# ABSTRACT

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| Title of Dissertation: | TELE-CONNECTING CONSUMPTION OF NATURAL RESOURCE USE AND ENVIORNMENTAL IMPACTS THROUGH (GLOBAL) SUPPLY CHAINS: APPLICATIONS OF THE MULTI-REGIONAL INPUT-OUTPUT MODEL |
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Natural resources are necessary inputs in production systems. In today's globalized world, local resource consumption can impact ecosystems on a global scale. With commodities and services being traded across economic and ecosystem boundaries, natural resources are appropriated and exchanged. The finite nature of natural resources, uneven distribution in space and time, and global trends in consumption are impacting resource availability. The overuse of resources can have severe consequences on ecosystems; further degrading quality and functioning. The rise and expansion of global supply chains, with ever-increasing exchanges of intermediate goods, deepens the complexity of assessing the negative environmental impacts of trade externalities and globalization. To understand the consequences of natural resource consumption in international trade, we incorporate environmental indicators

in an across-scale approach to examine and describe the spatial linkages between local consumption and environmental impacts in a meaningful and quantitative method.

Applying the tele-connections concept, this research utilizes the environmentally-extended multi-regional input-output model to quantify, track, and evaluate the hidden ‘virtual’ flows of natural resources and environmental impacts across economic supply chains. This research spatially identifies and traces the major trade routes conveying environmental pressures and impacts on local ecosystems on regions of production from distant centers of consumption. Our analysis demonstrates that resource consumption and scarcity transpire differently across system boundaries with variable resource endowments. Therefore, incorporating environmental relevance across scale is critical to understanding resource consumption and scarcity. The across scale perspective provides not only novel insight into the environmental pressures facing systems, but reveals ‘hotspots’ of environmental impacts. Numerous footprint and virtual trade studies have been conducted for a particular country, region, or globally, but with little attention to the tele-connection of consumption of natural resource and environmental impacts across scale in multiple places. This research demonstrates that incorporating relevant environmental indicators and a multi-scaled approach enhances the assessment of humanity’s resource consumption and impacts on the environment.

# TELE-CONNECTING CONSUMPTION OF NATURAL RESOURCE USE AND ENVIORNMENTAL IMPACTS THROUGH (GLOBAL) SUPPLY CHAINS: APPLICATIONS OF THE MULTI-REGIONAL INPUT-OUTPUT MODEL

by

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# Preface

Research in this dissertation has been previously published, or has been accepted for publication, in peer-reviewed journal articles. Specifically, the material presented in Chapters 4, 5, and 6.

# Dedication

*To my family,*

*Yuri, Emma, and Maya*

# Acknowledgements

I would like to thank committee members Drs. Klaus Hubacek, Kuishuang Feng, Laixiang Sun, Fernando Miralles-Wilhelm, and Giovanni Baiocchi for their support.

I am particularly grateful to my Advisor, Professor Klaus Hubacek, and Co-chair, Dr. Kuishuang Feng, for supporting me in undertaking this research. I would like to sincerely thank them both for their encouragement and guidance through this process. Every academic conversation was a solution-focused exploration; and every critique practical, brutally honest, and to the point. Both provided me the independence to pursue this research while keeping me focused and on track. Beyond the role of the Ph.D. student and the Advisor/Co-chair, I am deeply appreciative of Klaus' and Kuishuang's kindness and genuineness. I can still clearly recall discussing the, at the time, recent birth of my first child – the joy, elation, and tiredness – and feeling their sincerity and happiness reflected in our conversation.  Thank you.

Even while pursuing a Ph.D., life goes on. While matriculating at UMD, I continued to be employed full-time, became married, and started a family. My deepest heartfelt thanks go to my family for their support.  My beautiful wife for her constant sustenance and patience accommodating the seemingly endless number of hours spent on my doctorate. My two precious daughters for the many weekends, nights, hours, and minutes of family time and play time sacrificed in order to run one more analysis, read one more publication, edit one more sentence, etc.

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# Chapter 1: Introduction

## I. Introduction

Globalization increases the interconnectedness of the economy, people, and places around the world. The globalization of markets has resulted in cheaper commodities, increased economic growth of countries worldwide, and contributed to greater resource use efficiency. International trade can also have negative impacts on the environment**.** When commodities are produced and consumed domestically, the associated environmental impacts are felt within national borders. However, the increasing consumption of goods produced in foreign locations and traded internationally drives the displacement of these pressures to other parts of the world. Often commodities are produced and harvested in areas where short-term economic interests are primary and, coupled with weak institutions, the environmental costs are frequently ignored. Production and harvesting processes generate environmental impacts including land and water overuse, pollution of air, water, and soil, degradation of ecosystems, and biodiversity loss (European Commission, 2013). Trade itself, however, is not a driver of environmental degradation. The structure of the markets, the distribution of natural resources, and market failures (e.g. externalities) are the cause of environmental degradations (WTO, 2010). The rise and expansion of global supply chains, with ever-increasing exchanges of intermediate goods, deepens the complexity of assessing the negative environmental impacts of trade externalities and globalization (European Commission, 2013). Important questions arise concerning the consumption and trade of natural resources through regional and global supply chains, particularly their exhaustibility and externalities. To understand the consequences of natural resource consumption in international trade, we incorporate environmental indicators in an across-scale approach to examine and describe the spatial linkages between local consumption and environmental impacts in a meaningful and quantitative method.

The substitution of domestic resource consumption through imported goods traded internationally causes socio-environmental impacts. This paper explores whether the consumption of natural resources traded through supply chain networks mitigate or intensify local resource scarcity. Incorporating environmental indicators enables our analysis to differentiate between vastly different degrees of resource availability across regions and to quantify the degree to which consumed resources are actually scarce. Current approaches typically link final consumption to environmental impacts back to the aggregated country level. National level data assumes natural resource endowments – as well as the socio-environmental impacts associated with the production of goods – are homogenous within each country. This presents an ecological fallacy. There is significant spatial variation in natural resource endowments among regions within national borders. Our across-scale approach addresses this ecological fallacy pitfall by presenting a successive finer-scale analysis of the consumption of natural resources and associated environmental impacts through the global supply chain, a regional supply chain, and the inter-regional trade of a hydro-economic river basin catchment. This across-scale approach permits a more comprehensive examination that produces more spatially-explicit results and unveils the hidden (i.e. hidden due to data aggregation at the national level) causal linkages between consumers' choices and their environmental impacts; particularly in countries with large spatial variability in natural resource endowments and environmental impacts from centers of production.

Our global analysis investigates whether the redistribution of natural resources and environmental impacts via the international trade in food mitigates or intensifies national level resource scarcities around the world. Agriculture is the world's single largest driver of global environmental change (Steffen *et al.* 2011; Rockstrom *et al.*, 2017). Irrigated agriculture consumes 70% of freshwater withdrawals and has transformed nearly 40% of the planet's terrestrial surface area (Assouline *et al.*, 2015; Ramankutty *et al.*, 2008). Freshwater and arable land are necessary inputs for food production, but excess or overuse of these resources causes unsustainable environmental pollution and degradation. In the last fifty years, globalization has transformed the geography of food systems and altered the distribution of land and water across regions (Duarte *et al.*, 2016; MacDonald *et al.*, 2015); resulting in one-fifth of global cropland area (Kastner *et al.*, 2014) and one-fifth of global agriculture water (Hoekstra and Mekonnen, 2012) consumed solely for agriculture commodities exports. We investigate global agriculture supply chains to explore the influence of global trade in food on nations' arable land and freshwater resources. This study incorporates the environmental indicators water scarcity and land scarcity. The inclusion of environmental indicators for water scarcity or land scarcity in agriculture production publications remains mostly unexplored. Two exceptions are Pfister *et al.* (2011b) and Castillo *et al.* (2019) which incorporate both land scarcity and water scarcity indicators into their analysis of water consumption and land use for, respectively, the global production of 160 crops and the land-water nexus of bioenergy production in Brazil.

Our regional analysis investigates the redistribution of the natural resources water, energy, and food and environmental impacts at the sub-national level in East Asia's transnational inter-regional trade. East Asia is of particular interest due to the region's rapid economic growth and structural transformation into an integrated regional supply chain in the last half century. With substantial quantities of commodities and services being traded across economic and ecosystem boundaries, the inter-regional production networks in East Asia have significant implications on demand for local (i.e. sub-national) water-energy-food resources and environmental impacts. We investigate the supra-national structure of the Water-Energy-Food Nexus (WEFN) and environmental linkages between the three subsystems and examine the impacts and tradeoffs between each subsystem. This study incorporates the environmental indicators water scarcity and greenhouse gases ($CO_2$, $CH_4$, $N_2O$) and $SO_x$ emissions. Recently, the WEFN approach has become an increasingly popular perspective among scholars, but few publications incorporate analysis of environmental impacts.

Our inter-regional trade analysis of the Haihe River Basin as a hydro-economic unit (i.e. relatively homogeneous in both economic and hydrological attributes) investigates the redistribution of freshwater resources and environmental impacts within China. China's water challenge is rooted in the geographic mismatch between water and arable land availability. The Haihe River Basin faces acute water scarcity. The Basin encompasses the megacities of Beijing and Tianjin. The Basin has grown rapidly economically and is now responsible for 15% of total industrial production and 10% of total agricultural output in China (Liu *et al.* 2012; Sha *et al.* 2013). We quantify the total and scarce water consumption, footprint, and flows embodied in inter-regional trade in the Basin and examine to what extent the Basin reaps benefits from water import flows and shifts water pressure to other water scarce regions. Several studies have quantified China's direct and indirect water consumption at the national, regional, provincial, city, and river basin level, but none have incorporated both the natural geographic of a river basin as the analytical unit and water scarcity as an environmental indicator.

## II. Background

Over the last half-century, the world economy has changed profoundly. The world economy has become more integrated as a result of three factors: the lowering of transportation costs, the revolution in information and communication technology, and the lowering of barriers to foreign investment (e.g. allowing the transfer of managerial and manufacturing knowledge and financial resources). These factors have reduced the transaction costs of international commerce and allowed the emergence and evolution of global supply chains (WTO, 1999; Brakman *et al.*, 2015). The rapid growth, extent, and complexity of global supply chains have been an important factor in driving economic growth and raising living standards (IMF, 2013; Gasiorek and Lopez, 2014). Global supply chains divide up the production of goods and services into linked stages of production distributed across international borders and economies; a product originates from an established network of suppliers from multiple locations (ADB, 2014). Before the mid-1980s, globalization was mainly associated with production networks between developed nations; in particular among the Group of 7 (G7) countries (Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States). After the mid-1980s, production networks between developed and developing nations increased resulting in G7 world shares of income and exports plummeting (Baldwin and Lopez-Gonzalez, 2013). Today, developing countries contribute a much larger share of global trade (reaching 44% in 2012); consisting of increasing exports from developing countries to other developing countries. Consequently, developing countries are increasingly both sources of production and demand; i.e. their increasing share of global trade and growth in global GDP has resulted in a shift in the geography of demand (Horner, 2016). Production and consumption activities in both developed and developing countries are more and more dependent on increasing resources imported via international trade and the integration of different world regions into the global market (Bruckner *et al.*, 2012).

Access to resources is critical to economic growth, quality of life and wellbeing of populations, political stability, and modern society as we know it. Essential needs that were historically fulfilled by local resources (e.g. water, energy, and food) are increasingly outsourced (Tonini and Liu, 2017). The extension and thickening of the web of global connections has resulted in billions of people dependent on resources supplied from all over the world (Kissinger *et al.*, 2011). Kissinger *et al.* (2011) articulates the premise that today's highly interconnected dynamic global system is comprised of three components of mutual economic and ecological interdependence: 1) virtually every human population depends, in part, on resource flows from distant locations around the world; 2) ecological change in one region may impact the ecology or ecosystem services of other regions; and, 3) production and consumption in one geographic location can create adverse environmental burdens on ecosystems in other regions. Furthermore, resource consumption and interactions take place within the context of relevant drivers, such as increasing population, industrialization, demographic shifts to urban centers, rising income, changes in lifestyle patterns and dietary demands, and rising levels of pollution. In an increasingly interconnected world, these drivers can impact resource consumption and trade across large distances; i.e. drivers of resource consumption can originate from far beyond local and national boundaries (ADB, 2013).

The environment and trade are fundamentally linked. The WTO (2010) defines natural resources as "stock of materials that exist in the natural environment that are both scarce and economically useful in production or consumption, either in their raw state or after a minimal amount of processing". The environment provides the basic inputs for economic activity – forests, fisheries, metals, minerals, water, land – and production, in turn, is affected by the quantity, quality, and availability of resources (Pace and Gephart, 2016). Furthermore, critical ecosystem processes influence plant productivity, soil fertility, water quality, atmospheric chemistry, and many other local and global biophysical preconditions that humans, animals, and plants require to exist. Functioning ecosystems provide these preconditions. Human modifications to ecosystems – as well as to the biodiversity of the earth – can alter ecological functions and life support services (i.e. ecological services such as greenhouse gas regulation, water treatment, erosion control, soil quality control) vital to the well-being of human societies (Naeem *et al.*, 1999). Humans can alter local ecosystems by depleting and degrading resources (Pace and Gephart, 2016).

International trade relaxes feedbacks between consumers and their local environment; shifting or intensifying resource depletion and degradation. Linking the impacts of trade on an ecosystem or ecosystem service to distant production processes and consumption may not be apparent as the value chains of most products now span several countries (Tukker *et al.*, 2018). Only recently has the literature begun to appreciate the spatial dimension in tracing resource consumption and environmental stress across the economic supply chain to determine environmental impacts (Yu *et al.*, 2013; Hubacek *et al.*, 2014). The conceptual framework of tele-connections explicitly examines the socio-economic and environmental interactions between human and natural systems over distances. The term tele-connections originates from atmospheric sciences referring to climate anomalies that are related to each other and occur over large distances (Liu *et al.*, 2013a). The framework treats each location as a coupled human and natural system where both components interact with each other. Trade is a powerful force in creating tele-connections via the consumption of natural resources and the linkages to distant ecosystems of production. Local, national, and regional economies are all deeply embedded in global supply chains (Hubacek *et al.*, 2014).

With commodities and services being traded across economic and natural system boundaries, it is important to quantify how and where available natural resources are appropriated and the environmental impacts of consumption (Yang *et al.*, 2013; Hubacek *et al.*, 2014). The complementary 'virtual trade' and 'footprint' concepts are important indicators to characterize humanity's induced resource consumption and associated environmental impacts (Jeswani and Azapagic, 2011). The term 'virtual' extends beyond the natural resource or environmental pressure physically contained in the product to include the resource ‘embodied’ in products and used in the whole production chain of goods and services (Fang *et al.*, 2014). A ‘footprint’ is a quantitative measure of humanity’s appropriation of natural resources that describes how human activities impose burdens and impacts on ecosystems (Hoekstra, 2008).

## III. Research Objectives

The finite nature of natural resources, uneven distribution in space and time, and global trends in consumption are impacting natural resource availability and ecosystems at various scale (Grey *et al.*, 2013; Yang *et al.*, 2013). In today’s inter-connected world, countries may ‘displace’ or degrade natural resources in distant locations through imports to meet their own domestic demand for food and material consumption. Furthermore, the vulnerability of a region to environmental impacts from production and harvesting activities depends on the region’s natural resource endowments and ecosystem resilience. Countries endowed with abundant natural resources face a different set of challenges and priorities from countries with limited or unbalanced resources. This research incorporates environmental relevance across the whole supply chain and environmental indicators to determine the impacts of natural resource consumption in a meaningful and quantitative method. Using the well-established environmentally-extended multi-regional input-output (E-MRIO) model, this research spatially identifies and traces the major trade routes conveying environmental pressures and impacts on local ecosystems on regions of production from distant centers of consumption. In an interdependent world, it has become essential to adopt a coupled social-environmental across-scale approach to assess and examine the patterns of consumption and the environmental impacts of international trade.

This research includes the following objectives:

***Objective 1:*** ***Tele-connected investigation of the consumption of freshwater and arable land resources and environmental impacts embodied in the global food trade. Assess the mitigating or exacerbating effect of participation in the global food trade on countries' finite water and land resources.***

***Objective 2:*** ***Tele-connected investigation of the consumption of water, energy, and food resources and environmental impacts embodied in the East Asia regional trade. Assess and spatially characterize the impacts from regional trade on sub-national regions' resources and environment.***

***Objective 3:*** ***Tele-connected investigation of the consumption of freshwater and environmental impacts embodied in the Haihe River Basin catchment's trade within China. Assess and spatially characterize the mitigating or exacerbating effect of inter-regional trade of agriculture, industry, and energy final products on the Basin's water resources.***

## IV. Significance of Research

This research improves our empirical understanding of tele-connection and supply chains by investigating the inter-linked social, economic, and ecological relationships among geographical entities. Using the E-MRIO model, we track resource use across the whole economy and quantify the environmental impacts of human consumption. The tele-connected across-scale approach in this paper is challenging given that resource scarcity and resource management issues manifest themselves in different ways in the context of individual countries and regions with differing resource and technology endowments. Therefore, our research incorporates environmental indicators to account for resource scarcity relevance and to quantify the actual scarcity of resource flows. The analysis demonstrates how the across-scale perspective provides not only novel insight into the environmental pressures facing regions, but reveals loci ('hotspots') of environmental impacts and the origins of consumption demand. Numerous footprint and virtual resource flow studies have been conducted for a particular country, region, or globally, but with little attention to the tele-connection of environmental impacts or across-scale interactions of multiple places.

Publications of agriculture production typically describe the required input of one – arable land or freshwater – resource. Our analysis of the tele-connected global agriculture production supply chain and trade in food products (Chapter 4) adds to the research literature in the following ways: 1) incorporates both freshwater scarcity and arable land scarcity indicators to provide an analysis of the impact of the agriculture supply chain and trade in food on these two essential and finite natural resource inputs;

2) incorporates a novel method for calculating land scarcity in the form of the Land Appropriation Index, and; 3) the first to quantify the mitigating or exacerbating environmental effects of trade in virtual land and virtual water upon individual nations' land and water resources.

In general, the associated environmental impacts of resource consumption have been the ignored dimension within the water-energy-food nexus (WEFN) literature. A tele-connected WEFN approach is applied (Chapter 5) to investigate regional water, energy, and food consumption, the competing domestic and international demand for these resources, and the linked environmental impacts (water scarcity and greenhouse gases and $SO_x$ emissions) in East Asia's trade by modelling data contained in the Transnational Interregional Input-Output Table (TIIOT) for the year 2005 (IDE-JETRO). TIIOT contains region-specific economic production, consumption, and trade flows between China (seven regions), South Korea (four regions), and Japan (nine regions). The TIIOT data permits sub-national assessments of environmental impacts embodied in traded products in the East Asian countries. Our analysis adds to the research literature in the following: 1) first tele-connected WEFN analysis; 2), quantifies the inter-linkages between all three water-energy-food subsystems and associated environmental impacts across scale – i.e. sub-national, national, supra-national, and regional; 3) differentiates between domestic (within national borders) and foreign (transnational intra-regional) origins of environmental impacts and water-energy-food resources consumption, and; 4) new application of the harmonized TIIOT data improves consumption and environmental impact accounting at finer scale.

We analyze China's Haihe River Basin (Chapter 6) as a hydro-economic unit (i.e. relatively homogeneous in both economic and hydrological attributes) to investigate to what extent the Basin reaps benefits from water flows embodied in inter-regional trade and to what extent the Basin shifts the water pressure to other water scarce regions. Utilizing Geographical Information Systems (GIS) software, a proportional scaling for each province the Basin crosses or encompasses (total of eight administrative boundaries) is applied based on total economic output contained inside the watershed basin system boundary. This study is methodologically similar to earlier publications. However, this study explicitly models virtual water flows between the basin and individual provinces outside the basin and takes into account the relative scarcity and environmental impacts of water flows. Our analysis adds to the research literature in the following ways: 1) first tele-connected analysis of inter-regional virtual water and virtual scarce water trade flows between a hydrologic river basin catchment and provinces in China, and; 2) technical application of defining the Haihe River Basin catchment as a hydro-economic unit to improve consumption and environmental impact accounting at finer scale.

## V. Overview of the Dissertation

This dissertation consists of seven chapters, as follows:

Chapter 2 is a summary review of the virtual trade and footprint concepts; expounding on their origins and evolution in the research literature. The chapter includes a review of the different models that have been employed to operationalize the virtual trade and footprint concepts as a quantitative framework for analysis. The chapter also details the current applications of the concepts in providing a quantitative framework for other trending concepts and theories.

Chapter 3 provides the background and mathematical equations enabling this research's analysis, including: the origin and history of the input-output analysis (IOA) and multi-regional input-output (MRIO) model, the extension of the model to the environmentally-extended multi-regional input-output (E-MRIO) model, and the limitations of the model. The mathematical calculations of Leontief's input-output model, E-MRIO, environmental indicators, and stress indices are elaborated.

Chapter 4 analyzes the current global agriculture production supply chains and trade in food. Utilizing the E-MRIO model to analyze the global agriculture supply chain, our investigation quantifies the blue water and arable land inputs required in global agriculture production, incorporates water scarcity and arable land scarcity indicators, and quantifies the virtual natural resources and virtual environmental impacts embodied in the global food trade. Inclusion of environmental indicators provides insight into the implications of global agriculture production, food trade, resource depletion, and food security. Results reveal the significant volume of humanity's consumption of natural resources and generated environmental impacts embodied in the global trade in food.

Chapter 5 investigates the tele-connected consumption of the water-energy-food resources and associated environmental impacts in the East Asia region. This section also examines the structure of transnational inter-regional trade and the impacts and tradeoffs between each subsystem across scale. An increasing share of water-energy-food resource demand in the region is met through trade and imports. The challenge for these countries – particularly China due to its economic, demographic, and geopolitical size – is to achieve economic growth that is sustainable in meeting the demands of society (quality of life), economic growth, and environmental requirements. In East Asia, at the sub-national level, there is a mismatch between water-energy-food availability and final resource consumption and the lack of attention to environmental impacts in national economic growth strategies.

Chapter 6 investigates the Haihe River Basin's inter-regional virtual water flows between the hydrological basin and individual provinces outside the basin. The Haihe River Basin is emblematic of a hydrological system of importance and a region suffering chronic water stress and water shortage. The Basin is an extremely water stressed hydrological system which encompasses two megacities, is a region of major agricultural production, and is experiencing the detrimental impacts of rapid economic growth on its scarce water resources. This chapter focuses on how production and inter-regional trade structures affect the availability of water resources in the Haihe River Basin.

Chapter 7 provides a synopsis of the findings in the previous chapters and their contribution to the literature.

# Chapter 2: Literature Review

## I. Virtual Trade and Footprint Concepts

### *i. Origins*

The concept of ‘virtual’ trade originates from J. Anthony Allan’s (1994) discussion of ‘virtual’ water. Globally, the geographical mismatch between freshwater demand and available freshwater resources is a significant threat throughout the world. Allan (1994) introduced the virtual water concept on the premise that arid water-scarce nations and regions would import water-intensive products from other regions with comparative advantage in water resources – as a substitute to producing the same water-intensive products locally – while pursuing alternative economic production that contribute to the regional economy; thus, conserving local water resources (Allan, 1998, 2002). Water demand and water appropriation could continue to increase while the available resources were more or less fixed. The term ‘virtual’ extends beyond the water physically contained in the product to include the resource ‘embodied’ in products and used in the whole production chain of goods and services. The ‘virtual trade flow’ is the embodied resource traded between regions or exported to foreign countries (Daniel *et al.*,2011).

The concept of the ‘footprint’ originates from the idea of the ecological footprint (see Rees, 1992). In the early 2000s, the virtual water perspective was extended to the idea of the ‘water footprint’. Hoekstra and Hung (2002) initially introduced the concept of the ‘water footprint’ as an analogy to the ‘ecological footprint’. It was further developed by Chapagain (2006), Hoekstra and Chapagain (2007b, 2008), and Hoekstra *et al.* (2009) as the total virtual water content of products consumed by an individual, business, household, sector, city, country, or region. The 'water footprint' represents the total volume of direct and indirect freshwater used, consumed, and/or polluted (Hoesktra and Chapagain, 2007b). The water footprint is composed of 'green' (rainfall or soil moisture), 'blue' (surface water and groundwater), and 'grey' (volume of freshwater necessary to assimilate pollution loads) components (Hoekstra *et al.*, 2009, 2011; Feng *et al.*, 2011b). In general, green water has little to no alternative use beyond ecological uses or for (rainfed) agriculture production while blue water is – in some regions – in strong competition between industrial, domestic, agricultural, and ecological uses and consumers (Hoekstra and Chapagain, 2008; Ridoutt and Pfister, 2013). The footprint identifies the impact of a region's consumption of goods and services upon resource use and sustainability in other regions by examining inter-regional and global trade (as well as consumption impacts on resource demands within its own system boundary). The footprint of a defined system (e.g. nation, river basin) has two components: the internal and external footprint. The internal footprint refers to the sum of the footprints of a particular resource for all processes within a geographically delineated area (e.g. a province, nation, river basin). The external footprint refers to the appropriation of resources from outside the geographically delineated area in the form of goods and services imported into and consumed within (Hoekstra *et al.*, 2011; Galli *et al.*, 2012b).

*ii. Bottom-Up versus Top-Down Approach*

Several methods have been developed for footprint and virtual trade accounting. However, all footprint and virtual trade approaches of accounting fall into two categories: bottom-up or top-down. The bottom-up approach begins with the smallest unit assessing virtual trade and footprints and then aggregates each unit (Vanham and Bidoglio, 2013). One of the most attractive aspects of the bottom-up approach is its ability to provide detailed commodity information at the smallest level and relevant to people's daily life (Hoekstra and Chapagain, 2007b). The top-down approach begins at the highest level defined by the system boundary and then breaks down to lower levels according to further defined sub-boundaries (e.g., economic sectors, river basins, province or state) (Feng *et al.*, 2011a). The earliest footprint and virtual trade publications were calculated by multiplying crop trade flow (ton $yr^{-1}$) and the associated virtual water content (VWC, $m^3$ $ton^{-1}$) (e.g., Hoekstra and Hung 2005; Hoekstra and Mekonnen 2012; Vanham *et al.* 2013). This bottom-up volumetric water footprint methodology is capable of tracing the water consumption associated with different consumption items along the whole supply chain (Hoekstra *et al.*, 2009). The application of more systematic and sophisticated models – e.g. the Life Cycle Assessment (LCA) and input-output analysis (IOA) – in recent years has permitted comprehensive analysis of the inter-connections of water uses across economic sectors, administrative regions, and scale (e.g. country, household).

LCA is a bottom-up approach. LCA is an ISO standardized model and is often characterized as a "cradle-to-grave" approach. The LCA approach has been increasingly applied in the studies of virtual trade and footprint due to its ability to assess consumption of a product or service over its whole life cycle. LCA defines the system boundary at various scale and then assesses the overall resource consumption in respect to resource appropriation (and environmental damage). LCA has the ability to compare products from different regions with different resource use demands and different environmental conditions (e.g. water scarcity). LCA has the ability to provide detailed process analysis on specific products, but is time-consuming and requires huge amounts of data for multiple commodities (e.g. several thousand). The LCA approach is a very labor-intensive process and susceptible to significant truncation errors if the parameters of analysis are too narrow (resulting in key resource- or pollution-intensive processes not being included). For example, the calculation of the indirect water footprint of a particular crop may exclude the water consumed in producing the fertilizer, tools, and machinery used in the field. Therefore, the true water footprint of the crop will be underestimated (Cucek *et al.*, 2012; Chapagain and Tickner, 2012).

The IOA – as opposed to the bottom-up footprint accounting which only considers direct resource use – includes both direct and indirect water use throughout the supply chain (Zhang and Anadon, 2014). The top-down approach is established on assessments of total virtual flows (e.g. at the national or global scale) and allocates the direct and indirect flows to the economic network and sectors within a country. The IOA has been widely used in current footprint and virtual trade accounting literature. The IOA represents all economic transactions of production and consumption among different sectors in a defined economic system. The model uses categories designed to interface with a wide range of other data including economic, environmental, and social accounting, avoids imprecise definition of system boundaries, and avoids double counting as a specific resource input can only be allocated once to a final consumer (Daniels *et al.*, 2011).

Feng *et al.* (2011a) compared the top-down versus bottom-up approaches and determined the IOA possesses several advantages: able to distinguish between intermediate and final users; comprehensive system boundary scalable and capable of tracing the entire regional, national, or global supply chain; includes both direct and indirect consumption throughout the supply chain; and, avoids the bottom-up truncation error. The multi-regional input-output (MRIO) model is a variant of the IOA that operates with large databases. The main advantage of the IOA is that it allows calculating footprints for all products or industries across very complex supply chains (Bruckner *et al.*, 2012; Chen and Chen, 2013) and the MRIO model has the ability to take into account the different resource intensities in different countries (Feng *et al.*, 2011a; Wiedmann *et al.*, 2011). Input-output models are capable of providing a methodological framework to analyze international trade inter-linkages across national boundaries and at various scale (i.e. river basin, sub-national, nation, region, lifestyle group, or household) (Feng *et al.*, 2011a).

## II. A review of Virtual (Water) Trade and (Water) Footprint Publications

There have been a large number of studies on the complementary virtual water trade and water footprint concepts since they were introduced and the first published quantitative studies for different crop products (e.g. Hoekstra and Hung, 2002; Hoekstra, 2003; de Fraiture *et al.*, 2004). Early footprint and virtual trade publications focused on assessing the water embodied in agricultural commodities imports due to the water-intensive nature of agriculture production and the role of food trade as a mechanism to improve national water security in water-scarce countries (Chapagain *et al.*, 2006). Due to data limitations, the early bottom-up volumetric water calculation studies were limited in the scope of traded agricultural commodities considered. For example, Hoekstra and Hung (2002, 2005) considered only 38 primary crops, Oki and Kanae (2004) investigation included only five primary crops and three livestock products, and de Fraiture *et al.* (2004) analyzed only the global trade in cereals. These early publications estimated the virtual water flows and water footprints of agricultural commodities traded between countries and regions at the national (Chapagain and Orr, 2009; Ercin *et al.*, 2012; Ge *et al.*, 2011) and global (Hoekstra and Hung, 2002, 2005; Oki and Kanae, 2004; Chapagain and Hoekstra, 2004, 2008) scales. Later publications began to emphasize the role of virtual water trade in improving global water use efficiency and the alleviation of local water scarcity by estimating the water 'savings' (i.e. nations save domestic water resources by importing water-intensive products and exporting commodities that are less water-intensive) from agriculture trade at the global (Mekonnen and Hoekstra, 2010; Konar *et al.*, 2011; Fader *et al.*, 2011), national (Hanasaki *et al.*, 2010; Aldaya *et al.*, 2010; Schyns and Hoekstra, 2014), and commodities level (van Oel and Hoekstra, 2012; Ruini *et al.*, 2013; Hoekstra, 2014).

Arjen Hoekstra introduced the water footprint concept as an indicator of freshwater consumption, to quantify and map indirect water use. Subsequently, the Water Footprint Network (WFN) was established and advanced the volumetric methodology for assessing the water footprint (Hoekstra *et al.*, 2011). This methodology expresses the water footprint in a volume basis and does not reflect the potential environmental impacts of water use. This approach is primarily focused on water use indicators, better water management, and raising awareness of water issues (Jeswani and Azapagic, 2011). Recently, LCA has come to regard water consumption (and water pollution) as one of the potential causes of impacts depriving human users and ecosystems of water resources. In parallel to the water resources community (i.e. WFN) discovering the relevance of supply chain thinking, the LCA community recognized the importance of water use and developed comprehensive methodologies to include environmental impacts related to water in LCA studies. The main concepts have been codified in the international standard on water footprint (ISO 14046) and complemented by a number of guidelines (Boulay *et al.*, 2013; Pfister *et al.*, 2017).

The LCA was developed as a tool in the late 1960s to measure energy requirements and pollution impacts. It covers the whole product life cycle (goods and services) and has been applied to different industries and environmental impacts (Chang *et al.*, 2014). The history and aim of LCA is to quantify the potential environmental and human health impacts from a broad range of environmental issues including: climate change (Goedkoop and Spriensma, 1999; Hanafiah *et al.*, 2011), stratospheric ozone depletion (Hayashi *et al.*, 2002), eutrophication (Wenzel *et al.*, 1997), acidification (Heijungs *et al.*, 1992), thermal emissions from electric power generation (Pfister *et al.*, 2011c; Pfister and Suh, 2015), toxicological stress on human health and ecosystems (Hertwich *et al.*, 2001). See Pennington *et al.* (2004) for a detailed review. The LCA includes two levels of impact assessment metrics: mid-point and end-point. The mid-point metric describes the potential impact in the middle of the cause-effect chain (e.g. water scarcity). The end-point metric describes the damage incurred at the end of the cause-effect chain (e.g. health or ecosystem damages due to stratospheric ozone depletion) (Pfister *et al.*, 2017).

Ridoutt and Pfister (2010b) have criticized the volumetric approach to calculating the water footprint and virtual water flows for merely summing the consumptive water use of a commodity's life cycle with little attention to environmental relevance. They contend that due to the different forms (e.g., surface and groundwater) and regional variations in available water, a total life cycle water consumption measure is difficult to interpret and potentially misleading (Ridoutt and Pfister, 2010b). LCA focuses on quantitative impact indicators and the sustainability of products (Rebitzer *et al.*, 2004; Boulay *et al.*, 2013). Different LCA methods are available for the assessment of water use and consumption (e.g. Boulay *et al.*, 2011; Goedkoop *et al.*, 2009; Mila i Canals *et al.*, 2009; Pfister *et al.*, 2009; Frischknecht *et al.* 2009). See Jeswani and Azapagic (2011) for a review of LCA methodologies in assessing the water footprint and the impacts of water use. Goedkoop *et al.* (2009) utilizes the ReCiPe method to sum the water used at the mid-point level and does not assess its environmental impact or consider the end-point indicators. The water depletion indicator includes the water use from lakes, rivers, wells, and other (unspecified natural origin). Mila i Canals *et al.* (2009) incorporates two impact pathways: the freshwater ecosystem impact (FEI) and the freshwater depletion (FD). The FEI describes the impacts of changes in freshwater availability and the water cycle as a result of land use changes on ecosystem quality. A water stress index, defined as the ratio of the water withdrawal to the water available for human use minus the water needed for ecosystems, is applied to the FEI. Pfister *et al.* (2009) assesses the environmental impact of water consumption by adapting the

Eco-indicator 99 impact assessment method (Goedkoop and Spriensma, 2000). The three areas of focus and protection include: human health, ecosystem quality, and resource depletion. The impact of water consumption for human health is characterized by the lack of water for irrigation (leading to malnutrition), for ecosystems by the reduced availability of freshwater resulting in diminished vegetation cover and biodiversity (leading to reduced ecosystem quality), and for resources by the abiotic over utilization and depletion as defined by the Eco-indicator 99. Similar to Mila i Canals *et al.* (2009), Pfister *et al.* (2009) incorporates a water stress index but defined only as the ratio of water consumption to the water availability. The Water Scarcity Index (WSI) developed Pfister *et al.* (2009) provides a relevant impact-oriented water footprint with the ability to express the volumes of water consumed in terms of potential impact on water scarcity and ecosystems. The WSI is capable of weighting by source region and at the basin catchment level. The WSI has been predominantly applied using LCA (e.g., Ridoutt and Pfister, 2010a, 2013), but there are an increasing number of IOA publications incorporating the WSI (e.g., Lenzen *et al.*, 2013; Feng *et al.*, 2014a).

The IOA technique has a prominent tradition in modelling the interaction between economic sectors and water resources. Prior to the development of the 'virtual water' and 'water footprint' concepts, several early scholars extended the IOA in the late 1960s and early 1970s to investigate resource and environmental issues (e.g. Cumberland, 1966; Daly, 1968; Ayres and Kneese, 1969; Leontief, 1970; Victor, 1972; Isard, 1972). Daly (1968) and Isard (1972) integrated economic activities and ecological processes into a comprehensive analysis of a set of interactions (including water flows) within and between economic and environmental systems. Daly (1968) and Isard (1972) early attempts to capture abiotic, biotic, and non-life processes – or the “flows within the ecosystem” – were comprehensive in scope but faced significant modelling complexity issues (i.e. lacking in data, labor-intensive, and not practical in application) (Miller and Blair, 1985). Early on, Leontief (1970) developed the pollution-abatement model to account for environmental emissions. A row vector of pollution emission coefficients for each sector was added to represent generated pollution in the production chain. An ‘anti-pollution’ column was included to account for the eliminated emissions by pollution abatement industries and technologies. Carter and Ireri (1970) developed an inter-regional IOA extended by water-use coefficients to assess the water embodied in product flows between California and Arizona. Further early studies exploiting the well-known ability of the environmentally-extended IOA to model water flows include Lange’s (1997) and Lange’s (1998) investigation of water policies in South Africa – with a focus on Namibia – and Indonesia, respectively, applying the national resource accounting approach; Lenzen and Foran (2001) analysis of water usage in Australia, and; Bouhia’s (2001) scenario analysis utilizing a combined linear programming and IOA of water demand and water resource allocation.

*i. Criticisms of the Virtual Water and Water Footprint*

Within the last decade, several authors have criticized the virtual water trade and water footprint concept (Wichelns, 2004, 2005, 2010, 2011a, b, 2015; Ansink, 2010; Chapagain and Tickner, 2012; Perry, 2014). First, the virtual water concept was proposed by Allan (1994) to describe a water-stressed country’s strategy of importing water-intensive products and services according to the economic theory of comparative advantage. Several publications (de Fraiture *et al.*, 2004; Ramirez-Vallejo and Rogers, 2004; Kumar and Singh, 2005; Yang and Zehnder, 2007; Guan and Hubacek, 2007; Verma *et al.*, 2009; White *et al.*, 2018) have concluded that water-scarce countries or regions are not always net virtual water importers, but are, in some water-scarce countries or regions, net virtual water exporters. Second, the role of virtual water trade in attaining global water 'savings' between nations in the global trade system is, incorrectly, based on absolute and not relative advantage. For example, a country such as Japan which possesses a large urban population, limited per capita arable land, and is highly industrialized must import crop and livestock products to sustain continued economic development; engaging in international trade to be a net virtual water importer is not an optional policy decision for the nation (Wichelns, 2015). Third, the water footprint and virtual water trade do not take into consideration or compare the opportunity costs of production within or across trading partners (e.g. scarcity impact, ecosystem damage) (Wichelns, 2015). Ridoutt and Pfister (2010b) and Wichelns (2011a, b) have criticized the use of the water footprint alone based on total volume of water consumed as being 'misleading' and 'confusing', lacking environmental relevance, and disregarding of the impacts of water resource consumption and water scarcity on livelihoods and ecosystem services.

It is now generally acknowledged that there are numerous factors (e.g., land, labor, production technologies, domestic and international good prices, trade barriers, etc.) in addition to water resources endowment that dictate national policies and influence decision maker's choices between environmental, social, and economic trade-offs. Debaere (2014) determined that water is indeed a source of comparative advantage, but its impact on the export patterns of products appears less critical than that of other productive factors. Kumar and Singh (2005) analyzed 146 countries and determined that the quantity of available land is one of the factors that limit the production of agricultural goods and, thus, virtual water export. It is only under certain conditions, when trade is balanced (Ansink, 2010; Reimer, 2012) that abundance of water resources becomes a country's primary factor in trade policy decisions and the export of water embodied in traded goods. A water-scarce country's decision to import or export water-intensive products and services is a function of that country's alternative uses for its land, labor, physical capital, infrastructure, and water as well as its water resource abundance or scarcity. The relative abundance, availability, and productivity of the spectrum of inputs – including water resources – determine the appropriate national trade and economic policies (Wichelns, 2010, 2015; Perry, 2014). Zhao *et al.* (2019) was the first to introduce comparative advantage theory to quantitatively account for the driving forces on net virtual water export across China's 31 provinces between 1995 and 2015. Their study investigated the distribution of resource productivity and the opportunity costs of land, labor and water use in agricultural and non-agricultural sectors based on economic output per unit of resource consumption. Their results concluded that the main driving force determining the pattern of inter-regional virtual water flows across China was land productivity; the influence of labor and scarcity of water resources on inter-regional virtual water flows were limited. In other words, market forces in China reflect the scarcity of land resources but do not account for water scarcity.

## III. Evolution of the Virtual Trade and Footprint Concepts

The current applications of the footprint and virtual trade concepts reflect their evolution from focusing solely on economic water resource efficiency (i.e. water-scarce countries importing water-intensive products and exporting less water-intensive products) to addressing complex socio-economic and environmental factors associated with production, consumption, and trade. The footprint and virtual trade literature have moved beyond merely quantifying water use per unit of agriculture product to incorporate analysis across all sectors, quantifying a variety of resources and related environmental impacts, achieving greater granular analysis at smaller scales (e.g. household), combining selected indicators (e.g. a 'footprint family'), and offering a framework to measure and analyze other approaches (e.g. the Water-Energy-Food Nexus) in an integrated and systematic approach (Yang *et al.*, 2013; Fang *et al.*, 2014, 2015). The 'resource footprint' and 'virtual resource trade' provide the opportunity to link the consumption of goods and services to the use of natural resources in order to illustrate consumption patterns and global dimensions in resource governance and environmental impacts (Galli *et al.*, 2012a, b; Steen-Olsen *et al.*, 2012). The 'virtual resource trade' is the embodied resource or pollution byproduct traded between regions or exported to foreign countries.

LCA has become popular for evaluating the environmental impacts – particularly water, energy, and greenhouse gas emissions – of agriculture and food products including: livestock (Pelletier *et al.*, 2010a, b), crops (Nunez *et al.*, 2012; Pfister and Bayer, 2014; Bartzas and Komnitsas, 2017), agriculture land use (Jeswani *et al.*, 2018), ethanol production (Pieragostini *et al.*, 2014), milk (Thoma *et al.*, 2008), phosphorous emissions (Scherer and Pfister, 2015), meat (Pelletier, 2010; Ridoutt *et al.*, 2012), and processed food (Jefferies *et al.*, 2012) products. Ridoutt and Pfister (2010a) calculated the water footprint, incorporating water stress characterization factors, for Dolmio pasta sauce and Peanut M&M's products. Vora *et al.* (2017) investigated the network of interstate trade for 29 food commodities and estimated embodied irrigation energy and greenhouse gas (GHG) emissions in virtual water trade for the U.S.

EIOA has long been recognized as a reliable and consistent framework. Due to a lack of data, early EIOA applications focused on single countries. Only recently have researchers begun to aggregate national input-output tables (IOT) and trade data into global multi-regional input-output (GMRIO) tables (Tukker and Dietzenbacher, 2013). The development of the MRIO model covering the whole world economy has become an increasingly popular tool for trade-related environmental assessments (Lutter *et al.*, 2016). The EIOA and E-MRIO model have become popular frameworks for sustainability analysis (Wiedmann *et al.*, 2011; Daniels *et al.*, 2011). Within the last fifteen years, the EIOA and E-MRIO model have been applied to the virtual trade and footprint concepts to measure a variety of resources required to produce any commodity, such as: iron and steel (Dai, 2015), aluminum (Cullen and Allwood, 2013), steel (Cullen *et al.*, 2012), land (Weinzettel *et al.*, 2013; Yu *et al.*, 2013), peak oil resources (Kerschner *et al.*, 2013), emergy (Cho, 2013), value-added trade (Suder *et al.*, 2015; Kuroiwa, 2016; Wiedmann, 2016), energy (Karkacier and Goktolga, 2005; Liu, H. *et al.*, 2010), and materials (Bruckner *et al.*, 2012; Giljum *et al.*, 2014b; Wiedmann *et al.*, 2015b).

Input-output publications of virtual trade and footprint incorporating environmental indicators into resource consumption have become more prevalent. Incorporating environmental indicators into the analysis allows better understanding of the drivers of consumption, the bearers of environmental burden, and the regions benefiting and suffering from international trade in terms of natural resources depletion and ecosystem impact. Within the last decade, input-output models have been extended to characterize environmental impact footprints and virtual trade including: $CO_2$ (Du *et al.,* 2011; Feng *et al.*, 2013; Nie *et al.*, 2016), water pollution (Okadera *et al.*, 2006), water scarcity (Ridoutt and Pfister, 2010a, 2013; Lenzen *et al.*, 2013; Feng *et al.*, 2014a), biodiversity (Lenzen *et al.,* 2012a; Verones *et al.,* 2017), ecological (Galli *et al.*, 2012b), environmental (Hoekstra and Wiedmann, 2014), air pollution (Li, J. *et al.*, 2017), scarce land (Vivanco *et al.*, 2017), chemical (Guttikunda *et al.*, 2005), mercury (Li, J. *et al.*, 2017), phosphorus (Wang *et al.*, 2011), and nitrogen (Leach *et al.*, 2012).

Galli *et al.* (2012a) proposed a combination of complementary footprint indicators to provide a more complete picture of the complexity between consumption activities and environmental pressures conceptualized into a 'footprint family' (e.g., Cucek *et al.*, 2012; Galli *et al.*, 2012a, 2013; Ewing *et al.*, 2012; Steen-Olsen *et al.*, 2012, 2014; Fang *et al.*, 2014). Current footprint and virtual trade publications (not including 'footprint family' publications) typically incorporate two or more resource and/or environmental indicators, such as: land and metal scarcity (Vivanco *et al.*, 2017), land and water stress (Pfister *et al.*, 2011b), $CO_2$ and ecological (Hammond and Li, 2016), water and ecological (Hubacek *et al.,* 2009; Ewing *et al.*, 2012), $CO_2$, $SO_2$, and land

(Yu *et al.*, 2014), $CO_2$, $SO_2$, and $NO_x$ (Weber and Matthews, 2007), land, $CO_2$, and water (Lee, 2015), and energy, $CO_2$, material, water, and land (Wood *et al.*, 2018).

The ability of the virtual trade and footprint concepts to measure the human appropriation of natural resources at various scale for interpretation in the context of individual nations or regions provides a versatile and attractive framework. A framework which has recently been applied to several approaches in the literature, including: Material Flow Analysis (MFA), Water-Energy-Food (WEF) Nexus, and Planetary Boundaries. MFA is recognized for its ability to assess the biophysical metabolism of societies and to provide indicators for environmental pressures induced by human activities (Fischer-Kowalski and Huttler, 1999; Giljum, 2004). See Lutter *et al.* (2016) for a review of MFA. In the last few years, a number of MFA studies have been presented that incorporate virtual trade and footprints for the calculation of direct and indirect material resource inputs (e.g. biomass, metals, minerals, fuel) for production and consumption activities. The material footprint (MF) is identical to other environmental footprint indicators (Wiedmann *et al.*, 2015b) and summarizes the total amount of raw materials associated with final demand of a country or region (e.g., Schoer *et al.*, 2012; Giljum *et al.*, 2014a, b; Wiedmann *et al.*, 2015a, b; Kovanda and Weinzettel, 2016).

The combining of selected footprints to measure different aspects of environmental issues into an integrated system is a natural step. Recently, the Water-Energy-Food Nexus (WEFN) has become increasingly popular in conceptualizing and understanding the complex and dynamic interrelationships between water, energy, and food in order to better use and manage these limited resources sustainably. A ‘nexus’ among water-energy-food was conceived by the World Economic Forum to highlight the inseparable linkages between the use of natural resources and the universal human rights to water, energy, and food security (WEF, 2011). While the linkages between the three subsystems are well understood in a qualitative sense, the inability to describe the linkages quantitatively is lacking in the early WEFN literature. Current WEFN publications have become more sophisticated incorporating virtual trade flow and footprint accounting to quantitatively investigate two or all three subsystems (e.g., Ringler *et al.*, 2013; IRENA, 2015; Jeswani *et al.*, 2015; Vanham, 2016; Liu *et al.*, 2017).

The planetary boundaries concept puts forward quantitatively defined global limits to the anthropogenic perturbation of crucial Earth system processes (Rockström *et al.*, 2009; Steffen *et al.*, 2015). Rockström *et al.* (2009) proposed nine boundaries (climate change, biodiversity loss, nitrogen and phosphorus cycles, stratospheric ozone depletion, ocean acidification, freshwater use, land use change, chemical pollution, and atmospheric aerosol loading) that conservatively define safe operating boundaries for Earth's biophysical subsystems critical for sustaining both the planet and mankind. The set of boundaries represent an important conceptualization of global sustainability. Recently, virtual trade and footprints have been applied to provide a numerical assessment of resources throughout the world economy (Duchin and Levine, 2015) that are complementary to the scientifically derived estimates of Earth's biophysical planetary boundaries. Papers applying the virtual trade and footprint framework to the concept of planetary boundaries are beginning to appear in publications (see Fang *et al.*, 2015; Laurent and Owsianiak, 2017; O'Neill *et al.*, 2018).

## IV. Research Contribution to Virtual Trade and Footprint Literature

Numerous studies have been carried out modelling parts of the global food system; including phosphorus or nitrogen flows in cropland (Liu, J. *et al.*, 2010; van Vuuren *et al.*, 2010; Chen and Graedel, 2016), energy for food production (Jackson *et al.*, 2010; Daccache *et al.*, 2014), and quantification of agriculture land (Lugschitz *et al.*, 2011; Li and Di, 2013) or water (Mekonnen and Hoekstra, 2010; Liu and Yang, 2010) footprints and their virtual flows in the international food trade. Recently, there have been an increasing number of studies addressing both arable land and freshwater consumption in agriculture production and embodied in international trade at the country (Ridoutt *et al.*, 2014; Guo and Shen, 2015; Courtonne *et al.*, 2016) and global level (Galloway *et al.*, 2007; Fader *et al.*, 2011; MacDonald *et al.*, 2015; Chen *et al.*, 2018). However, these publications treat virtual arable land and freshwater resources as neutral flows in the food production system. Inclusion of environmental indicators for water scarcity (Berrittella *et al.* 2007; Pfister *et al.*, 2011b; Pfister and Bayer, 2014) or land scarcity (Pfister *et al.*, 2011b; Weinzettel *et al.*, 2013; Vivanco *et al.*, 2017) in agriculture production publications remains mostly unexplored. Less than a handful of publications have incorporated agriculture land scarcity into their analysis. Weinzettel *et al.* (2013) included a form of weighting based on the bio-productivity of the land and Pfister *et al.* (2011b) characterized land stress utilizing net primary productivity (NPP) as a proxy for potential land quality. Our paper's approach is similar to Vivanco *et al.* (2017) for calculating land scarcity for nations based on crop suitability areas defined by Fischer *et al.* (2012) Global Agro-ecological Zones (GAEZ). Even fewer studies have incorporated both water scarcity and land scarcity. Two exceptions are Pfister *et* *al.* (2011b) and Castillo *et al.* (2019). Pfister *et al.* (2011b) incorporated both land scarcity and water scarcity indicators into their analysis of the global water consumption and land use for the production of 160 crops and crop groups. Castillo *et al.* (2019) incorporated both land scarcity and water scarcity in their analysis of the water-land nexus of bioenergy production in Brazil to explore tradeoffs and synergies between bioethanol producer and consumer states Brazil. Our analysis of the tele-connected global agriculture production supply chain and trade in food products (Chapter 4) is the first to incorporate agriculture freshwater scarcity and arable land scarcity indicators to quantify the mitigating or exacerbating effects of trade upon individual nations' land and water resources.

Early water-energy-food nexus (WEFN) publications typically only analyzed two of the three subsystems in a nexus relationship: water-food nexus (Dalin *et al.*, 2014; Antonelli and Tamea, 2015; Vanham, 2016), food-energy nexus (Karkacier and Goktolga, 2005; Abdelradi and Serra, 2015), and water-energy nexus (Walker *et al.*, 2013; Murrant *et al.*, 2015; Gua *et al.*, 2016). Current WEFN publications have become more sophisticated and capable of investigating all three subsystems: for example, biomass or biofuel crop production (Bazilian *et al.,* 2013; Miara *et al.*, 2014; Mirzabaev *et al.*, 2015), future impact scenarios of climate change on WEFN (Ringler *et al.*, 2016), incorporating satellite remote sensing analysis to assess the WEFN (see review by Sanders and Masri, 2016), modeling water-energy-food interdependencies and management (Daher and Mohtar, 2015; Zimmerman *et al.*, 2016; Zhang and Vesselinov, 2017), and the consumption of water and energy in the production of greenhouse tomatoes in Spain (Irabien and Darton, 2016). In general, accounting for environmental impacts in the production and consumption of water-energy-food resources has been the ignored dimension of the nexus (i.e. over-using, depleting, and polluting unvalued or under-valued environmental resources and services) (Vora *et al.*, 2017). Our research is the first tele-connected WEFN analysis across scale utilizing the East Asia region-specific TIIOT dataset permitting modeling of socio-economic and environmental inter-linkages at finer scale (i.e. sub-national).

Guan and Hubacek (2007) was among the first to evaluate the inter-regional trade structure and its effects on water consumption and pollution via virtual water flows by developing an extended regional IO model for eight hydro-economic regions in China. Guan and Hubacek (2008) further utilized the innovative integrated hydro-economic IO model to analyze regional trade and to define water demand by production sectors and water degradation for North China. Feng *et al.* (2011b) developed a MRIO dividing the Yellow River Basin into three regions – the upper, middle, and lower reaches – according to the natural hydrological boundaries to assess the regional virtual water flows between the three reaches of the basin and the rest of China. However, although the focus of Feng *et al.* (2011b) was at the river basin catchment scale, as well as Zhao *et al.* (2010) and Zhi *et al.* (2014) for the Haihe River Basin, their studies analyzed virtual water flow only between the respective basin and the rest of China. Furthermore, all virtual flows are treated equally without distinguishing relative scarcity of the origin. Similar to our study, Feng *et al.* (2014a) incorporated water scarcity and ecosystem impact indicators to assess virtual scarce water flows and the associated ecosystem impacts. Nevertheless, their analytical units are administrative provinces rather than the natural geographic unit of the river basin. Our study on the Haihe River Basin

(Chapter 6) is the first to explicitly model the virtual water flows between the hydro-economic basin as an analytical unit and individual provinces outside the basin and takes into account the relative scarcity and environmental impacts of water flows.

# Chapter 3: Methodology

## I. Input-Output Analysis (IOA) and Multi-Regional Input-Output (MRIO) Analysis

Input-output analysis (IOA) was developed by Wassily Leontief in the late 1930s. Leontief received the Nobel Prize for Economic Science in 1973 for the development of the input-output methodology. Since the 1960s, many countries have been producing national input-output tables to research and track their economic production and structural changes. The IOA is based on data contained in national input-output tables (IOT). The IOT contains the entire economic activity of a nation aggregated by economic sectors and/or products and represents the flows of goods and services between those economic sectors (Hertwich and Peters, 2010). The Statistical Commission of the United Nations and the implementation of the System of National Accounts (SNA) have standardized and harmonized national input-output tables since 1968 (United Nations, 1999). A strength of the IOA is that the accounting framework utilizes United Nations standards for economic and environmental accounting which ensures a continuous process of data compilation and quality coherence.

The IOA is a practical extension of the classical theory of general inter-dependence capable of capturing the whole economy (e.g. region, country, world) as a single system. The IOA is based on magnitudes that can be measured (Kurz and Lager, 2000; Kurz and Salvadori, 2006). It is an analytical quantitative framework able to investigate the complex interdependencies within an economy; i.e. production and consumption between economic sectors. The IOA is inherently scalable and able to provide a quantitative consumption perspective of virtually any economic activity. The use of resource use coefficients in the IOA permits a comprehensive picture of resource use throughout the entire economic system. It can trace the stocks and flows of resources and pollution from extraction through production and consumption to recycling or disposal (Duchin, 1992). Leontief's economic IOA has been used in applications addressing questions on economy, labor, social issues, trade, energy, ecology, resource use, industrial ecology, and environmental science. The IOA has the capability to be extended to capture the natural resource embodied in products through the entire economic system and embodied in regional or international trade (Wiedmann *et al.*, 2011).

The multi-regional input-output (MRIO) model is a variant of the IOA that operates with large databases. The MRIO model links IOTs of several countries or regions via bilateral trade flows. The MRIO technique is able to model and represent the detailed flows of goods and services across and between multiple national economic sectors. The MRIO model accounts for the complex inter-dependencies of industries showing intermediate use, final demand, and gross output of different sectors across multiple national economies (Wiedmann, 2010). The MRIO model is able to differentiate regional and domestic technical coefficients from multiple regions or countries. Thus, the MRIO model captures the differing levels of technologies and the trade supply chains across several trading partners as well as feedback effects; i.e. changes in production in one region result from changes in intermediate demand in another region which were the result of demand changes in the first region. IOA and MRIO model focus on final consumption of a product and, via coefficients, assigns natural resource used in production to end-product consumers. The direct resource use coefficient is the measure for the sectoral resource use intensity. The MRIO model has the ability to distinguish a region's consumption footprint from its production footprint (Lenzen *et al.*, 2007; Duchin and Levine, 2015). The production-based footprint refers to resource use or emissions occurring within the borders of the country, both for national consumption and for export. The consumption-based footprint accounts for all resource use or emissions caused by final demand, including imports but excluding exports (Peters and Hertwich, 2008), i.e. it includes all upstream effects along (global) supply chains. The unambiguous link between production and consumption and the ability to extend the model to specific economy-wide production factors (e.g. water coefficients) throughout the entire system are the strengths of MRIO analysis. The MRIO model and MRIO databases are a well described and suitable foundation for global sustainability analysis (Wiedmann, 2010; Wiedmann *et al.*, 2011).

A number of recent research projects are devoted to the refinement of input-output tables to calculate footprint-type indicators and obtain greater detailed analysis (see Lenzen *et al.*, 2012b; Tukker and Dietzenbacher, 2013; Tukker *et al.*, 2018). The goal is to create global harmonized datasets with higher levels of sectoral detail. When IOTs are extended with environmental data to track embodied environmental resources throughout the entire supply chain the technique is called environmentally-extended input–output analysis (EIOA) (Bruckner *et al.*, 2015). EIOA has a long history in water accounting studies (Wiedmann, 2010) and has long been recognized as a technique in attributing pollution and resource use to final demand in a reliable and consistent framework (Miller and Blair, 1985, 2009). EIOA incorporates environmental indicators to measure different aspects of an economy in an integrated and systematic approach. The environmentally-extended MRIO (E-MRIO) model provides a framework that can assist in assessing environmental impacts by enabling comprehensive and systematic measurement of embodied natural resources along complex supply chains linking multiple regional economies. In this study the agriculture land use indicator represents land displaced from food production. The E-MRIO model is able to trace multiple environmental impacts driven by production, between sectors within an economic region and between regions, and, therefore, capable of analyzing the tele-connected interactions between the environment, economic, and social systems (Hubacek *et al.*, 2009). The E-MRIO model has a powerful capacity to assess specific resource intensities and environmental pressures – i.e. natural resources and pollutants 'embodied' in goods and services along the entire supply-chain to final consumption – and link it to national or regional specific environmental resource and economic conditions (Daniels *et al.*, 2011).

## II. Input-Output Methodology

### *i. Basic Input-Output Model*

The IOA is based on data contained in input-output tables. Each entry in the *i*-th row and *j*-th column illustrates the flow from the *i*-th sector to the *j*-th sector. The IOA consists of *N* linear equations depicting the production of an economy represented in Eq. (1):

$$x_i = \sum_{j=1}^{N} z_{ij} + y_i \quad (1)$$

where $N$ is the number of sectors in an economy; $\boldsymbol{x_i}$ is the total economic output of the $i$-th sector; $\boldsymbol{y_i}$ is the final demand of sector $i$. $\boldsymbol{z_{ij}}$ is the monetary flow from the $i$-th sector to the $j$-th sector.

The technical coefficient $\boldsymbol{a_{ij}}$ is provided in Eq. (2):

$$\boldsymbol{a_{ij} = z_{ij} / x_j} \quad (2)$$

where $\boldsymbol{a_{ij}}$ is derived by dividing the inter-sectoral flows from $i$ to $j$ ($\boldsymbol{z_{ij}}$) by total input of sector $j$ ($\boldsymbol{x_j}$). These technical coefficients $\boldsymbol{a_{ij}}$ are assumed to be fixed within the specified period of time. By substituting Eq. (2) to (1), the following equation is derived:

$$\boldsymbol{x_i = \sum_{j=1}^{N} a_{ij}\, x_j + y_i} \quad (3)$$

Eq. (3) can be written in the form of a matrix as below:

$$\boldsymbol{x = Ax + y} \quad (4)$$

where $\boldsymbol{A}$ is the coefficient matrix; $\boldsymbol{x}$ is a vector of sectoral output; $\boldsymbol{y}$ is a vector of final demand. Solving for $\boldsymbol{x}$ results in Eq. (5):

$$\boldsymbol{x = (I - A)^{-1}\, y} \quad (5)$$

where $(\boldsymbol{I - A})^{-1}$ is known as the Leontief inverse $\boldsymbol{L}$ matrix which captures both direct and indirect inputs required to satisfy final demand. $\boldsymbol{I}$ is the identity matrix.

*ii. Multi-Regional Input-Output Model*

The IOA accounts for the complex interdependences of industries; showing intermediate use, final demand and gross output of different sectors (Wiedmann, 2010). Early on, Leontief recognized that some commodities are produced not far from where they are consumed and others travel long distances from the place of their origin to their actual utilization. The MRIO model is an inter-regional flow model that takes into account the spillover and feedback effects beyond the borders of a regional economy by the inclusion of one (or more) additional regions in the system. The MRIO model extends the standard IO matrix to a larger economy that includes each industry in each country or region possessing a separate row and column. The MRIO model represents the complete input-output interactions of the defined national, regional, or global economy.

Just like the IOA, the MRIO model consists of *N* linear equations depicting the production of an economy represented in Eq. (1):

$$\boldsymbol{x_i} = \sum_{j=1}^{N} \boldsymbol{z_{ij}} + \boldsymbol{y_i} \tag{1}$$

The submatrix of intermediate use coefficient can be calculated directly by Eq. (6):

$$\boldsymbol{A^{rs}} = (\boldsymbol{a_{ij}^{rs}}) = (\boldsymbol{z_{ij}^{rs}} / \boldsymbol{x_j^{s}}) \tag{6}$$

where $\boldsymbol{z_{ij}^{rs}}$ represents the inter-sector flow from the *i*-th sector in region *r* to *j*-th sector in region *s*. $x_j^s$ is the total output of *j*-th sector in region *s*. The total number of regions is *R*. Let $\boldsymbol{x} = (\boldsymbol{x_i^s})$. The economy wide sectoral output is a vector (*NR* × 1) and can be shown as Eq. (7):

$$\boldsymbol{x} = (\boldsymbol{x_1^1} \cdots \boldsymbol{x_N^1} \ \cdots \boldsymbol{x_1^s} \cdots \boldsymbol{x_N^s} \cdots \boldsymbol{x_N^R} \ \cdots \boldsymbol{x_1^R})' = \begin{pmatrix} \boldsymbol{x^1} \\ \boldsymbol{x^2} \\ \vdots \\ \boldsymbol{x^R} \end{pmatrix} \tag{7}$$

The total number of final demand categories is $\boldsymbol{F} = (\boldsymbol{f_i^{rs}})$, where $\boldsymbol{f_i^{rs}}$ is the region's final demand for goods of sector *i* from region *r*. The final demand matrix (*NR* × *F*) can be shown as Eq. (8):

$$\mathbf{Y} = (\boldsymbol{y^{r,f}}) = \begin{pmatrix} \boldsymbol{y^{1,1}} & \boldsymbol{y^{1,2}} & \cdots & \boldsymbol{y^{1,F}} \\ \boldsymbol{y^{2,1}} & \boldsymbol{y^{2,2}} & \cdots & \boldsymbol{y^{2,F}} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{y^{R,1}} & \boldsymbol{y^{R,2}} & \cdots & \boldsymbol{y^{R,F}} \end{pmatrix} \tag{8}$$

where $\boldsymbol{y}^{r,f}$ represents the *f*-th category of final demand vector in region *r*. The total final demand vector (***y***) is the sum of the following five categories in this research: household consumption, government expenditure, capital formation, changes of inventory, and international export. Eqs. (1) and (6)-(8) can be written in a matrix form as Eq. (9):

$$\begin{pmatrix} \boldsymbol{x}^1 \\ \boldsymbol{x}^2 \\ \vdots \\ \boldsymbol{x}^R \end{pmatrix} = \begin{pmatrix} \boldsymbol{A}^{11} & \boldsymbol{A}^{12} & \cdots & \boldsymbol{A}^{1R} \\ \boldsymbol{A}^{21} & \boldsymbol{A}^{22} & \cdots & \boldsymbol{A}^{2R} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{A}^{R1} & \boldsymbol{A}^{R2} & \cdots & \boldsymbol{A}^{RR} \end{pmatrix} \begin{pmatrix} \boldsymbol{x}^1 \\ \boldsymbol{x}^2 \\ \vdots \\ \boldsymbol{x}^R \end{pmatrix} + \sum_f \begin{pmatrix} \boldsymbol{y}^{1,f} \\ \boldsymbol{y}^{2,f} \\ \vdots \\ \boldsymbol{y}^{R,f} \end{pmatrix} \tag{9}$$

where the coefficient matrix ***A*** (*NR* × *NR*) represents the intermediate input matrix across sectors and regions. Vector ***x*** represents total output of each economic sector in each region.

The mathematical structure can be re-written as Eq. (10):

$$\boldsymbol{x} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{y} \tag{10}$$

Solving for ***x*** results in Eq. (11):

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\, \boldsymbol{y} \tag{11}$$

where ***I*** is the identity matrix. The Leontief inverse ***L*** matrix $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ captures both direct and indirect inputs to satisfy one unit of final demand in monetary value.

### *iii. Environmental Indicators*

The MRIO table is extended with environmental coefficients of different environmental indicators. In order to capture both the direct and indirect resource consumption and emissions, the matrix of environmental-impact coefficients ***K*** (by environmental category, by sector, and by region) are multiplied with the Leontief matrix ***L*** and final demand vector ***y***, as presented in Eq. (12):

$$\boldsymbol{T} = \boldsymbol{K}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} \tag{12}$$

where $\boldsymbol{T}$ is a matrix representing different environmental-impact indicators. In matrix $\boldsymbol{K}$, each element, $\boldsymbol{k_j^{r,e}}$, represents direct impact on environmental category $e$ caused by per unit of economic output of sector $j$ in region $r$.

The environmental coefficients $\boldsymbol{k_j^{r,e}}$ are assumed to be fixed within the specified period of time. The environmental categories included in this research are water ($\boldsymbol{K_w}$), scarce water ($\boldsymbol{K_{sw}}$), arable land ($\boldsymbol{K_l}$), scarce arable land ($\boldsymbol{K_{sl}}$), and energy ($\boldsymbol{K_e}$) and the generation of $CO_2e$ ($\boldsymbol{K_c}$), $CH_4$ ($\boldsymbol{K_{CH4}}$), $N_2O$ ($\boldsymbol{K_{N2O}}$), and $SO_x$ ($\boldsymbol{K_{SOX}}$) air pollution.

*iv. Stress Indices*

Over the past thirty years many indices have been developed to characterize the volumetric scarcity of water based on human water requirements, water resources, environmental requirements, or water resources vulnerability (see reviews Brown and Matlock, 2011; Schmitz *et al.,* 2013). The Falkenmark Indicator is perhaps the most widely used volumetric measure of water stress based on per capita availability; categorizing water conditions in an area as no stress (>1,700 $m^3$ per capita/year), stress (1,000-1,700 $m^3$ per capita/year), scarcity (500-1,000 $m^3$ per capita/year), and absolute scarcity (<500 $m^3$ per capita/year) (Falkenmark *et al.,* 1989). Unlike the Falkenmark Indicator, several relative indicators were developed that measure the withdrawal-to-availability (WTA) ratio (Vorosmarty *et al.,* 2000; Alcamo *et al.,* 2003; Oki and Kanae, 2006; Hanasaki *et al.,* 2008). Ohlsson (2000) developed the Social Water Stress Index which incorporated the United Nations Human Development Index (HDI) as an approximation for the social adaptive capacity of a society. All of these water scarcity indices are expressed at the national scale. However, water is a localized renewable resource withdrawn from a location specific ecosystem with varying levels of availability and consumption patterns. The Water Scarcity Index (WSI) by Pfister *et al.* (2009) is capable of attaining global water scarcity information at ~50 km grid cells (0.5 arc minutes resolution).

Water stress is commonly defined as the ratio of total annual freshwater withdrawals to total freshwater availability. Water stress is defined as moderate and severe above a threshold of 20% and 40%, respectively. This paper adopts the WSI concept as defined and advanced by Pfister *et al.* (2009), ranging from 0 (no water stress) to 1 (maximum water stress). The water withdrawal-to-availability ratio (WTA), $WTA_m = \sum_n WU_{mn} / WA_m$, is calculated for each watershed $m$. Where $WA_m$ is the annual freshwater availability and $WU_{mn}$ is withdrawals for use $n$ in watershed $m$. $WTA_m$ is $WTA$ in watershed $m$. Use categories include industry, agriculture, and households. Pfister *et al.* (2009) applied a logistic curve in Eq. (13):

$$\boldsymbol{WSI = \frac{1}{1+e^{-6.4 \cdot WTA\left(\frac{1}{0.01}-1\right)}}} \quad (13)$$

where *WTA* is the weighted ratio of annual freshwater withdrawals for different users (i.e. industry, agriculture, and households) to annual freshwater availability calculated for each basin watershed accounting for annual and monthly precipitation variability and flow regulation by basin. The distribution curve is adjusted to result in a WSI of 0.5 for a WTA of 0.4 so that the threshold between moderate and severe water stress is expressed as the median value; i.e. a WSI value equal to or greater than (≥) 0.5 represents a severely stressed area. The WSI concept indicates the portion of water consumption that deprives freshwater to other users – or degree of ‘water deprivation’ – to indicate the pressure on renewable water resources. Scarcity weighting was incorporated into the calculation to account for the scarcity of the water being used. The weighted scarce water ($\boldsymbol{K_{sw}}$) is derived by applying Eq. (13) to water withdrawals ($\boldsymbol{K_w}$) from existing local freshwater resources. In other words, the WSI weighting converts total water use into scarce water use.

We have distinguished between actual water stress (WSI) and hypothetical water stress (*WSI). ***WSI** calculates the hypothetical water stress on the local hydrological system if the net importing region does not have virtual water inflows available (i.e. withdraws water entirely from local resources) and the net exporting region does not consume local water resources for agriculture exports (i.e. withdraws water only for domestic consumption demands) provided in Eq. (14):

$$^{*}\boldsymbol{WSI} = \frac{\mathbf{1}}{\mathbf{1}+\boldsymbol{e}^{-\mathbf{6.4}\cdot \boldsymbol{WTA}*\left(\frac{\mathbf{1}}{\mathbf{0.01}}-\mathbf{1}\right)}} \qquad (14)$$

where ***WTA**** is the ratio of the sum of annual freshwater withdrawals plus net virtual water embodied in agriculture imports divided by annual freshwater availability. The difference between *WSI and WSI represents the contribution of net virtual water flows in terms of mitigating or exacerbating water stress in agriculture production. When *WSI is higher than WSI the country is a net virtual crop water importer – mitigating water stress via net virtual crop water imports. When *WSI is lower than WSI the country is a net virtual crop water exporter – exacerbating water stress via net virtual crop water exports.

Only a handful of publications have incorporated some form of land scarcity into their analysis; no two are consistent in approach or method (Pfister *et al.*, 2011b; Steen-

Olsen *et al.*, 2012; Weinzettel *et al.*, 2013; Vivanco *et al.*, 2017). In general, the inclusion of land scarcity calculations in research publications remains largely unexplored. Steen-Olsen *et al.* (2012) for the EU27 member states and Weinzettel *et al.* (2013) for world regions investigated the land footprints associated with final demand consumption, which included a form of weighting based on the bio-productivity of the land. Similarly, Pfister *et al.* (2011b) investigated the impact of global crop production on land characterized by a land stress index utilizing net primary productivity (NPP) as a proxy for potential land quality. Vivanco *et al.* (2017) determined land scarcity for worldwide nations associated with the production of nine major crops based on crop suitability areas defined by Fischer *et al.* (2012) Global Agro-ecological Zones (GAEZ).

To calculate arable land scarcity, we incorporate the land appropriation index (LAI) for each country or region applying the scarcity approach defined by Lenzen *et al.* (2013): dividing actual cropland used by total arable land available. Ranging from 0 (no land stress) to 1 (maximum land stress) the land appropriation index (LAI) arises from cropland used from available arable land sources, which is expressed as Eq. (15):

$$\boldsymbol{LAI} = \frac{\boldsymbol{RU}}{\boldsymbol{Q}} \tag{15}$$

where $\boldsymbol{RU}$ is the annual cropland used for production and $\boldsymbol{Q}$ is the renewable arable land availability. Based on similar scarcity indices (e.g. Raskin, *et al.*, 1997; Alcamo *et al.*, 2000; IWMI, 2007), a LAI value equal to or greater than (≥) 0.4 is the threshold between moderate to severe land stress. Furthermore, our research designates the threshold of per capita arable land availability of 0.02 ha or less as LAI=1 (i.e. extreme arable land stress); per capita arable land availability data was obtained from the World

Bank Data Portal (World Bank, 2018). To distinguish scarce land from neutral or abundant land, scarce land was calculated by multiplying a country's or region's cropland use by its LAI. Weighted scarce arable land ($\boldsymbol{K_{sl}}$) is derived by applying Eq. (11) to arable land use ($\boldsymbol{K_l}$) from existing local resources.

We have distinguished between actual arable land stress (LAI) and hypothetical arable land stress (*LAI). ***LAI*** calculates the hypothetical land stress on the local terrestrial agriculture production system if the net importing region does not have virtual cropland inflows available (i.e. uses arable land entirely from local resources) and the net exporting region does not consume local cropland for agriculture exports (i.e. uses arable land only for domestic consumption demands) provided in Eq. (16):

$$\boldsymbol{{}^*LAI = \frac{RU+VR}{Q}} \tag{16}$$

where ***LAI*** is the sum of annual cropland used plus net virtual cropland embodied in agriculture imports and $\boldsymbol{Q}$ is the annual renewable arable land availability. The difference between *LAI and LAI represents the contribution of net virtual cropland flows in terms of mitigating or exacerbating land stress. When *LAI is higher than LAI the country is a net virtual cropland importer – mitigating land stress via net virtual cropland imports. When *LAI is lower than LAI the country is a net virtual cropland exporter – exacerbating land stress via net virtual cropland exports.

### III. Limitations of Input-Output Modelling

The limitations of input-output modelling are well documented in the literature. For a summary, see Wiedmann (2009), Lenzen *et al.* (2010), Daniels *et al.* (2011), and Wiedmann *et al.* (2011). MRIO analysis provides only a 'snapshot' of the state of an economy during a single accounting period, generally a year. Furthermore, this research applies the standard MRIO model, which does not have the ability to measure the impact of individual products. Since data is at the sector level – and not at the product level – it is difficult to separate specific resource-intensive processes from the results (Chapagain and Tickner, 2012). An alternative approach with higher sectoral resolution – such as the input-output assisted hybrid life cycle assessment (Suh *et al.*, 2004; Li *et al.*, 2012; Feng *et al.*, 2014b) – was not utilized given the data limitation and data computing requirement for a regional or global scale analysis.

A disadvantage of IO modeling is the level of aggregated data and the inherent assumption within the data that each economic sector produces a homogenous product output. Products with very different resource consumption (or generated pollution) intensities are mixed together and averaged into one sector, which can distort resource requirements (or pollution concentrations). This homogeneity assumption and data uncertainty due to sectoral aggregation error can lead to distortions of results. Averaging natural resource requirements for an economic sector (for example, spices versus fodder under 'crops nec') may under- or over-estimate the resource requirements and, therefore, the virtual flows in international trade (Steen-Olsen *et al.*, 2014; Bruckner *et al.*, 2015).

There is a large time-lag for the publications of MRIO datasets. MRIO datasets consist of multiple national input-output tables that require significant effort and time to harmonize. Significant time is required for the manipulation of original input-output information, creation of trade matrices, balancing of rows and columns, and transformation of the database into a uniform number of sectors for each country or region (which may involve additional data collection). The time lag of the data in the MRIO database is problematic as it may weaken the relevancy of the research aim of present-day issues as well as the policy implications derived from analysis results (Wiedmann *et al.*, 2011; Bruckner *et al.*, 2015).

A shortcoming of current global multi-regional input-output (GMRIO) databases is the lack of detailed trade flow data below the national level. National level data assumes natural resource endowments are homogenous within each country. This presents an ecological fallacy. It is important to note that significant spatial variations in natural resource endowments may occur within national borders. China, for example, is well documented in the literature for its spatial variation in water resources between the ‘dry’ North and ‘wet’ South (Guan and Hubacek, 2007, 2008). Recently, several methodologies have been developed (see Bachmann *et al.*, 2015; Wenz *et al.*, 2015; Wang *et al.*, 2015), which permit multiple spatial scales (i.e. global, national, sub-national, etc.) to be incorporated into an analysis; i.e. capturing the heterogeneity of sub-national regions within the global economy. However, the disadvantage of these approaches is the increased data inaccuracy due to the disaggregation approximations of trade flows from one region in one country to a region in another country.

Lastly, this study shares a common problem of IO analysis in its inability to account for multiple and simultaneous uses of agriculture land. In other words, interpretation problems arise when farming practices include multiple crops or fallow agriculture land following a traditional crop rotation cycle or land serving multiple economic purposes within a single year (Bruckner *et al.*, 2015).

# Chapter 4: Does global food trade increase or decrease land and water scarcity?

## I. Introduction

Our global analysis achieves Objective 1. This chapter investigates whether the redistribution of natural resources via agriculture supply chains mitigate or exacerbate countries' freshwater and arable land resource scarcities around the world. This study incorporates the environmental indicators water scarcity and land scarcity. The inclusion of both water scarcity or land scarcity indicators in agriculture production publications remains largely unexplored.

***Objective 1:*** ***Tele-connected investigation of the consumption of freshwater and arable land resources and environmental impacts embodied in the global food trade. Assess the mitigating or exacerbating effect of participation in the global food trade on countries' finite water and land resources.***

## II. Background

Modern agriculture has been successful in increasing food production and lifting hundreds of millions of households from food insecurity as a result of gains from "Green Revolution" technologies, including high-yielding cultivars, chemical fertilizers and pesticides, mechanization, and irrigation (Foley *et al.*, 2005). The unintended consequences and legacy of modern agriculture production is adverse impacts on biophysical resources and ecosystem processes; e.g. decrease in the biological productivity of land, modification of energy flows in the biosphere, loss of biodiversity, deforestation, deterioration of water quality, and desertification (Haberl *et al.*, 2014; Grafton *et al.*, 2016). Some scientists believe current consumption or degradation of these natural resources for agriculture production already exceeds their global regeneration rate (Molden, 2007; WEF, 2011; Bindraban *et al.*, 2012). Global food production presents a resource sustainability dilemma: freshwater and arable land are necessary inputs for food production, but excess or overuse of these resources causes unsustainable environmental pollution and degradation. Furthermore, in today's interconnected world, agriculture products are traded internationally. Local consumption is increasingly met by global supply chains (Yu *et al.*, 2013; Hubacek *et al.*, 2014). Changes in consumption patterns in one country may cause changes via international trade in production or shift environmental impacts elsewhere. An important question is if such redistribution of natural resources and environmental impacts via international trade in food mitigates or intensifies resource scarcities around the world. To answer this question, we investigate global agriculture supply chains to explore the influence of global trade in food on nations' arable land and freshwater resources.

Agriculture is the world's single largest driver of global environmental change (Steffen *et al.* 2011; Rockstrom *et al.*, 2017). Irrigated agriculture consumes 70% of freshwater withdrawals (Assouline *et al.*, 2015). Ramankutty *et al.* (2008) estimates current global agriculture production has transformed nearly 40% of the planet's terrestrial surface area. Large flows of phosphorus and nitrogen runoff cause eutrophication in freshwater and marine ecosystems, loss of biodiversity, soil acidification, and surface and groundwater contamination with negative impacts on human health (Liu, J. *et al.*, 2010; van Vuuren *et al.*, 2010). Reynolds (2013) estimated that 14% of $CO_2$ emissions and 36% of $NO_x$ global emissions are from food production; which cause acid rain, impact human health, and contribute to global warming (Heesterman, 2015). The paramount challenge ahead for a projected world population of 9 billion in 2050 is the necessity for global agriculture production to increase by 50-110% to meet global demand (FAO, 2014a; WEF, 2011; Rockström *et al.*, 2017). Irrigated agriculture will be critical to feeding the world population. FAO (2012) estimated that irrigated agriculture in the future will need to produce 44% of the world's food supply. Unprecedented amounts of water (Pfister *et al.*, 2011a; de Marsily *et al.*, 2016), land (Meyfroidt *et al.*, 2013; Bruckner *et al.*, 2015), and chemical inputs (Bodirsky *et al.*, 2014; Sattari *et al.*, 2016) will be required – and associated environmental impacts generated – to supply food for a growing and wealthier world population (FAO, 2014a; Davis *et al.*, 2017).

The major constraints to future agriculture expansion are available area of arable land and dwindling water resources for food production (Assouline *et al.*, 2015). These natural resources have significant temporal and spatial variance within and between countries and regions. For example, each country has a range of soils that vary in productivity and fragility (Blum and Eswaran, 2003). Globally, water and arable land shortages prevail in many water-scarce and arable land-scarce and overpopulated regions (WEF, 2011; Bogardi *et al.*, 2012). Of the planet's arable cropland, only a third is being farmed. The remaining uncultivated arable land is distributed unevenly (WEF, 2011). Similarly, the world's global freshwater resources are unevenly distributed. The amount of blue water consumed annually to meet national food production requirements varies greatly by country from 600-2500 $m^3$/y per capita (de Marsily *et al.*, 2016). In the future, major problems are expected to occur in countries in Asia and West Asia-North Africa where the ratio of farm land to available arable land is 75% and 87% (world average 37%) and the consumption of water for agriculture irrigation is 30% and 47% (world average 22%), respectively (de Marsily *et al.*, 2016).

In some countries and regions of the world, the capacity for domestic agriculture production is reduced by overexploitation or inappropriate use of their soil and freshwater resources (Blum and Eswaran, 2003; Foley *et al.*, 2005). When a society no longer has access to favorable conditions for the production of food or is no longer able to produce food in sufficient quantities (e.g. limited arable land, an increasing middle class affluence), imports from other regions can meet the population's food needs (Godfrey and Garnett, 2014; MacDonald *et al.*, 2015). The increasing international trade in commodities also involves significant exchanges of natural resources embodied in these goods (Carr *et al.*, 2013). In the last fifty years, globalization has transformed the geography of food systems and altered the distribution of land and water across regions (Duarte *et al.*, 2016; MacDonald *et al.*, 2015). One-fifth (20%) of global cropland area (Kastner *et al.*, 2014) and approximately one-fifth (19%) of global agriculture water (Hoekstra and Mekonnen, 2012) is consumed for exports of agriculture commodities. As globalization intensifies, demand for these limited resources grows, and, thereby, increases competition between agriculture and other economic sectors which impact both livelihoods and the environment (FAO, 2014a).

Supply chains spanning multiple countries also shifts natural resource depletion and environmental degradation via international trade (Carr *et al.*, 2013). The expansion of agriculture trade over large distances has shifted the burden of the environmental pressures associated with food production to the export-producing countries. The net result is that agriculture water and arable land is increasing in scarcity, even in countries well-endowed with water and arable land resources (FAO, 2012; MacDonald *et al.*, 2011; de Marsily *et al.*, 2016).

An analysis of the virtual trade of embodied natural resources and environmental impacts throughout agriculture supply chains is necessary to quantify the consequences placed upon limited biophysical resources. Incorporating environmental relevance in identifying and quantifying the biophysical limits of nations' resources is key to understanding their capacity to support increasing economic growth and an expanding human population. The objective of our investigation is to: 1) quantify the appropriation of freshwater and arable land in the global agriculture supply chain and determine how countries and regions contribute to the redistribution of virtual water and land resources; and, 2) evaluate the mitigating or amplifying impact of global trade in food upon nations' land scarcity and water scarcity. We use the environmentally-extended multi-regional input-input model to assess natural resource inputs and environmental impacts in global agriculture supply chains.

## III. Data

Our MRIO analysis utilized the latest Global Trade Analysis Project database version 9 (GTAP9), released on May 2015, for the year 2011 and extended with satellite environmental coefficients. The GTAP database, coordinated and published by the Center for Global Trade Analysis in Purdue University's Department of Agricultural Economics, is a harmonized global database of time series IOTs (domestic and import) for 120 individual countries and 20 regions, each with 57 sectors, balanced and harmonized bilateral trade data, macroeconomic data, and transport data (Aguiar *et al.*, 2016) (Peters *et al.*, 2011); see SI1 for the list of all 57 sectors.

This paper incorporates GTAP satellite environmental data for blue water (unit: cubic meter) and for land use (unit: hectare) for the year 2011 (Aguiar *et al.*, 2016). The available arable land was obtained from the Global Agro-ecological Zones (GAEZ) 3.0 model's crop suitability areas (CSA), indicating the area suitable to produce a crop per country/region (Fischer *et al.*, 2012). The CSA quantifies to what extent soil conditions match crop requirements per defined input parameters. For our study, the CSA was calculated with the following parameters – high input level (improved management assumption), rain-fed water supply, without $CO_2$ fertilization, and for all 49 major crops under current climate conditions. CSA's suitability index classifies eight land types for growing major crops, ranging from 'very high' to 'not suitable' (GAEZ, 2018). Our study considers only land suitability classified as 'very high', 'high', and 'good'.

### *i. Limitations*

The GTAP9 database is for the year 2011 and is the most current version. The age of the data is a significant shortcoming. However, the GTAP9 database offers broad geographical coverage across 57 sectors that permit in depth sectoral analysis or higher level regional attribution. It also has the advantage of complimentary and validated land and water satellite environmental data for 2011 published by the Center for Global

Trade Analysis. Furthermore, the benefit of adapting the GTAP9 database for MRIO analysis is that it does not require additional balancing.

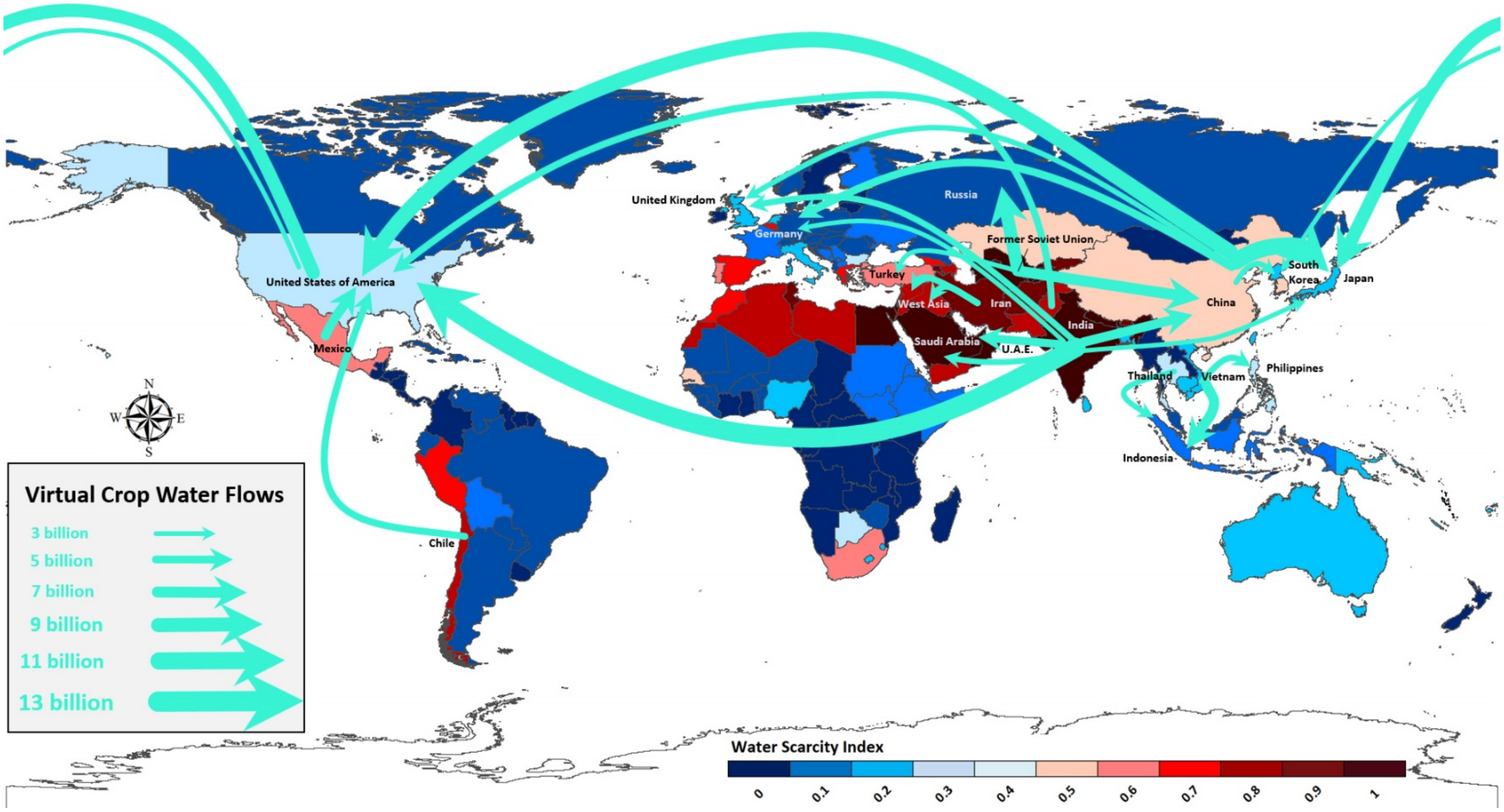
## IV. Results

### *i. Global Agriculture Production and Virtual Flows of the Food Trade*

Consumption of irrigated water in the global agriculture supply chain in 2011 was approximately 3 trillion cubic meters ($m^3$) for crop production; accounting for 91% of total human consumption of global blue water. Global crop cultivation utilized 1.5 billion hectares (ha); accounting for 24% of humanity's 6.2 billion ha global land use footprint. More critically, global agriculture consumed 1.8 trillion $m^3$ of scarce water (or 60% of total irrigation water used) for crop production. Scarce arable land used for global crop production was 749.9 million ha, or 50% of all cultivated land. A substantial quantity of these natural resources were consumed domestically for export of agriculture commodities to foreign destinations. The global food trade plays a significant role in the redistribution of land and freshwater resources. In 2011, total virtual blue water embodied in agriculture products traded was 615.5 billion $m^3$ for crop production, or 21% of all crop water consumption. Total land embodied in agriculture products traded was 447.4 million ha for crop production, or 30% of all cropland. Global agriculture trade of virtual scarce natural resources totaled 343.5 billion $m^3$ scarce water (or 20% of 1.8 trillion $m^3$) and 182.8 million ha scarce arable land (or 24% of 749.9 million ha) for crop production.

Figure 4.1 presents the largest net virtual flows of crop water embodied in agriculture products and the crop water scarcity of each country or region (i.e.

**Figure 4.1 National Water Scarcity and Net Virtual Crop Water Flows Embodied in Agriculture Products**

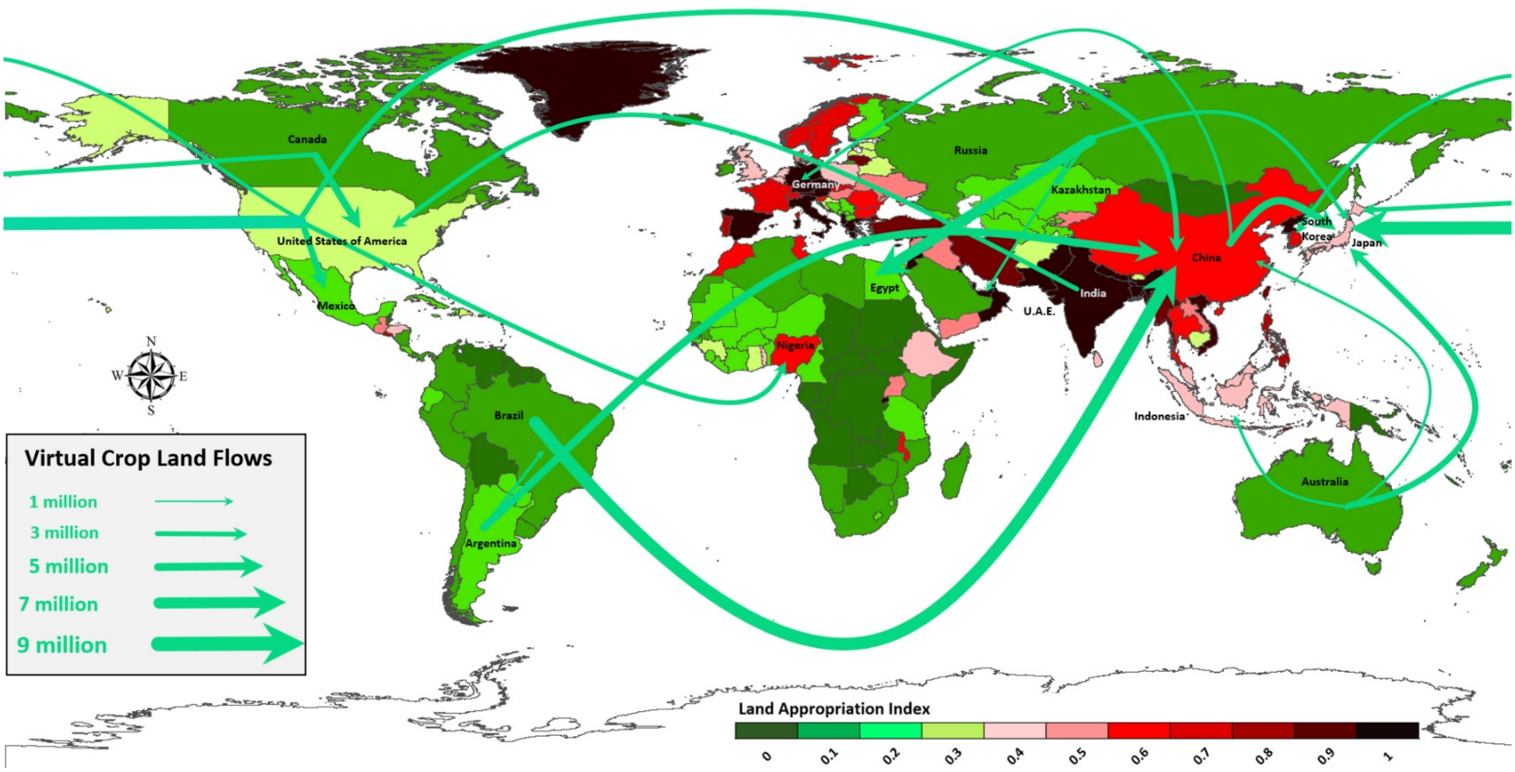



*Illustrates the crop water scarcity of each country or region in the world according to their agriculture WSI (ranging from WSI=0 water abundant to WSI=1 extreme water stress). Arrows represent the largest bilateral net virtual crop water flows (unit: cubic meter) from export (originating producer) countries and regions to import (final consumer) countries and regions.*

countries' endowment of freshwater resources relative to domestic crop production) in the world according to their agriculture WSI. Globally, 34 countries and regions are water abundant, 66 suffer slight to moderate water stress, 26 suffer severe water stress, and 13 suffer extreme water stress. Arrows represent net virtual crop water flows embodied in agriculture products from export (originating producer) countries and regions to import (final consumer) countries and regions. According to Figure 4.1, the largest net virtual crop water flows were mainly from water-scarce countries to more water-abundant countries. Extreme water-stressed India and severe water-stressed China were the largest net virtual crop water exporters. India's largest net virtual crop water export flows were to slightly water-stressed Germany (3.1 billion $m^3$), moderately water-stressed United States (12.6 billion $m^3$), Japan (3.2 billion $m^3$) and the United Kingdom (3.9 billion $m^3$), severe water-stressed China (5.8 billion $m^3$), and extreme water-stressed United Arab Emirates (5.3 billion $m^3$) and Saudi Arabia (3.7 billion $m^3$). China's largest net virtual crop water exports were to slightly water-stressed Germany (4.8 billion $m^3$) and moderately water-stressed Japan (10.3 billion $m^3$), South Korea (3.4 billion $m^3$), United Kingdom (3.3 billion $m^3$), and the United Sates (9.7 billion $m^3$). The largest net virtual crop water flows were composed primarily of processed agriculture product sectors including 'food products nec' (Japan 3.5 billion $m^3$ imports from the United States), 'beverages and tobacco products' (Japan 1.1 billion $m^3$ imports from the United States), 'wearing apparel' (United States 2.1 billion $m^3$ and China 1.1 billion $m^3$ imports from India; Japan 2 billion $m^3$ and United States 1.8 billion $m^3$ imports from China), and 'textiles' (United States 1.1 billion $m^3$ imports from China).

Figure 4.2 presents the largest net virtual flows of cropland embodied in agriculture products and the cropland scarcity of each country or region (i.e. countries' endowment of arable land relative to domestic crop production) in the world according to their agriculture LAI. Globally, 12 countries and regions are arable land abundant, 54 suffer slight to moderate land stress, 45 suffer severe arable land stress, and 28 suffer extreme arable land stress. Arrows represent net virtual cropland flows embodied in agriculture products from export (originating producer) countries and regions to import (final

**Figure 4.2 National Land Scarcity and Net Virtual Cropland Flows Embodied in Agriculture Products**




*Illustrates the cropland scarcity of each country or region in the world according to their LAI (ranging from LAI=0 arable land abundant to LAI=1 extreme arable land stress). Arrows represent the largest bilateral net virtual cropland flows (unit: hectare) from export (originating producer) countries and regions to import (final consumer) countries and regions.*

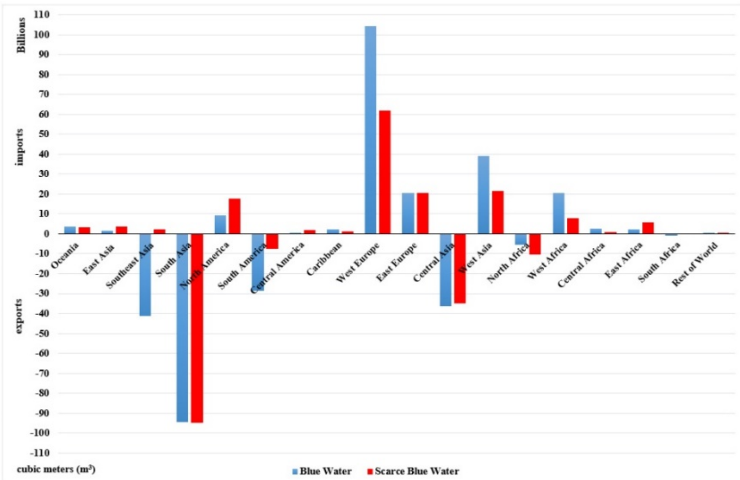
consumer) countries and regions. According to Figure 4.2, the largest net virtual cropland flows were mainly from land-abundant countries to land-scarce countries. The moderately land-stressed United States' largest net virtual crop land flows were to severe land-stressed Japan (8.2 million ha), China (3.4 million ha), Nigeria (2.9 million ha), and South Korea (2.5 million ha); as well as to moderately land-stressed Mexico (3.8 million ha). Severe land-stressed China was a net virtual cropland importer from the slightly land-stressed Brazil (8 million ha) and Argentina (4.7 million ha). Severe land-stressed Japan was a net virtual cropland importer from slightly land-stressed Australia (3.8 million ha) and Canada (3.1 million ha) and from severe land-stressed China (4.7 million ha). Extreme land-stressed India was a net virtual cropland exporter to the United States (2.9 million ha).

*ii. Virtual Water Scarcity and Land Scarcity Flows*

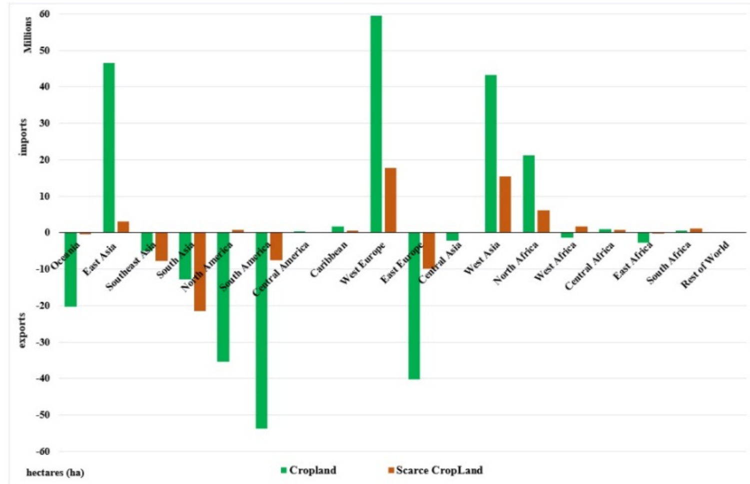
Viewing water scarcity and arable land scarcity in absolute terms provides another perspective of virtual scarce water and virtual scarce land flows. Given the high level of agriculture water and arable land scarcity among the largest net virtual exporters, it is not a surprise that a significant proportion of net virtual crop water and cropland export flows consisted of virtual scarce water and scarce land. For example, all virtual water and land exported by India – which suffers from extreme water stress and extreme arable land stress – were scarce water and scarce land. Figure 4.3a presents the regional net virtual crop water and virtual scarce crop water imports and exports; see SI2 for list of regions and their countries. According to Figure 4.3a, water-stressed countries in South Asia and Central Asia were significant exporters of both net virtual crop water and virtual scarce crop water. Conversely, more water-abundant countries in West Europe, East Europe, North America, and West Africa were importers of net virtual crop water and virtual scarce crop water. Figure 4.3b presents regional net virtual cropland and virtual scarce cropland imports and exports. According to Figure 4.3b, arable land-abundant countries in South America, North America, and East Europe were significant exporters of virtual cropland. Arable land-scarce countries in West Europe, East Asia, West Asia, and North Africa were significant importers of net virtual cropland.

**Figure 4.3 Regional Virtual Resources Embodied in Agriculture Products**

A. Net Virtual Water and Scarce Water




B. Net Virtual Cropland and Scarce Cropland



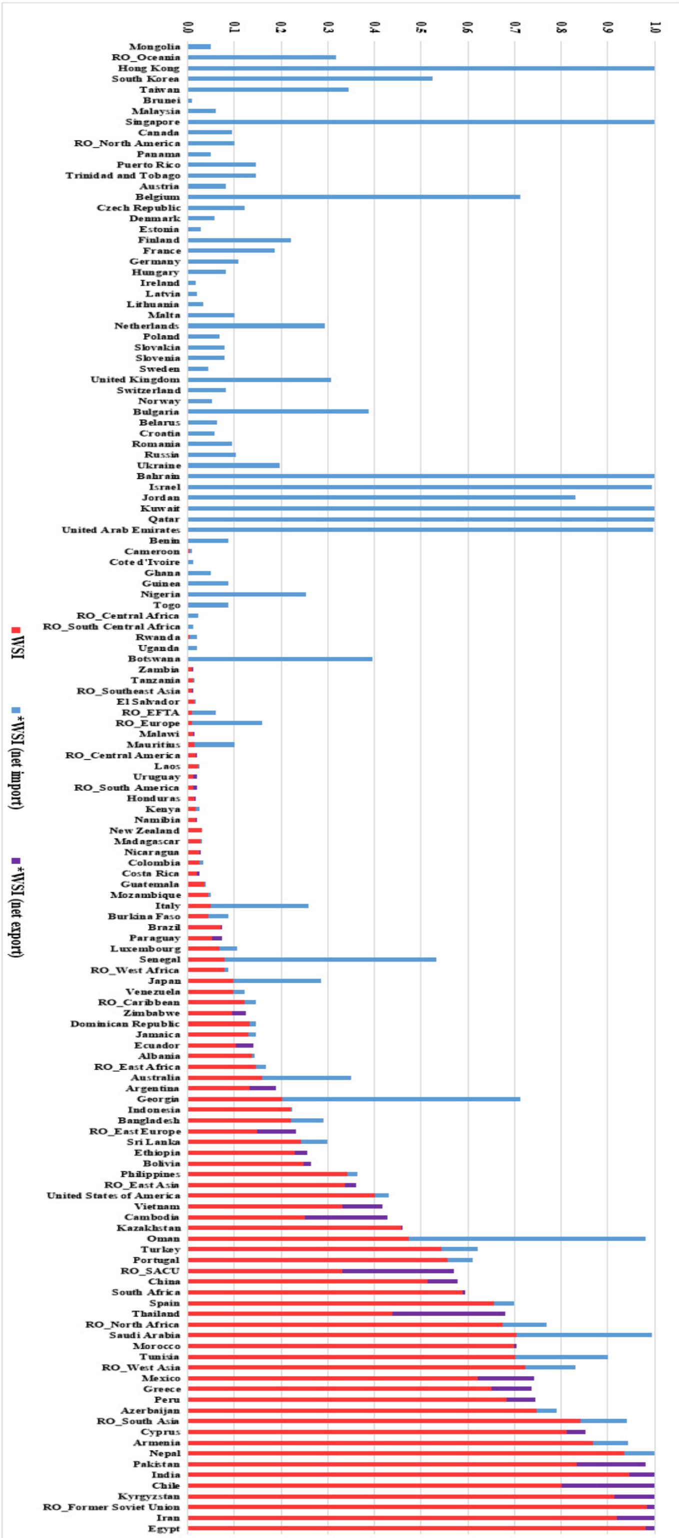

*iii. Impact of the Global Food Trade on Domestic Natural Resources*

This section investigates the impact of countries' participation in global food trade upon their water and land resources. Figure 4.4a compares the WSI to the hypothetical *WSI for crop production. *WSI refers to the hypothetical water stress on the local hydrological system if the net importing region does not have virtual water inflows available (i.e. withdraws water entirely from local resources) and the net exporting region does not consume local water resources for agriculture exports (i.e. withdraws water only for domestic consumption demands). According to Figure 4.4a, 39 countries and regions were net virtual crop water exporters and 100 countries and regions were net virtual crop water importers. Of the 39 net virtual exporters, 22 countries and regions demonstrated no significant change (i.e. $\Delta WSI < .1$). For example, slightly water-stressed Brazil (WSI=.1=*WSI) and severely water-stressed Kazakhstan (WSI=.7=*WSI) experienced no net change above the threshold due to their net virtual crop water exports. The remaining 17 net virtual exporters did increase their water stress (i.e. $\Delta WSI \geq .1$). These 17 countries included severe water-stressed Chile (WSI=.8, *WSI=1), Pakistan (WSI=.8, *WSI=1), Kyrgyzstan (WSI=.9, *WSI=1), China (WSI=.5, *WSI=.6), and Iran (WSI=.9, *WSI=1) and extreme water-stressed India. Conversely, of the 100 net virtual crop water importer countries and regions, 65 mitigated their agriculture water stress (i.e. $\Delta WSI \geq .1$) and 35 demonstrated no significant change (i.e. $\Delta WSI < .1$). Of the 65 net virtual crop water importer countries and regions, 48 fully ameliorated their crop water stress (*WSI=0). This included 7 extreme crop water-stressed countries (Hong Kong, Singapore, Bahrain, Israel, Kuwait, Qatar, United Arab Emirates).

Figure 4.4b compares the LAI to the hypothetical *LAI for crop production. *LAI refers to the hypothetical land stress on the local terrestrial agriculture production system if the net importing region does not have virtual cropland inflows available (i.e. uses arable land entirely from local resources) and the net exporting region does not consume local cropland for agriculture exports (i.e. uses arable land only for domestic consumption demands). According to Figure 4.4b, 50 countries and regions were net virtual exporters of cropland and 89 countries and regions were net virtual importers of cropland. Of the 50 net virtual exporters, 23 countries and regions demonstrated no significant change (i.e. $\Delta LAI < .1$). For example, slightly arable land-stressed Australia (LAI=.1=*LAI) and the United States (LAI=.3=*LAI) experienced no net change

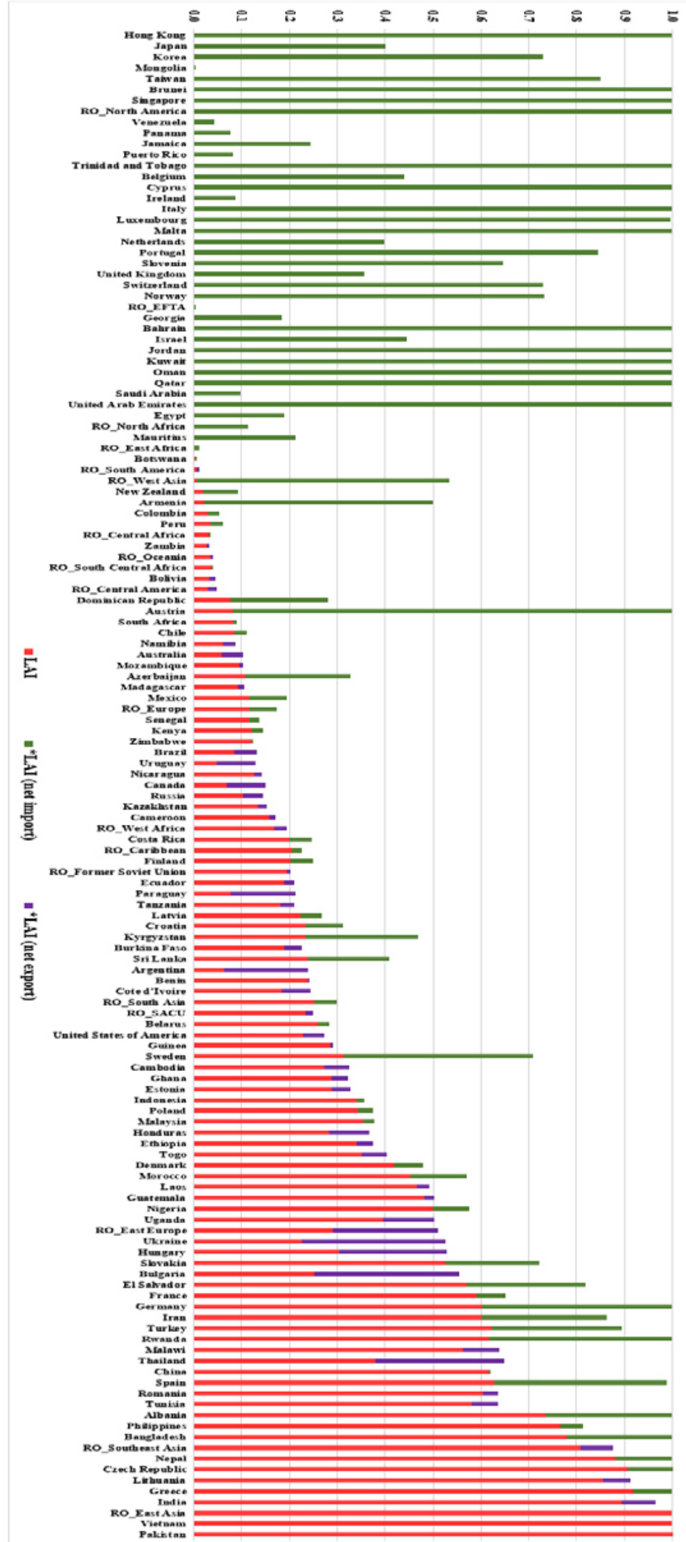
**Figure 4.4 Comparison of Water and Land Stress to Hypothetical Water and Land Stress**

**A.** Crop Water Stress




*Countries and regions arranged in order of increasing *WSI; representing water abundant (*WSI=0), slight to moderate water stress (*WSI=.1 to .4), severe water stress (*WSI=.5 to .9), and extreme water stress (*WSI=1).*

**B.** Crop Land Stress

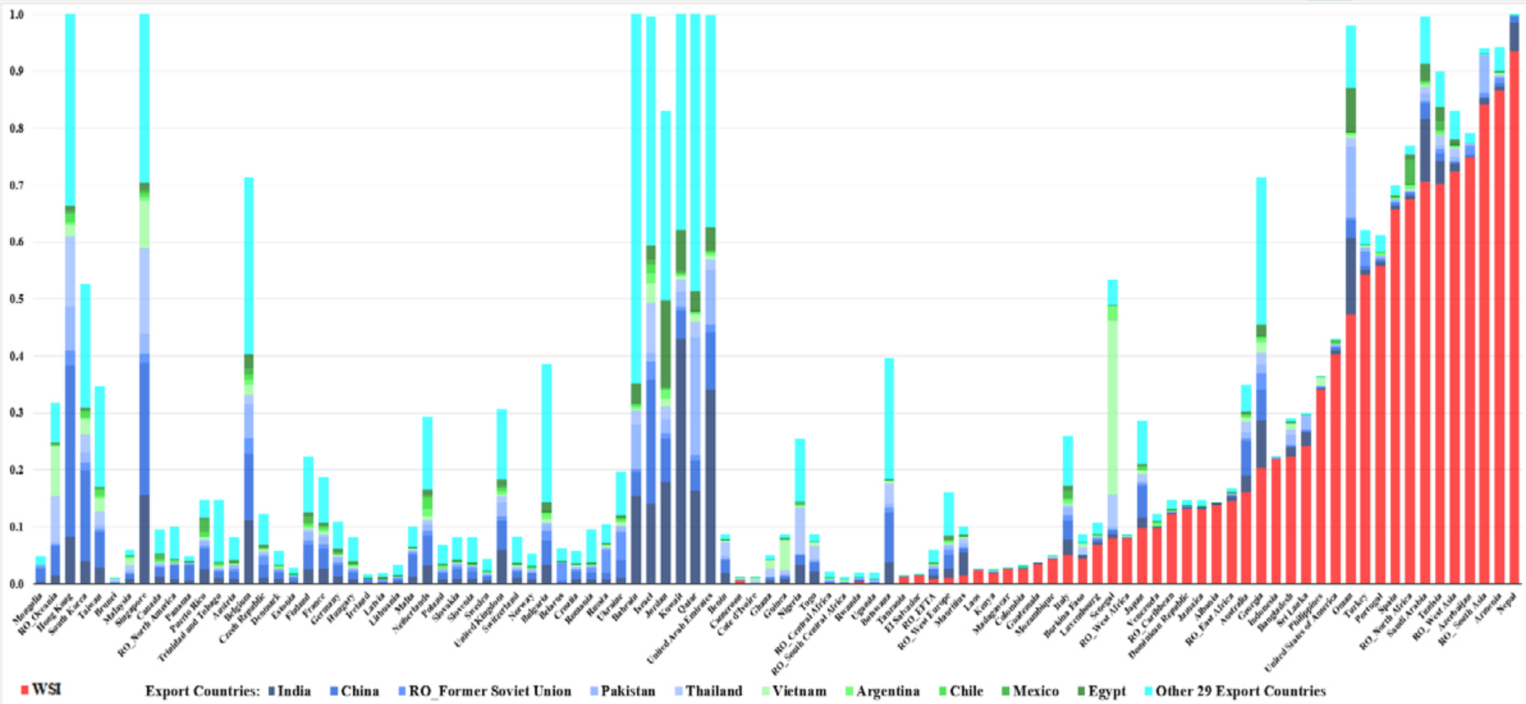



*Countries and regions arranged in order of increasing *LAI; representing land abundant (*LAI=0), slight to moderate land stress (*LAI=.1 to .3), severe land stress (*LAI=.4 to .9), and extreme land stress (*LAI=1).*

above the threshold due to their net virtual cropland exports. The remaining 27 net virtual exporters did increase their arable land-stress (i.e. $\Delta$LAI$\geq$.1). These 27 countries included severe arable land-stressed Lithuania (LAI=.9, *LAI=1), Thailand (LAI=.6, *LAI=.9), Bulgaria (LAI=.6, *LAI=.9), Hungary (LAI=.5, *LAI=.8), and Ukraine (LAI=.5, *LAI=.8). Conversely, of the 89 net virtual cropland importer countries and regions, 67 mitigated their arable land stress (i.e. $\Delta$LAI$\geq$.1) and 22 demonstrated no significant change (i.e. $\Delta$LAI$<$.1). Of the 67 net virtual cropland importer countries and regions, 40 fully ameliorated their cropland stress (*LAI=0). This included 15 extreme arable land-stressed (LAI=1) countries (Hong Kong, Brunei, Singapore, Rest of North America, Trinidad and Tobago, Cyprus, Italy, Luxembourg, Malta, Bahrain, Jordan, Kuwait, Oman, Qatar, United Arab Emirates).

Figures 4.4a and 4.4b illustrate the important role of international trade in the exchange of virtual land and virtual water embodied in agriculture products in both mitigating and exacerbating the national level scarcity of these natural resources. Figure 4.5 expands on Figure 4.4a by highlighting the direct influence on nations' and regions' agriculture WSI by the net virtual crop water imports from producer countries and regions. In other words, Figure 4.5 presents the 100 net virtual crop water import countries and regions and details the portion of their WSI that is mitigated by net virtual crop water flows from the 39 net virtual crop water export countries and regions. Only the top ten largest net virtual crop water export countries and region are individually presented. Globally, India is by far the largest net virtual crop water exporter (76.8 billion $m^3$), followed by China (53.3 billion $m^3$), Former Soviet Union (35.2 billion $m^3$), and Pakistan (30.9 billion $m^3$). After Egypt (10 billion $m^3$), the remaining 29 net

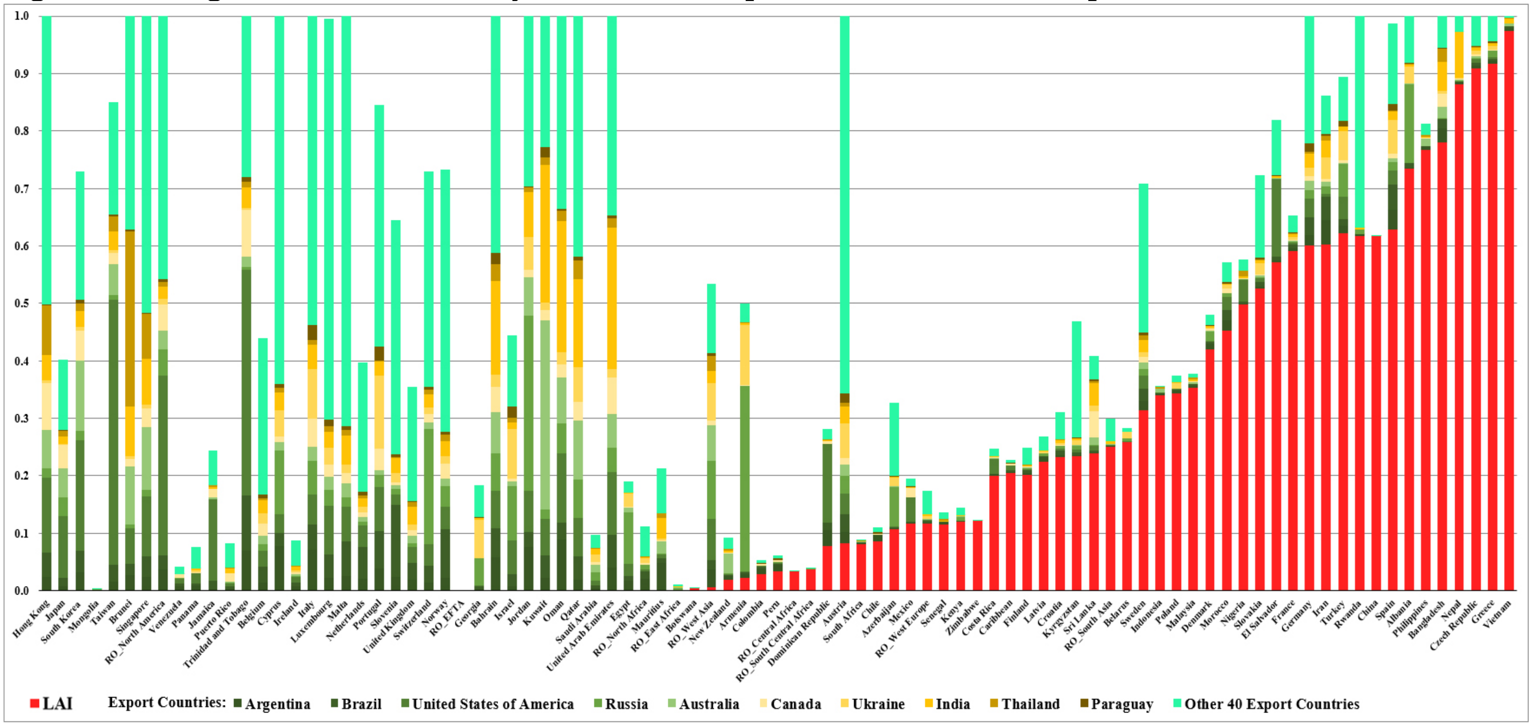
**Figure 4.5 Mitigation of Water Scarcity via Virtual Crop Water Flows from Net Export Countries**




*Graph illustrates Water Scarcity Index mitigation for net virtual crop water import countries and regions from net virtual crop water export countries and regions. The largest ten net virtual crop water export countries color coded as: top five (India, China, Former Soviet Union, Pakistan, Thailand) blue, next top five (Vietnam, Argentina, Chile, Mexico, Egypt) green, and 'Other 29 Export Countries' neon blue.*

virtual export countries and regions have much smaller net export flows and are, therefore, combined as ‘Other 29 Export Countries’. Our results show that the top ten largest net virtual crop water export countries and regions played a significant role in contributing to the mitigation of water stress in nations around the world. For example, India’s net virtual crop water embodied in agriculture exports contributed to Nepal’s (78%), Kuwait’s (43%), and Mauritius’ (47%) water stress mitigation. This does not imply that all three countries fully ameliorated their water stress. Merely that India’s net virtual crop water exports accounted for 78% of Nepal’s water stress mitigation from WSI=1 to *WSI=.9. In Kuwait’s situation, it’s WSI=1 was fully ameliorated to

**Figure 4.6 Mitigation of Land Scarcity via Virtual Cropland Flows from Net Export Countries**




*Graph illustrates the Land Appropriation Index mitigation for net virtual cropland import countries and regions from the net virtual cropland export countries and regions. The largest ten net virtual cropland export countries color coded as: top five (Argentina, Brazil, United States of America, Russia, Australia) green, next top five (Canada, Ukraine, India, Thailand, Paraguay) yellow, and 'Other 40 Export Countries' neon green.*

*WSI=0 and, therefore, India's net virtual crop water exports accounted for 43% of Kuwait's water stress amelioration. Globally, the top ten largest net virtual crop water export countries and region accounted for 63% (India 13.5%, China 13.7%, Former Soviet Union 4.6%, Pakistan 7.5%, Thailand 8%, Vietnam 7.2%, Argentina 1.9%, Chile 1.4%, Mexico 2.3%, Egypt 2.8%) of the water stress mitigation among the 100 net virtual crop water import countries and regions; the 'Other 29 Export Countries' accounted for the remaining 37%.

Figure 4.6 expands on Figure 4.4b by highlighting the direct influence on nations' and regions' LAI by the net virtual cropland imports from producer countries and regions. Figure 4.6 presents the 89 net virtual cropland import countries and details the portion of their LAI that is mitigated by net virtual cropland flows from the 50 net virtual cropland export countries and regions. Only the top ten largest net virtual cropland export countries are individually presented. Globally, Argentina is the largest net virtual cropland exporter (29.1 million ha), followed by Brazil (23.8 million ha), United States of America (23.7 million ha), Russia (21.9 million ha), Australia (20.8 million ha), Canada (18 million ha), Ukraine (16.7 million ha), India (16 million ha), Thailand (7.7 million ha), and Paraguay (4.8 million ha). The remaining 40 net virtual export countries and regions have been combined as 'Other 40 Export Countries'. Our results show that the top ten largest net virtual cropland export countries played a significant role in contributing to the mitigation of arable land stress in nations around the world. For example, Russia's net virtual cropland embodied in agriculture exports contributed to Albania's (51%), Armenia's (68%), and Egypt's (48%) arable land stress mitigation. Russia's net virtual cropland exports accounted for 48% of Egypt's arable land stress mitigation from LAI=.2 to *LAI=0 and 68% of Armenia's arable land stress mitigation from LAI=.5 to *LAI=0. Globally, the top ten largest net virtual cropland export countries accounted for 58% of the arable land stress mitigation among the 89 net virtual cropland import countries and regions; the 'Other 40 Export Countries' accounted for the remaining 42%.

## V. Conclusion

The required resource inputs for global agriculture production are spatially and temporally unevenly distributed, cannot be easily substituted, are degraded in quality and quantity by overuse and pollution, and are limited in nature. Countries lacking in natural resource endowments are able to overcome these limitations by importing agriculture products to feed their populations. However, trade can result in externalities that exacerbate resource scarcity and shift the burden of increasing environmental degradation. Huge virtual crop water and virtual cropland flows through trade activities significantly redistribute natural resources among the world's nations and regions. We have studied the extent of these virtual flows and the resulting impact on nations' and regions' water stress and land stress. The findings of this study raise the question of the viability of the current global trade in food.

Water scarcity and arable land scarcity are major environmental and economic concerns in many regions of the world. The overuse of resources can have severe consequences on ecosystems; further degrading ecosystem quality and functioning, impacting human health and potentially social stability. Furthermore, land scarcity and water scarcity imply limited expansion possibilities for key crops without major land conversions and/or irrigation infrastructure development. Natural resource consumption and scarcity play out differently in countries with differing resource endowments. Our analysis incorporated the agriculture WSI and LAI of countries and regions to highlight the exchange of embodied virtual resources and environmental impacts relative to a country's natural resource endowments (i.e. environmental relevance). Incorporating scarcity indicators and environmental relevance significantly changes the analysis of countries' production and consumption of limited resources.

A nation's participation in the international trade in agriculture products is a major driver of arable land and freshwater depletion in some countries and a mechanism for supplementing these limited resources for other countries; stabilizing or, in some cases, fully ameliorating a country's resource scarcity in agriculture production via virtual imports. Results from the hypothetical elimination of imports and exports of virtual land and virtual water embodied in agriculture products caused significant shifts in countries' and regions' LAI to *LAI and WSI to *WSI. The biggest beneficiaries from the trade in virtual crop water (*WSI>WSI) were small water-scarce and water-abundant countries and regions. For example, Singapore, fully ameliorated its water stress (WSI=1, *WSI=0) via net virtual crop water imports from larger nations such as India and China accounting for 16% and 23%, respectively, of Singapore's water stress mitigation. Meanwhile, for water-scarce export countries and regions, their water stress situation was further compounded by net virtual scarce water exports (*WSI<WSI); i.e. a situation with trade causing greater stress than hypothetically producing only for domestic consumption (*WSI). The trade in virtual cropland (*LAI>LAI) demonstrated a different pattern where land-abundant countries and regions were net virtual cropland exporters and land-scarce countries and regions were the beneficiaries. On the one hand, it is highly desirable for resource-scarce countries and regions (i.e. arable land-scarce) to import more virtual resources from countries with abundance in natural resources. On the other hand, from a resource conservation point of view, it is not desirable for resource-scarce countries and regions (i.e. water-scarce) to import virtual scarce resources from similar resource-scarce countries as this simply transfers the stress to other resource-scarce countries.

It is clear that the current supply-side oriented global trade in virtual crop water embodied in agriculture products is not sustainable. Thirty-nine countries and regions were net virtual crop water exporters to 100 import countries and regions. Of these 39 countries and regions, the ten largest net virtual crop water export countries and region accounted for 63% of the water stress mitigation among the 100 net virtual crop water import countries and regions. With the exception of moderately water-stressed Argentina and Vietnam, the ten largest net virtual crop water exporters included three severely water-stressed and five extreme water-stressed countries and regions. The global trade in virtual cropland embodied in agriculture products demonstrated a greater equitable distribution with 50 net virtual cropland export countries and regions to 89 net virtual cropland import countries and regions. Of these 50 countries and regions, the ten largest net virtual cropland export countries accounted for 58% of the arable land stress mitigation among the 89 net virtual cropland import countries and regions. With the exception of extreme arable land-stressed India and severe land-stressed Ukraine and Thailand, the ten largest net virtual crop water exporters included seven slight to moderately arable land-stressed countries.

China and India are of particular concern as both are significant net virtual scarce resource exporters with high population densities, limited water and arable land resources, and national export-oriented economic policies that exacerbate domestic resource availability among their populations. In particular, India exacerbated both its land stress and water stress (*LAI>LAI and *WSI>WSI) due to intensive use of resources for net virtual water and land exported for the benefit of foreign consumers. India and China used local water and land resources to produce their agriculture exports, without factoring in – or despite – their particular water and land stress situation. A reduction in the consumption of water and land intensive agriculture goods and services for export would reduce the burden on India’s and China’s domestic resources, contributing to reducing water and land shortages.

# Chapter 5: Tele-connected Value Chain Analysis of the Water-Energy-Food Nexus in East Asia.

## I. Introduction

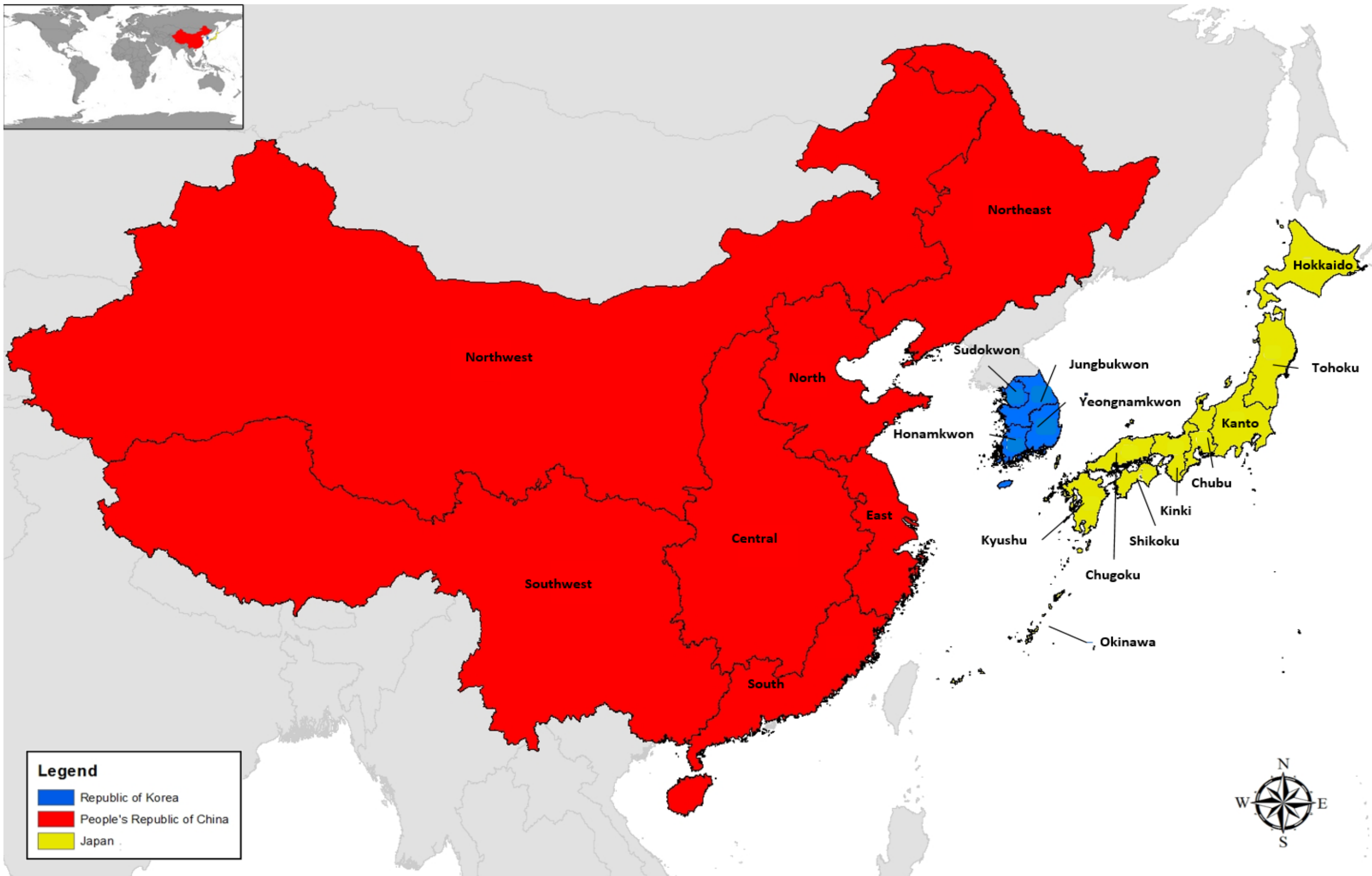
Our regional analysis achieves Objective 2. This chapter investigates the redistribution of the natural resources water, energy, and food and environmental impacts at the sub-national level in East Asia's transnational inter-regional trade. With substantial quantities of commodities and services being traded across economic and ecosystem boundaries, the inter-regional production networks in East Asia have significant implications on demand for local (i.e. sub-national) water-energy-food resources and environmental impacts. We investigate the supra-national structure of the Water-Energy-Food Nexus (WEFN) in the region and examine the linkages and environmental tradeoffs between the three subsystems. This study incorporates the indicators water scarcity and greenhouse gases ($CO_2$, $CH_4$, $N_2O$) and $SO_x$ emissions. Recently, the WEFN approach has become an increasingly popular perspective among scholars, but few publications incorporate analysis of environmental impacts.

***Objective 2:*** ***Tele-connected investigation of the consumption of water, energy, and food resources and environmental impacts embodied in the East Asia regional trade. Assess and spatially characterize the impacts from regional trade on sub-national regions' resources and environment.***

## II. Background

In today's globalized world, population increase and economic growth pose important challenges in securing sufficient water, energy, and food to meet demand at the sub-national (henceforth, regional), national, and supra-national level. East Asia is of particular interest due to the region's rapid economic growth, substantial population size, relatively recent regional economic structural transformation, and differing degree of resource availability and environmental pressures. The unprecedented rapid growth, extent, and complexity of global value chains (GVCs) since the 1980s have reshaped global trade and consumption of these three closely linked resources within and between countries (Gasiorek and Lopez, 2014). Policies for water, energy, and food – at the regional and national levels – have numerous interwoven challenges; including access to resources, environmental impacts, securing national priorities (e.g. economic growth), and national security. The inter-connectedness of the water, energy, and food subsystems has become ever more apparent as evidenced by the increasing application of the Water-Energy-Food Nexus (WEFN) approach to identify tradeoffs and the search for cross-sector efficiencies to these challenges not only within countries but across global supply chains. With substantial quantities of commodities and services being traded across economic and ecosystem boundaries, an integrated assessment quantifying the virtually traded resources (and linked environmental pressures) of all three subsystems is needed in order to better understand the complexity of the WEFN and to adopt a comprehensive management approach. Furthermore, solving the issues of limited resource availability and sustainability requires an understanding of the integrated structure of the supra-national, national, and regional – see Figure 5.1 –

**Figure 5.1 Map of East Asia's Regions**




economies in the context of the WEFN.

Over the past six decades, countries in the East Asia region have enjoyed some of the highest annual gross domestic product (GDP) growth rates in the world by pursuing independent export-oriented trade policies; dominated by trade with the United States (World Bank, 2007). The People's Republic of China, Japan, and the Republic of Korea (South Korea) each demonstrated 8% to 10% GDP growth rates for sustained periods of time; each achieving industrialization, urbanization, electrification, and motorization in the short span of 20 to 30 years (Pempel, 2013). The 1997-98 Asian Financial Crisis forced the East Asian countries to realign economic strategies and foster inter-regional economic cooperation – in the form of cross-border investments, financial coordination, trade, and inter-regional production networks – in order to avoid falling behind the European Union (EU) and North America GVCs (Aggarwal *et al.*, 2008). The three economies became increasingly integrated and restructured the intra-industrial division of production and services to build up a highly interdependent network. China's accession to the World Trade Organization in 2001 resulted in a tremendous economic and political shift in the region. By 2005, the East Asia GVC had become established centered on China at its core (Yunling, 2010; ADB, 2014).

GVCs divide up the production of goods and services into linked stages of production distributed across international borders and economies. Instead of producing a product originating from a single factory, a product originates from a network of suppliers from multiple locations (ADB, 2014). China, as the manufacturing hub in East Asia's production networks, has been the main driving force increasing the inter-regional economic interdependence and an engine of economic growth. Over 50% of China's export is composed of processing trade – i.e. raw materials, parts and components, technology and equipment, and economic services are exported from other East Asian economies to China for final processing and then exported to the U.S. and the EU. China's huge domestic market is also a source of export growth for neighboring countries for both manufactured products and primary commodities. Typically, this results in China possessing a substantial trade surplus with the U.S. and a considerable trade deficit with Japan and South Korea (Chiang, 2013; Kuroiwa and

Ozeki, 2010). In 2005, China's exports to Japan and South Korea totaled, respectively, $109.8 billion and $31.8 billion while imports were, respectively, $96.2 billion and $66.7 billion. There is a similar trade deficit between Japan and South Korea, Japan's exports to and imports from South Korea were $52 billion and $25.9 billion (IDE-JETRO). China's close production networks with Japan and South Korea – as well as its seemingly inexhaustible pools of low-wage workers and abundant raw materials – have allowed China to become the world's largest manufacturer and exporter (Gereffi, 2014). These inter-regional production networks have implications on demand for water-energy-food and ecosystems.

Recently, the WEFN approach has become an increasingly popular perspective among scholars. A 'nexus' among water-energy-food was conceived by the World Economic Forum to highlight the inseparable linkages between the use of resources and the universal human rights to water, energy, and food security (WEF, 2011). For example, water is consumed for the production of food and energy (e.g. fossil fuel processing, biofuels) and energy is necessary to transport, treat, and distribute water, fuel farming equipment, and manufacture chemical inputs necessary for agriculture production. The WEFN concept is based on systematic analysis of the interactions between the natural environment and human activities in order to better understand and to work towards a more balanced use of natural resources (FAO, 2014b).

While the nexus concept has been widely embraced, it is not a clearly defined construct or fully tested in practice (Wichelns, 2017). Despite not possessing a defined framework or a universal set of sectors to be analyzed, the concept has encouraged a wide range of approaches in a variety of WEFN contexts; for example, critical emphasis on particular subsystems including water (Vanham, 2016), food security (de Laurentiis *et al.*, 2016), climate change (Ringler *et al.*, 2013; Berardy and Chester, 2017), and so forth. A criticism of the nexus concept has been the lack of a clear definition of integration within the nexus which makes it difficult to establish what constitutes a 'successful' nexus analysis; creating significant challenges to developing nexus-orientated strategies. In other words, how to implement the WEFN and deliver real world solutions has proven difficult (Leck *et al.*, 2015; Wichelns, 2017). Taking an integrated view of such interlinked issues is highly challenging given that nexus issues manifest themselves in different ways in the context of individual countries with differing resource and technology endowments, governance and development trajectories.

The objective of this paper is to clarify the tele-connected supra-national structure of the WEFN and environmental linkages between the three subsystems and examine the impacts and tradeoffs between each subsystem across scale. The term *tele-connections* is used to describe the spatial linkages between local consumption and environmental impacts over large distances (Yu *et al.*, 2013; Hubacek *et al.*, 2014). This paper incorporates the environmental indicators water scarcity and $CO_2$, $CH_4$, $N_2O$, and $SO_x$ emissions. The major greenhouse gases $CO_2$, $CH_4$, and $N_2O$ (henceforth, GHG) caused by human activities have global implications contributing to the warming of the planet (USEPA, 2017). The group of sulfur oxide ($SO_x$) gases – including the component of greatest concern sulfur dioxide ($SO_2$) – is emitted primarily from the burning of fossil fuels by power plants, industry, and shipping. $SO_x$ is a pollutant whose effects are felt locally. Exposure to $SO_x$ has been linked to respiratory illnesses in humans, damage to plant foliage and growth, and is an important acid rain precursor (*ibid*, 2017). A tele-connected WEFN approach is applied to investigate regional water, energy, and food consumption, the competing domestic and international demand for these resources, and the linked environmental pressures in East Asia's transnational inter-regional trade by modelling data contained in the Transnational Interregional Input-Output Table (TIIOT) – which includes production, consumption, and trade flows between China, South Korea, and Japan – for the year 2005 (IDE-JETRO).

## III. Data

IDE-JETRO's 2005 TIIOT contains regional economic flows between China (seven regions), South Korea (four regions), and Japan (nine regions) aggregated into fifteen sectors (see SI3). The TIIOT also includes "other" countries (i.e. Taiwan, ASEAN5, United States) not incorporated into the WEFN analysis. The TIIOT links the sub-national (i.e. regional) inter-regional input-output tables of China, Japan, and South Korea into a single matrix using the bilateral trade data provided by the individual countries (sources: State Information Center of China, Bank of Korea, and IDE-JETRO). The table permits analysis of the economic linkages across borders and mapping the cross-national production networks in East Asia at the regional scale. The TIIOT was extended with satellite accounts for water, energy, agriculture land use, scarce water, and GHG and $SO_x$ emissions for each sector.

Water consumption was estimated based on the sectoral water withdrawal of each province within the region multiplied by the ratio of water withdrawal to water consumption in the agricultural, industrial, service and domestic sectors of that province. Water consumption is defined as water use that is not returned to the original water source after being withdrawn; consequently unavailable for other users within a given time period. Only ‘blue water’ in million $m^3$ was analyzed due to the data availability and its relevance to water policy. China’s water consumption ratios for the year 2008 were estimated based on official Water Resource Bulletins for river basins (e.g., *Yellow River Water Resource Bulletin*) and provincial Water Resource Bulletins (e.g., *Liaoning Water Resource Bulletin*). Additional economic and environmental data was obtained from official publications (e.g., *Beijing Statistical Yearbook 2009*). South Korea’s 2005 water consumption ratios were obtained from the Ministry of Land Transportation, Water Resources, and Policy Bureau, Statistics Korea, and WIOD. Japan’s 2007 water consumption ratios were obtained from the Research and Statistics Department, Minister's Secretariat Ministry of Economy, Trade and Industry, provincial water statistics (i.e. Niigata, Nagano, Shizuoka, and Fukui), and the Ministry of Land, Infrastructure, Transport, and Tourism.

The data for Japan, China, and South Korea analyzing the food (land unit: hectare) and energy (unit: terajoule) subsystems and $CO_2$, $CH_4$, and $N_2O$ (unit: $CO_2$ equivalent metric ton) and $SO_x$ (unit: metric ton) emissions were obtained from the World Input-Output Database (WIOD). All GHG emissions were converted into $CO_2$ equivalents to permit comparison. Each GHG has a different global warming potential (GWP) and persists in the atmosphere for different lengths of time. This paper follows the 100-year GWP for greenhouse gases reported by the United Nations Framework Convention on Climate Change: carbon dioxide (1x), methane (25x), and nitrous oxide (298x) (UNFCCC, 2017). Agriculture land use data was obtained from 2005 WIOD agriculture land accounts. The displacement of agriculture land is used as a proxy for the food subsystem of the WEFN. Total land consumed for the agriculture sector consisted of arable land, permanent crops, and pasture land types. Energy and GHG and $SO_x$ emissions were obtained from 2005 WIOD accounts. WIOD data for energy and $CO_2$ emissions consisted of 25 sources which were consolidated into nine: coal, oil, gas, hydropower, geothermal, solar, wind, nuclear, and biofuels.

In this study, we aggregated WIOD's 36 sectors to match with the TIIOT's 15 sectors at the national level; utilizing IDE-JETRO's expanded 76 intermediate sector classification table as reference for aggregation (see SI3). For example, WIOD 'food, beverages, and tobacco', 'leather and leather footwear', and 'wood and products of wood' sectors were consolidated into the 'other non-electrical consumption products for daily-use' sector. In order to analyze WIOD's national level energy, land, and GHG and $SO_x$ emissions data at the sub-national (i.e. regional) level, a proportional scaling was applied for each region and sector. To match these data with regions in East Asia, we disaggregated the respective national data to the seven China, nine Japan, and four South Korea regions according to their sectorial economic output. This scaling method assumes that the environmental pollution and resource consumption per unit of output (i.e. environmental coefficients) for a region are the same as at the national level.

Regional and national population data for 2005 was obtained from National Bureau of Statistics of China, the Statistics Bureau of Japan, Ministry of Internal Affairs and Communication, and Statistics Korea.

*i. Limitations*

The IDE-JETRO TIIOT is for the year 2005. The age of the data is a significant shortcoming. However, the 2005 TIIOT is the most current region-specific dataset for

East Asia. The 2005 TIIOT has two distinct advantages. First, the TIIOT's regional data specific to East Asia permits an analysis of the harmonized transnational inter-regional data of virtual trade in resources and environmental pressures at the supra-national to region and sub-national to sub-national level between China, Japan, and South Korea. There exist more current global multi-regional input-output (GMRIO) databases (Tukker and Dietzenbacher, 2013), but a major shortcoming of the GMRIO databases is the lack of detailed trade flow data below the national level, i.e. between regions. Recently, several methodologies have been developed (Bachmann *et al.*, 2015; Wenz *et al.*, 2015; Wang *et al.*, 2015) which permit multiple spatial scales (i.e. global, supra-national, national, regional, etc.) to be incorporated into an analysis; i.e. capturing the heterogeneity of regions within the global economy. However, the disadvantage of these approaches is increased data inaccuracy due to the disaggregation approximations of trade flows from one region in one country to a region in another country. Second, the TIIOT permits a unique window into the development of the East Asia GVC – prior to the 2008-9 global economic crisis – and the inter-regional production networks centered around China as the 'factory of the world' (Gereffi, 2014).

Data aggregation uncertainty exists due to the highly aggregated 15 sector TIIOT. For the energy and GHG and $SO_x$ air pollution data obtained from the 36-sector WIOD, the correspondence between the WIOD data and the TIIOT was many-to-one; resulting in greater aggregation of data. The water coefficient data sectors had variable sector count (not including direct household consumption) depending on the country and data source; i.e. Japan 24-sector, China 30-sector, and South Korea 12-sector. Japan's and

China's water data were aggregated to 15 sectors and, due to the fact that water data for South Korea had fewer sectors than the TIIOT, it was necessary to disaggregate the water data to the corresponding TIIOT sectors according to their sectoral economic output. This was done by assuming that the sectorial water intensity in the corresponding TIIOT sectors was the same as the intensity of the more highly aggregated original water data. Regarding aggregation at the sector level, for example, all agriculture is aggregated into one "agriculture" sector; including water intensive livestock, aquaculture, fruits, rice, and etc. production as well as lower water intensive agriculture crops. Averaging natural resource requirements for all crops and sectors under 'agriculture' may under- or over-estimate the water requirements and, therefore, the virtual flows in the East Asia transnational inter-regional trade (Daniels *et al.*, 2011).

Directly measuring food production and consumption in this MRIO WEFN analysis is challenging; i.e. developing a satellite account of food consumption coefficients would require a comprehensive database of the East Asian region's food consumption preferences and trends. This study incorporates agriculture land use data as a proxy for food production and consumption and trade across the East Asia region. The association of food production and consumption with the agriculture land use coefficient as a proxy has limitations in its application. First, the agriculture land use coefficient consists of the land types arable land, permanent crops, and pastures; which include a broad spectrum of food and non-food (e.g. wool) agriculture products. Second, as noted earlier in this section, due to aggregation of data under the 'agriculture' sector (i.e. inclusion of highly land intensive as well as low land intensive agriculture) there is the possibility for over-estimating the land use coefficient for food production and consumption. Third, this study does not have the ability to account for multiple and simultaneous uses of agriculture land, but that is a common problem of IO analysis using physical land coefficients.

## IV. Results

### *i. Direct Water-Energy-Food and Environmental Pressures*

In the water-energy linkage, water is necessary for energy extraction, conversion, transport and power generation (Siddiqi and Anadon, 2011). Water consumption for fossil energy (e.g. coal, crude oil, natural gas) extraction varies by geographical features and extraction technologies. All types of energy generation require water, but the amount of water needed is determined by thermal efficiency, heat sink accessibility, cooling systems, and the type of power plant. Thermoelectric forms of electricity generation include coal, oil, natural gas, and nuclear (Chang *et al.*, 2016; WEF, 2008). Thermal power plants constitute almost 80% of electricity generation worldwide. All thermoelectric plants that use steam turbines require water for cooling. Regardless of the fuel source, cooling is responsible for 80% to 90% of the water consumed in thermoelectric plants. There is a large range of results in the literature regarding the amount of water required by each form of energy generation technology. In terms of direct water withdrawals per unit of electricity production, nuclear is the largest and natural gas fired the least water consuming thermoelectric technology; solar and wind power systems consume almost no water for generating electricity (WEF, 2008; IEA, 2012; Tan and Zhi, 2016). Recently, there have been an increasing number of publications that calculate both direct water consumed and embodied water from all upstream inputs required by sector (e.g. oil extraction, oil refining, steel and concrete production for structures, crops for biofuel) to meet final energy demand (Li *et al.*, 2012; Holland *et al.*, 2015; Feng *et al.*, 2014b). For example, Feng *et al.* (2014b) analysis of the total life cycle water consumption (i.e. net amount of water consumed along the supply chain to produce 1/kWh of electricity) estimated that biomass and hydropower were the most water-intensive forms of energy generation, followed by coal, oil, nuclear, natural gas, solar, and wind. The water footprint of crops such as sugarcane, maize, and soybean is significantly higher than that of fossil energy generation (Chang *et al.*, 2016; Tan and Zhi, 2016). Considering the increase in water evaporation from dammed reservoirs, hydroelectric power generation is a significant water consumer in the water-energy linkage; additionally, dams may alter the timing of stream flows and conflicts may arise during periods of severe water shortage over water flow (Yillia, 2016).

Direct water consumption for electricity generation was the third largest consumer of water in China (16.3 billion $m^3$; 6% of national water consumption) and South Korea (900 million $m^3$; 21%). Electricity generation was the second largest consumer of water in Japan (18.1 billion $m^3$; 18%). National consumption of energy was 50.9 million TJ in China, 18.7 million TJ in Japan, and 7.3 million TJ in South Korea. Japan's and South Korea's consumption had an expected higher water requirement per kilowatt generated as a greater proportion of national electricity was obtained from water-intensive nuclear technology. In comparison, China's substantially larger and less water-intensive national electricity consumption was obtained primarily from coal.

The proportion of national electricity generation from different technologies were the following: China (coal 90%, hydropower 5%, oil 2%, nuclear 2%, gas 1%), Japan (nuclear 32%, gas 28%, coal 24%, oil 12%, hydropower 3%, geothermal 1%), and South Korea (nuclear 43%, coal 36%, gas 13%, oil 8%).

The water-food linkage mainly refers to the water required for agricultural products (e.g. livestock, crops). Animal products have a much larger water requirement compared to crops per calorie unit (Chang *et al.*, 2016). Food production in China was the largest direct water consumer in East Asia totaling 223.4 billion $m^3$ (77% of national water consumption). Nationally, food production in Japan and South Korea were similarly the largest direct water consumers accounting for, respectively, 54.7 billion $m^3$ (55%) and 1.7 billion $m^3$ (40%). The national food subsystem by land type consisted of the following: China's 118.3 million hectare (ha) (22.3%) arable land, 12.5 million ha (2.4%) permanent crops, and 400 million ha (75.4%) pasture; Japan's 4.3 million ha (93%) arable land, 324 thousand ha (7%) permanent crops, and 0 ha pasture; and South Korea's 1.6 million ha (87.4%) arable land, 181 thousand ha (9.6%) permanent crops, and 57 thousand ha (3%) pasture.

The energy-food linkage is the energy required for agriculture production; including fertilizer production, tillage, planting, weeding, pumping irrigation water, harvesting, transport, distribution, and storage as well as the energy used for inputs to these sectors (ADB, 2013; Chang *et al.*, 2016). Renewable forms of energy, in the form of biofuels, have become a major agricultural output in some countries; resulting in competition for land used for food production or energy production (Yillia, 2016). As noted earlier in the proportion of national electricity generation from different technologies, biofuel was not a significant national contributor and biofuel crops production was practically non-existent in East Asia in 2005. Direct energy consumption for agriculture production was relatively low in all East Asian countries. Energy consumption for agriculture production was 1.7 million TJ (3% of national energy consumption) in China, 251 thousand TJ (1%) in Japan, and 146 thousand TJ (2%) in South Korea.

In terms of environmental pressures, agriculture production was the largest consumer of direct scarce water for all three countries: 112.6 billion $m^3$ (80% of national scarce water consumption) in China, 7.9 billion $m^3$ (50%) in Japan, and 420 million $m^3$ (40%) in South Korea. Electricity generation was the second largest consumer of direct scarce water for Japan and the third largest for South Korea and China. Agriculture production was the largest emitter of direct GHG for all three East Asian countries. GHG emissions from agriculture production totaled 1 billion tons (t) (54% of national GHG emissions) in China, 1 billion t (54%) in Japan, and 36.3 million t (52%) in South Korea. Agriculture production was similarly the largest $SO_x$ emitter totaling 15.1 million t (51% of national $SO_x$ emissions) in China. In contrast, electricity generation in Japan and South Korea was responsible for the largest direct $SO_x$ emissions totaling, respectively, 789 thousand t (44%) and 601 thousand t (42%).

*ii. Direct and Indirect Virtual Water-Energy-Food and Environmental Flows*

**National Footprints:** Table 5.1 presents total direct and indirect (i.e. virtual flows) water-energy-food and environmental pressures by final household consumption. For example, Table 5.1 illustrates that the Secondary and Tertiary Sectors in China were responsible for consumption of, respectively, 80.2 million ha (19%) and 140 million ha

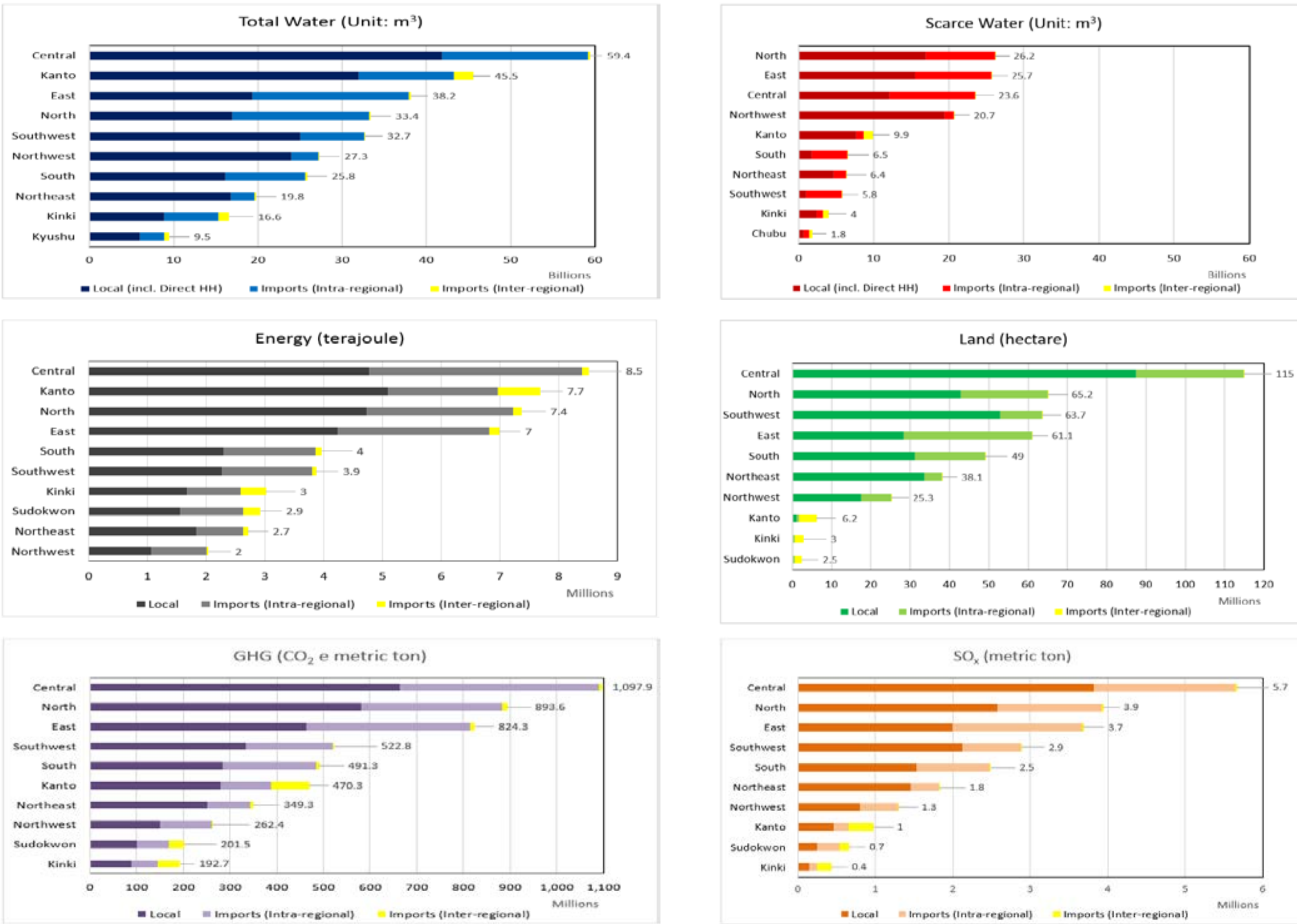
**Table 5.1 National Water-Energy-Food and Environmental Pressures Footprints**

| | People's Republic of China | | | | | | Japan | | | | | | Republic of Korea | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Resource: / unit: | Total Water (million m3) | Scarce Water (million m3) | Energy (terajoule) | Land (1,000 hectare) | GHG (CO2 e 1,000 ton) | SOx (1,000 ton) | Total Water (million m3) | Scarce Water (million m3) | Energy (terajoule) | Land (1,000 hectare) | GHG (CO2 e 1,000 ton) | SOx (1,000 ton) | Total Water (million m3) | Scarce Water (million m3) | Energy (terajoule) | Land (1,000 hectare) | GHG (CO2 e 1,000 ton) | SOx (1,000 ton) |
| **Primary Sectors** | **88,644** | **44,715** | **1,777,938** | **197,288** | **545,702** | **5,957** | **19,171** | **3,056** | **172,838** | **2,064** | **21,107** | **27** | **742** | **213** | **98,034** | **943** | **14,176** | **171** |
| | *37%* | *39%* | *5%* | *47%* | *12%* | *27%* | *19%* | *16%* | *1%* | *13%* | *2%* | *1%* | *12%* | *10%* | *2%* | *18%* | *4%* | *13%* |
| **Secondary Sectors** | **44,096** | **21,287** | **13,379,503** | **80,240** | **1,469,185** | **6,212** | **38,040** | **7,796** | **7,678,311** | **8,590** | **469,268** | **1,153** | **2,222** | **928** | **2,432,232** | **2,711** | **158,933** | **570** |
| | *19%* | *19%* | *38%* | *19%* | *33%* | *29%* | *38%* | *40%* | *42%* | *56%* | *42%* | *48%* | *37%* | *46%* | *43%* | *51%* | *40%* | *43%* |
| **Tertiary Sectors** | **77,485** | **38,405** | **20,293,137** | **139,958** | **2,426,588** | **9,621** | **27,841** | **5,552** | **10,231,486** | **4,795** | **639,788** | **1,214** | **1,647** | **592** | **3,175,834** | **1,625** | **227,320** | **593** |
| | *33%* | *33%* | *57%* | *34%* | *55%* | *44%* | *28%* | *29%* | *57%* | *31%* | *57%* | *51%* | *27%* | *29%* | *56%* | *31%* | *57%* | *44%* |
| Household water | 26,387 | 10,494 | | | | | 15,880 | 2,850 | | | | | 1,446 | 304 | | | | |
| | *11%* | *9%* | | | | | *16%* | *15%* | | | | | *24%* | *15%* | | | | |
| **Total** | **236,612** | **114,901** | **35,450,578** | **417,486** | **4,441,475** | **21,790** | **100,933** | **19,254** | **18,082,635** | **15,450** | **1,130,163** | **2,394** | **6,057** | **2,037** | **5,706,100** | **5,279** | **400,429** | **1,333** |

(34%) of the national agriculture land footprint. Japan's Secondary and Tertiary Sectors, respectively, accounted for 8.6 million ha (56%) and 4.8 million ha (31%) of the national agriculture land footprint. South Korea's Secondary and Tertiary Sectors, respectively, accounted for 2.7 million ha (51%) and 1.6 million ha (31%) of the national agriculture land footprint. In other words, virtual flows of agricultural commodities and the environmental pressures associated with the consumption of the commodities are accounted for per sector and region of final household consumption. Accounting for the hidden inter-regional virtual trade flows and footprints of each East Asian country provides a unique perspective of the WEFN analysis. The largest consumer of water in China totaling 88.6 billion $m^3$ (37% of national water footprint) was for the production of household consumption of agricultural products. In contrast, Japan's and South Korea's household consumption for industrial products were the largest consumers of water totaling, respectively, 38 billion $m^3$ (38%) and 2.2 billion $m^3$ (37%). The energy footprint of the consumption of agricultural products was relatively low in all three East Asian countries totaling: China 1.8 million TJ (5% of national energy footprint), Japan 173 thousand TJ (1%), and South Korea 98 thousand TJ (2%). In terms of environmental pressures, China's consumption of primary products caused the largest impact on scarce water totaling 44.7 billion $m^3$ (39% of national scarce water footprint). Japan's and South Korea's consumption of industrial products caused the largest amount of scarce water consumption along the supply chain totaling, respectively, 7.8 billion $m^3$ (38%) and 928 million $m^3$ (46%). The GHG ($CO_2$, $CH_4$, and $N_2O$) and $SO_x$ emissions footprints were largest for the consumption of services for all East Asian country.

**Regional Footprints:** Figure 5.2 illustrates the top ten regions with the largest water-energy-food and environmental pressures footprints in East Asia. All seven of China's regions are in the top ten. Central is the largest water-energy- food consumer and environmental pressure generator. In terms of East Asia's (i.e. China, Japan, and South Korea) regional footprints, China's Central region consumption represented 59.4 billion $m^3$ (17%) of total water, 23.6 billion $m^3$ (17%) of scarce water, 8.5 1.1 billion t (18%) of GHG and 5.7 million t (22.2%) of $SO_x$. In terms of water stress and energy, as a very water stressed country China would be the most adversely million TJ (14%) of energy, and 115 million ha (26%) of agriculture land and emitted affected. In East Asia, the largest consuming regions of direct and indirect scarce water inputs for electricity consumption were China's very water stressed East (3.8 billion $m^3$), slightly water stressed Central (1.5 billion $m^3$), and extremely water stressed North(1 billion

**Figure 5.2 Top Ten Regional Water-Energy-Food and Environmental Pressures Footprints**

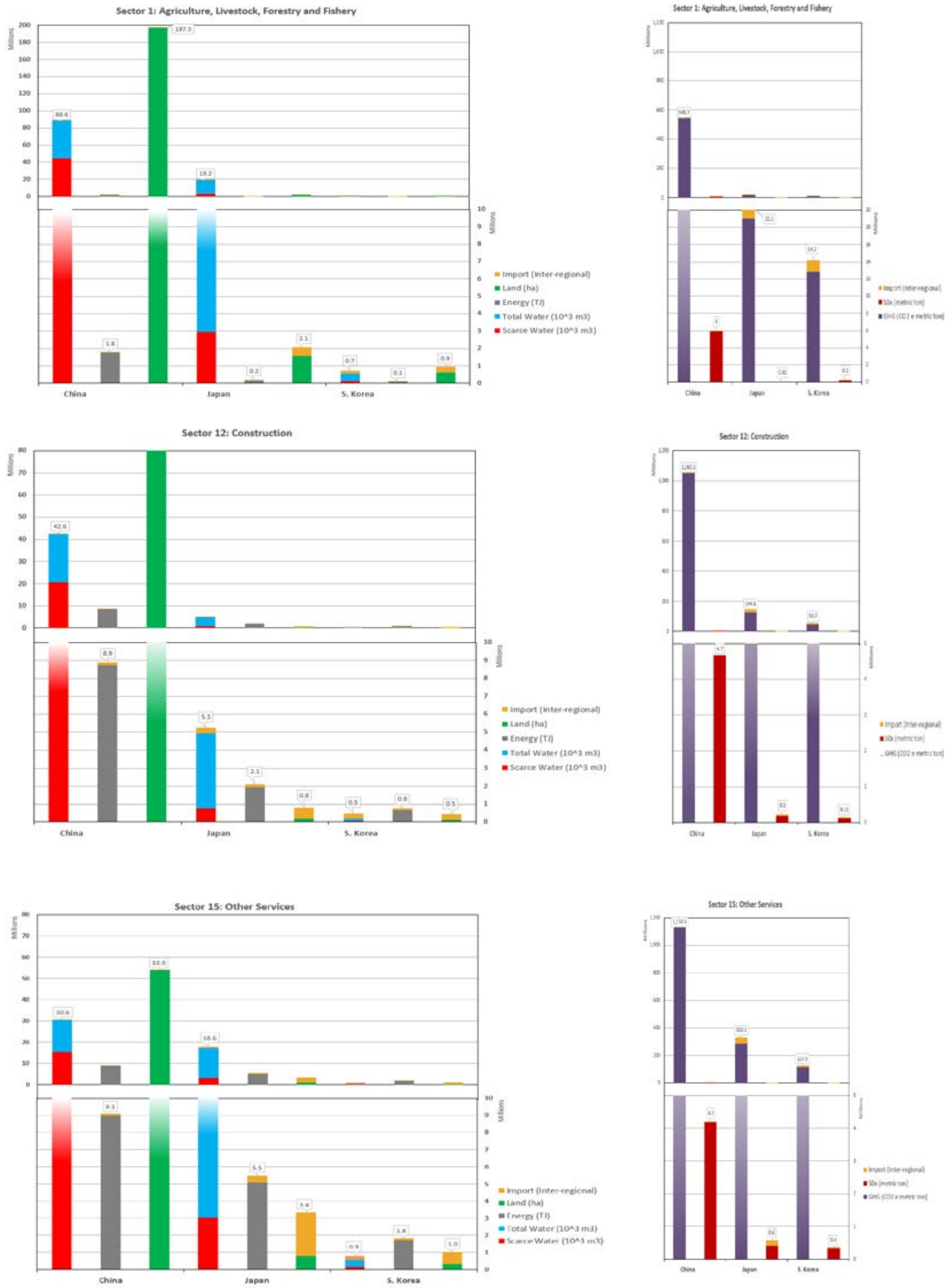



*The water footprint and scarce water footprint include, respectively, direct household water and household scarce water consumption. The region footprint is equal to local consumption (darker color) + imported intra-regional virtual flows (lighter color) + imported (yellow) inter-regional virtual flows.*

$m^3$) and Japan's slightly water stressed Kanto (1.8 billion $m^3$). The water-food linkage was dominated by China's regions. The top four water consuming regions for the production of agriculture products were Northwest (56.3 billion $m^3$), Central (53.5 billion $m^3$), East (33.2 billion $m^3$), and Southwest (25.2 billion $m^3$). The largest scarce water consuming regions for agricultural products were China's very water stressed Northwest 45.5 billion $m^3$), North (28 billion $m^3$), East (24.7 billion $m^3$), (and Central (17.9 billion $m^3$). The energy-food linkage demonstrates that the top four largest direct and indirect energy consumers for agricultural consumption were China's Central (631.5 thousand TJ), North (386.2 thousand TJ), East (357.2 thousand TJ), and Southwest (354.9 thousand TJ). Regionally, direct and indirect GHG and $SO_x$ emissions were dominated by China's regions. The North and Central contributed, respectively, 266.7 million t and 245.4 million t of GHG emissions from other services consumption. The Central and Southwest regions contributed, respectively, 1.7 million t and 1.1 million t of $SO_x$ emissions from agriculture consumption.

**Household Consumption of Commodities:** The panel charts in Figure 5.3 present the three top final household consumption of commodities in East Asia responsible for the largest energy-water-food and environmental pressure footprints. As noted in the section above, China's supply chain for agricultural products was the largest consumers of water and agriculture land footprints, followed by the construction sector with 42.6 million $m^3$ of water (18%), 80.2 million ha displaced agriculture land (19%), and 8.9 million TJ (25%) of energy. China's construction industries were also the second largest consumer of 20.8 million $m^3$ (18%) of scarce water and contributed 1 billion t (24%) GHG and 4.7 million t (21%) of $SO_x$ emissions. South Korea's and Japan's daily products (in Secondary Sectors) and other services (in Tertiary Sectors) were the top water-energy-food and scarce water consumers and the main contributor to GHG and $SO_x$ emissions. Supply chains for other services in Japan and South Korea were responsible for consumption of, respectively, 18.6 billion $m^3$ (18%) and 993 million

**Figure 5.3 Top Three Water-Energy-Food and Environmental Pressure Footprints by Final Consumption Sector**




*Note: The footprint is equal to local consumption + intra-regional +imported virtual flows. The panel charts highlight (yellow) virtual imports merely for illustrative purposes; i.e. virtual imports are not separate from the footprint.*

$m^3$ (16%) of water footprints, 3.4 million ha (22%) and 1 million ha (19%) of displaced agriculture land footprints, and 5.5 million TJ (30%) and 1.8 million TJ (32%) of energy footprints. Other services in both countries generated large environmental pressures responsible for 3.8 billion $m^3$ (20%) and 353 million $m^3$ (17%) consumption of scarce water footprints and contributed 333.1 million t (29%) and 127.9 million (32%) to the GHG footprints and 595 thousand t (25%) and 376 thousand t (28%) to the $SO_x$ footprints. Unlike China, agriculture products in Japan and South Korea was the second largest consumer of, respectively, 19.2 billion $m^3$ (19%) and 742 million $m^3$ (12%) of national water footprint and third largest consumer of 2.1 million ha (13%) and 943 thousand ha (18%) of national displaced agriculture land footprint. South Korea's agricultural commodities imports from China and Japan, respectively, constituted a significant proportion of its consumption footprints: 135.3 million $m^3$ and 29.4 million $m^3$ (or, combined, 22.2%) water footprint and 299.4 thousand ha and 1.8 thousand ha (or, combined, 32%) displaced agriculture land footprint of agriculture commodities consumption.

**Per Capita Final Household Consumption:** Table 5.2 provides the breakdown of per capita total water, scarce water, energy, and land consumption and GHG and $SO_x$ emissions by East Asian region. Table 5.2 illustrates that China's per capita consumption of water-energy-food and GHG and $SO_x$ gases emissions are relatively low in comparison to per capita consumption in Japan and South Korea. With the exception of land and scarce water, Japan's and South Korea's per capita consumption of energy and generation of GHG gases was several multiples greater than China's per capita consumption. Japan's per capita consumption of water was several multiples greater than both China's and South Korea's per capita consumption.

**Table 5.2 East Asian Countries Per Capita Consumption by Region**

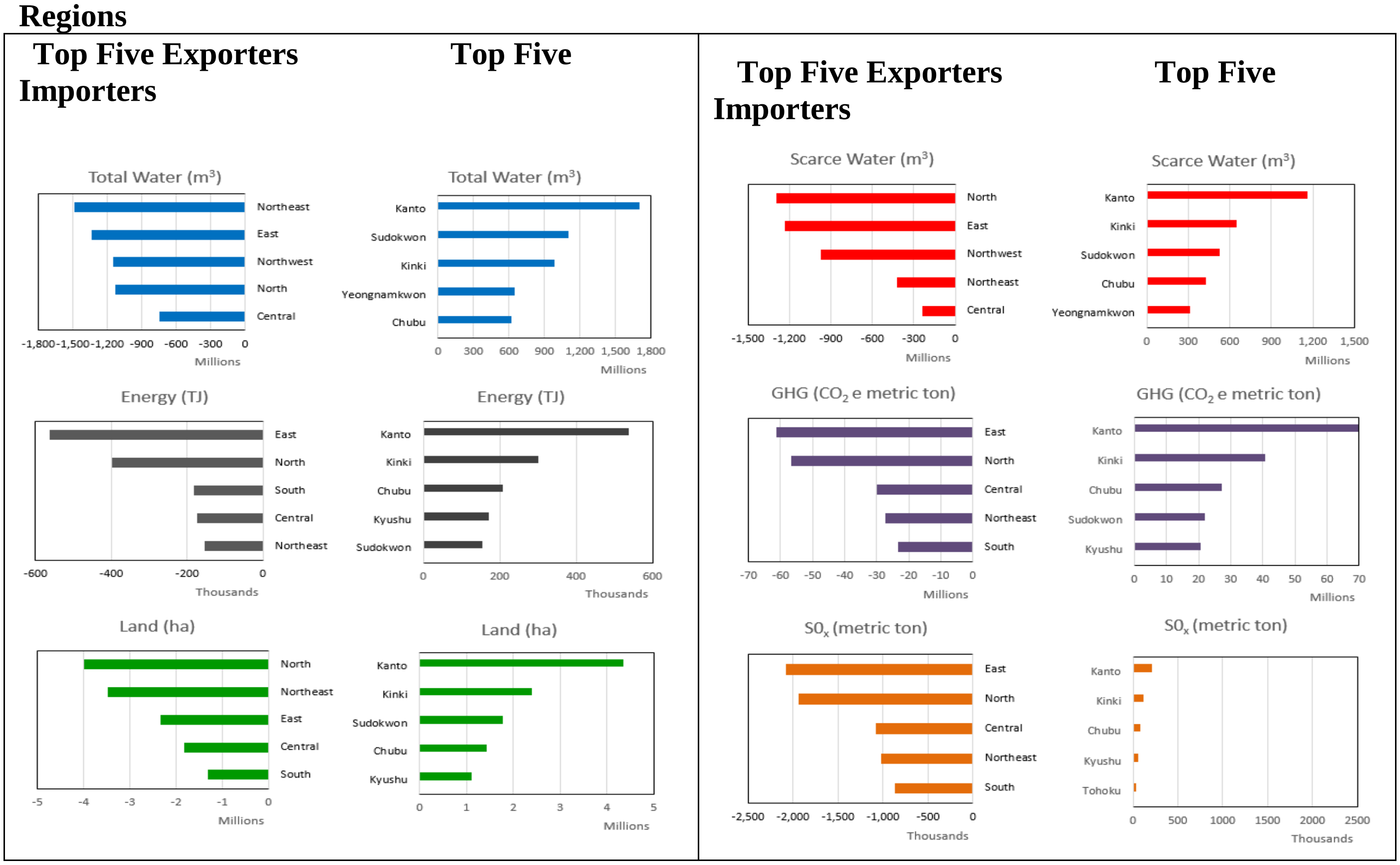
| Region | | Total Water | Scarce Water | Energy | Land | GHG Emission | $SO_x$ Emission |
|---|---|---|---|---|---|---|---|
| | | m3/capita | m3/capita | TJ/capita | ha/capita | $CO_2$ e metric ton/capita | metric ton/capita |
| China | Northeast | 184 | 59 | 0.03 | 0.35 | 3.25 | 0.02 |
| | North | 179 | 140 | 0.04 | 0.35 | 4.78 | 0.02 |
| | East | 270 | 182 | 0.05 | 0.43 | 5.82 | 0.03 |
| | South | 191 | 48 | 0.03 | 0.36 | 3.62 | 0.02 |
| | Central | 169 | 67 | 0.02 | 0.33 | 3.12 | 0.02 |
| | Northwest | 230 | 175 | 0.02 | 0.21 | 2.21 | 0.01 |
| | Southwest | 136 | 24 | 0.02 | 0.26 | 2.17 | 0.01 |
| Japan | Hokkaido | 924 | 80 | 0.14 | 0.14 | 9.15 | 0.02 |
| | Tohoku | 622 | 65 | 0.12 | 0.07 | 7.35 | 0.01 |
| | Kanto | 897 | 195 | 0.15 | 0.12 | 9.26 | 0.02 |
| | Chubu | 666 | 134 | 0.13 | 0.14 | 8.68 | 0.02 |
| | Kinki | 763 | 183 | 0.14 | 0.14 | 8.87 | 0.02 |
| | Chugoku | 677 | 92 | 0.14 | 0.09 | 8.68 | 0.02 |
| | Shikoku | 702 | 117 | 0.13 | 0.10 | 8.47 | 0.02 |
| | Kyushu | 710 | 88 | 0.13 | 0.12 | 8.58 | 0.02 |
| | Okinawa | 785 | 86 | 0.17 | 0.11 | 8.65 | 0.02 |
| S. Korea | Sudokwon | 99 | 39 | 0.13 | 0.11 | 8.85 | 0.03 |
| | Jungbukwon | 194 | 55 | 0.12 | 0.11 | 8.77 | 0.03 |
| | Yeongnamkwon | 134 | 40 | 0.11 | 0.12 | 7.96 | 0.03 |
| | Honamkwon | 162 | 52 | 0.11 | 0.11 | 7.73 | 0.03 |

*iii. Virtual Trade Flows Water-Energy-Food and Environmental Pressures*

**Regional Net Virtual Trade Flows:** Figure 5.4 presents the net virtual trade flow (*net flow* = *export* – *import*) of the top five net exporting and top five net importing regions of virtual water-energy-food and environmental pressures flows between regions. With the exception of the Southwest's scarce water (6 million $m^3$ net import), China's seven regions were all net virtual exporters of water-energy-food and burdened with the associated environmental pressures of production and trade.

Figure 5.4 Top Five Net Exporting Regions shows that the Northeast (1.5 billion $m^3$ total water), North (1.3 billion $m^3$ scarce water and 4 million ha land), and East (563 thousand TJ energy, 61.3 million t GHG, and 2.1 million t $SO_x$) were the largest net virtual exporters in East Asia. China's Northeast and North are significant agricultural and industrial production regions and the East region possesses a high concentration of industries and energy generation capacity. Figure 5.4 Top Five Net Importing Regions shows that Japan's Kanto is the largest net importer of 1.7 billion $m^3$ total water, 1.2

**Figure 5.4 Top Five Net Import/Export Virtual Water-Energy-Land and Environmental Pressures Regions**



billion $m^3$ scarce water, 539 thousand TJ energy, and 4.4 million ha agriculture land and outsourcing 69.7 million t GHG and 207.3 thousand t $SO_x$. With the exception of Okinawa's scarce water (152 million $m^3$ net export), Japan's nine regions were all net virtual importers of water-energy-food and generated environmental pressures in other East Asian TJ and 23.5 thousand TJ) net export, South Korea's four regions were all net virtual importers of water-energy-food and generated GHG emissions in other regions. All four of South Korea's regions were net exporters of $SO_x$ emissions.

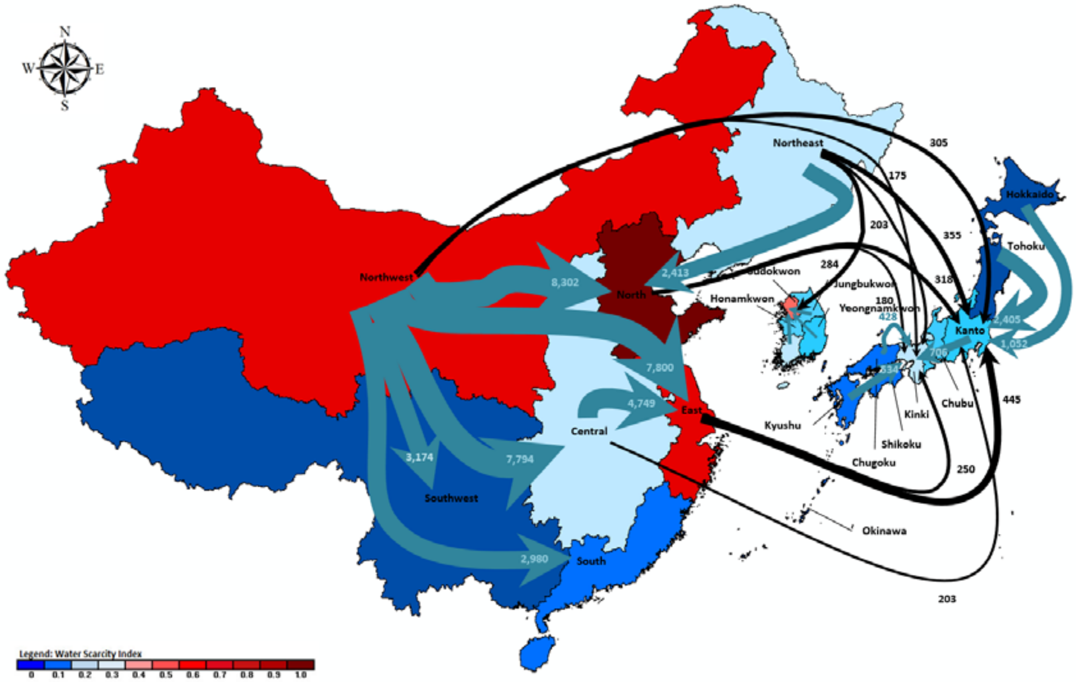
*iv. Net Intra-regional and Inter-regional Virtual Flows*

Figure 5.5a-f provides greater insight into the origins and pattern of intra-regional (i.e. within national boundaries) and transnational inter-regional (i.e. outside of national boundaries) virtual export flows of water-energy-food and environmental pressures (scarce water and GHG and $SO_x$ emissions) by region in East Asia. Figure 5.5a-b ranks the degree of water scarcity for all regions in China, Japan, and South Korea in terms of the Water Stress Index (WSI) (Pfister *et al.*, 2009). A WSI of 0.5 is the threshold between moderate and severe water stress. According to Figure 5.5a-b, Japan's regions range from water abundant to slightly water stressed, China's regions range from water abundant to extremely water stressed, and South Korea's regions are only slightly water stressed (Sudokwon is moderately water stressed). In terms of intra-regional virtual water flows: China's highly water stressed Northwest was a significant provider of both total water and scarce water to the extremely water stressed North, water stressed East, slightly water stressed Central, and water abundant Southwest and South; Japan's slightly water stressed Kanto was a recipient of virtual water from water abundant Hokkaido and Tohoku; and, moderately water stressed Sudokwon received virtual water from the slightly water stressed other three South Korean regions. In terms of transnational inter-regional virtual water flows, the top ten virtual flows all originated from China's slightly water stressed Northeast and very water stressed East and Northwest to Japan's slightly water stressed Kanto and Kinki and South Korea's moderately water stressed Sudokwon.

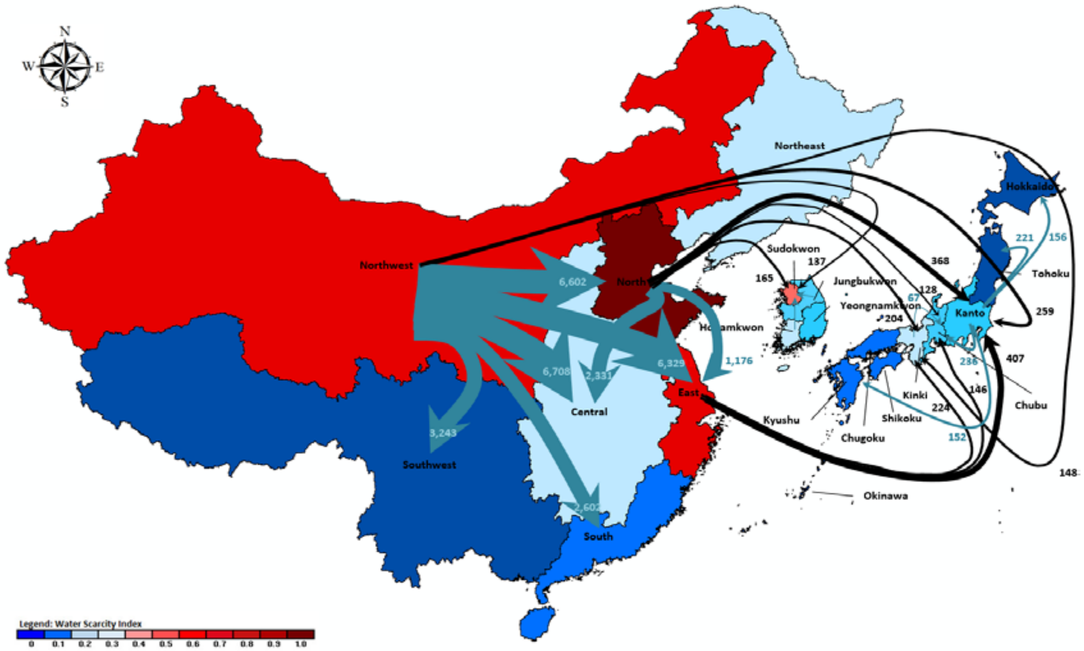
Figure 5.5c-f illustrates the intra-regional and transnational inter-regional virtual flows for energy and land and the offloading of GHG and $SO_x$ air pollutants. Figure 5.5c-f indicates regions which were net virtual exporters (dark blue) and net virtual importers (light blue). In terms of intra-regional virtual flows, China's Northeast, Northwest, and Central regions were burdened with environmental pressures and were significant exporters of virtual energy and land to the North and East regions. Similarly, Japan's Kanto and South Korea's Sudokwon regions were net virtual importers of intra-regional energy and land and were responsible for offloading environmental pressures. Transnational inter-regional virtual flows of energy and land demonstrate that China was a net virtual exporter to Japan and South Korea. China's North and East regions constitute seven of the top ten virtual energy export flows. Major recipients of China's virtual energy flows were Japan's Kanto, Kinki, and Chubu. China's Northeast, North, and East regions were virtual land exporters to Japan's Kanto and Kinki and South Korea's Sudokwon. Similarly, China bore the burden of environmental degradation from transnational inter-regional trade and the export of commodities to Japan and South Korea. China's regions incurred the largest amount of virtual GHG and $SO_x$ emissions in the North and East embodied in its trade of products and services to Japan and South Korea. Japan's Kanto and Kinki and South Korea's Sudokwon regions were

**Figure 5.5 East Asia Virtual Water-Energy-Food and Environmental Pressure (Scarce Water, $CO_2$, and non- $CO_2$) Flows by Region**

**a. Net Virtual Water Flows and Water Scarcity by Region (million cubic meters ($10^6$ $m^3$))**

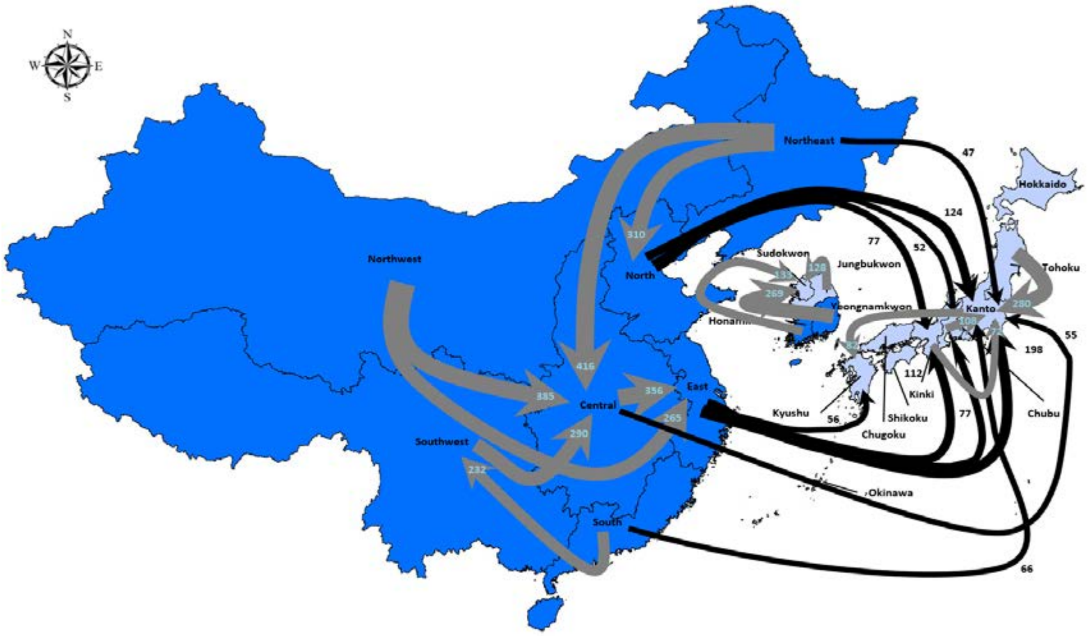



**b. Net Virtual Scarce Water Flows and Water Scarcity by Region (million cubic meters ($10^6$ $m^3$))**

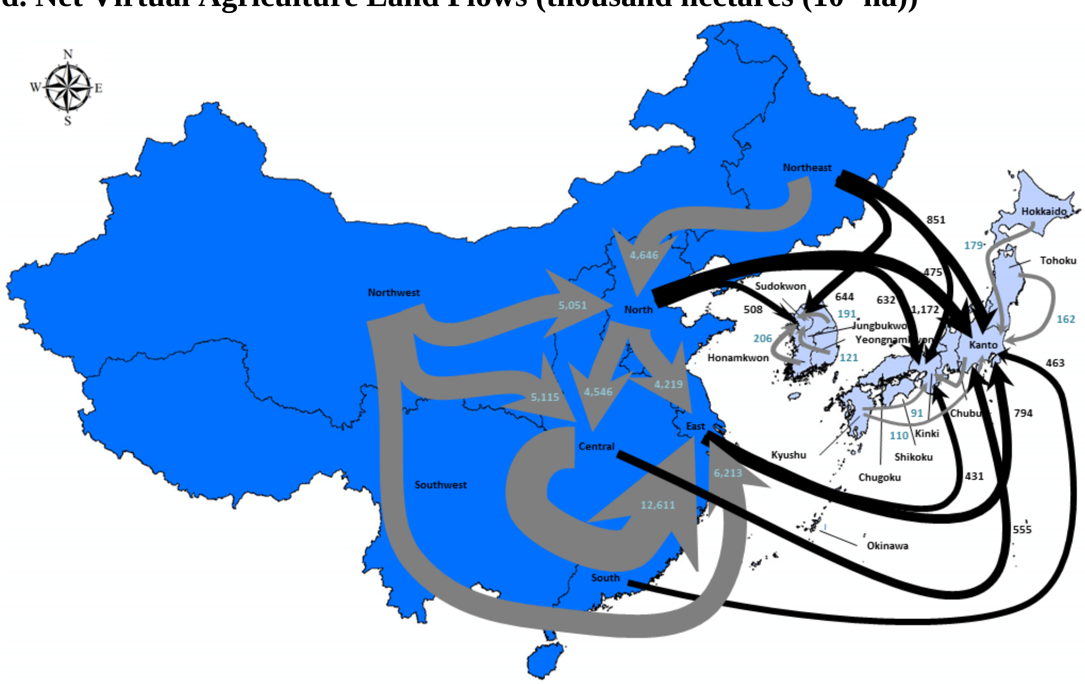



*Arrows are proportionate to the size (unit: million cubic meters) of the net flows (net flows = export – import) of virtual water trade: top seven China intra-regional, top five Japan intra-regional, top three South Korea intra-regional, and the top ten transnational inter-regional export destinations by region in East Asia. Figure 5.5a-b illustrates the level of water abundance or water stress by region based on Pfister et al. (2009) Water Scarcity Index (WSI); dark blue indicates water abundance, light blue slight water stress, pink moderate water stress, red high water stress, and dark red severe water stress.*

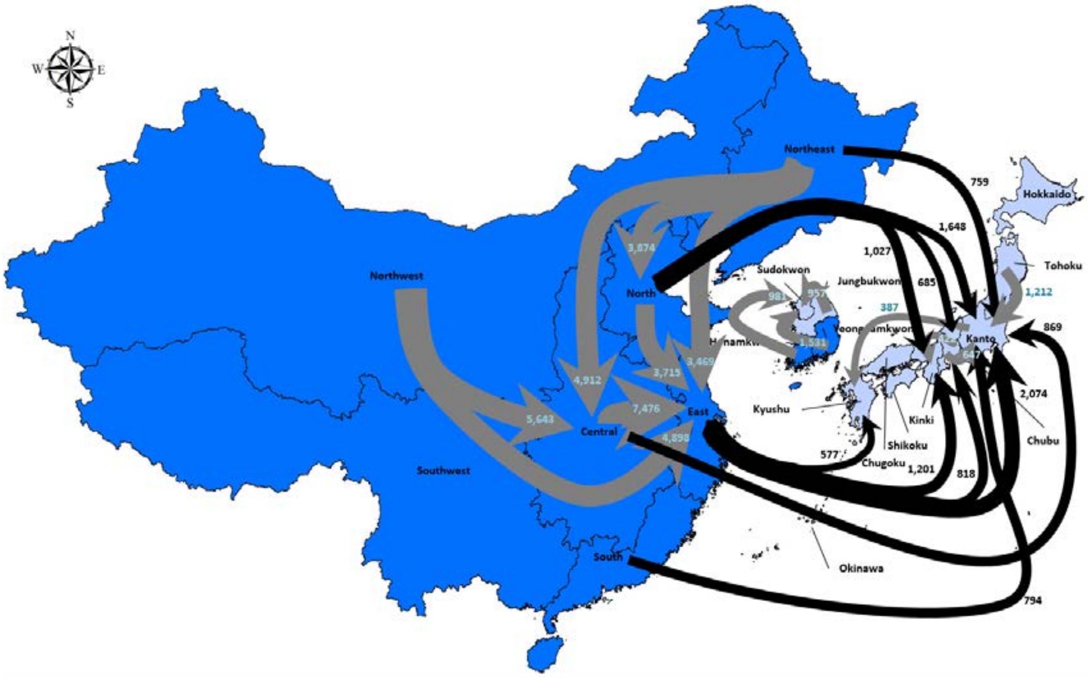
c. Net Virtual Energy Flows (petajoule ($10^{15}$ joule))



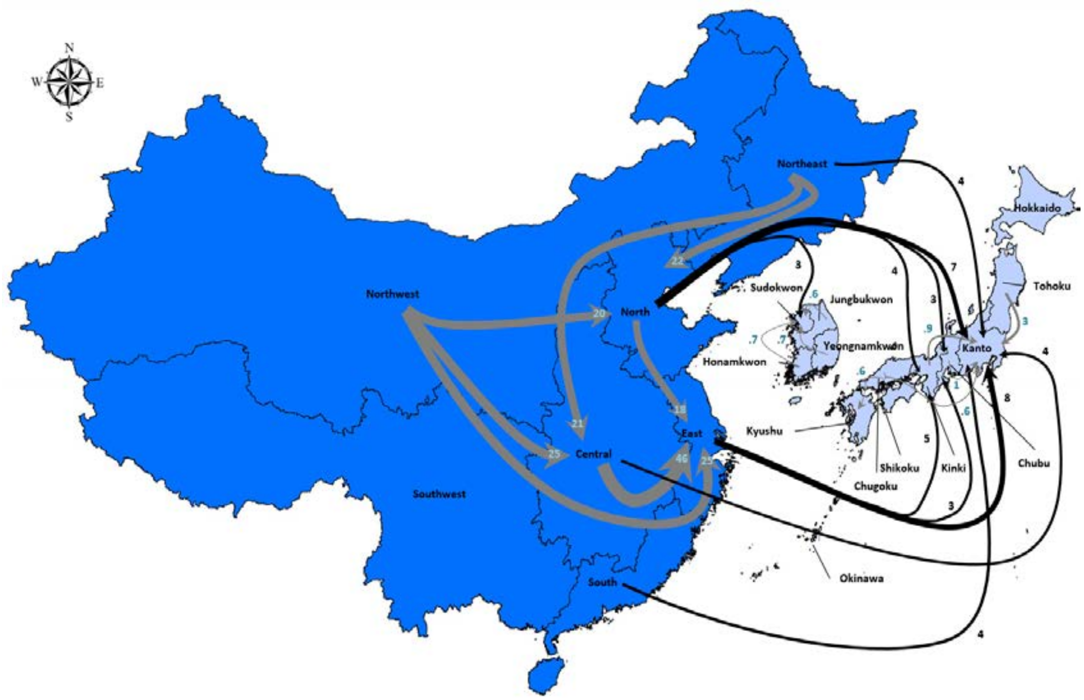

d. Net Virtual Agriculture Land Flows (thousand hectares ($10^3$ ha))



**e. Net Virtual Green House Gases Flows (ten thousand metric ton ($10^4$ t))**




**f. Net Virtual $SO_x$ Flows (ten thousand metric ton ($10^4$ t))**




*Arrows are proportionate to the size of the net flow (net flow = export – import) of virtual trade: top seven China intra-regional, top five Japan intra-regional, top three South Korea intra-regional, and the top ten transnational inter-regional export destinations by region in East Asia. In Figure 5.5c-f, dark blue indicates net virtual exporter and light blue net virtual importer region. Figure 5.5c-f shows both the largest intra-regional and transnational inter-regional net virtual flows embodied in trade: energy (unit: petajoule or one quadrillion joule), land (unit: thousand hectare), and GHG (unit: ten thousand metric ton) and $SO_x$ (unit: ten thousand metric ton) air pollutants.*

the major beneficiaries of this virtual environmental offloading.

## V. Conclusion

Globalization increases the interconnectedness of people, places, and the consumption of water-energy-food. Trade connects consumption of resources, production, and the exchange of products and services while at the same time distances impacts on foreign ecosystems. In economic value, China possessed a considerable trade deficit with South Korea and a small trade surplus with Japan. However, the results of this paper show that China's current national export oriented economic growth strategy – in the context of the hidden virtual flows of water, energy, and food (agriculture land) and environmental pressures – is not sustainable. In terms of water-energy-food, China was a substantial virtual net water-energy-food exporter to both Japan and South Korea. Overall, via inter-regional trade, China bore the burden of environmental pressures associated with the production of exports for the benefit of both Japan and South Korea. Competing national priorities and global drivers have a strong influence on the water-energy-food resources that requires consideration of withdrawal, environmental degradation, and resource scarcity. The nexus approach is, therefore, crucial in identifying entry points in a defined economy to identify and manage tradeoffs between the three subsystems and across various spatial scales.

The WEFN analysis reveals national economic and environmental priorities of each country in the East Asia region. China's significant water-energy-food investment and policy of maintaining 95% self-sufficiency in grain production signifies the strategic importance of its agriculture sector. China's prioritization of economic growth and trade in low value added sectors 'wearing apparel and textile products', 'products for daily use', 'household electrical appliances', and 'manufactured products' consumes a significant quantity of water-energy-food within its territory to satisfy consumers' demands in Japan and South Korea. For example, Japan's import from China accounted for 74% water, 79% energy, and 100% displaced agriculture land of household consumption for clothing and apparel commodities. Similarly, South Korea's imports from China accounted for 82% water, 36% energy, and 98% displaced agriculture land of household consumption for clothing and apparel commodities. China's national priorities surrounding water, energy, and food must necessarily balance between competing demands for national production and trade to support economic growth, maintain political stability, support livelihoods, and address increasing public awareness and concern over environmental quality (Liu and Mu, 2016). However, increasing competing demands for limited resources has resulted in tension between agricultural self-sufficiency and the requirements for water and energy supply for the industrializing economy.

Trade can be an important mechanism for overcoming a country's resource bottlenecks of water, energy, and food. South Korea's and Japan's national priorities place the agriculture sector at a lower priority and emphasize the manufacturing and services sectors. Japan's and South Korea's post-industrial economies (i.e. services and trade-based) are relatively uncoupled from domestic resource constraints. National energy and food security are interwoven with trade and foreign policy; e.g., Japan and South Korea are the world's fourth and fifth largest importers of crude oil and second and seventh largest importers of natural gas (World Factbook, 2016). Via inter-regional trade with Japan and China, South Korea imported and consumed 2.4 billion $m^3$ of virtual water embodied in products and services; significantly contributing to South Korea's total national water footprint of 6.1 billion $m^3$. Trade is an important mechanism for overcoming resource bottlenecks, but regional specialization is not necessarily mutually beneficial. The production, consumption, and trade of virtual water, energy, and food have negative environmental implications. Japan and South Korea externalize environmental impacts by importing low value added and pollution intensive commodities produced in China. In 2005, Japan and South Korea externalized virtual environmental pressures totaling 4.4 billion $m^3$ scarce water and 270.3 million t GHG and 1.1 million t $SO_x$ emissions by the consumption of China's exported goods and services.

WEFN interactions take place within the context of global drivers, increasing population and economic growth, international and regional trade, demographic shifts and urbanization, and increasing per capita prosperity with corresponding changes in lifestyle patterns and dietary demands. These drivers impact demand for energy and food production and use of limited water resources. East Asia, particularly China, is increasingly an urban society placing greater stress on water, energy, and food needs (ADB, 2013). China possesses over 20% of the world's population, but less than 7% of global freshwater resources. China is one of the most water stressed countries in the world. Water consumption is surging in China, particularly in the urban and industrial sectors. Annually, almost half of China's 650 largest cities suffer from water shortage. China suffers an estimated 40 billion $m^3$ annual water shortfall; urban water shortage of 5-6 billion $m^3$ and irrigation shortfall of 35 billion $m^3$ per year (Kahrl and Roland-Holst, 2008; Hofstedt, 2010). China is the world's largest energy consumer; as water availability is decreasing, water demand for electricity generation is increasing. China is the largest producer and consumer of agricultural products in the world. In 2005, China ranked number one in the production and consumption of paddy rice, cotton, wheat, coarse grains, corn, pork, chicken (broiler), walnuts, peaches and nectarines, plums, apricots, pears, grapes, and apples (USDA 2006a-c, 2008a-b, 2009). As the middle class grows in China, their dietary and lifestyle patterns change (e.g. increase in meat and luxury products consumption), consuming more water. China's annual per capita water requirement for food consumption increased from 255 $m^3$ in 1961 to 860 $m^3$ in 2003 (Chang *et al.*, 2016). China's large urbanization (more than 100 cities have at least one million inhabitants) are also placing increased demands on water and electricity. The prioritization of water for energy generation or industrial use over water for agricultural irrigation is increasingly common (Cai, 2008; Biba, 2016). According to FAO, China's total water withdrawal in 2005 was an estimated 554.1 $km^3$; comprised of 65% (358 $km^3$) for irrigation, 12% (67.5 $km^3$) for municipal use, and 23% (128.6 $km^3$) for industry. In comparison, China's total water withdrawal in 1993 was 525.5 $km^3$; of which, 77% (407.7 $km^3$) was for irrigation, 5% (25.2 $km^3$) for municipal use, and 18% (92.6 $km^3$) for industrial use (AQUASTAT, 2016).

With the continuing growth of China's economy and level of urbanization, China will require more resources to meet its growing domestic consumption, let alone sustain its national export strategy. Incorporating water scarcity into water consumption analysis permits a better understanding of the sectors causing water scarcity, the geographical distribution of regions suffering from water scarcity, and the impact of trade flows on both water-abundant and water-scarce regions. China's substantial intra-regional virtual water flows from water scarce regions to other water scarce or water abundant regions does not mitigate the problem of local water shortage; it shifts the problem and increases the ecological inequality between China’s regions. China’s overall national level water problem remains the same. Beyond the limitation on the availability of freshwater for direct household consumption within regions, there may be restrictions from water scarcity on food production and energy development. Similarly, limited energy availability (or high energy costs) may constrain the ability to provide adequately clean water and sanitation services to population centers or produce food. These interlinkages make it increasingly crucial to account, quantify, and comprehend the cross-sectoral impacts and trade-offs in regional, national, and supra-national economies and economic priorities. A government’s prioritization of economic growth and trade policies can result in water being diverted to industry and urban areas (over food production), and farm land appropriated for urban development. China’s major challenge will be efficiently managing and prioritizing its precious water-energy-land resources for domestic needs or export driven economic growth.

# Chapter 6: Hydro-economic MRIO Analysis of the Haihe River Basin's Total Water Footprint and Water Stress

## I. Introduction

Our local analysis achieves Objective 3. This chapter investigates the inter-regional trade of the Haihe River Basin as a hydro-economic unit (i.e. relatively homogeneous in both economic and hydrological attributes) and the redistribution of freshwater resources and environmental impacts within China. The Haihe River Basin faces acute water scarcity. We quantify the total and scarce water consumption, footprint, and flows embodied in inter-regional trade in the Basin and examine to what extent the Basin reaps benefits from water import flows and shifts water pressure to other water scarce regions. Several studies have quantified China's direct and indirect water consumption at the national, regional, provincial, city, and river basin level, but none have incorporated both the natural geographic of a river basin as the analytical unit and water scarcity as an environmental indicator.

***Objective 3:*** ***Tele-connected investigation of the consumption of freshwater and environmental impacts embodied in the Haihe River Basin catchment's trade within China. Assess and spatially characterize the mitigating or exacerbating effect of inter-regional trade of agriculture, industry, and energy final products on the Basin's water resources.***

## II. Background

China's economic achievement has been impressive since 1978. It now is the second largest economy in the world and has a middle class population of more than 300 million. But this momentum may not be sustained unless China is able to overcome one of the core challenges it faces: water scarcity. China's water challenge is rooted in the spatial mismatch between water and arable land availability. Currently, about 70% of arable land is located north of the Yangzi River where the availability of water resources is only about 17% of the national total. The sharpest contrast is in the Huanghe (Yellow River), Huaihe, and Haihe (3H) river basins, mainly located in the North China Plain. The 3H basins hosts one third of China's population and 40% of China's cultivated land, and accounts for 35% of the industrial output and 50% of the national grain production, but possesses only 7.6% of the nation's water resources (Liu *et al.*, 2013b). While the northward shift of the agricultural production "gravity center" in the last three decades is in line with the comparative advantage of the south in industrial production, this development is at the expense of ground water depletion, river discharge decline, and water pollution in the north. How to balance the trade-off between the relative short-run economic comparative advantage in the south and long-run sustainability of socioeconomic development in the north is an urgent strategic topic for China and also for the global community given China's high integration with the world economy.

Of the 3H river basins, the Haihe River Basin faces the acutest water scarcity issue. The Basin accounts for 3.4% of China's landmass and 10% of the population (approximately 134 million), but only 1.3% of China's total available water, resulting in an extremely low level of per capita water resources at 225 $m^3$ per year. More significantly, the Basin encompasses two megacities of significant political, industrial, cultural, and economic influence. Beijing is the capital of China and Tianjin is the economic center of north China. The Basin has grown rapidly economically and is now responsible for 15% of total industrial production and 10% of total agricultural output in China. Approximately 69% of cultivated land is under continuous wheat-maize farming and agriculture in the Bain depends heavily on irrigation (Moiwo *et al.,* 2011; Sha *et al.,* 2013; Liu *et al.*, 2012). This research purposely focuses on the Haihe River Basin. We quantify the total and scarce water consumption, footprint, and flows embedded in interregional trade in the Basin and examine to what extent the Basin reaps benefits from water flows embedded in interregional trade and to what extent the Basin shifts the water pressure to other water scarce regions. For this purpose, we establish an input-output table for the Basin and employ the multi-regional input-output (MRIO) model to calculate the water footprint (WF) through tracing the whole regional and national supply chain. To distinguish scarce water from neutral or abundant water, we incorporate the Water Stress Index (WSI) as an indicator of water scarcity (Pfister *et al.,* 2009) into the assessment of interregional virtual water trade flows of the Haihe River Basin.

*i. Study Area*

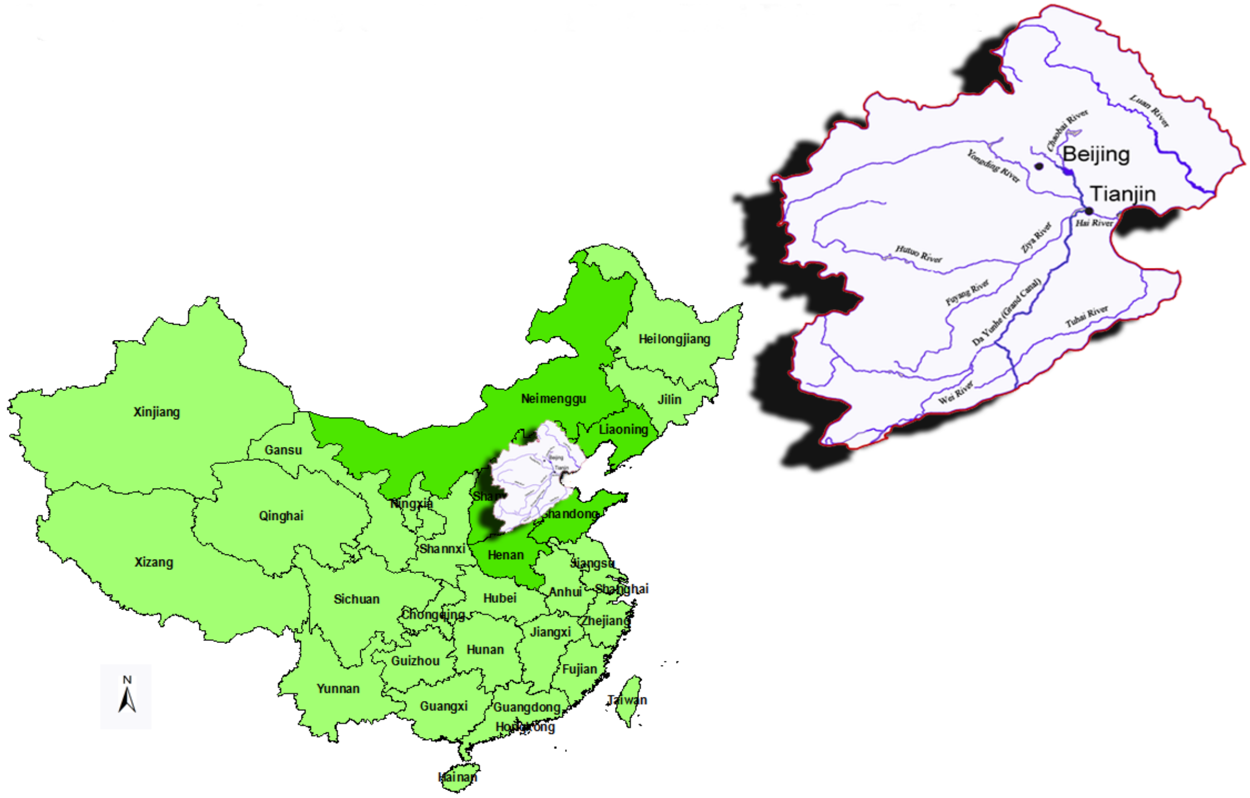
The Haihe River Basin is located between latitudes 35.01° N to 42.72° N and longitudes 111.95° E to 119.84° E (see Figure 6.1). Of the total land mass of 318,000 $km^2$, the area consisting of hills, mountains, and plateaus is 189,000 $km^2$, or 60%, in the northern and western parts, and the area consisting of plains is 129,000 $km^2$, or

40%, in the eastern and southern parts. The basin is bounded on the east by the Bohai Sea, the Yellow River in the south, the Yunzhong and Taiyue Mountains in the west, and the Mongolia Plateau in the north. The Haihe River has a total length of 1090 km and is composed of two large river systems: the Haihe River and the Luanhe River. The total basin drainage area is 263,631 $km^2$. Climate in the Haihe River Basin is subject to the continental monsoon regime. River flow is dependent on precipitation with over 80% falling during the summer months, 10-18% falling in spring and autumn, and 2% falling in winter. Average annual precipitation is 536-548mm.The basin has an estimated total amount of renewable water of 42.2 billion $m^3$; composed of 28.8 billion $m^3$ surface water and groundwater the remainder. Land surface elevation varies greatly between above 2000m in the mountain regions and below 5m in the littoral areas of the Bohai Sea (Liang *et al.*, 2011; AQUASTAT, 2013; Moiwo *et al.,* 2011).

Administratively speaking, the Haihe River Basin stretches across five provinces, one autonomous region, and two city-regions; including all of Hebei province, part of Liaoning province, the eastern part of Shanxi province, the northern part of Henan and Shandong provinces, part of the Inner Mongolia Autonomous Region, and Beijing and Tianjin. There is significant variation in the amount of land area of each province that falls within the Basin and in the level of industrial development, urbanization, and agricultural production; hence, water demand also varies greatly between provinces (World Bank and SEPA, 2003; Wang, X. *et al.,* 2009).

The Haihe River Basin has endured the exploitation of limited water resources and large-scale anthropogenic alteration and manipulation for over 1,500 years (Wei *et al.,*

**Figure 6.1 Provinces of China and the Haihe River Basin**




*Note: Location of Haihe River Basin. The dark green provinces represent the 8 administrative boundaries the Haihe River Basin crosses or encompasses – Beijing, Tianjin, Hebei, Inner Mongolia Autonomous Region, Liaoning, Shanxi, Henan, and Shandong. Original Source: Domagalski et al., 2001.*

2008). Beijing, as the capital of China for more than 700 years, and Tianjin, as the earliest industrial center of China and now the economic center of north China, are located in the Basin. This fact highlights the political, industrial, cultural, and economic significance of the Basin. The high population density of 370 persons per $km^2$ and low water resource endowment of 225 $m^3$ per person/year makes the Basin considerably water stressed.

## III. Data

In this paper, only ‘blue water’ is analyzed due to the data availability and its relevance to water use policy. Provincial water withdrawal at sector level was collected from *China Economic Census Yearbook 2008* (National Bureau of Statistics of China). This study analyzes water consumption which is defined as the water use that is not returned to the original water source after being withdrawn, thus consequently becomes unavailable for other users within a given time period (e.g. one year). Therefore, the water withdrawal can be much larger than water consumption. In this study, water consumption was estimated based on an observed ratio of water consumption to water withdrawal and for each sector. To estimate sectoral water consumption for each province, we multiply the sectoral water withdrawal of each province by the ratio of water withdrawal to water consumption in the agricultural, industrial, service and domestic sectors of that province, thereby assuming that the ratio of the specific sector is the same as for the aggregate sector. The ratios were estimated based on Water Resource Bulletins of different river basins (e.g. *Yellow River Water Resource Bulletin*) and provincial Water Resource Bulletins (e.g. *Liaoning Water Resource Bulletin*).

In this study, the 2007 China MRIO tables, which include 26 provinces and 4 city-regions, excluding Tibet and Taiwan, were used (Liu *et al.*, 2012). A more detailed description on the MRIO table can be found in Feng *et al.* (2013). Additional economic and population data was obtained from the *Beijing Statistical Yearbook 2009*, *Tianjin Statistical Yearbook 2009*, *Hebei Statistical Yearbook 2009*, and *Shanxi Statistical Yearbook 2009*.

This paper analyzed the Haihe River Basin as a hydro-economic unit (i.e. relatively homogeneous in both economic and hydrological attributes); similar to research conducted by Guan and Hubacek (2008). In order to analyze the water consumption and economic activities within the Basin, Geographical Information Systems (GIS) software was used to identify the county-level administrative boundaries that lie within the watershed basin system boundary. Utilizing the county-level economic or population data within each province, a proportional scaling method for each province based on total economic output contained inside the watershed basin system boundary was applied to the 2007 provincial IO tables. Where available, priority in proportional scaling of the IO data was based on the provincial economic data.

The Haihe River Basin hydro-economic unit incorporated proportionally scaled 2007 IO table data. The Basin includes 100% of Beijing, Tianjin, and Hebei based on all, or nearly all, of each province's GDP present within the basin. For other provinces, such as Shanxi, Henan, and Shandong, we disaggregate the IO tables into "inside basin" and "outside basin" IO tables based on the proportion of sectoral GDP or population within and outside of the basin for each province as follows: primary sector (42.7%), secondary sector (28.1%), and tertiary sector (24.5%) for Shanxi based on the province's corresponding GDP by primary, secondary, and tertiary industry in the Basin; proportional disaggregation of the IO data (22.4%) for Henan based on the proportion of the province's population within the Basin; and, proportional disaggregation of the IO data (25.5%) for Shandong based on the proportion of the province's population within the Basin. This analysis did not incorporate Liaoning or Inner Mongolia within the Haihe River Basin system due to their marginal economic contribution within the basin system boundary. The modified 2007 IO tables contained data for the Haihe River Basin, 22 provinces and 2 city-regions with original IO tables, 3 provinces (Shandong, Shanxi, and Henan) with disaggregated IO tables, and trade flows by sectors across these 28 regions. To distinguish the disaggregated IO tables from the original tables for Shandong, Shanxi, and Henan provinces, we labeled the disaggregated ones with ‘outside the basin’.

## IV. Results

### *i. Virtual Water and Total Water Footprint*

All results apply to the year 2007. Table 6.1 provides the local water consumption (including direct household water consumption), intra-basin virtual water flows, imported virtual water, and the total water footprint for all thirty sectors for the Haihe River Basin. For convenience, in Table 6.1, the thirty sectors have been aggregated – according to sector grouping – into only fifteen sectors. Local water consumption is the water from local water resources ultimately consumed by local final consumers; including direct household water consumption and the water consumed for the production of goods that are consumed by local final consumer. Intra-basin virtual water flow is the water embedded in services and goods traded within the basin. The imported virtual water is the water embedded in the imports of the basin. Therefore, local water consumption + intra-basin water flows + imported water is equal to the total water footprint (WF) of the basin. The total WF of the Haihe River Basin was 37.1 billion $m^3$ in 2007, of which local water consumption accounted for 9.1 billion $m^3$ or 24.5% (direct household water consumption alone was 2.4 billion $m^3$), intra-basin virtual water flows for 2.1 billion $m^3$ or 5.7%, and imported virtual water from other provinces for 25.9 billion $m^3$ or 69.7%. An interesting observation arrives here is that the Basin imported over two-thirds of its total water consumption in the form of virtual water from other provinces in China and the imports were dominated by the “processed food products” sector (9.1 billion $m^3$ or 35% of the total) and “agriculture” (5.6 billion $m^3$ or 21.5% of the total). If the importing flows were mainly from water rich region, interregional trade would be a very effective mechanism for mitigating the water stress issue of the Basin.

Table 6.1 also provides the WF by fifteen sectors plus direct household water consumption. The primary sectors (i.e. agricultural sectors) accounted for approximately 7.9 billion $m^3$ (21.2% of the total WF). The secondary sectors (i.e. the industrial and service sectors) accounted for approximately 18.2 billion $m^3$ (49% of the total WF). The tertiary sectors (i.e. services sectors) accounted for approximately 8.6 billion $m^3$ (23.3% of the total WF). The direct household water consumption accounted for approximately 2.4 billion $m^3$ (6.5% of the total WF). Clearly, the secondary sectors were the largest sectorial consumers of water and accounted for almost half of the total WF. This is to be expected as the Haihe River Basin contains several major population centers and is a regional industrial powerhouse. The Basin must import a huge amount of processed food products and textile products for its population and import various machinery and production elements to support its large industrial base.

Tables 6.2 and 6.3 illustrate that the total virtual water imported into the basin was 25.8 billion $m^3$ and total virtual water exported out of the basin was 14.6 billion $m^3$. It means that the Haihe River Basin is a net virtual water importer at a scale of 11.2 billion

**Table 6.1 Haihe River Basin – Total Water Footprint by Sector (unit: $10^6$ $m^3$)**

| Sectors | | Local | Intra-Basin | Imported | Total Footprint | Total WF by Sector (%) |
|---|---|---|---|---|---|---|
| ***Primary Sectors*** | | | | | | |
| Agriculture | | 1,818.4 | 483.3 | 5,578.5 | **7,880.2** | |
| | *SubTotal* | *1,818.4* | *483.3* | ***5,578.5*** | ***7,880.2*** | 21.2% |
| ***Secondary Sectors*** | | | | | | |
| Mining | | 0.1 | -22.2 | -128.8 | **-150.9** | |
| Processed food products | | 2,453.1 | 738.0 | 9,062.2 | **12,253.2** | |
| Textile and wearing apparel | | 266.8 | 129.8 | 2,844.3 | **3,241.0** | |
| Paper and wood products | | 142.1 | 8.0 | 165.4 | **315.5** | |
| Petroleum, chemicals and mineral products | | 12.9 | 34.9 | 288.2 | **336.0** | |
| Metal products | | -50.3 | -9.9 | -105.0 | **-165.1** | |
| Machinery and equipment | | 182.0 | 146.0 | 1,600.0 | **1,928.0** | |
| Other manufacturing | | 7.2 | 4.2 | 57.6 | **69.0** | |
| Electricity, gas and water | | 124.5 | 17.7 | 207.4 | **349.6** | |
| | *SubTotal* | *3,138.4* | *1,046.5* | *13,991.5* | ***18,176.4*** | 49.0% |
| ***Tertiary Sectors*** | | | | | | |
| Construction | | 619.8 | 272.2 | 2,466.7 | **3,358.7** | |
| Transportation services | | 66.0 | 6.6 | 68.1 | **140.7** | |
| Wholesale and retailing | | 70.0 | 18.0 | 261.1 | **349.1** | |
| Hotel and restaurant | | 182.7 | 80.2 | 1,035.6 | **1,298.6** | |
| Other services | | 793.4 | 218.4 | 2,473.1 | **3,484.9** | |
| | *SubTotal* | *1,731.9* | *595.4* | ***6,304.7*** | ***8,632.0*** | 23.3% |
| HH water consumption | | 2419.7 | | | **2,419.7** | 6.5% |
| **Total** | | **9,108.5** | **2,125.3** | **25,874.6** | **37,108.4** | **100.0%** |
| **Proportion of Total WF** | | **24.5%** | **5.7%** | **69.7%** | **100.0%** | |

$m^3$ or 30% of its total WF. This reinforces our observation that interregional trade might have significantly contributed to alleviating water stress in the Basin. Table 6.2 provides an account of the Basin's imported virtual water by province. Xinjiang stood out as the most important province which contributed to over a quarter – 7 billion $m^3$ – of the total imported virtual water to the Basin. The next largest exporter of virtual water to the Basin is Shandong (outside of the basin hydrological system), 2.3 billion

**Table 6.2 Imported Virtual Water into the Haihe River Basin (unit: $10^6$ $m^3$)**

| Provinces | Imported Virtual Water from… | Proportion of Imported Water |
|---|---|---|
| Shanxi *(outside basin)* | 768.0 | 3.0% |
| Inner Mongolia | 1,822.7 | 7.0% |
| Liaoning | 679.9 | 2.6% |
| Jilin | 648.8 | 2.5% |
| Heilongjiang | 2,034.2 | 7.9% |
| Shanghai | 165.2 | 0.6% |
| Jiangsu | 1,657.3 | 6.4% |
| Zhejiang | 444.4 | 1.7% |
| Anhui | 1,192.9 | 4.6% |
| Fujian | 397.9 | 1.5% |
| Jiangxi | 441.3 | 1.7% |
| Shandong *(outside basin)* | 2,325.9 | 9.0% |
| Henan *(outside basin)* | 1,537.0 | 5.9% |
| Hubei | 344.3 | 1.3% |
| Hunan | 588.8 | 2.3% |
| Guangdong | 694.2 | 2.7% |
| Guangxi | 1,015.0 | 3.9% |
| Hainan | 42.2 | 0.2% |
| Chongqing | 150.8 | 0.6% |
| Sichuan | 573.1 | 2.2% |
| Guizhou | 174.2 | 0.7% |
| Yunnan | 262.4 | 1.0% |
| Shaanxi | 379.6 | 1.5% |
| Gansu | 272.2 | 1.1% |
| Qinghai | 28.6 | 0.1% |
| Ningxia | 177.6 | 0.7% |
| Xinjiang | 7,056.1 | 27.3% |
| **Total** | **25,874.6** | **100.0%** |

**Table 6.3 Exported Virtual Water from the Haihe River Basin (unit: $10^6$ $m^3$)**

| Provinces | Exported Virtual Water to… | Proportion of Exported Water |
|---|---|---|
| Shanxi *(outside basin)* | 925.0 | 6.3% |
| Inner Mongolia | 189.8 | 1.3% |
| Liaoning | 406.3 | 2.8% |
| Jilin | 590.4 | 4.0% |
| Heilongjiang | 402.7 | 2.8% |
| Shanghai | 1,484.5 | 10.1% |
| Jiangsu | 1,024.0 | 7.0% |
| Zhejiang | 1,032.0 | 7.1% |
| Anhui | 502.0 | 3.4% |
| Fujian | 393.9 | 2.7% |
| Jiangxi | 243.2 | 1.7% |
| Shandong *(outside basin)* | 2,775.0 | 19.0% |
| Henan *(outside basin)* | 1,405.7 | 9.6% |
| Hubei | 380.9 | 2.6% |
| Hunan | 255.9 | 1.7% |
| Guangdong | 773.6 | 5.3% |
| Guangxi | 206.4 | 1.4% |
| Hainan | 18.7 | 0.1% |
| Chongqing | 174.2 | 1.2% |
| Sichuan | 272.0 | 1.9% |
| Guizhou | 140.9 | 1.0% |
| Yunnan | 175.3 | 1.2% |
| Shaanxi | 402.8 | 2.8% |
| Gansu | 136.5 | 0.9% |
| Qinghai | 45.2 | 0.3% |
| Ningxia | 60.0 | 0.4% |
| Xinjiang | 215.8 | 1.5% |
| **Total** | **14,632.7** | **100.0%** |

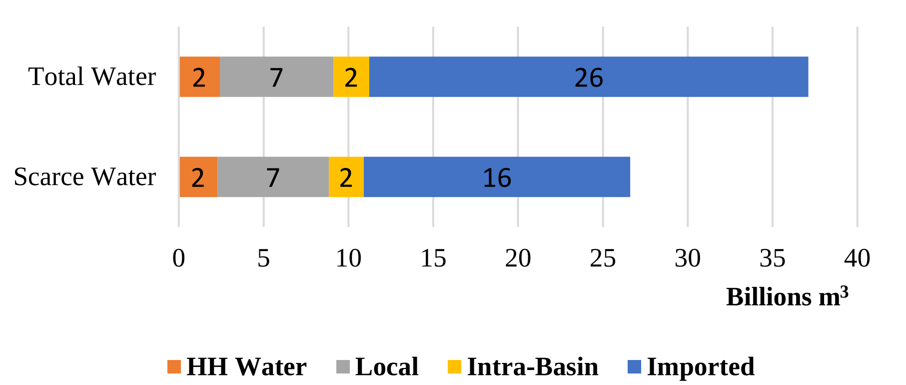
$m^3$ (or 9% of the Haihe River Basin's total imported virtual water). The Haihe River Basin is also a significant exporter of virtual water. Table 6.3 illustrates that the top three receivers of virtual water from the Basin are Shandong (outside the basin hydrological system), Shanghai and Henan (outside the basin hydrological system).

Tables 6.2 and 6.3 suggest that, overall, the net imports of virtual water were a substantial component in meeting the Haihe River Basin's final water consumption needs.

*ii. Total Virtual Water and Scarce Virtual Water*

Figure 6.2 provides the total WF and the scarce water footprint (SWF) of the Haihe River Basin including the direct household water consumption, local water consumption, intra-basin water consumption, and imported virtual water. Of the total 37.1 billion $m^3$ WF, 72% (or 26.7 billion $m^3$) was composed of scarce water. Furthermore, of the total 11.2 billion $m^3$ internal water consumption within the basin's boundaries (direct household + local + intra-basin), 11 billion $m^3$ or 98 percent was scarce water. The Haihe River Basin is an extremely water stressed hydrological

**Figure 6.2 Haihe River Basin Total Water and Scarce Water Footprint**

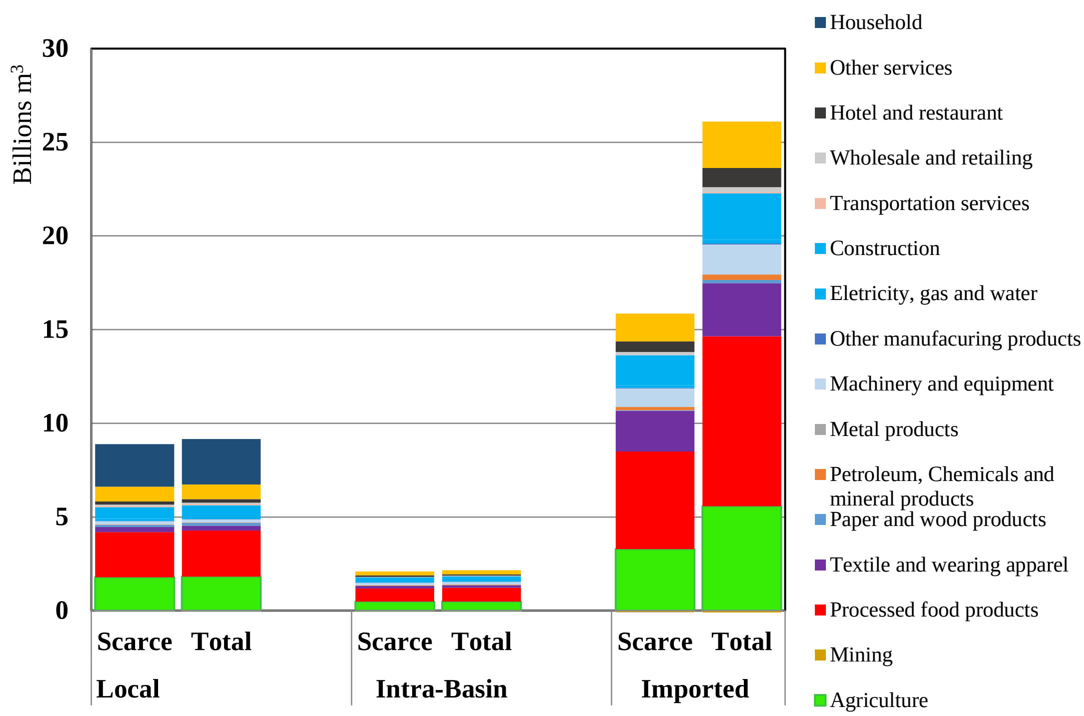



*Note: Direct household water consumption (a component of local water consumption) is presented separately in the Figure 6.2 for illustrative purposes.*

system. It is also worth highlighting that of the virtual water imported totaling 25.9 billion $m^3$, approximately 61% (or 15.7 billion $m^3$) was virtual scarce water. It means that a significant quantity of imported water into the water stressed Haihe River Basin is from other water stressed provinces and water basins.

Figure 6.3 provides another perspective of the total WF and the SWF by sector of the Haihe River Basin. Please note that in Figure 6.3 the direct household water consumption is combined with local water consumption. Figure 6.3 illustrates that the dominate water consuming sector for both total and scarce water are processed food

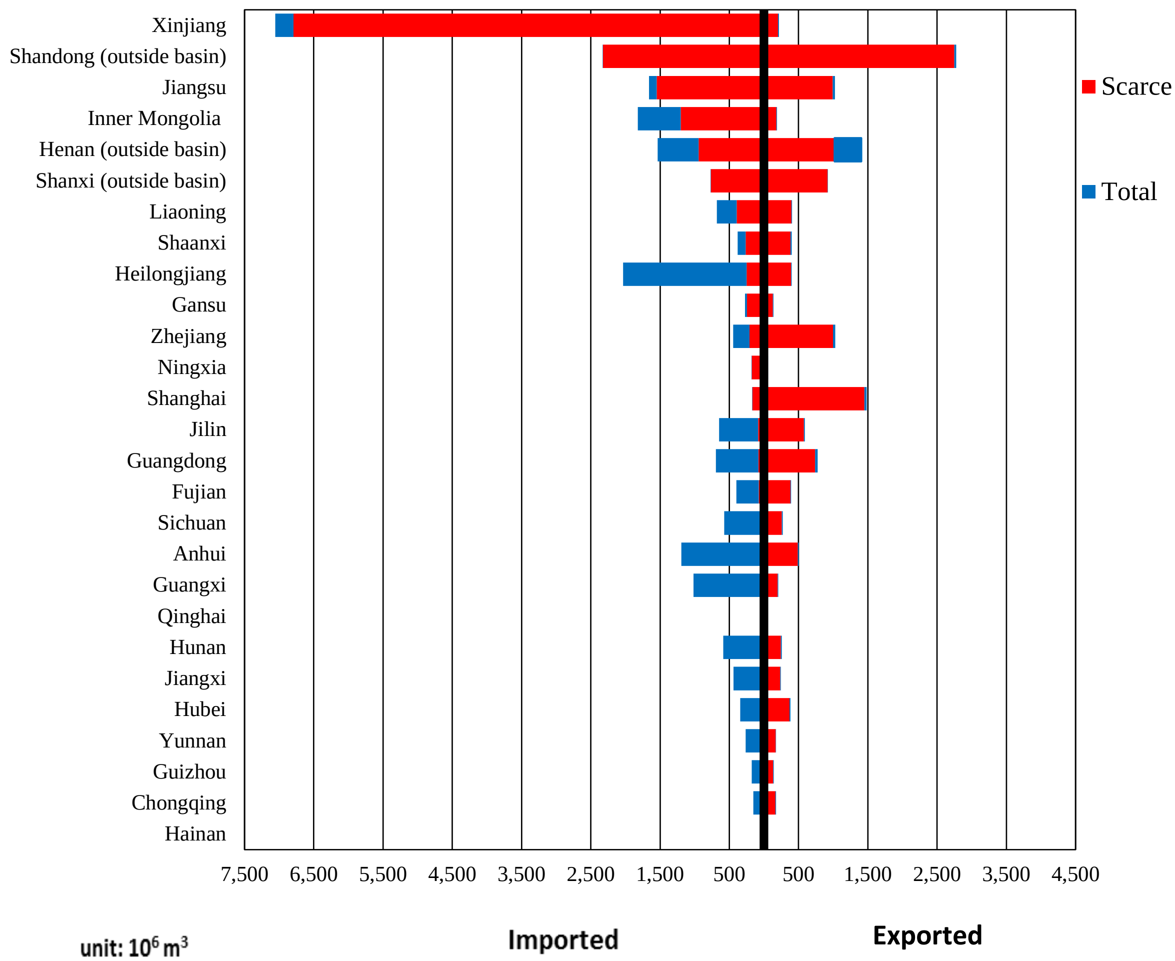
**Figure 6.3 Haihe River Basin Total Water and Scarce Water Footprint by Industry**



products and agriculture. A comparison of the internal hydrological basin's water consumption (local + intra-basin) between WF and SWF categories demonstrate that nearly all of the internal water consumption consists of scarce water for each industry. Figure 6.3 also illustrates that a significant amount of virtual water imported into the basin is composed of virtual scarce water. The two largest sectors of imported virtual water into the Haihe River Basin, processed food products and agriculture, were composed of 57.5% (5.2 billion $m^3$ of a total of 9.1 billion $m^3$) of scarce water and 59% (3.3 billion $m^3$ of a total of 5.6 billion $m^3$) of scarce water, respectively.

Figure 6.4 presents the total virtual water and virtual scarce water imported into and exported out of the Haihe River Basin by individual provinces. While virtual water imports from Heilongjiang, Jilin and the other 13 provinces below Jilin in the figure were highly desirable for addressing the water stress issue at both the basin and national levels, the figure reveals that the provinces at the top of the rank in the table in terms of constituting the largest sources of virtual water imported into the Haihe River Basin were, in fact, exporting significant quantities of virtual scarce water. Xinjiang is by far the largest net source of virtual water imported into the Haihe River Basin. Of the total 7.1 billion $m^3$ virtual water imported from Xinjiang, 6.8 billion $m^3$ (or 96.3%) consists of virtual scarce water. In contrast, Xinjiang's imports of virtual water from the Haihe River Basin was on a much smaller scale. Although Shandong (outside the basin system) was the number two virtual water exporters to the Basin at a scale of 2.3 billion $m^3$, the Basin's exports of virtual water to Shandong was much larger and thus resulting in a net export of about 0.5 billion $m^3$ to Shandong.

**Figure 6.4 Haihe River Basin's Total Water and Scarce Water Imports and Exports by Province**




Given the high level of water scarcity in the Haihe River Basin, it is not a surprise to see from Figure 6.4 that almost all of the Basin's exported virtual water consists of virtual scarce water. The Basin exported 14.6 billion $m^3$ of virtual water in 2007, of which 13.9 billion $m^3$ or 94.9% was virtual scarce water. In a very real sense, essentially all of the Hai River Basin's local (98.1%), intra-basin (96.9%), and exported virtual water (94.9%) was scarce water (see Figures 6.2, 6.3, and 6.4, respectively). Shandong (outside of the hydrological basin system) and Shanghai were the top two recipients of virtual water from the Basin and nearly all of it consisted of virtual scarce water. Figure 6.4 also illustrates that several water abundant provinces (particularly in the water-abundant South) are net importers of virtual water from the Haihe River Basin, including Zhejiang, Guangdong, and Anhui.

Table 6.4 lists the ranking of China's provinces in terms of the Water Stress Index (WSI). Figures 6.5 and 6.6 establish critical linkages between the Haihe River Basin and groups of similar WSI provinces in terms of total virtual water and scarce water resources embodied in intermediate or final products either imported into the Haihe River Basin or exported out of the Basin in 2007. Note in Figures 6.5 and 6.6 that the virtual water flow arrows (both total virtual water and virtual scarce water) represent cumulative water flows to groupings of similar WSI provinces. The two figures distinguish both the total virtual water and virtual scarce water trade linkages between the Haihe River Basin and other provinces in relation to the WSI for each of the provinces.

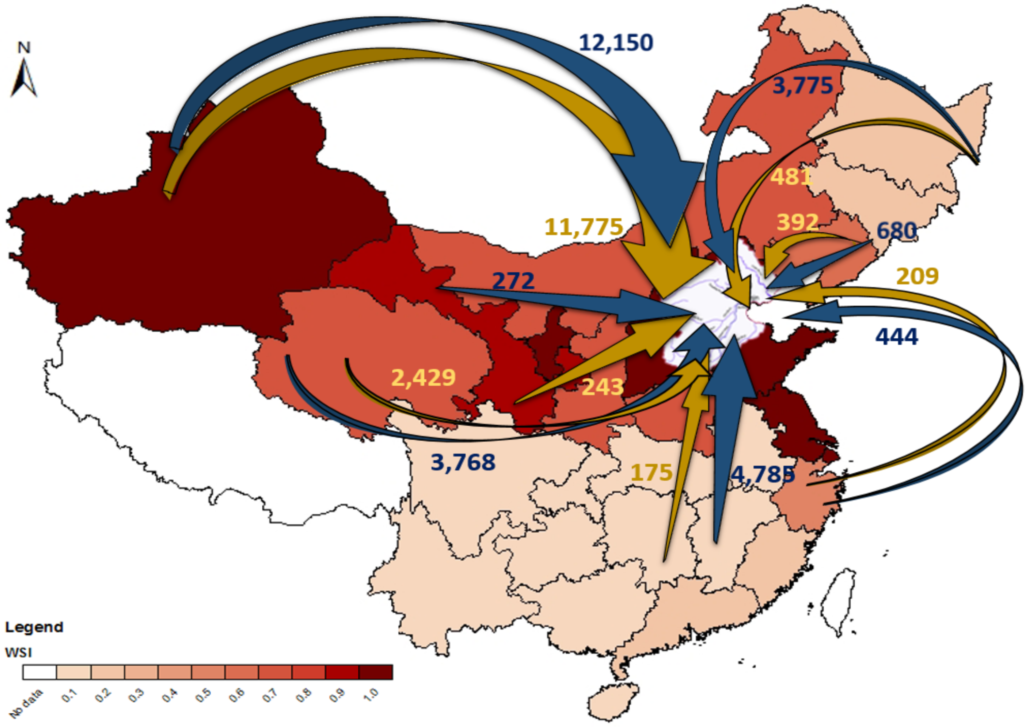
**Table 6.4 WSI China's Provinces**

| Province | WSI | Province | WSI |
|---|---|---|---|
| Tibet | 0.00 | Henan (inside) | 0.61 |
| Chongqing | 0.02 | Henan (outside) | 0.61 |
| Guizhou | 0.02 | Inner Mongolia | 0.66 |
| Yunnan | 0.03 | Qinghai | 0.67 |
| Hubei | 0.03 | Shaanxi | 0.69 |
| Guangxi | 0.03 | Gansu | 0.89 |
| Hainan | 0.03 | Jiangsu | 0.94 |
| Hunan | 0.03 | Xinjiang | 0.96 |
| Anhui | 0.03 | Ningxia | 0.99 |
| Jiangxi | 0.03 | Beijing | 1.00 |
| Sichuan | 0.10 | Tianjin | 1.00 |
| Guangdong | 0.11 | Hebei | 1.00 |
| Heilongjiang | 0.12 | Shanxi (inside) | 1.00 |
| Jilin | 0.13 | Shanxi (outside) | 1.00 |
| Fujian | 0.18 | Shanghai | 1.00 |
| Zhejiang | 0.47 | Shandong (inside) | 1.00 |
| Liaoning | 0.58 | Shandong (outside) | 1.00 |

Chongqing, Guizhou, Yunnan, Hubei, Guangxi, Hainan, Hunan, Anhui, Jiangxi, and Sichuan are grouped together based on their WSI range between0.01-0.10. The Haihe River Basin imported virtual water from these provinces totaling of 4,785 million $m^3$ (consisting of 175 million $m^3$ scarce water) and exported 2,370 million $m^3$ (consisting of 2,278 million $m^3$ scarce water). This indicates a beneficial net import of 2,415 million $m^3$ virtual water from these water rich provinces. Guangdong, Heilongjiang, Jilin, and Fujian are grouped together based on their WSI range between 0.11-0.20. The Haihe River Basin imported virtual water from these provinces totaling 3,775 million $m^3$ (consisting of 481 million $m^3$ scarce water) and exported 2,161 million $m^3$ (consisting of 2,091 million $m^3$ scarce water), resulting in a favorable net import of 1,614 million $m^3$. Zhejiang is the only province within the WSI range between 0.41-0.50. The Haihe River Basin was a net exporter of both virtual water and scarce water to Zhejiang with a total import of 444 million $m^3$ (consisting of 209 million $m^3$ scarce water) from and a total export of 1,032 million $m^3$ (consisting of 996 million $m^3$ scarce water) to this province. Liaoning is the only province within the WSI range between 0.51-0.60. The Haihe River Basin imported virtual water from this province totaling 680 million $m^3$ (consisting of 392 million $m^3$ scarce water) and exported 406 million $m^3$ (consisting of 397 million $m^3$ scarce water), thus benefiting from a moderate net importer status.

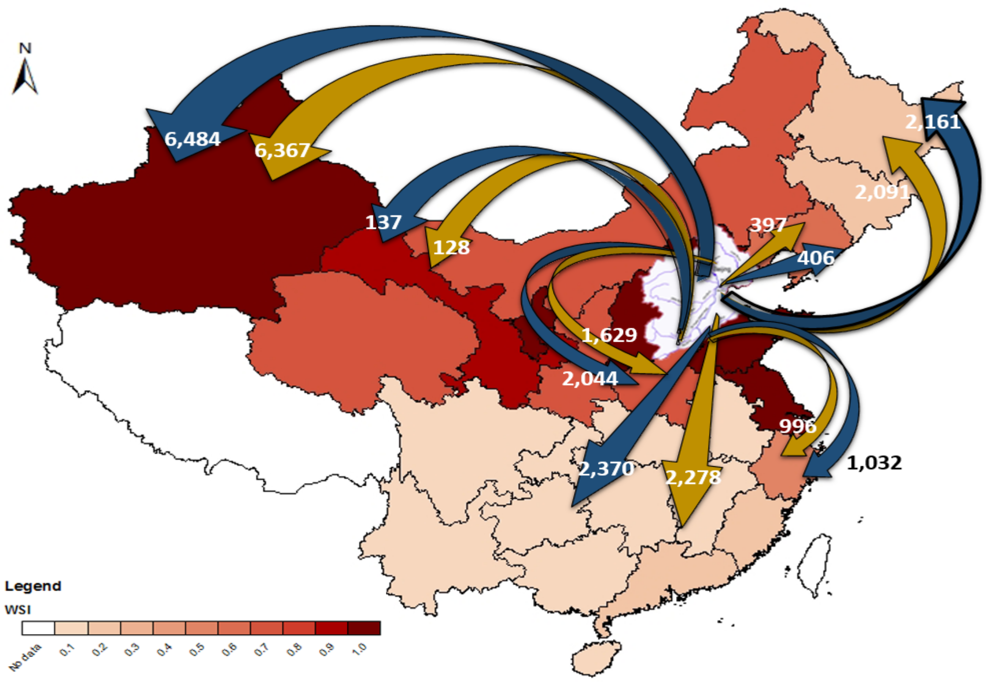
While being a net importer of virtual water with trade partners in water rich regions is highly desirable, keeping the same status with trade partners in similarly water-stressed regions would not be desirable from the perspective of China as a whole, because this simply transfer the stress to other water scarce regions. Figures 6.5 and 6.6

**Figure 6.5. Haihe River Basin Virtual Water and Virtual Scarce Water Imports**




*Blue arrows represent imported total virtual water ($10^6$ $m^3$) and yellow arrows represent the share of imported total virtual water that is scarce water ($10^6$ $m^3$) from the groupings of similar Water Stress Index provinces into the Hai River Basin.*

**Figure 6.6. Haihe River Basin Virtual Water and Virtual Scarce Water Exports**




*Blue arrows represent exported virtual total water ($10^6$ $m^3$) and yellow arrows represent the share of exported total virtual water that is scarce water ($10^6$ $m^3$) from the Hai River Basin to the groupings of similar Water Stress Index provinces.*

also reveal the latter concern. Henan (outside the hydrological basin system), Inner Mongolia, Qinghai, and Shaanxi are grouped together based on their WSI range between 0.61-0.70. The Haihe River Basin imported virtual water from these provinces totaling 3,768 million $m^3$ (consisting of 2,429 million $m^3$ scarce water) and exported 2,044 million $m^3$ (consisting of 1,629 million $m^3$ scarce water), leading to a net import of 1,724 million $m^3$. Gansu is the only province within the WSI range between 0.81-0.90. The Haihe River Basin imported virtual water from this province totaling 272 million $m^3$ (consisting of 243 million $m^3$ scarce water) and exported 137 million $m^3$ (consisting of 128 million $m^3$ scarce water), thus a net import of 135 million $m^3$. Jiangsu, Xinjiang, Ningxia, Shanxi (outside of the hydrological basin system), Shanghai, and Shandong (outside of the hydrological basin system) are grouped together based on their WSI range between 0.91-1.0. The Haihe River Basin imported virtual water from these provinces totaling 12,150 million $m^3$ (consisting of 11,776 million $m^3$ scarce water) and exported 6,484 million $m^3$ (consisting of 6,367 million $m^3$ scarce water), resulting in a net import at a large scale of 5,666 million $m^3$.

## V. Conclusion

Globally, water is becoming scarcer. The virtual water concept is an important tool in informing policy makers and in developing viable national policy options to mitigate spatial variability in water availability and demand. Ridoutt and Pfister (2010b) showed that 90% of water consumption is associated with the production of goods (i.e. virtual water) and not the direct water use by households. The Haihe River Basin in China was selected for this study due to its importance as a region of major agricultural production, center of political and cultural significance, and as a region suffering chronic water stress and water shortage while also enduring an increasing population, higher economic growth, and undergoing rapid urbanization. This case study of the Haihe River Basin employed the MRIO model to analyze the total water footprint (WF), total virtual water flows, and virtual scarce water flows of the basin as a hydro-economic unit. The economies of the five provinces, one autonomous region, and two city-regions that the Basin crosses or encompasses were proportionately scaled to accurately define the hydro-economic unit.

The Water Stress Index (WSI) method provides a consistent and accurate accounting of temporal and – combined with the MRIO model – spatial variability of water availability in a region or nation. As discussed in the Introduction, there is a lack of attention in existing literature to the transfer of 'scarce' water across scarce- or abundant-water regions/basins within a country. This paper addresses scarce water use in total water use by incorporating water scarcity as a factor in the Haihe River Basin's analysis. This paper also considered the impacts and pattern of trade between the Haihe River Basin and China's other provinces in the context of water scarcity using the WSI methodology. Assessing the scarce water associated with trade flows quantifies the amount of scarce water consumed via the inter-regional trade, thereby, identifying the trade flows that convey pressures on water resources from the Haihe River Basin to other regions of water scarcity.

The findings of this study reveal the water challenges faced by the Haihe River Basin. The results show that the total water footprint of the Haihe River Basin was 37.1 billion $m^3$ in the year 2007. The primary, secondary, and tertiary sectors and direct household water consumption consisted of approximately 7.9 billion $m^3$ (21.2%), 18.2

billion $m^3$ (49%), 8.6 billion $m^3$ (23.3%), and 2.4 billion $m^3$ (6.5%), respectively. The significant water consumption needs for the secondary sectors was to be expected as the Basin includes the major population and industrial centers Beijing, Tianjin, and Hebei. The ‘processed food products’ and ‘agriculture’ sectors alone accounted for 12.3 billion $m^3$ (33%) and 7.9 billion $m^3$ (21.2%) of the Basin’s total WF.

Our results show that including WSI significantly changes the analysis of inter-regional virtual water flows. Of the total WF, 72% (26.7 billion $m^3$ of the 37.1 billion $m^3$) was composed of scarce water. Furthermore, within its hydrological boundary (direct household + local + intra-basin) 98% of the Haihe River Basin’s water consumption was composed of scarce water. The Basin is an extremely water stressed hydrological system. Incorporating WSI scarcity weighting revealed that while about 39% of the total 25.9 billion $m^3$ virtual water imported into the basin was from water-rich regions, the other 61% was from similar water-scarce regions. Virtual water exported from the water-scarce Haihe River Basin was transferred to both water-abundant and water-scarce provinces. On the one hand, it is highly desirable for the Basin to import more virtual water from water rich regions. On the other hand, importing virtual scarce water from water stressed regions would not be desirable from the perspective of water management at the national level because the latter will lead to greater water stress in other water scarce regions. Therefore, it is important for policy makers to consider water scarcity in assessing virtual water flows and in the development of a virtual water trade strategy to mitigate local water scarcity. This study further adds legitimacy and importance to the virtual water research and the role of supply chains, indirect water, and scarce water flows analysis.

In a water constrained economy, the options to reduce total water and scarce water consumption include increasing supply, increasing water productivity, decreasing final demand, or changing the structure of production. China's government leaders acknowledge the water stressed plight in Northern China and, in 2002, approved the South North Water Transfer project (SNWT). When completed, the SNWT will greatly alleviate several of China's water scarcity-induced problems that have hindered economic development and rapid urbanization. However, Berkoff (2003) cautioned that the SNWT may merely continue to subsidize the low value agriculture and not be able to address the issue of water scarcity in Northern China.

As Lenzen *et al.* (2013) noted, a country's or region's relative water endowment is not the only factor that influences trade patterns. A country's or region's comparative advantage in production technology and opportunity costs relative to its trading partners must be taken into consideration as well. Consideration of virtual water flows is only one component of a larger water security strategy and policy for solving regional water scarcity. The virtual water concept combined with the WSI method is a practical and powerful tool to identify water-scarce regions and the virtual water flows to and from water-scarce and water-abundant regions. This study indicates that incorporating the WSI into virtual water analysis is critical in understanding the dynamics of inter-regional trade flows in terms of total virtual water and scarce water. Analysis of WF, virtual water flows, and scarce water is necessary in order to permit a holistic view of all water consuming sectors and to identify sensitive consumption sectors, centers of consumption, and regions of water scarcity to inform decision makers and inform policy to alleviate water shortage. In the Haihe River Basin, in order to implement a water security strategy based on the concept of virtual water flows, one recommended approach to ameliorate the Basin's water stress is to restructure its agricultural and industrial production and coordinate its inter-regional trade with outside provinces. Rapidly upgrading irrigation technology to raise water efficiency and reducing the production of water-intensive products in agriculture should receive the highest priority.

# Chapter 7: Conclusion

## I. Summary

The finite nature of natural resources, uneven distribution in space and time, and global trends in consumption are impacting resource availability. Natural resources are necessary inputs in production systems and, with commodities being traded across economic and ecosystem boundaries, natural resources are appropriated and exchanged via global supply chains. The overuse of resources can have severe consequences on ecosystems; further degrading quality and functioning. The rise and expansion of global supply chains, with ever-increasing exchanges of intermediate goods, deepens the complexity of assessing the negative environmental impacts of trade externalities and globalization. The substitution of domestic resource consumption through imported goods traded internationally causes socio-environmental impacts. The *tele-connections* concept provides a framework to explicitly analyze the spatial linkages between socio-economic and environmental interactions between human and natural systems over distances. This paper explores whether the consumption of natural resources traded through supply chain networks mitigate or exacerbate local resource scarcity. Applying the tele-connections concept, this research quantifies and tracks the hidden 'virtual' flows and national footprints of natural resources and environmental impacts across economic supply chains. Environmental indicators are incorporated in an across-scale approach to examine and describe the spatial linkages between local consumption and environmental impacts in a meaningful and quantitative.

The proper management of limited natural resources depends on the interlinkages of the global economic system and the preferences of consumers. In today's inter-connected world, countries may 'displace' or degrade natural resources in distant locations through imports to meet their own domestic demand for food and material consumption. The input-output technique is the appropriate model to analyze the inter-relationships between economy, resources, and the environment. Consumption is increasingly met by global supply chains. Evaluating virtual trade and footprints have become key approaches to understanding trends and how natural resources and environmental impacts are transferred among regions or countries. This research spatially identifies and traces the major trade routes conveying environmental pressures and impacts on local ecosystems on regions of production from distant centers of consumption. By articulating the linkages between production and consumption and environmental impacts, we take into account the social, economic, and ecological interdependence of societies. Furthermore, the vulnerability of a region to environmental impacts from production and harvesting activities depends on the region's natural resource endowments and ecosystem resilience. Incorporating environmental indicators enables our analysis to differentiate between vastly different degrees of resource availability across regions and to quantify the degree to which consumed resources are actually scarce.

In an interdependent world, it has become essential to adopt a coupled social-environmental across-scale approach to assess and examine the patterns of consumption and the environmental impacts of international trade. Our across-scale approach avoids the ecological fallacy pitfall by presenting a successive finer-scale analysis of the consumption of natural resources and associated environmental impacts through the global supply chain, a regional supply chain, and the inter-regional trade of a hydro-economic river basin catchment. This across-scale approach permits a more comprehensive examination that produces more spatially-explicit results and unveils the causal linkages between consumers' choices and their environmental impacts; particularly in countries with large spatial variability in natural resource endowments and environmental impacts from centers of production.

### *i. Research Objectives and Outcomes*

Objective 1 investigated the tele-connected consumption of freshwater and arable land resources and environmental impacts embodied in the global food trade. We examined and assessed the mitigating or exacerbating effect of participation in the global food trade on countries' finite water and land resources. The inclusion of the virtual trade in environmental impacts adds another perspective to the consumption, distribution, and degradation, in quality and quantity, of natural resources and ecosystems. Incorporating virtual trade flows into the analysis permits identifying the bearers of the environmental burden for agriculture exports as well as the regions benefiting and suffering from international trade in terms of natural resources depletion and ecosystem impact. Our analysis reveals how resource scarcity in a country or region can impact resource availability – via trade – in a foreign country. Counter-intuitively, our analysis shows that numerous water-scarce countries were net exporters of their virtual scarce resources to both water-abundant and similar water-scarce countries. Meanwhile, the trade in virtual cropland demonstrated a different pattern where land-abundant countries and regions were net virtual cropland exporters and land-scarce countries and regions were the beneficiaries. The exchange of embodied virtual resources and environmental impacts – relative to a country's natural resource endowments – provides additional insight into global consumption patterns and trends. Incorporating scarcity – land and water – significantly changes the analysis of countries' production and consumption of limited resources. Results from the hypothetical elimination of imports and exports of virtual land and virtual water embodied in agriculture products caused significant shifts in countries' and regions' land scarcity and water scarcity. In other words, a nation's participation in the international trade in agriculture products is a major driver of land and water depletion in some countries and a mechanism for supplementing limited land and water for other countries; stabilizing or, in some cases, fully ameliorating a country's resource scarcity in agriculture production via virtual imports.

Numerous publications have modelled the global food system. These publications typically focus on only one or two natural resource or environmental impact; e.g., P or N flows in cropland (Liu, J. *et al.*, 2010; Chen and Graedel, 2016), energy (Daccache *et al.*, 2014), agriculture land (Li and Di, 2013) water (Mekonnen and Hoekstra, 2010), excess P and N from fertilizers (Scherer and Pfister, 2015; Shibata *et al.*,2017), greenhouse gas (GHG) emissions (Vora *et al.*, 2017), scarcity in water (Berrittella *et al.*, 2007), and scarcity in arable land (Vivanco *et al.*, 2017). Our analysis adds to the research literature by incorporating both freshwater scarcity and arable land scarcity indicators, introduces a novel method for calculating global arable land scarcity, and quantifies the mitigating or exacerbating environmental effects of trade upon nations' land and water resources.

Objective 2 investigated the tele-connected consumption of water, energy, and food resources and environmental impacts embodied in the East Asia regional trade. We assessed and spatially characterized the impacts from regional trade on sub-national regions' resources and environment. A tele-connected WEFN approach provides a new perspective to the analysis of the interlinkages between water, energy, and food resource consumption. The inclusion of environmental impacts changes the WEFN dialogue to require consideration not only of resource withdrawal tradeoffs between the three subsystems, but also environmental degradation and resource scarcity issues. In economic value, China possesses a considerable trade deficit with South Korea and a small trade surplus with Japan. However, our results demonstrate that China's current national export oriented economic growth strategy – in the context of the hidden virtual flows of water, energy, and food (agriculture land) and environmental pressures – is not sustainable. In terms of water-energy-food, China was a substantial virtual net water-energy-food exporter to both Japan and South Korea; supplementing both countries' resource consumption. Overall, via transnational intra-regional trade, China bore the burden of environmental impacts associated with the production of exports for the benefit of both Japan and South Korea. Japan and South Korea externalized environmental impacts by importing low value added and pollution intensive commodities produced in China. In 2005, Japan and South Korea externalized net virtual environmental pressures totaling 4.4 billion $m^3$ scarce water and 270.3 million t GHG and 1.1 million t $SO_x$ emissions by the consumption of China's exported goods and services.

Recently, the WEFN approach has become an increasingly popular perspective among scholars. The vast majority of WEFN publications analyze only two of the three subsystems in a nexus relationship: water-food (Antonelli and Tamea, 2015; Vanham, 2016), food-energy (Karkacier and Goktolga, 2005; Abdelradi and Serra, 2015), and water-energy (Scott *et al.*, 2011; Vieira and Ghisi, 2016). Taking an integrated view of such interlinked issues is highly challenging given that nexus issues manifest themselves in different ways in the context of individual countries with differing resource and technology endowments, governance and development trajectories. Therefore, a 'successful' approach to resource management and sustainable development must be one that is capable of quantifying flows and inter-dependencies of water, energy, and food and environmental pressures. Our analysis adds to the research literature as the first tele-connected WEFN analysis across scale utilizing the East Asia region-specific TIIOT dataset permitting modeling of socio-economic and environmental inter-linkages at finer scale (i.e. sub-national, national, supra-national, and regional). Origins of water-energy-food resources consumption and environmental impacts are distinguished between domestic inter-regional trade and transnational intra-regional trade.

Objective 3 investigated the tele-connected consumption of freshwater and environmental impacts embodied in the Haihe River Basin catchment's trade within China. We assessed and spatially characterized the mitigating or exacerbating effect of inter-regional trade of agriculture, industry, and energy final products on the Basin's water resources. The Haihe River Basin in China was selected for this study due to its importance as a region of major agricultural production, center of political and cultural significance, and as a region suffering chronic water stress and water shortage while also enduring an increasing population, higher economic growth, and undergoing rapid urbanization. Our results show that incorporating water scarcity as an environmental indicator significantly changes the analysis of inter-regional virtual water flows. Of the total water footprint, 72% (26.7 billion $m^3$ of the 37.1 billion $m^3$) was composed of scarce water. Furthermore, within its hydrological boundary 98% of the Haihe River Basin's water consumption was composed of scarce water. Incorporating water scarcity weighting revealed that while about 39% of the total 25.9 billion $m^3$ virtual water imported into the basin was from water-rich regions, the other 61% was from similar water-scarce regions. Virtual water exported from the water-scarce Haihe River Basin was transferred to both water-abundant and water-scarce provinces.

Our study of China's Haihe River Basin is methodologically similar to earlier publications in the inter-regional river basin analysis approach. Guan and Hubacek (2007) was the first to evaluate the inter-regional trade structure and its effects on water consumption and pollution via virtual water flows by developing an extended regional IO model for eight hydro-economic regions in China. The focus of Feng *et al.* (2011b) (Yellow River) and Zhao *et al.* (2010) and Zhi *et al.* (2014) (Haihe River) were at the river basin catchment scale, but their studies analyzed virtual water flow only between the respective basin and the rest of China. Furthermore, all virtual flows are treated equally without distinguishing relative scarcity of the origin. Similar to our study, Feng *et al.* (2014a) incorporated water scarcity and ecosystem impact indicators to assess virtual scarce water flows and the associated ecosystem impacts. Nevertheless, their analytical units are administrative provinces rather than the natural geographic unit of the river basin. Our analysis adds to the research literature as the first tele-connected analysis of inter-regional virtual water and virtual scarce water trade flows between a hydrologic river basin catchment and provinces in China and advancing the technical application of defining the Haihe River Basin catchment as a hydro-economic unit to improve consumption and environmental impact accounting at finer scale.

## II. Research Insights

Trade has been promoted as the solution to overcoming resource bottlenecks. In a highly globalized world, trade can result in externalities that exacerbate resource scarcity and shift the burden of increasing environmental degradation to distant locations. The three individual studies presented in this dissertation each trace and quantify the unsustainable use of natural resources and associated environmental impacts from human production and consumption. As a whole, the three individual studies present an across scale approach to investigating the complex socio-economic and ecosystem inter-linkages in global supply chains. This research contributes to the efforts to address the issues of natural resource scarcity, management of natural resources, and the environmental degradation generated by human activities.

Environmental impact assessment and resource management requires consideration of the whole supply chain of natural resources and environmental impact required to make a product or deliver a service. Unsustainable use of natural resources requires the need to assess and understand the ecological impacts associated with consumption choices. However, current analysis still remains constrained by the highly aggregated country-to-country trade data and national production data; with the assumption that environmental impacts associated with production are homogenous within a country.

The research presented in this dissertation has shown that the increasingly complex global socio-economic and environmental interlinkages make it ever more crucial to account, quantify, and comprehend the cross-sectoral impacts within and between local, regional, national, and supra-national economies and global trade.

1. *Environmental Indicators* - Typically, the use of natural resources is consumed freely and without thought in the pursuit of economic activities and growth until it becomes limited or scarce. Natural resources are often unvalued or under-valued and rarely considered as factors of production. However, natural resources are primary inputs to all goods and services, directly or indirectly. This research adds to the literature by incorporating a consistent and accurate methodology to account for the utilization of natural resources (both directly and indirectly) in global supply chains via environmental scarcity indicators. The inclusion of environmental indicators significantly changes the analysis of virtual natural resource flows.
2. *Environmental Relevance* – Globally, the vulnerability of a region to environmental pressures and environmental impacts from human activities depends on the region's natural resource endowments and ecosystem resilience. Countries endowed with abundant natural resources face a different set of challenges and priorities from countries with limited or unbalanced resources. In today's inter-connected world, environmental relevance is critical to understanding resource consumption and scarcity. Assessing the virtual flows of scarce natural resources, accounting for environmental relevance, and spatially identifying the major trade routes conveying environmental pressures

and impacts on local ecosystems is an important step from merely tracing environmental pressures to quantifying environment impacts; both for the regions of production and the centers of consumption.

3. *Across Scale Approach* - The expansion of global supply chains increases the complexity of addressing trade's negative environmental effects. Local degradation is often the result of local activities, but can also be caused directly or indirectly by interactions with other regions. This research is the first across scale tele-connected analysis of global supply chains. This research reveals that tele-connected environmental pressures and environmental impacts occur across administrative and ecological boundaries and across scale; specifically: 1) impacts on national water and land resources from trade with foreign countries; 2) impacts on sub-national water, energy, and land resources from domestic inter-regional sub-regional trade and trade with foreign transnational intra-regional sub-regions and foreign countries, and; 3) impacts on the hydrologic river basin catchment from inter-regional trade.

This research improves our empirical understanding of tele-connections and global supply chains by tracing resource use across the whole economic system and quantifying the environmental impacts of human consumption. Quality of life, material well-being, and the state of the natural environment are integrally connected. These aspects must be assessed and considered as a whole in order to determine tradeoffs between them, as necessary. Only after the associated environmental pressures from our material utilization are quantified, transparent, and responsibility assessed between producers and consumers can strategies based on sustainable consumption and production be discussed to reduce humanity's burden on natural resources and the world's ecosystems.

# Appendices

**Supporting Information 01: GTAP9 Database Sectors**

| # | Code | Description | Detailed Sector Description |
|---|---|---|---|
| 1 | pdr | Paddy rice | Paddy Rice: rice, husked and unhusked |
| 2 | wht | Wheat | Wheat: wheat and muslin |
| 3 | gro | Cereal grains nec | Other Grains: maize (corn), barley, rye, oats, other cereals |
| 4 | v_f | Vegetables; fruit; nuts | Veg & Fruit: vegetables, fruit vegetables, fruit and nuts, potatoes, cassava, truffles |
| 5 | osd | Oil seeds | Oil Seeds: oil seeds and oleaginous fruit; soy beans, copra |
| 6 | c_b | Sugar cane; sugar beet | Cane & Beet: sugar cane and sugar beet |
| 7 | pfb | Plant-based fibers | Plant Fibers: cotton, flax, hemp, sisal and other raw vegetable materials used in textiles |
| 8 | ocr | Crops nec | Other Crops: live plants; cut flowers and flower buds; flower seeds and fruit seeds; vegetable seeds, beverage and spice crops, unmanufactured tobacco, cereal straw and husks, unprepared, whether or not chopped, ground, pressed or in the form of pellets; forage products, plants and parts of plants used primarily in perfumery, in pharmacy, or for insecticidal, fungicidal or similar purposes, sugar beet seed and seeds of forage plants, other raw vegetable materials |
| 9 | ctl | Bovine cattle; sheep and goats; horses | Cattle: cattle, sheep, goats, horses, asses, mules, and hinnies; and semen thereof |
| 10 | oap | Animal products nec | Other Animal Products: swine, poultry and other live animals; eggs, in shell, natural honey, snails; frogs' legs, edible products of animal origin n.e.c., hides, skins and fur skins, raw, insect waxes and spermaceti, whether or not refined or colored |
| 11 | rmk | Raw milk | Raw milk |
| 12 | wol | Wool; silk-worm cocoons | Wool: wool, silk, and other raw animal materials used in textile |
| 13 | frs | Forestry | Forestry: forestry, logging and related service activities |
| 14 | fsh | Fishing | Fishing: hunting, trapping and game propagation including related service activities, fishing, fish farms; service activities incidental to fishing |
| 15 | coa | Coal | Coal: mining and agglomeration of hard coal, lignite and peat |
| 16 | oil | Oil | Oil: extraction of crude petroleum and natural gas (part), service activities incidental to oil and gas extraction excluding surveying (part) |
| 17 | gas | Gas | Gas: extraction of crude petroleum and natural gas (part), service activities incidental to oil and gas extraction excluding surveying (part) |
| 18 | omn | Minerals nec | Other Mining: mining of metal ores, uranium, gems. other mining and quarrying |
| 19 | cmt | Bovine meat products | Cattle Meat: fresh or chilled meat and edible offal of cattle, sheep, goats, horses, asses, mules, and hinnies. raw fats or grease from any animal or bird. |
| 20 | omt | Meat products nec | Other Meat: pig meat and offal. preserves and prep. of meat, meat offal or blood, flours, meals and pellets of meat or inedible meat offal; greaves |
| 21 | vol | Vegetable oils and fats | Vegetable Oils: crude and refined oils of soya-bean, maize (corn), olive, sesame, ground-nut, olive, sunflower-seed, safflower, cotton-seed, rape, colza and canola, mustard, coconut palm, palm kernel, castor, tung jojoba, babassu and linseed, perhaps partly or wholly hydrogenated, inter-esterified, re-esterified or elaidinized. Also margarine and similar preparations, animal or vegetable waxes, fats and oils and their fractions, cotton linters, oil-cake and other solid residues resulting from the extraction of vegetable fats or oils; flours and meals of oil seeds or oleaginous fruits, except those of mustard; degras and other residues resulting from the treatment of fatty substances or animal or vegetable waxes. |
| 22 | mil | Dairy products | Milk: dairy products |
| 23 | pcr | Processed rice | Processed Rice: rice, semi- or wholly milled |
| 24 | sgr | Sugar | Sugar |
| 25 | ofd | Food products nec | Other Food: prepared and preserved fish or vegetables, fruit juices and vegetable juices, prepared and preserved fruit and nuts, all cereal flours, groats, meal and pellets of wheat, cereal groats, meal and pellets n.e.c., other cereal grain products (including corn flakes), other vegetable flours and meals, mixes and doughs for the preparation of bakers' wares, starches and starch products; sugars and sugar syrups n.e.c., preparations used in animal feeding, bakery products, cocoa, chocolate and sugar confectionery, macaroni, noodles, couscous and similar farinaceous products, food products n.e.c. |
| 26 | b_t | Beverages and tobacco products | Beverages and Tobacco products |
| 27 | tex | Textiles | Textiles: textiles and man-made fibers |
| 28 | wap | Wearing apparel | Wearing Apparel: Clothing, dressing and dyeing of fur |
| 29 | lea | Leather products | Leather: tanning and dressing of leather; luggage, handbags, saddlery, harness and footwear |
| 30 | lum | Wood products | Lumber: wood and products of wood and cork, except furniture; articles of straw and plaiting materials |
| 31 | ppp | Paper products; publishing | Paper & Paper Products: includes publishing, printing and reproduction of recorded media |
| 32 | p_c | Petroleum; coal products | Petroleum & Coke: coke oven products, refined petroleum products, processing of nuclear fuel |
| 33 | crp | Chemical; rubber; plastic products | Chemical Rubber Products: basic chemicals, other chemical products, rubber and plastics products |
| 34 | nmm | Mineral products nec | Non-Metallic Minerals: cement, plaster, lime, gravel, concrete |
| 35 | i_s | Ferrous metals | Iron & Steel: basic production and casting |
| 36 | nfm | Metals nec | Non-Ferrous Metals: production and casting of copper, aluminum, zinc, lead, gold, and silver |
| 37 | fmp | Metal products | Fabricated Metal Products: Sheet metal products, but not machinery and equipment |
| 38 | mvh | Motor vehicles and parts | Motor vehicles and parts: cars, lorries, trailers and semi-trailers |
| 39 | otn | Transport equipment nec | Other Transport Equipment: Manufacture of other transport equipment |
| 40 | ele | Electronic equipment | Electronic Equipment: office, accounting and computing machinery, radio, television and communication equipment and apparatus |
| 41 | ome | Machinery and equipment nec | Other Machinery & Equipment: electrical machinery and apparatus n.e.c., medical, precision and optical instruments, watches and clocks |
| 42 | omf | Manufactures nec | Other Manufacturing: includes recycling |
| 43 | ely | Electricity | Electricity: production, collection and distribution |
| 44 | gdt | Gas manufacture; distribution | Gas Distribution: distribution of gaseous fuels through mains; steam and hot water supply |
| 45 | wtr | Water | Water: collection, purification and distribution |
| 46 | cns | Construction | Construction: building houses factories offices and roads |
| 47 | trd | Trade | Trade: all retail sales; wholesale trade and commission trade; hotels and restaurants; repairs of motor vehicles and personal and household goods; retail sale of automotive fuel |
| 48 | otp | Transport nec | Other Transport: road, rail ; pipelines, auxiliary transport activities; travel agencies |
| 49 | wtp | Water transport | Water transport |
| 50 | atp | Air transport | Air transport |
| 51 | cmn | Communication | Communications: post and telecommunications |
| 52 | ofi | Financial services nec | Other Financial Intermediation: includes auxiliary activities but not insurance and pension funding (see next) |
| 53 | isr | Insurance | Insurance: includes pension funding, except compulsory social security |
| 54 | obs | Business services nec | Other Business Services: real estate, renting and business activities |
| 55 | ros | Recreational and other services | Recreation & Other Services: recreational, cultural and sporting activities, other service activities; private households with employed persons |
| 56 | osg | Public Admin.; Defense; Education; Health | Other Services (Government): public administration and defense; compulsory social security, education, health and social work, sewage and refuse disposal, sanitation and, activities of membership organizations, extra-territorial organizations |
| 57 | dwe | Dwellings | Dwellings: ownership of dwellings (imputed rents of houses occupied by owners) |

**Supporting Information 02: World Regions**

| Region | Countries |
|---|---|
| **Oceania** | Australia, New Zealand, Rest of Oceania (American Samoa, Cook Islands, Fiji, French Polynesia, Guam, Kiribati, Marshall Islands, Federated States of Micronesia, Nauru, New Caledonia, Niue, Northern Mariana Islands, Palau, Papua New Guinea, Pitcairn, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, United States Minor Outlying Islands, Vanuatu, Wallis and Futuna) |
| **East Asia** | People's Republic of China, Hong Kong, Japan, Republic of Korea, Taiwan, Mongolia, Rest of East Asia (Democratic People's Republic of Korea, Macao) |
| **Southeast Asia** | Brunei Darussalam, Cambodia, Indonesia, People's Democratic Republic of Lao, Malaysia, Philippines, Singapore, Thailand, Viet Nam, Rest of Southeast Asia (Myanmar, Timor Leste) |
| **South Asia** | Bangladesh, India, Nepal, Pakistan, Sri Lanka, Rest of South Asia (Afghanistan, Bhutan, Maldives) |
| **North America** | Canada, United States of America, Mexico, Rest of North America (Bermuda, Greenland, Saint Pierre and Miquelon) |
| **South America** | Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Rest of South America (Falkland Islands, French Guiana, Guyana, South Georgia and the South Sandwich Islands, Suriname) |
| **Central America** | Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Rest of Central America (Belize) |
| **Caribbean** | Dominican Republic, Jamaica, Puerto Rico, Trinidad and Tobago, Caribbean (Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Cayman Islands, Cuba, Dominica, Grenada, Haiti, Montserrat, Netherlands Antilles, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Turks and Caicos Islands, British Virgin Islands, U.S. Virgin Islands) |
| **West Europe** | Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom, Switzerland, Norway, Rest of EFTA (Iceland, Liechtenstein) |
| **East Europe** | Albania, Belarus, Croatia, Russian Federation, Ukraine, Rest of East Europe (Republic of Moldova), Rest of Europe (Andorra, Bosnia and Herzegovina, Faroe Islands, Gibraltar, Guernsey, Vatican City, Isle of Man, Jersey, Macedonia, Monaco, Montenegro, San Marino, Serbia, Kosovo) |
| **Central Asia** | Kazakhstan, Kyrgyzstan, Rest of Former Soviet Union (Tajikistan, Turkmenistan, Uzbekistan) |
| **West Asia** | Armenia, Azerbaijan, Georgia, Bahrain, Islamic Republic of Iran, Israel, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, Turkey, United Arab Emirates, Rest of West Asia (Iraq, Lebanon, Occupied Palestinian Territory, Syrian Arab Republic, Yemen) |
| **North Africa** | Egypt, Morocco, Tunisia, Rest of North Africa (Algeria, Libyan Arab Jamahiriya, Western Sahara) |
| **West Africa** | Benin, Burkina Faso, Cote d'Ivoire, Ghana, Guinea, Nigeria, Senegal, Togo, Rest of West Africa (Cape Verde, Gambia, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Saint Helena, Ascension and Tristan da Cunha, Sierra Leone) |
| **Central Africa** | Cameroon, Central Africa (Central African Republic, Chad, Congo, Equatorial Guinea, Gabon, Sao Tome and Principe), South Central Africa (Angola, Democratic Republic of the Congo) |
| **East Africa** | Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, United Republic of Tanzania, Uganda, Zambia, Zimbabwe, Rest of East Africa (Burundi, Comoros, Djibouti, Eritrea, Mayotte, Seychelles, Somalia, Sudan) |
| **South Africa** | Botswana, Namibia, South Africa, Rest of South African Customs Union (Lesotho, Swaziland) |
| **Rest of World** | (Antarctica, Bouvet Island, British Indian Ocean Territory, French Southern Territories) |

*Note: List of countries and sub-regions (e.g. "Rest of East Asia") based upon GTAP9 grouping of countries.*

**Supporting Information 03: IDE-JETRO's Intermediate Sector Classification Table**

| 15 Sector Classification | | 76 Sector Classification of the 2005 AIO Table | |
|---|---|---|---|
| Code | Description | Code | Description |
| **Intermediate Sectors** | | | |
| 1 | Agriculture, livestock, forestry and fishery | 001 | Paddy |
| | | 002 | Other grain |
| | | 003 | Food crops |
| | | 004 | Non-food crops |
| | | 005 | Livestock and poultry |
| | | 006 | Forestry |
| | | 007 | Fishery |
| 2 | Mining and quarrying | 008 | Crude petroleum and natural gas |
| | | 009 | Iron ore |
| | | 010 | Other metallic ore |
| | | 011 | Non-metallic ore and quarrying |
| 3 | Wearing apparel and other made-up textile products | 020 | Knitting |
| | | 021 | Wearing apparel |
| | | 022 | Other made-up textile products |
| 4 | Other non-electrical consumption products for daily-use | 013 | Fish products |
| | | 014 | Slaughtering, meat products and dairy products |
| | | 015 | Other food products |
| | | 016 | Beverage |
| | | 017 | Tobacco |
| | | 023 | Leather and leather products |
| | | 025 | Wooden furniture |
| 5 | Basic industrial materials | 012 | Milled grain and flour |
| | | 018 | Spinning |
| | | 019 | Weaving and dyeing |
| | | 024 | Timber |
| | | 026 | Other wooden products |
| | | 027 | Pulp and paper |
| | | 028 | Printing and publishing |
| | | 029 | Synthetic resins and fiber |
| | | 030 | Basic industrial chemicals |
| | | 031 | Chemical fertilizers and pesticides |
| | | 032 | Drugs and medicine |
| | | 033 | Other chemical products |
| | | 034 | Refined petroleum and its products |
| | | 035 | Plastic products |
| | | 036 | Tires and tubes |
| | | 037 | Other rubber products |
| | | 038 | Cement and cement products |
| | | 039 | Glass and glass products |
| | | 040 | Other non-metallic mineral products |
| | | 041 | Iron and steel |
| | | 042 | Non-ferrous metal |
| | | 043 | Metal products |
| 6 | Computers and electronic equipment | 050 | Electronic computing equipment |
| | | 051 | Semiconductors and integrated circuits |
| | | 052 | Other electronics and electronic products |
| 7 | Automobiles | 055 | Motor vehicles |
| | | 056 | Motor cycles |
| 8 | Industrial machinery | 044 | Boilers, engines and turbines |
| | | 045 | General machinery |
| | | 046 | Metal working machinery |
| | | 047 | Specialized machinery |
| 9 | Household electrical appliance | 049 | Television sets, radios, audios and communication equipment |

| | | | |
|---|---|---|---|
| | | 053 | Household electrical equipment |
| 10 | Other processed and assembled manufacturing products | 048 | Heavy electrical equipment |
| | | 054 | Lighting fixtures, batteries, wiring and others |
| | | 057 | Shipbuilding |
| | | 058 | Other transport equipment |
| | | 059 | Precision machines |
| | | 060 | Other manufacturing products |
| 11 | Electricity, gas and water supply | 061 | Electricity and gas |
| | | 062 | Water supply |
| 12 | Construction | 063 | Building construction |
| | | 064 | Other construction |
| 13 | Trade | 065 | Wholesale and retail trade |
| 14 | Transportation | 066 | Transportation |
| 15 | Other services | 067 | Telephone and telecommunication |
| | | 068 | Finance and insurance |
| | | 069 | Real estate |
| | | 070 | Education and research |
| | | 071 | Medical and health service |
| | | 072 | Restaurant |
| | | 073 | Hotel |
| | | 074 | Other services |
| | | 075 | Public administration |
| | | 076 | Unclassified |

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