

# Groundwater depletion embedded in domestic transfers and international exports of the United States

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## Abstract

The United States plays a key role in global food security by producing and exporting agricultural products. Groundwater irrigation is increasingly important in agricultural production, nearly tripling since records began in 1950. Increased reliance on groundwater and prolonged unsustainable pumping of aquifers has led to groundwater depletion in many areas. In this study, we ask: How much groundwater depletion is embedded in the domestic transfers and international agricultural exports of the United States? How much do domestic and international agricultural commodity fluxes rely on unsustainable groundwater use? To address these questions we quantify the amount of nonrenewable groundwater that is incorporated into agricultural commodities produced in the U.S. and transferred both within the country and exported internationally. We find that 26.3 km<sup>3</sup> of nonrenewable groundwater was transferred domestically in 2002 and 2.7 km<sup>3</sup> was sent abroad. In

14 2012, 34.8 km<sup>3</sup> was transferred domestically and 3.7 km<sup>3</sup> was exported. This indicates an increase of 32% in domestic transfers and 38% in international exports. In  
15 2002, we find that 1,491,126 kilotonnes (340 billion \$USD) of agricultural products  
16 reliant on nonrenewable groundwater were domestically transferred, while 119,048  
17 kilotonnes (47 billion \$USD) were exported. In 2012, the mass transfer of agricultural goods reliant on unsustainable groundwater decreased, but their value in  
18 national and international supply chains increased by 54% and 31%, respectively.  
19 Our results underscore the importance of the long-term risks posed to global agricultural supply chains from reliance on unsustainable groundwater use.  
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21

## 23 1 Introduction

24 Groundwater is increasingly important to agricultural production, as factors such as climate change, population growth, increasing water demand, and rising consumption of  
25 meat lead to more demands on water resources worldwide (Vörösmarty *et al.*, 2000;  
26 Mekonnen and Hoekstra, 2012; Wada *et al.*, 2012). Groundwater is also critical for  
27 maintaining agricultural supply chains during times of drought (Marston and Konar,  
28 2017). Groundwater depletion (GWD) occurs when groundwater abstraction exceeds the  
29 recharge rates of an aquifer over a persistent period of time, thus leading to unsustainable  
30 groundwater use (Wada *et al.*, 2012). This is a particularly important concern for locations  
31 that cannot meet their water demands using only renewable water supplies (Wada  
32 *et al.*, 2012; Gleeson *et al.*, 2012). Much GWD has been shown to support the international  
33 trade of agricultural commodities (Dalin *et al.*, 2017). Here, we examine how GWD  
34 in the United States is incorporated into national transfers and international exports of  
35 agricultural commodities.  
36

37 Most agricultural production both globally and within the U.S. is rainfed (Falkenmark  
38 and Rockström, 2004). However, agriculture is responsible for approximately 70% of freshwater withdrawals, and is by far the largest consumptive user of water resources (~90% of  
39 consumptive demands) (Postel *et al.*, 1996; Vörösmarty *et al.*, 2000; Gleick and Palaniapan,  
40 2010; Marston *et al.*, 2018). Irrigation systems are critical to buffer extreme weather  
41 impacts on crop production (Troy *et al.*, 2015) and to increase agricultural productivity (Davis *et al.*, 2017). Water use in the agricultural sector is facing many challenges.  
42 Demands from other water users, such as industry, municipalities, and recreation – as well  
43 as the need to allocate water to environmental services – are increasing (McDonald *et al.*,  
44 2011). Additionally, changes in climate variability and extremes will alter both the availability  
45 and demand for water resources, making it potentially more difficult for farmers  
46 to grow crops as they have done in the past, which threatens food security (Schmidhuber  
47 and Tubiello, 2007; Hertel *et al.*, 2010; Lobell *et al.*, 2011). Amidst these competing  
48 demands and increased variability of surface supplies, farmers are increasingly turning to  
49 groundwater to irrigate their crops (Marston and Konar, 2017).  
50

51 As a leading producer and exporter of staple agricultural commodities, the U.S. plays  
52

53 an important role in feeding the world (*Ercsey-Ravasz et al., 2012; Konar et al., 2018*).  
54 Over one third of the world's coarse grain (e.g. corn, barley, sorghum, oats and rye) and  
55 over 50% of the world's soybeans are produced by the United States (*U.S. Department of*  
56 *Agriculture Foreign Agricultural Service, 2019a,b*). The U.S. contributes a significant frac-  
57 tion of this production to global export markets. One third of the global export market  
58 in coarse grains is from the United States (*U.S. Department of Agriculture Foreign Agri-*  
59 *cultural Service, 2019a*). The U.S. contributes one third of soy to the world export mar-  
60 ket (*U.S. Department of Agriculture Foreign Agricultural Service, 2019b*). Coarse grain  
61 and soy crops are responsible for a large share of the world's food calorie intake (*D'Odorico*  
62 *et al., 2014*), making the U.S. an important contributor to global food security. Moreover,  
63 we have selected the U.S. for this study due to the availability of sub-national commodity  
64 flow data.

65 Much agricultural production and export in the U.S. has been enabled by irrigation  
66 from groundwater resources. The U.S. has the second highest rate of groundwater ab-  
67 straction (*Wagner, 2017; Esnault et al., 2014*) and is the second largest GWD exporter  
68 worldwide (*Dalin et al., 2017*). Roughly 18% of the domestic grain supply of the U.S. is  
69 produced in locations in which the aquifers are being used unsustainably (*Marston et al.,*  
70 *2015*). Agricultural production that depends on unsustainable groundwater use will even-  
71 tually become infeasible, once groundwater pumping reaches the physical or economic  
72 pumping constraints. It is therefore essential to understand the risks posed to domestic  
73 and international agricultural supply chains by the eventual declines in agricultural pro-  
74 duction from these locations. Here, we refer to domestic agricultural commodity transfers  
75 within the U.S. as 'transfers', and the associated GWD embedded in them as depletion  
76 water transfers (DWT). We use the term 'exports' to refer to agricultural commodity  
77 exports from the U.S. to other countries, and the associated GWD with these exports  
78 as depletion water exports (DWE). DWT and DWE enable us to assess the exposure of  
79 supply chains to GWD.

80 The main goal of this study is to understand how GWD is incorporated into complex  
81 national and international agricultural supply chains. Here, we assess the domestic and  
82 international agricultural commodity transfers of the United States that rely on unsus-  
83 tainable groundwater use. The main questions addressed by this study are: (1) How much  
84 groundwater depletion is embedded in the domestic transfers and exports of the United  
85 States? (2) How have virtual groundwater depletion transfers and exports changed over  
86 time? (3) What domestic locations are the largest sources of virtual groundwater deple-  
87 tion transfers and exports? (4) What is the mass and value of agricultural transfers and  
88 exports that rely on groundwater depletion? We present our methods in Section 2. We  
89 describe and discuss our results in Section 3. We conclude in Section 4.

## 90 2 Methods

91 In this section, we first describe how we estimate crop-specific groundwater depletion  
92 (GWD) [ $\text{m}^3$ ] within the United States. Second, we describe the U.S. government database  
93 of agricultural commodity transfers and exports. Then, we describe how we quantify the  
94 groundwater depletion embedded in transfers and exports. Finally, we explain major  
95 methodological assumptions and limitations. The spatial domain for this study is the  
96 Continental United States (CONUS), which excludes Alaska, Hawaii, and Puerto Rico.  
97 The focus of this study is the groundwater depletion embedded in agricultural transfers  
98 and exports, so we omit groundwater depletion associated with other economic sectors  
99 (e.g. industry, municipal use, etc.). Table 1 summarizes all data dependencies in this  
100 study.

### 101 2.1 Groundwater depletion by crop

102 We extract  $0.5 \times 0.5$  degree grids of groundwater depletion (GWD) within the United  
103 States from the global study of *Dalin et al.* (2017). We use existing PCR-GLOBWB  
104 modeled GWD in this study because they are highly studied and validated (*Wada et al.*,  
105 2012, 2014; *Dalin et al.*, 2017). Monthly GWD volumes were summed to arrive at  
106 annual values. This was done for the years 2000 and 2010. In this way, gridded,  
107 crop class-specific estimates of GWD [ $\text{km}^3 \text{ year}^{-1}$ ] were obtained. To aggregate  $0.5$  de-  
108 gree grids to U.S. counties, an area-weighted sum of the pixels overlapping each U.S.  
109 county was calculated. County scale values were then aggregated to FAF4 (refer to  
110 Section 2.2) and state polygons. A U.S. county to FAF zone crosswalk table was ob-  
111 tained from Oak Ridge National Laboratory (<https://www.ornl.gov/>). Shapefiles for  
112 political boundaries within the U.S. were obtained from the U.S. Census Bureau website  
113 (<https://www.census.gov/geo/maps-data/data/tiger-line.html>).

114 The PCR-Global Water Balance (PCR-GLOBWB) model (*Wada et al.*, 2012, 2014)  
115 was used to estimate GWD [ $\text{m}^3$ ] in *Dalin et al.* (2017). PCR-GLOBWB is a global hydro-  
116 logical and water resources model that runs on a  $0.5^\circ$  by  $0.5^\circ$  global grid. PCR-GLOBWB  
117 groundwater abstractions include all groundwater used for industrial, domestic, and agri-  
118 cultural sectors (irrigation and livestock demand) (*Wada et al.*, 2012). Groundwater  
119 abstraction estimates from PCR-GLOBWB have been extensively validated in previous  
120 studies. Simulated terrestrial water storage was compared against NASA Gravity Recov-  
121 ery and Climate Experiment (GRACE) satellite observations (*Wada et al.*, 2012). Criti-  
122 cally, groundwater abstraction values generated from PCR-GLOBWB are well validated  
123 within the United States (*Wada et al.*, 2012). A time series of national groundwater ab-  
124 straction and depletion values shows good agreement between PCR-GLOBWB and U.S.  
125 Geological Survey (USGS) data (*Hutson et al.*, 2004; *Maupin et al.*, 2014) (see Figure 3).  
126 Regional variations of surface water and groundwater withdrawal match reasonably well  
127 with reported subnational statistics for the U.S. (*Wada et al.*, 2014). Groundwater ab-

128 straction rates for the U.S. show good agreement with USGS county-level data on ground-  
129 water withdrawals (*Maupin et al.*, 2014). Fig 1 maps PCR-GLOBWB model estimates of  
130 groundwater abstraction and USGS statistical information on groundwater withdrawals.  
131 Note that the comparison between PCR-GLOBWB and USGS for the year 2000 (*Hutson*  
132 *et al.*, 2004) was already presented in *Wada et al.* (2012). Now, we additionally pro-  
133 vide mapped comparison between PCR-GLOBWB and USGS for 2010 (*Maupin et al.*,  
134 2014). Fig 1 illustrates that PCR-GLOBWB captures the temporal and spatial distribu-  
135 tion of groundwater use within the U.S. to a reasonable extent. Metrics that compare  
136 the spatial correlation of groundwater abstraction between PCR-GLOBWB and USGS  
137 are provided in Table 2. Table 2 quantitatively indicates good spatial agreement between  
138 PCR-GLOBWB model estimates of groundwater abstractions over time.

139 To determine GWD for irrigation, the PCR-GLOBWB model was used to simulate  
140 crop water use for the 26 irrigated crop classes provided in the MIRCA2000 database (*Port-*  
141 *mann et al.*, 2010). MIRCA2000 provides information on 26 crop classes (listed in the  
142 Supporting Information), including crop-specific calendars and growing season lengths.  
143 Daily climate data (1979-2010) were retrieved from the ERA-Interim reanalysis, where  
144 the precipitation was corrected with GPCP precipitation (GPCP: Global Precipitation  
145 Climatology Project; <http://www.gewex.org/gpcp.html>) (*Dee et al.*, 2011). The initial  
146 conditions of PCR-GLOBWB are obtained with at least a 50-year spin up, as is com-  
147 mon practice (*Sutanudjaja et al.*, 2018). The initial soil moisture conditions are modeled  
148 from 1960-2010 using only two crop types (paddy and non-paddy). A dynamic irrigation  
149 scheme was implemented in which paddy and nonpaddy crops were separately parame-  
150 terized. This allows for the feedback between the application of irrigation water and the  
151 corresponding changes in surface and soil water balance to be considered.

152 These results are then used as model inputs for 2000 and 2010 in which groundwa-  
153 ter depletion for all 26 crops is modeled. PCR-GLOBWB partitioned the surface water,  
154 groundwater, and soil moisture used to meet agricultural demand. Crop factors per grid  
155 cell were used to calculate reference and potential evapotranspiration, which were then  
156 used to calculate irrigation water demands for each crop. Irrigation water demand is  
157 the amount of water that needs to be additionally supplied to ensure maximum crop  
158 growth, taking irrigation losses (i.e. conveyance) into account. Irrigated cropland areas  
159 were taken from the MIRCA2000 dataset for the year 2000 and scaled to year 2010 using  
160 annual national irrigated cropland areas data from the Food and Agricultural Organiza-  
161 tion (FAO) (<http://www.fao.org/faostat/en/#data/RL>). Maps on the comparison of  
162 irrigated areas between MIRCA and USDA are shown in Figure 2. Irrigated area com-  
163 pares reasonably well across states and time periods in MIRCA and USDA data sets.  
164 Table 3 provides spatial correlation indices between MIRCA and USDA, showing very  
165 good agreement (i.e.  $R^2=0.92$  in 2000;  $R^2=0.87$  in 2010).

166 Surface water availability was calculated by subtracting upstream consumptive water  
167 use from agriculture, industry, livestock, and households from cumulative discharge along  
168 river networks at the daily time step from 1979-2010. We refer to *Sutanudjaja et al.* (2018)

for detailed descriptions of river routing (i.e. kinematic wave). PCR-GLOBWB was then used to simulate natural groundwater recharge rates and combined with irrigation return flows, which were estimated based on soil properties such as hydraulic conductivity, country-specific irrigation efficiency factors, and irrigated crop areas. The sum of natural and irrigation recharge was used as total groundwater recharge. Grid-based groundwater abstraction for irrigation was then calculated on a monthly basis for each year based on the IGRAC reported country database (<https://www.un-igrac.org/>). Water demand was used as a proxy for downscaling reported country-level groundwater abstraction, and it was assumed that groundwater was used to satisfy the demand that could not be met with the available precipitation and surface water for that grid cell. If applicable, national desalination statistics were obtained for years 1960-2010 and then downscaled onto a global coastal ribbon of ~40 km based on gridded population densities. Return flows were calculated for the industrial and domestic sectors based on recycling ratios calculated for each country. This coupling of water availability and water demand dynamically simulates actual water use at a daily time step rather than potential water demand that is independent of available water, and therefore accounting for interactions between human water use and terrestrial fluxes.

Finally, groundwater abstraction in excess of groundwater recharge was used to determine GWD. In order to distinguish nonrenewable groundwater abstraction from renewable water sources, the amount of groundwater pumped for each irrigated crop on the basis of crop growing areas and seasons is considered, including multicropping practices and sub-grid variability of different crop types. Crop-specific groundwater abstraction in excess of simulated groundwater recharge is used to estimate GWD by crop.

## 2.2 Agricultural production and supply chain data

U.S. crop production data for the corresponding crops of each MIRCA crop class were obtained from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) census (<https://quickstats.nass.usda.gov/>). County-level production data for the year 2012 and state-level data for 2002 was collected, since census data are only available for years ending with '2' and '7'. All production units are converted to tons. Some data from USDA are suppressed in order to protect the privacy of farmers, more often at the county scale. In these instances, the sum of all available county production data are summed and subtracted from the state total, and this difference is uniformly distributed among all suppressed counties. State-level 2002 data were also taken from USDA census when available, and data for this year is also somewhat sparse. To make up for this, different techniques were used to estimate missing values. 2002 survey yield rates and harvested areas for the crop of interest were multiplied together to get tonnage of production for the state, or production values from preceding and succeeding years were averaged if available. In cases where neither of these methods were applicable, national-level production for the crop was taken from the Food and Agriculture Orga-

208 nization (FAO) FAOSTAT database (<http://www.fao.org/faostat/en/#data/QC>) for  
209 the year 2002, and state portions were scaled according to their 2012 production value  
210 distribution.

211 Commodity flow data are from the Freight Analysis Framework version 4 (FAF4)  
212 database (FAF4, 2015). This database is provided by the U.S. Department of Trans-  
213 portation and represents a collaboration between the Bureau of Transportation Statistics  
214 and the Federal Highway Administration. FAF4 is built on 2012 Commodity Flow Survey  
215 (CFS) data (CFS, 2013), which provides detailed information on the origin, destination,  
216 mode of transport, distance, and value (in USD and tons) for each transport link. FAF4  
217 data is available for bilateral transfers between FAF4 zones, as well as eight international  
218 regions (refer to the Supporting Information for the list of world regions included by  
219 FAF4). There are 132 FAF4 zones in the U.S. and they represent a combination of Mu-  
220 nicipal Statistical Areas (MSAs) and Remainder of State (see Supporting Information for  
221 a map and list of FAF zones). FAF4 data are available for the years 1997, 2002, 2007,  
222 and 2012. For this study, we select the years 2002 and 2012, since they are the closest to  
223 the GWD estimates available from *Dalin et al.* (2017) for years 2000 and 2010. Note that  
224 FAF4 is available at the state spatial resolution for 2002 and FAF spatial resolution for  
225 2012 (see Table 1).

226 The Standard Classification of Transported Goods (SCTG) coding system (<https://bhs.econ.census.gov>) is used to classify commodity flows. A full list of the SCTG  
227 commodity classes is provided in the Supporting Information. Here, we select the 3 SCTG  
228 categories composed of raw agricultural goods. We select SCTG 2: cereal grains, SCTG  
229 3: all other agricultural products excluding animal feed and forage products, and SCTG  
230 4: animal feed and other products of animal origin. The MIRCA2000 crop classes are  
231 mapped to SCTG commodity categories in the Supporting Information. In this way, FAF4  
232 supply chain information is relatively refined in its spatial resolution (e.g. sub-national),  
233 but has a relatively coarse commodity categorization (e.g. agricultural commodity classes,  
234 not specific crops).

## 236 **2.3 Groundwater depletion embedded in commodity flows**

237 Here, we describe how we calculate the amount of GWD embedded in domestic transfers  
238 and international exports. We refer to depletion water flows (DWF) as the generic term  
239 for GWD embedded in both domestic transfers and international exports. We calculate  
240 DWF as:

$$DWF_{o,d,c,y} = GWD_{o,c,y} \times \frac{F_{o,d,c,y}}{\sum F_{o,c,y}} \quad (1)$$

241 where  $GWD$  is groundwater depletion [ $\text{m}^3$ ],  $F$  is agricultural commodity flow mass  
242 (i.e. either domestic transfer or international export) [kilotonnes],  $o$  is state or FAF zone  
243 of origin,  $d$  is destination,  $c$  is SCTG commodity group, and  $y$  is year. Individual out-flows

244 (e.g.  $F_{o,d,c,y}$ , indexed by an origin-destination pair) are normalized by all outflows (e.g.  
245  $F_{o,c,y}$ , not indexed by destination). In this way, the GWD in each location of production  
246 is proportionally assigned to commodity fluxes and the amount of GWD exported from  
247 each region is bounded by the total GWD found by the physical model estimates.

248 GWD embodied in commodity transfers within the United States are referred to as  
249 depletion water transfers (DWT). GWD embodied in international exports are referred to  
250 as depletion water exports (DWE). Note that this approach makes two key assumptions:  
251 (1) that each trade flow is comprised of goods produced in the location of origin, and (2)  
252 that the composition of all outflows remains consistent regardless of the destination. For  
253 example, if Illinois sends SCTG 2: grains to both Florida and Colorado the proportion  
254 of corn in each bilateral link will be the same. This is despite the fact that Colorado  
255 may demand more corn from Illinois than does Florida. Note that a transfer may remain  
256 within the FAF zone of origin (i.e. a “self-loop”).

## 257 2.4 Assumptions

258 One major limitation of our study is the temporal mismatch between available input data.  
259 We match GWD in 2000 with agricultural supply chain data for the year 2002. We match  
260 GWD in 2010 with agricultural data for the year 2012. GWD data by crop is only available  
261 for 2000 and 2010 from *Dalin et al.* (2017), while U.S. agricultural census information  
262 is available in years ending in ‘2’ and ‘7’ (see Table 1). This temporal mismatch is a  
263 major limitation of our statistical approach and our results would be improved if we had  
264 consistent time periods. However, groundwater use and depletion is relatively constant at  
265 the national scale for our study domain (refer to Supporting Information). This gives us  
266 confidence that our estimated values of GWD are appropriate to pair with the available  
267 supply chain statistics.

268 There are many assumptions that influence the GWD estimates. A notable PCR-  
269 GLOBWB assumption is that of maximum crop growth, which will not always accurately  
270 reflect actual farming conditions. This assumption relies on optimal irrigation in the  
271 model to ensure no crop stress. This optimal irrigation assumption means that irrigation  
272 water demand may be overestimated in many cases. Of note, this maximum crop  
273 growth leads to another assumption that all irrigated areas are productive. Where a crop  
274 had irrigated area in 2000, it is assumed to again be grown in 2010 to maximum crop  
275 growth, regardless of whether these crops were actually moved (this is not captured by  
276 the FAOSTAT scaling we use) or were unproductive. Another relevant model assumption  
277 pertains to irrigation efficiency, or the volume of applied water that is taken up by crops.  
278 There is a single irrigation efficiency value for the entire US (*Rohwer et al.*, 2007), which  
279 will miss technological differences in irrigation across the country. Additionally, the flux  
280 based method of PCR-GLOBWB ignores additional capture from surface supplies and  
281 does not consider available groundwater resources. Yet, PCR-GLOBWB is constrained  
282 by national statistics on groundwater use from IGRAC (see Section 2.4 of *Wada et al.*

283 (2012) for details). This ensures that model estimates of groundwater use will be in a  
284 reasonably close range to national statistics, yet does not invalidate the comparison be-  
285 tween PCR-GLOBWB pixels and county-scale USGS information, as these are spatially  
286 resolved and not used to force the model.

287 FAF data also comes with its own assumptions. Domestic production and consumption  
288 information underpins the FAF commodity transfers. However, FAF presents information  
289 on commodity transfers principally for transportation planning. For this reason, a new  
290 commodity flux is reported each time a commodity transformation occurs (i.e. corn  
291 to high fructose corn syrup). This means that production and consumption flows are  
292 not perfectly modeled and double counting of embodied resources is a potential issue.  
293 However, since we focus on agricultural commodities this issue of double counting will  
294 not be as problematic in this study. Additionally, we quantify virtual fluxes but do not  
295 transform our estimate values into water footprints of consumption largely for this reason.

296 Equation 1 indicates that we assign *GWD* proportionately to out-fluxes. Note that  
297 commodity fluxes are provided by SCTG commodity categories while GWD values are  
298 estimated for specific crops. To twin SCTG commodity categories of FAF fluxes with  
299 GWD estimates we assume that the commodity composition of all outflows is the same  
300 regardless of the destination. The values of SCTG commodity fluxes vary by destination.  
301 However, our approach assumes that the crops contained within each SCTG commodity  
302 category (e.g. corn within SCTG 2) will be distributed to locations in the same proportion.  
303 This assumption is necessary because we do not have information on the fluxes of specific  
304 crops, but only the fluxes of SCTG commodity categories. Importantly, our approach  
305 ensures that the volume of GWD assigned to each outflow does not exceed the physical  
306 volume of GWD estimated by the PCR-GLOBWB model.

307 We assume that SCTG 4 is made up entirely of animal feed and do not explicitly  
308 model eggs, honey, or any other products of animal origin. This assumption is sup-  
309 ported by production data on animal feed, hay and haylage, and other animal products  
310 from the U.S. Department of Agriculture (USDA) Economic Research Service (<https://data.ers.usda.gov/FEED-GRAINS-custom-query.aspx>) and USDA-NASS (<https://quickstats.nass.usda.gov/>). National level annual data on these groups were com-  
311 pared when available (e.g. for 2011, 2012, and 2015) and animal feed was estimated to  
312 comprise over 95% of the total tonnage for USDA classes that fall under the SCTG4  
313 category. Then, we paired SCTG 4 with the MIRCA class ‘Managed grassland/pasture’.  
314 In this way we assume that the vast majority of GWD of this commodity class is due to  
315 animal feed, and that other products of animal origin (i.e. animal hair, bones, wool) are  
316 negligible in comparison.

### 3 Results and discussion

#### 3.1 How much groundwater depletion is embedded in U.S. transfers and exports?

We present GWD at the county spatial scale for 2000 and 2010 (see Fig 4). Fig 4 illustrates that most GWD occurs in the western portion of the U.S., since this part of the country is heavily irrigated under a more arid climate. Correspondingly, Western states have large depletion water footprints (see Table 4). Arizona has the largest depletion water footprint (398 [m<sup>3</sup>/ton]), followed by Texas (210 [m<sup>3</sup>/ton]), and Colorado (196 [m<sup>3</sup>/ton]).

Fig 4 illustrates that GWD has increased in key aquifers in the United States. In particular, the Central Valley aquifer in central and southern California and the High Plains aquifer along the eastern edge of the Rocky Mountains have experienced increasing levels of GWD, as we would expect. Importantly, major groundwater aquifers show the greatest increase in GWD over the course of the decade (see Fig 4B). According to a USGS report, these three major aquifer regions contributed to 67% of U.S. GWD between 1900 and 2008, while that statistic jumps to 93% of national GWD when restricted to the time period from 2000 to 2008 (*Konikow, 2013*).

We estimate the total volume of groundwater depletion in 2000 to be 29.1 km<sup>3</sup>, while total GWD in 2010 is 38.5 km<sup>3</sup> (refer to Table 5). For comparison, *Marston et al. (2015)* found 33.89 km<sup>3</sup> of total groundwater was consumed for crop production within the High Plains (17.93), Mississippi Embayment (9.18), and Central Valley (6.81) aquifer systems for the year 2007. Note that the current study accounts for groundwater depletion in all locations throughout the U.S., whereas *Marston et al. (2015)* only accounted for the three most depleted aquifers. USGS reports crop groundwater withdrawals from counties overlying these aquifers as 46.31 km<sup>3</sup> for the year 2005.

Fig 1 shows that spatially resolved estimates of groundwater abstraction compare well with USGS groundwater use data. However, we require modeled estimates of crop-specific groundwater depletion for this study, and these data are not as readily available in the USGS data across the nation. Discrepancies between modeled estimates and USGS data on GWD occur over the Mississippi Embayment region in particular. The Mississippi Embayment aquifer is not captured as well by our model estimates, likely due to the specific crops that we consider. Modeled estimates show a much smaller spatial range of depletion over this aquifer region than USGS data show (*Konikow, 2013; Clark et al., 2011*) (see Fig 4). Any inconsistencies in GWD estimates will carry through all of our estimates of GWD transfers and exports. Despite this, these GWD estimates are currently the best available option due to being crop-specific and highly resolved in space.

The total amount of GWD embedded in flows was 29.1 km<sup>3</sup> in 2002. Of this total, 26.3 km<sup>3</sup> is DWT and 2.7 km<sup>3</sup> are DWE. This means that approximately 91% of all groundwater depletion is embedded in domestic transfers and 9% is embedded in international exports in 2002. The total volume of GWD embedded in transfers and exports was 38.5

358 km<sup>3</sup> for 2012, of which 34.8 km<sup>3</sup> are DWT and 3.74 km<sup>3</sup> are DWE. This means that an  
359 (unsustainable) volume roughly the size of Lake Mead was transferred domestically in  
360 2012 (Lake Mead is 35.7 km<sup>3</sup>). For 2012, approximately 90% of groundwater depletion  
361 flows was embedded in domestic transfers, while 10% was shipped abroad.

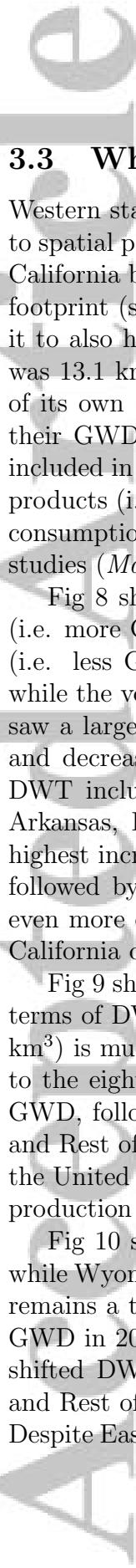
### 362 3.2 How has embedded groundwater depletion changed over 363 time?

364 GWD for irrigation in the U.S. has increased over time. From 2000 to 2010 there was  
365 a 32.7% increase in GWD overall. GWD changes in time across the U.S. in a spatially  
366 heterogeneous way. For the most part, large areas of the western U.S. have reduced  
367 their GWD (note the many green and blue counties in Fig 4). However, GWD increases  
368 are particularly pronounced in portions of the Central Valley and High Plains aquifers.  
369 There are also significant increases in GWD for southern Arizona, areas of Nevada, Utah,  
370 Wyoming, Idaho, and Florida between 2000 and 2010 (see Fig 4).

371 Despite declines in state average domestic agricultural transfers, the total volume of  
372 GWD embedded in transfers increased by 32.1% (26.3 km<sup>3</sup> in 2002 to 34.8 km<sup>3</sup> in 2012).  
373 Total DWE increased by 38.0% (2.7 km<sup>3</sup> in 2002 to 3.7 km<sup>3</sup> in 2012; see Table 5). The  
374 SCTG group with the highest increase in total volume for DWT was SCTG 2 cereal grains  
375 at a 58.5% increase (see Table 6). SCTG 4 animal products had the highest increase in  
376 total volume for DWE with a 144.4% increase. DWE for cereal grains was the only group  
377 to have a decrease in total volume traded, with a 3.2% decrease between 2002 and 2012.

378 Table 5 shows that an average of 34.8 km<sup>3</sup> GWD was transferred domestically in 2010.  
379 The average volume of GWD exported across all states and commodity groups in 2010  
380 was 3.74 km<sup>3</sup>. By SCTG group, the highest state average of GWD in domestic transfers  
381 is for animal products in both 2000 and 2010. In 2000 the mean was 11.06 km<sup>3</sup> and  
382 in 2010 a mean of 13.76 km<sup>3</sup> was transferred (refer to Table 6). The highest mean for  
383 international exports by state was associated with SCTG 3 for both years, with 1.32 km<sup>3</sup>  
384 in 2000 and 1.66 km<sup>3</sup> in 2010.

385 Mean GWD embedded in flows has increased between the two study years (see Ta-  
386 ble 5). This is despite declines in total agricultural transfers over time. This indicates  
387 that both domestic agricultural transfers and international exports are originating more  
388 in locations that deplete groundwater and/or production locations are more intensively  
389 relying on fossil groundwater. In other words, agricultural commodity fluxes have become  
390 increasingly reliant on GWD. The cross-sectional variance of GWD in transfers and ex-  
391 ports is increasing over time. This indicates that the GWD in transfers and exports is  
392 becoming more heterogeneous over time, with some production locations using even more  
393 unsustainable groundwater. This same trend is observed in DWT for all SCTG groups  
394 and DWE of SCTG 4 (refer to Table 6). However, means and variances of DWE for  
395 SCTG 2 decreased. This means that GWD is increasingly being used for higher value  
396 agricultural transfers and exports.



### 397 3.3 What locations exchange the most groundwater depletion?

398 Western states are the largest sources of virtual GWD (see Figs 5 and 6), corresponding  
399 to spatial patterns of GWD in production (see Fig 4). Table 7 ranks states by their DWT.  
400 California by far transfers the most GWD, despite not having the largest depletion water  
401 footprint (see Table 4). California does have the largest agricultural production, leading  
402 it to also have the largest total volume of GWD. The outflow of GWD from California  
403 was 13.1 km<sup>3</sup> in 2012. However, Fig 7 makes it clear that California actually uses most  
404 of its own GWD. In fact, all of the major GWD transfer states retain the majority of  
405 their GWD. It is important to note that only raw crop products and animal feed are  
406 included in this study. These products are often sourced locally as input into higher value  
407 products (i.e. meat, textiles, processed foods), which are then shipped elsewhere for final  
408 consumption. The importance of GWD to the California economy is consistent with other  
409 studies (*Marston and Konar, 2017; Marston et al., 2018*).

410 Fig 8 shows changes in DWT from 2002 to 2012. Fig 8A presents positive changes  
411 (i.e. more GWD in transfers from 2000 to 2010) while Fig 8B presents negative changes  
412 (i.e. less GWD in transfers from 2000 to 2010). The volume in Fig 8A is 11.8 km<sup>3</sup>,  
413 while the volume in Fig 8B is 3.4 km<sup>3</sup>. Mississippi had no outflows of GWD in 2000, but  
414 saw a large increase in 2010. Pennsylvania, Delaware, and Michigan were the opposite,  
415 and decreased by 100% in all SCTG categories. States that had the largest gains in  
416 DWT include Nebraska, Utah, Idaho, Wyoming, Montana, Colorado, and California.  
417 Arkansas, Florida, and Arizona also saw major increases in DWT. California has the  
418 highest increase in GWD transfers, an increase of 2.9 km<sup>3</sup> from 2002 to 2012 (see Fig 8),  
419 followed by Nebraska with an increase of 1.5 km<sup>3</sup>. Note that groundwater played an  
420 even more critical role to agricultural supply chains originating in the Central Valley of  
421 California during the drought of 2012-2014 (*Marston and Konar, 2017*).

422 Fig 9 shows DWE for the year 2012. California and Texas are the two largest states in  
423 terms of DWE. However, note that the volume of DWE captured by this graph (i.e. 3.7  
424 km<sup>3</sup>) is much smaller than the volume of DWT captured in Fig 7 (i.e. 34.8 km<sup>3</sup>). DWE  
425 to the eight major world regions are shown in Fig 9. East Asia is the top recipient of  
426 GWD, followed by Canada, Mexico, and Central Asia. Southeast Asia, Africa, Europe,  
427 and Rest of the Americas receive relatively small volumes of GWD in their imports from  
428 the United States. This highlights that certain world regions may have more exposure to  
429 production risk from falling water tables in their supply chains than other world regions.

430 Fig 10 shows the changes in DWE. California exhibits the most significant increase,  
431 while Wyoming and Colorado have the largest reduction. Despite this reduction, Colorado  
432 remains a top contributor to DWE in 2012. Arizona, followed by New York, export less  
433 GWD in 2012, after exporting to all eight world regions in 2002. California significantly  
434 shifted DWE patterns in 2012, changing its largest destinations from Europe, Africa,  
435 and Rest of the Americas to primarily East Asia, followed by Central Asia and Canada.  
436 Despite East Asia being the top destination for GWD only in 2010, it is the top destination

437 for agricultural exports in terms of mass for both years. Upon further investigation of the  
438 types of products California exports to East Asia, FAF4 data shows that SCTG4 made  
439 up the majority of exports to East Asia in 2002, while in 2012, the mass of SCTG 3 went  
440 from the least amount exported to the most. This is despite the mass of SCTG 4 exports  
441 increasing during the decade as well. This shows that GWD has become more important  
442 for fresh produce production and exports over time.

### 443 **3.4 What food flows are reliant on groundwater depletion?**

444 The mass of food in the national and international agricultural supply chain that relies  
445 on groundwater depletion has decreased over time (see Table 8). Agricultural products  
446 reliant on nonrenewable groundwater domestically transferred was 1,491,126 kilotonnes in  
447 2002, falling to 1,412,242 kilotonnes in 2012. This is a decrease of 78,884 kilotonnes, or a  
448 5.3% decrease, in agricultural products reliant on GWD that were transferred within the  
449 U.S. Similarly, 119,048 kilotonnes of agricultural products reliant on GWD were exported  
450 in 2002, while 94,247 kilotonnes were exported in 2010. This is a decrease of 20.8%  
451 in mass terms. For comparison, the mass of production reliant on GWD decreased by  
452 11.5%. The top five crop classes reliant on GWD for production in terms of mass for  
453 2002 were maize, followed by grasslands/pastures, citrus, soybeans, and wheat. In 2012,  
454 the crops that were most reliant on GWD were vegetables, fruits, and nuts, followed by  
455 grasslands/pastures, maize in fourth, and wheat again at fifth most.

456 Conversely, the dollar value of agricultural commodities in both national and interna-  
457 tional agricultural supply chains has increased (see Table 8). The value of agriculture in  
458 the U.S. supply chain has increased from 340 billion \$USD in 2002 to 524 billion \$USD  
459 in 2012. This is an increase of \$183 billion, or 54%. This means that all but \$2 billion  
460 of the increase over the course of the decade required GWD to produce in some amount.  
461 Similarly, the value in the international trade system increased from 47,036 million \$USD  
462 in 2002 to 61,808 million \$USD in 2012, an increase of \$14.8 billion, or a 31% increase. For  
463 both transfers and exports as well as both years, SCTG 3 makes up the largest component  
464 of commodities that are reliant on GWD in terms of \$USD. This is despite SCTG 2 mak-  
465 ing up the largest component of commodities reliant on GWD in terms of mass across  
466 both transfers and exports and both years. This indicates that groundwater depletion  
467 is increasingly being allocated to higher value crops, as was shown for California during  
468 drought (*Marston and Konar, 2017*). Importantly, we capture this transition to using  
469 GWD for higher-value agricultural goods despite the fact that we do not use GWD for  
470 the drought period (2012-2015). These higher-value agricultural goods – goods that fall  
471 into the SCTG3 class and also became the top GWD-intensive MIRCA classes for 2012 –  
472 are also more water-intensive to produce. Not only is depleted groundwater increasingly  
473 being allocated to higher-value crops, they are being allocated to crops that demand more  
474 water to produce per unit of mass (*Marston and Konar, 2017*). Hence, overall GWD for  
475 agriculture increases, despite the fact that the mass of agricultural goods produced has

476 decreased.

477 Table 9 provides a ranked list of links by their mass and dollar values for both transfers  
478 and exports. The largest link transfers that rely on GWD are all intra-state transfers in  
479 terms of both mass and value. For example, Iowa-Iowa is the largest link in terms of  
480 DWT by mass (128,610 [kilotonnes]), followed by Illinois-Illinois (103,195 [kilotonnes]),  
481 and Minnesota-Minnesota (101,052 [kilotonnes]). The California-California link is the fifth  
482 most in mass but the most highly valued (45,075 [million \$USD]). Iowa-Iowa (34,874 [mil-  
483 lion \$USD]), Illinois-Illinois (29,580 [million \$USD]), and Minnesota-Minnesota (24,481  
484 [million \$USD]) are also the most valuable transfers that depend on GWD. The top DWE  
485 are from West Coast ports to East Asia in both mass and value units. Other large export  
486 links are from the Central U.S. ports to Mexico and Canada. Exports to Southeast Asia  
487 and Oceania are the fifth and ninth largest in mass, but are not in the top ten for value.

### 488 3.5 Limitations of the study

489 A major limitation of our study is that input data are not available for the same time  
490 period. We pair GWD data for 2000 and 2010 with FAF information on agricultural fluxes  
491 for 2002 and 2012, respectively. National groundwater use exhibits a relatively stable trend  
492 (see Supporting Information). However, this will mask local temporal variations that are  
493 likely to be important. We are confident that our results are conservative for two major  
494 reasons. First, PCR-GLOBWB underestimates GWD in the Mississippi Embayment  
495 aquifer area. This means that we are not estimating a large volume of GWD in national  
496 and international agricultural fluxes associated with this aquifer. Our study would be  
497 improved by better estimates of GWD in the Mississippi Embayment. However, it is  
498 preferable to provide conservative values, which is what we do. Future work might consider  
499 using USGS information on depletion in the Mississippi Embayment (*Konikow, 2013*) to  
500 scale PCR-GLOBWB output.

501 Second, we use GWD values for 2010 with 2012 flux data. The year 2012 marked the  
502 start of a severe drought in California, in which groundwater use increased in the Central  
503 Valley, leading to greater virtual groundwater exports (*Marston and Konar, 2017*). It is  
504 likely that much of this was from unsustainable sources. So, we again underestimate the  
505 GWD embedded in domestic transfers and exports. Additionally, we do not include grapes  
506 in our study (see the SI), which farmers increasingly planted over the course of the drought  
507 in California, in order to obtain more revenue per unit of irrigation water (*Marston and*  
508 *Konar, 2017*). Limitations in the match between MIRCA and SCTG crop categories, and  
509 coarse commodity flux information, limits our ability to assess GWD embedded in the  
510 supply chains of specific crops, an issue which is likely to be more pronounced for cash  
511 crops.

512 Another important limitation of our study is that it focuses solely on agricultural  
513 production and supply chains. This will underestimate the value of GWD to national  
514 and global supply chains. Agricultural products will be processed and refined into more

515 complex agri-food/fuel items. By only quantifying the GWD embedded in agricultural  
516 supply chains, we are missing the potentially important role of groundwater to higher level  
517 commodities. However, restricting our study to only agricultural items has the benefit  
518 of minimizing double counting of groundwater embodied in the supply chain. The FAF4  
519 supply chain data does not provide explicit production and consumption fluxes. This  
520 means that double counting is a problem when items are processed and refined. We  
521 avoid this issue by focusing only on raw crop items. Future work that disentangles the  
522 production and consumption accounting would further our understanding of the true role  
523 of groundwater in all agri-food/fuel supply chains.

524 Future work could improve the inclusion of local information into a groundwater model.  
525 We used the PCR-GLOBWB model which relies on several global inputs. However, more  
526 local information is available for the United States, that would improve the accuracy of  
527 groundwater modeling. For example, our input grids of crop locations were based on  
528 MIRCA rather than USDA county-scale statistics of crop areas. Similarly, time-varying  
529 crop calendars would enable physical models to better assess crop water demands during  
530 the growing season, rather than the crop calendars fixed circa 2000 in MIRCA. Configuring  
531 PCR-GLOBWB is beyond the scope of the current study, whose main objective is to bring  
532 GWD estimates together with agricultural flux data. Refined estimates of GWD based on  
533 local government data would improve our estimates of GWD in this important country.  
534 Additionally, future research could use more spatially-resolved estimates of the agri-food  
535 supply chain of the United States (*Lin et al., 2019*).

## 536 4 Conclusion

537 In this study, we quantified the volume of groundwater depletion embedded in U.S. domes-  
538 tic transfers and exports. Results reveal that there have been large increases in ground-  
539 water depletion transfers domestically via fresh produce transfers and internationally via  
540 animal feed exports. Between 2002 and 2012, the total volume of groundwater depletion  
541 embedded in U.S. domestic transfers increased by 32.1% and groundwater depletion em-  
542 bedded in international exports of the U.S. increased by 38.0%. California contributes  
543 the most groundwater depletion to both the national and international agricultural supply  
544 chains of the United States, and is the largest consumer of its own groundwater depletion.  
545 East Asia imports the most embedded groundwater depletion of any world region, with  
546 1.62 km<sup>3</sup> imported.

547 The mass of food in the national and international agricultural supply chain of the  
548 U.S. that relies on groundwater depletion has decreased over time. 1,491,126 kilotonnes of  
549 agricultural products reliant on nonrenewable groundwater was domestically transferred  
550 in 2002, falling to 1,412,242 kilotonnes in 2012. Similarly, 119,048 kilotonnes was exported  
551 in 2002, while 94,247 kilotonnes was exported in 2012. However, the value of agricultural  
552 commodities in both national and international agricultural supply chains has increased.

553 The value of agriculture in the U.S. supply chain has increased from 340,407 million  
554 \$USD in 2002 to 523,926 million \$USD in 2012 (a 54% increase) while the value in the  
555 international trade system increased from 47,036 million \$USD in 2002 to 61,808 million  
556 \$USD in 2012 (a 31% increase). This indicates that there has been an increase in the  
557 groundwater depletion footprint of agricultural commodities and that (unsustainable)  
558 groundwater use is increasingly being allocated to higher value crops.

559 This study shows that large volumes of groundwater depletion are embedded in the  
560 national agricultural supply chain of the United States, as well as in its international  
561 exports. The volume of unsustainable groundwater resources in these supply chains has  
562 increased over time. However, it is unclear if trade is driving overexploitation of ground-  
563 water resources. It is possible that even more groundwater would be unsustainably mined  
564 in an agricultural system without trade (i.e. one of ‘self-sufficiency’ or ‘autarky’). Would  
565 more or less groundwater be depleted in the absence of trade? To determine if trade  
566 is leading to more groundwater being unsustainably used, we would need to use causal  
567 inference techniques, such as those employed by *Dang and Konar (2018)*. We call for  
568 future work to examine the causal impact of trade on groundwater depletion.

569 Eventually, the mass and value of agricultural commodities produced with unsus-  
570 tainable groundwater will need to be replaced with production from elsewhere, once the  
571 groundwater reserves are no longer viable to mine. The groundwater depletion embedded  
572 in agricultural supply chains represents its exposure to unsustainable water use. Future  
573 research should assess the vulnerability of agricultural supply chains to unsustainable  
574 water use. Exposure to long-term water risk is one factor that may be important to consider  
575 in a cost-benefit assessment of agricultural policies. Going forward, researchers, policy  
576 makers, and supply chain managers should assess the threats posed to future food supply  
577 chains from depleted groundwater reserves.

578

## 579 Acknowledgments

580

581 This material is based upon work supported by the National Science Foundation Grant  
582 No. ACI-1639529 (“INFEWS/T1: Mesoscale Data Fusion to Map and Model the U.S.  
583 Food, Energy, and Water (FEW) System”), EAR-1534544 (“Hazards SEES: Under-  
584 standing Cross-Scale Interactions of Trade and Food Policy to Improve Resilience to Drought  
585 Risk”), and CBET-1844773 (“CAREER: A National Strategy for a Resilient Food Sup-  
586 ply Chain”). Any opinions, findings, and conclusions or recommendations expressed in  
587 this material are those of the author(s) and do not necessarily reflect the views of the  
588 National Science Foundation. All data sources are listed in the methods section of the  
589 paper and are freely available online. Please note that we provide key variables estimated  
590 in this study in the Supporting Information document in an effort to enable research  
591 reproducibility.

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Table 1: List of data dependencies in this study.

Name	Source	Temporal Range	Temporal resolution	Spatial boundary	Spatial resolution
FAF4 Commodity Flows	(FAF4, 2015)	1997-2007	Annually, every 5 years	United States	U.S. States
FAF4 Commodity Flows	(FAF4, 2015)	2012-2017	Annually, all years	United States	U.S. FAF Zones
USGS Water Use	(Manpin <i>et al.</i> , 2014)	1985-2015	Annually, every 5 years	United States	U.S. counties
PCR-GLOBWB total groundwater abstraction	(Wada <i>et al.</i> , 2012)	1960-2010	Monthly, all years	Global	0.5 degree
PCR-GLOBWB total groundwater depletion	(Wada <i>et al.</i> , 2012)	2000-2010	Monthly, all years	Global	0.5 degree
PCR-GLOBWB crop-specific groundwater depletion	(Dalin <i>et al.</i> , 2017)	2000 and 2010	Monthly, all years	Global	0.5 degree
MIRCA irrigated areas & crop calendars	(Portmann <i>et al.</i> , 2010)	2000	Monthly	Global	0.5 degree
USDA agricultural statistics	NASS	1997-2017	Varies by crop	United States	U.S. counties

Table 2: Correlation metrics between groundwater abstraction as reported by PCR-GLOBWB and USGS. Metrics are provided for both 2000 and 2010. ‘R2’ is R-squared value; ‘R2 Adjusted’ is adjusted R-squared value; ‘MAE’ is mean absolute error; ‘RMSE’ is root mean squared error; ‘Jaccard’ is the Jaccard similarity index; and ‘SMC’ is the simple matching coefficient.

Year	R2	R2 Adjusted	MAE	RMSE	Jaccard	SMC
2000	0.65	0.65	20.77	70.37	0.96	0.96
2010	0.54	0.54	22.19	79.48	0.99	0.99

Table 3: Correlation metrics between irrigated area as reported by MIRCA and USDA. Metrics are provided for both 2000 and 2010. ‘R2’ is R-squared value; ‘R2 Adjusted’ is adjusted R-squared value; ‘MAE’ is mean absolute error; ‘RMSE’ is root mean squared error; ‘Jaccard’ is the Jaccard similarity index; and ‘SMC’ is the simple matching coefficient.

Year	R2	R2 Adjusted	MAE	RMSE	Jaccard	SMC
2000	0.92	0.92	127143.26	332514.57	0.98	0.98
2010	0.87	0.87	147900.69	372134.74	1.00	1.00

Table 4: States with the most groundwater depletion in 2012. The top 10 states in terms of GWD are provided along with their total agricultural production [tons] and depletion footprint [ $\text{m}^3/\text{ton}$ ].

Rank	State	Total GWD [ $\text{m}^3 \times 10^6$ ]	Total Production [tons]	Depletion footprint [ $\text{m}^3/\text{ton}$ ]
1	California	14,886	83,480,978	178
2	Texas	5,554	26,468,531	210
3	Colorado	2,634	13,449,191	196
4	Nebraska	2,468	49,017,580	50
5	Arizona	2,468	6,197,385	398
6	Idaho	1,959	27,321,870	72
7	Kansas	1,040	32,291,438	32
8	Arizona	1,017	15,803,537	64
9	Washington	670	18,548,859	36
10	New Jersey	217	1,431,924	152

Table 5: Summary statistics of key variables in 2002 and 2012. The total, mean, and variance across states are provided for groundwater depletion (GWD) [ $\text{km}^3$ ], total domestic transfers of agricultural items [kilotonnes], GWD embedded in domestic agricultural transfers [ $\text{km}^3$ ], total international agricultural exports [kilotonnes], and GWD embedded in international agricultural exports [ $\text{km}^3$ ].

	GWD [ $\text{km}^3$ ]	Agricultural transfers [kilotonnes]	GWD transfers [ $\text{km}^3$ ]	Agricultural exports [kilotonnes]	GWD exports [ $\text{km}^3$ ]
2002 Total	29.1	1,754,910	26.3	144,125	2.71
2002 Mean	0.581	35,098	0.527	2,883	0.054
2002 Variance	3.17	1,363,459,770	2.485	29,972,974	0.045
2012 Total	38.5	1,596,027	34.8	155,519	3.74
2012 Mean	0.771	31,921	0.696	3,110	0.075
2012 Variance	5.043	1,622,203,009	3.927	79,260,479	0.077

Table 6: Summary statistics of groundwater depletion (GWD) [ $\text{km}^3$ ] embedded in domestic transfers and international exports by SCTG commodity group. The total, mean, and variance of GWD in state transfers and exports is provided for each commodity group.

	SCTG2 transfers	SCTG2 exports	SCTG3 transfers	SCTG3 exports	SCTG4 transfers	SCTG4 exports
2002 Total	5.34	0.89	9.95	1.32	11.06	0.50
2002 Mean	0.1067	0.0178	0.1990	0.0265	0.2211	0.0099
2002 Variance	0.0893	0.0057	0.5776	0.0113	0.4062	0.0014
2012 Total	8.46	0.86	12.58	1.66	13.76	1.22
2012 Mean	0.1692	0.0172	0.2515	0.0333	0.2753	0.0243
2012 Variance	0.1539	0.0043	0.9332	0.0171	0.5671	0.0092

Table 7: Top outflow and inflow regions in 2012. Units are in km<sup>3</sup>. ‘Out-flows’ indicates depletion water transfers (DWT) out of a state; ‘Exports’ indicates depletion water exports (DWE) out of a state; ‘In-transfers’ indicates depletion water transfers (DWT) into a state; and ‘Imports’ indicates depletion water exports (DWE) from the US to their recipient world countries and/or regions. Note that state-level self-loops are included in both outflow and inflow categorization.

Rank	State	Out-Transfers	State	Exports
1	California	13.10	California	1.79
2	Texas	4.70	Texas	0.86
3	Colorado	2.61	Washington	0.37
4	Nebraska	2.41	Arizona	0.22
5	Arizona	2.25	Utah	0.08
6	Idaho	1.93	Kansas	0.06
7	Utah	1.07	Nebraska	0.05
8	New Mexico	1.03	Oregon	0.05
9	Kansas	0.98	Arkansas	0.04
10	Arkansas	0.97	Illinois	0.03
Rank	State	In-Transfers	World region	Imports
1	California	12.86	East Asia	1.62
2	Texas	4.64	Canada	0.57
3	Colorado	2.41	Mexico	0.44
4	Idaho	2.15	Southwest and Central Asia	0.38
5	Nebraska	2.14	Southeast Asia	0.23
6	Arizona	1.82	Africa	0.22
7	New Mexico	0.97	Europe	0.17
8	Arkansas	0.87	Rest of the Americas	0.12
9	Kansas	0.74		
10	Wyoming	0.70		

Table 8: Total mass and value of transfers and exports reliant on GWD.

	Mass transfer [kilotonnes]	Value transfer [million \$USD]	Mass export [kilotonnes]	Value export [million \$USD]
2002	1,491,126	340,407	119,048	47,036
2012	1,412,242	523,926	94,247	61,808

Table 9: Ranks of origin-destination flows that rely most on GWD. The top 10 links that are most reliant on GWD in terms of both mass and value are provided.

Rank	Link	Mass transfer [kilotonnes]	Link	Value transfer [million \$USD]
1	Iowa-Iowa	128,610	California-California	45,075
2	Illinois-Illinois	103,195	Iowa-Iowa	34,874
3	Minnesota-Minnesota	101,052	Illinois-Illinois	29,580
4	Nebraska-Nebraska	98,407	Minnesota-Minnesota	24,481
5	California-California	66,759	Nebraska-Nebraska	21,838
6	Kansas-Kansas	60,897	Texas-Texas	19,691
7	North Dakota-North Dakota	50,573	Kansas-Kansas	14,997
8	Texas-Texas	45,758	Indiana-Indiana	13,079
9	South Dakota-South Dakota	42,385	North Dakota-North Dakota	12,902
10	Indiana-Indiana	39,653	Florida-Florida	12,383

Rank	Link	Mass export [kilotonnes]	Link	Value export [million \$USD]
1	Washington-E Asia	23,209	Washington-E Asia	9,614
2	Oregon-E Asia	5,260	California-E Asia	5,248
3	Illinois-E Asia	4,710	California-Canada	2,886
4	California-E Asia	4,282	California-Europe	2,309
5	Washington-SE Asia/Oceania	3,268	Oregon-E Asia	1,822
6	Iowa-Mexico	3,014	Illinois-E Asia	1,776
7	Texas-Mexico	2,633	Texas-E Asia	1,733
8	California-Canada	2,391	California-SW/Central Asia	1,643
9	Illinois-SE Asia/Oceania	1,967	Texas-Mexico	1,586
10	Nebraska-Mexico	1,964	Iowa-Mexico	1,344

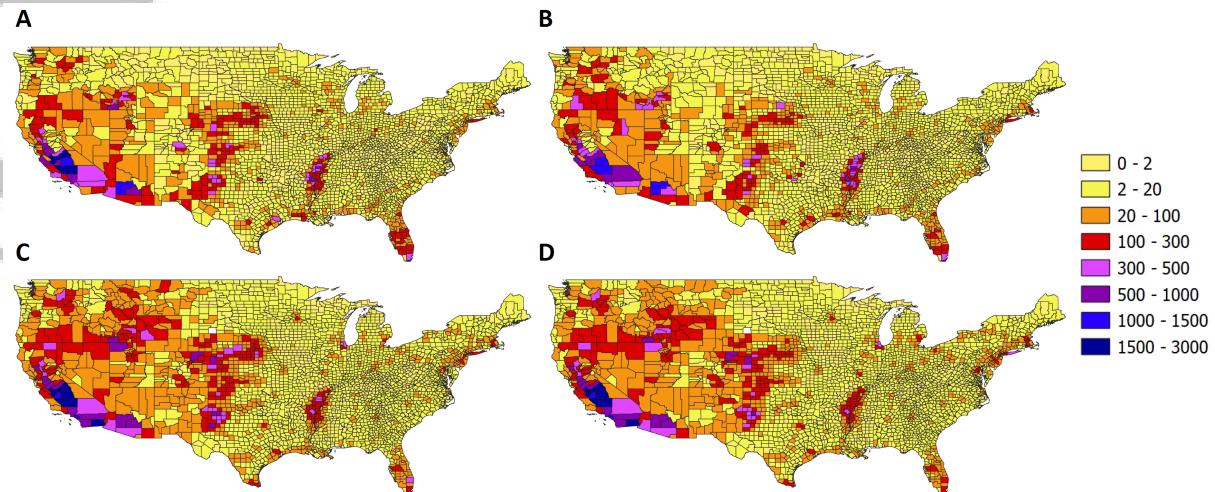


Figure 1: Maps of groundwater abstraction in the United States. Groundwater abstractions [ $\text{m}^3 \times 10^6$ ] for each U.S. county is shown for the year 2000 in the first column (Panel A, C) and 2010 in the second column (Panel B, D). Groundwater withdrawals from the U.S. Geological Survey (*Hutson et al.*, 2004; *Maupin et al.*, 2014) are mapped in the first row (Panel A, B). Groundwater abstractions modeled by PCR-GLOBWB are mapped in the second row (Panel C, D). Note that PCR-GLOBWB captures the spatial and time trend of U.S. Geological Survey data to a reasonable degree.

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Figure 2: Map of irrigated areas [hectares] in the United States. The top row (Panel A, B) shows USDA data. The bottom row (Panel C, D) shows MIRCA data. The first column (Panel A, C) shows 2000 and the second row (Panel B, D) shows 2010. ‘Irrigated Harvest Area’ from USDA-NASS Quickstats is mapped for the following crops: Corn (grain and silage), Cotton, Hay & Haylage, Oats, Peanuts, Southern peas (cowpeas), Rye, Sorghum (grain, silage, and syrup), Soybeans, Wheat, Grasses & Legumes, Barley, Beans (excluding chickpeas and lima), Camelina, Jojoba, Peas, Popcorn, Triticale, Rice, Buckwheat, Canola, Dill, Flaxseed, Herbs (dry), Hops, Vetch Legumes, Millet (proso), Mint, Safflower, Sesame, Sugarbeets, Sunflower, Switchgrass, Wild rice, Emmer & spelt, Tobacco, Sugarcane, Legumes, Ginger root, Pineapples, Taro, Mustard seed, Miscanthus, Lentils, Rapeseed, Guar, Potatoes, Sweet potatoes, Ginseng, Sweet rice, Lotus root, and Other Field Crops. The maps of total irrigated area compares reasonably well in space and time across data sources.

## Groundwater Trends

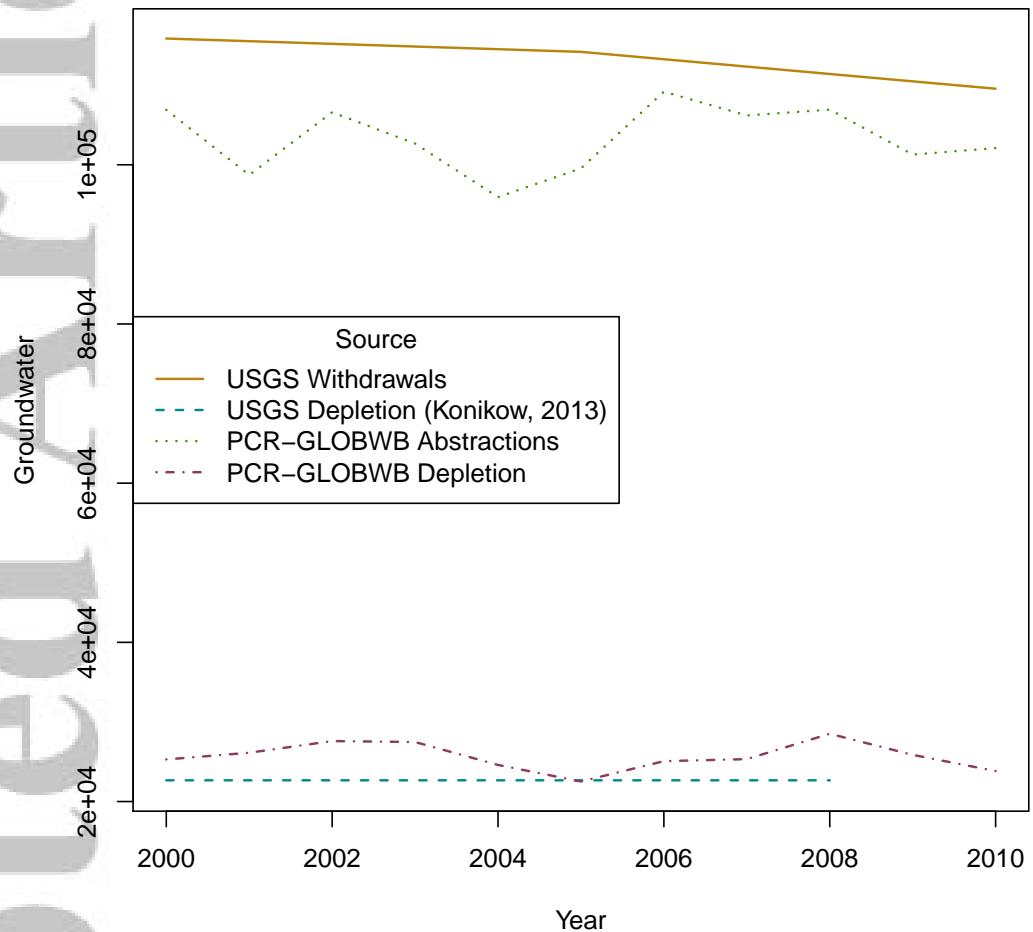


Figure 3: Time series of national groundwater use [Mm<sup>3</sup>/year]. USGS groundwater withdrawals is compared with groundwater abstractions from PCR-GLOBWB. A trend line is fit to USGS withdrawals for 2000, 2005, and 2010. USGS annual groundwater depletion for major aquifers is calculated from Konikow (2013). This was calculated as the difference between the groundwater depletion volume from 1900-2008 vs. 1900-2000. This difference was then divided by 9 and attributed to each of the nine years from 2000-2008. USGS groundwater depletion is compared with PCR-GLOBWB groundwater depletion. The national trends compare reasonably well between the USGS data and the PCR-GLOBWB model estimates.

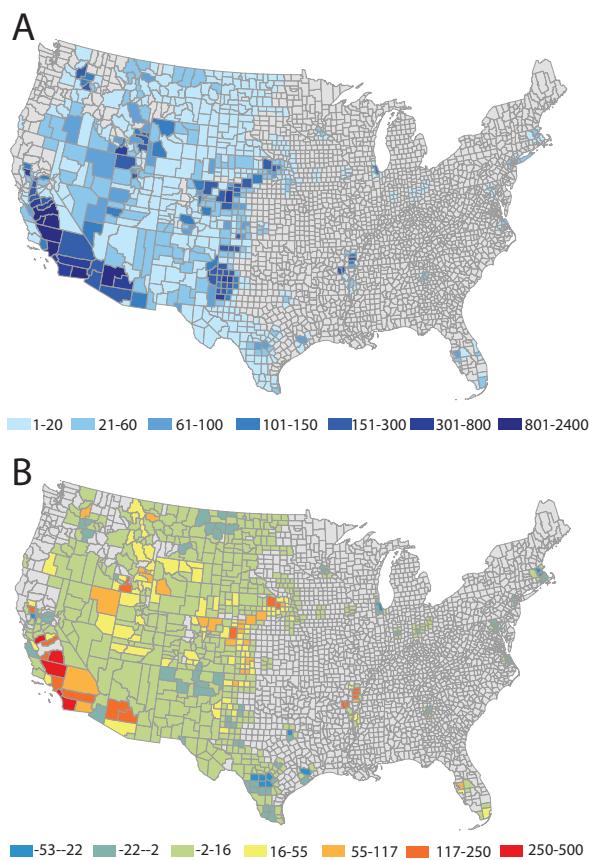


Figure 4: Maps of groundwater depletion in the United States. Groundwater depletion [ $\text{m}^3 \times 10^6$ ] for each U.S. county is shown for the year 2010 (Panel A). Changes from 2000 to 2010 are mapped in Panel B.

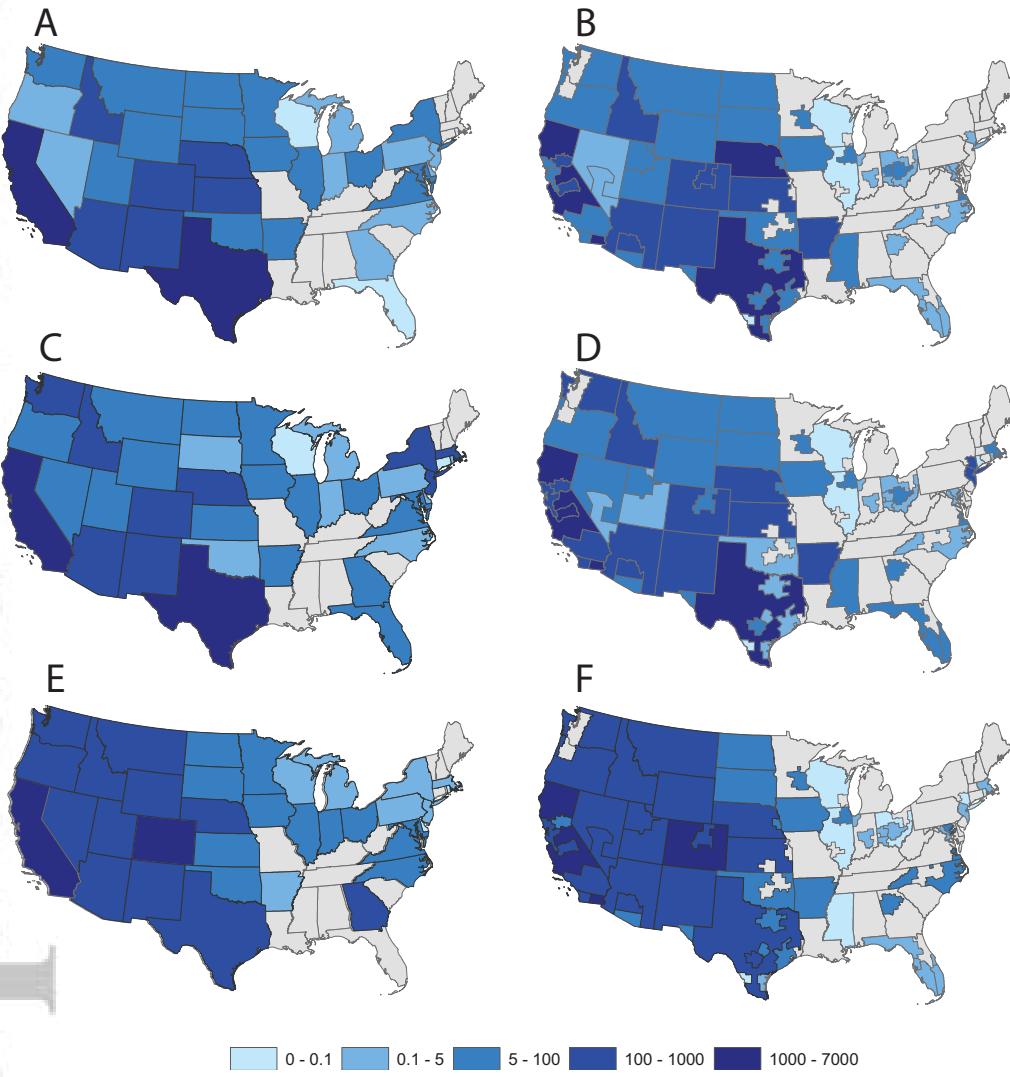


Figure 5: Maps of groundwater depletion transfers within the United States. Groundwater depletion out-flows [ $10^6 \text{ m}^3 \text{ year}^{-1}$ ] are provided for each agricultural commodity class considered in this study. The first row (Panels A, B) shows grains (SCTG 2); the second row (Panels C, D) shows fresh produce (SCTG 3); and the third row (Panels E, F) shows animal feed (SCTG 4). The first column (Panels A, C, E) shows the year 2000 and the second column (Panels B, D, F) shows the year 2010. Note that domestic transfers are calculated at the state spatial scale in 2002 and the FAF zone spatial scale in 2012.

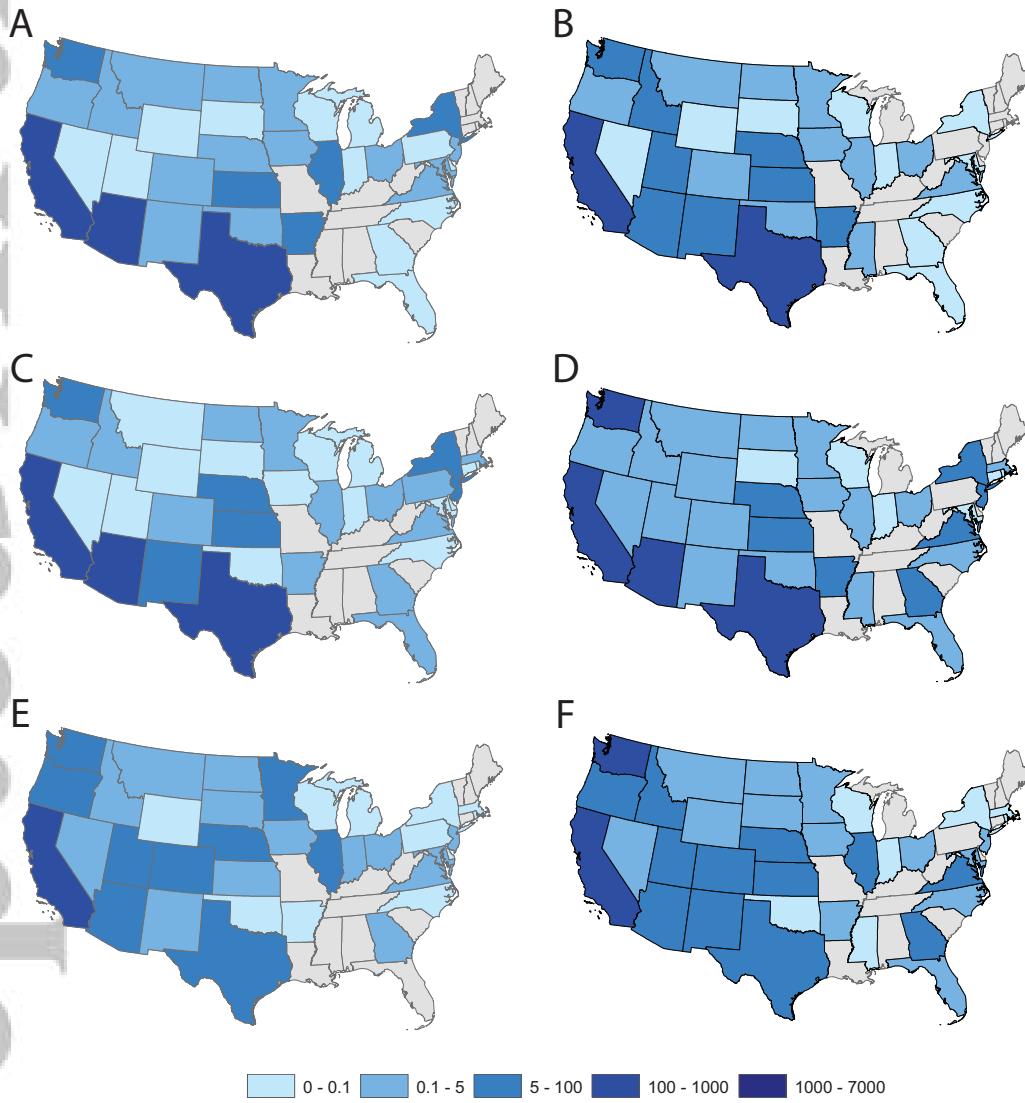


Figure 6: Maps of groundwater depletion exports from the United States. Exports of groundwater depletion [ $10^6 \text{ m}^3 \text{ year}^{-1}$ ] are provided at the state spatial scale and for each agricultural commodity class considered in this study. The top row (Panels A, B) shows the groundwater depletion exports of grains (SCTG 2), the middle row (Panels C, D) shows the groundwater depletion exports of fresh produce (SCTG 3), and the bottom row (Panels E, F) shows the groundwater depletion exports of animal feed (SCTG 4). The first column (Panels A, C, E) shows groundwater depletion exports in 2002. The second column (Panels B, D, and F) shows groundwater depletion exports in 2012.

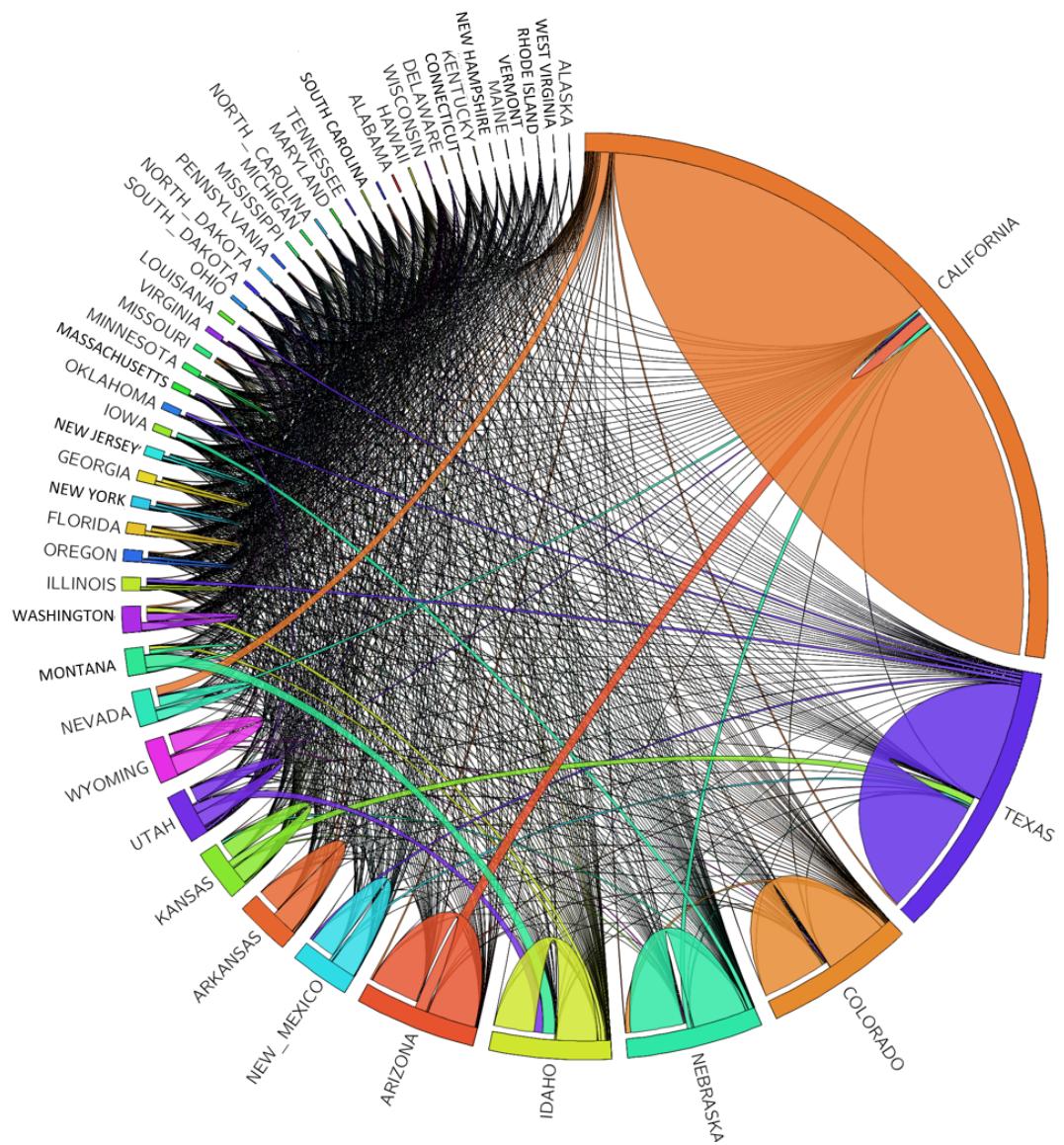


Figure 7: Circos graph of domestic groundwater depletion transfers in 2012. States are plotted clockwise in descending order of their total groundwater depletion volume embedded in their commodity outflows. The size of the length of arc around the circle indicates the total volume of each state as a percentage of total domestic transfers. Outflow volume is indicated with links emanating from the arc of the same color. Inflow volume is indicated with a white area separating the arc from links of a different color. The volume of groundwater depletion captured in this graph is  $34.8 \text{ km}^3 \text{ yr}^{-1}$ .

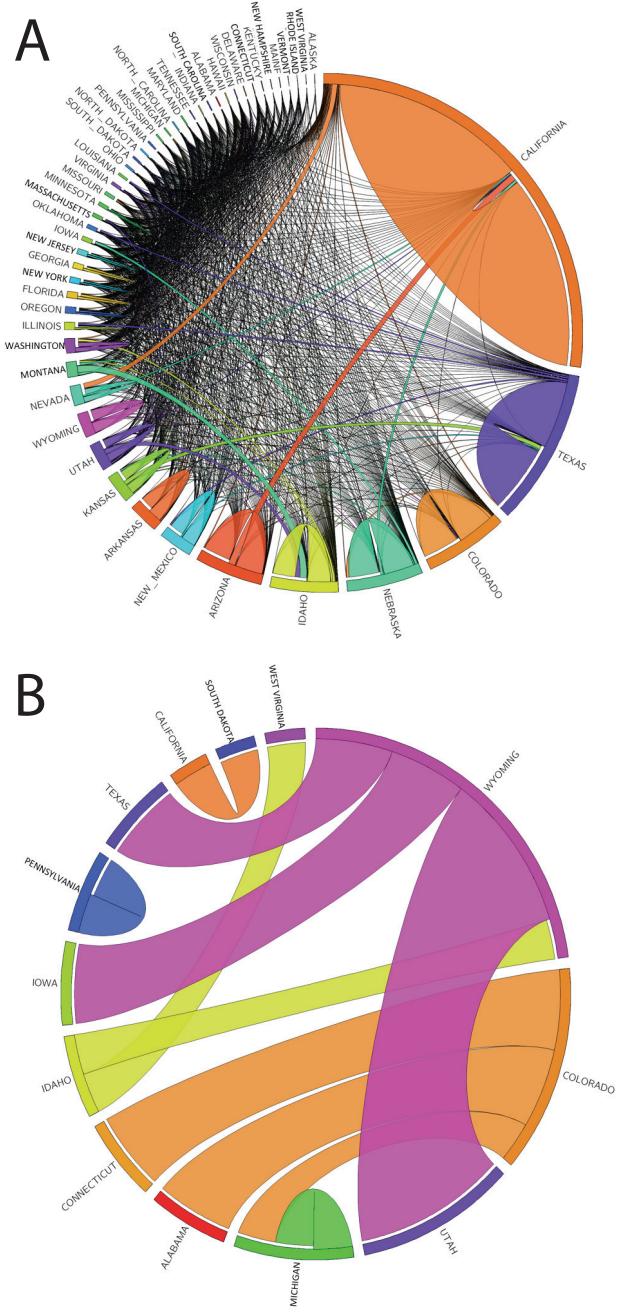


Figure 8: Circos graph of changes in groundwater depletion transfers. Positive (A) and negative (B) values are shown for domestic transfers. The total volume graphed in Panel A is  $11.8 \text{ km}^3 \text{ yr}^{-1}$  and the total volume graphed in Panel B is  $3.4 \text{ km}^3 \text{ yr}^{-1}$ . In 2012, Colorado is using more of its own groundwater depletion, but sending less to other states.

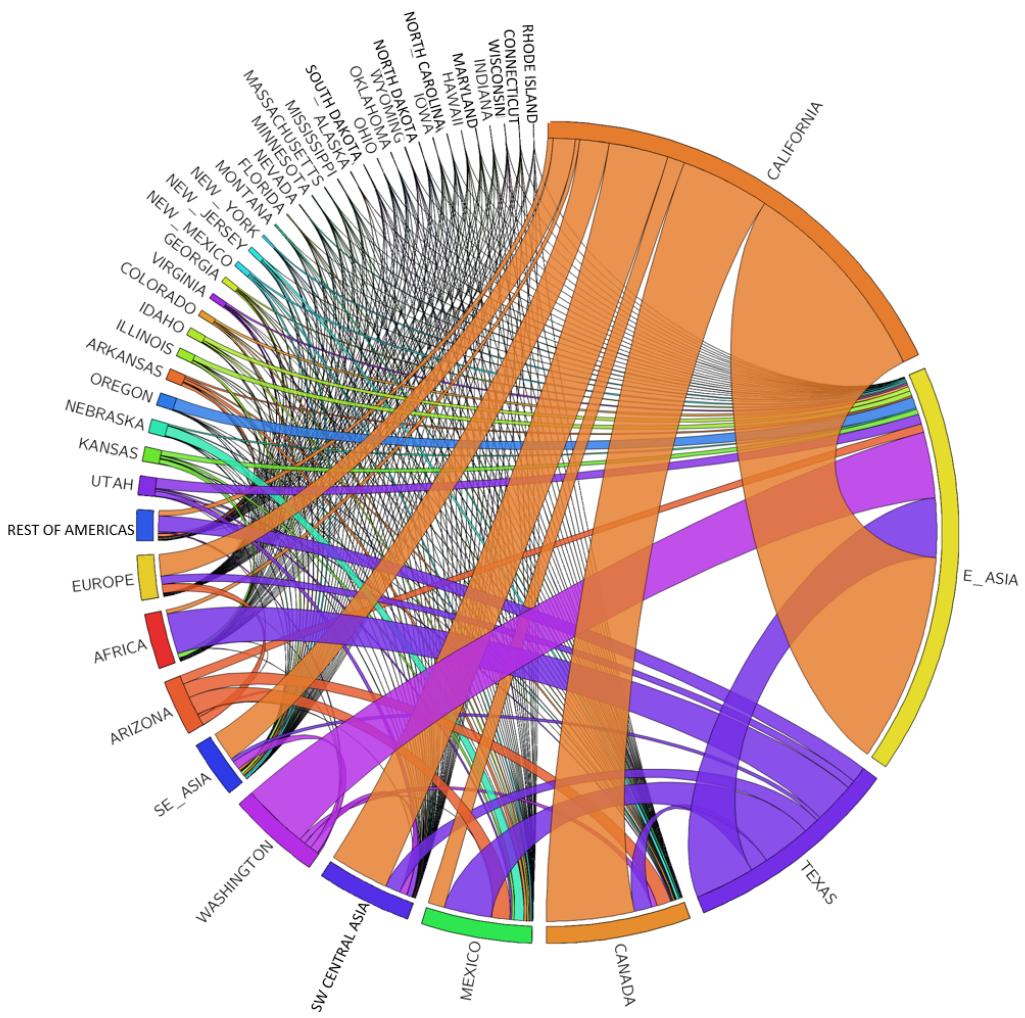


Figure 9: Circos graph of international groundwater depletion exports in 2012. States and world regions are plotted clockwise in descending order of the total groundwater depletion volume embedded in their commodity trade. International export volume is indicated with links emanating from the outer bar of the same color. The volume of groundwater depletion captured in this graph is  $3.7 \text{ km}^3 \text{ yr}^{-1}$ .

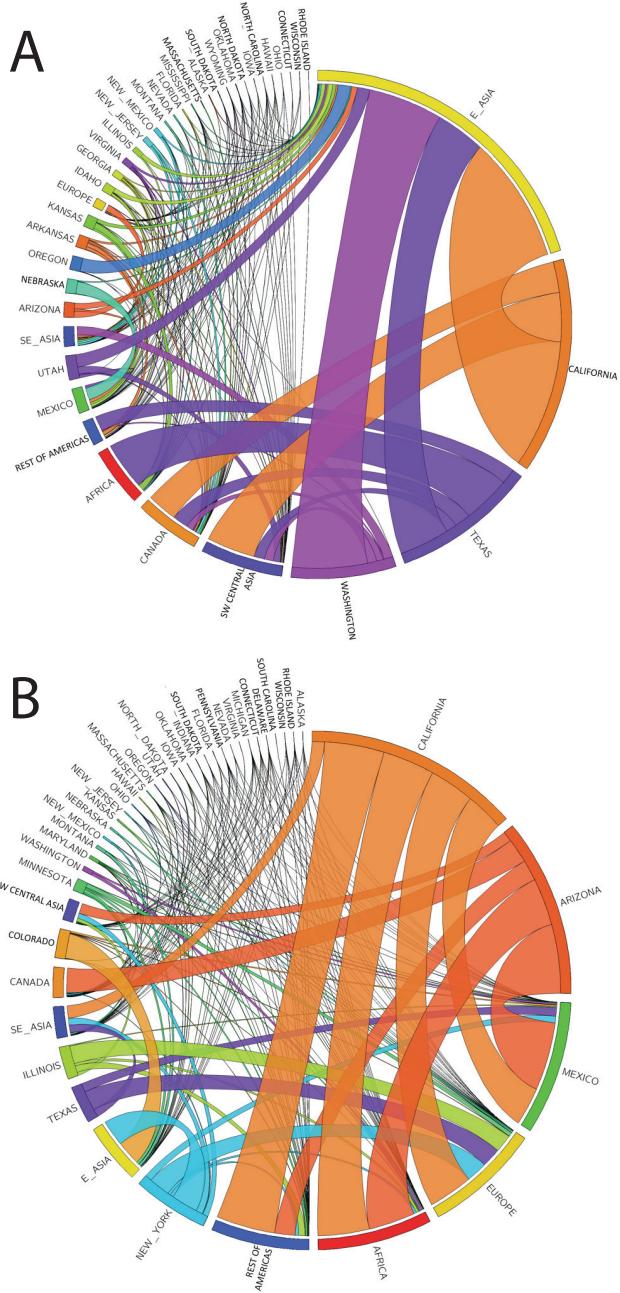


Figure 10: Circos graph of changes in groundwater depletion exports. Positive (A) and negative (B) values are shown for international exports. The total volume graphed in Panel A is  $1.7 \text{ km}^3 \text{ yr}^{-1}$  and the total volume graphed in Panel B is  $0.66 \text{ km}^3 \text{ yr}^{-1}$ . In 2012, California is sending more virtual groundwater depletion to Eastern Asia and less to Europe.

Figure 1.

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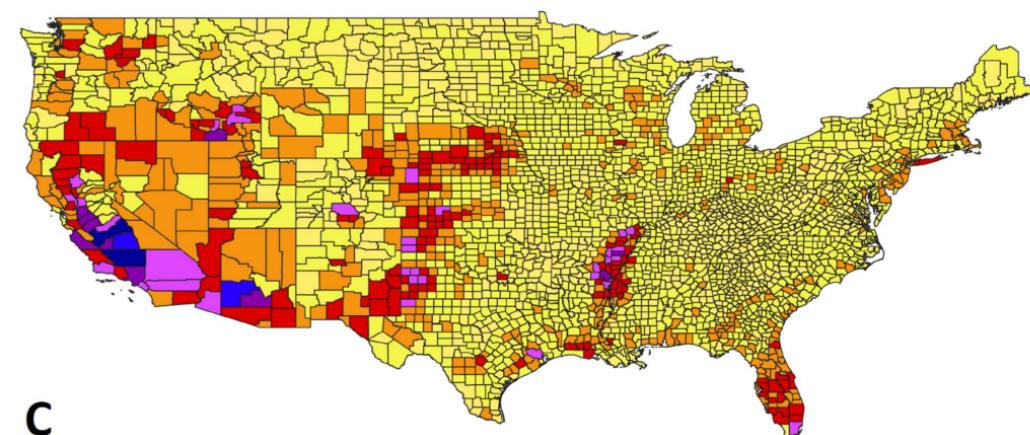
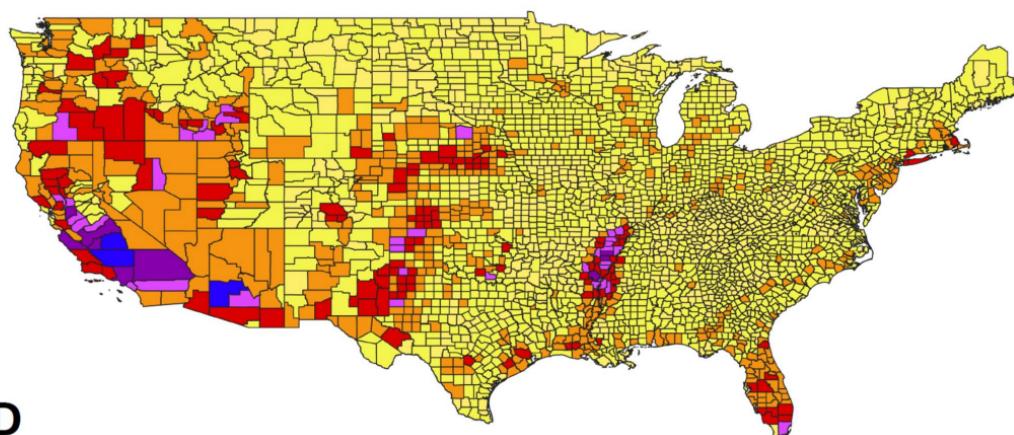
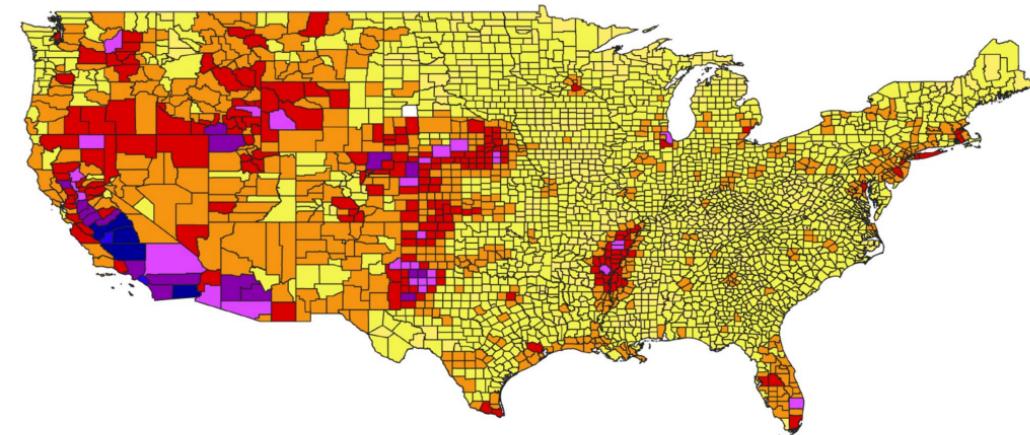
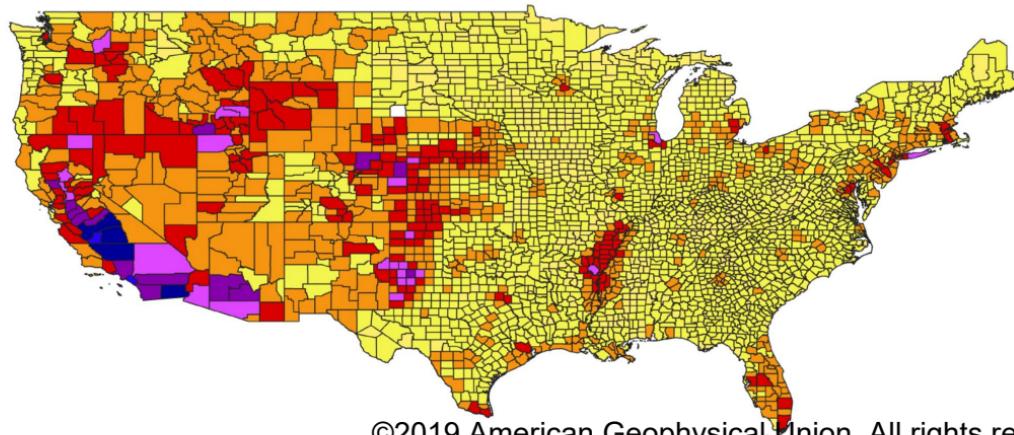
**A****B****C****D**

Figure 2.

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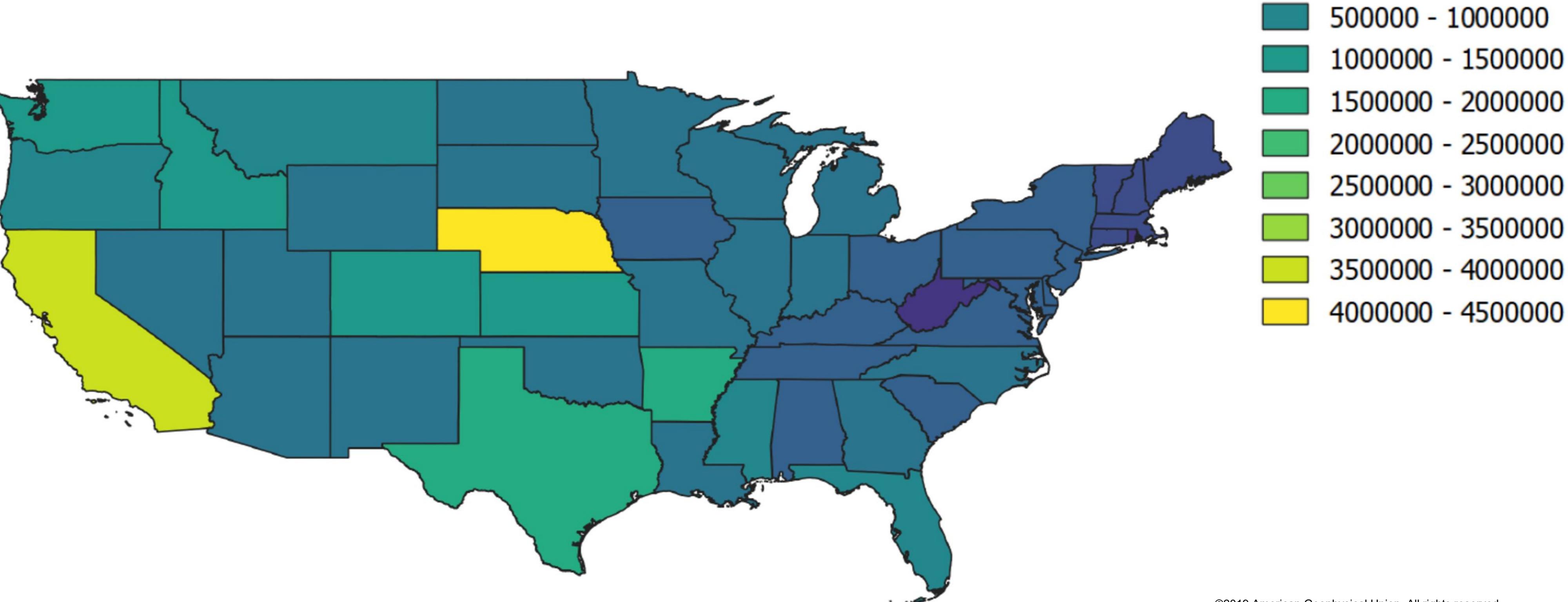
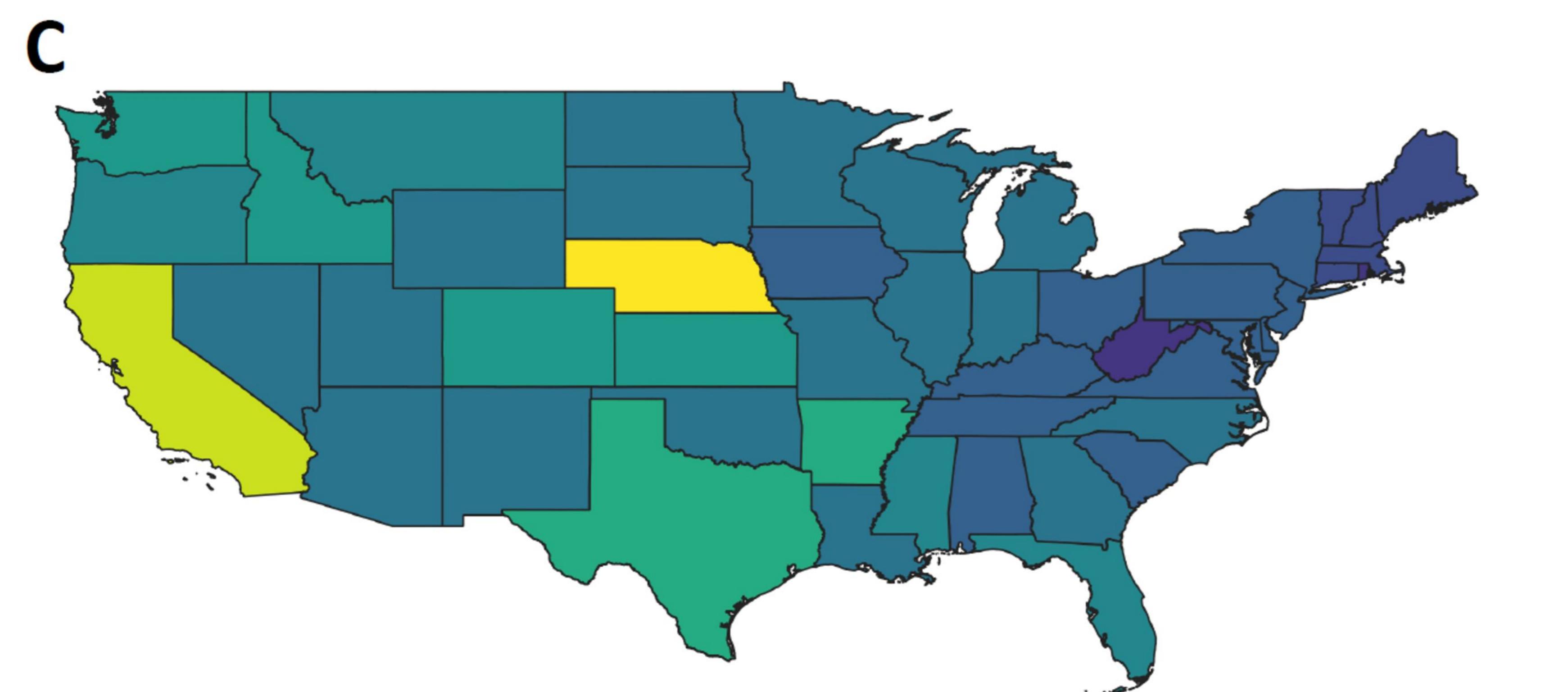
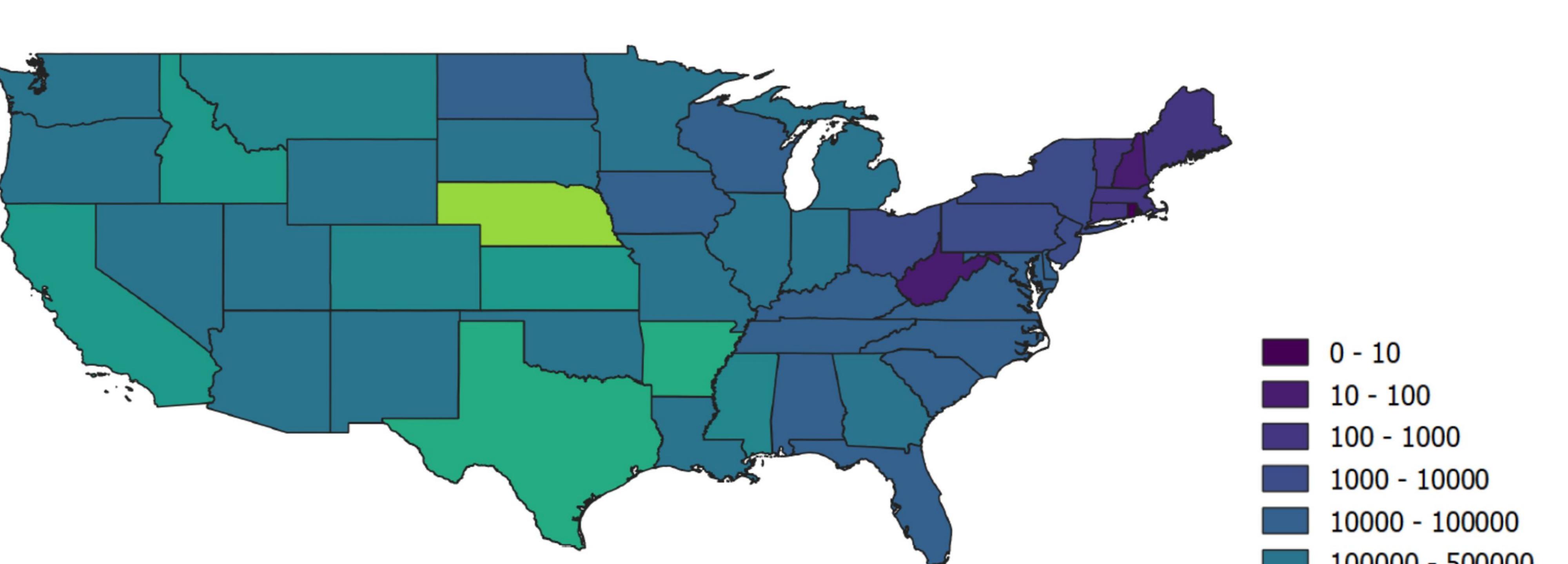
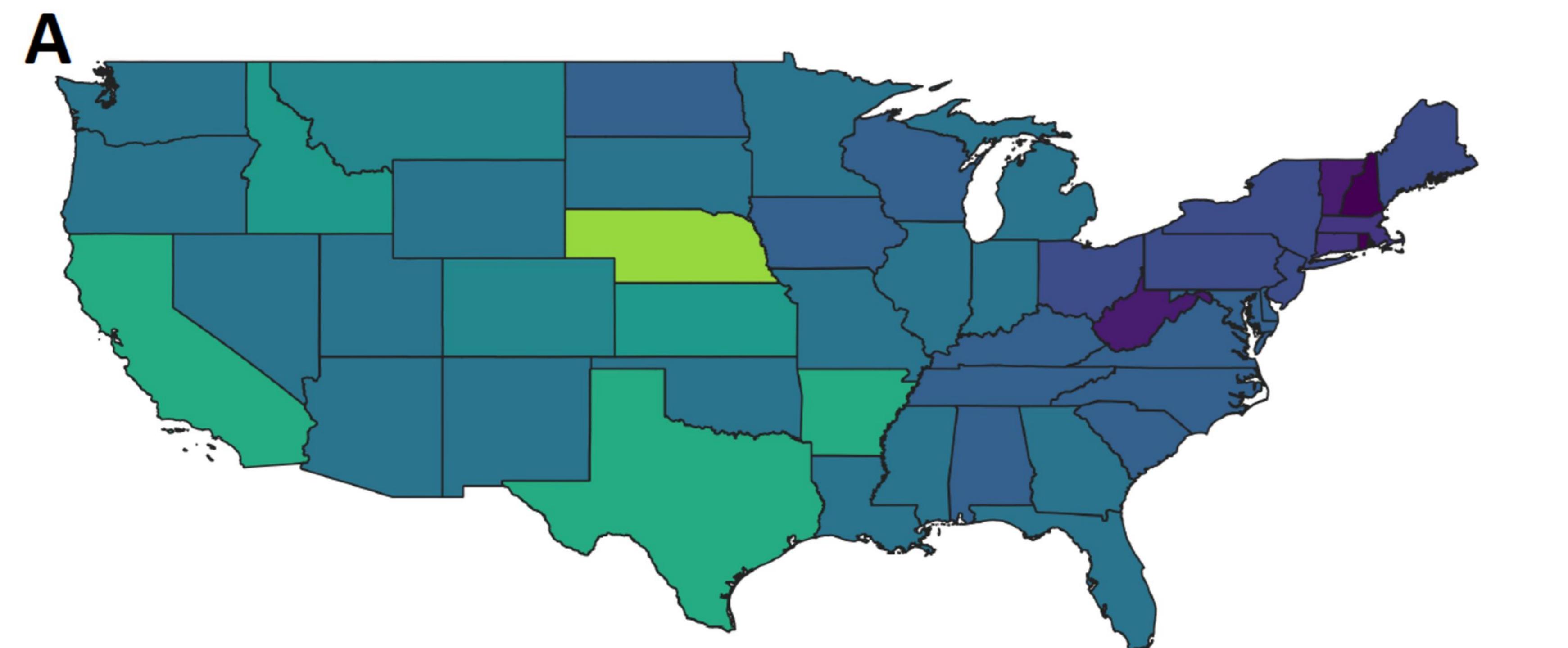


Figure 3.

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## Groundwater Trends

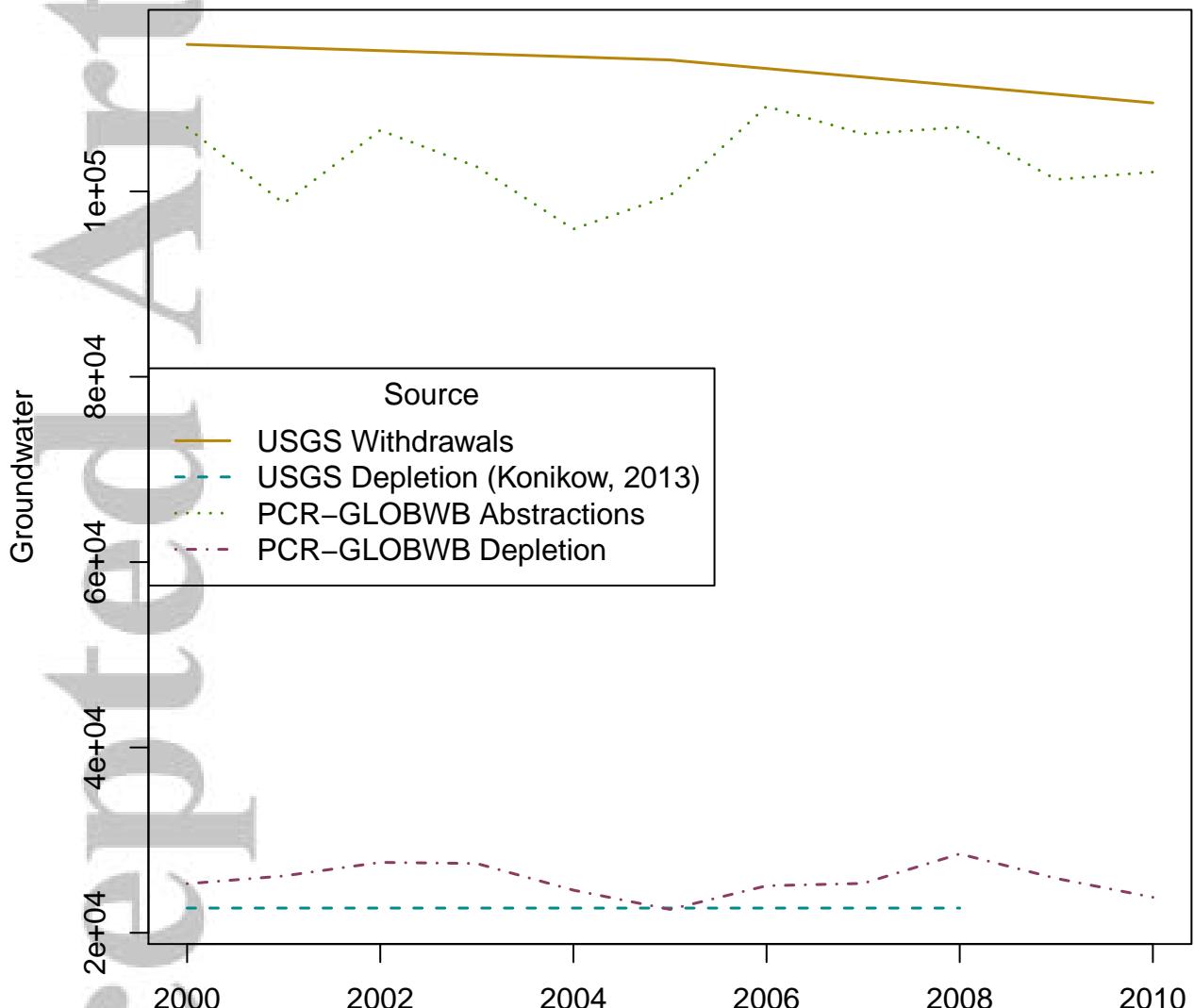
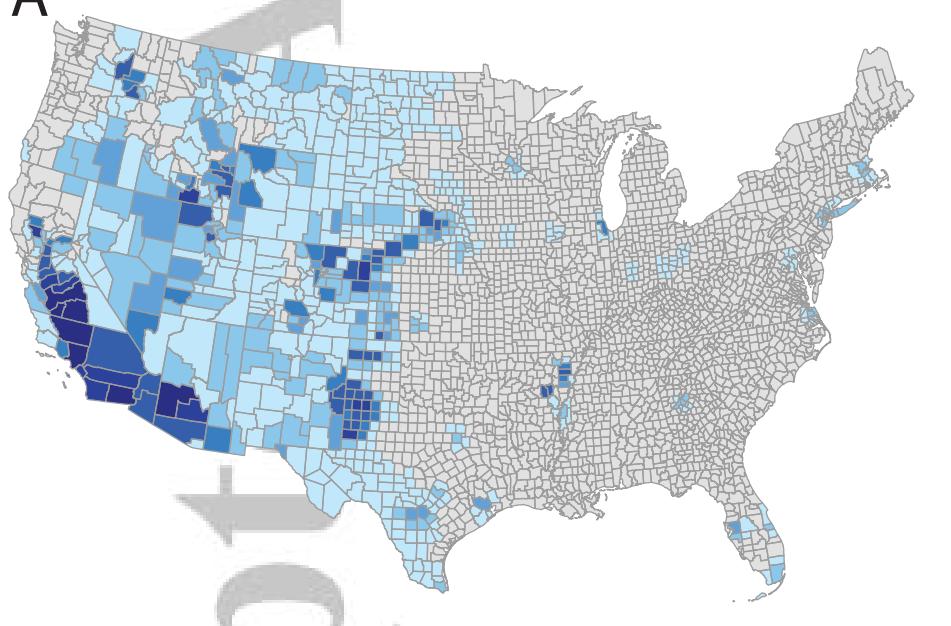


Figure 4.

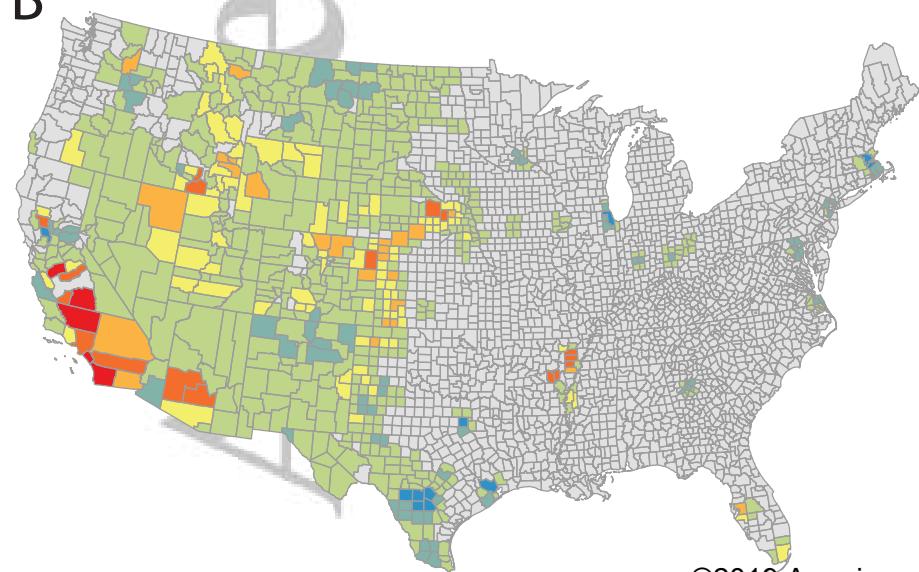
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A



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Figure 5.

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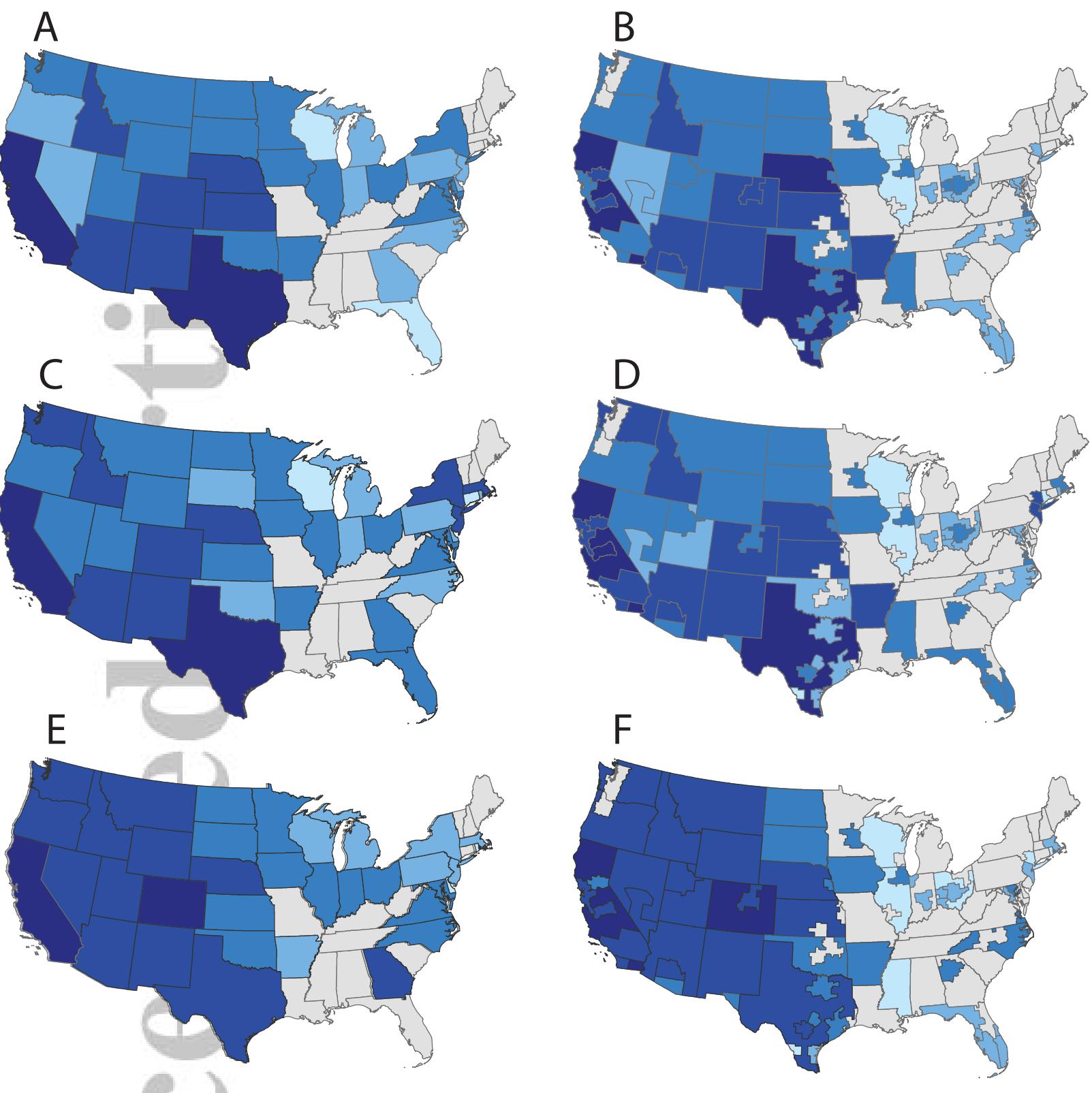
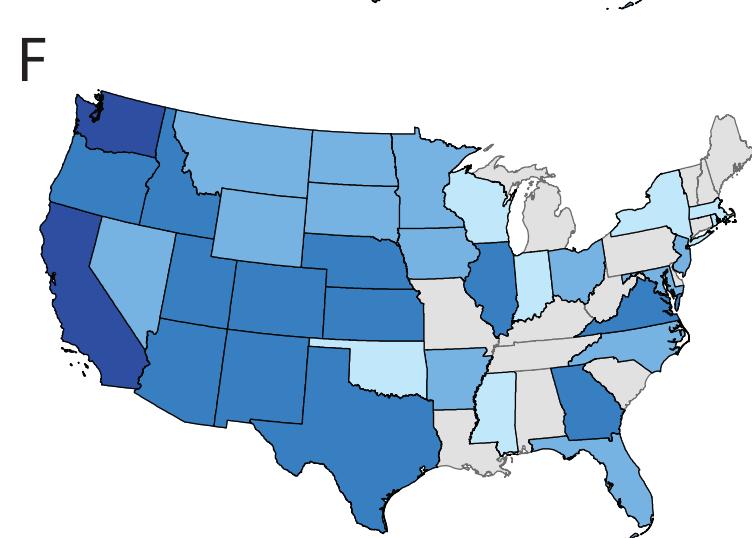
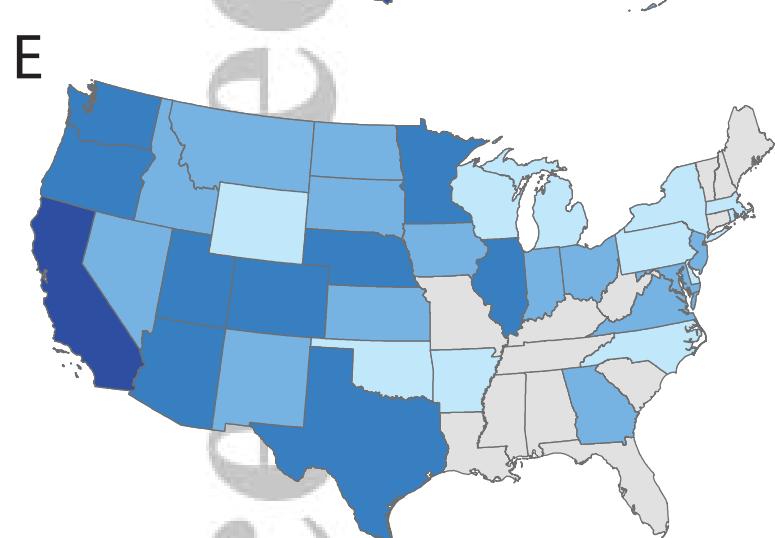
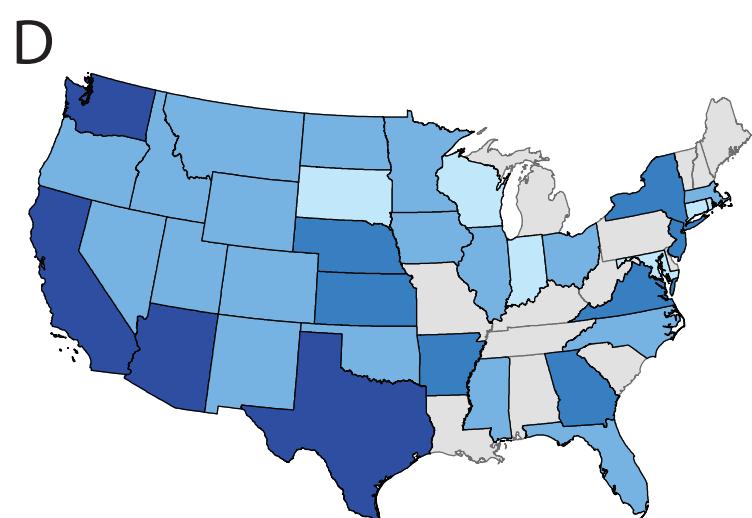
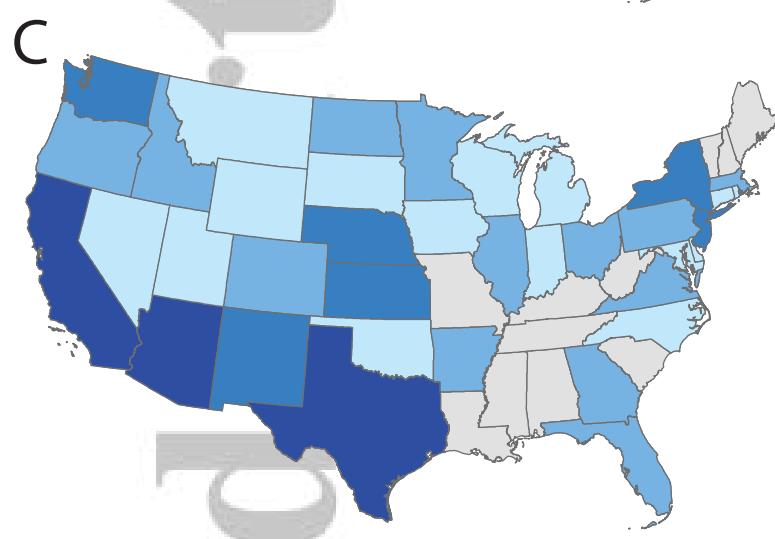
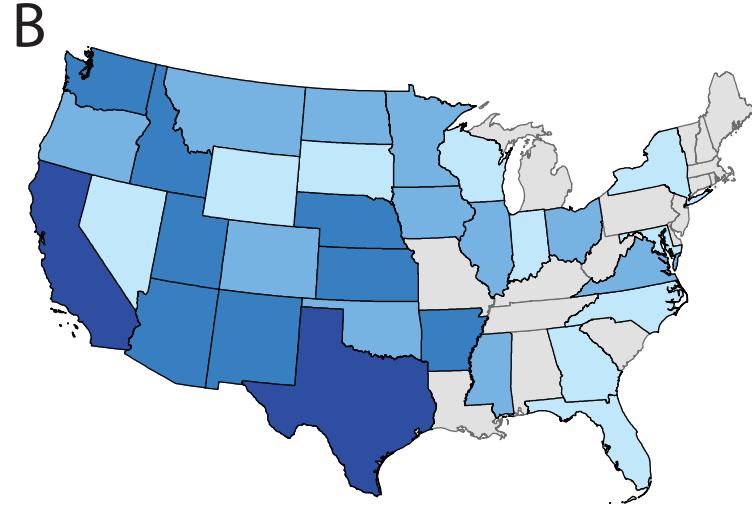
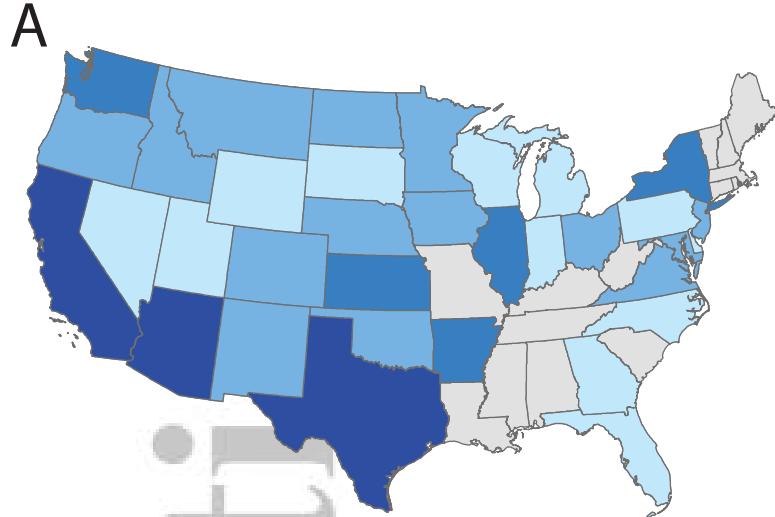


Figure 6.

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Figure 7.

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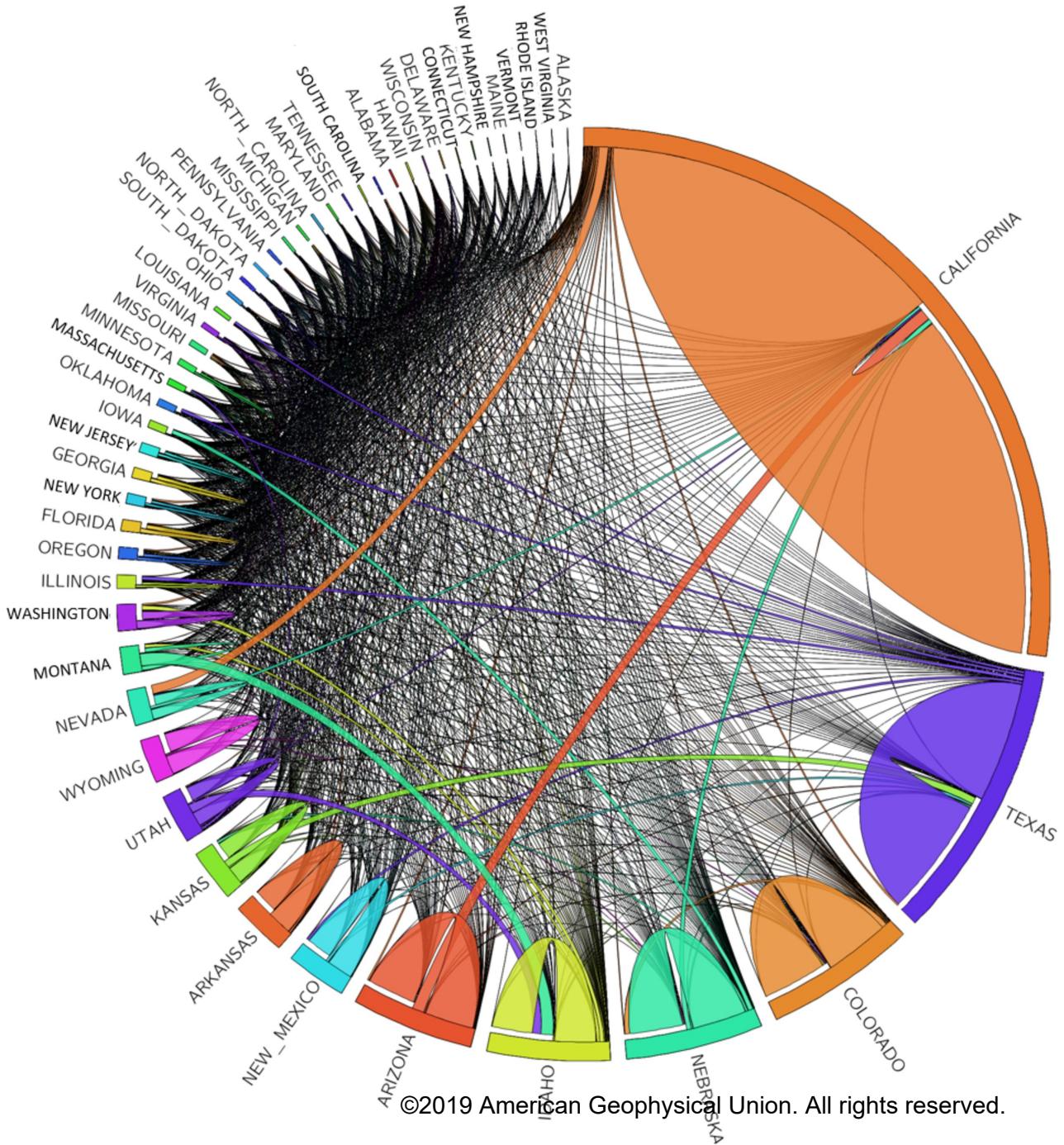
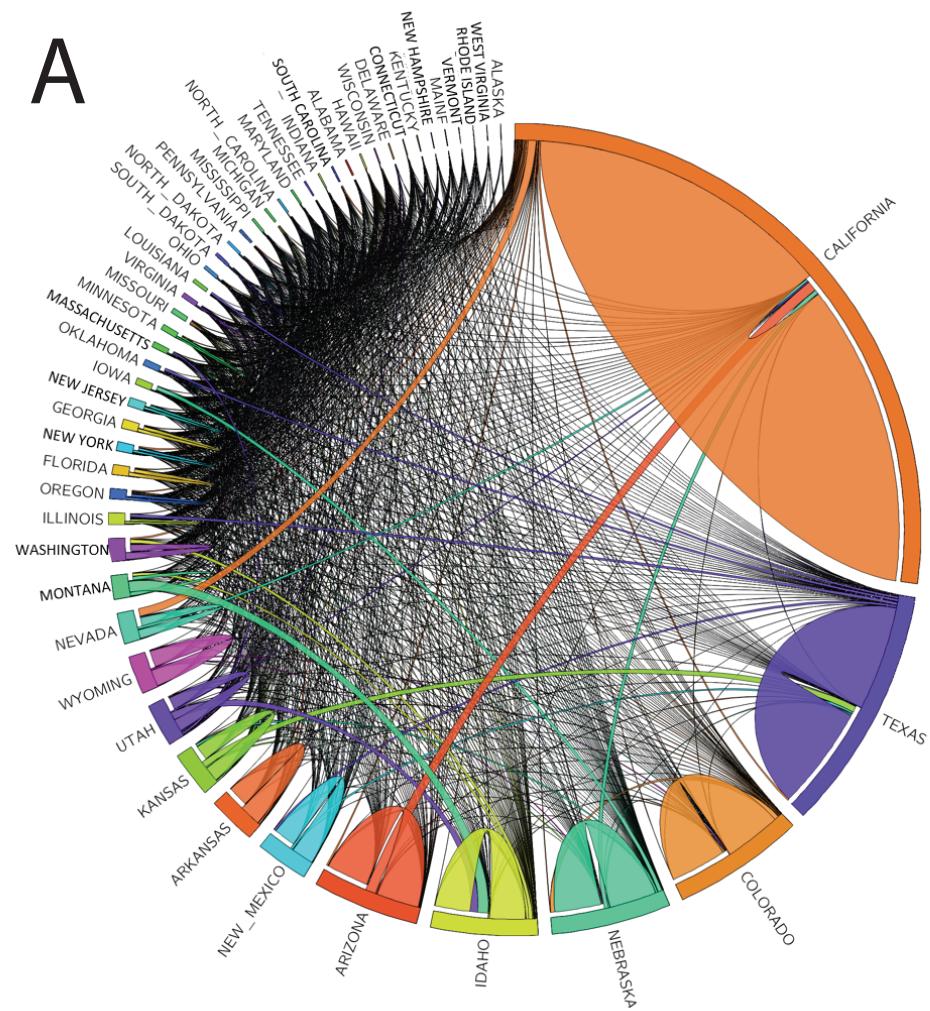


Figure 8.

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A



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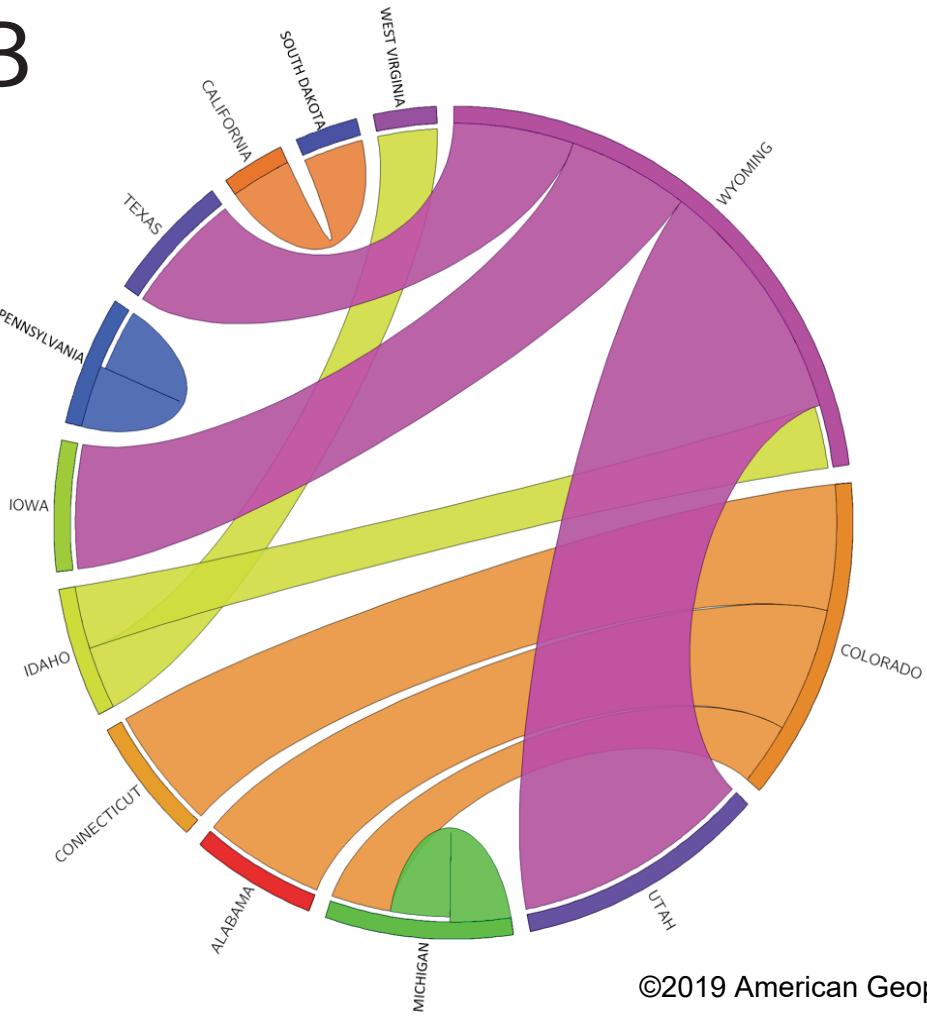


Figure 9.

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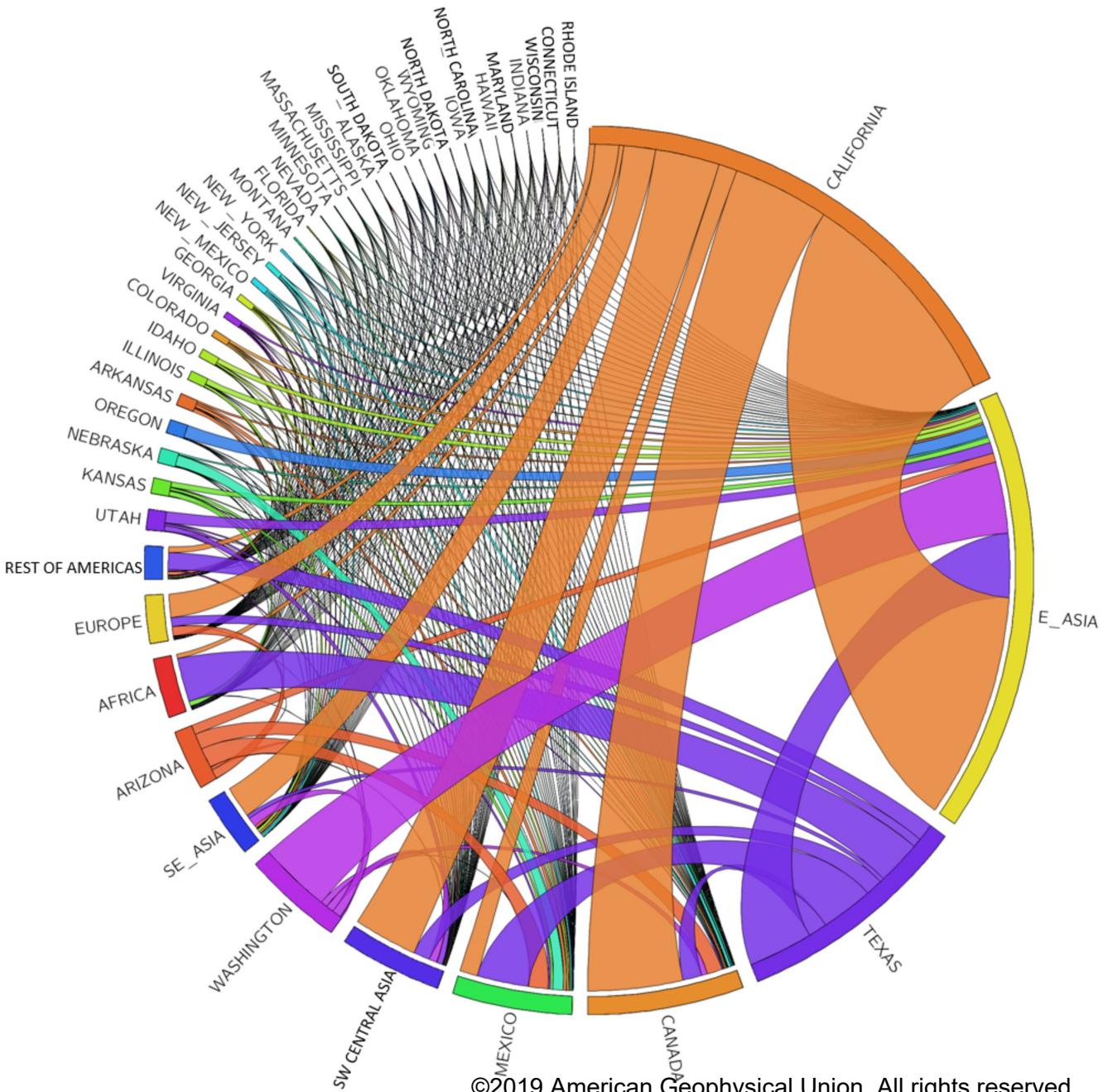
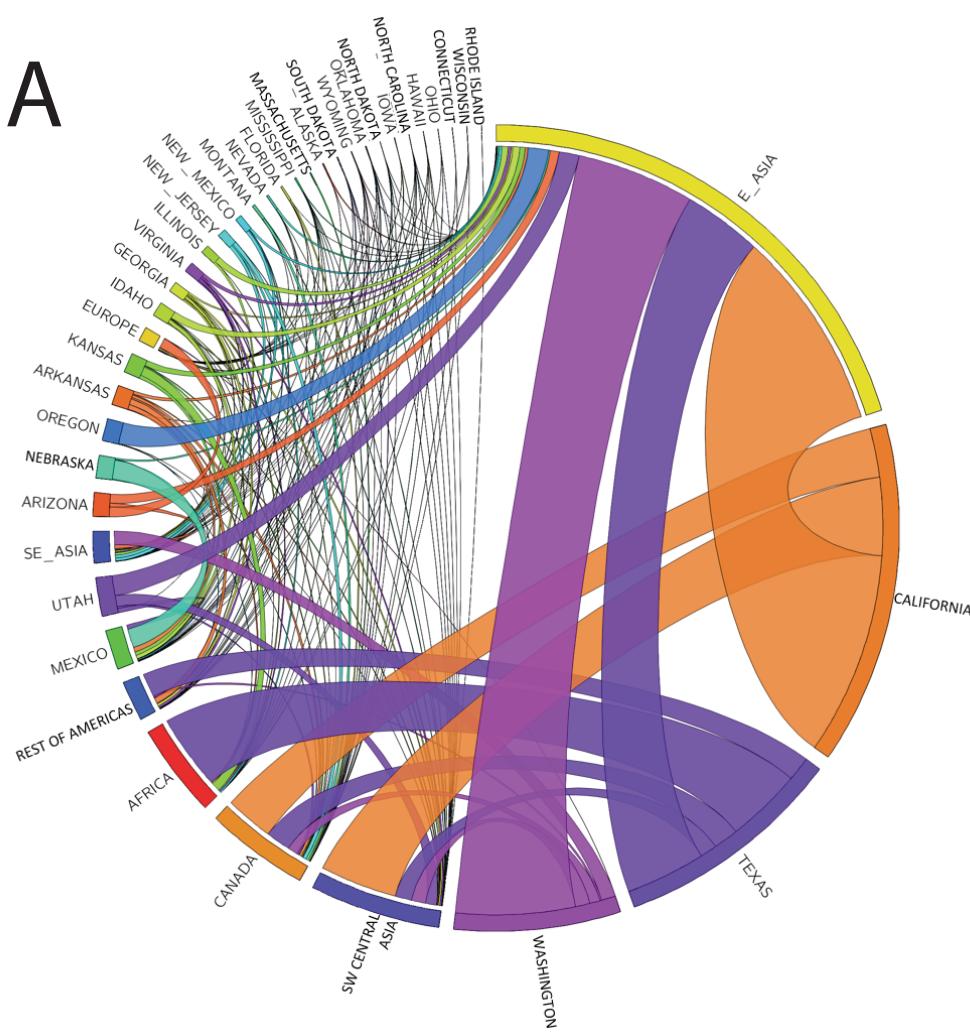


Figure 10.

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A



B

