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Estimating Water Footprint and Water Economic Values in the Southeastern U.S.

Di Sheng
University of Tennessee, Knoxville, dsheng@vols.utk.edu

To the Graduate Council:

I am submitting herewith a thesis written by Di Sheng entitled "Estimating Water Footprint and Water Economic Values in the Southeastern U.S.." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Economics.

Dayton M. Lambert, Major Professor

We have read this thesis and recommend its acceptance:

Christopher Clark, Burton English, David Hughes, Chad Hellwinckel

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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DEDICATION

This thesis is dedicated to my mother.

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ABSTRACT

Population growth and climate change have brought water disputes to the southeastern United States. To achieve sustainable water use of the region's water resources and to alleviate future water stress, it is important to determine 1) current water quantity used to support regional economic activities, and 2) the economic value of water in the southeastern U.S. This thesis has three objectives: 1) build a Multi-Regional Input-Output (MRIO) model to describe multi-regional transactions for the following analyses; 2) conduct a water footprint analysis to evaluate how much water use is required for meeting changes in final demand of specific region and economic sectors; 3) set up an MRIO Linear Programming (MRIO-LP) to determine water use demand curves for the southeastern U.S.

The water footprint analysis indicates that water requirements embedded in the production of a good varies across study region. The MRIO-LP analysis reveals that economic transactions between regions have a significant impact on the water used to meet regional economic demand. The shadow value of water is higher when multi-regional transactions are introduced into the LP model. In general, the southeastern U.S. economy is less likely to experience water stress until the water availability decrease to 60% of the 2010 USGS level of 82,825,409 acre feet. At this level, the aggregated industry price for water in the southeastern U.S. ranges between 4,041 $/ac.ft. to 5,614 $/ac.ft., depending on assumptions pertaining to inter-regional transactions.

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CHAPTER 1: INTRODUCTION

Background

Population growth introduced a growing concern about the future water use in the southeastern United States (U.S.). Georgia, Alabama and Florida have been battling over the water use in two river basins for decades (SELC, 2017)[1]. The upper stream user, Georgia, continuously increases its water withdrawals to support the booming metro-Atlanta. Water withdrawals for the metropolitan region of Atlanta increased from 275 million gallons a day to 360 million gallons a day, along with an 80% increase in population from 1992 to 2013 (Hawkins, 2016). Alabama and Florida questioned Georgia's water management, and concerned that Atlanta's growing demand for water would limit the region's future water availability. Several law suits resulted, giving rise to the "Tri-State water wars" (SELC, 2008). In addition, the entire southeastern U.S. continues to expand economically and demographically. The southeastern U.S. consists of eleven states, including Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia. Each of these states experienced population growth from 2010 to 2016. Six of these states have higher population growth rates than the U.S. average from 2010 to 2016 (Table 1)[2]. These eleven states account for 26.03% of the U.S. water withdrawals (USGS, 2010). Specifically, agricultural sectors account for 21.35% of the total water withdrawal in the southeastern U.S. Of this amount, 83.89% is for irrigation (USGS, 2010). Eight states have increased irrigated acres from 2002 to 2012 (USDA, 2007, 2012) (Table 2).

Climate change also introduces vulnerability into the southeastern U.S.'s water endowments, with respect to agriculture and hydropower sectors (Barczak, 2008; DOE, 2014). In

[1] The Alabama-Coosa-Tallapoosa basin and the Apalachicola-Chattahoochee-Flint basin.
[2] States with higher population growth rate than the U.S. average are Florida, South Carolina, North Carolina, Georgia, Virginia and Tennessee.

general, the 2007 drought caused the southeastern U.S. to lose more than $1.3 billion in major field crops (Manuel, 2008). The average corn yield of North Carolina and Tennessee decreased by 32% and 15% in 2007, respectively (USDA, 2012). In addition, low reservoir levels forced Tennessee and North Carolina to substitute water with fossil fuels to generate power in 2007 (Manuel, 2008). Unfortunately, the negative consequences from drought are likely to continue in the future. According to the Third National Climate Assessment (Melillo et al., 2014), most regions in the U.S. are expected to experience more frequent seasonal droughts, and longer-term droughts are expected to intensify in the southern Great Plains, and the Southeast.

Increasing water demand coupled with potential reductions in water availability due to droughts are a backdrop for the current water disputes about water availability and vulnerability. Quantifying current water use and forecasting the potential impact of water scarcity on the regional economy could be useful for developing proactive plans to sustain economic growth if the region's water availability were to decline over some sustained period of time.

Research Questions

This thesis aims to address two questions:

1. How are water resources allocated to support current economic activities, and what is the contribution value of water across economic sectors in the southeastern U.S.?

2. How will decreases in water availability affect the southeastern U.S. economy in terms of the cost of water required to meet final demands for the economy's products.

Research Objectives

This thesis aims to answer these two questions with the following objectives:

1) Construct a model to describe the southeastern U.S. economic linkages between regions and sectors (Chapter 2);

2) Generate indicators to measure water requirements corresponding with current economic activities (Chapter 3);

3) Determine the economic value of water (water shadow values) and Gross Regional Product (GRP) in the southeastern U.S. under different assumptions about economic structure and water availability (Chapter 4).

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U.S. Department of the Interior – U.S. Geological Survey (USGS) National Water Information System: Estimated Use of Water in the United States County-Level Data for 2010

Appendix A

Tables

Table 1. State Population and Population Growth Rate in the Southeastern U.S.

Region	2010 Population	2016 Population	Growth Rate
Florida	18,849,098	20,612,439	9.36%
South Carolina	4,635,943	4,961,119	7.01%
North Carolina	9,558,915	10,146,788	6.15%
Georgia	9,713,521	10,310,371	6.14%
Virginia	8,025,773	8,411,808	4.81%
Tennessee	6,356,671	6,651,194	4.63%
U.S.	**309,348,193**	**323,127,513**	**4.45%**
Louisiana	4,544,996	4,681,666	3.01%
Arkansas	2,921,995	2,988,248	2.27%
Kentucky	4,348,662	4,436,974	2.03%
Alabama	4,785,492	4,863,300	1.63%
Mississippi	2,970,322	2,988,726	0.62%

Source: Annual Estimates of the Resident Population for the United States, Regions, States, and Puerto Rico: April 1, 2010 to July 1, 2016 (NST-EST2016-01). U.S. Census Bureau, Population Division.

Table 2. Irrigated Acres of State and the Southeastern U.S. in 2002, 2007 and 2012

Region	Irrigated Acres in 2012	Irrigated Acres in 2007	Irrigated Acres in 2002
Alabama	113,008	112,819	108,783
Arkansas	4,803,902	4,460,682	4,149,766
Florida	**1,493,320**	**1,552,118**	**1,815,174**
Georgia	1,125,355	1,017,773	870,810
Kentucky	73,573	58,730	36,751
Louisiana	1,092,881	954,353	938,841
Mississippi	1,651,978	1,368,661	1,175,530
North Carolina	**174,526**	**232,075**	**264,057**
South Carolina	159,239	132,439	95,642
Tennessee	146,442	81,405	61,217
Virginia	**68,651**	**82,187**	**98,913**
Southeastern U.S.	10,902,875	10,053,242	9,615,484
U.S.	55,822,231	56,599,305	55,311,236

Source: 2007 Census of Agriculture and 2012 Census of Agriculture;
Note: States highlighted in bold had decreases in irrigated acres.

CHAPTER 2: DETERMINING A MULTI-REGIONAL DIRECT REQUIREMENT MATRIX

Abstract

The environmental impact of economic activities is concordant with an economy's transaction flows. This chapter constructs a multi-regional direct requirement matrix (A^M) to capture both inter-industrial and inter-regional transactions for the southeastern U.S.'s economy. Location quotients are used to construct a column trade coefficient model for bridging sub-regional direct requirement matrices.

Introduction

Environmental burdens, such as Green House Gas (GHG) emissions, energy consumption and water use are coupled with the monetary value of goods and services transactions (Leontief, 1970; Henry and Bowen, 1981; Miller and Blair, 2009; Blackhurst, et al., 2010, Okadera et al., 2014). There are two types of economic transactions. The first are inter-industrial transactions. Outputs from one industry are used as intermediate inputs in the production of another industry's output. For example, electric power generated in the fossil fuel sector could be used for extracting coal; or aluminum could be used to can fruits and vegetables. The second type of transactions are inter-regional transactions. According to the World Bank, exports of goods and services account for more than 20% of global Gross Domestic Product (GDP) (World Bank, 2015). In the United States, the ratio of exports and imports to GDP exceeded 11.05% and 13.73% from 2007 to 2016 (Bureau of Economic Analysis, 2017) (Table 3). Based on the 2013 Impact Analysis for Planning model (IMPLAN) (MIG, Inc., 2013) estimates, intermediate imports are 29.50% of Gross Regional Product (GRP), and domestic exports account for 26.69% of the GRP in the southeastern U.S. Intermediate imports include the industry output imported from other regions as inputs used for local production, and domestic exports include industry output exported to other domestic regions to support local production (IMPLAN, MIG, Inc., 2013)

This chapter develops a multi-regional direct requirement matrix that quantifies the economic inter-regional and sectoral transaction flows in the southeastern U.S. This mstrix is later used to examine agriculture's water footprint in the southeastern U.S. (Chapter 3) and to estimate the regional water shadow values (Chapter 4).

Previous Studies

Leontief (1936) developed the Input-Output (IO) model to quantify interdependencies between economic sectors. Leontief's model depicted the U.S. economy of the early 20th century at the national level. Since Leontief's contribution, IO models have been widely used to analyze national and regional economies. Barna (1952) analyzed the structural relationships of the British economy with an IO model. Simpson and Tsukui (1965) conducted IO analyses for the economies of the U.S., Japan, Norway, Italy and Spain to determine the common elements across these economies.

Leontief extended an IO model to explain how pollutants and labor can be incorporated into conventional IO analyses (Leontief, 1970). This framework, today called Environmental Input-Output (EIO) analysis, was used by Henry and Bowen (1981) and later by Blackhurst and colleagues (Blackhurst et al., 2010) to study the direct and indirect industrial water use in the U.S.

Variations in production technologies and economic linkages across regions suggest the importance of IO modeling at regional levels. Isard and Kuenne (1953) conducted a regional IO analysis to study the steel industry in the Greater New York-Philadelphia region. Miller (1957) studied the aluminum industry in the Pacific Northwest using a regional IO model. Isard and

Logford (1971) discussed details of a regional IO model for the Philadelphia Standard Metropolitan Statistical Area level. Hughes and Holland (1994) developed a core-periphery model to analyze the economic growth in Washington.

When national IO accounts are downscaled to regional levels, it becomes apparent how dependent a region's economy is on the economic activities occurring in other regions. Isard (1951) first introduced the inter-regional IO analysis by dividing the U.S. into three sub-regions and three industries. Later, Chenery (1953) developed a two-region economy with an inter-regional IO model for Italy using trade coefficients to structure local supply patterns and export shares to characterize the inter-regional transactions. Moses (1955) also used a trade coefficient method to develop a nine region IO model of the U.S. economy. Polenske (1970) compared the row trade coefficient, column trade coefficient, and gravity model estimates of inter-regional transaction flows. Polenske concluded that the column trade coefficient method performed best. Hewings et al. (2001) used Polenske's column trade coefficient method to build a multi-regional input-output (MRIO) model for four regions in the Chicago metropolitan area. This thesis extends the trade coefficient approach of Hewings and co-authors to develop a multi-regional IO model for evaluating how water use is embedded in the transaction flows characterizing the southeastern U.S. economy.

Spatial Units of Analysis

The spatial units of analysis are the Bureau of Economic Analysis (BEA) economic regions. The BEA regions are defined as the relevant regional markets related to the metropolitan or micropolitan statistical areas that serve as regional centers of economic activity (Johnson and Kort, 2004). BEA regions are used here because each BEA is assumed to experience minimal cross-hauling effects. Cross-hauling effects are defined as the "simultaneous and geographically overlapping shipments from various production centers" (Stigler, 1949, p. 1149). In other words, a commodity is simultaneously exported from and imported into the same region. Kronenberg (2009) indicated that product homogeneity is a key factor determining the degree and magnitude of cross-hauling effects. For economic impact estimates, cross-hauling effects tend to be stronger in relatively smaller regions (Robison and Miller, 1988; Flegg and Tohmo, 2013). In contrast, larger regions, which tend to produce relatively more heterogeneous products, are believed to experience relatively weaker cross-hauling effects (Klijs et al., 2016). BEA regions are delineated by labor commuting patterns; therefore, they mirror the functional hierarchy of regional economies (Johnson and Kort, 2004). Delineation of BEA regions is also related to central place theory (Christaller, 1933; Ullman, 1941). According to central place theory, consumers tend to minimize travel costs. Surrounding markets therefore depend on the nearest centralized, larger economies. In this way, it is reasonable to assume that related surrounding markets are mainly served by central metropolitan areas, which are typically the core of a BEA region. Cross-boundary commuting activities, and concomitantly, cross-hauling effects, are likely (not definitely) minimized at BEA levels.

For this research, BEA regions in the southeastern U.S. are used as primary economic units of analysis. Some counties with borders outside the southeastern U.S are excluded (Figure 1). There are 43 BEAs comprising the study region. The study region includes 763 counties.

Estimation of a Multi-Regional Direct Requirement Matrix

The input-output (IO) analysis developed by Leontief in the 1930s (Leontief, 1936) is derived from input-output transaction tables (Figure 2). An input-output transaction table comprises the inter-industry transaction flows, final demand for goods, and value added to the economy. Final demands are the sales from sectors to final markets. Final demand consists of household consumption, government purchases, investment, and exports. Value added "accounts for the non-industrial input in the production, such as labor, depreciation of capital, indirect business taxes, and imports" (Miller and Blair, 2009, p. 3). Each row of the transaction table indicates how the output of a sector is distributed to other sectors as an intermediate input or to meet final demand. Each column of the transaction table describes the component (expenditures) of input requirements from other sectors and the value added generated from the production of a good.

The IO model reduces to a system of linear equations:

$$X_i - \sum_j a_{ij} X_j = Y_i \ \forall i \tag{1}$$

where X_i and Y_i denote the output and final demand of sector *i* (*j* aliases *i*), and the parameter a_{ij} is a technical coefficient indicating how many currency units of output in sector *i* are required to produce one currency unit of output in sector *j*.

The technical coefficient a_{ij} is calculated as:

$$a_{ij} = \frac{Z_{ij}}{X_j} \tag{2}$$

where X_j is the output of sector *j*, and Z_{ij} is the currency value of transactions from sector *i* to sector *j* to produce X_j.

The direct requirement matrix *A* is a matrix of technical coefficients a_{ij} ($A = [a_{ij}]$). In matrix form, the IO model is:

$$X - AX = Y \tag{3a}$$

where *X* is a vector of total industry output and *Y* is a vector of final demand. Units are typically expressed in monetary value (e.g., dollars). Equation 3 is oftentimes arranged as:

$$X = (I - A)^{-1} Y \tag{3b}$$

where the $(I - A)^{-1}$ matrix indicate the marginal change in the total industry output, given a one unit change in final demand. $(I - A)^{-1}$ is usually referred to as the "Leontief Inverse" matrix.

Multi-Regional Input-Output Analysis

A multi-regional direct requirement matrix (A^M) incorporates transaction flows between regions and across sectors by augmenting the standard IO model ($A = [a_{ij}]$) to accommodate inter-regional transaction flows. The matrix A^Mconsists of intra-regional input coefficients (a_{ij}^{rr}) and inter-regional input coefficients (a_{ij}^{rs}) that describe how many currency units of output from sector *i* in region *r* are required to produce one currency unit of output of sector *j* in region *s* (*s* aliases *r*) (Miller and Blair, 2009) [3]. Similar to equation (2), each a_{ij}^{rs} is calculated as:

$$a_{ij}^{rs} = \frac{z_{ij}^{rs}}{X_j^s} \tag{4}$$

where X_j^s denotes the total industry output of sector *j* in region *s*, and Z_{ij}^{rs} is the currency value of transaction from sector *i* in region *r* to sector *j* in region *s* to produce X_j^s.

Methods of Estimating Regional Input Coefficients

The fundamental problem of constructing A^M is access to multi-regional transactions Z_{ij}^{rs} in equation (4). Surveys on multi-regional transactions have been conducted to derive regional input coefficients (Tiebout, 1962). Unfortunately, data for Z_{ij}^{rs} is difficult and expensive to acquire. A "second best" approach requires estimation of inter-regional transactions using available data (typically collected at a regional or sub-regional level), and use of export based

[3] In this thesis, the intra-regional input coefficient and the inter-regional input coefficients are referred to *regional input coefficients*.

theory to characterize trade relations. There have been considerable efforts to formulate regional input coefficients using non-survey or partial-survey methods (Round, 1983).

Miller and Blair (2009) summarize the most common approaches. First, one could formulate an estimate of the regional technical coefficient (a^r) as:

$$a^r = \beta^r a^N \tag{5}$$

where a^N is a national level input-output coefficient; a^r denotes a regional technical coefficient; and β^r is a coefficient representing technology differences between regional and national production.

Second, regional input coefficients (a^{rr} and a^{sr}) are estimated as:

$$a^{sr} = \begin{cases} \gamma^r a^r & r = s \\ a^r - a^{rr} & r \neq s \end{cases} \tag{6}$$

where *s* is the input-providing (exporting) region and *r* is the output-producing (importing) region. The parameter γ^r is the proportion of local purchases. The local purchase proportion could be estimated with the supply-demand pooling method by equation (7) when data is available (Miller and Blair, 2009):

$$\gamma^r = \frac{X^r - E^r}{X^r + M^r - E^r} \tag{7}$$

where X^r is the local total industry output, E^r are local exports, and M^r are the local imports into region *r*.

There are two received methods to estimate the β^r and γ^r in equations (5) and (6). One approach uses an iterative method (for example, the RAS procedure) (Bacharach, 1970; Macgill, 1977; Szyrmer, 1989). The RAS procedure estimates the β^r and γ^r simultaneously, updating the existing direct requirement matrix *A* subject to horizontal sum and vertical sum constraints.

The second approach uses Location Quotients (LQ) to determine a region's propensity to export (or import) a good or service (Leigh, 1970; Isserman, 1977; Flegg et al., 1995). The LQ method uses regional economic data to indicate regional specialization in an economic activity; in other words, the region's comparative advantage in producing a good or service (Shaffer, Deller and Marcouiller, 2004):

$$LQ_i^r = \frac{E_i^r/E^r}{E_i^N/E^N} \tag{8}$$

where *E* is a variable indicating economic activity or size. Total industry output, employment, income and other economic indicators may be used to proxy *E* (Miller and Blair, 2009).

The LQs are then used to determine Chenery-Moses trade coefficients. The trade coefficients are used to build a multi-regional direct requirement matrix. Chenery (1953) and Moses's (1955) regional trade coefficient model was later modified by Hewings et al. (2001) and Lenzen et al. (2004) to construct an MRIO model. One critical issue of the LQ approach is its inability to account for cross-hauling effects. This results in potentially overestimating intra-regional purchases, and thereby possibly underestimating interregional trade flows (Richardson, 1985; Flegg and Tohmo, 2013). Since BEA regions are assumed to experience minimal cross-hauling effects by their design, the LQ approach seems to be a reasonable "second-best" compromise to more computational, data-intensive methods.

Estimating Regional Input Coefficients with the LQ Approach

Use of the LQ approach to define inter-regional linkages is rooted in export base theory (Isserman, 1980b). According to export base theory, the economy is divided into internal demand sectors (local demand) and external demand sectors (export). Exports drive regional economic development. The greater a region's comparative advantage, the more exports that region will generate (Shaffer, Deller and Marcouiller, 2004). Hence, when $LQ_i^r > 1$, the economic activity of sector *i*, region *r*, is more concentrated compared with the aggregated regional level's activities. The LQ therefore indicates a region's comparative advantage in its production capacity and its propensity to export goods from sector *i* to other regions. When $LQ_i^r < 1$, economic activity of sector *i* in region *r* is less intense and there is a greater propensity to import goods to meet local demand for goods of sector *i*.

Export shares (ex_i^r) can be calculated as Isserman (1980b) suggested:

$$ex_i^r = \begin{cases} 1 - \frac{1}{LQ_i^r} & LQ_i^r > 1 \\ 0 & LQ_i^r \leq 1 \end{cases} \tag{9}$$

The critical assumption using LQs to determine export shares in this way is that all local consumption of commodities that region *r* exports are produced locally, which necessarily implies there are no cross-hauling effects at work (Isserman, 1980b).

This thesis uses Hewings et al.'s modification of the Chenery-Moses MRIO model and Polenske's research to develop a multi-regional input-output model for analyzing the water footprint and water shadow value for the southeastern U.S. as equation (10):

$$x_i^r = \sum_s \sum_j CT_i^{rs} a_{ij}^s x_j^s + \sum_s CT_i^{rs} y_j^s \tag{10}$$

where *i* (*j*) denotes a distributing (receiving) sector, *r* (*s*) denotes an exporting (importing) region; x is Total Industry Output (TIO), and y is final demand. The elements of the multiregional direct requirement matrix (a_{ij}^{rs}) are estimated by multiplying column trade coefficients (CT_i^{rs}) and regional technical coefficients (a_{ij}^s). The steps to estimate the CT_i^{rs} follow.

First, the export shares (ex_i^r) from equation (9) are distributed to other receiving regions, based on the regional economic size and distance between regions to formulate a row trade coefficient (Polenske, 1970).

$$ratio^s = \frac{e^s/D^{rs}}{\sum_s e^s/D^{rs}} \ \forall\ s; \tag{11a}$$

where $ratio^s$ is the "receiving ratio" from region *r* to *s*; and e^s is a variable indicating economic size. In this chapter, e^s is the total regional employment of region s. The parameter D^{rs} is the distance between region *s* and region *r*. The Euclidean distance is used here and calculated as:

$$D^{rs} = \sqrt{(h^s - h^r)^2 + (v^s - v^r)^2} \qquad (11b)$$

where *h* and *r* are the xy-centroids of a BEA region.

The underlying assumption implied by the receiving ratio is that as the distance between regions increases, interregional trade intensity decreases. In addition, it is assumed that the impacts of distance and economic size are constant across all sectors. This is a rather strict assumption, and implies homogeneous transportation costs per unit of economic benefit. For example, the transportation cost of per dollar revenue generated by the forestry sector is assumed to be identical to that of the utilities sector.

Second, the row trade coefficients RT_i^{rs} are calculated as:

$$RT_i^{rs} = ratio^s \cdot ex_i^r \qquad (12a)$$

subject to the normalization,

$$\sum_s RT_i^{rs} = 1 \qquad (12b)$$

This restriction forces uniform trading pattern across all sectors with a homogeneous productivity (Moses, 1955; Hewings et al, 2001; Lenzen et al, 2004).

Next, transformations of row trade coefficient to column trade coefficients are calculated as follows (Hewings et al., 2001):

$$CT_i^{rs} = \frac{RT_i^{rs} \cdot e^r}{\sum_r RT_i^{rs} \cdot e^r} \qquad (13a)$$

where e^r is total employment in region r. The CT_i^{rs} are normalized as,

$$\sum_r CT_i^{rs} = 1 \qquad (13b)$$

Fourth, a column trade coefficient matrix *C* is generated for pairs of regions:

$$C = \begin{bmatrix} C^{rr} & C^{rs} \\ C^{sr} & C^{ss} \end{bmatrix} = \begin{bmatrix} CT_1^{rr} & 0 & \dots & 0 & CT_1^{rs} & 0 & \dots & 0 \\ 0 & CT_2^{rr} & \dots & 0 & 0 & CT_2^{rs} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & CT_n^{rr} & 0 & 0 & \dots & CT_n^{rs} \\ CT_1^{sr} & 0 & \dots & 0 & CT_1^{ss} & 0 & \dots & 0 \\ 0 & CT_2^{sr} & \dots & 0 & 0 & CT_2^{ss} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & CT_n^{sr} & 0 & 0 & \dots & CT_n^{ss} \end{bmatrix} \tag{14}$$

for *i=1, 2, …, n* sectors.

Finally, the *C* matrix is used to generate off-diagonal direct requirement matrices representing transaction linkages between regions. The resulting multi-regional direct requirement matrix A^M is

$$A^M = C \begin{bmatrix} A^r & 0 \\ 0 & A^s \end{bmatrix} = \begin{bmatrix} A^{rr} & A^{rs} \\ A^{sr} & A^{ss} \end{bmatrix} \tag{15}$$

The off-diagonal matrices A^{sr} and A^{rs} in equation (15) measure the value intensity of inter-regional transactions.

Multi-regional direct requirement matrices constructed with the LQ approach has been criticized and modified to account for cross-hauling effects (Morrison and Smith, 1974; Round, 1983); for example, the Cross Industry Location Quotients (CILQ) (Schafer and Chu, 1969) and Flegg’s Location Quotients (FLQ) (Flegg, Webber and Elliott, 1995). Variants of LQs have also been used, but each has limitations. The CILQ index admits some cross-hauling effects, but the index is unable to account for all cross-hauling purchases. In addition, the CILQ index does not adequately capture regional economic size (Round, 1983). The FLQ index accounts for a region’s economic size and cross-hauling. However, the FLQ index requires estimation of a coefficient and is difficult to empirically determine (Flegg, Webber and Elliott, 1995).

This study uses the conventional form of Location Quotient (sometimes referred to as a “Simple Location Quotient”, SLQ, in literature), calculated as:

$$SLQ_i^r = \frac{e_i^r/e^r}{e_i^N/e^N} \tag{16}$$

where e_i is regional employment in sector i; e denotes the total regional employment, and r and N represent the sub-regional BEA level and entire southeastern U.S. level, respectively. The numerator is the sub-regional sector intensity of sector i, and the denominator is the southeastern U.S. sector intensity. Under the assumption that labor productivity is identical across all BEAs and sectors, employment is a suitable proxy to describe the economic activity.

The SLQ is used in this study for three reasons. First, Schafer and Chu (1969) and Morrison and Smith (1974) concluded that SLQs provided close estimates of a regional IO tables compared to survey-based IO tables. Second, BEA regions are assumed to experience minimal cross-hauling effects. Third, the SLQ is the best choice considering the data availability[4].

Data

Sector and regional employment and distances between BEA regions are used to determine the export shares. Counties are aggregated into BEA regions based on the U.S. county shape file from ESRI ArcGIS (Esri Data and Maps, 2017) to generate the BEA centroids.

Regional employment of the 536 economic sectors (Table 4) were obtained from the IMPLAN data base (MIG, Inc., 2013).

This study focuses on industry to industry relationships. Therefore, the direct requirement matrices ($A^r = [a_{ij}^r]$) (536×536) for all 43 BEA regions were built based on the $I \times I$ tables extracted from the IMPLAN data base (MIG, Inc., 2013).

[4] Table 6 in Appendix shows formulas of these three LQs

Results and Discussion

The rank of each BEA direct requirement matrix (A^r) is determined to summarize the inter-industrial linkages in each BEA region (Table 5). Each A^r matrix has 536 rows and 536 columns. When the matrix rank is less than 536, it implies that at least one sector does not link with other sectors (for example, non-tradable commodities). The matrix rank of economies producing relatively more non-tradable commodities is relatively lower.

Based on the matrix ranks, BEA 19 (Birmingham-Hoover, AL) exhibits the most intra-regional linkages (rank = 429), while BEA 68 (Anderson, Greenville and Spartanburg, SC) has the lowest number of intra-regional linkages (rank = 235).

Figures were used to qualitatively generalize the A^M $(536 \times 43\ by\ 536 \times 43)$ to highlight the matrix's structure. The *spy* function in Matlab software (MathWorks, 2016) is used to visualize the A^M. This function plots the sparsity pattern of any matrix"[5]. If a regional input coefficient is 0, then the corresponding cell in the *spy* figure is empty; otherwise, it is blue. In this case, a blue dot indicates transactions between corresponding regions and sectors (Figure 3). The rows of A^M represent distributing (selling) sectors *i* (*j*). Row elements indicate how one dollar output of distributing sector *i* is used in the production receiving sectors *j*. The columns are receiving (purchasing) sectors. Column elements indicate how many unit output from sectors *i* is used to produce one dollar output of sector *j*. For each column (output sector), every row represents an input sector supporting the output sector. Empty cells indicate that no inputs are required from the row sector for the output sector's production. The diagonal square matrices (536×536) are the *intraregional* economic linkages in each BEA region.

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[5] The function information can be found at:
https://www.mathworks.com/help/matlab/ref/spy.html

The *spy* figure of the first four BEA regions are presented for closer inspection and explication (Figure 4). The four square matrices on the matrix diagonal are the *intraregional* input coefficients of first four BEA regions. The off-diagonal cells in the matrix describe the *interregional* transaction relationship.

In this example, it is unsurprising to find numerous rows with empty off-diagonal cells. These sectors do not contribute to the production of goods in other sectors in other regions (Figure 4). There are two additional reasons for zero contributions to other regions. First, those sectors' LQs are less than or equal to 1; i.e., then export share is zero (equation 9). In this case, this sector does not contribute to the production of goods in other regions. Second, the corresponding distributing sector's outputs are non-tradable goods (such as the construction of residential structures, highways and streets). These commodities cannot be traded between regions. There are also vertical blank columns indicating zero output for the corresponding regional sectors (Figure 4).

The A^M matrix constructed in this chapter is used in Chapter 3 to analyze the southeastern U.S.'s water footprint. In Chapter 4, A^M is used to estimate the water shadow value in the southeastern U.S.

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Appendix B

Figures

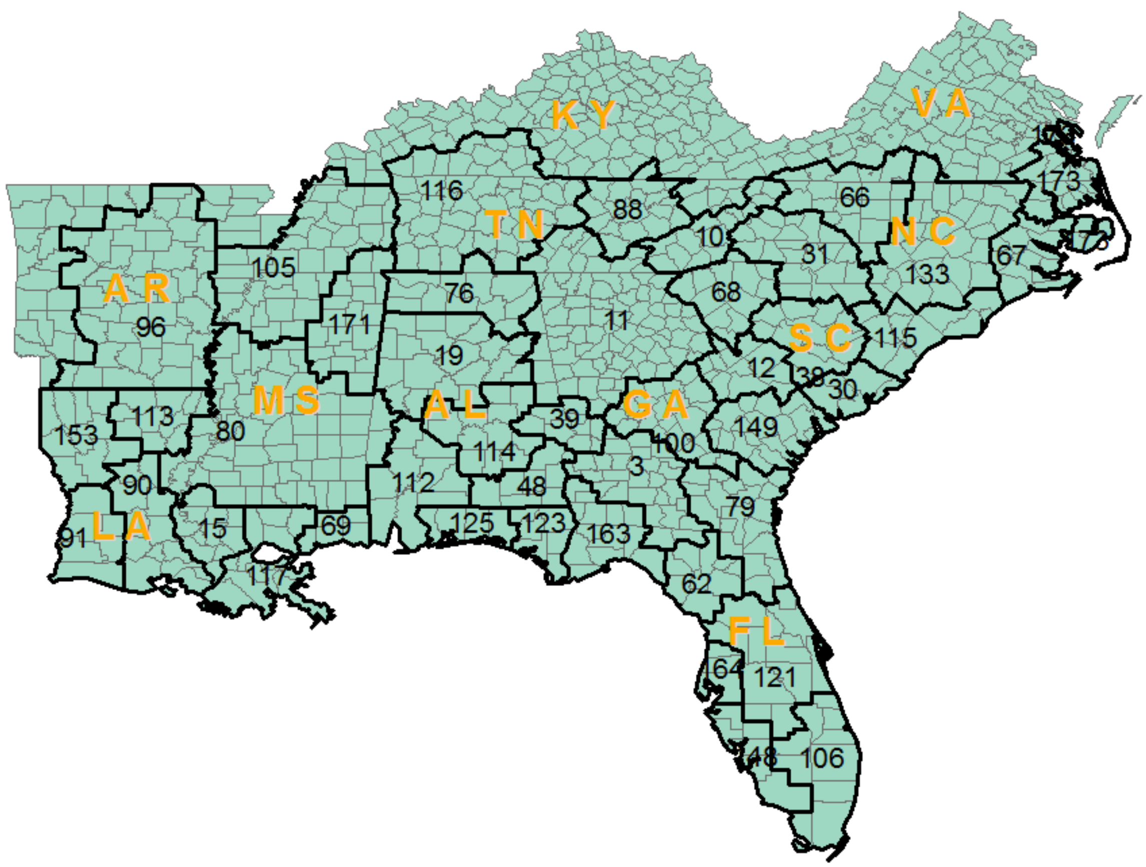

Figure 1. Bureau of Economic Analysis Regions of the Study Area
Source: ERSI ArcGIS

		PRODUCERS AS CONSUMERS								FINAL DEMAND			
		Agric.	Mining	Const.	Manuf.	Trade	Transp.	Services	Other	Personal Consumption Expenditures	Gross Private Domestic Investment	Govt. Purchases of Goods & Services	Net Exports of Goods & Services
PRODUCERS	Agriculture												
	Mining												
	Construction												
	Manufacturing												
	Trade												
	Transportation												
	Services												
	Other Industry												
VALUE ADDED	Employees	Employee compensation								GROSS DOMESTIC PRODUCT			
	Business Owners and Capital	Profit-type income and capital consumption allowances											
	Government	Indirect business taxes											

Figure 2. Input-Output Transactions Table
Source: Miller and Blair (2009), page 3.

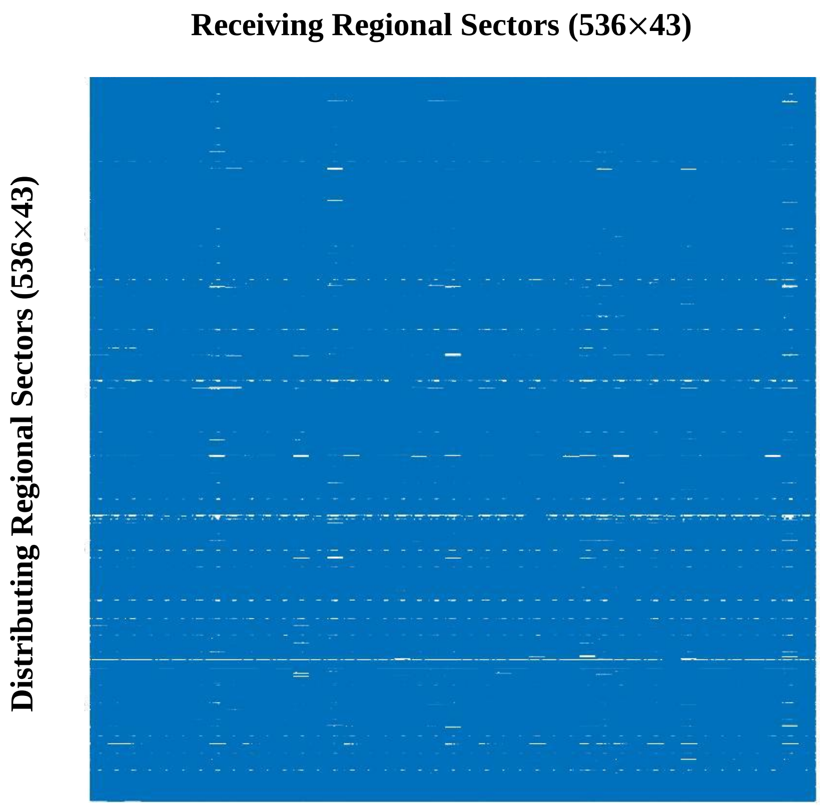

Figure 3. Spy Figure of the Southeastern U.S. Multi-Regional Direct Requirement Matrix

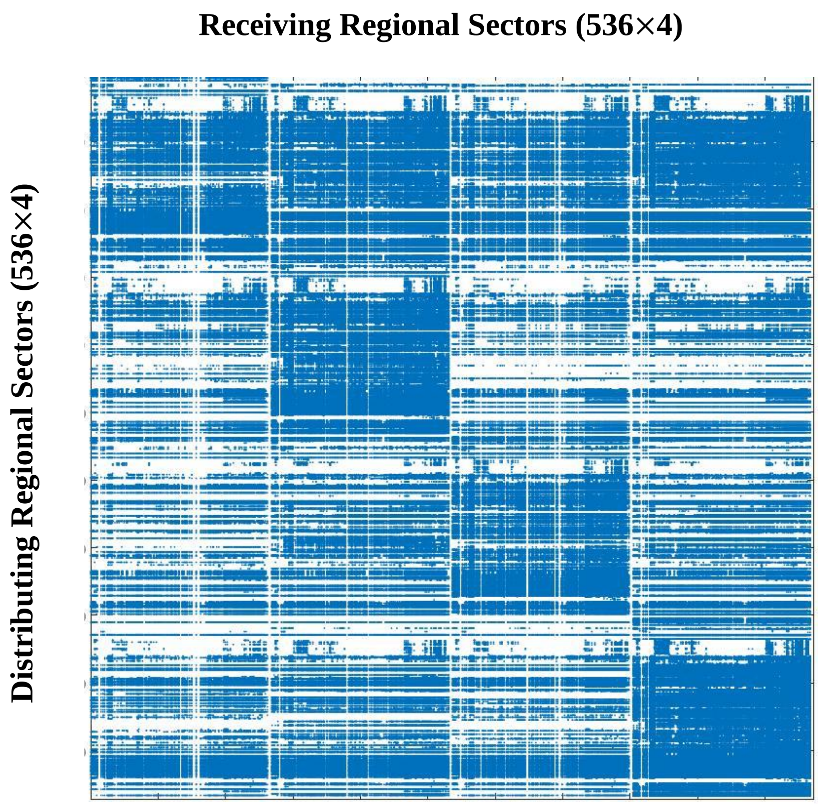

Figure 4. Spy Figure of the Multiregional Direct Requirement Matrix of the First Four BEA Regions

Note: The first four BEA regions are: BEA 03 (Albany and Valdosta, GA); BEA 10 (Asheville, NC); BEA 11 (Atlanta, GA) and BEA 12 (Augusta-Richmond, GA-SC);

Tables

Table 3. Exports and Imports of Commodities and Services in the U.S., 2007 to 2016

Year	Exports (million $)	Imports (million $)	GDP (million $)	Export proportion	Import proportion
2007	1,653,548	2,358,922	14,391,149	11.49%	16.39%
2008	1,841,612	2,550,339	14,626,598	12.59%	17.44%
2009	1,583,053	1,966,827	14,320,114	11.05%	13.73%
2010	1,853,606	2,348,263	14,859,772	12.47%	15.80%
2011	2,127,021	2,675,646	15,406,002	13.81%	17.37%
2012	2,218,989	2,755,762	16,041,243	13.83%	17.18%
2013	2,293,457	2,755,334	16,576,738	13.84%	16.62%
2014	2,376,577	2,866,754	17,277,518	13.76%	16.59%
2015	2,261,163	2,761,525	17,925,143	12.61%	15.41%
2016	2,212,079	2,712,639	18,456,292	11.99%	14.70%

Source: Bureau of Economic Analysis, International Trade and Investment Country Facts. https://www.bea.gov/international/factsheet/factsheet.cfm?Area=000

Table 4. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
1	Oilseed farming	1	Primary Agricultural Crops
2	Grain farming	1	Primary Agricultural Crops
3	Vegetable and melon farming	1	Primary Agricultural Crops
4	Fruit farming	1	Primary Agricultural Crops
5	Tree nut farming	1	Primary Agricultural Crops
6	Greenhouse, nursery, and floriculture production	1	Primary Agricultural Crops
7	Tobacco farming	1	Primary Agricultural Crops
8	Cotton farming	1	Primary Agricultural Crops
9	Sugarcane and sugar beet farming	1	Primary Agricultural Crops
10	All other crop farming	1	Primary Agricultural Crops
11	Beef cattle ranching and farming, including feedlots and dual-purpose ranching and farming	2	Primary Agriculture Livestock
12	Dairy cattle and milk production	2	Primary Agriculture Livestock
13	Poultry and egg production	2	Primary Agriculture Livestock
14	Animal production, except cattle and poultry and eggs	2	Primary Agriculture Livestock
15	Forestry, forest products, and timber tract production	3	Forestry Inputs
16	Commercial logging	3	Forestry Inputs
17	Commercial fishing	2	Primary Agriculture Livestock
18	Commercial hunting and trapping	2	Primary Agriculture Livestock
19	Support activities for agriculture and forestry	1	Primary Agricultural Crops
20	Extraction of natural gas and crude petroleum	4	Mining
21	Extraction of natural gas liquids	4	Mining
22	Coal mining	4	Mining
23	Iron ore mining	4	Mining
24	Gold ore mining	4	Mining

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
25	Silver ore mining	**4**	Mining
26	Lead and zinc ore mining	**4**	Mining
27	Copper ore mining	**4**	Mining
28	Uranium-radium-vanadium ore mining	**4**	Mining
29	Other metal ore mining	**4**	Mining
30	Stone mining and quarrying	**4**	Mining
31	Sand and gravel mining	**4**	Mining
32	Other clay, ceramic, refractory minerals mining	**4**	Mining
33	Potash, soda, and borate mineral mining	**4**	Mining
34	Phosphate rock mining	**4**	Mining
35	Other chemical and fertilizer mineral mining	**4**	Mining
36	Other nonmetallic minerals	**4**	Mining
37	Drilling oil and gas wells	**4**	Mining
38	Support activities for oil and gas operations	**4**	Mining
39	Metal mining services	**5**	Services
40	Other nonmetallic minerals services	**5**	Services
41	Electric power generation - Hydroelectric	**6**	Utilities
42	Electric power generation - Fossil fuel	**6**	Utilities
43	Electric power generation - Nuclear	**6**	Utilities
44	Electric power generation - Solar	**6**	Utilities
45	Electric power generation - Wind	**6**	Utilities
46	Electric power generation - Geothermal	**6**	Utilities
47	Electric power generation - Biomass	**6**	Utilities
48	Electric power generation - All other	**6**	Utilities
49	Electric power transmission and distribution	**6**	Utilities
50	Natural gas distribution	**6**	Utilities
51	Water, sewage and other systems	**7**	Water, Sewage, and other systems
52	Construction of new health care structures	**8**	Construction
53	Construction of new manufacturing structures	**8**	Construction

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
54	Construction of new power and communication structures	**8**	Construction
55	Construction of new educational and vocational structures	**8**	Construction
56	Construction of new highways and streets	**8**	Construction
57	Construction of new commercial structures, including farm structures	**8**	Construction
58	Construction of other new nonresidential structures	**8**	Construction
59	Construction of new single-family residential structures	**8**	Construction
60	Construction of new multifamily residential structures	**8**	Construction
61	Construction of other new residential structures	**8**	Construction
62	Maintenance and repair construction of nonresidential structures	**8**	Construction
63	Maintenance and repair construction of residential structures	**8**	Construction
64	Maintenance and repair construction of highways, streets, bridges, and tunnels	**8**	Construction
65	Dog and cat food manufacturing	**9**	Secondary Agriculture
66	Other animal food manufacturing	**9**	Secondary Agriculture
67	Flour milling	**9**	Secondary Agriculture
68	Rice milling	**9**	Secondary Agriculture
69	Malt manufacturing	**9**	Secondary Agriculture
70	Wet corn milling	**9**	Secondary Agriculture
71	Soybean and other oilseed processing	**9**	Secondary Agriculture
72	Fats and oils refining and blending	**9**	Secondary Agriculture
73	Breakfast cereal manufacturing	**9**	Secondary Agriculture
74	Beet sugar manufacturing	**9**	Secondary Agriculture
75	Sugar cane mills and refining	**9**	Secondary Agriculture

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
76	Nonchocolate confectionery manufacturing	**9**	Secondary Agriculture
77	Chocolate and confectionery manufacturing from cacao beans	**9**	Secondary Agriculture
78	Confectionery manufacturing from purchased chocolate	**9**	Secondary Agriculture
79	Frozen fruits, juices and vegetables manufacturing	**9**	Secondary Agriculture
80	Frozen specialties manufacturing	**9**	Secondary Agriculture
81	Canned fruits and vegetables manufacturing	**9**	Secondary Agriculture
82	Canned specialties	**9**	Secondary Agriculture
83	Dehydrated food products manufacturing	**9**	Secondary Agriculture
84	Fluid milk manufacturing	**9**	Secondary Agriculture
85	Creamery butter manufacturing	**9**	Secondary Agriculture
86	Cheese manufacturing	**9**	Secondary Agriculture
87	Dry, condensed, and evaporated dairy product manufacturing	**9**	Secondary Agriculture
88	Ice cream and frozen dessert manufacturing	**9**	Secondary Agriculture
89	Animal, except poultry, slaughtering	**9**	Secondary Agriculture
90	Meat processed from carcasses	**9**	Secondary Agriculture
91	Rendering and meat byproduct processing	**9**	Secondary Agriculture
92	Poultry processing	**9**	Secondary Agriculture
93	Seafood product preparation and packaging	**9**	Secondary Agriculture
94	Bread and bakery product, except frozen, manufacturing	**9**	Secondary Agriculture
95	Frozen cakes and other pastries manufacturing	**9**	Secondary Agriculture
96	Cookie and cracker manufacturing	**9**	Secondary Agriculture
97	Dry pasta, mixes, and dough manufacturing	**9**	Secondary Agriculture
98	Tortilla manufacturing	**9**	Secondary Agriculture
99	Roasted nuts and peanut butter manufacturing	**9**	Secondary Agriculture
100	Other snack food manufacturing	**9**	Secondary Agriculture

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
101	Coffee and tea manufacturing	**9**	Secondary Agriculture
102	Flavoring syrup and concentrate manufacturing	**9**	Secondary Agriculture
103	Mayonnaise, dressing, and sauce manufacturing	**9**	Secondary Agriculture
104	Spice and extract manufacturing	**9**	Secondary Agriculture
105	All other food manufacturing	**9**	Secondary Agriculture
106	Bottled and canned soft drinks & water	**9**	Secondary Agriculture
107	Manufactured ice	**10**	Manufacturing
108	Breweries	**9**	Secondary Agriculture
109	Wineries	**9**	Secondary Agriculture
110	Distilleries	**9**	Secondary Agriculture
111	Tobacco product manufacturing	**9**	Secondary Agriculture
112	Fiber, yarn, and thread mills	**9**	Secondary Agriculture
113	Broadwoven fabric mills	**9**	Secondary Agriculture
114	Narrow fabric mills and schiffli machine embroidery	**9**	Secondary Agriculture
115	Nonwoven fabric mills	**9**	Secondary Agriculture
116	Knit fabric mills	**9**	Secondary Agriculture
117	Textile and fabric finishing mills	**9**	Secondary Agriculture
118	Fabric coating mills	**9**	Secondary Agriculture
119	Carpet and rug mills	**9**	Secondary Agriculture
120	Curtain and linen mills	**9**	Secondary Agriculture
121	Textile bag and canvas mills	**9**	Secondary Agriculture
122	Rope, cordage, twine, tire cord and tire fabric mills	**9**	Secondary Agriculture
123	Other textile product mills	**9**	Secondary Agriculture
124	Hosiery and sock mills	**9**	Secondary Agriculture
125	Other apparel knitting mills	**9**	Secondary Agriculture
126	Cut and sew apparel contractors	**9**	Secondary Agriculture
127	Men's and boys' cut and sew apparel manufacturing	**9**	Secondary Agriculture

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
128	Women's and girls' cut and sew apparel manufacturing	**9**	Secondary Agriculture
129	Other cut and sew apparel manufacturing	**9**	Secondary Agriculture
130	Apparel accessories and other apparel manufacturing	**9**	Secondary Agriculture
131	Leather and hide tanning and finishing	**9**	Secondary Agriculture
132	Footwear manufacturing	**9**	Secondary Agriculture
133	Other leather and allied product manufacturing	**9**	Secondary Agriculture
134	Sawmills	**11**	Primary Forestry
135	Wood preservation	**11**	Primary Forestry
136	Veneer and plywood manufacturing	**12**	Secondary Forestry
137	Engineered wood member and truss manufacturing	**12**	Secondary Forestry
138	Reconstituted wood product manufacturing	**12**	Secondary Forestry
139	Wood windows and door manufacturing	**12**	Secondary Forestry
140	Cut stock, resawing lumber, and planing	**12**	Secondary Forestry
141	Other millwork, including flooring	**12**	Secondary Forestry
142	Wood container and pallet manufacturing	**12**	Secondary Forestry
143	Manufactured home (mobile home) manufacturing	**12**	Secondary Forestry
144	Prefabricated wood building manufacturing	**12**	Secondary Forestry
145	All other miscellaneous wood product manufacturing	**12**	Secondary Forestry
146	Pulp mills	**11**	Primary Forestry
147	Paper mills	**11**	Primary Forestry
148	Paperboard mills	**11**	Primary Forestry
149	Paperboard container manufacturing	**12**	Secondary Forestry
150	Paper bag and coated and treated paper manufacturing	**12**	Secondary Forestry
151	Stationery product manufacturing	**12**	Secondary Forestry
152	Sanitary paper product manufacturing	**12**	Secondary Forestry

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
153	All other converted paper product manufacturing	**12**	Secondary Forestry
154	Printing	**10**	Manufacturing
155	Support activities for printing	**10**	Manufacturing
156	Petroleum refineries	**10**	Manufacturing
157	Asphalt paving mixture and block manufacturing	**10**	Manufacturing
158	Asphalt shingle and coating materials manufacturing	**10**	Manufacturing
159	Petroleum lubricating oil and grease manufacturing	**10**	Manufacturing
160	All other petroleum and coal products manufacturing	**10**	Manufacturing
161	Petrochemical manufacturing	**10**	Manufacturing
162	Industrial gas manufacturing	**10**	Manufacturing
163	Synthetic dye and pigment manufacturing	**10**	Manufacturing
164	Other basic inorganic chemical manufacturing	**10**	Manufacturing
165	Other basic organic chemical manufacturing	**10**	Manufacturing
166	Plastics material and resin manufacturing	**10**	Manufacturing
167	Synthetic rubber manufacturing	**10**	Manufacturing
168	Artificial and synthetic fibers and filaments manufacturing	**10**	Manufacturing
169	Nitrogenous fertilizer manufacturing	**13**	Agricultural Inputs
170	Phosphatic fertilizer manufacturing	**13**	Agricultural Inputs
171	Fertilizer mixing	**13**	Agricultural Inputs
172	Pesticide and other agricultural chemical manufacturing	**13**	Agricultural Inputs
173	Medicinal and botanical manufacturing	**10**	Manufacturing
174	Pharmaceutical preparation manufacturing	**10**	Manufacturing
175	In-vitro diagnostic substance manufacturing	**10**	Manufacturing
176	Biological product (except diagnostic) manufacturing	**10**	Manufacturing

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
177	Paint and coating manufacturing	**10**	Manufacturing
178	Adhesive manufacturing	**10**	Manufacturing
179	Soap and other detergent manufacturing	**10**	Manufacturing
180	Polish and other sanitation good manufacturing	**10**	Manufacturing
181	Surface active agent manufacturing	**10**	Manufacturing
182	Toilet preparation manufacturing	**10**	Manufacturing
183	Printing ink manufacturing	**10**	Manufacturing
184	Explosives manufacturing	**10**	Manufacturing
185	Custom compounding of purchased resins	**10**	Manufacturing
186	Photographic film and chemical manufacturing	**10**	Manufacturing
187	Other miscellaneous chemical product manufacturing	**10**	Manufacturing
188	Plastics packaging materials and unlaminated film and sheet manufacturing	**10**	Manufacturing
189	Unlaminated plastics profile shape manufacturing	**10**	Manufacturing
190	Plastics pipe and pipe fitting manufacturing	**10**	Manufacturing
191	Laminated plastics plate, sheet (except packaging), and shape manufacturing	**10**	Manufacturing
192	Polystyrene foam product manufacturing	**10**	Manufacturing
193	Urethane and other foam product (except polystyrene) manufacturing	**10**	Manufacturing
194	Plastics bottle manufacturing	**10**	Manufacturing
195	Other plastics product manufacturing	**10**	Manufacturing
196	Tire manufacturing	**10**	Manufacturing
197	Rubber and plastics hoses and belting manufacturing	**10**	Manufacturing
198	Other rubber product manufacturing	**10**	Manufacturing
199	Pottery, ceramics, and plumbing fixture manufacturing	**10**	Manufacturing

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
200	Brick, tile, and other structural clay product manufacturing	**10**	Manufacturing
201	Flat glass manufacturing	**10**	Manufacturing
202	Other pressed and blown glass and glassware manufacturing	**10**	Manufacturing
203	Glass container manufacturing	**10**	Manufacturing
204	Glass product manufacturing made of purchased glass	**10**	Manufacturing
205	Cement manufacturing	**10**	Manufacturing
206	Ready-mix concrete manufacturing	**10**	Manufacturing
207	Concrete block and brick manufacturing	**10**	Manufacturing
208	Concrete pipe manufacturing	**10**	Manufacturing
209	Other concrete product manufacturing	**10**	Manufacturing
210	Lime manufacturing	**13**	Agricultural Inputs
211	Gypsum product manufacturing	**10**	Manufacturing
212	Abrasive product manufacturing	**10**	Manufacturing
213	Cut stone and stone product manufacturing	**10**	Manufacturing
214	Ground or treated mineral and earth manufacturing	**10**	Manufacturing
215	Mineral wool manufacturing	**10**	Manufacturing
216	Miscellaneous nonmetallic mineral products manufacturing	**10**	Manufacturing
217	Iron and steel mills and ferroalloy manufacturing	**10**	Manufacturing
218	Iron, steel pipe and tube manufacturing from purchased steel	**10**	Manufacturing
219	Rolled steel shape manufacturing	**10**	Manufacturing
220	Steel wire drawing	**10**	Manufacturing
221	Alumina refining and primary aluminum production	**10**	Manufacturing
222	Secondary smelting and alloying of aluminum	**10**	Manufacturing
223	Aluminum sheet, plate, and foil manufacturing	**10**	Manufacturing

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
224	Other aluminum rolling, drawing and extruding	**10**	Manufacturing
225	Nonferrous metal (exc aluminum) smelting and refining	**10**	Manufacturing
226	Copper rolling, drawing, extruding and alloying	**10**	Manufacturing
227	Nonferrous metal, except copper and aluminum, shaping	**10**	Manufacturing
228	Secondary processing of other nonferrous metals	**10**	Manufacturing
229	Ferrous metal foundries	**10**	Manufacturing
230	Nonferrous metal foundries	**10**	Manufacturing
231	Iron and steel forging	**10**	Manufacturing
232	Nonferrous forging	**10**	Manufacturing
233	Custom roll forming	**10**	Manufacturing
234	Crown and closure manufacturing and metal stamping	**10**	Manufacturing
235	Cutlery, utensil, pot, and pan manufacturing	**10**	Manufacturing
236	Handtool manufacturing	**10**	Manufacturing
237	Prefabricated metal buildings and components manufacturing	**10**	Manufacturing
238	Fabricated structural metal manufacturing	**10**	Manufacturing
239	Plate work manufacturing	**10**	Manufacturing
240	Metal window and door manufacturing	**10**	Manufacturing
241	Sheet metal work manufacturing	**10**	Manufacturing
242	Ornamental and architectural metal work manufacturing	**10**	Manufacturing
243	Power boiler and heat exchanger manufacturing	**10**	Manufacturing
244	Metal tank (heavy gauge) manufacturing	**10**	Manufacturing
245	Metal cans manufacturing	**10**	Manufacturing
246	Metal barrels, drums and pails manufacturing	**10**	Manufacturing
247	Hardware manufacturing	**10**	Manufacturing

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
248	Spring and wire product manufacturing	**10**	Manufacturing
249	Machine shops	**10**	Manufacturing
250	Turned product and screw, nut, and bolt manufacturing	**10**	Manufacturing
251	Metal heat treating	**10**	Manufacturing
252	Metal coating and nonprecious engraving	**10**	Manufacturing
253	Electroplating, anodizing, and coloring metal	**10**	Manufacturing
254	Valve and fittings, other than plumbing, manufacturing	**10**	Manufacturing
255	Plumbing fixture fitting and trim manufacturing	**10**	Manufacturing
256	Ball and roller bearing manufacturing	**10**	Manufacturing
257	Small arms ammunition manufacturing	**10**	Manufacturing
258	Ammunition, except for small arms, manufacturing	**10**	Manufacturing
259	Small arms, ordnance, and accessories manufacturing	**10**	Manufacturing
260	Fabricated pipe and pipe fitting manufacturing	**10**	Manufacturing
261	Other fabricated metal manufacturing	**10**	Manufacturing
262	Farm machinery and equipment manufacturing	**13**	Agricultural Inputs
263	Lawn and garden equipment manufacturing	**13**	Agricultural Inputs
264	Construction machinery manufacturing	**10**	Manufacturing
265	Mining machinery and equipment manufacturing	**10**	Manufacturing
266	Oil and gas field machinery and equipment manufacturing	**10**	Manufacturing
267	Food product machinery manufacturing	**10**	Manufacturing
268	Semiconductor machinery manufacturing	**10**	Manufacturing
269	Sawmill, woodworking, and paper machinery	**11**	Primary Forestry
270	Printing machinery and equipment manufacturing	**10**	Manufacturing
271	All other industrial machinery manufacturing	**10**	Manufacturing
272	Optical instrument and lens manufacturing	**10**	Manufacturing

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
273	Photographic and photocopying equipment manufacturing	**10**	Manufacturing
274	Other commercial service industry machinery manufacturing	**10**	Manufacturing
275	Air purification and ventilation equipment manufacturing	**10**	Manufacturing
276	Heating equipment (except warm air furnaces) manufacturing	**10**	Manufacturing
277	Air conditioning, refrigeration, and warm air heating equipment manufacturing	**10**	Manufacturing
278	Industrial mold manufacturing	**10**	Manufacturing
279	Special tool, die, jig, and fixture manufacturing	**10**	Manufacturing
280	Cutting tool and machine tool accessory manufacturing	**10**	Manufacturing
281	Machine tool manufacturing	**10**	Manufacturing
282	Rolling mill and other metalworking machinery manufacturing	**10**	Manufacturing
283	Turbine and turbine generator set units manufacturing	**10**	Manufacturing
284	Speed changer, industrial high-speed drive, and gear manufacturing	**10**	Manufacturing
285	Mechanical power transmission equipment manufacturing	**10**	Manufacturing
286	Other engine equipment manufacturing	**10**	Manufacturing
287	Pump and pumping equipment manufacturing	**10**	Manufacturing
288	Air and gas compressor manufacturing	**10**	Manufacturing
289	Measuring and dispensing pump manufacturing	**10**	Manufacturing
290	Elevator and moving stairway manufacturing	**10**	Manufacturing
291	Conveyor and conveying equipment manufacturing	**10**	Manufacturing

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
292	Overhead cranes, hoists, and monorail systems manufacturing	**10**	Manufacturing
293	Industrial truck, trailer, and stacker manufacturing	**10**	Manufacturing
294	Power-driven handtool manufacturing	**10**	Manufacturing
295	Welding and soldering equipment manufacturing	**10**	Manufacturing
296	Packaging machinery manufacturing	**10**	Manufacturing
297	Industrial process furnace and oven manufacturing	**10**	Manufacturing
298	Fluid power cylinder and actuator manufacturing	**10**	Manufacturing
299	Fluid power pump and motor manufacturing	**10**	Manufacturing
300	Scales, balances, and miscellaneous general purpose machinery manufacturing	**10**	Manufacturing
301	Electronic computer manufacturing	**10**	Manufacturing
302	Computer storage device manufacturing	**10**	Manufacturing
303	Computer terminals and other computer peripheral equipment manufacturing	**10**	Manufacturing
304	Telephone apparatus manufacturing	**10**	Manufacturing
305	Broadcast and wireless communications equipment manufacturing	**10**	Manufacturing
306	Other communications equipment manufacturing	**10**	Manufacturing
307	Audio and video equipment manufacturing	**10**	Manufacturing
308	Bare printed circuit board manufacturing	**10**	Manufacturing
309	Semiconductor and related device manufacturing	**10**	Manufacturing
310	Capacitor, resistor, coil, transformer, and other inductor manufacturing	**10**	Manufacturing
311	Electronic connector manufacturing	**10**	Manufacturing
312	Printed circuit assembly (electronic assembly) manufacturing	**10**	Manufacturing
313	Other electronic component manufacturing	**10**	Manufacturing
314	Electromedical and electrotherapeutic apparatus manufacturing	**10**	Manufacturing

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
315	Search, detection, and navigation instruments manufacturing	**10**	Manufacturing
316	Automatic environmental control manufacturing	**10**	Manufacturing
317	Industrial process variable instruments manufacturing	**10**	Manufacturing
318	Totalizing fluid meter and counting device manufacturing	**10**	Manufacturing
319	Electricity and signal testing instruments manufacturing	**10**	Manufacturing
320	Analytical laboratory instrument manufacturing	**10**	Manufacturing
321	Irradiation apparatus manufacturing	**10**	Manufacturing
322	Watch, clock, and other measuring and controlling device manufacturing	**10**	Manufacturing
323	Blank magnetic and optical recording media manufacturing	**10**	Manufacturing
324	Software and other prerecorded and record reproducing	**10**	Manufacturing
325	Electric lamp bulb and part manufacturing	**10**	Manufacturing
326	Lighting fixture manufacturing	**10**	Manufacturing
327	Small electrical appliance manufacturing	**10**	Manufacturing
328	Household cooking appliance manufacturing	**10**	Manufacturing
329	Household refrigerator and home freezer manufacturing	**10**	Manufacturing
330	Household laundry equipment manufacturing	**10**	Manufacturing
331	Other major household appliance manufacturing	**10**	Manufacturing
332	Power, distribution, and specialty transformer manufacturing	**10**	Manufacturing
333	Motor and generator manufacturing	**10**	Manufacturing
334	Switchgear and switchboard apparatus manufacturing	**10**	Manufacturing

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
335	Relay and industrial control manufacturing	**10**	Manufacturing
336	Storage battery manufacturing	**10**	Manufacturing
337	Primary battery manufacturing	**10**	Manufacturing
338	Fiber optic cable manufacturing	**10**	Manufacturing
339	Other communication and energy wire manufacturing	**10**	Manufacturing
340	Wiring device manufacturing	**10**	Manufacturing
341	Carbon and graphite product manufacturing	**10**	Manufacturing
342	All other miscellaneous electrical equipment and component manufacturing	**10**	Manufacturing
343	Automobile manufacturing	**10**	Manufacturing
344	Light truck and utility vehicle manufacturing	**10**	Manufacturing
345	Heavy duty truck manufacturing	**10**	Manufacturing
346	Motor vehicle body manufacturing	**10**	Manufacturing
347	Truck trailer manufacturing	**10**	Manufacturing
348	Motor home manufacturing	**10**	Manufacturing
349	Travel trailer and camper manufacturing	**10**	Manufacturing
350	Motor vehicle gasoline engine and engine parts manufacturing	**10**	Manufacturing
351	Motor vehicle electrical and electronic equipment manufacturing	**10**	Manufacturing
352	Motor vehicle steering, suspension component (except spring), and brake systems manufacturing	**10**	Manufacturing
353	Motor vehicle transmission and power train parts manufacturing	**10**	Manufacturing
354	Motor vehicle seating and interior trim manufacturing	**10**	Manufacturing
355	Motor vehicle metal stamping	**10**	Manufacturing
356	Other motor vehicle parts manufacturing	**10**	Manufacturing
357	Aircraft manufacturing	**10**	Manufacturing

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
358	Aircraft engine and engine parts manufacturing	**10**	Manufacturing
359	Other aircraft parts and auxiliary equipment manufacturing	**10**	Manufacturing
360	Guided missile and space vehicle manufacturing	**10**	Manufacturing
361	Propulsion units and parts for space vehicles and guided missiles manufacturing	**10**	Manufacturing
362	Railroad rolling stock manufacturing	**10**	Manufacturing
363	Ship building and repairing	**10**	Manufacturing
364	Boat building	**10**	Manufacturing
365	Motorcycle, bicycle, and parts manufacturing	**10**	Manufacturing
366	Military armored vehicle, tank, and tank component manufacturing	**10**	Manufacturing
367	All other transportation equipment manufacturing	**10**	Manufacturing
368	Wood kitchen cabinet and countertop manufacturing	**12**	Secondary Forestry
369	Upholstered household furniture manufacturing	**12**	Secondary Forestry
370	Nonupholstered wood household furniture manufacturing	**12**	Secondary Forestry
371	Other household nonupholstered furniture manufacturing	**12**	Secondary Forestry
372	Institutional furniture manufacturing	**12**	Secondary Forestry
373	Wood office furniture manufacturing	**12**	Secondary Forestry
374	Custom architectural woodwork and millwork	**12**	Secondary Forestry
375	Office furniture, except wood, manufacturing	**10**	Manufacturing
376	Showcase, partition, shelving, and locker manufacturing	**12**	Secondary Forestry
377	Mattress manufacturing	**12**	Secondary Forestry
378	Blind and shade manufacturing	**12**	Secondary Forestry
379	Surgical and medical instrument manufacturing	**10**	Manufacturing
380	Surgical appliance and supplies manufacturing	**10**	Manufacturing

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
381	Dental equipment and supplies manufacturing	**10**	Manufacturing
382	Ophthalmic goods manufacturing	**10**	Manufacturing
383	Dental laboratories	**10**	Manufacturing
384	Jewelry and silverware manufacturing	**10**	Manufacturing
385	Sporting and athletic goods manufacturing	**10**	Manufacturing
386	Doll, toy, and game manufacturing	**10**	Manufacturing
387	Office supplies (except paper) manufacturing	**10**	Manufacturing
388	Sign manufacturing	**10**	Manufacturing
389	Gasket, packing, and sealing device manufacturing	**10**	Manufacturing
390	Musical instrument manufacturing	**10**	Manufacturing
391	Fasteners, buttons, needles, and pins manufacturing	**10**	Manufacturing
392	Broom, brush, and mop manufacturing	**10**	Manufacturing
393	Burial casket manufacturing	**10**	Manufacturing
394	All other miscellaneous manufacturing	**10**	Manufacturing
395	Wholesale trade	**14**	Wholesale Trade
396	Retail - Motor vehicle and parts dealers	**15**	Retail Trade
397	Retail - Furniture and home furnishings stores	**15**	Retail Trade
398	Retail - Electronics and appliance stores	**15**	Retail Trade
399	Retail - Building material and garden equipment and supplies stores	**15**	Retail Trade
400	Retail - Food and beverage stores	**15**	Retail Trade
401	Retail - Health and personal care stores	**15**	Retail Trade
402	Retail - Gasoline stores	**15**	Retail Trade
403	Retail - Clothing and clothing accessories stores	**15**	Retail Trade
404	Retail - Sporting goods, hobby, musical instrument and book stores	**15**	Retail Trade
405	Retail - General merchandise stores	**15**	Retail Trade
406	Retail - Miscellaneious store retailers	**15**	Retail Trade
407	Retail - Nonstore retailers	**15**	Retail Trade

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
408	Air transportation	**16**	Transportation
409	Rail transportation	**16**	Transportation
410	Water transportation	**16**	Transportation
411	Truck transportation	**16**	Transportation
412	Transit and ground passenger transportation	**16**	Transportation
413	Pipeline transportation	**16**	Transportation
414	Scenic and sightseeing transportation and support activities for transportation	**16**	Transportation
415	Couriers and messengers	**5**	Services
416	Warehousing and storage	**5**	Services
417	Newspaper publishers	**5**	Services
418	Periodical publishers	**5**	Services
419	Book publishers	**5**	Services
420	Directory, mailing list, and other publishers	**5**	Services
421	Greeting card publishing	**5**	Services
422	Software publishers	**5**	Services
423	Motion picture and video industries	**5**	Services
424	Sound recording industries	**5**	Services
425	Radio and television broadcasting	**5**	Services
426	Cable and other subscription programming	**5**	Services
427	Wired telecommunications carriers	**5**	Services
428	Wireless telecommunications carriers (except satellite)	**5**	Services
429	Satellite, telecommunications resellers, and all other telecommunications	**5**	Services
430	Data processing, hosting, and related services	**5**	Services
431	News syndicates, libraries, archives and all other information services	**5**	Services

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
432	Internet publishing and broadcasting and web search portals	**5**	Services
433	Monetary authorities and depository credit intermediation	**17**	Finance
434	Nondepository credit intermediation and related activities	**17**	Finance
435	Securities and commodity contracts intermediation and brokerage	**17**	Finance
436	Other financial investment activities	**17**	Finance
437	Insurance carriers	**18**	Insurance
438	Insurance agencies, brokerages, and related activities	**18**	Insurance
439	Funds, trusts, and other financial vehicles	**17**	Finance
440	Real estate	**19**	Real Estate
441	Owner-occupied dwellings	**19**	Real Estate
442	Automotive equipment rental and leasing	**5**	Services
443	General and consumer goods rental except video tapes and discs	**5**	Services
444	Video tape and disc rental	**5**	Services
445	Commercial and industrial machinery and equipment rental and leasing	**5**	Services
446	Lessors of nonfinancial intangible assets	**5**	Services
447	Legal services	**5**	Services
448	Accounting, tax preparation, bookkeeping, and payroll services	**5**	Services
449	Architectural, engineering, and related services	**5**	Services
450	Specialized design services	**5**	Services
451	Custom computer programming services	**5**	Services
452	Computer systems design services	**5**	Services

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
453	Other computer related services, including facilities management	**5**	Services
454	Management consulting services	**5**	Services
455	Environmental and other technical consulting services	**5**	Services
456	Scientific research and development services	**5**	Services
457	Advertising, public relations, and related services	**5**	Services
458	Photographic services	**5**	Services
459	Veterinary services	**5**	Services
460	Marketing research and all other miscellaneous professional, scientific, and technical services	**5**	Services
461	Management of companies and enterprises	**5**	Services
462	Office administrative services	**5**	Services
463	Facilities support services	**5**	Services
464	Employment services	**5**	Services
465	Business support services	**5**	Services
466	Travel arrangement and reservation services	**5**	Services
467	Investigation and security services	**5**	Services
468	Services to buildings	**5**	Services
469	Landscape and horticultural services	**5**	Services
470	Other support services	**5**	Services
471	Waste management and remediation services	**5**	Services
472	Elementary and secondary schools	**20**	Government
473	Junior colleges, colleges, universities, and professional schools	**20**	Government
474	Other educational services	**5**	Services
475	Offices of physicians	**5**	Services
476	Offices of dentists	**5**	Services
477	Offices of other health practitioners	**5**	Services

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
478	Outpatient care centers	**5**	Services
479	Medical and diagnostic laboratories	**5**	Services
480	Home health care services	**5**	Services
481	Other ambulatory health care services	**5**	Services
482	Hospitals	**5**	Services
483	Nursing and community care facilities	**5**	Services
484	Residential mental retardation, mental health, substance abuse and other facilities	**5**	Services
485	Individual and family services	**5**	Services
486	Community food, housing, and other relief services, including rehabilitation services	**5**	Services
487	Child day care services	**5**	Services
488	Performing arts companies	**5**	Services
489	Commercial Sports Except Racing	**5**	Services
490	Racing and Track Operation	**5**	Services
491	Promoters of performing arts and sports and agents for public figures	**5**	Services
492	Independent artists, writers, and performers	**5**	Services
493	Museums, historical sites, zoos, and parks	**5**	Services
494	Amusement parks and arcades	**5**	Services
495	Gambling industries (except casino hotels)	**5**	Services
496	Other amusement and recreation industries	**5**	Services
497	Fitness and recreational sports centers	**5**	Services
498	Bowling centers	**5**	Services
499	Hotels and motels, including casino hotels	**5**	Services
500	Other accommodations	**5**	Services
501	Full-service restaurants	**5**	Services
502	Limited-service restaurants	**5**	Services
503	All other food and drinking places	**5**	Services

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector	Aggregated Sector Name
504	Automotive repair and maintenance, except car washes	**5**	Services
505	Car washes	**5**	Services
506	Electronic and precision equipment repair and maintenance	**5**	Services
507	Commercial and industrial machinery and equipment repair and maintenance	**5**	Services
508	Personal and household goods repair and maintenance	**5**	Services
509	Personal care services	**5**	Services
510	Death care services	**5**	Services
511	Dry-cleaning and laundry services	**5**	Services
512	Other personal services	**5**	Services
513	Religious organizations	**21**	Other
514	Grantmaking, giving, and social advocacy organizations	**21**	Other
515	Business and professional associations	**21**	Other
516	Labor and civic organizations	**21**	Other
517	Private households	**5**	Services
518	Postal service	**20**	Government
519	Federal electric utilities	**20**	Government
520	Other federal government enterprises	**20**	Government
521	State government passenger transit	**20**	Government
522	State government electric utilities	**20**	Government
523	Other state government enterprises	**20**	Government
524	Local government passenger transit	**20**	Government
525	Local government electric utilities	**21**	Other
526	Other local government enterprises	**21**	Other
527	Used and secondhand goods	**21**	Other

Table 4. Continued. IMPLAN 536 Sectors and Aggregated 21 Sectors

IMPLAN Sector	IMPLAN Sector Name	Aggregated Sector[6]	Aggregated Sector Name
528	Scrap	**21**	Other
529	Rest of the world adjustment	**20**	Government
530	Noncomparable imports	**20**	Government
531	Employment and payroll of state govt, non-education	**20**	Government
532	Employment and payroll of state govt, education	**20**	Government
533	Employment and payroll of local govt, non-education	**20**	Government
534	Employment and payroll of local govt, education	**20**	Government
535	Employment and payroll of federal govt, non-military	**20**	Government
536	Employment and payroll of federal govt, military	**20**	Government

Source: IMPLAN (MIG, Inc., 2013) and Owen et al (2017).

[6] Aggregated sectors are discussed and used in Chapter 4.

Table 5. Rank of the Southeastern US and BEA Regional Direct Requirement A^M Matrices

Region	Metropolitan Area	Rank of Matrix	Region	Metropolitan Area	Rank of Matrix
BEA3	Albany, Valdosta; GA	294	BEA96	Little Rock; AR	426
BEA10	Asheville; NC	351	BEA100	Macon; GA	324
BEA11	Atlanta; GA	289	BEA105	Memphis; TN	358
BEA12	Augusta-Richmond; GA-SC	414	BEA106	Miami-Fort Lauderdale-Miami Beach; FL	393
BEA15	Baton Rouge; LA	458	BEA112	Mobile; AL	330
BEA19	Birmingham-Hoover; AL	460	BEA113	Monroe-Bastrop; LA	436
BEA30	Charleston; SC	308	BEA114	Montgomery; AL	360
BEA31	Charlotte; NC	253	BEA115	Wilmington; NC & Florence; SC	266
BEA38	Columbia; SC	296	BEA116	Nashville; TN	249
BEA39	Columbus; GA-AL	358	BEA117	New Orleans; LA	288
BEA48	Dothan; AL	432	BEA121	Orlando; FL	413
BEA62	Gainesville; FL	374	BEA123	Panama City-Lynn Haven; FL	288
BEA66	Greensboro--Winston-Salem--High Point; NC	289	BEA125	Fort Walton Beach; FL	404
BEA67	Jackson, Greenville; SC	451	BEA133	Raleigh-Durham-Cary; NC	244
BEA68	Greenville-Spartanburg-Anderson; SC	235	BEA148	Sarasota-Bradenton-Venice; FL	378
BEA69	Gulfport-Biloxi-Pascagoula; MS	294	BEA149	Savannah; GA	401
BEA76	Huntsville-Decatur; AL	430	BEA153	Shreveport-Bossier City; LA	370
BEA79	Jacksonville; FL & Brunswick; GA	401	BEA163	Tallahassee; FL	380
BEA80	Jackson-Yazoo City; MS	318	BEA164	Tampa-St. Petersburg-Clearwater; FL	336
BEA88	Knoxville-Sevierville-La Follette; TN	333	BEA171	Columbus-West Point; MS	236
BEA90	Lafayette-Acadiana; LA	309	BEA173	Virginia Beach; FL	389
BEA91	Lake Charles; LA	276	SE U.S.	/	492

Source: IMPLAN (MIG, Inc., 2013)

Note: Rank of matrix indicates how many sectors have inter-industrial linkages with each other. Therefore, a higher rank indicates that the region has more sectors with inter-industrial linkages. Lower ranks imply fewer sectors have inter-industrial linkages.

Table 6. Formula of the Three Location Quotients Techniques

Location Quotient	**Formula**
Simple Location Quotient	$LQ_i^r = \frac{e_i^r/e^r}{e_i^N/e^N}$
Cross Industry Location Quotient	$CILQ_{ij}^r = \frac{SLQ_i^r}{SLQ_j^r} = \frac{e_i^r/e_i^N}{e_j^r/e_j^N}$
Flegg's Location Quotient	$FLQ_{ij}^r = \begin{cases} CILQ_{ij} \cdot \lambda^* & \text{for } i \neq j \\ SLQ_i \cdot \lambda^* & \text{for } i = j \end{cases}$

Source: Miller and Blair (2009), pages 349, 353 and 354.

CHAPTER 3: MULTI-REGIONAL WATER FOOTPRINT ANALYSIS

Abstract

Water footprints indicate the impact the production of a commodity has on water use. Water footprints quantify the volume and indicates the location of water use. This chapter applies and Environmental Input-Output Life-Cycle Analysis (EIO-LCA) model is used to evaluate the water footprint of each BEA region and economic sector in the southeastern U.S. in this chapter using the results from Chapter 2.

Introduction

The objectives of this chapter are: 1) to quantify the water use requirements for meeting changes in final demand in the economic sectors of southeastern U.S.; (2) to quantify and qualitatively evaluate interdependencies across regions and economic sectors in terms of water use.

Water is an essential input along the entire supply chain. Blackhurst et al. (2010) found that 60% of water withdrawals are used indirectly (e.g., water that is used to produce intermediate inputs), and that 96% of 428 U.S. industrial sectors require more indirect water use than direct water use. Both direct and indirect water use should therefore be quantified when estimating the quantity of water used in economic activities. In addition, it is also important to determine where water use originates in an inter-regional economic transaction context. Over the period 1997–2001, 2.85×10^8 acre-feet (352 Gm^3) water were conserved each year because of the international trade of agricultural products (Chapagain, Hoekstra and Savenije, 2006a). Quantifying the water embedded in trade flows, especially in food trade, may also alleviate local water scarcity (Yang and Zehnder, 2007).

The concept of a “water footprint” (WF) was introduced by Hoekstra and Hung in 2002. The concept is widely applied in water use and water scarcity research (e.g., Chapagain et al., 2006; Zhao et al., 2009; Mokonnen and Hoekstra, 2010 (a,b); Brown and Marty, 2011; Hoekstra and Mokonnen, 2012). A WF analysis indicates the volume and the region of direct and indirect water use along a supply chain (Aldaya, 2012).

A WF analysis may also reveal regional or economic-sectoral differences in water productivity that impact regional economic growth and water allocation (Mekonnen et al., 2015). Kijne et al. (2003) introduced the concept of the “water productivity” (WP) to measure the ability of an agricultural system to produce food, subject to water availability. The WP concept was later applied as an indicator to assess agricultural outcomes such as crop yield, food equivalence and income (Cook, Gichuki and Turral, 2006). Macro-level WP indices were also developed to evaluate direct and indirect monetary values of net benefits from water use (Cook, Gichuki and Turral, 2006).

A WP index describes the economic output of water use, but a WF analysis evaluates the water required to achieve or sustain some level of economic output. Holding other conditions constant, a lower WF for same level of industry output indicates a higher WP (Hoekstra and Hung, 2005, Liu et al. 2007b). Identifying the WF/WP relationship across different regions could also provide information for improving water use efficiency or developing proactive plans for managing water resources (Bouman and Tuong, 2001; Cook, Gichuki and Turral, 2006).

Input-Output Life-Cycle Analysis (IO-LCA)

Life-Cycle Analysis (LCA)

Life-Cycle Analysis (LCA) is a tool to evaluate the overall environmental impacts of an entire supply chain of a commodity or production process (ISO-14010). Environmental impacts include, but are not limited to, energy, water and air emissions resulting from the production (Matthews, Hendrickson and Matthews, 2015). An LCA identifies inputs, outputs and environmental impacts of specific commodities, from raw material requirements to waste management (Figure 5). LCA is therefore also called a “cradle-to-grave” approach for assessing production systems (Klopffer, 1997). Spath, Mann and Kerr (1999) used an LCA to analyze the environmental impacts of U.S. coal-fired power plants. Cedeberg et al. (2003) used LCA to compare the environmental burden of various co-products of milk production. The DOE evaluated the energy impact of LED lighting with an LCA (DOE, 2012). Orsi et al. (2016) used LCA to estimate petroleum energy use and CO_2 emissions. These studies are examples of “traditional” process-based LCA approach.

A traditional process-based LCA poses two issues. First, it is difficult to establish analysis boundaries. In other words, it is hard to determine what inputs and outputs should be included in the assessment (Hendrickson et al 1998). Second, circularity effects of typical economies introduce large data requirements to account for all materials and processes involved in the production of a commodity and its life cycle process (Matthews, Hendrickson and Matthews, 2015).

Input-Output Model and LCA

Macro-economic models that incorporate pollutant and natural resource requirements into economic transactions were introduced by Leontief (1970). Leontief extended his conventional IO model to measure the environmental impact of economic activities. Similar to the economic inputs required to produce a target output, the requirements of resource inputs for a desired output level generates a measure of the environmental burdens corresponding with an economic activity. Considering each sector in an IO model as one step in the production process, the IO model includes every possible process in the production of a good. The IO model largely circumvents issues of traditional process-based LCA for three reasons: 1) an IO approach to LCA envelops the entire economy; therefore, establishing analysis boundaries is less difficult; 2) the direct requirement matrix of an IO model comprises non-zero diagonal elements, which accounts for the circularities in an economy (Leontief, 1936; Miller and Blair, 2009); 3) once supporting data is prepared, it takes little time to finish the analysis using linear algebra. Many studies have incorporated IO models into LCA. Moriguchi et al. (1993) used an IO model with LCA to evaluate CO_2 emissions of automobiles in Japan. Development of integrated IO-LCA models has also advanced rapidly since 2000 (Machado et al., 2001; Norris 2002; Lenzen 2002; Suh and Huppes, 2005). In an IO model, all information pertaining to direct and indirect purchases required for production are embodied in the "Leontief Inverse" matrix $(I - A)^{-1}$ (Miller and Blair, 2009). The matrix A is the direct requirement matrix. Appending environmental burden data to the Leontief inverse matrix generates the environmental impact of economic activities (Leontief, 1970). The Environmental Input-Output (EIO) model is therefore an alternative representation of a product's life cycle, resulting in what is called an Economic Input-Output Life Cycle Assessment (EIO-LCA) model (Hendrickson et al, 1998). Cicas et al.

(2007) applied an EIO-LCA model to estimate the electricity, fuel use, and air emissions of regional economic activities. Blackhurst et al. (2010) examined the direct and indirect water use for 428 economic sectors in the U.S with an EIO-LCA model. Egilmez, Kucukvar and Tatari (2013) quantified the air emission, energy use, water withdrawals and pollution of manufacture industry in the U.S. with an EIO-LCA model. The EIO-LCA model, supporting data, and a programming scripts developed by the Green Design Institute of Carnegie Mellon University has contributed extensively to similar modeling efforts[7].

Multiple Regional EIO-LCA Models

The EIO-LCA framework has been extended to inter-regional transaction contexts (Schaeffer and de Sa, 1996; Hubacek and Giljum, 2003; Shui and Harriss, 2006; Norman, Charpentier and MacLean, 2007; Zhao and Jackson, 2016). Shui and Harriss (2006) employed an EIO-LCA to estimate the CO_2 emission generated from U.S.-China trade. They found that if the U.S. had produced some commodities domestically instead of importing the same amount of goods and services from China, U.S. CO_2 emissions would be higher. Liang, Fan and Wei (2007) developed a Multi-Regional IO-LCA model of eight regions in China to project CO_2 emissions at regional levels under different economic and population assumptions. Norman, Charpentier and MacLean (2007) estimated energy use and greenhouse gas emissions of trade between Canada and the United States with an multi-regional EIO-LCA model. They found trade between regions had significant impacts on the environmental impact assessment. Okadera et al. (2014) estimated the water footprints of fifteen provinces along the Yangtze River with a MRIO model. Their results indicated that regional WFs under multi-regional transactions were 11% larger than WFs

[7] www.eiolca.net

estimated without multi-regional transactions modeling. In this study, an EIO-LCA model is extended to include regional interactions to determine the WF (WP) of changes in final demand for 536 economic sectors and 43 BEA regions in the southeastern U.S.

Method

The objective of an EIO-LCA analysis is to quantify the total impact a change in industry output has on an environmental indicator (Matthews, Hendrickson and Matthews, 2015). Changes in industry output are driven by changes in final demand for a good. Given some projection of a change in final demand, the direct and indirect requirements of industry output are subsequently determined. Next, the environmental impacts of each sector are estimated. Finally, environmental impact multipliers of all sectors are aggregated to determine the total environmental impacts of an economic activity. Henry and Bowen (1981) applied this framework to determine the direct, indirect and induced water use required to meet every dollar final demand for 64 sectors in the South Carolina. Blackhurst et al. (2010) used this approach to determine the direct and indirect water used in 428 U.S. industrial sectors.

Matthews, Hendrickson and Matthews (2015) presented a comprehensive discussion of the EIO-LCA approach. The total environmental impacts generated from a given level of final demand are estimated with an EIO-LCA model as:

$$\Delta R = W\Delta X = W(I - A)^{-1}\Delta Y \qquad (13a)$$

where ΔR denotes the overall changes in an environmental indicator, subject to changes in total industry output, ΔX; ΔY denotes a change in final demand; and W is a matrix with diagonal elements of environmental burden coefficients (Leontief, 1970; Hendrickson, 1998; Matthews, Hendrickson and Matthews, 2015). The matrix $(I - A)^{-1}$ is the 'Leontief Inverse' matrix, indicating the direct and indirect purchase requirements for a given ΔY.

In this chapter, multi-regional transactions are estimated for 43 BEA region and 536 IMPLAN sectors as,

$$\Delta X = (I - CA)^{-1} C \Delta Y \qquad (13b)$$

where the matrix C is a matrix of column trade coefficients, and *A* is a diagonal matrix with BEA-specific regional direct requirement matrices on the diagonal (Miller and Blair, 2009). The matrix $CA(= A^M)$ is the multi-regional direct requirement matrix introduced in Chapter 2.

Overall environmental impacts are calculated as:

$$\Delta R = W \Delta X = W (I - CA)^{-1} C \Delta Y \qquad (13c)$$

where ΔR is a vector $[(536 \times 43) \times 1]$, with each element indicating the total (direct plus indirect) water use along the supply chain (water footprint) corresponding with the projected change in final demand ΔY $[(536 \times 43) \times 1]$. The matrix W $(536 \times 43) \times (536 \times 43)$ is a diagonal matrix with elements indicating water used for economic activities. The matrix $(I - CA)^{-1}$ is a multi-regional "Leontief Inverse" matrix $(536 \times 43) \times (536 \times 43)$.

To compare differences in the regional water productivity of a sector, water multipliers indicate the water used for a 1-unit (e.g., 1 dollar) change in final demand. For example, the vector of regional total water multipliers (*M*) $[1 \times (536 \times 43)]$ is generated as:

$$M = w(I - CA)^{-1} C \qquad (14)$$

where each element of *M* indicates the WF of a one dollar increase of final demand for a specific sector and region. The *w* is water use coefficient vector $[(1 \times (536 \times 43)]$. Regions with higher multipliers require more water to meet the same level of final demand.

To identify the linkage among sectors and across regions in terms of water use, the regional water multipliers of all input sectors are calculated as:

$$Z = W(I - CA)^{-1}C \qquad (15)$$

where Z is a $[(536 \times 43 \times 536 \times 43)]$ matrix indicating the water use required by each input sector across all regions for one dollar increase in the final demand of a good. The matrix W (= $diag(w)$) is a $[(536 \times 43 \times 536 \times 43)]$ diagonal matrix.

Data

Water withdrawal coefficients

Water withdrawal is chosen to the measure water use. Sector-specific water withdrawal coefficients representing water withdrawals per dollar unit of Total Industry Output (TIO) are calculated by dividing estimated water withdrawals by the TIO of a sector (Hendrickson et al., 1998; Blackhurst et al., 2010; Owen et al., 2017):

$$\omega_i^r = \frac{ww_i^r}{X_i^r} \qquad (16)$$

where ω_i^r, ww_i^r and X_i^r denote respectively a water withdrawal coefficient (acre feet/dollar), water withdrawal (acre feet), and total industry output (dollar units) of sector *i*, in region *r*. The TIO (X_i^r) is from the 2013 IMPLAN data base (MIG, Inc., 2013).

Water Withdrawal

The United States Geological Survey (USGS) provides county level water withdrawal (including both surface and ground water) estimates (million gallons per day) of eight aggregated economic and demographic categories every five years. The latest available publication of USGS data on water withdrawal is used in this study (USGS, 2010). The eight categories of water withdrawal used by the USGS are Public Supply, Domestic, Irrigation, Thermoelectric Power, Industrial, Mining, Livestock and Aquaculture. The thermoelectric industry dominates water withdrawal in the southeastern U.S. (65.87%), and irrigation is the second largest (17.91%) water withdrawal. Industrial water withdrawal accounts for 6.34% of total water withdrawal in the region (Figure 6). However, these eight categories are not detailed enough for the EIO-LCA analysis. A downscaling method suggested by Owen et al. (2017) is used to apportion county level USGS water withdrawal from its eight categories into 536 IMPLAN sectors used here.

"Irrigation" water withdrawals are estimated from the "Irrigation, total withdrawals, fresh, in Mgal/d[8]". The irrigation water withdrawals were distributed across 10 IMPLAN agricultural crop sectors based on crop irrigated acres (USDA, 2007) and crop water requirements (UDSA, 1976). "Livestock" water withdrawals ("Livestock, total withdrawals, fresh, in Mgal/d") and "Aquaculture" water withdrawals ("withdrawals, total (fresh + saline), in Mgal/d") were distributed across 4 IMPLAN livestock sectors based on the head of livestock (NASS, 2007) and livestock water use coefficients from previous literature (Ministry of Agriculture, Food and Rural Affairs, Ontario, 2010). "Public Supply" water withdrawals include the "Public Supply, total withdrawals, total (fresh + saline), in Mgal/d"; the sector consists of water delivered both to household and economic sectors.

This chapter only focuses on the direct and indirect (Type I)[9] environmental impact of economic activities, and the household sector is not included in this study. Therefore, the Public

[8] Mgal/d=Million gallons per day

[9] Type I multipliers include the direct or initial spending and indirect business transaction between each other. Type II multipliers include Type I multiplier effects and household spending based on income earned from the direct and indirect effects (the induced effect) (Conway, 1977).

Supply deliveries to domestic ("Domestic, deliveries from Public Supply, in Mgal/d") are subtracted from the Public Supply withdrawal. The remaining Public Supply water use was allocated to other sectors based on their purchase rate[10] from the "Water, sewage and other system sector". "Mining" consists of "Mining, total withdrawals, total (fresh + saline), in Mgal/d" was distributed across 21 IMPLAN mining sectors based on corresponding sectoral water use coefficients from an EIO-LCA model (Green Design Institute, Carnegie Mellon University, 2008) and IMPLAN (MIG, Inc., 2013) total industry output (TIO). Similarly, "Industrial" water withdrawals ("Industrial, self-supplied total withdrawals, total (fresh + saline) in Mgal/d") are distributed across 482 IMPLAN industrial sectors, and "Thermoelectric" water withdrawals ("Thermoelectric, total withdrawals, total (fresh + saline), in Mgal/d") are distributed across 9 IMPLAN thermoelectric sectors

County level water withdrawals by sector were aggregated into BEA regions as:

$$\sum_{county} ww_i^{county} = ww_i^r \quad \forall\, r \tag{17}$$

where ww_i^{county} is the water withdrawal of county belonging to BEA region r, and ww_i^r is the water withdrawal of BEA region r.

Product Prices

To present the water footprints of agriculture products in a more familiar measurement, the water footprint measured in gallons of water per dollar of final demand is transferred to gallons of water per pound of final demand for those agricultural products. Products prices are therefore collected from USDA NASS survey[11]. 2013 annual price of soybeans, upland cotton

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[10] The sector i's purchase rate from the "Water, sewage and other system" sector (k) from is the technical coefficient a_{ki}.

[11] Product prices of Oilseeds, Grain, Cotton, Beef Cattle, Dairy and Poultry used in this thesis are 0.253 $/lb, 0.117 $/lb, 0.772 $/lb, 0.952 $/lb, 0.179 $/lb and 0.486 $/lb, respectively.

and milk were used to present product price of sectors “Oilseed”, “Cotton” and “Dairy”. The average annual price of wheat, rice and cotton is used as “Grain” product price. The average annual price of cattle (calves and others) in 2010 NASS survey is used as the price of “Beef Cattle” product price. The average annual price of chicken (broiler and others) and market annual price egg in 2007 NASS are used to calculate the price of “Poultry” product. The weight of per bushels crop information is referred to Rowlett (2001)[12]. The weight of one dozen of egg is set as 1.5 dollars per pound. Take oilseeds as an example, the 2013 annual price of soybeans was 14.1 $/bu, and the weight of one bushel of soybeans is 60 pound based on information from Rowlett (2001). Therefore, the oilseeds product price is calculated as

$14.1\ (\$/bu) \big/ 60\ (lb/bu) \approx 0.24\ (\$/lb)$. Other product prices are calculated in same way.

Results and Discussion

Water withdrawals are heterogeneous across regions and sectors. BEA 96 (Little Rock, Pine Bluff; AR), BEA 76 (Decatur, Huntsville; AL), BEA 31 (Charlotte; NC), BEA 117 (New Orleans; LA), BEA 11 (Atlanta; GA, Chattanooga; TN) and BEA 106 (Miami, Fort Launderdale; FL) are the six largest water withdrawing BEA regions. These six BEA regions withdrew more than five million acre feet of water in 2010 (Table 7).

Water Withdrawal Coefficients

The estimated water withdrawal coefficients of 14 agricultural IMPLAN sectors are compared with those generated by the Green Design Institute (Carnegie Mellon University,

[12] U.S. Commercial Bushel Sizes. Access at: https://www.unc.edu/~rowlett/units/scales/bushels.html

2008) and Owen et al. (2017) (Table 8)[13]. The Green Design Institute (Carnegie Mellon University, 2008) water withdrawal coefficients are at the national level. Owen et al.'s (2017) focus was on Tennessee. This analysis covers 43 BEA regions in 11 states in the southeastern U.S. (Figure 1). Differences in estimated water withdrawal coefficients may be due to differences in soil moisture, precipitation patterns and field practices between regions and their contributions to BEA regional economies. There are several water withdrawal coefficients estimated to be zero, both in this study and Owen et al. (2017). The zero coefficients result because these commodities or goods are not produced.

Water Multipliers

Total Water Multipliers

Total water multipliers in gallons/$ (Table 9) and gallons/lb of products (Table 10) of six agricultural sectors generated from the Multi-Regional EIO-LCA are compared with national multipliers generated from the EIO-LCA of Green Design Institute (Carnegie Mellon University, 2008), Mekonnen and Hoekstra (2010 a,b), Chapagain and Hoekstra (2010) and Chapagain, Hoekstra, Savenije and Gautam (2005). These six agricultural sectors are "Oilseed farming", "Grain farming", "Cotton farming", "Beef cattle ranching and farming including feedlots and dual-purpose ranching and farming", "Dairy cattle and milk production" and "Poultry and egg production". Means, maximum and minimum of the southeastern U.S. are calculated from the multipliers estimated for the 43 BEA regions of each agricultural sector (Tables 9, 10).

The variation of crop water multipliers is larger than the variation of the livestock water multipliers (Tables 9, 10). It is also evident that the water multipliers calculated by the Green

[13] Carnegie Mellon University Green Design Institute. (2008) Economic Input-Output Life Cycle Assessment (EIO-LCA), US 1997 Industry Benchmark model, available from: http://www.eiolca.net

Design Institute (Carnegie Mellon University, 2008) of four agricultural sectors are higher than the maximum multiplier values of those estimated here. There are three reasons why this might occur. First, there are significant differences in the direct requirement matrices (*A*) used in this study and the Green Design Institute (Carnegie Mellon University, 2008). The national level *A* matrix from Green Design Institute (Carnegie Mellon University, 2008) has more inter-industrial linkages than the BEA regional *A* matrices because it corresponds with the national economy. Second, Green Design Institute (Carnegie Mellon University, 2008) finds larger water withdrawal coefficients for "Grain", "Cotton", "Beef Cattle", "Dairy" and "Poultry" that the average water withdrawal coefficients of 43 BEAs' corresponding sectors. In addition, regional differences in growing conditions in the southeast U.S. may also contribute to the relatively lower water withdrawal multipliers estimated here.

Crops and dairy water multipliers estimated by Mekonnen and Hoekstra (2010, a,b) and Chapagain, Hoekstra, Savenije and Gautam (2005) fall between the range of this study's estimates, while their beef cattle and poultry multipliers are larger than the highest multipliers of these sectors determined here.

Linkage among Regions and Sectors

BEA regions were ranked by the TIO of the six agriculture sectors analyzed here to facilitate detailed comparisons. BEA 105 (Memphis, Jackson; TN) was chosen because it had the highest TIO for Oilseeds (Table 11) and Grain (Table 12) among 43 BEA regions. BEA 03 (Albany, Valdosta; GA) had the largest TIO for Cotton (Table 13). BEA 116 (Nashville; TN) exhibited the largest Beef Cattle TIO (Table 14). BEA 62 (Gainesville; FL) had the largest TIO for the Dairy sector (Table 15), and BEA 11 (Atlanta; GA & Chattanooga; TN) the largest

Poultry TIO (Table 16). BEAs 105, 03, 116, 62 and 11 are therefore selected to summarize the water multiplier results for these agricultural sectors (Figure 7).

Water multiplier ranking figures characterize the linkage between input and output sectors in terms of water withdrawal (gallons) to meet final demand. Colors inside each bar indicate the BEA regions where water is used to meet a change in final demand for the selected sector and region. A bar with more colors exhibits relatively more inter-regional linkages in terms of water use. If the color representing the region itself dominates the figure, it indicates this region is relatively independent with respect to water use virtually embedded in other region's production; i.e., the region is self-sufficient (Miller and Blair, 2009).

The water footprint analysis suggests that 18.72 gallons of water are required to meet a one dollar increase in final demand for beef cattle in BEA 116 (Figure 8). Of these 18.72 gallons of water, most water use originates from the beef sector in BEA 116, followed by the electric power transmission and distribution sector in BEA 116.

The dairy sector, represented by BEA 62, requires 3.36 gallons of water withdrawal, in total, to meet a one dollar increase in final demand for dairy products (Figure 9). There are transactions evident between BEA 62 and other BEA regions engaged in dairy production. "Electric power transmission and distribution" from BEA 62 and other BEA regions yields a larger water multiplier contribution, followed by the "Dairy" sector, mainly originating from BEA 62. The "Other animal" sector, of which more than half originating from other BEA regions, accounts for the third largest contribution to the total water multiplier. "Fossil fuel", "Other Crops", "Nuclear", "Sugar", "Grain", "Beef" sectors also contribute to the water multiplier of dairy production in BEA 62.

The grain (Figure 10) and oilseeds sector (Figure 11) in BEA 105 appear to be self-sufficient. The “Oilseeds” sector in BEA 105 requires 186.83 gallons of water withdrawal to meet a one dollar increase in final demand for oilseed products. Of this amount, 180 gallons of water withdrawals originate from local oilseeds production in BEA 105. The “Grain” sector in BEA 105 requires 302.21 gallons of water to meet a one dollar increase in final demand, with more than 290 gallons of the water used due to activity in the grain sector. About 250 gallons of water are used during the local production of grain in BEA 105, whereas less than 50 gallons of water are withdrawn in other supporting BEA regions.

A one dollar increase in final demand for poultry products in BEA 11 requires 1.55 gallons of water withdrawal along its supply chain (Figure 12). The poultry sector in BEA 11 exhibits significant interaction with other sectors and regions as well (Figure 12). “Electric power transmission and distribution” is the leading input sector in terms of water requirements; more than half of water used to provide energy originates from other BEA regions. The grain sector, which contains a small proportion of local grain production, is the second largest water yielding sector. Following afterwards are the fossil fuel sector, the poultry sector itself, and then other animal foods from various BEA regions.

The cotton sector in BEA 03 largely depends on local water withdrawn for the production of cotton (Figure 13). There are 69.28 gallons of water required to meet a one dollar increase in final demand for cotton in BEA 03. The “Tree nut” and the “Transmission and Distribution” from other BEA regions also account for the water required to meet an increase in final demand for cotton in BEA 03.

In general, water is used along the entire production supply chain and is transacted as virtual water embedded in regional trade flows. Different regional WF multipliers of similar sectors are suggestive of different regional water withdrawal practices. Different input sectors in regional WF multipliers are also indicative of various regional water use efficiencies and production structures across BEA regions. For example, more than half of the water requirements are implicated in the production of intermediate inputs from other regions to meet final demand for poultry in BEA 11. In addition, BEA 11 only requires 1.55 gallons of water to satisfy a one dollar increase in poultry final demand, while the largest estimated poultry water multiplier among 43 BEA regions is 12.31 gallons of water. Similarly, the dairy sector in BEA 62 is largely dependent on other BEA regions to meet its final demand. While BEA 62 only requires 3.36 gallons of water to meet a one dollar increase in final demand for dairy products, the largest multiplier observed across the 43 BEA regions for this sector is 46.52 gallons. Comparison of the multipliers between different regions of the same sector provides information about sector efficiency in a particular region in terms of water use. The comparison also indicates a region’s comparative advantage with respect to water use efficiency.

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Appendix C

Figures

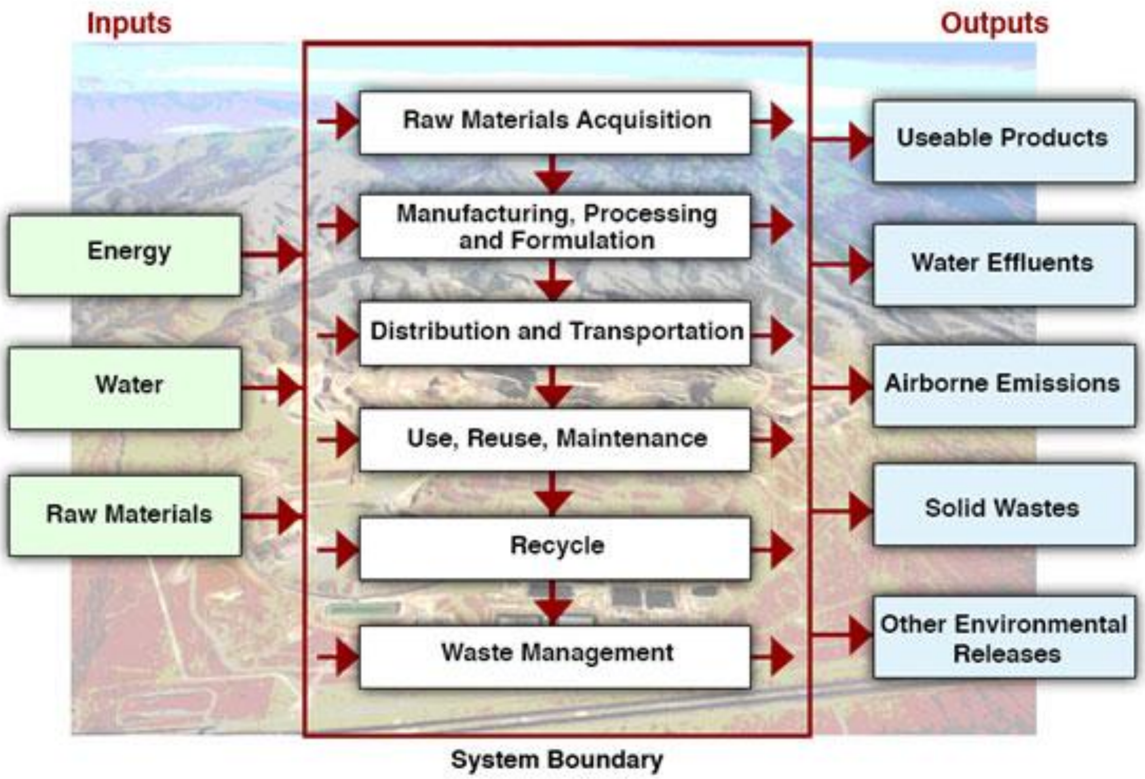

Figure 5. Inputs and Outputs over a Product's Life Cycle
Source: Allan Chen, 2008 April 18.
http://newscenter.lbl.gov/2008/04/18/life-cycle-analysis/

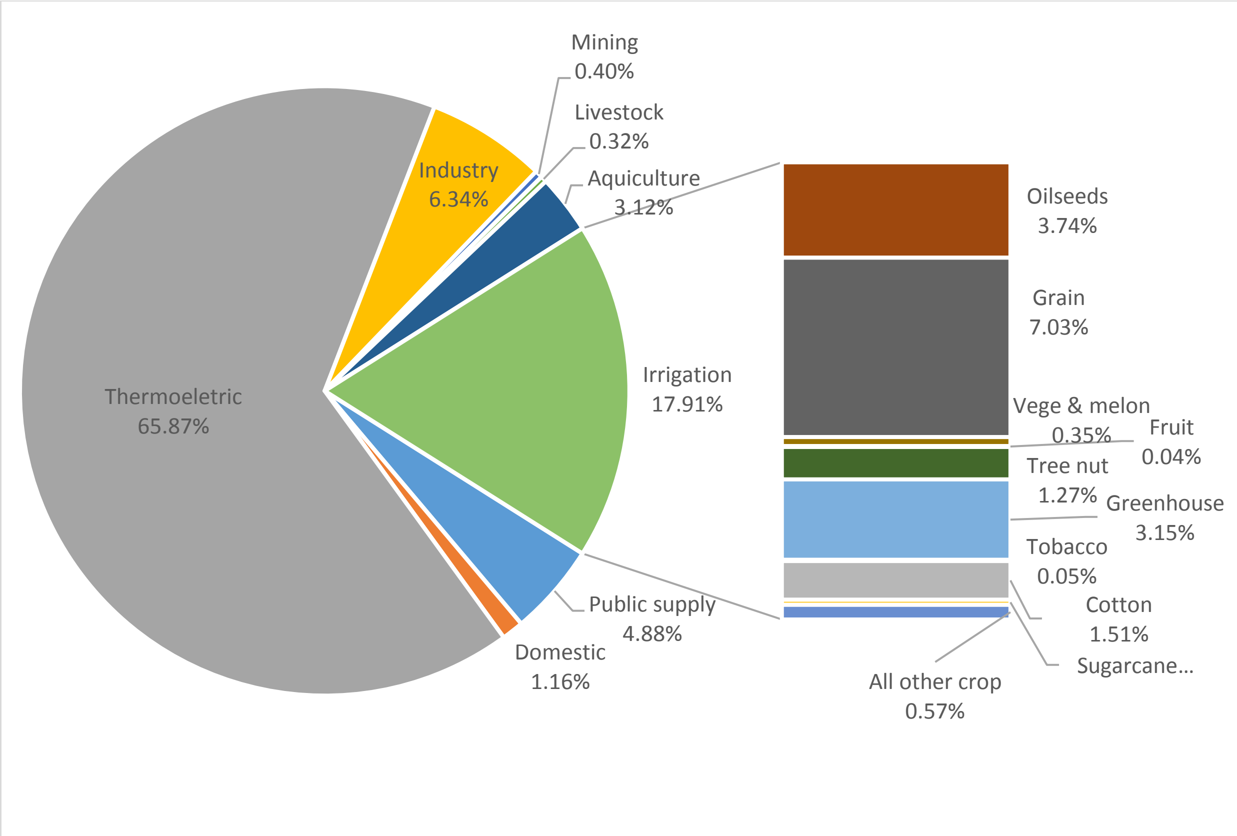

Figure 6. Water Withdrawal Distribution across the USGS Sectors in the Southeastern U.S.
Source: Author's estimation based on USGS (2010).

Figure 7. Selected BEA Regions

Note: Metropolitan areas of selected BEA regions with highest Total Industry Output of 6 agricultural sectors are: Albany and Valdosta (BEA 03, Cotton), Atlanta (BEA 11, Poultry), Gainesville (BEA 62, Dairy), Memphis (BEA 105, Oilseeds and Grain) and Nashville (BEA 116, Oilseeds and Grain).

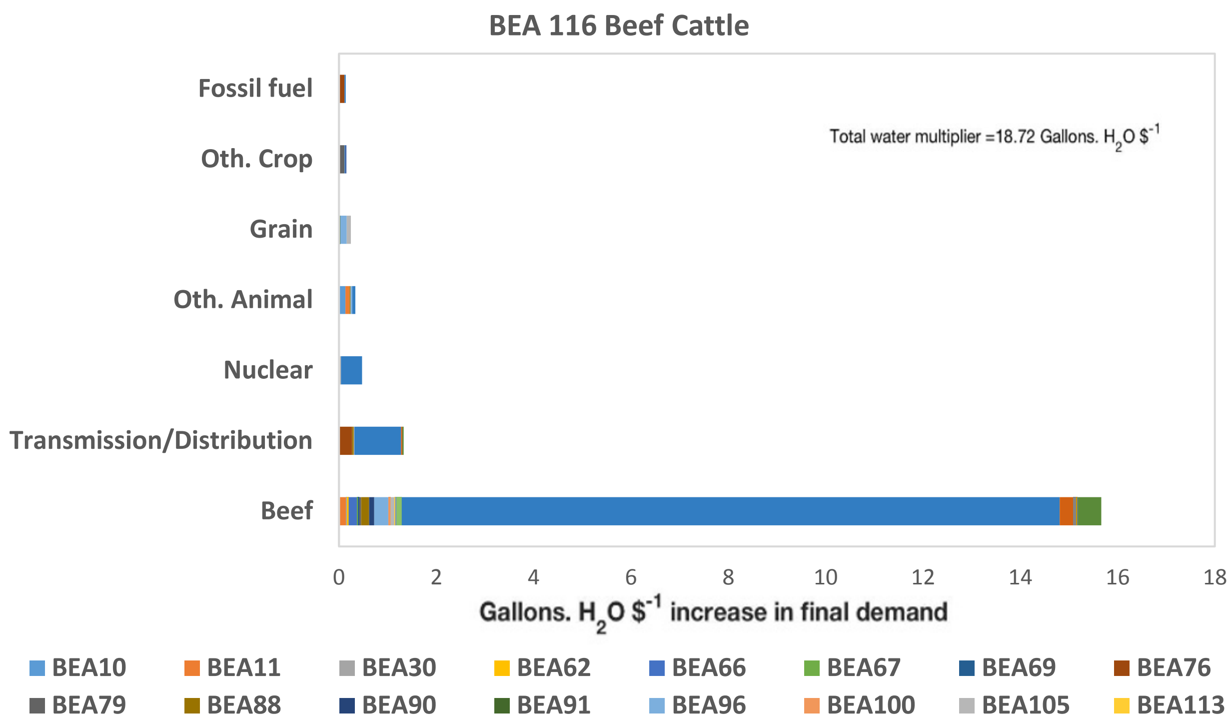

Figure 8. Water Multipliers for Beef Cattle in BEA 116 (Nashville; TN)
Source: Author's calculation
Note: Refer to Table 5 in this thesis for the metropolitan area of each BEA region.

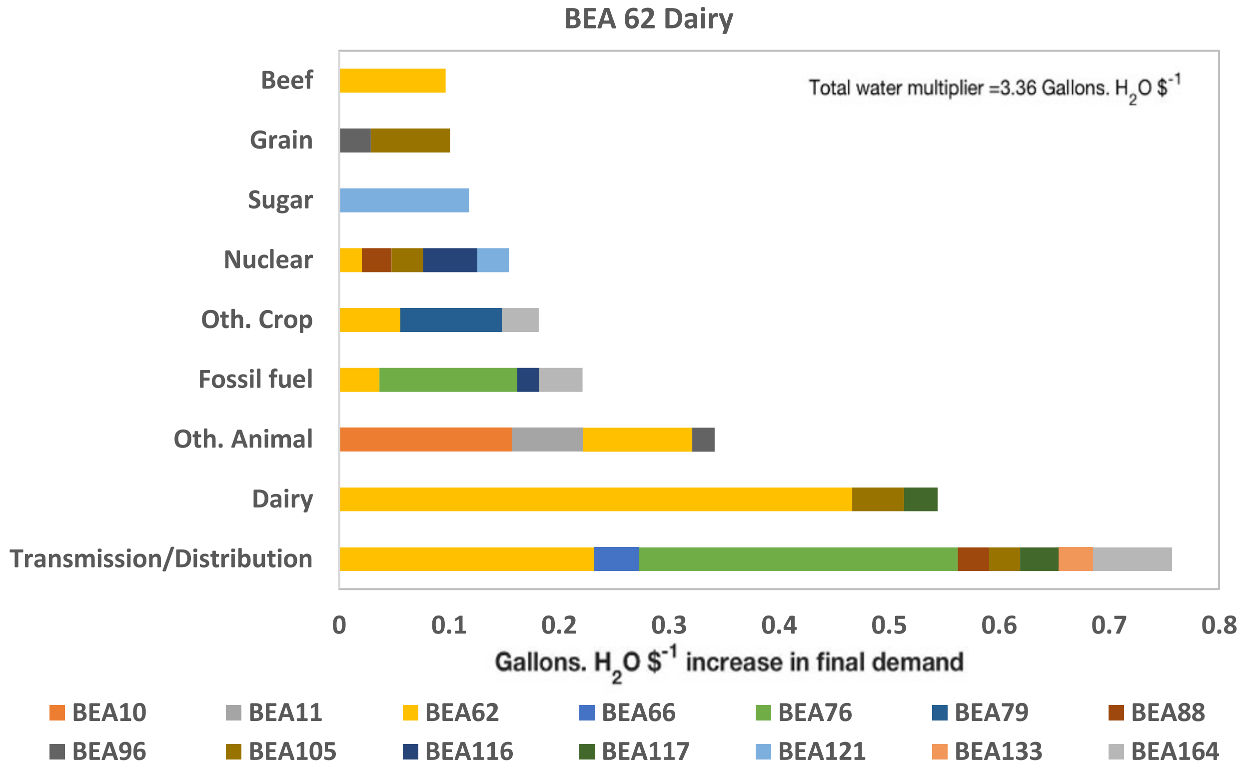

Figure 9. Rank of Input Sectors Water Multipliers for Dairy in BEA 62 (Gainesville; FL)
Source: Author's calculation
Note: Refer to Table 5 in this thesis for the metropolitan area of each BEA region.

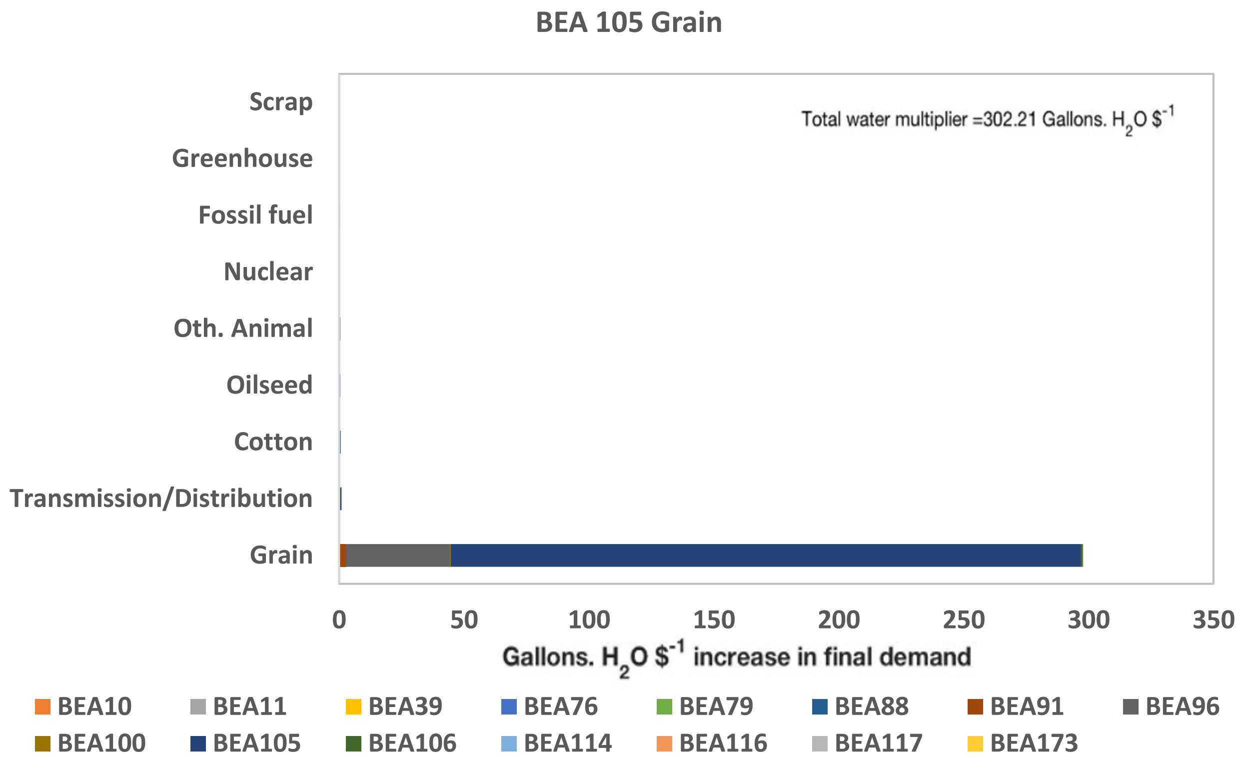

Figure 10. Rank of Input Sectors Water Multipliers for Grain in BEA 105 (Memphis, Jackson; TN)
Source: Author's calculation
Note: Refer to Table 5 in this thesis for the metropolitan area of each BEA region.

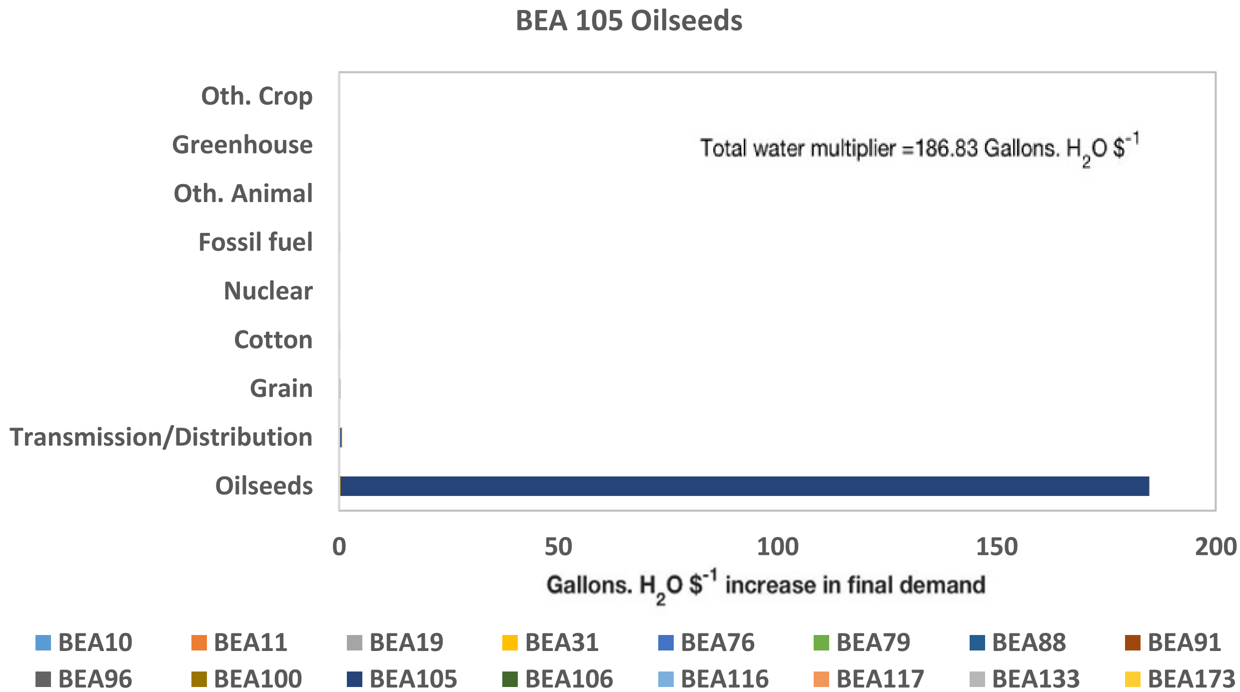

Figure 11. Rank of Input Sectors Water Multipliers for Oilseeds in BEA 105 (Memphis, Jackson; TN)

Source: Author's calculation

Note: Refer to Table 5 in this thesis for the metropolitan area of each BEA region.

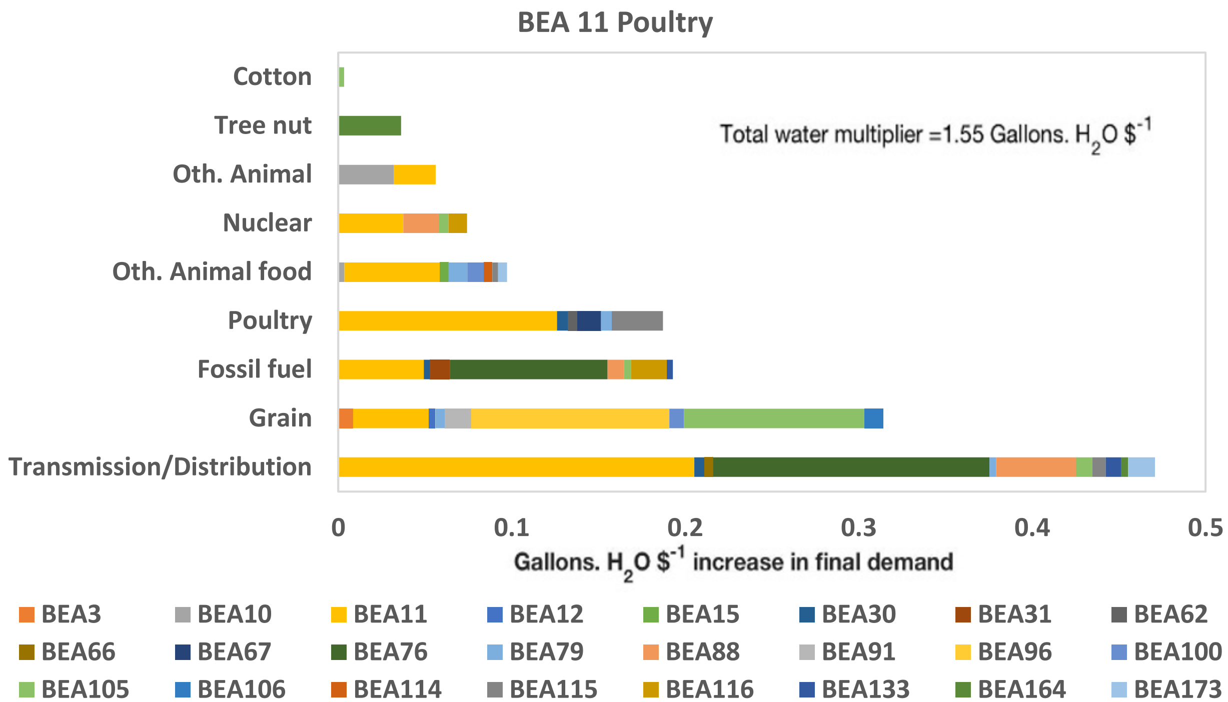

Figure 12. Rank of Input Sectors Water Multipliers for Poultry in BEA 11 (Atlanta; GA & Chattanooga; TN)

Source: Author's calculation

Note: Refer to Table 5 in this thesis for the metropolitan area of each BEA region.

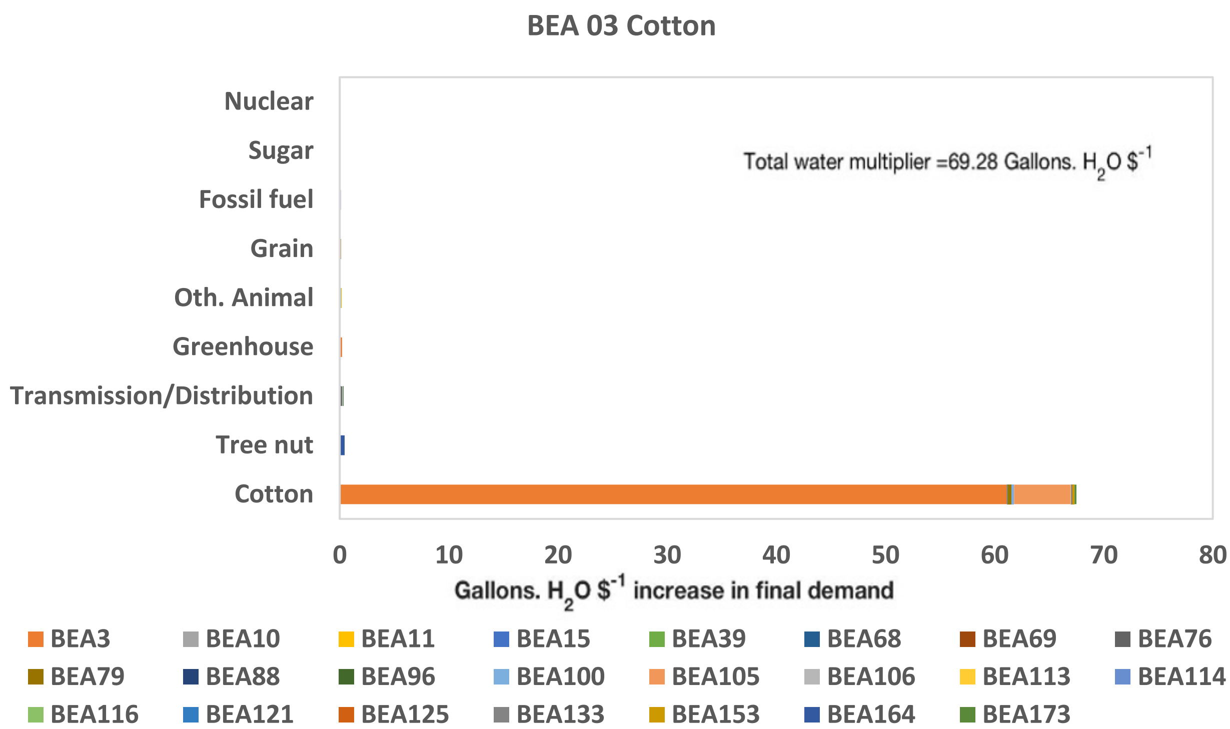

Figure 13. Rank of Input Sectors Water Multipliers for Cotton in BEA 03 (Albany, Valdosta; GA)

Source: Author's calculation

Note: Refer to Table 5 in this thesis for the metropolitan area of each BEA region.

Tables

Table 7. BEA Regions with Water Withdrawal Over Five Millions Acre Feet in the Southeastern U.S.

BEA	Metropolitan Area	Total Water Withdrawal (Acre-feet)
BEA 96	Little Rock, Pine Bluff (AR)	6,845,378
BEA 76	Decatur, Huntsville (AL)	6,333,013
BEA 31	Charlotte (NC)	6,103,597
BEA 117	New Orleans (LA)	5,212,298
BEA 11	Atlanta (GA), Chattanooga (TN)	5,209,397
BEA 106	Miami, Fort Launderdale (FL)	5,100,205

Note: 1 Acre-foot ≈ 325,851 gallons
Source: Author's calculation based on USGS (2010) data

Table 8. Comparison of Water Withdrawal Coefficients

IMPLAN sector	Estimated Coefficient (Acre-feet/$)	Owen (2016) (Acre-feet/$)	CMU (Acre-feet/$)
Oilseed	37.64	1.34	8.83
Grain	71.29	8.07	1196.66
Vegetable and melon	24.96	15.54	236.34
Fruit	9.64	4.78	463.10
Tree nut	5068.34	1.67	450.02
Greenhouse and nursery	335.01	57.31	52.63
Tobacco	13.51	2.87	19.24
Cotton	76.20	1.47	1246.68
Sugarcane and sugar beet	26.76	0.00	758.65
All other crop	207.24	3.89	38.57
Beef cattle	11.24	0.89	43.70
Dairy cattle and milk	1.81	79.22	4.95
Poultry and egg	1.07	6.54	1.32
Other Animals	928.30	334.91	16.02

Note: 1 Acre-foot ≈ 325,851 gallons
Source: Estimated coefficients are from author's estimation based on USGS (2010); Owen (2016) presents the coefficients that were estimated for Tennessee; CMU represents the coefficients that were provided in the EIO-LCA U.S. model by Carnegie Mellon University.

Table 9. Comparison of Water Multipliers in Gallons per Dollar for Six Agricultural Sectors

Region	Oilseeds (gallons/$)	Grain (gallons/$)	Cotton (gallons/$)	Beef Cattle (gallons/$)	Dairy (gallons/$)	Poultry (gallons/$)
CMU U.S.	75.27	1296.89	1391.38	198.44	130.34	269.80
M&H U.S.	44.24	296.83	342.36	29.67	39.74	14.68
S.E. Mean	35.71	84.79	73.31	18.13	7.50	3.20
S.E. Max	588.41	455.06	1414.23	58.62	46.52	12.31
S.E. Min	0.86	15.61	4.81	9.03	2.79	1.09
BEA3	73.47	117.04	69.28	15.96	5.72	3.00
BEA10	11.98	59.44	27.18	58.62	23.46	2.14
BEA11	3.03	26.06	10.78	11.55	4.74	1.55
BEA12	56.00	58.55	24.00	15.31	4.19	2.16
BEA15	0.86	123.66	27.93	17.82	6.22	3.79
BEA19	2.41	35.75	15.78	10.84	4.50	1.85
BEA30	3.08	23.67	6.71	13.75	6.35	1.90
BEA31	3.20	17.03	7.51	15.37	5.67	2.29
BEA38	11.06	35.06	8.02	12.70	4.28	1.74
BEA39	52.68	52.51	21.43	16.58	7.27	1.30
BEA48	1.97	37.23	17.10	12.13	5.12	1.59
BEA62	2.38	51.94	13.51	14.77	3.36	1.80
BEA66	5.18	18.79	8.30	16.06	7.71	2.28
BEA67	3.10	15.76	7.01	29.61	3.06	10.86
BEA68	3.84	19.71	11.33	14.30	7.24	2.05
BEA69	1.68	25.03	10.89	20.54	5.83	1.97
BEA76	6.68	37.50	24.34	12.74	12.67	6.82
BEA79	6.90	49.97	15.19	9.96	3.14	1.37
BEA80	153.69	335.92	290.16	16.29	6.40	3.20
BEA88	4.56	53.95	21.09	17.62	7.22	2.29
BEA90	6.84	324.21	28.94	18.09	7.81	4.73
BEA91	24.73	362.59	237.42	20.44	12.80	12.31
BEA96	588.41	455.06	1414.23	15.92	11.51	1.18
BEA100	31.19	68.65	67.54	15.10	5.17	2.34
BEA105	186.83	302.21	175.40	21.40	10.14	8.51
BEA106	4.02	59.86	15.47	19.04	3.11	1.60
BEA112	2.76	24.75	12.67	15.80	6.44	2.03
BEA113	31.68	153.69	94.22	12.44	4.31	1.91
BEA114	4.41	90.12	29.71	11.47	4.86	1.85
BEA115	3.80	15.61	8.18	18.74	5.33	4.27
BEA116	3.36	32.53	24.24	18.72	8.21	3.06
BEA117	3.33	52.56	11.09	18.07	8.07	6.02

Table 9. Continued. Comparison of Water Multipliers in Gallons per Dollar for Six Agricultural Sectors

Region	Oilseeds (gallons/$)	Grain (gallons/$)	Cotton (gallons/$)	Beef Cattle (gallons/$)	Dairy (gallons/$)	Poultry (gallons/$)
BEA121	3.10	45.03	5.30	13.72	7.47	2.08
BEA123	2.89	38.05	29.15	16.55	2.79	2.19
BEA125	2.18	22.27	23.53	12.95	4.86	5.33
BEA133	4.59	19.72	7.87	18.16	6.31	3.81
BEA148	11.55	32.64	4.81	53.40	46.52	2.32
BEA149	30.34	38.07	12.50	13.32	3.71	1.09
BEA153	85.93	51.01	51.66	13.10	5.70	2.21
BEA163	86.25	135.94	181.87	12.47	2.87	1.27
BEA164	2.55	27.55	12.75	9.03	4.72	3.61
BEA171	1.46	57.60	44.61	25.80	6.04	4.02
BEA173	5.43	41.65	21.45	33.41	9.69	3.99

Note: BEA regional multipliers and S.E. mean, max and min are calculated by author based on 43 BEA regional water multipliers; CMU U.S. denotes multipliers calculated based on the EIO-LCA model developed by the Carnegie Mellon University Green Design Institute; M&H are Mekonnen and Hoekstra (2010, a,b)

Refer to Table 5 in this thesis for the metropolitan area of each BEA region.

Table 10. Commodity Prices and Comparison of Water Multipliers in Gallons per Pound for Six Agricultural Sectors

Region	Oilseeds (gallons/lb)	Grain (gallons/lb)	Cotton (gallons/ lb)	Beef Cattle (gallons/ lb)	Dairy (gallons/ lb)	Poultry (gallons/ lb)
CMU U.S.	17.69	151.32	1074.15	188.87	23.39	131.21
M&H U.S.	11.02	39.38	161.17	62.91	7.19	18.99
S.E. Mean	8.39	9.89	56.59	17.26	1.35	1.56
S.E. Max	138.28	53.10	1091.79	55.79	8.35	5.99
S.E. Min	0.20	1.82	3.71	8.60	0.50	0.53
BEA3	17.27	13.66	53.48	15.19	1.03	1.46
BEA10	2.81	6.94	20.99	55.79	4.21	1.04
BEA11	0.71	3.04	8.32	11.00	0.85	0.75
BEA12	13.16	6.83	18.53	14.57	0.75	1.05
BEA15	0.20	14.43	21.56	16.96	1.12	1.84
BEA19	0.57	4.17	12.18	10.31	0.81	0.90
BEA30	0.72	2.76	5.18	13.08	1.14	0.92
BEA31	0.75	1.99	5.80	14.63	1.02	1.12
BEA38	2.60	4.09	6.19	12.08	0.77	0.85
BEA39	12.38	6.13	16.54	15.78	1.30	0.63
BEA48	0.46	4.34	13.20	11.55	0.92	0.77
BEA62	0.56	6.06	10.43	14.06	0.60	0.88
BEA66	1.22	2.19	6.41	15.29	1.38	1.11
BEA67	0.73	1.84	5.42	28.18	0.55	5.28
BEA68	0.90	2.30	8.75	13.61	1.30	1.00
BEA69	0.40	2.92	8.41	19.55	1.05	0.96
BEA76	1.57	4.38	18.79	12.13	2.27	3.32
BEA79	1.62	5.83	11.73	9.48	0.56	0.67
BEA80	36.12	39.19	224.00	15.51	1.15	1.56
BEA88	1.07	6.29	16.28	16.77	1.29	1.11
BEA90	1.61	37.83	22.34	17.22	1.40	2.30

Table 10. Continued. Comparison of Water Multipliers in Gallons per Pound for Six Agricultural Sectors

Region	Oilseeds (gallons/lb)	Grain (gallons/lb)	Cotton (gallons/ lb)	Beef Cattle (gallons/ lb)	Dairy (gallons/ lb)	Poultry (gallons/ lb)
BEA91	5.81	42.31	183.29	19.45	2.30	5.99
BEA96	138.28	53.10	1091.79	15.16	2.07	0.57
BEA100	7.33	8.01	52.14	14.37	0.93	1.14
BEA105	43.90	35.26	135.41	20.37	1.82	4.14
BEA106	0.95	6.98	11.94	18.12	0.56	0.78
BEA112	0.65	2.89	9.78	15.04	1.15	0.99
BEA113	7.44	17.93	72.74	11.84	0.77	0.93
BEA114	1.04	10.52	22.94	10.91	0.87	0.90
BEA115	0.89	1.82	6.31	17.84	0.96	2.08
BEA116	0.79	3.80	18.72	17.82	1.47	1.49
BEA117	0.78	6.13	8.56	17.20	1.45	2.93
BEA121	0.73	5.25	4.09	13.06	1.34	1.01
BEA123	0.68	4.44	22.51	15.75	0.50	1.06
BEA125	0.51	2.60	18.17	12.33	0.87	2.59
BEA133	1.08	2.30	6.08	17.28	1.13	1.85
BEA148	2.72	3.81	3.71	50.83	8.35	1.13
BEA149	7.13	4.44	9.65	12.68	0.67	0.53
BEA153	20.19	5.95	39.88	12.47	1.02	1.07
BEA163	20.27	15.86	140.41	11.87	0.51	0.62
BEA164	0.60	3.21	9.84	8.60	0.85	1.75
BEA171	0.34	6.72	34.44	24.56	1.08	1.95
BEA173	1.28	4.86	16.56	31.80	1.74	1.94

Note: BEA regional multipliers and S.E. mean, max and min are calculated by author based on 43 BEA regional water multipliers; CMU U.S. denotes multipliers calculated based on the EIO-LCA model developed by the Carnegie Mellon University Green Design Institute; M&H are Mekonnen and Hoekstra (2010, a,b); Example for multiplier's (gallon/lb) calculation of oilseeds in BEA 173:
$5.43\ gallons/\$ \times 0.235\ \$/lb \approx 1.28\ gallons/lb.$
Refer to Table 5 in this thesis for the metropolitan area of each BEA region.

Table 11. Total Industry Output and Water withdrawal of BEA Regions with the Largest Total Industry Output of Oilseeds Farming

BEA	Metropolitan Area	Total Industry Output ($)	Water Withdrawal (Acre-feet)
BEA105	Memphis, Jackson (TN)	1,409,011,597	882,380
BEA80	Hattiesburg, Jackson (MS)	883,798,340	470,483
BEA96	Little Rock, Pine Bluff (AR)	864,338,623	1,717,500
BEA116	Nashville (TN)	506,935,883	559
BEA133	Durham, Raleigh (NC)	245,428,955	2,132

Note: 1 Acre-foot ≈ 325,851 gallons

Source: Author's calculation based on USGS (2010) data and IMPLAN 2013 (MIG, Inc., 2013).

Table 12. Total Industry Output and Water withdrawal of BEA Regions with the Largest Total Industry Output of Grain Farming

BEA	Metropolitan Area	Total Industry Output ($)	Water Withdrawal (Acre-feet)
BEA105	Memphis, Jackson (TN)	1,415,672,729	1,373,312
BEA96	Little Rock, Pine Bluff (AR)	1,253,059,937	2,527,752
BEA80	Hattiesburg, Jackson (MS)	961,656,494	1,055,893
BEA116	Nashville (TN)	589,527,222	2,295
BEA113	Monroe (LA)	420,853,149	156,940

Note: 1 Acre-feet ≈ 325,851 gallons
Source: Author's calculation based on USGS (2010) data and IMPLAN 2013 (MIG, Inc., 2013).

Table 13. Total Industry Output and Water withdrawal of BEA Regions with the Largest Total Industry Output of Cotton Farming

BEA	Metropolitan Area	Total Industry Output ($)	Water Withdrawal (Acre-feet)
BEA03	Albany, Valdosta (GA)	536,537,842	128,753
BEA105	Memphis, Jackson (TN)	380,135,956	339,203
BEA80	Hattiesburg, Jackson (MS)	240,679,550	243,244
BEA133	Durham, Raleigh (NC)	183,720,383	992
BEA163	Tallahassee (FL)	165,322,556	117,421

Note: 1 Acre-feet ≈ 325,851 gallons

Source: Author’s calculation based on USGS (2010) data and IMPLAN 2013 (MIG, Inc., 2013).

Table 14. Total Industry Output and Water withdrawal of BEA Regions with the Largest Total Industry Output of Beef Cattle Ranching and Farming, including Feedlots and Dual-Purpose Ranching and Farming

BEA	Metropolitan Area	Total Industry Output ($)	Water Withdrawal (Acre-feet)
BEA116	Nashville (TN)	488,907,837	19,432
BEA11	Atlanta (GA), Chattanooga (TN)	293,856,384	5,833
BEA121	Orlando (FL)	251,683,105	4,410
BEA96	Little Rock, Pine Bluff (AR)	216,465,851	8,013
BEA76	Decatur, Huntsville (AL)	154,625,351	2,881

Note: 1 Acre-feet ≈ 325,851 gallons

Source: Author’s calculation based on USGS (2010) data and IMPLAN 2013 (MIG, Inc., 2013).

Table 15. Total Industry Output and Water withdrawal of BEA Regions with the Largest Total Industry Output of Dairy Cattle and Milk Production

BEA	Metropolitan Area	Total Industry Output ($)	Water Withdrawal (Acre-feet)
BEA62	Gainesville (FL)	186,218,109	307
BEA116	Nashville (TN)	182,340,057	1,636
BEA106	Miami, Fort Launderdale (FL)	173,382,309	198
BEA11	Atlanta (GA), Chattanooga (TN)	165,631,607	411
BEA121	Orlando (FL)	105,132,843	146

Note: 1 Acre-feet ≈ 325,851 gallons

Source: Author's calculation based on USGS (2010) data and IMPLAN 2013 (MIG, Inc., 2013).

Table 16. Total Industry Output and Water withdrawal of BEA Regions with the Largest Total Industry Output of Poultry and Egg Production

BEA	Metropolitan Area	Total Industry Output ($)	Water Withdrawal (Acre-feet)
BEA11	Atlanta (GA), Chattanooga (TN)	$4,140,231,934	16,033
BEA80	Hattiesburg, Jackson (MS)	$2,713,275,391	10,279
BEA133	Durham, Raleigh (NC)	$1,983,029,175	24,881
BEA96	Little Rock, Pine Bluff (AR)	$1,441,154,663	8,328
BEA31	Charlotte (NC)	$1,347,626,099	5,965

Note: 1 Acre-feet ≈ 325,851 gallons

Source: Author's calculation based on USGS (2010) data and IMPLAN 2013 (MIG, Inc., 2013).

CHAPTER 4: A MULTI-REGIONAL INPUT-OUTPUT LINEAR PROGRAM FOR WATER SHADOW VALUE

Abstract

The water shadow values provide important information for developing proactive plans for addressing water scarcity. This chapter uses a multiregional input-output linear programming model to determine the threshold at which the southeastern U.S.'s economy would be impacted, given reductions in water availability.

Introduction

Drought is expected to occur more frequently in the southeastern U.S. (Melillo et al., 2014). What are the potential impacts of unanticipated water scarcity events on the southeastern U.S.'s economy? What value do these region's economies place on water? *Ex ante* determination of the shadow values of water to an industry could provide guidance to proactive planning for sustaining water use efficiency and the allocation of limited water resources to productive sectors. The water footprint analysis of Chapter 3 is only descriptive. The analysis sheds little information about the economic impacts water scarcity could have on the region's economy, industrial demand for water, and the shadow value of water corresponding with region- and sector-specific demands. This chapter 1) estimates the shadow value of water across regions in the southeastern U.S.; and 2) determines Gross Regional Product (GRP) levels under water availability scenarios and concomitant impacts on the southeastern U.S.'s economy. Both objectives are achieved using an Input-Output Linear Programming model with different assumptions about inter-regional linkages and final demand targets.

Input-Output (IO) Analysis and Linear Programming (LP)

Linear programming (LP) is an approach to support production and resource allocation decisions in lieu of resource scarcity (Miller and Blair, 2009). Leontief's IO model, in fact, is a special case of linear programming. Wood and Dantzig (1949) described linear programming as a generalization of an IO model. The IO table is a picture of an economy in equilibrium. Linear, and more generally, mathematical programming techniques, leverage the data in IO tables by modeling the processes that generate equilibria to determine the optimal allocation of scarce resources in an economy.

An IO model combined with an LP model, referred to as an IO-LP model, generates results to that could be used to plan for sustainable economic growth and project how virtual price for a resource change as it becomes less abundant (Henry and Bowen, 1981). In an IO-LP model, the IO part of the model defines the production functions, structure, and capacity constraints of an economy. LP is then used to estimate the shadow values of a particular resource. Shadow values indicate how resources could be allocated from lower to higher marginal value product uses.

IO-LP models have been widely used to study economic activities and their corresponding environmental impacts. Dantzig (1976) used an optimization model in an IO analysis of the energy sector. The study minimized the labor and material cost of operations, subject to final demand and resource constraints. Henry and Bowen (1981) used an IO-LP model to estimate the shadow value of water in South Carolina. They expanded their research by examining different agricultural water demand scenarios (Henry and Bowen, 1982). Harris and Rea (1984) conducted a similar study on Northwestern Nevada's water use with an updated national input-output table. Harris and Malloy (1986) included population growth in labor supply into an IO-LP, examining the effect of water resource limitations on economic growth in Nevada. Goicoechea and Harris (1987) used a multi-objective IO-LP model to evaluate the trade-offs between regional income, regional employment, and energy consumption in Oklahoma. López-Morales and Duchin (2011) used an IO-LP model to evaluate the impacts of a water price schedule and water withdrawal regulations on irrigation technologies. Springer and Duchin (2014) combined an inter-regional input-output model with linear programming to evaluate food demand scenarios. Lopez-Morales and Duchin (2015) used a similar approach to investigate how water withdrawal regulations impact regional economic growth. Riberio et al. (2016) applied an IO-LP model to study how CO_2 emission regulation would impact Brazil's economy.

Methods

To reduce the complexity of the modeling process, the 536 IMPLAN sectors used in previous chapters were aggregated to 21 sectors. These 21 aggregated sectors are: "Primary Agriculture Crops ", "Primary Agriculture Livestock ", "Forestry Inputs", "Mining", "Services", "Utilities", "Water, sewage and other systems", "Construction", "Secondary Agriculture", "Manufacturing", "Primary Forestry", "Secondary Forestry", "Agriculture Inputs", "Wholesale trade", "Retail Trade", "Transportation", "Finance", "Insurance", "Real Estate", "Government", and "Miscellaneous". The aggregation scheme is suggested by AIM-AG bi-annual reports[14] and Owen et al. (2017).

The general set-up of the IO-LP model used here follows Henry and Bowen (1981). The IO-LP model maximizes Gross Regional Product (GRP), subject to regional water availability, labor availability, and corresponding final demand for goods produced by the 21 sectors. The

[14] http://aimag.ag.utk.edu/rp.html

GRP measure is similar to Gross Domestic Product (GDP). According to OCED (2002), the GDP is the sum of the gross values added of production, thus the GRP objective value is calculated as the regional sum of gross value added to the economy.

Linear Programming Scenarios

Five scenarios are analyzed to examine different assumptions about water availability, inter-regional transactions, and final demand in the southeastern U.S. Scenarios 1 and 2 (Table 17) compare water shadow values estimated using an IO-LP and a Multi-Regional Input-Output Linear Programming (MRIO-LP) model, respectively, when a BEA-specific final demand constraints are imposed. Scenarios 3 and 4 (Table 17) conduct a similar comparison except that final demand for a sector's product is aggregated to the southeastern U.S. region. Scenario 5 evaluates what happens when the southeastern U.S. is self-contained (the region does not use intermediate inputs from outside the region) (Table 17).

The objective of all three scenarios is to maximize Gross Regional Product (GRP), yielding shadow values of water determined by incrementally decreasing water availability.

Scenario 1

This scenario assumes each BEA produces goods (output) without intermediate inputs from other BEA regions. TIO discounted for intermediate input uses cannot exceed BEA regional final demand. Therefore, inputs produced in other BEA regions to satisfy local production and final demand are permitted.

The objective is:

$$\max_{X_j^s} Z = \sum_j \sum_s V_j^s \cdot X_j^s \qquad (18a)$$

subject to

$$(X_i^r - \sum_s \sum_j \tilde{a}_{ij}^{rs} X_j^s) \leq Y_i^r \quad \forall\, r, i \tag{19a}$$

$$\sum_j X_j^s \cdot \omega_j^s \leq W^s\ [\lambda_s] \quad \forall\, s \tag{20a}$$

$$X_j^s \cdot l_j^s \leq L_j^s\ [\gamma_s] \quad \forall\, s, j \tag{21a}$$

where Z, the objective value, is total Gross Regional Product (GRP) of all 43 BEA regions; *i* denotes input sectors, *j* denotes output sectors (*i* aliases *j*); *r* denotes the providing (exporting) region, and *s* denotes the receiving (importing) region (*s* aliases *r*). Inter-regional transactions for intermediate inputs are not allowed. Therefore,

$$\tilde{a}_{ij}^{rs} = \begin{cases} 0 & when\ r \neq s \\ a_{ij}^r & when\ r = s \end{cases} \tag{22}$$

and a_{ij}^r is the BEA regional technical coefficient from the direct requirement matrix A^r in IMPLAN (MIG, Inc., 2013). The decision variables X_j^s are the total industry output (TIO) of sector *j*, region *s*. Parameters V_j^s, ω_j^s and l_j^s are value added coefficients, water withdrawal coefficients, and labor coefficients corresponding for sector *j*, region *s*, respectively. The parameter W^s is water availability in region *s*, and L_j^s is the labor available in sector *j*, region *s* (equations 20a, 21a, respectively). The variable λ_s is the water shadow value in region s, and the variable γ_s is the wage shadow value in region *s*.

Scenario 2

This scenario permits inter-regional transactions of intermediate input for local production. Total industry output scaled by the production technology cannot exceed BEA regional final demand upper bound.

$$\max_{X_j^s} Z = \sum_j \sum_s V_j^s \cdot X_j^s \tag{18b}$$

subject to

$$(X_i^r - \sum_s \sum_j a_{ij}^{rs} X_j^s) \leq Y_i^r \quad \forall\, r, i \tag{19b}$$

$$\sum_j X_j^s \cdot \omega_j^s \leq W^s \; [\lambda_s] \quad \forall\, s \tag{20b}$$

$$X_j^s \cdot l_j^s \leq L_j^s \; [\gamma_s] \quad \forall\, s, j \tag{21b}$$

The coefficient a_{ij}^{rs} is an element of the multi-regional direct requirement matrix (determined as A^M; Chapter 2), describing how many monetary units of output by sector *i*, region *r*, are required to produce one monetary unit of output by sector *j*, region *s*. Other variables and parameters are defined in scenario 1.

Scenario 3

This scenario does not allow inter-regional transactions of intermediate inputs for local production. Total industry output, adjusted for intermediate input uses, are aggregated for each sector across all BEAs, and cannot exceed aggregated final demand. Equation 19c constrains the southeastern U.S. to be a single production unit.

The objective is:

$$\max_{X_j^s} Z = \sum_j \sum_s V_j^s \cdot X_j^s \tag{18c}$$

subject to

$$\sum_r (X_i^r - \sum_j \tilde{a}_{ij}^{rs} X_j^r) \leq \sum_r Y_i^r \quad \forall\, i \tag{19c}$$

$$\sum_j X_j^r \cdot \omega_j^r \leq W^r \; [\lambda_r] \quad \forall\, r \tag{20c}$$

$$X_j^r \cdot l_j^r \leq L_j^r \; [\gamma_r] \quad \forall\, r, j \tag{21c}$$

where all variables and parameters are defined same as the scenario 1.

Scenario 4

This scenario also assumes the southeastern U.S. performs as a single production unit, but allows inter-regional transactions of intermediate inputs through matrix $A^M (= [a_{ij}^{rs}])$ (Chapter

2). This scenario maximizes GRP, subject to water and labor availability and final demand constraints:

$$\max_{X_j^s} Z = \sum_j \sum_s V_j^s \cdot X_j^s \qquad (18d)$$

subject to

$$\sum_r (X_i^r - \sum_s \sum_j a_{ij}^{rs} X_j^s) \leq \sum_r Y_i^r \quad \forall\, i \qquad (19d)$$

$$\sum_j X_j^s \cdot \omega_j^s \leq W^s \; [\lambda_s] \quad \forall\, s \qquad (20d)$$

$$X_j^s \cdot l_j^s \leq L_j^s \; [\gamma_s] \quad \forall\, s, j \qquad (21d)$$

where all variables and parameters are defined in scenario 2.

Scenario 5

Multi-regional transactions are permitted in scenario 5. The southeastern U.S. is assumed to be a single, self-contained production unit; no intermediate inputs are purchased from outside southeastern U.S. to meet final demand, as equation 19e suggests. The current final demand of the southeastern U.S. by sector from IMPLAN (MIG, Inc., 2013) is used as the lower bound on final demand (Y_i^{SE}). The southeastern U.S. final demand Y_i^{SE} is smaller than the sum of the BEA regional final demand $\sum_r Y_i^r$. This occurs because the final demand of each BEA counts exports to the rest of world, which includes other BEA regions. The southeastern U.S. final demand (Y_i^{SE}) only includes its exports beyond the southeastern U.S. region.

The objective is to maximize GRP, satisfying a lower bound target of final demand and subject to labor and water resource availability:

$$\max_{X_j^s} Z = \sum_j \sum_s V_j^s \cdot X_j^s \qquad (18e)$$

subject to

$$\sum_r (X_i^r - \sum_s \sum_j a_{ij}^{rs} X_j^s) \geq Y_i^{SE} \quad \forall\, i \qquad (19e)$$

$$\sum_j X_j^s \cdot \omega_j^s \leq W^s \; [\lambda^s] \quad \forall \, s \qquad (20e)$$

$$X_j^s \cdot l_j^s \leq L_j^s \; [\gamma_s] \quad \forall \, s, j \qquad (21e)$$

where Y_i^{SE} is final demand of aggregated sector *i*. Other variable and parameter definitions follow scenario 4.

Calculating Water Shadow Values

To determine the shadow value of water, water availability in each BEA region is reduced from 100% of the USGS 2010 water withdrawal levels by 5% until only 20% of the USGS (2010) level remains. The decrease is uniform across all region and occurs simultaneously. The resulting shadow value of water (λ^s) is the marginal change (in monetary units) in the objective value (GRP) due to a unit change of water availability in region *s*. The (λ^s,W^s) pairs define the regional water demand curve for each region *s*.

To generate an aggregated water demand curve for the southeastern U.S., the ideal way would be to horizontally sum up the water demand curves derived for each BEA region. However, due to scaling problems, a proxy of the aggregated shadow value is calculated as the change in GRP with respect to a one acre-foot decrease in the southeastern U.S. total water availability; i.e.,

$$\lambda^{SE} = \frac{\Delta GRP}{\Delta W} \qquad (23a)$$

When ΔW equals 1 acre foot, ΔGRP corresponds with the aggregated water shadow value, λ^{SE}. This method is essentially a finite difference (backward Euler) approximation of the aggregated shadow value. The aggregated water shadow value generated using the finite difference approximation does not necessary produce the one that generated by horizontally summation of all BEA regional water shadow values.

Replace constraint (20a, b, c, d and e) with equation (23b),

$$\sum_j X_j^s \cdot \omega_j^s \leq W^s - d^s \quad \forall s \tag{23b}$$

$$d^s = \frac{W^s}{\sum_s W^s} \quad \forall s \tag{23c}$$

The change in water availability of the southeastern U.S. is proportionally distributed across BEAs according to their water endowments. The apportioned difference for each BEA is measured by d^s. For example, if region *s* accounts for 3.6% of the entire southeastern U.S. water availability, then then right hand side of equation 23b will be $W^s - 0.036$ for region *s*.

The new GRP (GRP^1) objective value are calculated for each water availability scenario (5%, 10%,…, 80% decrease), and are then compared with original *GRP* (GRP^0) that were generated with equation (20c). The change between the original *GRP* and new *GRP* ($\Delta GRP = GRP^0 - GRP^1$) is the aggregated shadow value water (λ^{SE}).

Data

A multi-regional direct requirement matrix of dimension (21×43 by 21×43) is constructed using the method discussed in Chapter 2. The aggregated regional direct requirement matrices and aggregated employment were extracted from the 2013 IMPLAN data base (MIG, Inc., 2013).

Water withdrawal coefficients estimated in Chapter 3 are aggregated to 21 economic sectors as:

$$\omega_i^r = \frac{\sum_m \omega_m^r X_m^r}{\sum_m X_m^r} \; \forall \, i \; (i = 1,2, \dots ,21) \tag{24a}$$

where *m* denotes an IMPLAN sector belonging to aggregated sector *i*; ω_i^r are the water withdrawal coefficients aggregated to sector *i*; and ω_m^r and X_m^r are the water withdrawal coefficient and TIO of sector *m* of aggregated sector *i*, region *r*, respectively.

Regional value added coefficients (V_i^r) and regional labor coefficients (l_i^r) corresponding with each sector are calculated, respectively, as:

$$V_i^r = \frac{VA_i^r}{X_i^r} \qquad (24b)$$

$$l_i^r = \frac{L_i^r}{X_i^r} \qquad (24c)$$

where VA_i^r and L_i^r are the total value added and employment of aggregated sector *i*, region *r*, respectively. The total value added (*VA*), total industry output (*X*) and final demand (*Y*) used here are aggregated to the 21 sector level and also obtained from the IMPLAN data base (MIG, Inc., 2013).

Results and Discussion

Comparison of scenarios 1, 2, 3 and 4 (Figure 14, Table 18) indicate that GRP in scenario 4 is higher than that of scenario 3 at same water availability level. The same relationship exists between scenarios 2 and 1. This is because inter-regional transactions between regions increase the total industry output requirement to meet the same level of final demand. Therefore, higher GRPs are generated in scenarios 2 and 4 compared to scenarios 1 and 3, respectively. In addition, the GRP in scenario 3 is larger than that from scenario 1. Scenarios 4 and 2 have the same relationship. This results from relaxing the final demand constraint. A less restricted final demand constraint allows a region with higher water use efficiency to produce more output to meet a higher level of final demand. This allows total industry output to increase with a fixed water endowment. Therefore, a relaxed final demand constraint leads to a higher GRP.

A different economic assumption is imposed in scenario 5. In scenario 5, the southeastern U.S. is assumed to be self-contained. The GRP of scenario 5 decreases rapidly when water availability decreases to 70% of the 2010 USGS level (Figure 14). This rapid change is also evident in the aggregated industry water demand curve (Figure 15). The water shadow value increases from 1031 dollar per acre-foot to 4837 dollars per acre-foot the water availability decreases from 75% to 70% of 2010 USGS level (Table 19). Subsequent reductions in water availability generate larger increases in the shadow value of water (Table 19). When water availability decreases to 60% of the 2010 USGS water availability, the southeastern U.S. is no longer able to meet target final demands with its water resource endowments.

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Appendix D

Figures

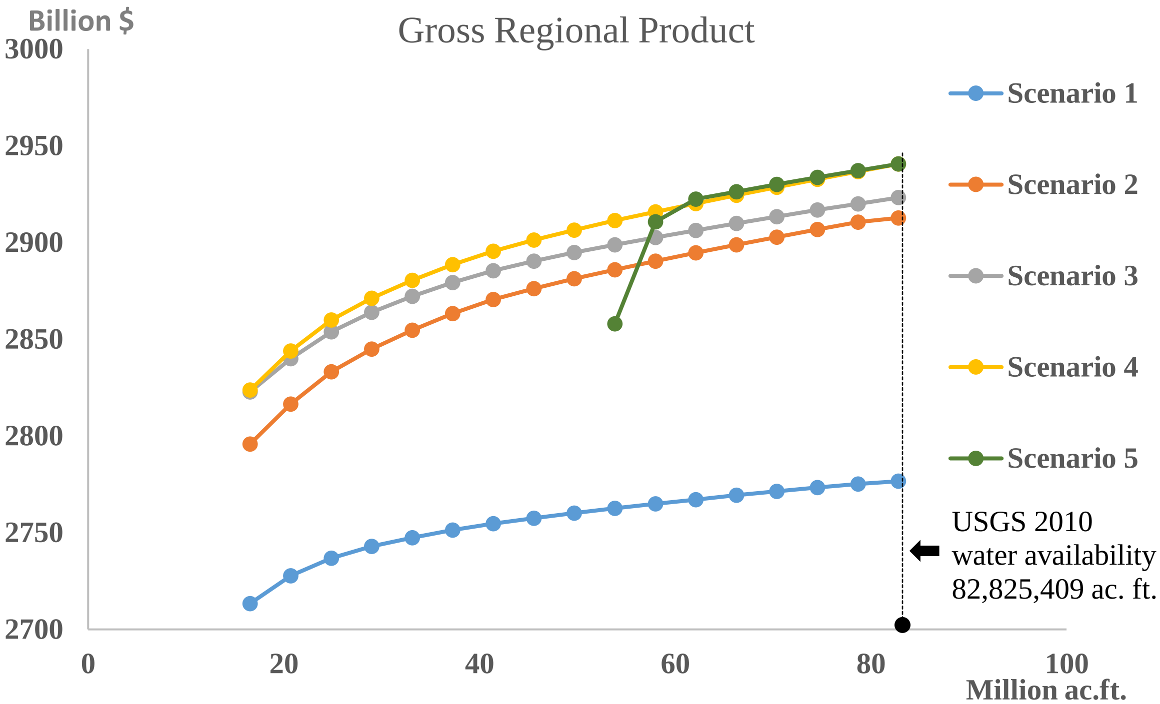

Figure 14. Gross Regional Product

Notes:

Scenario 1 is an IO-LP model with BEA-specific final demand as an upper bound. Transactions from other BEA regions inside the southeastern U.S. are restricted.

Scenario 2 is an MRIO-LP model with BEA-specific final demand as an upper bound. Transactions from other regions inside the southeastern U.S. are allowed for regional production.

Scenario 3 is an IO-LP model with final demand aggregated across regions for each sector as an upper bound. Transactions from other BEA regions inside the southeastern U.S. are restricted.

Scenario 4 is an MRIO-LP model with final demand aggregated across regions for each sector as an upper bound. Transactions from other regions inside the southeastern U.S. are allowed for regional production.

Scenario 5 is an MRIO-LP model with the southeastern U.S. final demand as the final demand lower bound. Transactions from other regions inside the southeastern U.S. are allowed, but transactions from outside the southeastern U.S. are restricted for regional production.

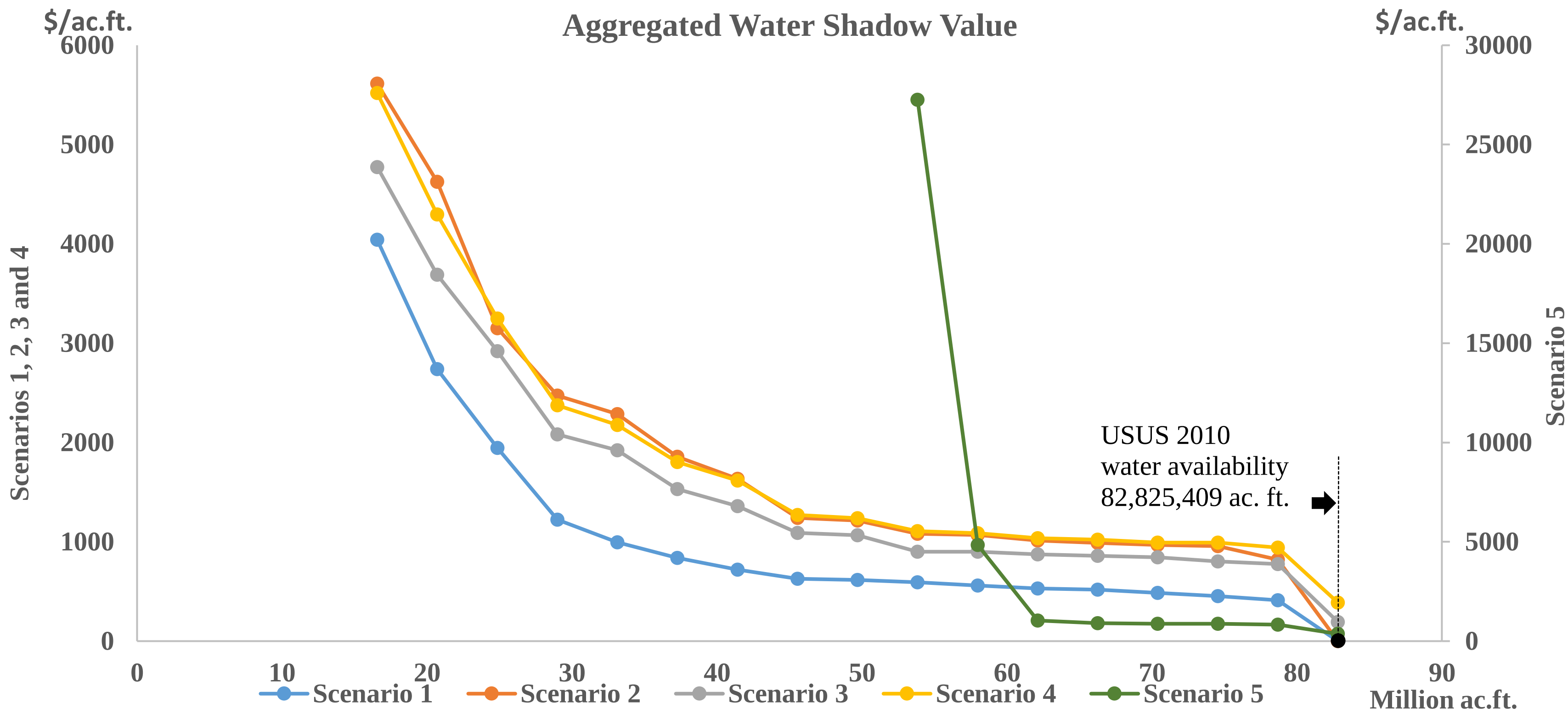

Figure 15. Shadow Value of Water

Notes:

Scenario 1 is an IO-LP model with BEA regional final demand upper bound. Transactions from other BEA regions inside the southeastern U.S. are restricted. Scenario 2 is an MRIO-LP model with BEA regional final demand upper bound. Transactions from other regions inside the southeastern U.S. are allowed for regional production. Scenario 3 is an IO-LP model with the BEA regional final demand sum as the final demand upper bound. Transactions from other BEA regions inside the southeastern U.S. are restricted. Scenario 4 is an MRIO-LP model with the BEA regional final demand sum as the final demand upper bound. Transactions from other regions inside the southeastern U.S. are allowed for regional production. Scenario 5 is an MRIO-LP model with the southeastern U.S. final demand as the final demand lower bound. Transactions from other regions inside the southeastern U.S. are allowed, but transactions from outside the southeastern U.S. are restricted for regional production.

Tables

Table 17. Scenario Description

	$\boldsymbol{A = \tilde{A} = diag(A^r)}$	$\boldsymbol{A = A^M}$
$\boldsymbol{(I - A)X^r \leq Y^r}$	Scenario 1	Scenario 2
$\sum_r \boldsymbol{(I - A)X^r} \leq \sum_r \boldsymbol{Y^r}$	Scenario 3	Scenario 4
$\sum_r \boldsymbol{(I - A)X^r} \geq \boldsymbol{Y^{SE}}$	Not applicable	Scenario 5

Note:
Y is final demand, and *X* is Total Industry Output (TIO); *r* is BEA regional level, and *SE* is the southeastern U.S. level. *A* is direct requirement matrix, and *M* denotes multi-regional.

Table 18. Southeastern U.S. Gross Regional Product (GRP) (million $)

Water Availability (%)	Water Availability (ac.ft.)	Southeastern U.S. GRP				
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
100	82,825,409	2,776,601	2,912,749	2,923,214	2,940,626	82,825,409
95	78,684,139	2,775,150	2,910,553	2,920,036	2,936,747	78,684,139
90	74,542,868	2,773,360	2,906,846	2,916,771	2,932,741	74,542,868
85	70,401,598	2,771,384	2,902,840	2,913,362	2,928,635	70,401,598
80	66,260,327	2,769,312	2,898,814	2,909,839	2,924,482	66,260,327
75	62,119,057	2,767,149	2,894,650	2,906,228	2,920,207	62,119,057
70	57,977,786	2,764,924	2,890,388	2,902,580	2,915,842	57,977,786
65	53,836,516	2,762,555	2,885,959	2,898,849	2,911,313	53,836,516
60	49,695,245	2,760,074	2,881,290	2,894,824	2,906,460	NA
55	45,553,975	2,757,488	2,876,194	2,890,335	2,901,231	NA
50	41,412,705	2,754,618	2,870,536	2,885,407	2,895,543	NA
45	37,271,434	2,751,413	2,863,357	2,879,380	2,888,519	NA
40	33,130,164	2,747,344	2,854,744	2,872,189	2,880,499	NA
35	28,988,893	2,742,915	2,844,943	2,863,981	2,871,178	NA
30	24,847,623	2,736,851	2,833,144	2,853,840	2,860,028	NA
25	20,706,352	2,727,692	2,816,512	2,839,900	2,843,980	NA
20	16,565,082	2,713,391	2,795,852	2,822,820	2,823,696	NA

Source: Author's calculation and UGSG (2010) water withdrawal data

Note: NA indicates infeasibility;

Scenario 1 is an IO-LP model with BEA regional final demand upper bound. Transactions from other BEA regions inside the southeastern U.S. are restricted. Scenario 2 is an MRIO-LP model with BEA regional final demand upper bound. Transactions from other regions inside the southeastern U.S. are allowed for regional production. Scenario 3 is an IO-LP model with the BEA regional final demand sum as the final demand upper bound. Transactions from other BEA regions inside the southeastern U.S. are restricted. Scenario 4 is an MRIO-LP model with the BEA regional final demand sum as the final demand upper bound. Transactions from other regions inside the southeastern U.S. are allowed for regional production. Scenario 5 is an MRIO-LP model with the southeastern U.S. final demand as the final demand lower bound. Transactions from other regions inside the southeastern U.S. are allowed, but transactions from outside the southeastern U.S. are restricted for regional production.

Table 19. Southeastern U.S. Water Shadow Values ($/ac.ft.)

Water Availability (%)	Water Availability (ac.ft.)	Southeastern U.S. Water Shadow Value				
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
100	82,825,409	0	0	194	388	367
95	78,684,139	412	821	775	941	836
90	74,542,868	455	957	803	991	877
85	70,401,598	487	969	845	993	879
80	66,260,327	519	988	859	1,023	906
75	62,119,057	530	1,014	874	1,038	1,031
70	57,977,786	560	1,069	901	1,086	4,837
65	53,836,516	592	1,080	901	1,106	27,256
60	49,695,245	615	1,213	1,066	1,239	NA
55	45,553,975	629	1,241	1,089	1,272	NA
50	41,412,705	719	1,635	1,360	1,617	NA
45	37,271,434	837	1,858	1,531	1,804	NA
40	33,130,164	995	2,286	1,921	2,178	NA
35	28,988,893	1,224	2,471	2,081	2,374	NA
30	24,847,623	1,946	3,150	2,921	3,248	NA
25	20,706,352	2,739	4,626	3,688	4,297	NA
20	16,565,082	4,041	5,614	4,775	5,519	NA

Source: Author’s calculation and UGSG (2010) water withdrawal data
Notes: NA indicates infeasibility;
Scenario 1 is an IO-LP model with BEA regional final demand upper bound. Transactions from other BEA regions inside the southeastern U.S. are restricted. Scenario 2 is an MRIO-LP model with BEA regional final demand upper bound. Transactions from other regions inside the southeastern U.S. are allowed for regional production. Scenario 3 is an IO-LP model with the BEA regional final demand sum as the final demand upper bound. Transactions from other BEA regions inside the southeastern U.S. are restricted. Scenario 4 is an MRIO-LP model with the BEA regional final demand sum as the final demand upper bound. Transactions from other regions inside the southeastern U.S. are allowed for regional production. Scenario 5 is an MRIO-LP model with the southeastern U.S. final demand as the final demand lower bound. Transactions from other regions inside the southeastern U.S. are allowed, but transactions from outside the southeastern U.S. are restricted for regional production.

CHAPTER 5: CONCLUSION

The southeastern U.S. is experiencing an increasing water demand due to population expansion and increased demand for water, which fueled water disputes between Georgia, Alabama and Florida. Drought in 2007 and 2012 significantly impacted the agricultural and hydro-power sectors in Georgia, Tennessee and North Carolina. The 2007 and 2012 droughts revealed the southeastern vulnerabilities in the southeastern region's water resources. Droughts are expected to become more frequent in the southeastern U.S. This thesis aimed to evaluate how water scarcity could impact the southeastern U.S. economy by answering two questions: 1) how water resources in the southeastern U.S. are currently allocated to meet the regional economic demand; 2) how reductions in water endowments impact the shadow value of water in the southeastern U.S. A multi-regional water footprint analysis and a Multi-Regional Input-Output Linear Programming (MRIO-LP) were used to answer these questions.

A multi-regional input-output model is built first to describe the southeastern U.S. structure in Chapter 2. Then, an EIO-LCA was used to estimate water footprints (Chapter 3). Comparisons of water footprints across different regions and sectors revealed regional differences in water productivity. Decomposing total water footprints into constituent parts highlighted regional interdependencies with respect to water use and final demand. Due to the relatively large water requirements of the agricultural sectors, regions with largest industry output of six agricultural sectors were selected. Results indicate there are significant dependencies among BEA regions in terms of water withdrawals. In addition, large differences in water withdrawal pattern and water management between various regions exist. Finally, five scenarios with different economic structure assumptions were set up to simulate the allocation of limited water resources among competing sectors to maximize the Gross Regional Product (GRP) in the Chapter 4. In addition, the shadow value of water was also determined from those five scenarios at various water availability levels. The results indicate that the southeastern U.S. is able to meet the regional final demand without inputs from the rest of the world until water availability decreases to 60% of 2010 USGS level. It is also observed that the southeastern GRP is higher and water shadow value is lower when transactions among regions are allowed to meet the regional final demand. Generally speaking, the southeastern U.S. economy is less likely to experience decline due to water stress unless there is a sharp decrease in water availability.

Limitations of this thesis primarily lie in two aspects. First is the measure of water use and water availability. Water withdrawal, instead of water consumption, is used to evaluate water use, which overestimates the water use in economy. In addition, water withdrawals in 2010 is used as the water availability, which is smaller than the actual water availability. In this way, the potential water stress is overstated. Second is the estimation of the multi-regional direct requirement matrix (A^M). There are several rather strict assumptions using the LQ and column trade coefficient to estimate the regional input coefficients. Homogenous demand, no cross-hauling effects and identical transportation cost with corresponding economic benefits are assumed. However, these assumptions may not hold in actual practices. Lack of data of actual A^M, there is little known about the estimation performance. It is better to involve more survey data for estimating the A^M if possible.

VITA

Di Sheng is from Wuhan, Hubei, China. She earned her bachelor's degree of International Economics and Trade with honor from Zhongnan University of Economics and Law in 2014. She also received a bachelor's degree of Computing Science in 2014. During her degree, she led two projects with funding to study regional economic problems. Upon completion of her undergraduate degree, Di spent one month for a cycling trip from Chengdu to Lhasa to experience different economy structure and culture in China. She worked in Helen Doron Education Group as sale consultant for early education upon returning from Lhasa. Di started to study and work as a graduate research assistantship of the Agricultural and Natural Resource Economics Department at The University of Tennessee in the fall of 2015. She is expected to graduate with a Master of Science degree in Agricultural Economics and a Minor in Statistics in August, 2017.