What Factors Drive the Changes in Water Withdrawals in the U.S. Agriculture and Food Manufacturing Industries?

Andre F. T. Avelino

National Renewable Energy Laboratory

Sandy Dall'Erba

ACE and REAL,

University of Illinois

REAL 19-T-4

August, 2019

Regional Economics Applications Laboratory
67 Mumford Hall
1301 West Gregory Drive
Urbana, IL, 61801
Phone: (217) 333- 4740

What Factors Drive the Changes in Water Withdrawals in the U.S. Agriculture and Food Manufacturing Industries?

Andre F. T. Avelino† and Sandy Dall'erba‡

† National Renewable Energy Laboratory, Golden, CO
‡ Department of Agricultural and Consumer Economics, Regional Economics Applications Laboratory, University of Illinois at Urbana-Champaign

Abstract: Recent studies on the impact of climate change anticipate a significant decrease in both the availability and quality of water resources in the next half-century, which will directly impact domestic and international food supply chain linkages. In the U.S., agricultural production requires less irrigated water than in the past but it is still responsible for more than a third of total water withdrawals. To better understand the evolution of water use in this sector, we perform a structural decomposition analysis over the 1995-2010 period using the Exiobase 3 database. More precisely, we emphasize i) the evolution of water withdrawals for 8 different crops and 6 livestock categories, ii) the difference in results based on the U.S. Geological Survey's water consumption data vs. Hoekstra's water footprint data, and iii) the trends in the pre-crisis (1995-2005) and post-crisis (2005-2010) periods. Our results show that the pre-crisis period experienced an overall decline in water withdrawals in the production of all crops except oil seeds (which includes soybeans). For such crop, the increase in water use comes primarily from a greater water intensity and changes in international interindustrial trade patterns. This increase persisted in the post-2005 period but was driven primarily by direct exports to industries and changes in the average global expenditure structure. We also find that changes in the production structure of the U.S. food manufacturing sector contributed to an increase in water use in agriculture pre-2005 but to a decrease post-2005. Livestock has also shown a decline in water use during the entire period, mainly driven by domestic final demand and a change in the mix of livestock. Overall, these results will help develop future water-saving strategies in the U.S. as the country, like its trade partners, will meet increasing challenges to secure food availability in the face of climate change.

1. INTRODUCTION

According to estimates from the U.S. Geological Survey [USGS], the 2015's total water use in the United States reached its lowest level since the 1970's following a consistent decline post 2008-crisis (Dieter *et al.*, 2018). With a per capita water withdrawal of 366 thousand gallons/year, the country is the highest water user of all developed nations,. It is 29% more than Canada (Food and Agriculture Organization [FAO], 2019; Statistics Canada, 2019). In the U.S., the water use trend has varied significantly in the last eighty years with three distinctive periods. The first one, from 1950-1980, saw an increase in water use driven by irrigation, public supply and, more importantly, thermoelectric generation. From 1980-2005, we observe an initially sharp decline in water use in most sectors followed by stable consumption levels until 2005. This decline can be partially attributed to higher energy prices and a downturn in the farm economy during the 1980s (Solley *et al*., 1993) as well as the increasing adoption of recirculating cooling systems in thermal power plants due to the Clean Water Act of 1972 (Kenny *et al*., 2009). Another contributing factor is the change in the structure of the U.S. economy with a decrease in the presence of manufacturing and a move towards a service economy. From 2005 onwards, the economic crisis led to a new wave of reduction in water use that is primarily driven by a decrease in thermoelectric power (Figure 1).

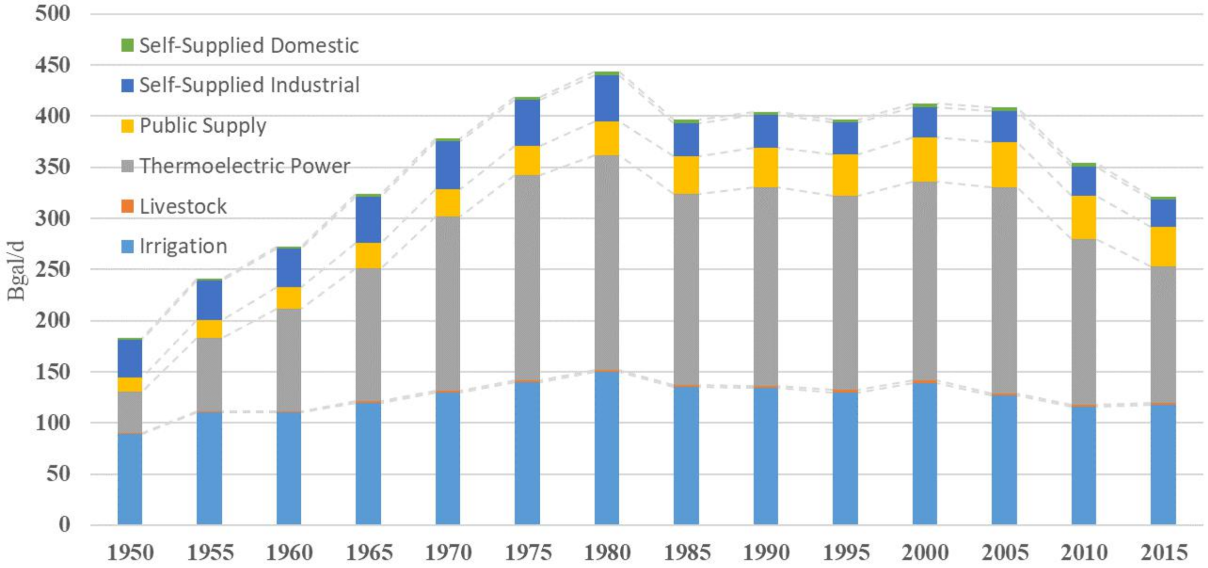


Figure 1. Water use by major category in the United States (Dieter *et al*., 2018)

Irrigation and livestock are responsible for about a third of all water withdrawals in the United States and have exhibited a declining trend despite an increase in irrigated acres in the country, particularly in oil seeds crops (Dieter *et al*., 2018). The year 2000 was atypical, because much of the country experienced a long drought spell (especially the Southern and Western states) which contributed to an increase in water withdrawals in agriculture, hence contrasting with the persistent decline in water use since the 1980s (Hutson *et al*., 2004). Given that food represents on average 12.9% of American household's expenditures and that the agribusiness industry (which comprises agriculture, food manufacturing and related industries) is responsible for 5.5% of the gross national product (United States Department of Agriculture [USDA], 2018), water availability is essential for food security and economic growth in the United States.

In order to get more insights into the sources of the change in water use in the U.S. agribusiness sector, we perform a structural decomposition analysis (SDA) over 1995-2010 that isolates the respective roles of structural changes in the American food industry value chain, in international trade and in water consumption per unit of production. While the SDA approach has been widely used in the water literature in multiregional contexts (Roson and Sartori, 2015; Deng *et al.*, 2016; Incera *et al.*, 2017), applications on the U.S. have focused on the national level only (Wang *et al.*, 2014; 2015), hence omitting to consider the role of external drivers.

Wang *et al.* (2014) combine USGS water withdrawal data with the national U.S. benchmark input-output tables to analyze the influence of five drivers (water intensity, technology structure, population, per capita GDP and consumption structure) in the 3% increase in total water use over 1997-2002. The authors find that while technology and consumption pattern changes reduced water use, such negative impact was more than compensated by an increase in population, per capita GDP and water intensity. Although agriculture and the food industry were among the largest water users in the period (the second and third respectively), they showed opposite trends in terms of water withdrawals: an increase in agriculture but a decrease in the food industry. Changes in the final demand level (per capita GDP and total population) and water intensity contributed to an increase in water use in both sectors, which was partially compensated by the negative effect of changes in the consumption structure. In addition, technology changes lead to an increase in water withdrawals for agriculture but to a decrease for food manufacturing.

In a follow up study, Wang *et al.* (2015) update the analysis for 2005-2010, showing that the overall decline in water withdrawals observed in the period was driven by a decrease in water use intensity (mainly in power generation and agricultural sectors), by changes in the technology structure and by a reduction in per capita GDP. Counteracting such effects, population growth and changes in consumption patterns positively contributed to an increase in water use.

This paper contributes to the literature by combining an extended global multi-regional input-output database (EXIOBASE) with local water consumption data from the U.S. Geological Survey over 1995-2010 to obtain a more complete picture of the drivers of recent water withdrawals in the country. Given the position of the U.S. in international trade, the use of a multi-regional database will also allow us to assess the influence of evolving trade patterns in water use. We focus on the evolution of water withdrawals for 8 different crop groups, 6 livestock categories and 11 food manufacturing industries for the period.

In the next section we detail the structural decomposition formulation applied in this study, followed by data sources in Section 3. Results and discussion are shown in Section 4, and conclusions and policy implications in Section 5.

2. METHODOLOGY

SDA is a comparative statics exercise in which changes in total water use are decomposed in a series of factors that explain the observed overall variation in the period. This is accomplished by splitting a mathematical identity into several components that isolate the change in one set of parameters at a time while keeping the others fixed in a reference point. Given a set of factors, however, a structural decomposition is not unique as its reference points can be changed into equivalent forms. As the number of parameters increases, the number of equivalent forms grows in a factorial fashion (see Dietzenbacher and Los, 1998). Therefore, although this methodological section shows one possible decomposition form, the results presented in Section 4 display the average effect and standard deviation of all equivalent decomposition permutations for each factor.

Let us denote by $\mathbf{x}$ the vector of total gross output by industry, by $\mathbf{w}$ the vector of total water use, by $\mathbf{c}$ the vector of direct water input coefficients ($\mathbf{c}_i = \mathbf{w}_i/\mathbf{x}_i$), by $\mathbf{L}$ the Leontief Inverse matrix and by $\mathbf{y}$ the vector of final demand.[1] Subindices 0 and 1 indicate the first and last year respectively. We start with a basic three factor decomposition of total change in water use ($\Delta\mathbf{w}$) as shown in Equation 1:

$$\Delta\mathbf{w} = \Delta(\mathbf{cLy}) = \hat{\mathbf{c}}_1\mathbf{L}_1\mathbf{y}_1 - \hat{\mathbf{c}}_0\mathbf{L}_0\mathbf{y}_0 = \Delta\hat{\mathbf{c}}\mathbf{L}_0\mathbf{y}_0 + \hat{\mathbf{c}}_1\Delta\mathbf{L}\mathbf{y}_0 + \hat{\mathbf{c}}_1\mathbf{L}_1\Delta\mathbf{y} \qquad (1)$$

where $\Delta\hat{\mathbf{c}}\mathbf{L}_0\mathbf{y}_0$ is the contribution of changes in direct water consumption in each sector (intensity effect); $\hat{\mathbf{c}}_1\Delta\mathbf{L}\mathbf{y}_0$ is the contribution of changes in the sector's own technology and in the local and foreign interindustrial linkages, including trade between countries (technology effect); and $\hat{\mathbf{c}}_1\mathbf{L}_1\Delta\mathbf{y}$ is the contribution of changes in domestic and foreign final demand (final demand effect).

Because this structural analysis is performed in a multi-regional context, the technology effect captures the impact of changes in both intra- and inter-regional linkages. To produce a finer picture of these underlying factors, we need to decompose the technology effect further. For a given domestic (American) sector h, we can subset the changes in technology into different partitions (Figure 2):

$$\begin{aligned}\Delta\mathbf{L} = \mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LO}}\mathbf{L}_0 + \mathbf{L}_1\Delta\mathbf{A}^{\mathrm{EO}}\mathbf{L}_0 + \mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LS}}\mathbf{L}_0 + \mathbf{L}_1\Delta\mathbf{A}^{\mathrm{ES}}\mathbf{L}_0 + \mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LI}}\mathbf{L}_0 + \mathbf{L}_1\Delta\mathbf{A}^{\mathrm{EI}}\mathbf{L}_0 \\ + \mathbf{L}_1\Delta\mathbf{A}^{\mathrm{AT}}\mathbf{L}_0\end{aligned} \qquad (2)$$

where:

$\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LO}}\mathbf{L}_0$ (local own effect): isolates the contribution of changes in the mix of domestic inputs purchased directly by sector h;

$\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{EO}}\mathbf{L}_0$ (external own effect): isolates the contribution of changes in the mix of foreign inputs (imports) purchased directly by sector h;

$\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LS}}\mathbf{L}_0$ (local substitution effect): measures the impact of changes in the direct sale of sector h to other domestic sectors;

$\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{ES}}\mathbf{L}_0$ (external substitution effect): measures the impact of changes in the direct sale of sector h to foreign sectors (i.e., changes in the export structure of h);

$\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LI}}\mathbf{L}_0$ (local interrelational effect): isolates the contribution of changes in the production structure of all domestic sectors except h;

$\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{EI}}\mathbf{L}_0$ (external interrelational effect): isolates the contribution of changes in the production structure of other countries (except international trade flows);

---

[1] The standard input-output notation is used in this paper. Matrices are named in bold capital letters, vectors in bold lower-case letters and scalars in italic lower-case letters. The matrix $\mathbf{I}$ is an identity matrix of appropriate dimensions.

$\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{AT}}\mathbf{L}_0$ (trade effect): isolates the contribution of changes in international trade flows of all sectors (domestic and foreign) except of sector h (which are already considered in the external own/substitution effects).

In addition, we further decompose the local interrelational effect to explicitly highlight the contribution of structural changes in the agricultural sectors ($\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LIA}}\mathbf{L}_0$), in the food manufacturing sectors ($\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LIM}}\mathbf{L}_0$) and in the remaining sectors ($\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LIO}}\mathbf{L}_0$).

$$\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LI}}\mathbf{L}_0 = \mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LIA}}\mathbf{L}_0 + \mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LIM}}\mathbf{L}_0 + \mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LIO}}\mathbf{L}_0 \tag{3}$$

Finally, we split final demand into local and foreign households' total expenditures ($\mathbf{y}^{\mathrm{LH}}$ and $\mathbf{y}^{\mathrm{EH}}$ respectively) and group the remaining components (aggregate of government, change in inventories and gross fixed investments) into the rest of the local and foreign final demand ($\mathbf{y}^{\mathrm{LR}}$ and $\mathbf{y}^{\mathrm{ER}}$ respectively).

$$\mathbf{y} = \mathbf{y}^{\mathrm{LH}} + \mathbf{y}^{\mathrm{EH}} + \mathbf{y}^{\mathrm{LR}} + \mathbf{y}^{\mathrm{ER}} \tag{4}$$

This split allows us to decompose the changes in households' expenditures into changes in total local (L) and external (E) expenditures ($\Delta\omega$), changes in population size (Δp) and changes in expenditure shares ($\Delta\mathbf{s}$):

$$\begin{aligned}\Delta\mathbf{y} = {} & \left(\Delta\omega^{\mathrm{L}} p_0^{\mathrm{L}} \mathbf{s}_0^{\mathrm{L}} + \omega_1^{\mathrm{L}} \Delta p^{\mathrm{L}} \mathbf{s}_0^{\mathrm{L}} + \omega_1^{\mathrm{L}} p_1^{\mathrm{L}} \Delta\mathbf{s}^{\mathrm{L}}\right) + \left(\Delta\omega^{\mathrm{E}} p_0^{\mathrm{E}} \mathbf{s}_0^{\mathrm{E}} + \omega_1^{\mathrm{E}} \Delta p^{\mathrm{E}} \mathbf{s}_0^{\mathrm{E}} + \omega_1^{\mathrm{E}} p_1^{\mathrm{E}} \Delta\mathbf{s}^{\mathrm{E}}\right) \\ & + \Delta\mathbf{y}^{\mathrm{LR}} + \Delta\mathbf{y}^{\mathrm{ER}}\end{aligned} \tag{5}$$

A summary of all decomposition factors is shown in Table 1.

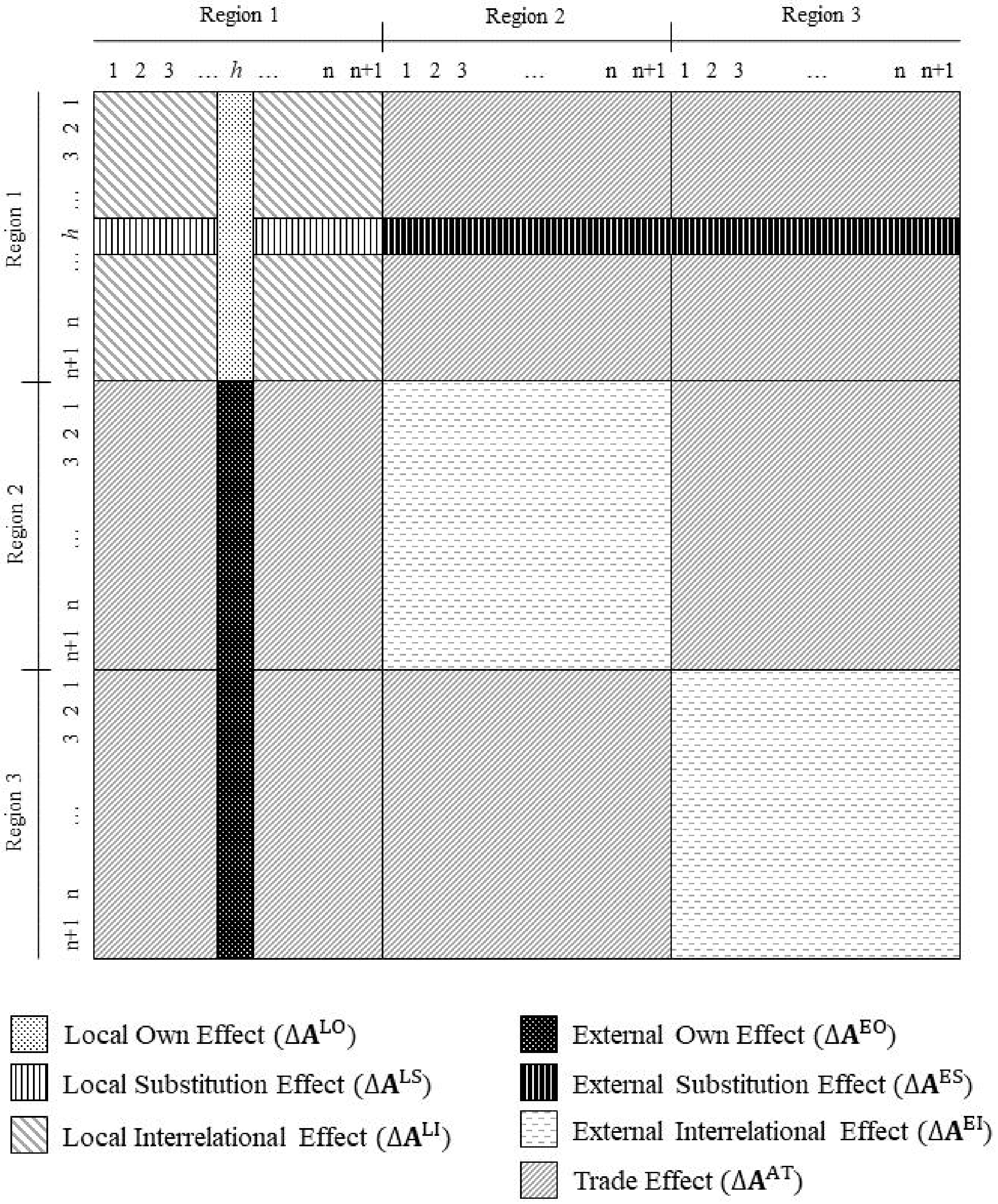


Figure 2. Direct input requirement matrix (**A**) partitions

Table 1. Summary of SDA Factors

Factor	Description	Abbreviation

$\Delta\hat{\mathbf{c}}\mathbf{L}_0\mathbf{y}_0$	Water Intensity Effect	Wr
$\hat{\mathbf{c}}_1\Delta\mathbf{L}\mathbf{y}_0$	Technology Effect	T
$\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LO}}\mathbf{L}_0$	Local Own Effect	LO
$\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{EO}}\mathbf{L}_0$	External Own Effect	EO
$\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LS}}\mathbf{L}_0$	Local Substitution Effect	LS
$\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{ES}}\mathbf{L}_0$	External Substitution Effect	ES
$\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LI}}\mathbf{L}_0$	Local Interrelational Effect	LI
$\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LIA}}\mathbf{L}_0$	Local Agricultural Sectors Effect	LIA
$\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LIM}}\mathbf{L}_0$	Local Food Manufacturing Sectors Effect	LIM
$\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{LIO}}\mathbf{L}_0$	Local Remaining Sectors Effect	LIO
$\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{EI}}\mathbf{L}_0$	External Interrelational Effect	EI
$\mathbf{L}_1\Delta\mathbf{A}^{\mathrm{AT}}\mathbf{L}_0$	Trade Effect	AT
$\hat{\mathbf{c}}_1\mathbf{L}_1\Delta\mathbf{y}$	Final Demand Effect	Y
$\Delta\omega^{\mathrm{L}}p_0^{\mathrm{L}}\mathbf{s}_0^{\mathrm{L}}$	Local Total Expenditures Effect	L_INC
$\omega_1^{\mathrm{L}}\Delta p^{\mathrm{L}}\mathbf{s}_0^{\mathrm{L}}$	Local Population Effect	L_POP
$\omega_1^{\mathrm{L}}p_1^{\mathrm{L}}\Delta\mathbf{s}^{\mathrm{L}}$	Local Expenditure Share Effect	L_EXP
$\Delta\omega^{\mathrm{E}}p_0^{\mathrm{E}}\mathbf{s}_0^{\mathrm{E}}$	External Total Expenditures Effect	E_INC
$\omega_1^{\mathrm{E}}\Delta p^{\mathrm{E}}\mathbf{s}_0^{\mathrm{E}}$	External Population Effect	E_POP
$\omega_1^{\mathrm{E}}p_1^{\mathrm{E}}\Delta\mathbf{s}^{\mathrm{E}}$	External Expenditure Share Effect	E_EXP
$\Delta\mathbf{y}^{\mathrm{LR}}$	Other Local Final Demand Effect	L_OTH
$\Delta\mathbf{y}^{\mathrm{ER}}$	Other External Final Demand Effect	E_OTH

3. DATA

EXIOBASE 3 provides the environmentally extended global multi-regional input-output (EE-GMRIO) database used in this paper (Stadler *et al.*, 2018). Four EE-GMRIO databases with water indicators are currently available: World Input-Output Database (WIOD) (Timmer *et al.*, 2015), Eora (Lenzen *et al.*, 2012), GTAP-MRIO (Peters *et al.*, 2011) and EXIOBASE 3 (Stadler *et al.*, 2018). A detailed comparison of these datasets can be found in Tukker *et al.* (2018). Among them, EXIOBASE 3 provides the most disaggregated number of harmonized sectors in agriculture and food manufacturing, a feature that we will exploit in the rest of this paper.

The EXIOBASE dataset is comprised of 165 sectors for 45 countries and 4 aggregated rest of the world regions. Due to the current lack of information on industrial and final demand deflators used in the construction of the dataset, we deflated the tables to 2010 constant prices using the procedure and data from the WIOD Release 2013 (Timmer *et al.*, 2015). This procedure involves deflating the entire GMRIO system for a given year using price deflators in national currency and then adjusting for exchange rate variations with the U.S. dollar[2]. The WIOD' Social Economic Accounts (SEA) are available for 35 industries, 40 countries and a single rest of the world region for 1995-2009. The year 2010 was built by bridging the SEA for WIOD Release 2016 with the previous industrial classification system (ISIC Rev.4 to ISIC Rev. 3). Therefore, the countries in EXIOBASE were aggregated to the same regional distribution as WIOD's to perform the deflation. We also aggregate the original 165 sectors of EXIOBASE into 65, keeping the original disaggregation for crops, livestock and food industries. For the sectors that are more disaggregated than the original 35 from WIOD, we use the same price deflator as their respective aggregated sectors. The final sectoral disaggregation is shown in Table A1.

The water data comes from the USGS' "Estimated Use of Water" survey instead of the blue water data provided by EXIOBASE. When comparing both datasets for water use in irrigation and livestock (Figure 3), we note a significant discrepancy in both levels and trends. This is due to methodological differences in the construction of those data. EXIOBASE's water data is based on Mekonnen and Hoekstra's (2011) 1995-2009 average water consumption coefficient by crop scaled for each year using country-specific crop production data from the Food and Agricultural Organization (Stadler *et al.*, 2018 – Supporting Information 4). On the other hand, USGS data are based on a survey performed every 5-years in the United States. Although none of these datasets provide a comprehensive picture of water use in the country, USGS is the official source of water information for the United States so we opted to replace EXIOBASE's blue water estimates with those from USGS.

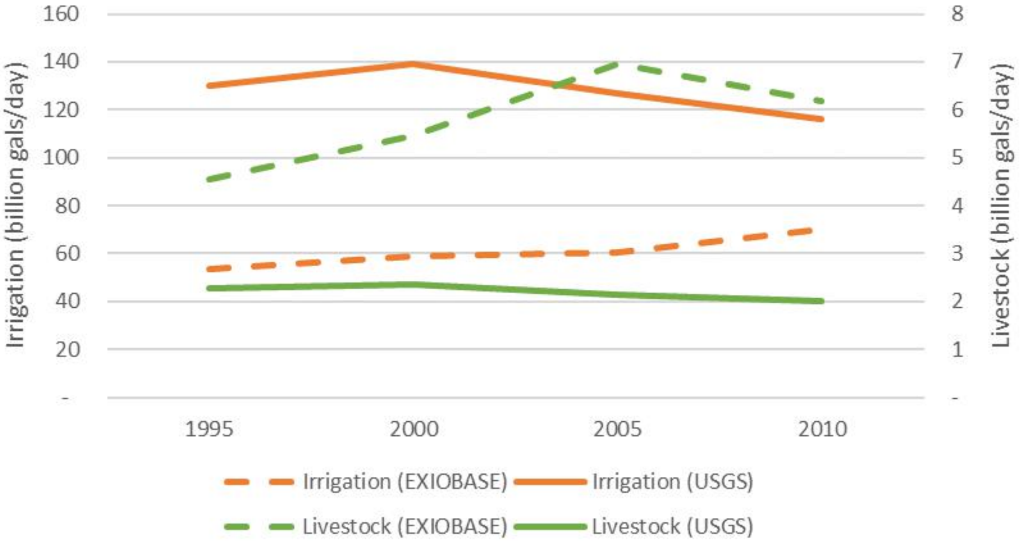


Figure 3. Comparison of blue water consumed in irrigation and livestock (Based on data from Dieter *et al.*, 2018; Stadler *et al.*, 2018)

The USGS provides inventories of water withdrawals in a 5-year interval since 1950. It covers eight main categories: *public supply*, *self-supplied domestic*, *livestock*, *irrigation*, *thermoelectric power*,

---

[2] More details about this procedure can be found here: http://www.wiod.org/protected3/data/update_dec14/Sources_methods_pyp_dec2014.pdf

self-supplied industrial, *mining,* and *aquaculture*.[3] We do not include the *commercial* category because it was discontinued after 1995. To match the remaining seven categories to the 65 industries from EXIOBASE, we follow the procedure originally suggested in Blackhurst *et al*. (2010) and later replicated in other U.S. water focused papers (e.g. Wang *et al*., 2014, 2015; Marston *et al*., 2018).

Public supply is distributed across all economic sectors and final demand according to their expenditures on sector 47 "Collection, purification and distribution of water" in the GMRIO table. We are assuming that all consumers face the same price structure for water supply due to data limitations. Given our sectoral disaggregation, *thermoelectric power*, *mining*, *aquaculture* and *self-supplied domestic* were directly allocated to "Electricity and gas" (sector 46), "Mining and quarrying" (sector 20), "Fishing operating of fish hatcheries and fish farms" (sector 19) and households in the final demand respectively.

In order to distribute water use for *irrigation* among our eight crop categories, we use data from the U.S. Census of Irrigation for the years 1994, 1998, 2003 and 2008. For each year, we calculate the total estimated water use for irrigation in each crop by multiplying the amount of irrigated acres harvested with its average acre-feet of water applied per acre. Then, after grouping these crops to match our crop disaggregation (see Table A2), we distribute the USGS *irrigation* data according to the shares of total water use in each crop.

We use inventory data from the U.S. Census of Agriculture (USDA, 1999; 2004; 2009; 2014) and animal-specific water use coefficients from Lovelace (2009) to distribute *Livestock* water use among our six livestock categories. Animals are matched to their respective EXIOBASE sector (see Table A3) and USGS water data is distributed accordingly.

Self-supplied industrial water withdrawal data are combined with information on water use per employee from the Canadian Industrial Water Use Survey (Statistics Canada, 2019) in order to be allocated across our 25 manufacturing sectors. We assume that U.S. industries follow a similar pattern of water consumption as their Canadian counterparts. Using employment data from EXIOBASE for both Canada and the U.S., we scale the water use by industry and distribute the USGS data according to the industry shares. Since the Industrial Water Use Survey is only available from 2005 onwards (bi-annually), we linearly backcast the Canadian data to 1995. Finally, the last variable needed for Equation 5 is population. Its data are obtained from the World Bank (2019).

4. RESULTS

Our estimates for total water use indicate that after power generation, crop production and food manufacturing are the top water users throughout the period. The 2015 estimates of Wang *et al*. (2014) reach the same conclusions. The agribusiness sector as a whole is consistently the second largest user (Table 2). Vegetables and cereal crops consume the most water overall although oil seeds is the crop that experienced the largest increase in water use throughout the period and has become the 7th largest consumer among all sectors in 2010. Aquaculture (part of the fishing industry) has also substantially increased water use in the period. However, there is an overall decline (-9%) in water consumption in

---

[3] USGS categories have evolved throughout the different surveys.

the agribusiness sectors, with a few notable exceptions such as oil seeds, some animal products (not elsewhere classified), fishing, processing of meat pigs and sugar refining (Figure 4).

Table 2. Rank of agribusiness sectors by water use (largest to lowest)

Sector	Water Use Rank 1995	2000	2005	2010	Total Change in Water Use 1995-2010 (Mm3)	
AGRIBUSINESS SECTORS*	2	2	2	2	-18,493	-9%
CROP PRODUCTION*	2	2	2	2	-20,906	-12%
Rice	4	4	4	5	-7,646	-39%
Wheat	6	6	7	6	-770	-7%
Cereal Grains	3	3	3	3	-2,225	-6%
Vegetables, Fruits and Nuts	2	2	2	2	-1,353	-2%
Oil Seeds	11	9	8	7	4,689	98%
Sugar Cane and Beets	13	17	16	19	-1,845	-49%
Plant-based Fibers	5	5	5	8	-9,491	-55%
Crops n.e.c.	8	8	10	10	-2,266	-26%
LIVESTOCK PRODUCTION*	9	10	9	9	-441	-14%
Cattle Farming	27	26	24	24	-289	-23%
Pigs Farming	37	35	31	30	-24	-4%
Poultry Farming	45	46	39	34	-7	-2%
Meat Animals n.e.c.	53	53	52	49	-19	-30%
Animal Products n.e.c.	58	57	57	56	3	348%
Raw Milk	30	29	26	25	-105	-11%
FISHING INDUSTRY	12	10	6	4	7,862	174%
FOOD MANUFACTURING*	3	3	3	3	-5,008	-22%
Processing of Meat Cattle	42	44	47	46	-386	-82%
Processing of Meat Pigs	34	33	33	14	3,941	559%
Processing of Meat Poultry	38	36	36	43	-493	-78%
Production of Meat Products n.e.c.	16	49	21	21	-1,636	-48%
Processing Vegetable Oils and Fats	56	58	58	58	-18	-100%
Processing of Dairy Products	21	23	22	33	-1,408	-82%
Processed Rice	51	34	35	57	-114	-98%
Sugar Refining	29	47	27	9	6,288	514%
Processing of Food Products n.e.c.	14	7	9	18	-1,783	-48%
Manufacture of Beverages	7	12	15	26	-9,299	-92%
Manufacture of Fish Products	49	51	49	52	-100	-78%

*Rank of the aggregated sector in relation to all other sectors of the economy; n.e.c. = not elsewhere classified

During this period, the overall composition of the livestock sector has changed, with a significant increase in the volume of both poultry (+22%) and pigs (+8%), and a decline in cattle heads (-15%) (Figure 5). For agriculture, we observe an overall 1.2% increase in the number of irrigated acres (Figure 6), which was partially compensated by the adoption of more water-efficient irrigation systems (Kenny *et al*., 2009). We also note the large expansion of oil seeds acreage (+79%) that resulted from changes in commodity prices, growing exports of soybeans (USDA, 2019) and the increasing use of irrigation from 37% to 56% of the planted area (USDA, 1999; 2009).

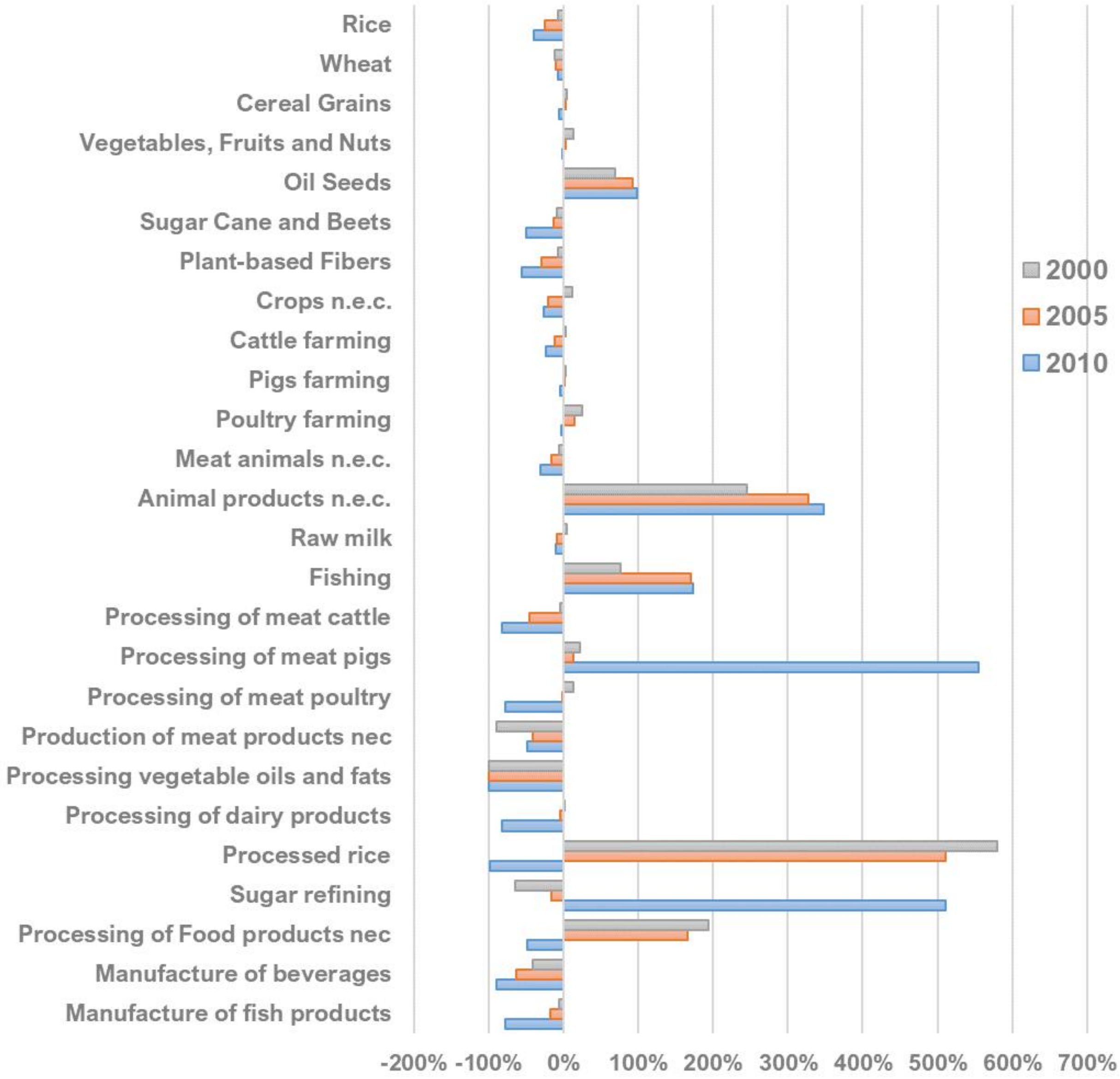


Figure 4. Annual percentage change in water use in agribusiness sectors

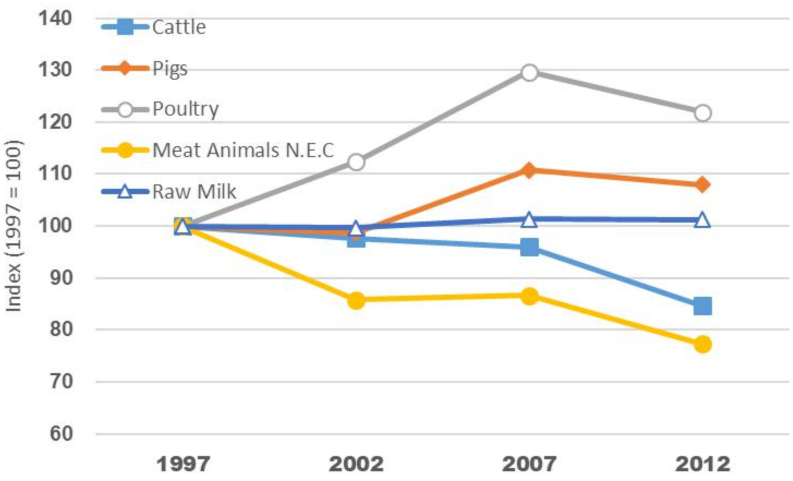


Figure 5. Accumulated change in livestock volumes, 1997 = 100 (Based on data from USDA, 1999; 2014)

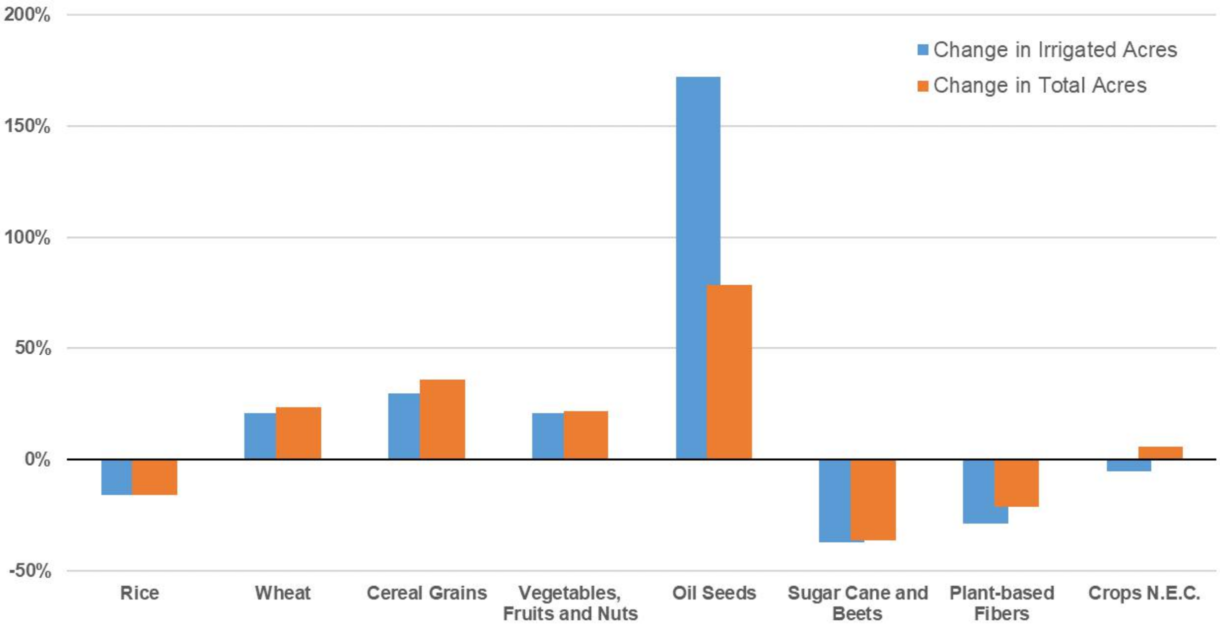


Figure 6. Change in total and irrigated acres by crop category (1994-2008) (Based on data from USDA, 1999; 2014)

Throughout the period, water intensity has been the main contributor of the decrease in water withdrawals in the agricultural sectors (Figure 7) which can be partially attributed to a wide adoption of pressure systems, such as sprinklers and low-flow systems, to replace the traditional gravity irrigation system (Dieter *et al*., 2018). As an example, Bae and Dall'erba (2018) find that, for the state of Arizona only, if each crop were to be irrigated exclusively by the most efficient available system, up to 19.17% of the current amount of irrigated water could be saved.

We also find that, in the pre-crisis period, structural changes in the economy (technology effect) contributed to the decrease in water use while final demand had the opposite effect (Figure 7 top). As expected, post-2008, changes in final demand have contributed to a reduction in water withdrawals in all sectors except oil seeds (Figure 7 bottom).[4]

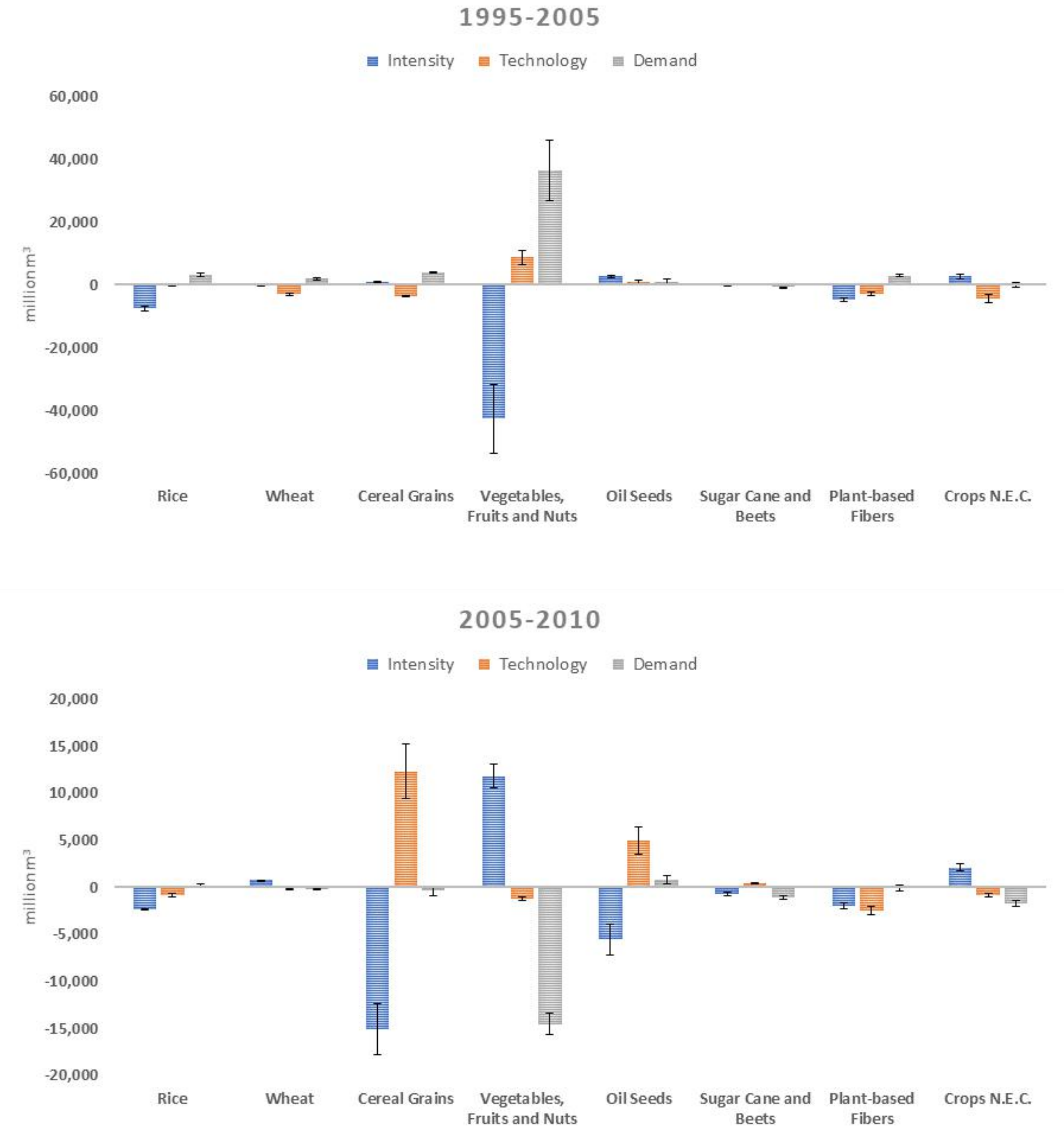


Figure 7. Aggregated drivers of water use change (1995-2005, 2005-2010), agriculture

---

[4] The average acre feet of water withdrawals in the vegetables, fruits and nuts sector increased from 1.98 in 2005 to 2.06 in 2010 (USDA, 1999; 2014). This change has driven the positive influence of water intensity in this sector.

When it comes to livestock, the two periods show diametrically different drivers: while changes in technology and final demand increased water use over the 1995-2005 period, their magnitude was less than that of water intensity changes (Figure 8 top). During the post-crisis period, however, the latter factor positively influenced changes in water withdrawals. This shift can be partially attributed to livestock that saw an increase in the inventories of pigs, poultry and dairy cows[5] (Figure 5). Such increase in water use has been mostly compensated by a negative contribution from the other two drivers (Figure 8 bottom).

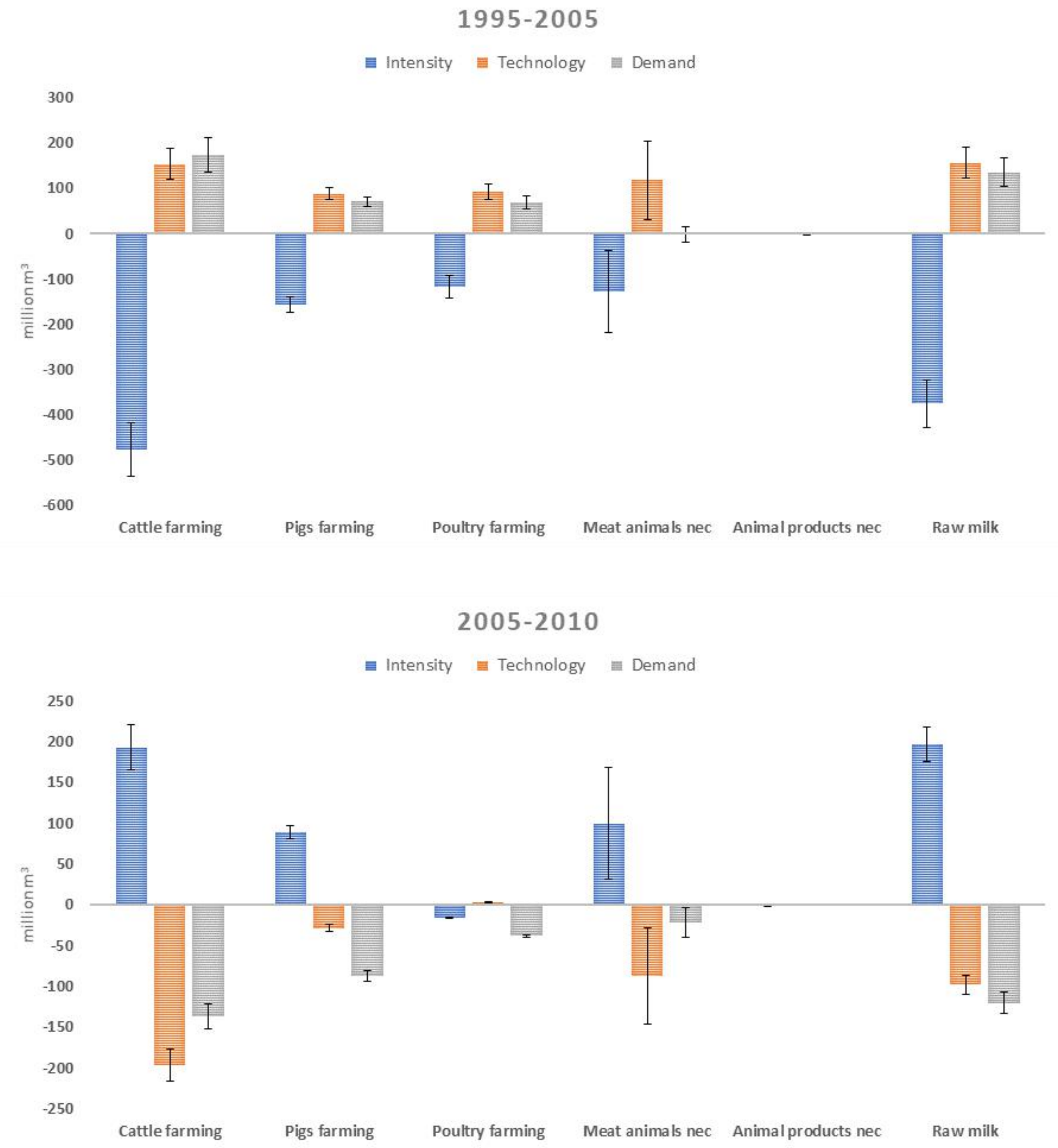


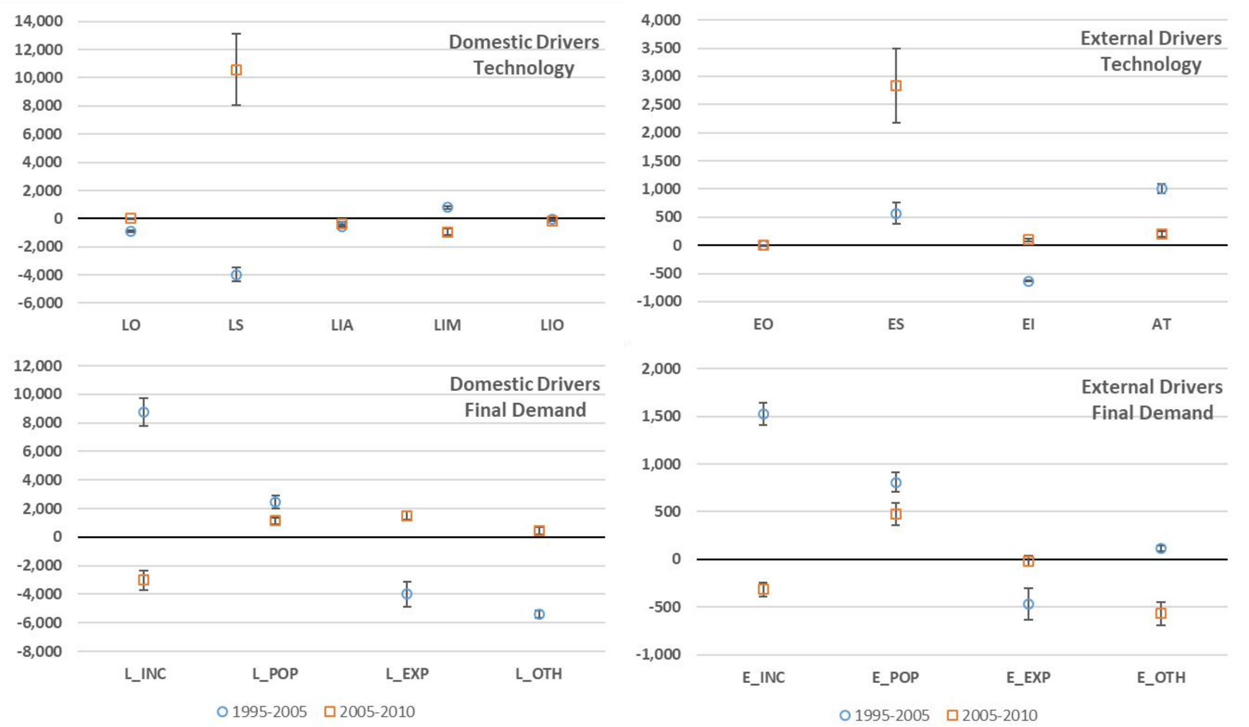
Figure 8. Aggregated drivers of water use change (1995-2005, 2005-2010), livestock

---

[5] On average, dairy cows consume three times more water than beef cattle (Lovelace, 2009).

While the results above are based on Equation 1, we can get more insights into the drivers of the change in water use by relying on Equations 2-5. This section uses this more detailed decomposition as well as all other possible alternatives to report their average effect and standard deviation in Figures 9-11. They focus on cereal grains, vegetables, fruits and nuts, and oil seeds respectively as the first two are the largest water consumers among all crops and the latter one experienced the largest increase over 1995-2010 (Table 2).

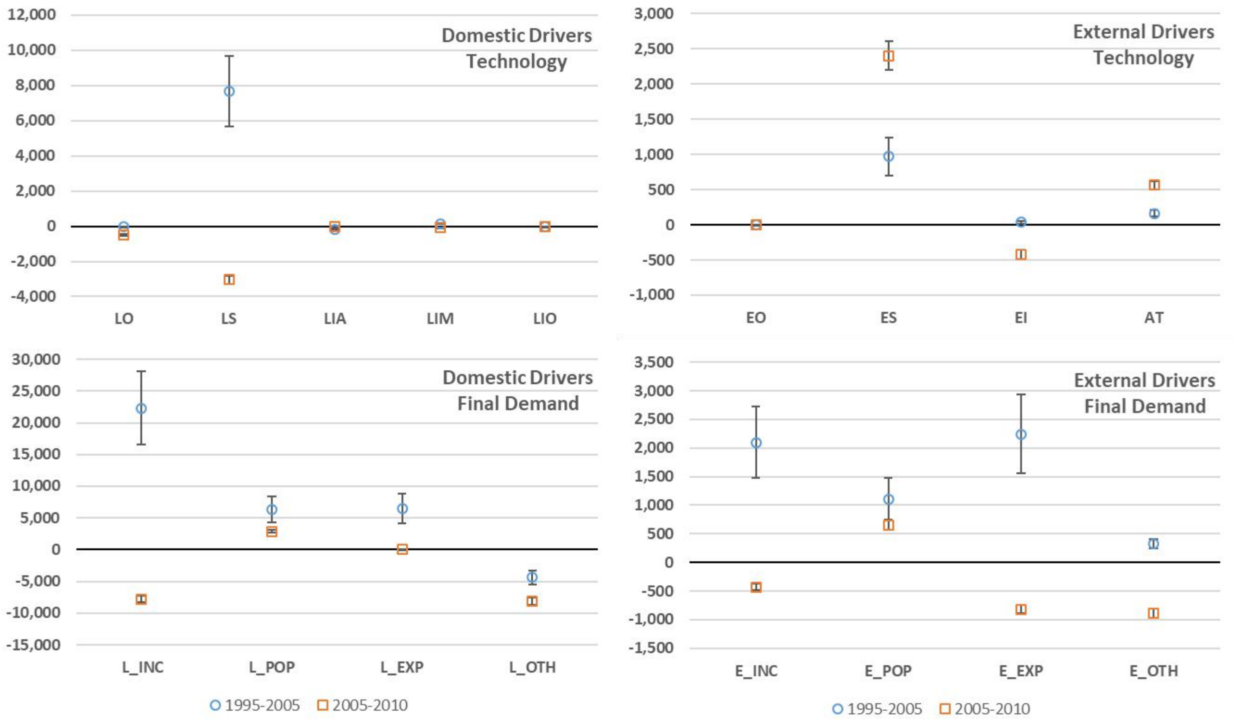
The results in Figure 9 indicate that it is mostly domestic factors that have driven the change in water withdrawals in the cultivation of cereal grains. The negative technology effect over 1995-2005 is primarily driven by changes in the domestic sales of the sector (*LS*) which more than compensated the positive contribution of changes in international trade (*ES* and *AT*) (direct exports, mostly to Mexico, and indirect trade linkages). For the same period, the positive final demand effect was a result of changes in per capita income and population (domestic with *L_INC* and *L_POP* and external with *E_INC* and *E_POP*), compensating the mitigating contribution of changes in domestic household's consumption structure (*L_EXP*). Post-crisis, the positive effect of technology on water withdrawals was the result of changes in domestic sales (*LS*) and international sales (*ES*) of cereal grains. For the latter, the effect mostly came from interindustrial exports to Mexico, Korea and Japan.



Note: Dots and squares show the average impact of all the possible rotations in Equations 2-5. Whiskers show the size of the standard deviation of these rotations. Decomposition of the technology driver is provided in the top charts and the decomposition of the final demand drivers in the bottom charts. The abbreviations for the factors are described in Table 1. Values in the y-axis are in million m^3 of water.

Figure 9. Decomposition of the water use drivers in the cultivation of cereal grains

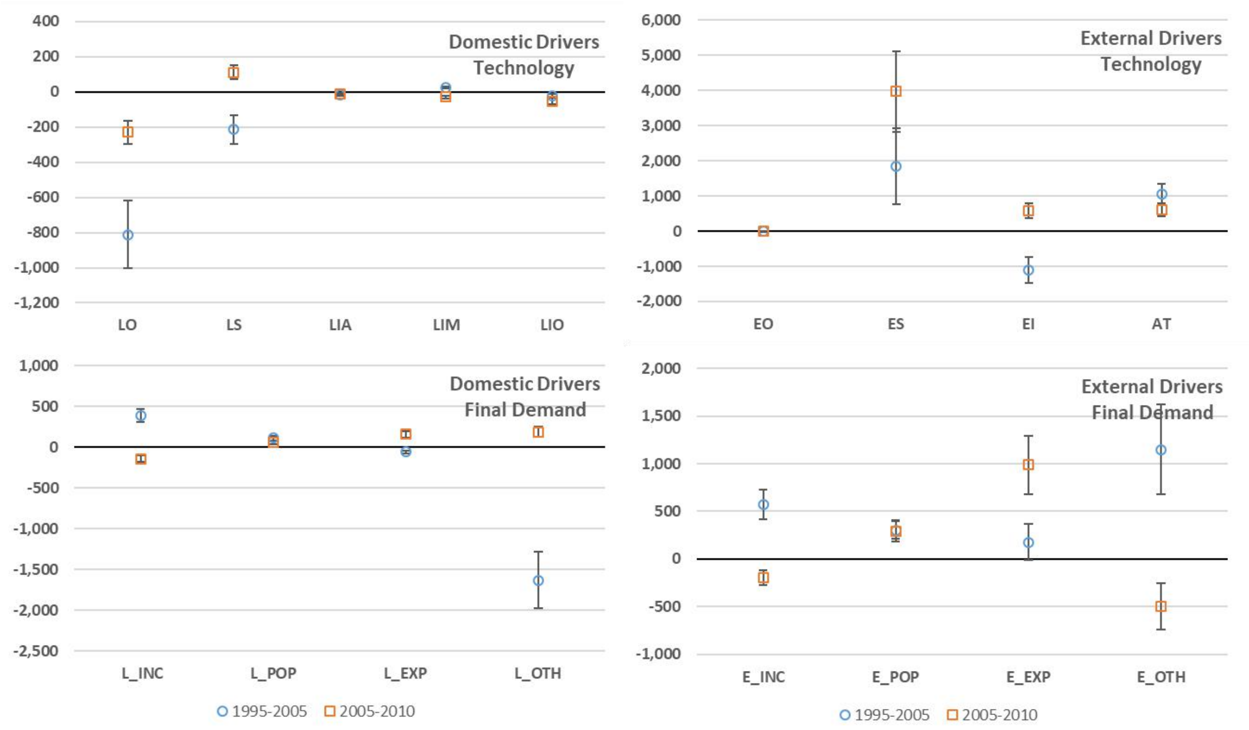
Similarly to cereal grains, the domestic drivers are the main contributors to water use change in the vegetable and fruits sectors (Figure 10). The positive contribution of technology in the pre-crisis period derives mainly from the positive effect of changes in local sales (*LS*) and exports, especially to Canada (*ES* and *AT*). We also find that the positive contribution of final demand comes from both domestic and foreign changes in household's consumption. Over 2005-2010, the changes in water withdrawals are mitigated by changes in technology. The largest effects take place through changes in local sales (*LS*) that compensate any positive effects from exports and changes in local household income (*L_INC*) and in the consumption of other components of final demand (*L_OTH*).



Note: Dots and squares show the average impact of all the possible rotations in Equations 2-5. Whiskers show the size of the standard deviation of these rotations. Decomposition of the technology driver is provided in the top charts and the decomposition of the final demand drivers in the bottom charts. The abbreviations for the factors are described in Table 1. Values in the y-axis are in million m^3 of water.

Figure 10. Decomposition of the water use drivers in the cultivation of vegetable, fruits and nuts

Oil seeds are the only crop which consistently increase water withdrawals over the period, even in the post 2008-crisis. External factors have been the primary drivers of its water use change (Figure 11). The main contributor to this increase has been the direct exports to industries in China (*ES*) and changes in foreign household's consumption mix (*E_EXP*). Domestic final demand drivers have contributed marginally to the increase in water use post-2008 while local technology effects have, for the most part, mitigated the water withdrawals particularly through changes in the consumption of domestic inputs (*LO*).

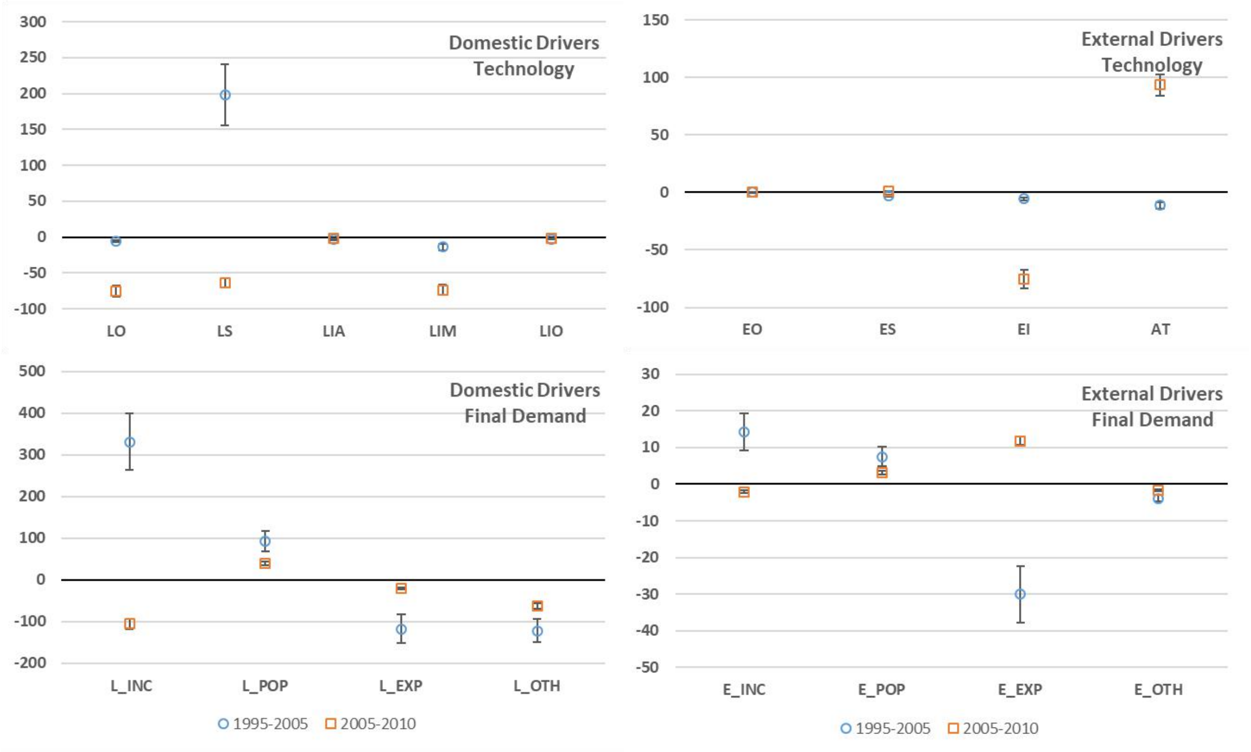


Note: Dots and squares show the average impact of all the possible rotations in Equations 2-5. Whiskers show the size of the standard deviation of these rotations. Decomposition of the technology driver is provided in the top charts and the decomposition of the final demand drivers in the bottom charts. The abbreviations for the factors are described in Table 1. Values in the y-axis are in million m^3 of water.

Figure 11. Decomposition of the water use drivers in the cultivation of oil seeds

As shown in Figure 5, the inventory of cattle decreased dramatically over 1995-2010, hence contributing to a 23% reduction in water use. Such reduction is mainly attributed to water intensity effects in the pre-crisis period and to both technology and final demand effects in the post-2008 period. Local structural changes in the sector (own (*LO*) and substitution effects (*LS*)), downstream effects in the production chain (food manufacturing (*LIM*)), as well as external interrelational effects (*EI*), have been the primary drivers of the technology effect (Figure 12). Meanwhile, decline in local income (L_INC) and changes in the expenditure mix (L_EXP) have been the main contributors for the final demand.

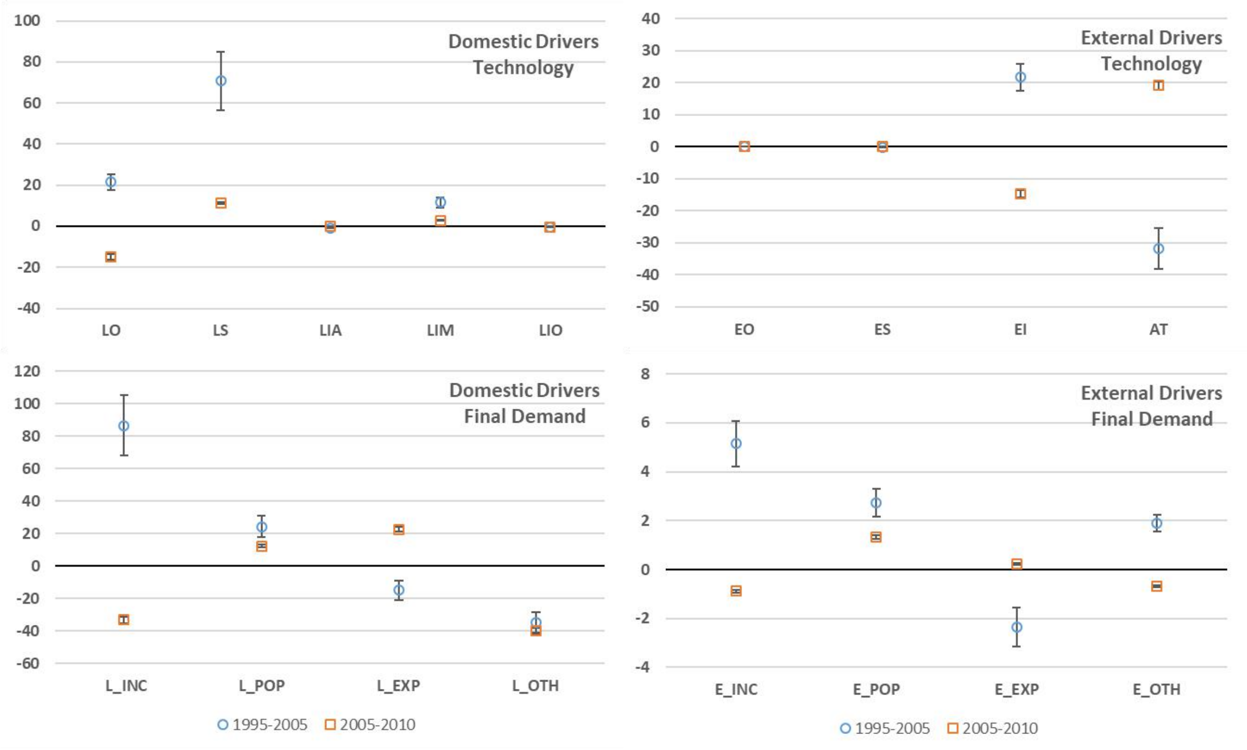
Figure 5 also indicates that the poultry inventory has increased significantly from 1995-2010 even though water use for poultry has decreased slightly over that period. Before the crisis, the final demand and technology effects have contributed to an increase in water use. The latter two have seen changes driven especially by its downstream production chain (*LS* and *LIM*), income (*L_INC*) and local population growth (*L_POP*) (Figure 13). In the post-crisis period, changes in indirect trade (*AT*) and in the mix of final demand (*L_EXP*) (substituting red meat for poultry) are the two largest drivers of water use increase in this period. On the other hand, changes in the local income and other components of final demand (*L_INC*; *L_OTH*) contributed to its decrease (see Figure 8).



Note: Dots and squares show the average impact of all the possible rotations in Equations 2-5. Whiskers show the size of the standard deviation of these rotations. Decomposition of the technology driver is provided in the top charts and the decomposition of the final demand drivers in the bottom charts. The abbreviations for the factors are described in Table 1. Values in the y-axis are in million m^3 of water.

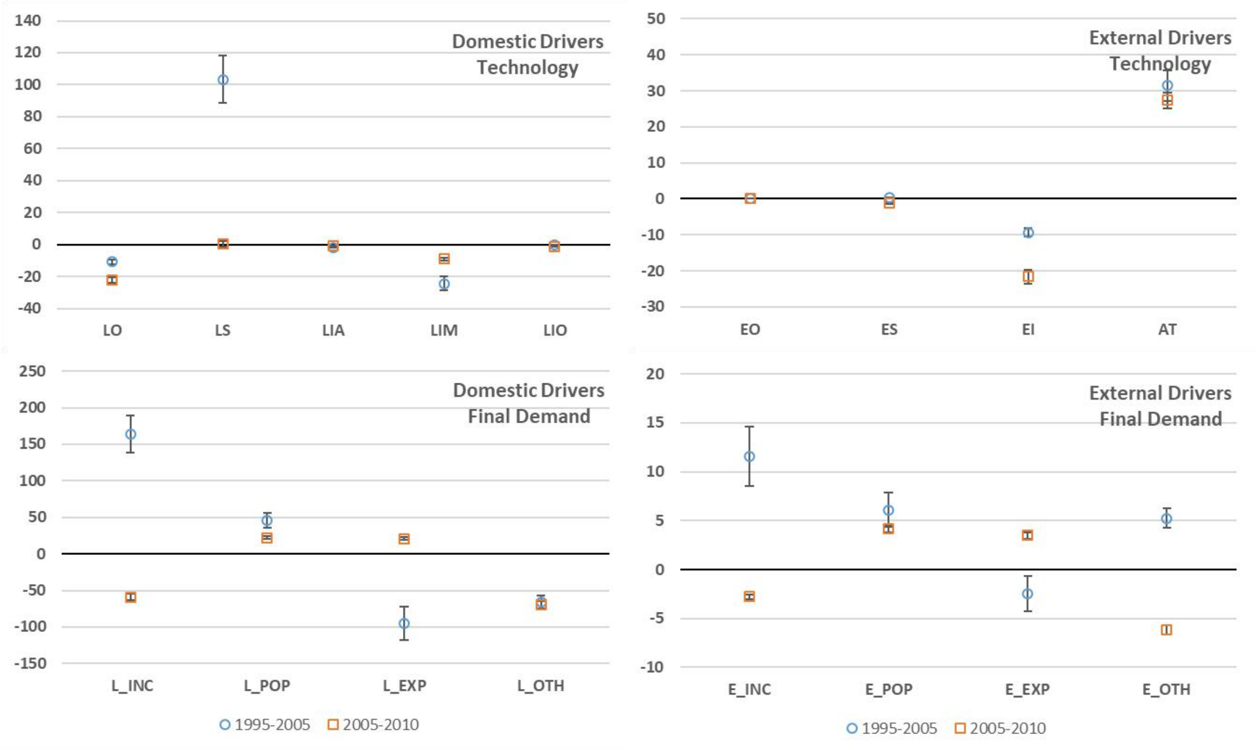
Figure 12. Decomposition of the water use drivers in cattle farming

Similar to poultry, pigs' water consumption is mainly domestically driven, increasing slightly in the pre-crisis period and then declining after the crisis. As indicated in figure 14, the observed increase in water use over 1995-2005 was driven mainly by changes in local sale structure (*LS*) and domestic income effects (*L_INC*). Indirect trade (*AT*) contributed slightly to it too. After 2005, the decline in water use was also domestically driven (especially via final demand), which more than compensated the increase generated by water intensity and indirect trade effects (*AT*).



Note: Dots and squares show the average impact of all the possible rotations in Equations 2-5. Whiskers show the size of the standard deviation of these rotations. Decomposition of the technology driver is provided in the top charts and the decomposition of the final demand drivers in the bottom charts. The abbreviations for the factors are described in Table 1. Values in the y-axis are in million m^3 of water.

Figure 13. Decomposition of the water use drivers in poultry farming



Note: Dots and squares show the average impact of all the possible rotations in Equations 2-5. Whiskers show the size of the standard deviation of these rotations. Decomposition of the technology driver is provided in the top charts and the decomposition of the final demand drivers in the bottom charts. The abbreviations for the factors are described in Table 1. Values in the y-axis are in million m^3 of water.

Figure 14. Decomposition of the water use drivers in pigs farming

5. CONCLUSIONS

Water availability is a paramount input to sustain an agribusiness industry that represents 5.5% of the U.S. gross domestic product. As farmers adapt to increasingly less predictable weather conditions by expanding the use of irrigation in their fields, understanding the drivers of the change in water use by the agribusiness sector becomes essential in devising more efficient policies to sustainably manage water for the future.

Our study finds that despite an overall decline in water withdraws for irrigation pre-2008 crisis, oil seeds crops (mainly soybeans) experienced an increase in water use driven primarily by greater water intensity, increasing exports to foreign industries as well as indirect trade effects. Such increase persisted in the post-crisis period (2008-on) but was driven primarily by direct exports to industries and changes in average global expenditure structure. We also find that the evolution in the production structure of the U.S. food manufacturing sector contributed to an increase in water use in agriculture in the pre-crisis period and to a decrease post-2005. Moreover, water use in crops show a high sensitivity to foreign drivers, especially exports to NAFTA partners, China, Japan and Korea.

Livestock has also shown a parallel decline in water use during the period, with cattle (beef and milk cows) being the most water intensive sector. While changes in household expenditure in red meat products have contributed to a reduction in water use throughout the period, changes in per capita expenditures have increased water withdrawals in the livestock sector during the pre-crisis period. These changes have been mainly domestically driven.

Although for most of the U.S. agribusiness sectors the major drivers of water use are local, for a few sectors like oil seeds crops it is a set of external drivers that have contributed the most to changes in water use. With the prospect of increasing water scarcity across the world, we believe that external factors will have a growing role in water withdrawals in the U.S. Indeed, due to increasingly global value-added chains, it is essential to analyze water use in a multiregional context like we do in this paper. To produce a more complete picture of past and current trends, however, more comprehensive water datasets are necessary at both the local and the world levels.

REFERENCES

Bae, J., & Dall'erba, S. (2018). Crop production, Export of Virtual Water and Water-Saving Strategies in Arizona. *Ecological Economics*, 146, 148-156.

Blackhurst, M., Hendrickson, C. & Vidal, J. (2010). Direct and Indirect Water for U.S. Industrial Sectors. *Environmental Science and Technology*, 44, 2126-2130.

Debaere, & Kurzendoerfer, A. (2015). Decomposing US Water Withdrawal since 1950. *Journal of the Association of Environmental and Resource Economists*, 4(1), 155-196.

Deng, G., Ma, Y., & Li, X. (2016). Regional water footprint evaluation and trend analysis of China-based on interregional input-output model. *Journal of Cleaner Production*, 112, 4674-4682.

Dieter, C. A., Maupin, M. A., Caldwell, R. R., Harris, M. A., Ivahnenko, T. I., Lovelace, J. K., Barber, N. L., & Linsey, K. S. (2018). *Estimated Use of Water in the United States in 2015*. U.S. Geological Survey, Circular 1441. https://doi.org/10.3133/cir1441.

Dietzenbacher, E., & Los, B. (1998). Structural Decomposition Techniques: Sense and Sensitivity. *Economic Systems Research*, 10(4), 307-324.

Food and Agriculture Organization. (2019). AQUASTAT Dataset. Retrieved from: http://www.fao.org/nr/water/aquastat/water_use/index.stm, accessed 6 Mar. 2019.

Hutson, S. S., Barber, N. L., Kenny, J. F., Linsey, K. S., Lumia, D. S., & Maupin, M.A. (2004). *Estimated use of water in the United States in 2000*. U.S. Geological Survey Circular 1268.

Incera, A., Avelino, A., & Solís, A. (2017). Gray water and environmental externalities: International patterns of water pollution through a structural decomposition analysis. *Journal of Cleaner Production*, 165, 1174-1187.

Kenny, J. F., Barber, N. L., Hutson, S. S., Linsey, K. S., Lovelace, J. K., & Maupin, M. A. (2009). *Estimated Use of Water in the United States in 2005*. U.S. Geological Survey, Circular 1344.

Lenzen, M., Kanemoto, K., Moran, D., & Geschke, A. (2012). Mapping the structure of the world economy. *Environmental Science & Technology*, 46(15), 8374-8381.

Lovelace, J. (2009). Method for Estimating Water Withdrawals for Livestock in the United States, 2005. U.S. Geological Survey, Scientific Investigations Report 2009-5041. Reston: U.S. Geological Survey.

Marston, L., Ao, Y., Konar, M., Mekonnen, M., & Hoekstra, A. (2018). High-Resolution Water Footprints of Production of the United States. *Water Resources Research*, 54, 2288–2316.

Mekonnen, M. M., & Hoekstra, A.Y. (2011). The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences*, 15(5), 1577-1600.

Peters, G., Minx, J., Weber, C., & Edenhofer, O. (2011). Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences of the United States of America*, 108(21), 8903-8908.

Roson, R., & Sartori, M. (2015). A decomposition and comparison analysis of international water footprint time series. *Sustainability*, 7, 5304-5320.

Solley, W. B., Pierce, R. R., & Perlman, H. A. (1993). *Estimated Use of Water in the United States in 1990*. U.S. Geological Survey, Circular 1081.

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C., Simas, M., Schmidt, S., … , Tukker, A. (2018). EXIOBASE 3 – Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. *Journal of Industrial Ecology*, 22(3), 502-5015.

Statistics Canada. (2019). *Industrial Water Use, Environment Accounts and Statistics Division*. Retrieved from: https://www150.statcan.gc.ca/n1/en/catalogue/16-401-X, accessed 1 Jan. 2019.

Timmer, M., Dietzenbacher, E., Los, B., Stehrer, R., & de Vries, G. (2015). An Illustrated User Guide to the World Input-Output Database: the Case of Global Automotive Production. *Review of International Economics*, 23, 575-605.

Tukker, A., de Koning, A., Owen, A., Lutter, S., Bruckner, M., … , Hoeskstra, R. (2018). Towards Robust, Authoritative Assessments of Environmental Impacts Embodied in Trade: Current State and Recommendations. *Journal of Industrial Ecology*, 22(3), 585-598.

United States Department of Agriculture. (1999). 1997 Census of Agriculture. United States Department of Agriculture.

United States Department of Agriculture. (2004). 2002 Census of Agriculture. United States Department of Agriculture.

United States Department of Agriculture. (2009). 2007 Census of Agriculture. United States Department of Agriculture.

United States Department of Agriculture. (2014). 2012 Census of Agriculture. United States Department of Agriculture.

United States Department of Agriculture. (2018). Ag and Food Sectors and the Economy. Available in https://www.ers.usda.gov/data-products/ag-and-food-statistics-charting-the-essentials/ag-and-food-sectors-and-the-economy/

United States Department of Agriculture. (2019). Market Outlook – Soybeans and Oil Crops, July 2019. Available in https://www.ers.usda.gov/topics/crops/soybeans-oil-crops/market-outlook/

Wang, H., Small, M., & Dzombak, D. (2014). Factors Governing Change in Water Withdrawals for U.S. Industrial Sectors from 1997 to 2002. *Environmental Science & Technology*, 48, 3420-3429.

Wang, H., Small, M., & Dzombak, D. (2015). Improved Efficiency Reduces U.S. Industrial Water Withdrawals, 2005−2010. *Environmental Science & Technology Letters*, 2, 79-83.

World Bank. (2019). World Bank Open Data – Population Total [Dataset]. Retrieved from https://data.worldbank.org/indicator/SP.POP.TOTL, accessed 6 Mar. 2019.

APPENDICES

Table A1. Sector Disaggregation

Order	Sector Description
1	Cultivation of paddy rice
2	Cultivation of wheat
3	Cultivation of cereal grains n.e.c.
4	Cultivation of vegetables, fruit, nuts
5	Cultivation of oil seeds
6	Cultivation of sugar cane, sugar beet
7	Cultivation of plant-based fibers
8	Cultivation of crops n.e.c.
9	Cattle farming
10	Pigs farming
11	Poultry farming
12	Meat animals n.e.c.
13	Animal products n.e.c.
14	Raw milk
15	Wool, silk-worm cocoons
16	Manure treatment (conventional), storage and land application
17	Manure treatment (biogas), storage and land application
18	Forestry, logging and related service activities
19	Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing
20	Mining and Quarrying
21	Processing of meat cattle
22	Processing of meat pigs
23	Processing of meat poultry
24	Production of meat products n.e.c.
25	Processing vegetable oils and fats
26	Processing of dairy products
27	Processed rice
28	Sugar refining
29	Processing of Food products n.e.c.
30	Manufacture of beverages
31	Manufacture of fish products
32	Manufacture of tobacco products
33	Textiles and Textile Products
34	Leather, Leather and Footwear
35	Wood and Products of Wood and Cork
36	Pulp, Paper, Paper, Printing and Publishing
37	Coke, Refined Petroleum and Nuclear Fuel
38	Chemicals and Chemical Products

Table A1. Sector Disaggregation (cont.)

Order	Sector Description
39	Rubber and Plastics
40	Other Non-Metallic Mineral
41	Basic Metals and Fabricated Metal
42	Machinery, n.e.c.
43	Electrical and Optical Equipment
44	Transport Equipment
45	Manufacturing, n.e.c.; Recycling
46	Electricity and Gas
47	Collection, purification and distribution of water
48	Construction
49	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel
50	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles
51	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods
52	Hotels and Restaurants
53	Inland Transport
54	Water Transport
55	Air Transport
56	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies
57	Post and Telecommunications
58	Financial Intermediation
59	Real Estate Activities
60	Renting of M&Eq and Other Business Activities
61	Public Admin and Defense; Compulsory Social Security
62	Education
63	Health and Social Work
64	Other Community, Social and Personal Services
65	Private Households with Employed Persons

Table A2. Bridge between USDA Census of Irrigation and EXIOBASE, Crops

USDA	EXIOBASE
Corn for grain or seed	Cultivation of cereal grains n.e.c.
Corn for silage or greenchop	Cultivation of cereal grains n.e.c.
Sorghum for grain or speed	Cultivation of cereal grains n.e.c.
Wheat for grain or seed	Cultivation of wheat
Barley for grain or seed	Cultivation of cereal grains n.e.c.
Soybeans for beans	Cultivation of oil seeds
Beans, dry edible	Cultivation of crops n.e.c.
Rice	Cultivation of paddy rice
Other small grains (oats, rye, etc.)	Cultivation of cereal grains n.e.c.
Alfalfa and alfalfa mixtures (dry hay, greenchop, and silage)	Cultivation of vegetables, fruit, nuts
All other hay (dry hay, haylage, grass silage, and greenchop)	Cultivation of vegetables, fruit, nuts
Peanuts for nuts	Cultivation of vegetables, fruit, nuts
All cotton	Cultivation of plant-based fibers
Sugarbeets for sugar	Cultivation of sugar cane, sugar beet
Tobacco, all types	Cultivation of crops n.e.c.
Potatoes	Cultivation of vegetables, fruit, nuts
Land in vegetables	Cultivation of vegetables, fruit, nuts
Sweet corn	Cultivation of vegetables, fruit, nuts
Tomatoes	Cultivation of vegetables, fruit, nuts
Lettuce and romaine	Cultivation of vegetables, fruit, nuts
Berries, bearing and non-bearing	Cultivation of vegetables, fruit, nuts
Land in bearing and non-bearing orchards, vineyards, and nut trees	Cultivation of vegetables, fruit, nuts
All other crops	Cultivation of crops n.e.c.

Table A3. Bridge between USDA Census of Agriculture and EXIOBASE, Livestock

USDA	EXIOBASE
Cattle, Cows, Milk	Raw milk
Cattle, Cows, Beef	Cattle farming
Hogs	Pigs farming
Chicken, Broilers	Poultry farming
Turkeys	Poultry farming
Sheep and Lambs	Meat animals n.e.c.
Goats	Meat animals n.e.c.