hecksher-Ohlin definition). Second, we demonstrate that relative water productivity and food trade display an inverted u-shape, suggesting a disregard for water resources relative to the lack of other inputs (capital, technology, qualified labor) in relatively water scarce countries. To address water scarcity, we advise policy makers in water-inefficient countries to re-allocate trade flows for water-intensive products that are only benefitting from cheap labor - and focus on water productivity for water-intensive products that require specific land-climate context. Meat, Vegetables and Fruits are the three sectors for which there seems to be a high margin for improvement.

JEL classification: F14, O13, P28, Q17, Q25, Q27

Keywords: Water Endowments, Water Productivity, Crop Water Requirements, International Trade, Food Security, Gravity

2.1 Introduction

The claim that the wars of the future will likely occur over freshwater have resonated in various policy circles. Given that water is crucial for basic survival, irreplaceable, transcends international borders, and often scarce, it follows that states will take up arms to defend access to a shared river. Yet scholarly research has largely debunked this claim, touting the notable absence of inter-state violence over shared water as an indication of what the future may hold (Wolf, 1998 and 2003).

Several conjectures have been offered to explain the absence of water wars. Some authors have stressed the cooperation-inducing nature of scarce water finding that decreased water availability actually motivates the formation of international water treaties (Dinar 2009; Tir and Ackerman 2009). Other scholars have pointed to the role of so-called second-order resources or institutional capacity (such as water augmentation technologies and know-how) as a means of dealing with physical water scarcity (Ohlsson 1999; Turton and Ohlsson 2000). A third explanation, and the focus of this investigation, pertains to the role of trade in water-intense food products or embedded water (Allan 1993, 1997). Popularly known as "virtual water," the concept suggests that agricultural and non-agricultural commodities require water, and by importing such products countries are spared the economic and political stress of mobilizing the needed allocation of water to produce the product indigenously (Allan 2001 and 2002).

To date, the topic of virtual water has received a great deal of attention in the extant literature. Two competing arguments have been advanced. The first considers water endowments, and in particular exporter-importer relative water endowments, as the main motivation for trade in water-embedded food products suggesting that virtual water flows from relatively water rich countries to water poor countries. The alternative explanation places the focus on exporter-importer relative water productivity, suggesting that virtual water flows from countries using water relatively more efficiently in comparison to those using water less efficiently. Methodologically, both explanations have been analyzed and explored in the context of national and regional case studies (Yang and Zehnder 2002; De Fraiture et al. 2004; Kumar and Singh 2005; Verma et al. 2005; Ma et al. 2006; Novo et al. 2009; Mekonnen and Hoekstra 2014) and, in some isolated cases, cross-national empirical investigations albeit with product or time restrictions (Hoekstra and Hung 2002 and 2005; Hoekstra and Chapagain 2007; Fracasso 2014).

Despite the merits of the two above arguments, the literature has still not reached any type of consensus. If the first reason for this is methodological, the second is that water is only one of many factors that farmers and countries will consider when choosing which crops to grow. Among these factors are world demand, prices, competition and historical crops/know-how. Keeping this in mind, this paper sets out to make two main contributions to the existing literature. First, we consider the determinants of virtual water flows by empirically assessing the two competing explanations. By examining these two arguments side-by-side we are able to ascertain the strength of each explanation as it relates to understanding virtual water flows and food trade. Our second contribution is methodological given that we undertake a cross-national empirical study using panel data, as opposed to a case-study approach or cross-sectional data approach, which spans more than a decade of trade relations between countries.

Using a gravity model approach with two high dimensional effects, as established in Head and Mayer (2013), our results demonstrate that food bilateral trade flows are positively correlated with exporter-importer water endowment asymmetries, revealing that the driest countries indeed

resort to food trade to alleviate water scarcity as originally conceived by Allan (1991) and act according to their comparative advantage. We also find that relative water footprint asymmetries at the product level also matter but with strong non-linear effects. As expected, food flows from relatively more productive to less productive countries, thus saving water globally. However, past a certain threshold, high water productive countries import products from relatively low water productive nations thus challenging the validity of comparative advantage as far as water productivity is concerned. Our data also show that between 1994 and 2007, food trade from more to less water productive countries resulted in saving $4750km^3$ of water which represents around 25% of the total $18700km^3$ of water that was traded during that period. We also find that in terms of water savings, cereal trade is currently the most efficient in the distribution of goods from relatively more to less water productive countries.

Below we begin with a theoretical discussion of the two competing explanations pertaining to virtual water flows. We then discuss additional independent and control variables important for understanding trade in water embedded products. After operationalizing our variables and explaining our identification strategy, we discuss the results and conclude with some lessons as well as policy implications.

2.2 Explaining Virtual Water Flows: Water Endowments versus Water Productivity

The term "virtual water" was coined in 1993 by Tony Allan to draw attention to the notion that serious local water shortages could be effectively ameliorated by global economic processes. The Middle East and North Africa, or MENA, was used as an example of a region embodying significant food imports. While some scholars had contended that the high food imports was a sign of the region's dismal failure in feeding its own people, others argued that food imports actually provided an opportunity for the region's economies to solve their serious and deteriorating water scarcity. In other words, the political and economic impacts brought about by water scarcity (such as a possible armed conflict over scarce water resources) was moderated by the region's ability to reach out to other watersheds in the world, through international trade in virtual water or water embedded in imported agricultural products (Hakimian 2002). This claim also corresponded to the more general neo-liberal argument proposed by the international trade literature, suggesting that the probability of war is lower for countries that trade more while also enhancing cooperative political relations (Mansfield and Pollins 2003; Martin, Mayer, Thoenig, 2007).

The general virtual water contention stems from Ricardo's comparative advantage (1817) and the ensuing Heschker-Ohlin-Samuelson model (1941) on factor endowment in international trade: countries will export products that use their abundant and cheap factor of production and import products that use the countries' scarce factors. To date, a variety of studies have examined the endowment contention. In some cases, the argument has been confirmed yet in other cases ambiguous, nuanced, or even contradictory results were identified. Yang and Zehnder (2002), for example, found that while the relation between water endowments and virtual water trade patterns seemed to follow the rules of comparative advantage for cereal trade in certain southern Mediterranean countries, such patterns were confined to a restricted sample of countries. Yang et al. (2003) found that a clear negative correlation between water endowments and cereal imports existed only beneath a certain threshold (less than 2000 m^3 of water per capita per year for a specific country)[1].

[1] According to the Falkenmark indicator (1989), a country is considered under water stress if its water avail-

Finally, the literature also revealed that certain countries actually had counter-intuitive production and trade strategies related to their water endowments as in the famous cases of water-poor Northern China exporting food to better-endowed Southern China (Ma 2004, Ma et al. 2006, Guan and Hubacek 2007, Liu and Zeng 2012) and flood-prone Eastern India importing food from drier states of the country (Verma et al., 2008). In many cases, the issue of food security/self-sufficiency appeared as a main driver for agricultural subsidization, extensive irrigation schemes in dry areas and massive food imports even when water was relatively abundant. Most recently, and employing a large-n methodology, Fracasso (2014) finds that national water endowments as well as pressures on natural resources indeed determine virtual water flows between countries. While the study is limited to a single year, the results are robust across the estimation models.

The diversity in results pertaining to the endowment contention suggests that water availability may not be a sufficient policy criterion for explaining international trade in water embedded products (Wichelns, 2010). Scholars further contended that endowments likely played a minor role compared to other variables such as climate and land (Verma et al. 2005, Kumar and Singh 2005) as well as labor, capital, politics, economics, history, and culture (Turton 2000, El Fadel and Maroun 2003, Warner 2003, Novo et al. 2009, Hoekstra 2010, and many others). These results led some to conclude that although virtual water is conceptually based on the Heckscher-Ohlin framework, the model performed poorly (Ansink 2010).

As an alternative to the water endowment contention, studies have also suggested that a major indicator of food production and export strategies was the amount of water required to produce a unit of crop or livestock, namely water footprint. The water footprint as exemplified in the Water Footprint Network (WFP) introduced by Hoekstra and Hung (2002) and further elaborated by Chapagain and Hoekstra (2004) is a complex variable that varies within countries and across regions. It is driven by exogenous climatic and soil conditions, as well as a large range of endogenous factors such as economic strength (Turton, 2000), government subsidies, technology, capital, labor and food security policies (Wichelns, 2010, De Fraiture et al., 2004; Novo et al., 2009).

Water Footprint figures provide relevant information on the structure of food markets and have been widely used in quantitative studies at the global, national, sectoral and product levels. For instance, Hoekstra and Hung (2002) first quantified volumes of all virtual water trade flows between 1995-1999 showing that 13% of water used for crop production in the world was not used for domestic consumption but was virtually exported. At the national level, Chapagain and Orr (2008) computed that 62% of the United Kingdom's virtual water was accounted for by imports, highlighting the country's dependency on food imports. At the sectoral level, Chapagain et al (2006), showed that 84% of the water footprint of cotton in Europe is located outside Europe, specifically impacting water resources from scarce regions in India and Uzbekistan. Comparing countries' performance in water footprints, De Fraiture (2004) also demonstrated that India produces 0.39 kg of wheat for every m^3 of water used compared to 0.72 in the US. Still, India is among the largest exporters of wheat, thus implying an inefficient allocation of water resources at the global level. The water footprint argument thus reveals much about our dependency towards resources, and even more, whether it is a local or foreign water-dependency.

ability is less than 1700 m^3 per capita per year. This figure includes daily water requirement (drinking water, sanitation, bathing and food preparation) and embedded water in food, textile, energy, etc.

Comparing water footprint figures also sheds light on differences in the productivity of water use across regions and countries. However these figures remain difficult to interpret because of the diversity of inputs and local conditions. Water resources are also often overlooked as essential inputs, which means that high levels of water productivity may or may not be sustainable.[2] In general, using water productivity figures requires to consider the larger political and historical context. For instance groundwater depletion and low water productivity in India cannot be observed separately from food security policies and the Green Revolution (Singh, 2006). Water scarcity in Kenya has been argued to be less restrictive than lack of other expensive inputs such as capital and technology making Kenya a highly water-productive nation at the cost of its own resources (Ong and Swallow, 2003). On the other hand, capital-abundant nations like Israel or Singapore have massively invested in water-saving technologies and achieved high levels of water productivity. The interpretation of our results will thus take these factors into consideration.

2.3 Data

Although the extant literature has examined the water endowment and productivity arguments separately and largely from a qualitative or limited (focusing on specific regions) quantitative fashion, the two arguments have not been subject to systematic, country-pair and cross-national scrutiny. In addition, no empirical cross-national study has been conducted on a cross-sector or time series level. This paper empirically sets out to fill the lacuna in the literature and shed further light on this debate.

2.3.1 Bilateral trade flows

This paper considers annual bilateral trade flows between 1994 and 2007 at the product level in tons as the dependent variable. Trade flows are taken from the BACI dataset, as developed in the CEPII report by Gaulier and Zignago (2010). They provide data at the highest level of product disaggregation, 6 digits Harmonized System (HS) code from 1994 to 2007. The original data is sourced from the COMTRADE database of the UN Statistical Division and were harmonized for more than 200 countries since 1994. The BACI dataset is particularly suitable for this investigation because it deals with missing data by employing a reconciliation methodology[3]. Missing values of bilateral trade for a specific product can occur if one or both of the countries fail to report their trade flows. BACI utilizes the double information available on each trade flow to provide a unique "reconciled" value for each flow reported by at least one of the partners. The only missing values are those of two non-reporting countries[4]. Our dataset also distinguishes directions of trade: observations consist in reported trade flows of a particular product p from exporter i to importer j at year t.

[2]Water productivity is easier to achieve under rain-fed conditions but knowledge and technology can dramatically improve water efficiency and offset - to a certain extent - the impact of a drier climate. On the other hand, the absence of capital investment and knowledge in farming and climate uncertainties can easily foster sub-optimal use of water.

[3]Reconciliation provides an explanation for the discrepancy between the import and export statistics of trading partners by identifying conceptual reasons for them and explaining differences in data collection and processing. See United Nations (2004). Similar to COMTRADE, BACI does not report zero values of trade because of computational issues. It also does not report zero values for products no longer, but previously, traded between two countries, raising the issue of selection bias. Furthermore, a missing observation is considered a zero when at least one of the trading partners reports its trade to the UN. If both partners are not reporting, the missing observation is considered a true missing value.

[4]See Gaulier and Zignago (2010) for more detailed explanations

2.3.2 Relative water endowments and footprints

To test our two arguments we quantify and compare the impact of relative water-land endowments and water productivity on food trade. These indicators are both measured as a ratio to identify how asymmetries in endowments and productivities between exporting and importing countries shape their food trade strategies.

In order to capture the effect of resource endowment asymmetries, we include the ratio of actual renewable water resources per ha of land for our country pairs, following the reasoning that when access to arable land increases, the ability for a country to use its water resource and raise livestock or produce crops increases (Kumar and Singh, 2004). Actual renewable water resources per year are taken from the FAO Aquastat dataset and arable land data is provided by the World Bank indicators[5]. Total renewable water resources are the sum of Internal Renewable Water Resource (IRWR)[6] and External Renewable Water Resource (ERWR)[7]. Although the IRWR is roughly fixed across time, the ERWR can vary with time. Total water resources per capita thus decrease over time because of population increase and political or climatic events changing the ERWR.

We include a squared term to account for non-linear effects of resource asymmetries on virtual water trade and to identify whether excessive asymmetries might affect bilateral trade of food products. Indeed, Yang et al. (2002), De Fraiture et al (2004) and Wichelns (2010) claim that the significance of water scarcity over food trade is strongest for water poor countries. In the result tables, the variables will be displayed as $RatioWaterLand$ and $RatioWaterLand^2$.

We hypothesize that virtual water exports will be positively correlated with water per land asymmetries, supporting the literature which has demonstrated that a country's ability to produce is largely determined by the amount of arable land it has access to and water availability (Kumar and Singh 2004).

Water productivity figures are taken from Mekonnen and Hoekstra (2011) and Chapagain and Hoekstra (2003) for crops and livestock respectively[8]. Mekonnen and Hoekstra (2011) provide national water footprint figures for 146 crops disaggregated at the 6-digit HS level, averaged over the period 1996 to 2005. We use their data for 146 crops - which correspond to 102 different sub-categories (HS4) of 18 major crops (HS2) - and 144 livestock products (HS6). Appendix A provides a detailed description of the crops and livestock products we cover in this analysis.

We control for relative values of water footprint for a specific crop/livestock product p traded

[5]Visit http://www.fao.org/nr/water/aquastat/dbase/index.stm and http://data.worldbank.org/indicator

[6]Long-term annual flow of rivers and recharge of aquifers generated from endogenous precipitation

[7]Resources not generated in the country, including inflows from upstream countries, border lakes and/or rivers; takes into account the quantity of flow reserved by the upstream or downstream country through formal or informal agreements

[8]These studies on water footprint, as well as others (Chapagain et al. 2006a; Yang and Zehnder, 2007), have made a point of distinguishing between blue, green and grey water. In this paper, we do not make the distinction between water types for two reasons: one pertains to the issues around the economic interpretation of green versus blue water; the other relates to computational issues. Blue water is volume of surface and groundwater consumed or evaporated as a result of the production of a good. Green water is rainwater that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetatio. Grey water is the volume of freshwater required to assimilate the load of pollutants based on existing water quality standards. The relevance of dividing empirical estimates of virtual water flows into blue, green and grey components has been questioned (Wichelns, 2010) because the methodology is not based on a conceptual framework able to guide policies. It has been suggested that the opportunity cost of green water is smaller than that of blue water (Yang et al., 2006; Aldaya et al. 2008, 2010) while Wichelns argues this interpretation can be overturned according to local country characteristics.

between the exporter i and the importer j. We also include the squared term of productivity ratios for the same reasons as above. In the regression tables, they will be displayed as $RatioWFP$ and $RatioWFP^2$.

Water footprint figures are available for about 77% of trade flows provided by BACI, hence we restrict our analysis to the trade flows for which we have this information. We hypothesize that the exporter-importer ratio of water footprint for a specific product should be negatively correlated with exports, thus supporting the fact that countries make use of their relative comparative advantage in water resources.

2.3.3 Gravity and control data

We include a set of control variables associated with gravity models for trade as well as additional variables that impact the extent of food trade. In all, these variables proxy for the countries' geographic proximity, cultural affinity, and political relations as well as demographic and economic conditions.

Gravity Variables

We utilize control variables inherent to gravity models for trade (Tinbergen 1962). Referred to as multilateral resistance terms they include the distance between trade partners, contiguity of the states, language and common colonizer (Anderson and van Wincoop, 2003). We hypothesize that as the distance between trade partners diminishes and/or when trade partners are immediate neighbors sharing a border, the level of trade will increase. States sharing a common language and common colonizer should also evince increased trade. Data for these variables is taken from Head, Mayer and Ries (2010).

Recent research has demonstrated that overall trade relations are also an important component of a trade gravity model (Carrere 2006). In particular, regional trade agreements (RTAs) have been shown to promote peaceful relations between states as well as increased inter-state trade (Mansfield and Pollins 2003; Carrere 2006). We account for the states' membership in a RTA (using a dummy variable) utilizing data in Head et al (2010).

Demographic and Economic Controls

A growing population is one of the main drivers of increased water withdrawals as well as food imports (Rosegrant and Ringler, 2000; Liu et al., 2008; Ercin and Hoekstra, 2014). Taking population data from the Penn World Table (PWT) 7.0,[9] we include the relative rate of exporter-importer population increase from one year to another allowing us to compare the level of strain on each trading partner.

We hypothesize that countries with a high rate of population growth will need to either increase food production should they have the means to do so or decrease exports/increase imports to satisfy national demand. This would mean a negative correlation between the ratio of population rate of increase and exports.

The economic power of a country also plays an important role in a country's ability to engage in virtual water trade. Turton (2000) explains that the very difference between countries that use virtual water as a rationale coping strategy and those who resort to food aid is the ability to pay, thus increasing the economic leverage offered by a developed industrial-based economy

[9]It is provided by Alan Heston, Robert Summers and Bettina Aten, Penn World Table Version 7.0, Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania, May 2011.

over a developing, predominantly agriculture-based one. Hoekstra (2010) discusses the ability of rich countries to invest capital into water-efficient technologies, hence increasing a countries' own comparative advantage in producing water-intensive goods. Furthermore, food trade is subject to particularly high trade costs which end up excluding certain developing countries (Hoekstra and Hung, 2002; Reimer, 2012).

Following Dinar et al. (2011), we measure asymmetries of wealth by considering the ratio of GDP per capita, taken from the World Penn Table as well (gdp per capita is derived from growth rates at 2005 constant prices). Since the wealthiest countries in the world are also among the largest exporters of virtual water, we hypothesize that exports will increase along with the ratio of wealth between the exporting and the importing country. However, we also recognize that very poor countries may not be able to participate in the global virtual water trade. Hence we measure for both a linear and quadratic relationship.

We also control for asymmetries in food price levels since access to, and trade, in food is mainly constrained by incomes and food prices. We utilize a food price index, provided by the FAO, and calculate a ratio measured as food purchasing power parity (FoodPPP) divided by the general PPP. This ratio of domestic food price index captures the importance of food in the overall consumption basket and we expect that the indicator will be higher for least developed countries. These nations are not self-sufficient in domestic food production and are financially constrained when considering food imports, suggesting that this variable should be negatively correlated with exports.

2.3.4 Summary Statistics

Table 2.1 provides summary statistics for the variables of interest. The dependent variable, virtual water exports, is at the dyadic-year-product level. The explanatory variables are all country-pair and year specific, apart from contiguity, common colonizer, common language and distance which are fixed over time. Our study covers 179 countries, 2113 products from 25 different trade sectors. All of the countries have at least 1 million inhabitants so as to reduce the effect of specific local conditions of small countries on the analysis (see Yang et al. 2003).

We observe that exporting countries display a smaller average water-land endowment in comparison to importing nations, but with a smaller standard deviation. Indeed, part of the importing countries in this study tend to feature extreme values of water-per-ha-of-land endowments, further away from the mean. Importing countries that display low values of water-per-ha-of-land values vindicate the water endowment argument as they resort to trade to compensate the lack of resources . Maximum values represent either small-medium countries (Singapore, Papua New Guinea, Liberia) that entirely rely on imports, or important producing countries (Chile, Malaysia, Norway, Columbia) with high demand effects. Exporting countries feature a lower water footprint average, meaning a higher average water productivity, in favor of the comparative advantage argument. Exporting nations are also wealthier on average.

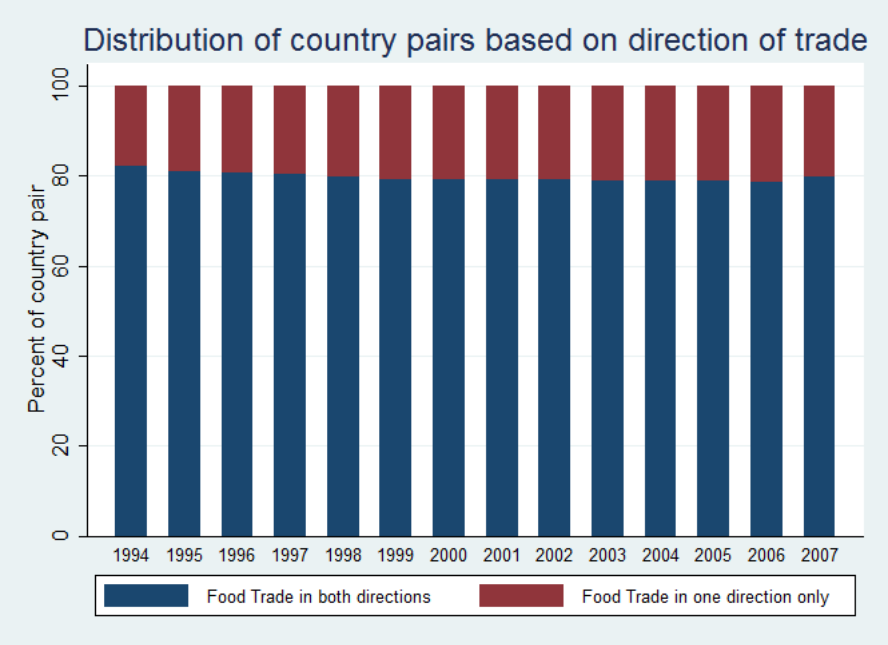
Figure 2.1 shows the distribution of country pairs according to the direction of trade. Roughly 80% of country pairs, as established by the BACI data, trade food and account for over 85% of virtual water exports every year. Out of the country pairs that trade in both directions, 16% actually trade the same product; when this is the case, both trade flows still appear as two discrete observations between the partners, once for each direction.

Table 2.1: Summary statistics

Variable	Mean	Std. Dev.	Min.	Max.
$FoodExports_{ijt}$	6437174.135	128079557.556	0	76820332544
$WaterLand_i$	72150.648	172025.846	345.168	4150259
$WaterLand_j$	90143.380	225446.173	345.168	4150259
$RatioWaterLand$	5.773	31.908	0	6287.918
WFP_i	7784.384	23328.793	5.808	1575091
WFP_j	9211.91	30484.489	4	1575091
$ratioWFP$	1.232	2.179	0.002	253.764
$GDPpc_i$	20114.824	14363.151	160.797	100110.977
$GDPpc_j$	18554.37	14711.632	160.797	100110.977
$ratioGDPpc$	4.127	10.821	0.003	337.555
$FoodPriceIndex_i$	1.345	0.302	0.75	4.33
$FoodPriceIndex_j$	1.406	0.336	0.75	4.33
$RatioPriceindex$	1.008	0.314	0.231	4.33
$PopEvol_i$	1.004	1.26	-3.782	19.105
$PopEvol_j$	1.119	1.646	-3.782	19.105
$RatioPopEvol$	3.583	52.083	-2380.994	4204.476
$Contiguity_{ij}$	0.132	0.339	0	1
$CommonColonizer_{ij}$	0.045	0.207	0	1
$CommonLanguage_{ij}$	0.197	0.398	0	1
$Distance$	5203.31	4369.028	114.637	19650.135
RTA	0.301	0.459	0	1

Note: exporting country i, importing country j, year t , RTA = Regional Trade Agreement

Figure 2.1: Distribution of country pairs according to direction of trade



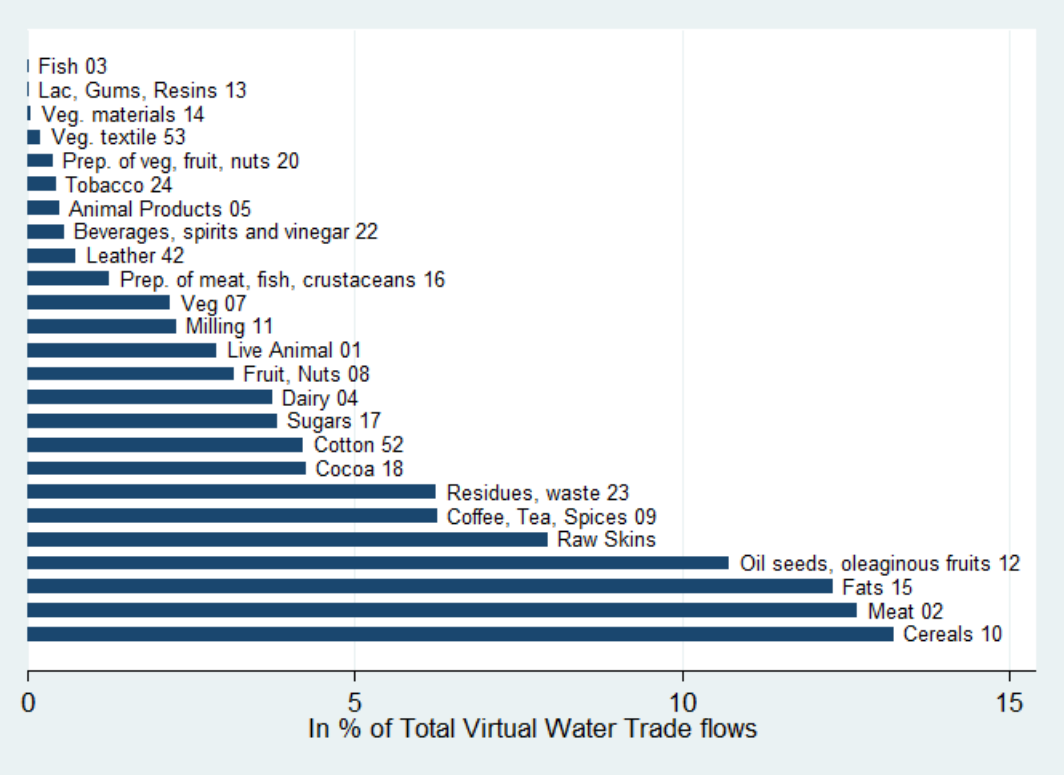
Sectoral Statistics

Food sectors are not equally accountable for water withdrawal around the world and it is interesting to aggregate our trade data to reveal different patterns across sectors. Figure 2.2 shows the distribution of trade flows between 1994 and 2007 according to sector. Products from the Cereal (HS10), Meat (HS02), Fats (HS15) and Oil Seeds (HS12) sectors are the most traded between 1994 and 2007 and represent just a little less than 50% of all bilateral virtual water trade flows. In particular, in our period of study from 1994 to 2007, Cereal and Meat trade flows have had the highest increase (53%) while Fats and Oil Seeds have increased by 42%. This has consequences in terms of crop strategy for developing countries willing to access the international trade market. Therefore, sectoral analysis have consequences in terms of policy recommendations for water-stressed countries: are they choosing crops because of high world demand in detriment of water resources? Are they impacted by competition and price shocks or are they benefiting from increased demand?

Given the availability of water footprint data in $m^3.ton^{-1}$ for both the exporter and the importer as well as quantities in tons, we are able to compute the counterfactual amount of water that would have been used if the importer had produced locally rather than import. The difference between the real and the counterfactual water footprint gives us the amount of water saved or additionally consumed through trade. Figure 2.3 shows the distribution of global water savings as a percentage of total water traded between 1994 and 2007, and according to sector.

We can see that, on average, between 1994 and 2007, the sector for which inter-state trade saved the most water globally is cereals, relieving water withdrawals for slightly more than 7% of the total amount of virtual water trade. This result is similar to De Fraiture et al. (2004), who

Figure 2.2: Share of Trade Flows according to food sector between 1994 and 2007: cereals, meat, fats and oil seeds make up for almost half of total virtual water trade



find that in 1995 global crop water use in cereal production would have been higher by 6% had it not been for international trade. Out of 18700 km^3 of embedded water being traded between 1994 and 2007, cereal importers have saved around 1350 km^3 of water that would have otherwise been depleted. The second sector for which trade has contributed to water savings is "Oil seeds and oleaginous fruits", for which the amount of water saved corresponds to an average of 2.7% relative to total virtual water traded between 1994 and 2007.

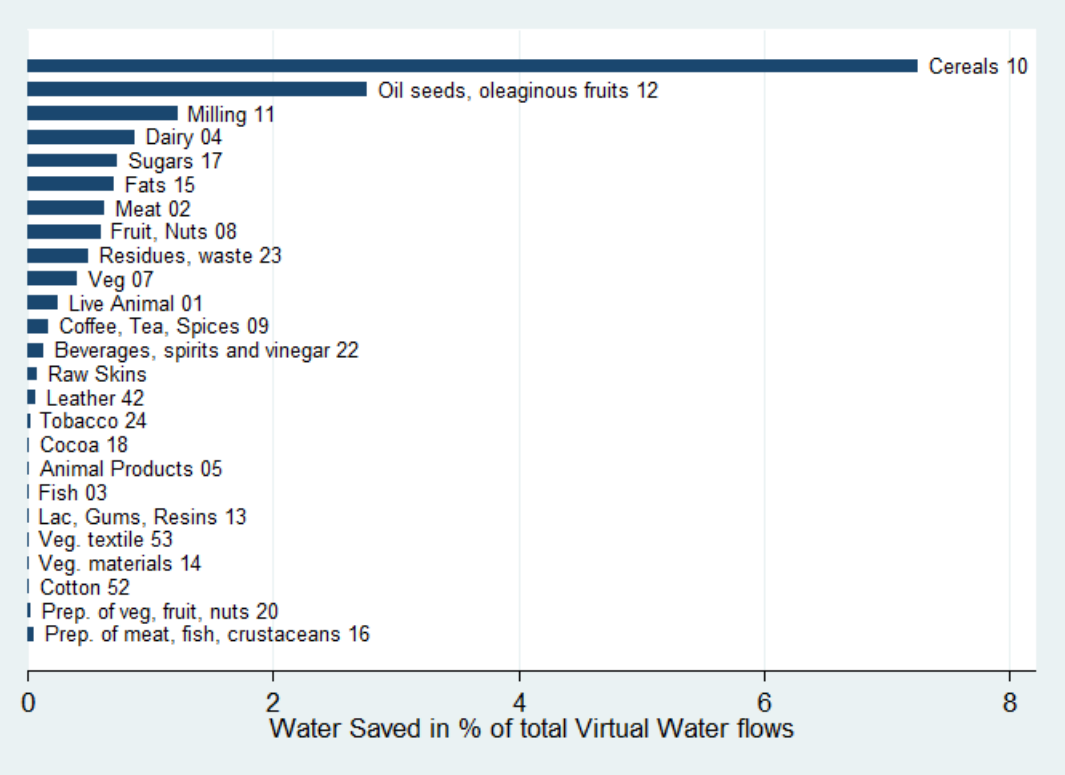
The most traded and water savings sectors are roughly dominated by the most water-abundant regions: North America, Brazil, Canada, China

2.4 Econometric Methodology

We perform our analysis of bilateral export flows at the product-dyad-year level and so our gravity model needs to address several issues.

Our dyads will display strong heterogeneity, exacerbated by unobserved factors (such as culture and and other types of qualitative exxchanges) that will affect the level of trade and be correlated with the explanatory variables. Therefore the econometric analysis needs to account for unobservable country-pair effects and potential heteroskedaticity. We control for country heterogeneity by using a gravity model with two time-varying effects (Head and Mayer, 2013) at

Figure 2.3: How Sectors contribute to saving water through international trade between 1994-2007



the exporter-product-year level and the importer-product-year level. Our time-varying country-product effects will control for all omitted variables that are cross-sectionally specific, such as variations in national economic indicators, political shocks, relations with other countries (excluding the trading partner), etc. Our explanatory variables on the other hand will be strictly bilateral and cover time-varying and constant characteristics.

We estimate country's i export volume of trade to country j as:

$$lnQ_{ijpt} = \alpha_{ipt} + \alpha_{jpt} + \beta_{ijpt} Z_{ijpt} + \lambda.Controls_{ijpt} + \epsilon_{ijpt} \tag{2.1}$$

where i is the exporter country, j the importer country, p is the traded product at year $t \in$ [1994;2007]. Q_{ijpt} is the volume of exports from country i to j for product p at year t, expressed in tons. The intercept has two parts: α_{ipt} which is specific to product p, year t in country i and α_{jpt} which is specific to country j. The error term ϵ_{ijpt} is assumed to be normally distributed with zero mean and constant variance for all observations. It is also assumed that the errors are pairwise uncorrelated.

We assume here that the slope coefficients are constant across country pairs and over time. The 1 x k row vector Z_{ijpt} comprises all of our explanatory bilateral variables which are the

following:

$$RatioWaterLand_{ijt} = \frac{WaterpLand_{it}}{WaterpLand_{jt}} \tag{2.2}$$

for year t, exporting country i and importing country j.

$$RatioWFP_{ijp} = \frac{WFP_{ip}}{WFP_{jp}} \tag{2.3}$$

for product p exported from country i to country j.

The 1 x k row vector $Controls_{ijpt}$ comprises our own control variables and those of the traditional gravity models. We also control for non-linear effects of asymmetries in population growth by including the squared term of this ratio. These variables will be displayed as *RatioPopEvol* and $RatioPopEvol^2$ where:

$$RatioPopEvol = \frac{pop_{it} - pop_{it-1}}{pop_{it-1}} / \frac{pop_{jt} - pop_{jt-1}}{pop_{jt-1}} \tag{2.4}$$

The ratio of GDP per capita is modeled as $ratioGDPpc$ and $ratioGDPpc^2$ where:

$$ratioGDPpc = \frac{GDPpc_{it}}{GDPpc_{jt}} \tag{2.5}$$

Food purchasing power parity (FoodPPP) divided by the general PPP:

$$RatioPPP = \frac{FoodPPP_{it}}{PPP_{it}} / \frac{FoodPPP_{jt}}{PPP_{jt}} \tag{2.6}$$

Patterns of trade make up another important control. Countries are likely to trade a product p in year t if they were already trading it the previous year. By including a dummy variable that indicates whether a product was traded the year before, we capture characteristics of trade that generally reflect on trade patterns that are not necessarily related to comparative advantage in water-land endowments or water productivity. The dummy is defined in the following way:

$$Crop(t-1)_{ijpt} = \begin{cases} = 1 & \text{if product was traded in t-1 between i and j} \\ 0 & \text{if not} \end{cases} \tag{2.7}$$

We expect the coefficient on this dummy to be strongly significant and positive.

Lastly, we include a dummy variable for whether the country-pair is trading the product in both directions, allowing us to consider for external factors affecting traded other than water endowments: economic and business opportunities, dynamic and/or inefficient management of stock.

We use the reg2hdfe command to estimate our linear regression model with two high dimensional fixed effects provided by Guimaraes and Portugal (2010).

2.5 Results

Table 2.2 displays results for OLS analysis with quadratic terms, with the second regression being clustered at the exporter-year-sector level. The clustered analysis covers 1,548,173 observations,

over 26587 groups[10].

Table 2.2: Linear regression with two high dimensional fixed effects

	(1) **Food exports**		(2) **Food exports**	
Water explanatory variables				
$ratioWaterLand$	-0.00337***	(0.000331)	0.00137***	(0.000338)
$ratioWaterLand^2$	0.00000168***	(0.000000229)	-0.000000790*	(0.000000322)
$ratioWFP$	-0.230***	(0.0173)	-0.0548***	(0.00652)
$ratioWFP^2$	0.00174***	(0.000268)	0.000384***	(0.0000707)
Control Variables				
$ratioGDPcap$			0.0117***	(0.00263)
$ratioGDPcap^2$			-0.000108***	(0.0000269)
$ratioPPP$			-1.269*	(0.637)
$ratioPPP^2$			0.0179	(0.129)
$ratioPopEvol$			-0.000254***	(0.0000218)
$ratioPopEvol^2$			2.85e-08***	(3.83e-09)
BilateralTrade			0.0114	(0.0246)
CropDummy			1.100***	(0.0111)
Gravity Controls				
Contiguity			0.938***	(0.0184)
ComColonizer			0.234***	(0.0358)
ComLanguage			0.225***	(0.0152)
ln(Distance)			-0.810***	(0.0113)
RTA			0.260***	(0.0200)
N	1945345		1547241	
df_r	573740		476169	

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Water-land relative endowments

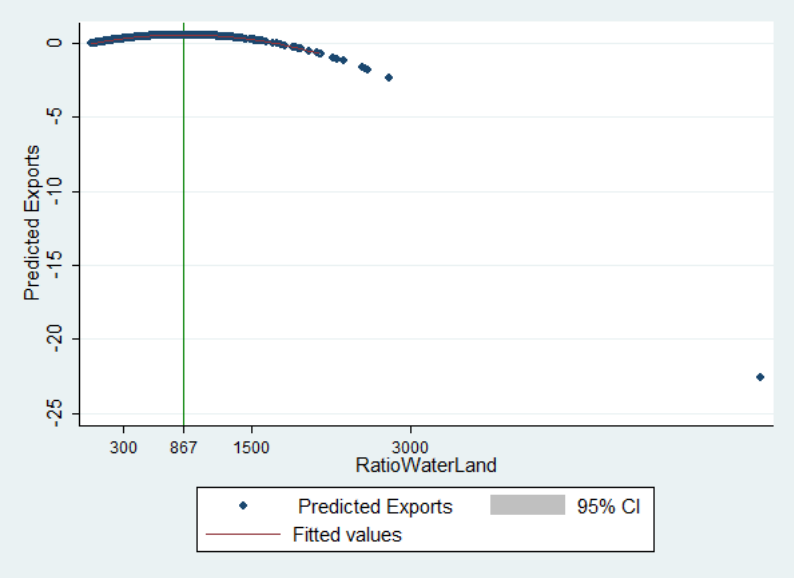
The results for clustered regressions display a weak non-linear relationship between exporter-importer water-land ratio and food exports: the linear and quadratic term are significant at the 1% level.

Figure 2.4 plots the predicted values of predicted exports according to the ratio of water-land endowments[11].

[10] We ran the regressions with many different clusters and got similar results for all coefficients, apart from the quadratic term of the ratio of food price indexes which lost its significancy. We also performed the regression without the quadratic terms to observe the linear effects of our variables on food exports (see Appendix for regression table) and obtained similar results.

[11] For small values of $\Delta RatioWaterLand$, the effect on exports can be computed as follows: $log(Q_{ijt}) \approx 0.00137 * RatioWaterLand - 0.00000079 * RatioWaterLand^2)$
and $\Delta log(Q_{ijt}) \approx 100 * (0.00137 - 0.00000158 * RatioWaterLand)\Delta$ RatioWaterLand

Figure 2.4: Non-linearity of water per land asymmetries on predicted exports between 1994 and 2007



Our regression results show that a one standard deviation from 10 to 41.908 in the exporter-importer water-land ratio leads to a 4.2% increase in food exports. The slope is relatively weak and decreases as water-land asymmetries increase[12]. This suggests that keeping other factors constant, countries are using their relative comparative advantage in water until a point where the water-land asymmetry becomes so high that the trend inverses. The left side of the curve is in line with Allan's theory of virtual water, suggesting that water-land resources do play a role - albeit slightly given our weak coefficients - in shaping countries' food production and trade strategies.

The result does not mean that relatively water scarce countries do not export to relatively water rich nations, but simply that overall food trade flows in the right direction, strictly from a water-land resource point of view. This trend is validated for country-pairs displaying below-80 exporter-importer water-land ratios, which is about 99% of our sample, for which the exporter-importer water-land ratio is beneath 80. Beyond 80 and up to 500 are country-pairs for which the exporter is among the top 10 water-land rich nations in the world (USA, Brazil, Canada, China, Columbia, etc.), thus displaying a very high water-land asymmetry relative to the importing nations.

Over 867, the trend inverses itself. This threshold is extremely high and in fact concerns all trade flows to Saudi Arabia, the second driest country in terms of water-land resources (with an average of 650 m^3 of water per ha per year) behind Libya (380 m^3 of water per ha per year). In this case, water-abundant exporters such as Brazil, Canada, Chile, Congo, Ecuador, Malaysia,

[12]We also performed the regressions without the quadratic term, and results are shown in appendix C shows the result table when performing regressions without the quadratic terms. The coefficient for the RatioWaterLand variable is very significant and positive: a one standard deviation increase in water endowment asymmetries increases exports by 2%.

Peru, New Zealand or Singapore send decreasing quantities of food to Saudi Arabia. This can be explained by the statistical nature of our model at the exporter-importer level. First, Ecuador, Malaysia, Congo, Chile and New Zealand are the richest countries in water per capita and in water per land, hence the exceptionally high water-per-land ratio[13]. Second, because of trade diversification, Saudi Arabia is importing from a very large number of countries, each making up for a smaller fraction of its total imports. The highest water-land ratios are actually between New Zealand and Libya and Singapore and Libya, with ratios of over 2000[14].

In terms of quantitative effects, the coefficient on RatioWaterLand takes on a weak value because our dependent variable is at the product level, which is the most disaggregated. This is further discussed below, when we perform the regressions at the sectoral level.

Figure 2.5: Distribution of VW exports based on country-pair asymmetry of water endowment per ha of land

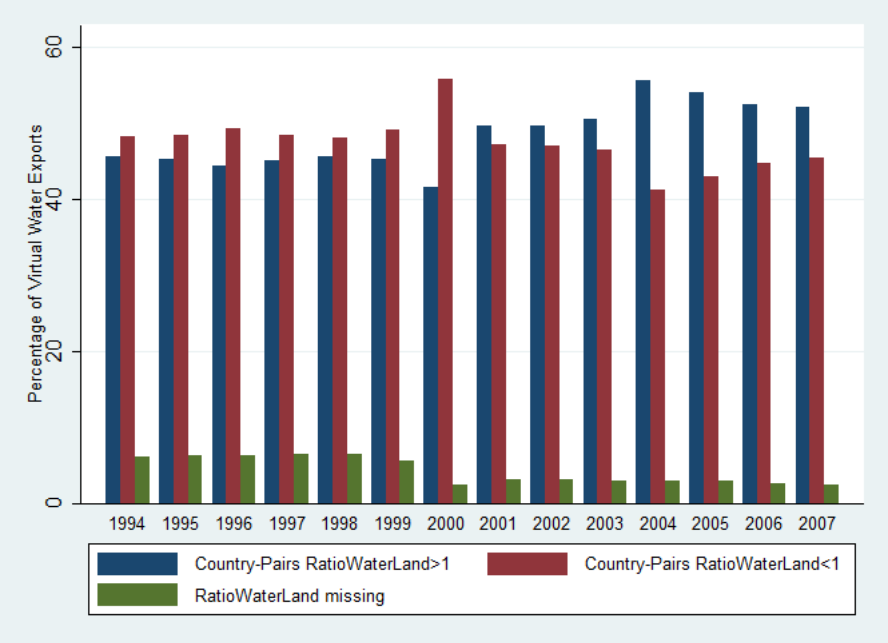


Figure 2.5 also shows that food flows are almost equally divided between countries with water-per-land ratios above and below one (45% of virtual water trade occurs between country-pairs with water-per-land ratio below one). This is because 80% of our country-pairs trade in both directions and are represented at least twice as depicted in figure 3[15]. These figures show

[13]The case of Singapore stands out, as it is among the poorest countries in water per capita but among the richest in water per hectare of land. Furthermore, Singapore's exports are built up by the fact that the nation re-exports around 70% of its food imports, mainly dairy products, frozen poultry and poultry parts.

[14]The outlier value of over 6000 is between Papua New Guinea and Saudi Arabi, which account for only one observation in our dataset, for one trade flow in 1995.

[15]There will be one observation for each product that country-pairs trade, unidirectionally; country-pairs will appear more than one time if they trade more than one product.

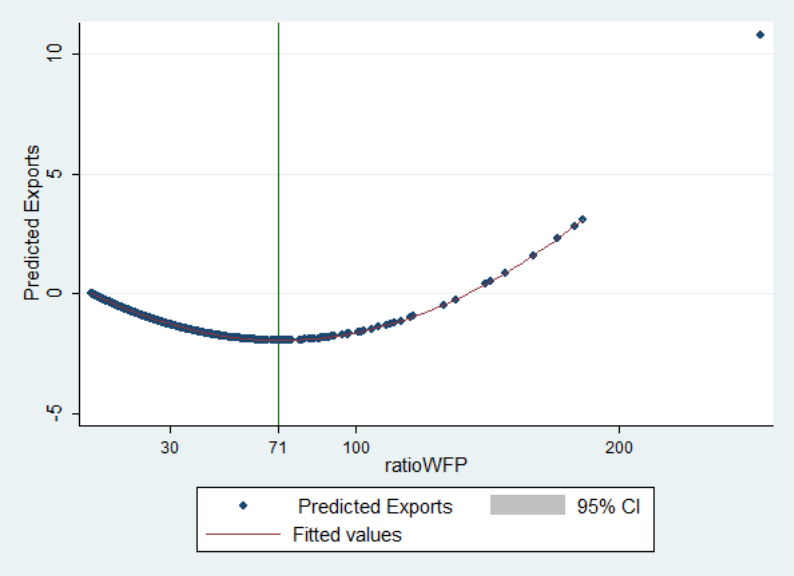
that relatively less-endowed countries are as likely as their better-endowed counterparts to be exporting virtual water.

Both these results are important: first, they suggest that relatively less-endowed countries are exporters as much as their relatively better-endowed trading partners. Second, they also show that water-rich nations are exporting higher volumes of virtual water, thus arguing in favor of a positive effect of water endowments on food and virtual water exports.

Relative Water Footprints

We now turn to the analysis of the coefficients of relative water footprints at the product level. Water footprint is the inverse of water productivity - meaning that the higher the exporter-importer ratio of water footprint for a specific product, the more water the exporting country uses to produce a unit of the product and so the less water productive. Figure 2.6 plots the predicted values of food exports according to exporter-importer water footprints ratio.

Figure 2.6: Non-linearity of water footprints on predicted values of exports



Our data shows that the water footprint ratio at the product level has a strongly significant non-linear effect on exports both in the non-clustered and clustered models. The variable is fixed for each country-pair and product across years[16]

The quadratic function is decreasing in water footprint asymmetries until the threshold value of 71, after which it increases. On the left side of 71, a one standard deviation increase in water footprint asymmetries from 10 to 12.179 will decrease exports of the product by 10% which is a very strong decreasing effect. The slope decreases along with asymmetries: a one standard deviation change from 30 to 32.179 decreases virtual water exports by 6%. On the right side of the curve, a one standard deviation increase in water footprint ratios from 100 increases exports by 5%.

[16]The effects can be seen through the equation: $log(Q_{ijt}) \approx (-0.0548 * RatioWFP + 0.000384 * RatioWFP^2)$ and so: $\Delta log(Q_{ijt}) \approx 100 * (-0.058 + 0.000768 * RatioWFP)\Delta RatioWFP$

We hypothesized that a country exports a product only if he is relatively more water efficient $ratioWFP = \frac{WFP_{ip}}{WFP_{jp}} < 1$. As a matter of fact, about 40% of trade flows are between countries with a water footprint ratio lower than 1 (meaning the exporter has a higher water productivity) and the rest are roughly divided between missing water footprints and water footprint ratios higher than 1 (30% and 30%, respectively). If we consider only the existing data on water footprints, then 57% of trade flows are between countries with a water footprint ratio lower than 1. This in fact means that (keeping relative water endowment and other relative economic and social factors constant), our hypothesis is validated for more than half of our sample. To the extent, we can claim that food production and trade behave according to the comparative advantage argument, as far as water productivity is concerned.

The non-linearity of the water footprint ratio, however, suggests that as the exporter-importer water productivity gap increases, the trend is inversed: virtual water flows from relatively less to more water efficient countries. This is counter-intuitive in terms of comparative advantage as suggested in the existing literature. Several explanations are in order. The threshold value of 69 is quite high and only 309 trade flows are reported to be above it, representing only 0.014% of the sample. This is negligible, yet the quantities of exports are sufficiently high for our coefficients to stay significant and change signs. In addition, we mentioned that decision-making within agriculture results from many different factors pertaining to labor, capital, technology and so on, meaning that countries with relatively low productivity for certain products may still decide to produce them. Furthermore, because there are few country-pairs on the right side of the curve, we can easily distinguish them and better understand this result.

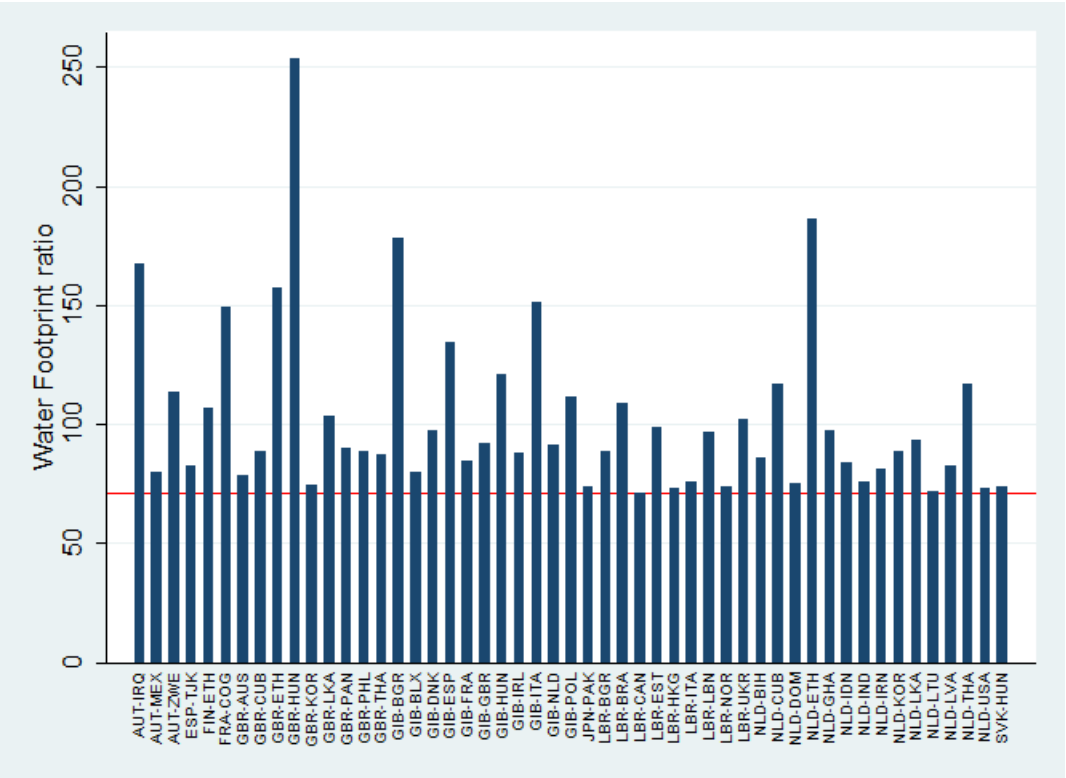
We understand that there are two kinds of products flowing in the wrong direction, water productivity-wise: the first are those mostly relying on cheap labor and production, with no specific needs in climate (meat, common vegetables or cereals). In this case, they could be produced elsewhere but exporting countries are driven by short term economic profits. Through smart re-allocation of trade flows, international trade could indeed enhance water scarcity.

The second are products which require specific climatic and land conditions, such as high temperatures for exotic fruits and vegetables, or coffee, cocoa or spices. These countries have an undeniable advantage in those products and there are few other alternatives. In this case, efforts should be directed towards higher water efficiency rather than reallocation of trade.

Figure 2.7 shows the country-pairs with the highest levels of exporter-importer water footprints ratio. We found that the 309 country-pairs actually concerned a small number of importing nations, yet a higher number of exporters, so we labeled the x-axis in the importer-exporter format (although the y-axis is still to be read as exporter-importer water footprint ratio). There are five main nations which import products for which they are over 71 times more water productive than their exporting counterpart: Austria, Great-Britain, Gibraltar, Liberia and the Netherlands. Apart from Liberia, these countries are OECD members who are also known to be exporters of virtual water. Despite their relative abundance in water resources, there are different explanations as to why they are importing from relatively less water-efficient countries. The Netherlands and Austria lack available land. As such, their amount of water per ha of land is relatively higher than other countries, but their total levels of food production are significantly lower than the rest of Europe. Great-Britain has historically favored industries over agriculture since the 19th century, hence the need to resort to imports to satisfy demand. Moreover, western diets and rising populations are increasing demand for crops and livestock and the need to resort to imports.

Furthermore, these countries are not only importing from water abundant, developed coun-

Figure 2.7: Country-pairs with highest Water Footprint ratios



tries but also from developing nations, suggesting the importance of export, or "cash" crop production for the latter. Through the mechanisms of contract farming (Key and Runsten, 1990), farmers in developing countries are incentivized by international agribusiness firms to switch from subsistence crops, locally sold and consumed, to crops specifically destined for exports. Firms thus benefit from cheaper labor and land and can easily satisfy western demand for food goods; yet in developing countries water management practices are often sub-optimal, in particular for irrigated crops, leading relatively less water-efficient countries to export to relatively more water productive nations. Although not the focus of this paper, the complex issue of water pricing is also part of the explanation for the inadequate use of water relative to the theory of comparative advantage. Indeed, the absence of any water scarcity rent leads food markets to perceive water resources equivalently, regardless from their location in the world and regional scarcity (Wichelns, 2010).

Liberia, on the other hand, is among the ten least developed countries in the world and imports over 90% of its staple food as it benefits from international food aid programs. But because of the country's former intensive production in cash crops such as rubber, palm oil, coffee and cocoa, it still displays stronger water efficiency than certain western countries for certain products (specifically for sectors HS20 - Preparations of vegetables, fruits and nuts - and HS40 - Raw Hides, Skins and Leather). As such, the counter-intuitive relationship between imports and relatively higher water productivity in Liberia partly stems from a previous domination of

export crops in the country.

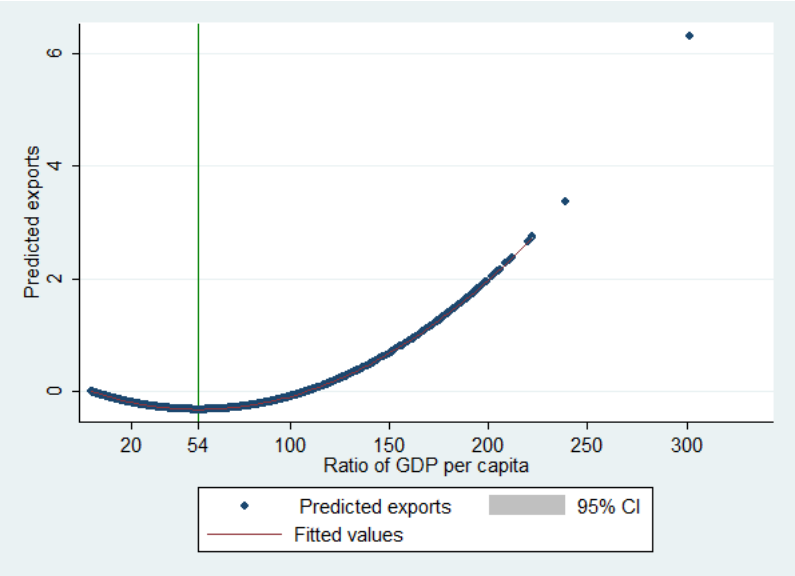
Time-varying and fixed control variables

Our time-varying control variables include ratios of wealth and food price indices. Our fixed controls include the exporter-importer ratio of population increase between 1994 and 2007 as well as customary international trade dummy variables for contiguity, common colonizer, common language, distance and the existence of Regional Trade Agreements (which remain constant for our time span of 13 years).

Relative wealth

GDP per capita is considered as a measure of wealth (Dinar and Dinar, 2011) which is bound to be correlated with the ability to invest in agricultural production and engage in trade. Wealthy nations are generally large exporters and importers of food - but remain net exporters of virtual water, whereas relatively poorer nations are often net virtual water importers (Hoekstra and Hung, 2002)[17]. Our results show that asymmetries of wealth have a non-linear effect on food exports, with an inverted u-shape with a high distribution of observations on the right of the threshold value 55. Figure 2.8 shows the distribution of predicted exports according to values of GDP per capita ratios.

Figure 2.8: Non-linearity of wealth asymmetries on predicted values of food exports



On the left side of the curve, food exports increase along with wealth asymmetries. On this part of the curve, a change in wealth asymmetry from 10 to 20 (meaning the exporting country's GDP per cap is 20 times that of the importing nation) induces an increase in virtual water exports

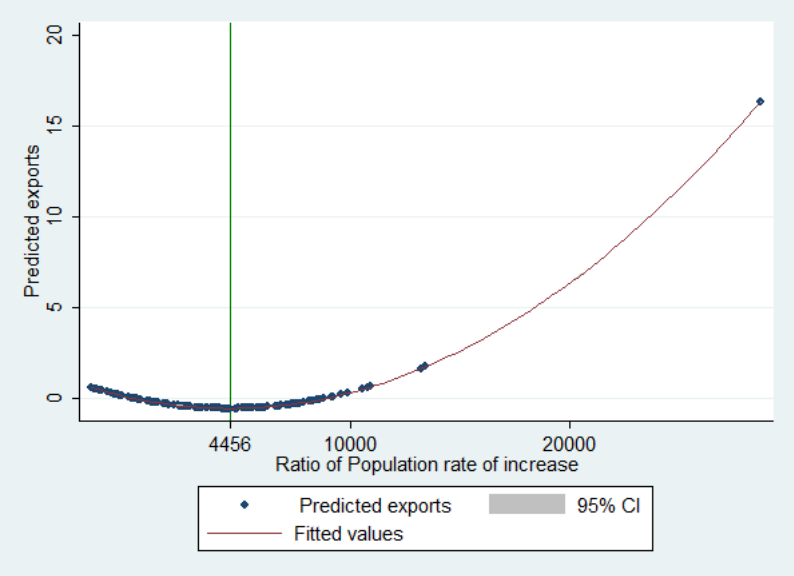
[17]This does not exclude that patterns of exports and imports in developing countries tend to vary from year to year.

of approximately 8.6%, a very strong effect. The slope then decreases around the value of 54 and then becomes increasingly negative[18]. What our results suggest is that exports do flow from relatively wealthier to poorer countries, but only up to a point. Above an asymmetry of 54, food exports from wealthy to very poor countries will decrease. Summary statistics show that 50% of country-pairs have GDP per capita ratios below 1 and 90% below 10. Country-pairs with above 10 and beyond asymmetries in GDP per capita generally involve wealthy or emerging nations as exporters and among the poorest nations as importers, mostly from the African continent. Above the threshold of 55, exports decrease because countries are financially excluded from food trade - country pairs above the value of 100 include Ethiopia, Liberia, Malawi and Zimbabwe as importers. This is also in line with De Fraiture et al. (2003) who find that most food trade occurs between rich countries – we find that 90% of food trade occurs between countries whose wealth asymmetry does not go beyond a ratio value of 10.

Relative population growth

According to our results, the exporter-importer ratio of population increase has a slightly non-linear impact on predicted food exports, with a strong negative effect on the linear term. The regression is plotted in Figure 2.9[19].

Figure 2.9: Predicted Virtual Water exports according to ratio of population rate of increase



Ercin and Hoekstra (2014) identify population growth as a main driver of change in water scarcity. The need to feed a growing population exerts pressure on water resources and food production processes and thus modifies trading patterns. Developing countries, in particular

[18]The effects are: $log(VWexp) \approx 0.0117 * RatioGDPcap - 0.000108 * RatioGDPcap^2$ and so: $\Delta log(VWexp) \approx 100 * (0.0117 + 0.000216 * RatioGDPcap)\Delta RatioGDPcap$

[19]Results according to:
$log(VWexp) \approx -0.000254 * PopInc + 0.0000000285 * PopInc^2$ and so: $\Delta log(VWexp) \approx 100.(-0.000254 + 0.000000057 * PopInc)\Delta PopInc$

in the African continent, are more vulnerable to this threat: Africa's population is expected to double from 1.1 to 2.4 billion by 2050 (Population Reference Bureau) while the population of more developed regions is expected to increase minimally, from 1.25 to 1.28 billion by 2100 (United Nations Population Fund). Water management and infrastructures for agriculture are still lagging behind in many developing countries, making them unfit to rapidly react to an increase in population and food demand. They can resort to increase imports to satisfy national demand, while developed nations with enhanced investment capacities may have the ability to increase production, decrease exports and/or increase imports. The strong negative coefficient confirms that relatively higher (lower) population growth pressure will translate into less (more) exports.[20].

Relative Food Purchasing Power Parity

Measures of food price indices help capture the importance of food in the overall consumption basket and take the highest values for the least developed countries. One can expect these high values to stem from insufficient local production, difficult access to a diversified basket of consumption goods and high vulnerability to international price shocks. Our regression shows that the coefficient on the exporter-importer food price purchasing power ratio variable is linear and negative at the 10% significance level, meaning that countries with relatively high food price indices resort to imports.

Gravity controls: contiguity, common colonizer, common language, distance and RTAs

The gravity controls behave according to expectations in the extant literature on international trade. Indeed, contiguity, common colonizer and common language are all highly significant and positively correlated with food exports.

If the exporting and importing countries are contiguous, exports of food products almost double as they increase by 93.5%. Having been colonized by the same nation will also increases food trade (in our analysis by 25%), which is in line with the results of Head, Mayer and Ries (2010). Sharing a common language increases virtual water exports by 23.2%. As predicted by international trade theories, a 1% increase in distance between the exporting and importing countries decreases virtual water exports by 0.8%. The positive effect of Regional Trade Agreements on food trade flows is also supported by the literature (Martin, Mayer and Thoenig, 2012).

Effect of bilateral and persistent trade of a product

Our results show that reconducting trade of a same product from year to year and trading in both directions are strongly and positively correlated with virtual water exports. These variables are utilized to capture any country-pair effects and provide more robustness to our results.

2.6 Sectoral Analysis

Our model considers panel data of food exports from 1994 to 2007 at the product level, regardless of the sectors. Sub-sampling for sectors is interesting from an operational point of view: countries often specialize vertically, within a sector, because of the many advantages it brings (transaction costs, know-how, seasonal crops, etc.). Sectors are generally historically determined

[20]The very high ratios of population rate of increase (above 4000) are all attributable to trade flows towards the Czech Republic, whose rate of natural population growth was negative from 1994 to 2005.

by local conditions and know-how, and thus provide indications as to local management and water practices. For instance, paddy rice requires different types of infrastructures and landscapes than wheat. Furthermore, it enables us to give policy recommendations regarding specialization or diversification for water-stressed countries, which is harder to do at the product level.

Turning to a sectoral analysis will also allow to capture heterogeneity within the overall economy of food production, and observe comparative advantage and positive production spillovers within the same category of products. The analysis is conducted by sub-sampling our data according to HS2 categories of products, further described in Appendix 2.8.

It is interesting to interpret these results in light of Figures 2.2 and 2.3 (% share of sectors in total trade and how sectors contribute to saving water through international trade) because of the underlying hypothesis:

- As seen in Figure 2.2, the most traded goods are those from the cereal, meat, fat and oil seed sectors. These are among the most water-consuming sectors and we should thus expect these sectors to have a higher sensitivity to available water resources.
- The most water saving sectors (again cereals, oil seeds and milling) are the ones for which the amount of embedded water exported is lower than what would have been used if the importing country had produced the good locally. As the gap between water efficiency increases, so does the amount of water saved. We should thus expect food exports, for these specific sectors, to be significantly correlated with water footprint asymmetries.

The model used is the same as the one used previously: the dependent variable is at the product, country-pair and year level but the number of observations per sample is reduced to the number of trade flows belonging to the same sector. Table 2.3 displays the results of the coefficients for our two main variables of interest, asymmetry in water endowments and in water footprints. The coefficients with a level of significance of at least 10% are in bold.

The results show important inter-sectoral differences in the way they relate to exporter-importer water-land endowments and productivity asymmetries. We see here that sectoral trade flows do not behave exactly like their disaggregated components. Indeed, trade flows for 12 out of 25 sectors are significantly correlated to water-land asymmetries and 13 display significant correlation to water footprint differences just as for our model at the product level. In addition, even when we find a significant non-linear relationship with our variables of interest, the squared term is almost always very weak.

Among the top six traded sectors which represent over 50% of total virtual water trade between 1994 and 2007, around half display significant coefficients for the water endowment asymmetry variable, with the same sign as with product-level data. These sectors are: Cereals (HS2 10), Food residues and waste (HS2 23) and Fats (HS2 15)[21]. This is in line with our previous result: sectors that behave accordingly to comparative advantage in water are the ones that save more water through trade.

Fruits and Nuts (HS2 08) and Vegetable materials (HS2 14) are the only sector to behave in the opposite way: exports decrease as the exporter is relatively better endowed, until a threshold where the trend inverses. Both these sectors are highly monopolized by China (44% of exports). For fruits and nuts, countries like Spain and Madagascar take an additional 20% and for Vegetable materials, Indonesia, Vietnam and Malaysia totalize 17% of exports. In both cases, up to 40% of

[21]Fats display a strong positive linear relationship while cereals and food residues and waste display non-linear coefficients, suggesting that food exports behave accordingly with water-land asymmetries up to a certain threshold.

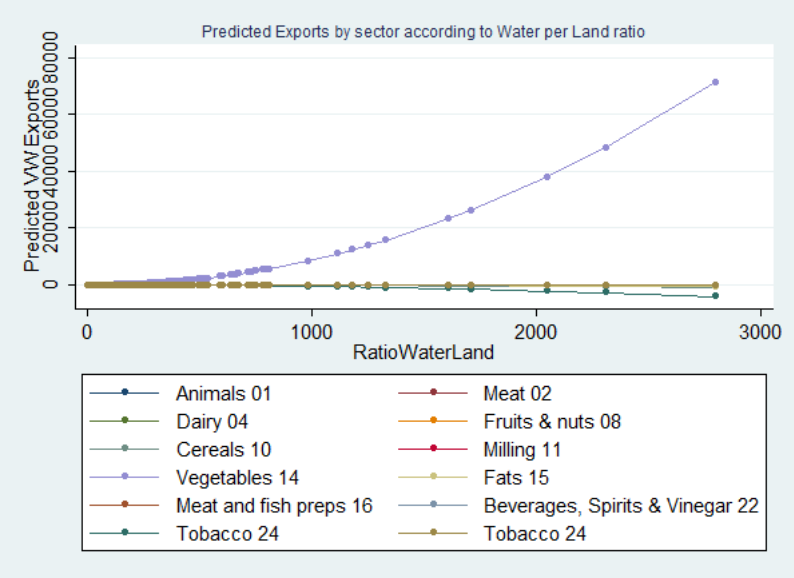
Table 2.3: Linear regression with two high dimensional fixed effects - Sector analysis

	Variables				
Sectors	Intercept	RatioWL	$(RatioWL)^2$	RatioWFP	$(RatioWFP)^2$
Live Animal 1	10	**0.00296****	**-0.00000204***	-0.141	0.0209
Meat 2	-18	**0.00133***	-0.000000905	0.0190	0.0218
Fish 3	8.5	-0.00180	0.0000165	-0.0952	-0.00334
Dairy 4	17	**0.00177****	**-0.00000114***	**-0.554*****	**0.0275*****
Animal Prod. 5	11	-0.000408	0.00000228*	1.084	-0.219*
Vegetables 7	17	0.00374	-0.0000144	**-0.0467*****	**0.000320*****
Fruits, Nuts 8	8	**-0.00263***	0.00000260	**-0.0555****	0.000483
Coffee, Tea, Spices 9	12	0.0158	-0.000124	**0.0716***	**-0.000997****
Cereals 10	16	**0.0209*****	**-0.000101*****	**-0.224****	0.00716
Milling 11	5	**0.00999***	-0.0000281	**-0.131***	**0.00330***
Oil Seeds 12	7	-0.00195	0.0000198*	-0.0513	0.00329**
Lac, Gums, Resins 13	-19	-0.000924	0.00927*	-0.223	0.193
Veg. Materials 14	16.5	**-0.446***	**0.00927***	0.333	0.0163
Fats 15	4	**0.0279****	-0.0000716	**-0.354*****	**0.00659***
Prep. of meat, fish 16	8	**0.00332*****	-0.00000200	**0.235*****	-0.00747
Sugars 17	13	0.00120	-0.00000628	0.477	-0.0191
Cocoa 18	-19	0.0688	-0.00216	11.89	-1.898
Prep. of Veg. 20	4	0.000464	0.000000193	-0.0260	0.000440
Beverages 22	6.5	**0.00344****	**-0.0000167*****	-0.0658	0.00355
Food Waste 23	16	**0.06*****	**-0.000534*****	**-3.999*****	**0.405*****
Tobacco 24	4	**0.00877*****	**-0.0000171*****	**-0.154***	0.00646
Raw Skins 41	6	0.000143	9.18e-08	**1.085*****	**-0.108*****
Leather 42	5	-0.000470	0.000000535	**3.032*****	**-0.226*****
Cotton 52	7.5	0.0188	-0.0000429	**-0.867***	0.106**
Other Veg. Text. 53	13	-0.00899	-0.00000867	0.199	-0.0140*

exports are for western countries (Europe and USA) with higher water endowments per hectare of land, hence the initial declining trend. These sectors require time and hard to exit; high demand increase in developing countries has also stirred production and exports.

Figure 2.10 shows predicted exports by sectors according to water endowment asymmetries. The figure only shows the sectors for which the coefficients in table 2.3 are significant[22].

Figure 2.10: Predicted food exports by sector according to Water per Land ratio



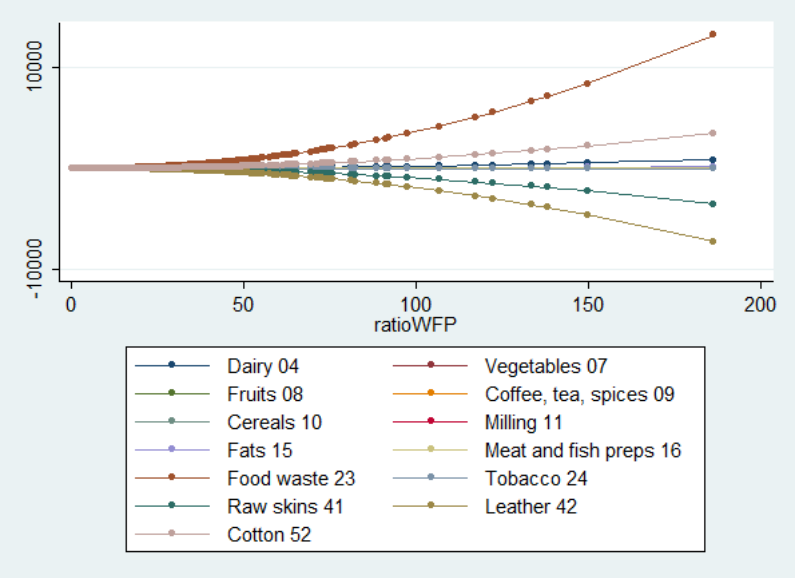
On the other hand, virtual water trade flows in the Coffee, Tea and Spices (HS2 09), Prep. of meat and fish (HS2 08), Raw skins (HS2 41) and Leather (HS2 42) sectors diverge from those prescribed by our expectations for water productivity. For these sectors, exports first go from less to more water productive countries at first: indeed, they are among the top export products for former colonies, developing and water scarce countries such as Burundi and Uganda for coffee,

We interpret these differences as resulting from the existence, or the absence, of complimentary production factors to water resources and the persistence of traditional and colonial heritage. Livestock and grazing have traditionally been part of rural activity around the world - even in relatively water poor countries - while coffee, tea and spice production was largely implemented in former colonies (Columbia and Vietnam for instance) because of favorable climatic conditions and cheap labor. Oil seed production is much more spread out around the world which also explains the absence of a strong correlation between food exports and resource endowment asymmetries. Food residues and Fats require the appropriate processing infrastructures mostly found in developed - and relatively water abundant - countries. The cereal sector, although an important part of agriculture in many developing - and relatively water scarce - countries, is largely monopolized by three water rich producers, the USA, Brazil and Argentina. Accounting for over 50% of cereal production in 2007, they are bound to increase the importance of water-land asymmetries within our sample.

[22]We can see that the two sharpest slopes are indeed for the Cereal and Food waste sectors while other sectors have a very flat slope as their sensitivity to water per land asymmetry is very weak.

Regarding our second variable of interest, even if the quadratic effects are moderately strong, sectors seem to be much more sensitive to water footprint asymmetries. This is shown in Figure 2.11, which displays the predicted food exports by sector according to water footprint asymmetries. The figure only shows the sectors for which the coefficients in table 3 are significant.

Figure 2.11: Predicted food exports by sector according to Water Footprint ratios



We should expect virtual water exports to be significantly, and negatively, correlated with water footprint asymmetries within the most water-saving sectors. Indeed, water is being saved when an exporter is relatively more water efficient than the importer. As this ratio decreases, more water is saved, hence the likelihood of exports increasing to the extent that countries care about the depletion of their water resources.

This hypothesis is validated for 13 out of 25 sectors, including three among the top four water saving sectors; cereals, milling and dairy. Again, these are sectors for which production is highly dominated by a small number of water rich and water-efficient countries exporting to relatively less water productive nations.

The sectoral analysis is thus interesting because it demonstrates how asymmetries of power translate into agricultural production and trade strategies. For most traded sectors in the world (cereals, meat, fruits, coffee), dominated by a few producing nations, virtual water and food trade offsets the unequal distribution of water resources and inefficient water practices around the world. Regarding the other sectors, production is more spread out geographically, suggesting that the water constraint is supplanted by other types of economic constraints such as technology, capital or qualified labor.

2.7 Conclusion

Food trade has been argued to be important for understanding why conflict over scarce water resources has not taken place as often as some scholars and practitioners have predicted. In choosing what to export and import, countries consider world demand, prices, competition, historical crops and local resources, namely water. This article attempts to answer the question of whether food and virtual water are traded based on the concept of comparative advantage. We investigate the main motivation for virtual water trade by comparing two distinct arguments. The first suggests that countries adopt food production and trade strategies according to their water resource availability (an Hecksher-Ohlin comparative advantage). The second argument suggests that trade strategies are determined by the efficiency of water use (as a Ricardian advantage). Our model includes additional control variables important for understanding trade and food production.

Our results demonstrate that most countries do resort to food trade to alleviate water paucity, although nations described by very high water scarcity persist in being excluded from global food trade. This finding empirically validates earlier theories about virtual water trade and food (Allan, 1991). Our results also validate more recent explanations of virtual water - those regarding water productivity. We find that countries that are more productive water users export water intense products to less water productive countries. Yet this relationship is valid only up to a point. We also find a strong non-linear relationship between exporter-importer water footprint ratios and food exports. In other words, relatively less water efficient - and less water-endowed - nations are exporting to relatively more water-efficient and water-rich countries. While we do not consider the possible social benefits brought upon by such policies, concerns regarding efficiency, the equitable redistribution of cash crops and secure access to food among locals are of relevance.

Our empirical cross-national methodology allows us to identify the nuances of bilateral food trade. Both endowment and productivity seem to motivate trade in water intensive products as less water endowed and productive states import from more water endowed and productive states. This finding is at the heart of understanding why states have averted violent conflict over scarce water resources. That said, our results also suggest that even water poor countries export water intense products. The same can be said for states that are unproductive in their water use.

We recommend two types of actions for water-inefficent countries exporting goods to more efficient nations: if the products are mostly oriented towards cheap labor, then public policy makers should re-think the allocation of water for production and trade (vegetables, meat offals, oil seeds, etc.). If products need specific climate-land context, such as exotic vegetables or fruits, coffee, tea and spices, then policy makers should focus on improving water productivity.

Increasing knowledge about virtual water flows, endowments and productivity should help countries implement more efficient use of their water resources for agricultural, industrial and individual consumption. More recently, Ercin and Hoekstra (2014) constructed four scenarios of water footprint for 2050, arguing that reducing humanity's water footprint is possible, provided that we modify our consumption patterns and through reallocation of food production across regions, according to local comparative advantages. Since most agricultural sectors across the globe are highly subsidized, it seems unfeasible that governments may wish to stop producing basic crops despite low water productivity. Nevertheless, such information can be valuable in order to foster innovation and technology use to increase crop yield and decrease water footprint. It can also help farmers get a better sense of which crops to cultivate.

One of the main challenges remains that of data collection for enhanced computations of water footprint values. Water footprint measurements mainly constitute a mixture of climatic and soil characteristics data (e.g. soil, land, evapotranspiration, temperature, etc.). But productivity is also endogenous to the economic, political and historical strengths of a country and these factors cannot be overlooked when building and implementing sustainable water management policies.

2.8 Appendices

2.8.1 World Customs Organization - HS Nomenclature 2012

- HS01 - Live animals
- HS02 - Meat and edible meat offal
- HS03 - Fish and crustaceans, molluscs and other aquatic invertebrates
- HS04 - Dairy products; birds' eggs; natural honey; edible products of animal origin, not elsewhere specified or included
- HS05 - Products of animal origin, not elsewhere specified or included
- HS07 - Edible vegetables and certain roots and tubers
- HS08 - Edible fruit and nuts; peel of citrus fruit or melons
- HS09 - Coffee, tea, matÃĺ and spices
- HS10 - Cereals
- HS11 - Products of the milling industry; malt; starches; inulin; wheat gluten
- HS12 - Oil seeds and oleaginous fruits; miscellaneous grains, seeds and fruit; industrial or medicinal plants; straw and fodder
- HS13 - Lac; gums, resins and other vegetable saps and extracts
- HS14 - Vegetable plaiting materials; vegetable products not elsewhere specified or included
- HS15 - Animal or vegetable fats and oils and their cleavage products; prepared edible fats; animal or vegetable waxes
- HS16 - Preparations of meat, of fish or of crustaceans, molluscs or other aquatic invertebrates
- HS17 - Sugars and sugar confectionery
- HS18 - Cocoa and cocoa preparations
- HS20 - Preparations of vegetables, fruit, nuts or other parts of plants
- HS22 - Beverages, spirits and vinegar
- HS23 - Residues and waste from the food industries; prepared animal fodder
- HS24 - Tobacco and manufactured tobacco substitutes
- HS41 - Raw hides, skins and leather
- HS42 - Articles of leather; saddlery and harness; travel goods, handbags and similar containers; articles of animal gut (other than silk-worm gut)
- HS44 - Wood and articles of wood; wood charcoal
- HS52 - Cotton
- HS53 - Other vegetable textile fibres; paper yarn and woven fabrics of paper yarn

Chapter 3

Food production and cursed water resources: challenging trade diversification mechanisms

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Abstract

This paper investigates diversification patterns of food exports in countries subject to water stress. Using an adjusted Theil index in terms of embedded water in trade, we analyze food exports from 1994 to 2007 at a global level and find that growth and water availability have opposite effects on diversification. While food exports tend to diversify with water availability, they display higher concentration as GDP increases. Furthermore, we find that water-intensive goods display lower survival in time when countries are water-scarce and have lower water efficiency than world average. In fact, water-scarce countries have unstable diversifying trade patterns with water-intensive goods disappearing and re-appearing throughout our period of study, revealing that the inefficient use of water resources is a main obstacle to sustainable trade diversification. We conclude that inefficient water management and insufficient investments in water efficiency are an obstacle to exiting water dependency by inducing similar economic impacts as those caused by "traditional" cursed resources such as oil, natural gas or minerals. We recommend that water-scarce countries focus on improving the water footprint of a small number of goods in order to trigger positive spillovers to other crops and other sectors of the economy in order to diversify.

JEL classification:

Keywords: Water Endowments, International Trade, Food Security

3.1 Introduction

In the attempt to understand the links between international trade and growth, much attention has been given to export and import patterns. Most studies have found that trade diversification is positively correlated with development (Haussmann & Rodrik, 2003; Klinger & Lederman, 2006; Parteka & Tamberi, 2013), challenging traditional theories of specialization according to comparative advantages and factor accumulation (Smith, Ricardo, Hecksher-Ohlin). In particular, studies have found a u-shape relationship between export/import concentration and gdp per capita (Cadot, Carrere & Strauss-Kahn, 2011; Mohan 2016)[1] suggesting that past a certain level of income, after having diversified, very rich countries undergo a reconcentration process. The resource curse literature has offered many insights into the economic mechanisms of countries featuring concentrated exports and slow growth at the very left of the curve. While some argue that heavily relying on natural endowments increases vulnerability in facing price and supply shocks, regulatory changes, and new competition (Prebisch, 1950; Sachs and Warner, 1995; Sala-i-Martin and Subramanian, 2003; Auty, 2000 and 2001), others bring forward that export concentration - and not resource endowments - endogenous to bad policies and institutional deficiencies, is in itself the cause of stagnating development (Maloney, 2007; Frankel, 2012).

Although the resource curse literature blames resource dependency for hampered growth an development, the debate has overlooked a traditional determinant of trade patterns, namely factor endowments (Cadot, Carrere & Strauss-Kahn, 2011). Given that 70% of water withdrawn in the world is for agriculture (FAO) and that the agriculture's sector share of GDP still exceeds 40% in many poor countries (such as the Central African Republic, Mali, Sierra Leone, or Togo), we state that agriculture-dependence is water-dependence. While case studies have largely focused on oil, natural gas or minerals, it is legitimate for water resources to be studied within the on-going resource curse debate. This article investigates the specific case of water dependency and the inability of water-scarce or water-inefficient countries with no other major resources to develop and diversify. To do so, we rely on a measure of the Theil entropy index adapted to incorporate flows of embedded water used to produce the goods.

This study faces three major challenges, the first pertaining to the specific status of water resources and the absence of standard, global economic tools enabling similar analysis to the recourse curse literature. Water suffers from poor institutional background and proper regulation, unlike oil or gas, and as such is not properly priced (with very few exceptions of price mechanisms with water markets in Australia, South Africa or California). As a result, in most developing countries, water is withdrawn with little consideration for future needs and as such, high levels of agricultural concentration in poor developing countries are generally not determined by the extent of water availability but rather by a shortage of other production factors (Wichelns, 2010; El Fadel and Maroun 2003, Warner 2003, Novo et al. 2009). Water dependence is thus not chosen as a strategy per say but results from lack of alternatives.

Furthermore, in developing countries where agriculture makes up for a large share of GDP, agricultural dependence is water dependence, regardless of water availability, a main difference with "traditional" cursed resources where resource dependence is based solely on availability. This is why we cannot explain failure to diversify with purely exogenous factors affecting the resource-based markets (as in the oil crisis). Equally complex, we cannot argue that agriculture dependence is crowding out manufacturing and hampering innovation because developing countries stuck in the primary sector (agriculture in this paper) generally do not overlook the

[1] They find a turning point around US$ 23,000 gdp per capita.

industrial and services sector (Frankel, 2012).

Second, the choice of metrics and scale will be important to give an accurate picture of countries' water availability. Water abundant countries have large amount of water reserves in total, per capita and per hectare of land. Water scarce countries can be short of water per capita but abundant in water per hectare of land or all of the above. Metrics will affect the interpretation of our results leading to counterintuitive results (as suggested by Sachs and Warner, 2001 using natural resource exports as a share of GDP instead of net exports of resources per worker by Leamer in 1984). [2]

Our third challenge is that of dealing with a debate over trade diversification that still features weak theoretical guidance and focuses mostly on empirical methodology with little consensus over metric, scale or measures (Mau 2015). The difficulty lies mainly in isolating the causality mechanisms between export diversification and growth and there are several cases where causation runs from productivity to trade patterns (Ricardian models, Melitz, 2003; Feenstra and Kee, 2008), while trade is also shown to enhance productivity (Broda, Greenfield and Weinstein, 2006) when firms learn by exporting (see for instance Haddad, 1993; Tybout and Westbrook, 1995). The challenge of building a strong identification model will come from both GDP per capita and trade diversification being highly endogenous variables and this paper will test our arguments both with static and dynamic panel estimates (system GMM) to overturn these issues. Furthermore, by focusing solely on the agricultural sector, we are possibly better isolating economic mechanisms as opposed to much of the literature which generally looks at a high number of sectors or thousands or different product categories (Mau 2015).

We study global food exports from 1994 to 2007 using the BACI dataset for agricultural exports as developed in the CEPII report by Gaulier and Zignago (2010) and originally sourced from COMTRADE at the 6-digit (HS6) and 2-digit (HS2) levels. We use the FAO Aquastat data for water availability and crop prices and use the Water Footprint Network for data on water efficiency at the country-product level. We investigate export concentration patterns using an adapted measure of the Theil index, build to account for the amount of water embedded in the exported goods based on their water footprint. Our results show that the Theil index for food exports has an inverted u-shape relationship with GDP per capita, as opposed to traditional results in the literature for the whole of exports. The Water Theil index is not affected by GDP per capita. On the other hand, both the Theil and Water Theil index diversify along water availability, showing that endowments do affect countries' export patterns and strategies. We find that water-intensive goods survive less in time than less water-intensive goods, a result emphasized when water is scarce and growth is low. Our results show that water scarcity and water inefficiency explains an important part of food export concentration and constitutes an obstacle to development and diversification for agriculture-dependent countries.

We start by providing a brief overview of virtual water issues and relating them to the many results within the resource curse and growth literature. We then explain our two models relating different diversification measures to growth according, water endowments and water efficiency.

[2] As an example, water availability per ha of land will put a country such as Singapore in the top ten although it is not highly diversified in food exports - thus denying the correlation between abundance and concentration - whereas water availability per capita will place it among the scarciest countries, thus over-estimating the positive correlation between scarcity and concentration.

3.2 Virtual Water flows and concentrated exports

This study is built upon the growing literature addressing trade diversification, the resource curse and virtual water trade. Virtual water is a concept coined by Tony Allan (1995) designating the amount of water (in liters per unit) required to produce a unit of good and virtually traded between countries through exports[3]. While the virtual water literature has addressed food production in relation to water as a comparative advantage, it has not done so in the context of trade diversification patterns. From the resource curse literature perspective, focus has been mostly given to oil and mineral rich countries and how countries have failed or succeeded in combining growth and resource abundance (mineral abundance and growth in the US, Wright and Czelusta 2002; oil in Saudi Arabia; forestry in Scandinavia in Blomström and Kokko 2003). But no studies have specifically addressed how water endowments and water productivity relate to food exports and diversification. The afore mentioned reason is the lack of standard tools to study water from a global point of view: there are no water markets on a global scale, no water price and little information on water availability and provisions, preventing water resources from constituting a solid basis for food production strategies (Wichelns, 2010). This article relates two features of the trade diversification to water endowments and virtual water trade.

1. Slow growth and low diversification are related to resource dependence

Although the causality between export/import patterns and growth has not reached a consensus, diversification has been found to be correlated with increasing growth in gdp per capita. Results suggest that import and export diversification stir local competition and innovation, enable knowledge accumulation and risk mitigation regarding price shocks and volatility, regulatory changes and new competitors. Imbs and Wacziarg (2003), later confirmed by Koren and Tenreyro (2007) demonstrated a u-shape pattern between production diversification and gdp per capita. The same u-shape was computed for exports (Haussman and Rodrik, 2003; Klinger and Lederman, 2006; Parteka, 2007; Cadot, Carrere and Strauss-Kahn, 2011; Mohan 2016) finding that as countries develop, exports diversify until reaching a certain level of income around US$ 22,000 to 30,000 gdp per capita (2005 constant PPP) above which they concentrate again.

Most developing countries on the left side of the curve still heavily rely the agricultural sector, sometimes employing from 50-90% of the population (South Centre, 2001), out of which 70-95% are small holder farmers. These farmers traditionally survive on subsistence crops; while some have experimented with export crops (or "cash" crops) in the past two decades, they are less likely to access farming technologies to adapt their production to high-valued crops and benefit from increased exports. Small farmers rely on land and water availability to produce food, hence developing countries stuck in the primary sector are heavily dependent on water resources and are highly concentrated. The literature on virtual water trade has indeed shown that poor water-scarce countries were, counter-intuitively, producing agricultural goods although they have little comparative advantage in water (De Fraiture et al, 2013; Delbourg and Dinar, WP). Yet a thriving number of case studies have shown that countries do produce according to comparative advantage (Yang and Zehnder, 2002; Yang et al., 2003) and were generally on the right track to development. It seems that if diversifying exports goes hand in hand with growth and development, it is necessarily correlated with an increase in comparative advantage, water efficiency and positive spillovers to other sectors of the economy.

[3]Virtual water measures were estimated by the Water Footprint Network (Hoekstra and Hung, 2002, and further elaborated by Chapagain and Hoekstra, 2004) and have enabled to study the relationship between food exports, water productivity and water endowments.

2. Innovation and Positive Spillovers as a means to overturn the resource curse

Although the resource curse literature has identified the economic mechanisms behind successful trade diversification and growth, there is still much to be explained for countries on the left side of the u-shape. Poorer nations stuck in slow growth and highly concentrated production and export patterns have been the topic of intensive scrutiny (Sachs and Warner, 1995; Tornell and Lane, 1999; Gylfason, 2008; Martin and Mitra, 2006 among others). While some argue that concentrated exports increases vulnerability in facing price and supply shocks, regulatory changes, and new competition (Prebisch, 1950; Sachs and Warner, 1995; Sala-i-Martin and Subramanian, 2003; Auty, 2000 and 2001), others bring forward the endogeneity between concentrated exports and bad policies and how interaction with institutional deficiencies can, in itself, hamper production strategies and growth (Mehlum, Moene and Torvik, 2005, Brunnschweiler and Bulte, 2007, Areski and van der Ploeg, 2011).

These arguments assume that natural resource availability is the cause of concentrated exports but Ledeman and Maloney (2007) and Frankel (2010) have suggested that it is not the resource but lack of investments and diversity within resource dependent production that causes concentration and slow growth. Concentration in itself is harmful to growth. Martin and Mitra (2001), Wright (2001), Irwin (2001) or Blomstrom and Kokko (2001) provide a more optimistic view and conclude that resource abundant countries are not doomed to have lower economic and political development, showing many cases of growth being stirred by exports and technological innovation within very concentrated economies such as forestry in Scandinavia or mining in certain US regions.

The pros and cons of natural resource availability for growth lead to one important conclusion: resource abundance is not the culprit for slow growth. It is rather how countries will structure their economy around it that will matter. In the case of water resources, technologies enable more efficient consumption by increasing water productivity (the amount of good produced per liter of water consumed) and water savings. They help us consume the right amount of water at the right time and right place. Product-water footprints differ across the globe as they depend on exogenous (climate, soil, water) and endogenous factors (human input, technology). Technology is generally available to farmers in rich countries and large agrifood companies operating in developing regions, inducing lower water footprints and therefore relative comparative advantage in producing food products. This relates to Bonaglia and Fukosaku (2003) who suggest that natural resources today can stir technological content, able to generate the development of upstream and downstream activities.

This is true for water: countries who have invested in water technologies have succeeded in making water dependence a driver for innovation, with important spillovers into the manufacturing/industrial sector sectors (such as Israel or Singapore), an argument also supported by Martin and Mitra (2001). Although the largest food producers in the world - India, Brazil, the United States, Australia and China - are currently suffering from serious groundwater depletion, water shortages and droughts because of increased demand for good and variety (Krugman 1979) and unregulated water policies leading to common-pool resource problems (Tornell and Lane, 1999), water issues are being addressed through technology. Unfortunately, India and China are still largely disadvantaged in terms of water productivity. Nations heavily relying on agriculture and water, therefore, are not forever destined to slow growth patterns, but require investment, intensification of production and diversification. In their case, water efficiency is the first challenge they meet which argues that water productivity is a main determinant of production and export intensification.

3. Using the proper tools to analyze diversification of exports

Most empirical analyses on trade diversification rely on three different measures of diversification and concentration: the Herfindahl index, Theil's entropy index and the Gini index. High values for these indices indicate high concentration patterns at the chosen level of disaggregation. This article focuses on the Theil index because it can be decomposed into extensive and intensive margins. Two mechanisms can induce diversification of exports:1) an increase in the number of new goods exported (or active lines) from one year to another, or the extensive margin and 2) an increase in the quantity of goods already being traded or the intensive margin. The intensive and extensive margin are essential in understanding what happens when countries diversify: new products might say something about local economic and institutional conditions such as more entrepreneurs risking to export new products, inside-the-frontier innovations (Klinger and Lederman, 2006) or copying existing products abroad.

Evenett and Venables (2002), Brenton and Newfarmer (2007) and Cadot et al (2011) show that the intensive margin makes up for most of trade growth (around 80%) but that variations in concentration and diversification are mostly driven by the extensive margin. As poor countries develop, the number of active lines as well as the number of destination for exports increases. Above the turning point, concentration changes occur at the extensive margin, where rich countries tend to forgo products with lower added value and focus on goods for which they are highly productive. We will use the decomposition of the Theil index, bearing in ming that these indicators fail to provide any analysis of the determinants of concentration and diversification.

3.3 Export concentration, agricultural dependence and water resources

3.3.1 Data

Our food trade data is taken from the BACI dataset, as developed in the CEPII report by Gaulier and Zignago (2010). We chose the BACI data over the FAO trade statistics for agricultural commodities because is deals with missing data by employing a reconciliation methodology[4]. Indeed, missing values of trade for a specific product can occur if one or both of the countries fail to report their trade flows. BACI utilizes the double information available on each trade flow to provide a unique "reconciled" value for each flow reported by at least one of the partners, providing more complete data[5]. Using the BACI data also enables to be consistent with the study from Delbourg and Dinar (Working Paper) on virtual water flows and relative water efficiency. The data provides production data in quantity and value at the highest level of product disaggregation, 6 digits Harmonized System (HS) code from 1994 to 2007.

[4]Reconciliation provides an explanation for the discrepancy between the import and export statistics of trading partners by identifying conceptual reasons for them and explaining differences in data collection and processing. See United Nations (2004). Similar to COMTRADE, BACI does not report zero values of trade because of computational issues. It also does not report zero values for products no longer, but previously, traded between two countries, raising the issue of selection bias. Furthermore, a missing observation is considered a zero when at least one of the trading partners reports its trade to the UN. If both partners are not reporting, the missing observation is considered a true missing value.

[5]See Gaulier and Zignago (2010) for more detailed explanations

Actual renewable water resources per year in $m^3/year/person$ are taken from the FAO Aquastat dataset and arable land data is provided by the World Bank indicators[6]. Total renewable water resources are the sum of Internal Renewable Water Resource (IRWR)[7] and External Renewable Water Resource (ERWR)[8] where IRWR and ERWR are computed in the following way:

$$IRWR = R + I - (Q_{OUT} - Q_{IN}) \tag{3.1}$$

where R is the surface runoff (long-term average annual flow of surface water generated by direct runoff from endogenous precipitation), I is groundwater recharge generated by precipitation and Q_{OUT} is groundwater drainage into rivers and Q_{IN} is seepage from rivers into aquifers.

$$ERWR = SW_{IN} + SW_{PR} + SW_{PL} + GW_{IN} \tag{3.2}$$

where SW_{IN} is the surface water entering the country, SW_{PR} is the accounted flow of border rivers, SW_{PL} is the accounted part of shared lakes and GW_{IN} is the groundwater entering the country.

The water footprint in m^3/ton is provided by the Virtual Water Footprint network, in particular the articles of Mekonnen and Hoekstra (2011) and Chapagain and Hoekstra (2003). We use their data for 690 products (crops and livestock prducts) - which correspond to 24 different major categories (HS2). Appendix A provides a detailed description of the crops and livestock products we cover in this analysis. If we were to look at HS2 9 (Coffee, Tea, Mate and Spices) the HS6 level would distinguish "roasted, not decaffeinated coffee" (HS6 090121) from "roasted and decaffeinated" (090122). The HS2 category 10 (Cereals) separates "durum wheat" (HS6 100110) from "corn seeds" (100510) and "maize" (100590). We limit our data for products with available water footprints.

3.3.2 The Theil and Water Theil index

We base our analysis on the Theil entropy index (Theil, 1972) and the number of actives export lines at the country-year level and at the product-country level.

Let n be the total number of potential export lines (active and non-active) for country i in year t and x_{itk} the export quantity of product $k \in [1, n]$. Theil's index is defined as:

$$T_{it} = \frac{1}{n} \sum_{k=1}^{n} \frac{x_{itk}}{\mu_{it}} \ln(\frac{x_{itk}}{\mu_{it}}) \tag{3.3}$$

where $\mu_{it} = \frac{1}{n} \sum_{k=1}^{n} x_{itk}$.

The Theil index can be decomposed additively into within-groups and between-groups components. Let n_j be the number of export lines in group j The between-group component of Theil's index is defined as:

$$T_{it}^{B} = \sum_{j=0}^{J} \frac{n_j}{n} \frac{\mu_j}{\mu} ln \left(\frac{\mu_j}{\mu} \right) \tag{3.4}$$

[6]Visit http://www.fao.org/nr/water/aquastat/dbase/index.stm and http://data.worldbank.org/indicator

[7]Long-term annual flow of rivers and recharge of aquifers generated from endogenous precipitation

[8]Resources not generated in the country, including inflows from upstream countries, border lakes and/or rivers; takes into account the quantity of flow reserved by the upstream or downstream country through formal or informal agreements

and the within-group component is defined as follows:

$$T_{it}^{W} = \sum_{j=0}^{J} \frac{n_j}{n} \frac{\mu_j}{\mu} T_j \tag{3.5}$$

where

$$T_{it}^{W} + T_{it}^{B} = T_{it} \tag{3.6}$$

Cadot, Carrere & Strauss-Kahn (2011) partition their data into two groups, one made of active export lines and one made of inactive export lines. Given this partition, the within-group Theil index measure changes at the intensive margin (concentration among active lines) and the between-group Theil index measure changes at the extensive margin (in the number of active lines).

In this study we compute two Theil index: one fitting the above description, and one replacing the exported quantity of product k at year t by country i, namely x_{itk}, by its associated volume of embedded water, or its water footprint, expressed in m^3/ton and computed in the following way:

$$WFP_{itk} = x_{itk} * WFP_{ik} \tag{3.7}$$

The Water Theil index is defined as:

$$WaterTheil_{it} = \frac{1}{n} \sum_{k=1}^{n} \frac{WFP_{itk}}{\mu_{it}} \ln(\frac{WFP_{itk}}{\mu_{it}}) \text{ with } T \in [0, +\infty] \tag{3.8}$$

where $\mu_{it} = \frac{1}{n} \sum_{k=1}^{n} WFP_{itk}$.

The within and between components of the WaterTheil are build as above in equations (4) and (5). Given their construction, using the water footprint of products will leave the between-groups component unchanged but will alter the within-groups component of the Theil index.

3.3.3 Descriptive statistics

The baseline sample covers 195 countries across 13 years from 1994 to 2007 and unlike Cadot, Carrere and Strauss-Kahn (2011), we include micro-states with population below 1 million as these countries face many similar water issues (such as scarcity and pollution) and are in many cases as diverse in agricultural production as larger countries. Our sample has 2,723 data points (one for each country and year) and 875,589 at the country-year-product level.

Our countries are divided into four different water categories according to the water availability indicator (Falkenmark) and into four income categories according to the World Bank Atlas method. Table 3.1 shows how our countries are spread throughout both categories: in terms of income, high, upper-middle and low-middle income nations are roughly equally present in the data (25%) while low income countries represent only 20%. In terms of water category, the no stress category is much more representative than the rest, roughly 77% of our sample.

To understand the extent of water dependence, we look at the share of agriculture in total exports which spans from 1.6% (reached by Honk-Kong and Singapore) to over 88% in Malawi until 2004. Figure 3.1 shows the share of agriculture in total exports against GDP per capita and water availability per capita for our 147 countries. The left graph shows a fairly distinct pattern where countries with a large share of agricultural products are low income ones. 25%

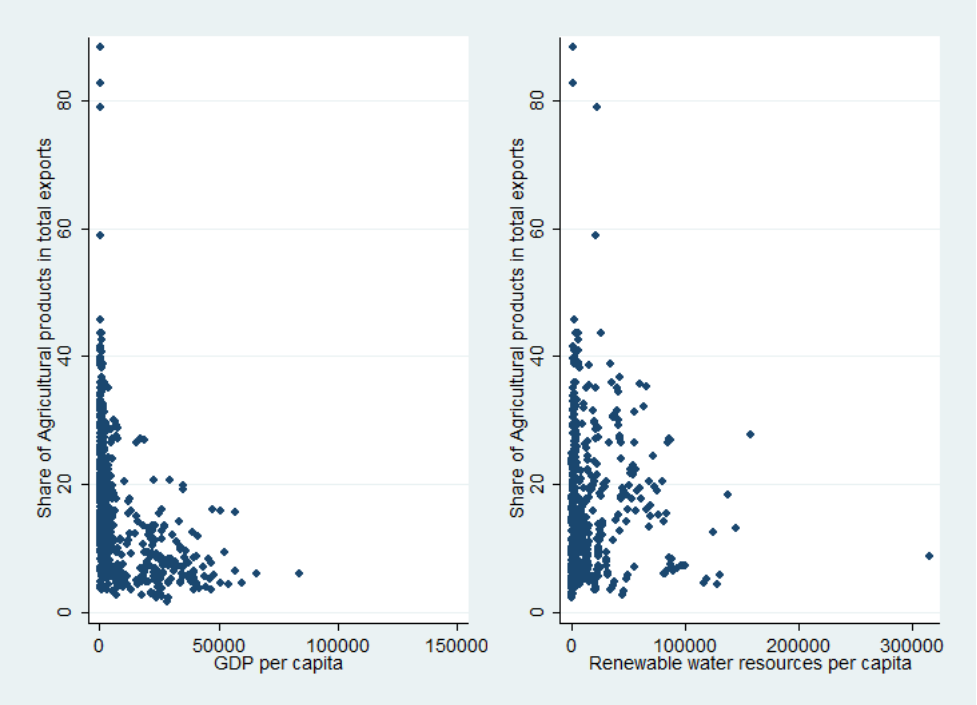
Table 3.1: **Number of countries in water and income categories**

Water Category	**HI** $> 12276\$pc$	**UMI** $[3976, 12275]\$pc$	**LMI** $[1006, 3975]\$pc$	**LI** $< 1005\$pc$	Total
Absolute Scarcity $< 500m^3$pc	8	3	2	0	13
Scarcity $\in [500, 1000]m^3$pc	2	2	4	2	10
Stress $\in [1000, 1700]m^3$pc	4	3	6	8	21
No Stress $> 1700m^3$pc	37	45	45	26	153
Total	51	53	57	36	

Source: Author statistics

of our sample has a share of agricultural exports over 20% of the total and in 2007, countries with the highest share were all from the African continent: Malawi, Guinea-Bissau, Benin, Ivory Coast, Senegal, Kenya and Niger. Argentina and Uruguay also display a high agricultural share in exports (30%), just as New Zealand (over 25%) the only high-income country to feature in this category.

Figure 3.1: Share of agriculture in total exports against GDP per capita and water availability per capita, 1994-2007



The right graph shows that the patterns are very distinct as well: countries with the largest share of agricultural exports are also the scarcest. As a matter of fact, the same countries resurface for both measures of water availability on the left side of the graphs: Malawi, Guinea-Bissau, Benin and Senegal, among the least endowed countries in water resources, although they are not considered at risk in terms of water availability per capita (definition of the Falkenmark indicator). There seems to be a clear correspondence between agricultural dependence, low growth and water scarcity.

Table 3.2 displays summary statistics for our variables of interest from both samples: the disaggregated dataset at the product-country-year level and the aggregated data at the country-year level.

Table 3.2: Summary statistics

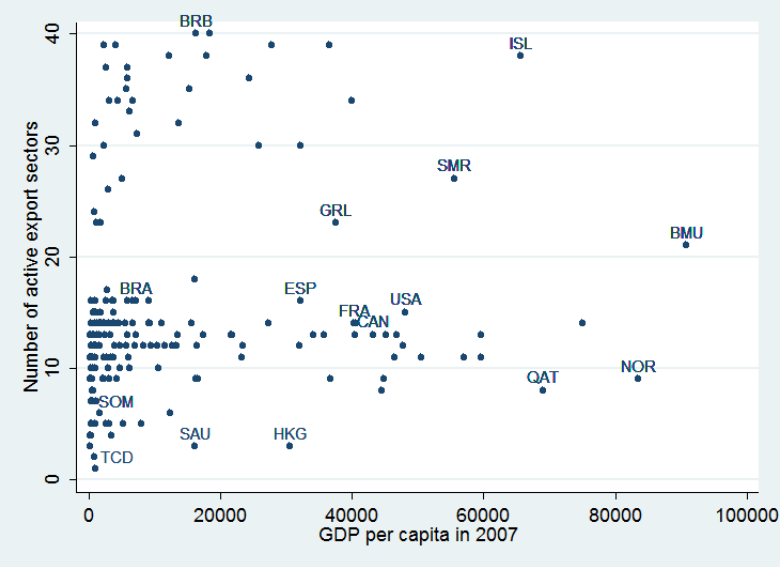
Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**	**Data**
Theil	3.678	0.963	1.4	6.645	Aggr.
WaterTheil	3.88	1.218	1.759	6.899	Aggr.
TBetween	1.429	0.819	0.09	5.724	Aggr.
TWithin	2.303	0.815	0	5.40	Aggr.
WaterTB	1.429	0.819	0.09	5.724	Aggr.
WaterTW	2.476	1.127	0	6.216	Aggr.
$ActiveLines_{i,t}$	80	80.2	1	433	Disaggr.
Sectors	13.202	5.9	1	24	Disaggr.
$Subsistence_{p,i}$	4.21	5.07	0	14	Disaggr.
ShareAgr (%)	15.802	10.367	1.649	88.324	Aggr.
GDPpc	8553.498	14289.287	64.81	170632.956	Aggr.
Waterpc	17232.328	32805.698	7.828	314221.094	Aggr.
WaterLand	123141.528	371361.856	345.168	4150259	Aggr.

Note: Aggr. is data at the country, year level;
Disaggr. is data at the product, country, year level

The Theil index is computed at the most disaggregated HS6 level, featuring a large number of export lines with small trade values. The index spans from 1.4 (reached by Afghanistan in 1994, China until 1996 and Benelux and Spain until 2006 to 6.6 (in Guinea-Bissau in 1999 and Chad in 2005). The highest level of food export concentration at the HS6 level are achieved by low-income and water stressed countries: Burundi, Cuba, Gabon, Guinea-Bissau, Iraq, Rwanda and Chad.

The number of annual active export lines per country/year reaches over 400 mostly for small countries (Bihar, Island, Guyana, Fidji, Cyprus and Barbados). The maximum is reached for Fidji in 2006. It is very low, with a minimum of 3, for poor developing and water-stressed countries such as Angola, Armenia, Eritrea, Liberia, Chad or Guinea-Bissau from 1994 to 2007. On the other hand, top exporters have around the average number of active lines with very little variation over the period 1994-2007: in the USA, the number of active lines varies between 116 and 119; in France, between 90 and 95 and in China between 136 and 139. The average number of export lines is at 80 per country, a third of the maximum, which means that there is room for

Figure 3.2: Number of active export sectors according to GDP per capita from 1994-2007



diversification at the extensive margin for developing countries.

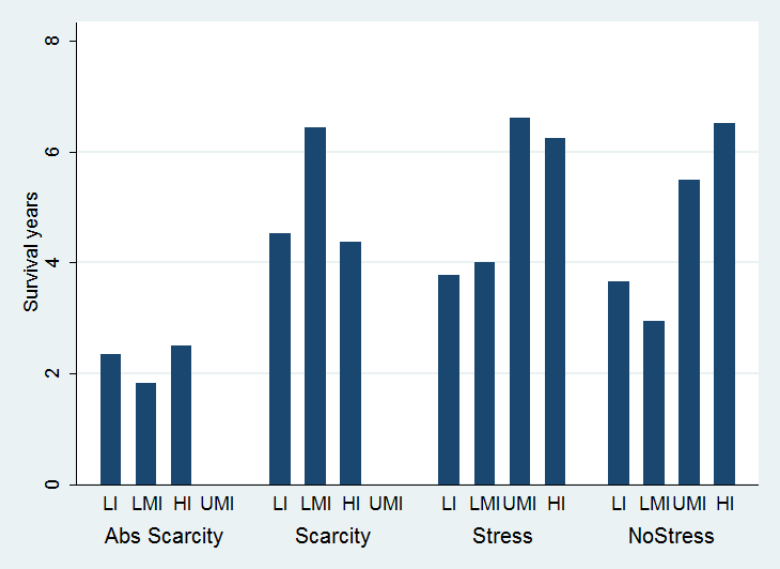
Sectoral statistics

An interesting feature is that the wealthiest countries display stable export patterns in comparison to developing or water-scarce nations. The number of sectors (HS2 level) that the top 10 exporters are active in remains stable over the years (from 13 to 16 for the USA, France, Brazil, Canada and Australia and China). On the other hand, small countries like Barbados, Fidji Islands and Cyprus, or water-scarce nations such as Qatar, vary from 10 (in 2007) to 40 sectors (in 2000). Very poor and water scarce nations such as Armenia or Somalia even started off with a minimum of one export sector in 1994 (HS2 22 category "Beverages, spirits and vinegar" for Armenia and HS2 41 products "Raw hides, skins and leather for Somalia) but never exported within more than 8 sectors until 2007. Figure 3.2 shows the average number of active export sectors per country from 1994 to 2007 against GDP per capita.

Product survival, namely the total number of (non-consecutive) years that a product has been exported by country i also provides information on the stability of production and trade patterns. Products live for an average of 4.9 years between 1994 and 2007 but Figure 3.3 shows that products have a higher survival rate in High Income countries than in Low Income nations, 6.2 vs 2.2 years. On the other hand, there is little difference between water categories: lowest survival is for absolutely scarce countries (a little less than 4 years) and highest is for countries under water stress (a little less than 6 years). Since the number of years are not necessarily consecutive, disappearing products are perhaps still being produced in the country but not exported during a specific year.

In terms of water footprint, Figure 3.4 shows that, on average, the same products survive in countries where water productivity is higher than average (lower water footprint). Lower

Figure 3.3: Average subsistence years for a product in each country according to income and water categories, 1994-2007



footprint means a comparative advantage in producing a good and countries seem to be inferring production strategies from this.

3.4 Regression results

We specify two different regression models, the first one explaining country-year level variables (Theil and Water Theil index and number of export lines) and the second featuring country-product-year level data (survival rate for a product in a given country from 1994 to 2007).

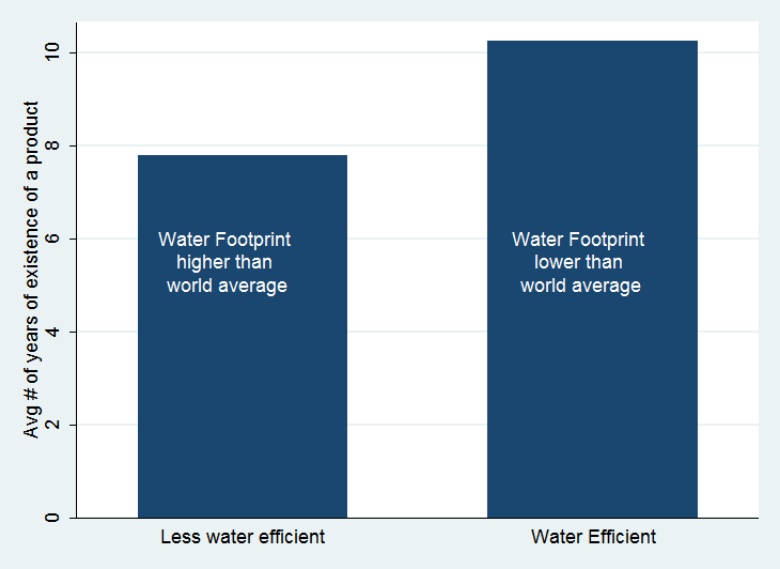
3.4.1 Theil, Water Theil and water-dependence

To explain food export diversification, we follow Cadot, Carrere and Strauss-Kahn (2011) and perform quadratic polynomial regressions of the Theil and Water Theil index and the number of export lines on per capita GDP using fixed effects according to the following:

$$Y_{it} = \alpha_0 + \beta.Z_{it} + \epsilon_{it} \tag{3.9}$$

where:
Y_{it} is alternatively the Theil and the Water Theil index and their associated between-groups and within-groups components
i is the exporter country
t is the year $\in$ [1994 , 2007]
α_0 is the intercept which captures country-year effects
ϵ_{it} error term, assumed to be normally distributed with zero mean and constant variance for all

Figure 3.4: Average years of existence for a product depending on whether countries' water footprint are higher or lower than the world's average



observations (it is also assumed that the errors are pairwise uncorrelated)

We assume here that the slope coefficients are constant across country pairs and over time. The 1 x k row vector Z_{it} comprises all of our explanatory bilateral variables which are the following: $GDPpc_{it}$ and $GDPpc_{it}^2$, $Waterpc_{it}$ and $Waterpc_{it}^2$ which is the actual water resource in m^3 per capita in year t for country i at the linear and quadratic level.

Results are reported in Table 3.3 for within effects: columns 1-3 show coefficients for the Theil index against GDP (column 1) and water availability per capita (column 2) and then considering them together, adding an interaction term (column 3). Columns 4-6 show similar regression coefficients for the Water Theil index.

Our first result is that GDP per capita and the Theil index for food exports have a non-linear relationship in the form of an inverted u-shape, unlike previous results in the literature for the whole of exports. This means that countries concentrate their food exports as they develop and, past a (relatively high) threshold of US$ 39,016 of GDP per capita, start diversifying again. This non-linear relationship disappears when controlling for water resources and becomes strictly positive, meaning that keeping water availability constant, food exports concentrate along with growth. This result suggests that countries specialize in products for which they have a comparative advantage, although we cannot yet infer if it is labor, capital or water-related.

On the other hand, the Theil index has a u-shape relationship with water availability, even when controlling for growth: food exports seem to diversify along with water abundance, before re-concentrating again above a very high threshold of $170,316 m^3/pc$, above which we find only one country, Congo. When omitting Congo from the data, the Theil index is significantly and

Table 3.3: Within Regression results for the Theil index and the Water Theil index

	(1) Theil	(2) Theil	(3) Theil	(4) WTheil	(5) WTheil	(6) WTheil
GDPpc	0.0000238***		0.0000190*	0.000000599		-0.00000796
	(5.57)		(2.21)	(0.10)		(-1.41)
$GDPpc^2$	-3.05e-10***		-2.26e-10	2.19e-11		5.84e-11
	(-9.96)		(-1.87)	(0.31)		(0.66)
Waterpc		-0.0000140*	-0.0000156*		-0.0000170***	-0.00000425
		(-2.13)	(-2.32)		(-3.35)	(-0.92)
$Waterpc^2$		4.11e-11**	4.44e-11**		4.39e-11***	2.18e-11
		(2.63)	(2.82)		(3.66)	(1.90)
GDPxWater			1.28e-10			1.73e-10*
			(1.18)			(2.07)
_cons	3.233***	3.670***	3.599***	3.617***	3.784***	3.481***
	(59.53)	(33.80)	(31.81)	(72.12)	(45.19)	(45.32)
Turning point	US$ 39,016	170,316m^3/pc	/	/	193,621m^3/pc	/
N	2594	1964	1950	2447	1958	1944
R^2	0.066	0.023	0.027	0.025	0.028	0.008
adj. R^2	-0.013	-0.062	-0.059	-0.061	-0.057	-0.072

Period	1994-2007				
Countries	Andorra	Austria	Australia	Belgium	Bermuda
on the right	Canada	Germany	Denmark	Finland	France
of turning point	Great Britain	Ireland	Island	Koweit	Luxembourg
US$ 39,016 in 2007	Netherlands	Norway	Qatar	San Marino	Switzerland
	Sweden	UAE	USA		

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

negatively correlated with water availability and the non-linear relationship disappears. Hence countries with abundant water use it to diversify their production and food exports. The interaction term between GDP and water availability is not significant for the Theil index which is likely due to omitted variables affecting the relation between growth and water use such as institutions, geography and climate. Performing a quick quadratic regression of GDP per capita against water per capita suggests that water is non-linearly correlated to GDP in the form of an inverted u-shape but the statistical correlation between the two variables is close to null, meaning that we cannot infer a sufficiently strong relation between both variables.

Our Water Theil index is not significantly correlated with GDP per capita, but displays a strongly significant u-shape relationship with water availability. This means that countries are diversifying their water use across agricultural goods as they are water abundant until a very threshold where they re-concentrate. This time, omitting Congo will maintain the non-linear relationship but will lower the turning point to $135,779 m^3/pc$ above which we find Papua New Guinea and Gabon. When controlling for GDP per capita, only the interaction term is positively and significantly correlated with the Water Theil index. GDP does not have an effect of Water Theil when water availability is null (which is never the case) and vice-versa, but they do have a positive effect as they interact, which means that growth and water availability together will mostly lead to concentration in water use for food exports.

We find 24 countries on the right side of the turning point of the Theil index, among which oil-rich and water-scarce nations such as the United Arab Emirates, Koweit and Qatar; small countries with high water-land ratios such as Austria, Benelux countries, Denmark and Singapore; and among the top 2 producers in the world, the USA and Canada. Food exports in these countries are diversifying towards a greater number of lines.

Figure 3.5: Within and Between components of the Theil and Water Theil index, 1994-2007

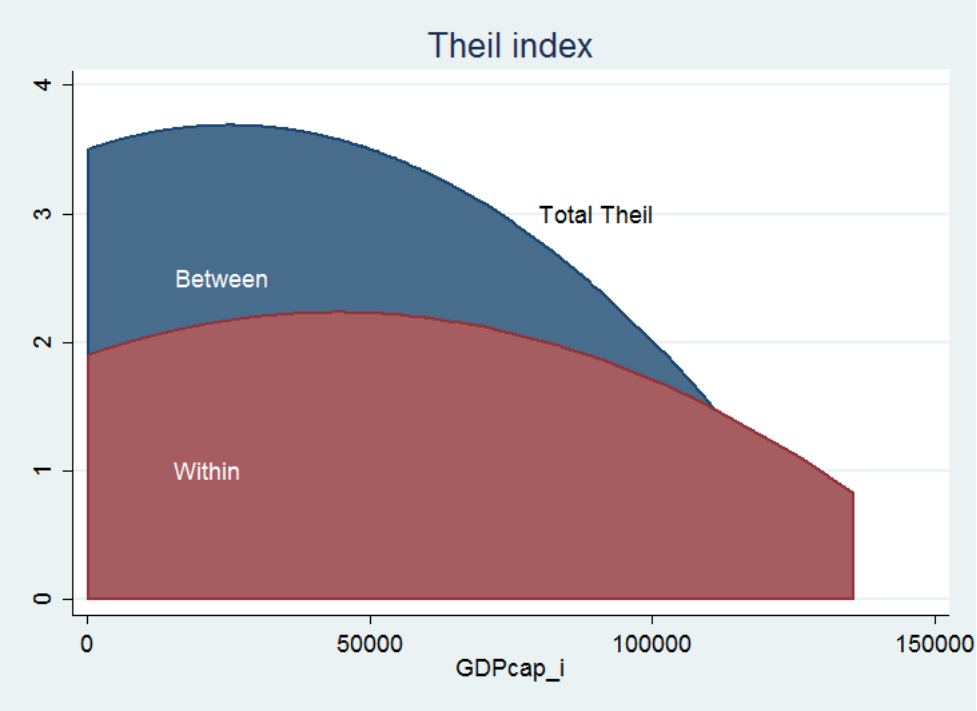


Figure 3.5 depicts the contribution of the between and within components to the overall Theil for food exports, worldwide, between 1994 and 2007 (within regression results are in table 3.6 in Appendix 3.6.2). We observe that both components follow opposing trends against GDP per capita: the between component has a u-shape relation with GDP per capita (diversification then re-concentration) while the within component first undergoes concentration and then re-diversification (inverted u-shape). Between and within components generally follow the same trend; the fact that they do not shows that there are two mechanisms at play.

The first one is that countries focus on products for which they have a relatively lower than average water footprint, namely some sort of comparative advantage in the use of water for agriculture. This increases their within margin. As they develop, so does their access to technology, capital, human capital and control of water resources (through proper monitoring, water-saving technologies, etc.) inducing higher water efficiency and thus production intensification and higher export concentration.

The second mechanism is at the between margin: developing countries have an unstable pattern of diversification, as many water intensive goods are appearing and then randomly disappearing. As countries open new lines every year, even though they probably will not last long, this decreases the between margin and the Theil index. As countries develop, there is a natural selection of products (as we saw with the within margin) which induces the closing of several lines, just as in the traditional explanation, and thus the re-concentration trend (increase in the between margin).

Because our results suggest that the Theil index is positively correlated with GDP per capita,

it seems that the within inverted u-shape wins over the between components. But because coefficient results are higher for the between components, we can also infer that variations in trade patterns are driven by the extensive margin. For water scarce countries, water use is thus an obstacle to diversification and development.

We now estimate our model using the Generalized Methods of Moments (system GMM) following Roodman (2009) to overturn the absence of any outside instrument for GDP per capita for our large panel. System GMM will generate internal instruments by using past changes in variable values to predict their current levels. We use this approach to instrument GDP per capita which is assumed to be endogenous to diversification (Acemoglu and Zilibotti 1997; Hausmann and Rodrik 2003; Lederman and Maloney 2003; Hesse 2008). Water availability per capita is exogenous and thus treated as an external instrument. Our results are displayed in Table 3.4.

The system GMM confirms that GDP per capita is significantly correlated to the Theil index at the 1% level in the form of an inverted u-shape. This relation is maintained when controlling for water availability although with lower statistical significance. The interaction term is not significant as earlier. We find a higher turning point for the Theil index of US$ 43,846, which points that the diversification phase in food exports concerns very few wealthy nations and occurs at a later stage in development. Water resources are still non-linearly correlated with the Theil index as well, in the form of a u-shape. The system GMM thus confirms that growth and water resources operate in opposite ways regarding product diversification.

The fourth column looks at the Water Theil index and system GMM confirms that growth has no effect on virtual water diversification, but column 5 shows that water resources are still non-linearly correlated to the Water Theil index in the form of a u-shape. This relationship is maintained when controlling for growth; the interaction term is significant and positive, confirming that wealth and water availability interact so as to foster water concentration. Hence countries, as they develop, display a higher equality in virtual water share, suggesting that they focus on a smaller number of products, thereby increasing productivity and water efficiency for those products. Positive spillover to other crops in the use of water enable those countries to diversify at the extensive margin.

3.4.2 Food export diversification and water efficiency

We now focus our analysis on water efficiency at the country-product level. Each year, products are appearing and disappearing from countries' export tables and we can associate each line with its own water footprint. We perform our second regression model at the country-product level (there is no time dimension here) and our dependent variable is the number of years that a product is exported by a country from 1994 to 2007 (its survival in time). Since our dependent variable ranges from 0 to 14, we perform a negative binomial regression as follows:

$$Survival_{ip} = \alpha_0 + \beta_1.WFP_{ip} + \beta_2.IncomeCat_i + \beta_3.WaterCat_i + \epsilon_{ip} \tag{3.10}$$

where i is the exporter country, p is the exported product, WFP_{ip} is country i's product water footprint in m^3/ton, $IncomeCat_i$ is the income category of the country from 1994 to 2007 and $WaterCat_i$ is its water category over the same period. The intercept captures country-product effects and the error term ϵ_{ip} is assumed to be normally distributed with zero mean and constant variance for all observations. It is also assumed that the errors are pairwise uncorrelated. We take the "High Income" and "No Stress" categories as references to avoid multi-collinearity between our independent variables. Our coefficient results for our categories must thus be interpreted as

Table 3.4: System GMM regression results for agricultural exports, 1994-2007

	(1) Theil	(2) Theil	(3) Theil	(4) WTheil	(5) WTheil	(6) WTheil
GDPpc	0.0000399***		0.0000291*	0.00000468		0.0000139
	(3.72)		(2.47)	(0.47)		(1.39)
$GDPpc^2$	-4.55e-10***		-3.59e-10*	-3.51e-11		-2.09e-10
	(-4.40)		(-2.55)	(-0.32)		(-1.84)
Waterpc		-0.0000175*	-0.0000176		-0.0000153*	-0.0000163*
		(-1.99)	(-1.71)		(-2.05)	(-2.17)
$Watercpc^2$		4.85e-11**	5.28e-11**		4.22e-11**	3.94e-11*
		(2.83)	(2.77)		(2.66)	(2.58)
GDP*Water			1.75e-10			2.08e-10*
			(1.21)			(2.01)
Turning point	US$ 43,846					
ar2	-1.219	-1.878	-2.060	-1.814	-1.894	-2.189
hansen	78.16	73.58	71.74	66.82	75.17	77.40
hansenp	0.348	0.492	0.553	0.711	0.440	0.371
Instruments	89	89	92	89	89	92
Groups	1812	1819	1799	1806	1812	1806

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 3.5: Negative binomial regression of export product subsistence from 1994 to 2007

	(1) Survival	(2) Survival	(3) Survival
Water Footprint	-0.00000349***	-0.00000352***	-0.00000332***
	(-5.48)	(-5.61)	(-5.14)
Low Income	-0.708***		-0.791***
	(-20.24)		(-22.36)
Low-Middle Income	-0.135***		-0.170***
	(-3.59)		(-4.51)
Upper Middle Income	0.0382		-0.0467
	(0.90)		(-1.10)
Abs Scarce		-0.762***	-0.916***
		(-13.87)	(-16.72)
Scarce		-0.0103	0.0654
		(-0.13)	(0.87)
Stress		0.110*	0.153***
		(2.34)	(3.30)
_cons	1.691***	1.483***	1.767***
	(62.10)	(98.13)	(62.81)
lnalpha	1.33	1.35	1.31
	(0.012)	(.012)	(.012)
_cons	1.336***	1.366***	1.317***
	(105.07)	(108.29)	(103.03)
N	23687	23687	23687

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

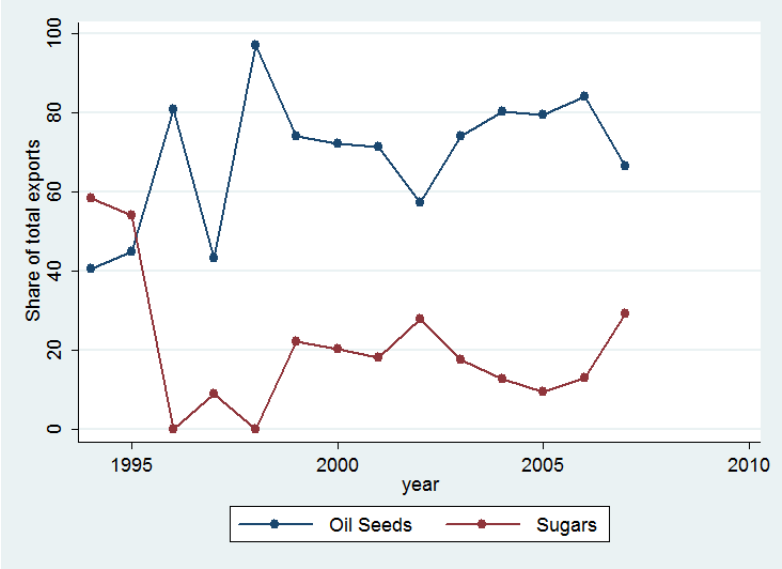
the difference between each category and the omitted category represented by the constant.

Results are reported in table 3.5 and all show high levels of significance. In all three columns, we see that the water footprint of products is negatively correlated with their survival in time, meaning that products tend to disappear faster if they are water-intensive. A high water footprint revealing poor water efficiency, we can induce that water is indeed a constraining factor for production and contributes to changes in the extensive (within) margin.

In column 1, the coefficient on high income is significant at the 1% level and equal to 1.691, meaning that all other coefficient are positive as well and that survival of products is correlated with wealth. In column 2, all coefficients are positive but again, the coefficient is for countries with little or no water stress. As such, products live longer in relatively more abundant water countries. In column 3, controlling for both income and water categories increases the intensity of coefficients. Water-intensive products are less likely to survive, a result which is emphasized in low-income and absolutely scarce countries. This result is fairly intuitive and reveals that water resources do constrain production and food exports. If water-intensive goods do not subsist long in water scarce countries, it means that they are replacing those products with other goods.

Case study: Ethiopia

Figure 3.6: Share of HS2 17 "Sugars" and HS2 12 "Oil Seeds" in total food exports, Ethiopia, 1994-2007

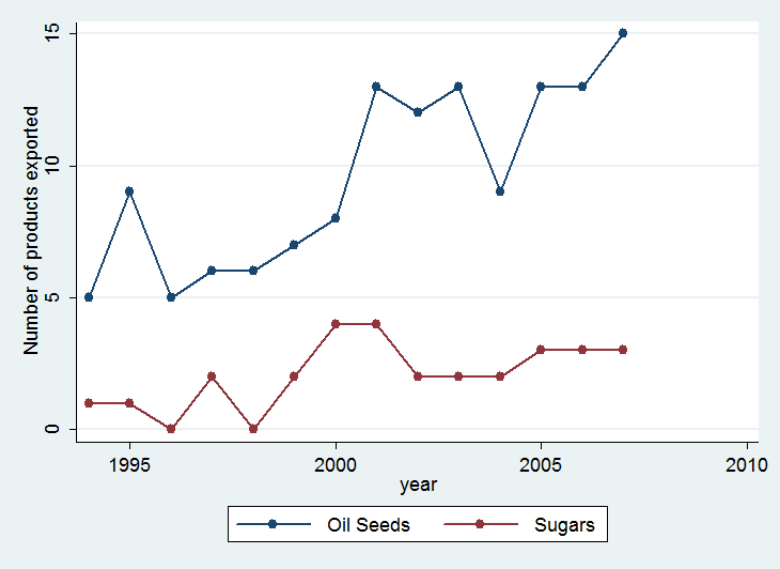


We illustrate this point by taking the case of Ethiopia whose Water Theil index has been varying between 1994 and 2007 (as illustrated in the appendix, figure 3.8). Ethiopia's main export sector in 1994 was HS2 17 "Sugars" which represented almost 60% of exports followed by HS2 12 "Oil Seeds" with 40% of total, as represented in Figure 3.6. In 2007, the trend was inversed, Oil Seeds became the first export sector with a 66% share in 2007 and Sugar was second with a 30% share. Within the "Oil Seeds" sector, Ethiopia exports 13 different products and 3 within the "Sugars" sector. Table 3.7 in the appendix lists these products in the decreasing order of their water footprint of those products, in m^3/ton and the current minimum water footprint for that product in the corresponding country.

Our data shows that HS6 120740 "Sesame seeds" makes up for 81% of the total "Oil Seeds" exports with a water footprint of 6383 m^3/ton, in front of HS6 120799 "Other oil seeds with a share of 15% and a water footprint of $10851 m^3/ton$. While these two products make up for most of the share of exports in Oil Seeds, they are not Ethiopia's best bet in terms if water comparative advantage, as would Sugar Beet or Sugar Cane seem (with only twice the water footprint as the minimum reference).

We see in figure 3.7 that the number of products exported within Oil Seeds has almost tripled, thus showing that Ethiopia has diversified within its extensive Theil margin that is by opening new lines (and sometimes closing them, as in 2004). The products that closed in 2004 were 120400 (Linseed), 120500 (Rape or Colza seeds), 120720 (Cotton seeds), 120890 (Flours and Meal of other oil seeds), 121020 (Hop cones). Specifically Flours and Meal and linseed are among the top 4 water-intensive products for that sector and actually display very unstable trade patterns (disappear and re-appear every other year). On the other hand, cotton seeds have among the smallest water footprints for the country.

Figure 3.7: Number of products exported according to sectors, Ethiopia, 1994-2007



Regarding the Sugars sector, the very little number of products make up for 30% part of Ethiopia's exports in 2007 and HS6 "Cane Molass" makes up for 71% of the sector's exports. It so happens that this is the crop for which is Ethiopia is relatively more water efficient than the other two (HS6 170199 and HS170111 which are both Cane sugar crops) whose water footprint are almost 4 times as high. The product actually made up almost 100% of the sector's exports until 2000, where it was replaced as top exports by the cane sugar crops; out of those two, only the less water-intensive remained as an important export crops, "Cane Sugar" HS6 170111.

While we cannot conclude here that out of all the available crops to grow and export, countries do focus on the ones for which they are most water efficient. However, we can notice that, as far as Ethiopia is concerned, it has opened up new lines of products that were among the least water intensive.

3.5 Conclusion

This paper addresses diversification patterns of agricultural exports in relation to water availability from a global perspective from 1994 to 2007. The objective is to fill a gap in the abundant literature on trade diversification regarding natural factor endowments and contribute to explaining the role of water resources in food production, food security and development.

Because agricultural dependence is water dependence, we study how water availability and water productivity affect agricultural exports using a water-measure of the Theil entropy index. Our study shows that, unlike previous results for the whole of exports, the traditional Theil index for agricultural products has an inverted u-shape relationship with growth. This implies that countries tend to concentrate their exports on fewer agricultural goods (extensive margin)

within a limited number of sectors before diversifying beyond a high threshold of gdp per capita. Diversification of food exports thus concerns a limited number of wealthy countries. This result can be partly explained by agricultural intensification brought by capital and innovation as the country develops. Richer countries have a higher share of large farm-holders with little crop diversification. On the other hand, poorer nations feature weaker institutions to manage land and production, hence a larger number of small farm-holders. Furthermore, we find that the effect of growth on agricultural diversification is somewhat limited, a result driven by many rich and water-abundant countries still being water-inefficient.

On the other hand, countries diversify with water availability before re-concentrating. Water endowments thus offer countries a way to naturally diversify, at the intensive margin (more water increases production capacities) and at the extensive margin (more water increases diversity of crops).

We find that products which are relatively less water-intensive will be exported for a longer time. Water-intensive goods are even more unlikely to survive in developing and water scarce nations.

Our last finding is that out of their available bundle of available crops, countries do not necessarily chose to focus on those for which they are the most water-efficient. Market effects have a role to play, but it also shows that if countries are exporting to trading partners which are relatively less water-efficient (Delbourg and Dinar), water is still not a sufficient criterion for production strategies within the country.

This paper recommends that nations should focus on a small number of crops and improve their water footprints through technology and innovation in farming methods before diversifying. This will increase water efficiency, enable knowledge, capital and human acculumation and intensify production, leading those countries to develop and travel across the diversification cone.

3.6 Appendices

3.6.1 World Customs Organization - HS Nomenclature 2012

- HS01 - Live animals
- HS02 - Meat and edible meat offal
- HS03 - Fish and crustaceans, molluscs and other aquatic invertebrates
- HS04 - Dairy products; birds' eggs; natural honey; edible products of animal origin, not elsewhere specified or included
- HS05 - Products of animal origin, not elsewhere specified or included
- HS07 - Edible vegetables and certain roots and tubers
- HS08 - Edible fruit and nuts; peel of citrus fruit or melons
- HS09 - Coffee, tea, matÃĺ and spices
- HS10 - Cereals
- HS11 - Products of the milling industry; malt; starches; inulin; wheat gluten
- HS12 - Oil seeds and oleaginous fruits; miscellaneous grains, seeds and fruit; industrial or medicinal plants; straw and fodder
- HS13 - Lac; gums, resins and other vegetable saps and extracts
- HS14 - Vegetable plaiting materials; vegetable products not elsewhere specified or included
- HS15 - Animal or vegetable fats and oils and their cleavage products; prepared edible fats; animal or vegetable waxes
- HS16 - Preparations of meat, of fish or of crustaceans, molluscs or other aquatic invertebrates
- HS17 - Sugars and sugar confectionery
- HS18 - Cocoa and cocoa preparations
- HS20 - Preparations of vegetables, fruit, nuts or other parts of plants
- HS22 - Beverages, spirits and vinegar
- HS23 - Residues and waste from the food industries; prepared animal fodder
- HS24 - Tobacco and manufactured tobacco substitutes

3.6.2 Additional regression results

Table 3.6: Within regression results for between and within components of the Theil index, 1994-2007

	(1) Theil Between	(2) Theil Within
GDPpc	-0.0000198***	0.0000150***
	(-5.02)	(3.42)
$GDPpc^2$	1.22e-10**	-1.69e-10***
	(2.74)	(-3.41)
_cons	1.674***	1.912***
	(68.48)	(70.42)
N	2572	2572
R^2	0.017	0.005
adj. R^2	-0.061	-0.074

t statistics in parentheses

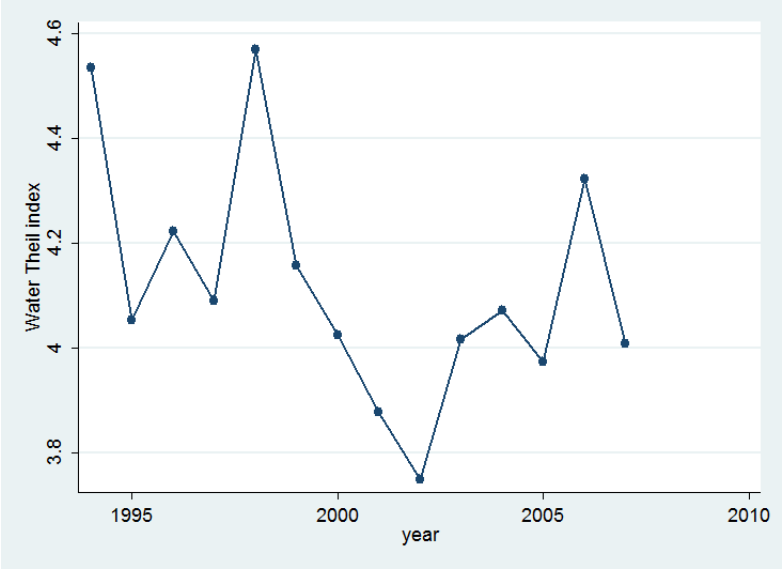
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 3.7: Within regression results for between and within components of the Theil index, 1994-2007

HS6	HS2 12 - Oil Seeds	WFP (m^3/ton)	Best WFP i(m^3/ton)
120890	Flours and Meal of Other Oil Seeds	13564	2586
120799	Other Oil Seeds	10851	1229
120760	Safflower Seeds	8348	2509
120400	Linseed	8219	789
120740	Sesame Seeds	6383	429
120810	Flours and Meal of Soya Beans	5602	874
120210	Ground-nuts	5578	889
120100	Soya Beans	4762	743
120500	Rape or Colza Seeds	4284	935
121020	Hop Cones	4050	1428
120750	Mustard Seeds	3078	75
120720	Cotton Seeds	2293	568
121299	Other Vegetable Products	1153	97

3.6.3 The Oil Seeds and Sugars sector in Ethiopia

Figure 3.8: Water Theil Index for Ethiopia, 1994-2007



This paper investigates the impact of water endowments and water productivity on developing countries heavily relying on agriculture and struggling to diversify their exports and develop. We analyze food exports from 1994 to 2007 at a global level and find that growth and water availability have opposite effects: both food and virtual water exports concentrate along with

Table 3.8: Within regression results for between and within components of the Theil index, 1994-2007

HS6	HS2 17 -Sugars	WFP (m^3/ton)	Best WFP i(m^3/ton)
170199	Other Cane or Beet Sugar	1482	560
170111	Cane Sugar	1304	478
170310	Cane Molasses	412	151

GDP per capita but diversify with water availability. Furthermore, we find that water-intensive goods display lower subsistence in time when countries are water-scarce and have lower water efficiency than world average. In fact, water-scarce countries have unstable diversifying trade patterns with water-intensive goods disappearing and re-appearing throughout our period of study, revealing that the inefficient use of water resources is a main obstacle to sustainable trade diversification. We conclude that inefficient water management and insufficient investments in water efficiency are an obstacle to exiting water dependency by inducing similar economic impacts as those caused by "traditional" cursed resources such as oil, natural gas or minerals. We recommend that water-scarce countries focus on improving the water footprint of a small number of goods in order to trigger positive spillovers to other crops and other sectors of the economy in order to diversify.

Conclusion

This thesis contributes to the ongoing debate about whether water scarcity will lead to growing water conflicts and potential threats to global food security. Using quantitative tools and econometric methodologies, it addresses the empirical allocation of water resources in the context of transboundary water management and international trade of agriculture. Although the analysis and suggestions derive from economic theories of common pool resources and recent empirical findings in environmental economics, this thesis also includes a variety of references and panel datasets taken from the geography, international relations, history and hydrology literature.

The first chapter, co-authored with Eric Strobl, addresses transboundary water management between African countries sharing a common river basin in a upstream-downstream position between 1949 and 2007. We study what triggers cooperation over water and what determines the outcome, whether cooperative or conflictive, by measuring the asymmetry of water run-off, namely streamflow, between countries. We find that cooperation is likelier when there is little economic and water asymmetries between countries and that nations perceive dams as projects likely to minimize those asymmetries rather than increase them, thus enhancing cooperation. Because economically stronger downstream nations generally take the lead in cooperation, we argue that geographical asymmetries can be offset by economics. The article also shows that cooperation is independent from past cooperation, meaning that transboundary basins with a history of tensions over water may likely cooperate in the near future.

The second chapter addresses the determinants of bilateral trade of virtual water and investigates whether countries do trade according to their comparative advantage in water, proxied by water endowments and water productivity. Using panel data of bilateral trade between 1994 and 2007 at a global level, we find that that exporter-importer relative water endowments have a positive effect on food trade, suggesting that the driest countries use trade as a means to alleviate water scarcity. We also show that relative water productivity and food trade display an inverted u-shape, suggesting a threshold effect in demand in developed countries and a disregard for water resources relative to the lack of other inputs (such as capital, technology or qualified labor) in relatively water-scarce countries. As such, countries do not take water endowments enough into consideration when making decisions about food production and trade.

The third chapter further investigates food trade through the perspective of the causality debate between trade diversification and growth. Using the same panel data as in the previous chapter, this time from a unilateral perspective, it makes the case that food dependence is water dependence and relates water endowments and productivity to export diversification. The article shows that growth and water availability have two opposite effects on trade patterns: exports concentrate with growth but diversify with water availability. The interaction effect is positive, showing that countries, as they develop, concentrate on fewer products for which they have com-

parative advantage in water productivity. In fact, water intensive goods display lower subsistence in time when countries are water scarce rather than water abundant. As such, we argue that inefficient management of water resources and sub-optimal water productivity prevent countries from fully developing their production potential and exiting the state of water/agriculture dependency and slow growth. We recommend that water-scarce countries focus on improving the water footprint of a small number of goods in order to trigger positive spillovers to other crops and other sectors of the economy before attempting to diversify and develop.

The use of quantitative tools applied to water economics is crucial to fully account for available water resources and implement sustainable water practices. Unfortunately, food security policies are mostly about quantity and production intensification when they should also tackle the vital question of water resources which, in many parts of the producing world, are completely dried out. Yet water resources are hardly ever considered in the equation. This is because of a never-ending cycle between the lack of precise data on the state of our resources and the absence of any water pricing mechanisms. The first element deprives our farmers and consumers from detailed knowledge about how scarce the water can be and prevents relevant authorities from assigning a real economic value; the second does not give the incentive to collect data, hence knowledge, about water since the resource is basically free.

This thesis advocates that a major solution to addressing water resources properly is pooling knowledge between disciplines that each have their own understanding, knowledge and data about water resources. While econometric methodologies are essential to analyzing wide panel datasets and making robust policy recommendations, the hydrological features need to be properly computed by academics with an understanding of water cycles, with the help of climatologists, geographers and historians. Furthermore, while water economics can argue in favor of water pricing mechanisms and water allocation schemes, the implementation of such solutions need to be done at the local context, with the consent of local agents and consumers.

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Title: Ensuring Water Security through Cooperation and Food Trade

Keywords: Water, Transboundary Management, International Trade, Diversification, Water Footprint

This thesis contributes to the ongoing debate about whether water scarcity will lead to growing water conflicts and potential threats to food security. Using quantitative and econometric tools, it addresses the empirical allocation of water resources in the context of shared water and international trade of agriculture.

Chapter 1, co-authored with Prof. Eric Strobl, studies transboundary water management between upstream and downstream African countries (1949-2007). We find very little evidence for water conflicts over the years, even though cooperation is likelier when there is little economic and water asymmetries between countries. We also show that wealthy downstream nations mostly take the lead in cooperation, especially when they are at least as well off as the previous year. Results indicate that dams are a factor of cooperation and that cooperation between countries does not suffer from past conflicts, giving hope to many African nations with conflictive history.

Chapter 2, co-authored with Prof. Shlomi Dinar, investigates whether countries produce and trade food according to their comparative advantage in water. Using panel data of bilateral trade at a global level (1994-2007), we find that the driest countries use trade as a means to alleviate water scarcity. Relative water productivity and food trade display an inverted u-shape, suggesting a threshold effect in demand and a disregard for water resources relative to the lack of other inputs (such as capital, technology or qualified labor) in water-scarce countries. Countries do not take water endowments enough into consideration when deciding about production and food is traded in the wrong direction, from less to relatively more water productive nations.

Because agricultural-dependence is water-dependence, we end by asking whether water scarcity can be a threat to development. Chapter 3 shows that exports concentrate with growth but diversify with water availability. The interaction effect is positive, suggesting that countries, as they develop, concentrate on fewer products for which they have comparative advantage in water. As water intensive goods display lower subsistence in time in water-scarce countries, we argue that inefficient management of water prevents countries from developing and exiting the state of water/agriculture dependency and slow growth. We recommend that water-scarce countries focus on improving the water footprint of a small number of goods in order to trigger positive spillovers.

Titre: Assurer l'avenir de nos réserves en eau à travers la coopération et le commerce international

Mots-clés: Eau, Gestion Transfrontalière, Commerce International, Diversification, Empreinte Eau

Cette thèse de doctorat en économie s'inscrit dans le grand débat sur la rareté des ressources en eau et des impacts potentiels sur nos économies et notre sécurité alimentaire. Avec l'usage d'outils quantitatifs et économétriques, elle étudie les mécanismes de répartition de l'eau d'abord lorsqu'elle doit être partagée par plusieurs pays et ensuite lorsqu'elle est utilisée par l'agriculture et virtuellement expédiée à travers les aliments par le commerce international alimentaire.

Le premier chapitre, co-écrit avec le Prof. Eric Strobl, étudie les conflits de l'eau entre pays Africains situés en amont-aval d'un fleuve et contraints de partager la ressource. Entre 1949 et 2007 nous trouvons peu de traces de conflits, même si la paix est souvent contingente à une situation égalitaire en termes d'accès à l'eau. En effet, c'est l'asymétrie de l'approvisionnement qui est en jeu mais le pays en aval, défavorisé par sa position, arrive souvent à contre-carrer ce désavantage par une pression économique (comme dans le cas de l'Egypte, en aval, face à l'Ethiopie). Nos analyses montrent également que l'absence de coopération ne présage en rien des coopérations futures, un résultat encourageant pour les basins transfrontaliers où l'entente est encore difficile.

Le deuxième chapitre, co-écrit avec le Prof. Shlomi Dinar, s'intéresse à la théorie des avantages comparatifs liés à l'eau dans le commerce international alimentaire. En étudiant les flux commerciaux entre 1994 et 2007, on comprend que les pays les plus pauvres en eau sont contraints d'importer les produits qu'ils ne peuvent eux-mêmes produire sur place, faute d'eau. Il y a un bien un avantage comparatif à la ressource. En revanche, nous montrons qu'en termes de productivité-eau (la quantité produite par litre d'eau utilisé), les pays s'échangent des biens pour lesquels ils n'ont pas nécessairement d'avantage, voire bien le contraire. L'eau est donc négligée dans l'équation lorsqu'il s'agit des stratégies de production et d'exports.

La thèse se penche ensuite sur ces pays pauvres en eau et souvent dépendants du secteur agricole. En particulier, le troisième chapitre s'inspire des théories qui prédisent que le développement économique va de pair avec la diversification de la production et des exportations. Or un manque d'eau contraint nécessairement les pays dans leur stratégie de diversification. Nous montrons que les pays avec une eau rare et une productivité-eau faible ne peuvent se développer par l'agriculture, à moins de se concentrer sur un petit nombre de produits. Investir dans des technologies de l'eau pour un nombre restreint de produits permet d'intensifier la production et d'avoir des externalités positives sur d'autres cultures potentielles. La concentration est donc souhaitable avant la diversification. Une meilleure gestion de l'eau (dans sa quantité et sa productivité) peut ainsi, à terme, être bénéfique pour le développement économique.