Is the world running out of fresh water?

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Systematic global assessments of the world's evolving water resources have been an expanding area of work in the scientific literature in recent years (e.g., Rodell et al., 2018), but have thus far received little attention in economics. While the total quantity of water contained within the earth and its atmosphere is fixed over time, the water available *for human consumption* can evolve dynamically. Indeed, Tapley et al. (2019) estimate that recent decades have seen a substantial transfer of water mass from land, where most water is fresh and usable by humans, to the oceans, which are generally prohibitively expensive to desalinate for human use.

Even within the earth's land area, the welfare consequences of water resource depletion can differ substantially across space. Declining water availability is more likely to be harmful in regions that are highly populated, have low existing water resources, and are highly specialized or especially productive in agriculture, which is by far humanity's most water-intensive endeavor. Existing scientific literature has raised a range of concerns about the implications of trends in water resources for topics of first order importance in economics, including threats to global food supplies (Gleick and Cooley, 2021), and the role of global markets in mediating local water depletion (Dalin et al., 2017).

In this paper, we leverage a newly assembled collection of globally comprehensive geospatial and remotely sensed data from Carleton, Crews and Nath (2023) to establish a set of stylized facts about the evolution of water resources in recent decades and its potential implications for human welfare. We restrict our attention to arable land, given that agriculture accounts for ∼90% of human water use (Mekonnen and Hoekstra, 2011). We show that, on average, global arable land is *not* losing water resources over time.[1] Almost exactly equal shares of the world's arable land are losing and gaining water over the last two decades, and the net change in total water volume is almost exactly zero.

However, while there is no overall net trend in water available for global agriculture, some regions are experiencing rapid water loss that may be cause for concern. We show that the parts of the world losing water fastest are home to a disproportionate share of the world's population and exhibit low average rainfall and surface water availability. Reassuringly, these rapidly depleting regions have the least conducive soil and climate conditions for agriculture of any arable land on Earth, though they are farmed intensively enough to account for a substantial share of current global agricultural production.

Finally, we investigate the role of global trade in mediating the consequences of local water scarcity by computing global water use embedded in international agricultural shipments. We show that "virtual water" imports flow into some of the water-scarcest regions, preventing further water depletion. The contribution of this paper is limited to these descriptive facts, but we emphasize that recent advances in data availability and the pressing importance of this topic presents a range of opportunities for future work in economics on open questions about global policy, international trade, water resources, and welfare.

I. Global Trends in Fresh Water Resources

For much of human history, global data on water resources was limited to a patchwork collection of observations from wells and gauges measuring groundwater, rivers, and rainfall, all of which suffered from inconsistent geographic

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[1] Stable water supplies on arable land can be reconciled with large transfers of water from land to the oceans by evidence that the latter is dominated by melting ice from mountain ranges and glaciers (Chen, Wilson and Tapley, 2013).

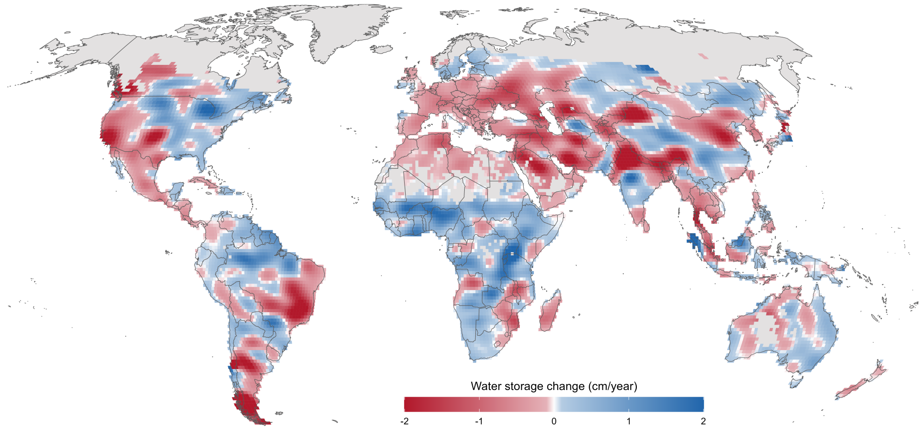

FIGURE 1. TRENDS IN TOTAL WATER STORAGE OVER ARABLE LANDS

Note: Annual changes in total water storage (TWS) over arable land during the Gravity Recovery and Climate Experiment (GRACE) satellite record (2003-2022). Colors indicate the linear trend in TWS (in centimeters of equivalent water height per year) for each $\sim 1^\circ$ equal-area grid cell. Trends are estimated via grid-specific regressions including monthly fixed effects. GRACE data are derived from the Goddard Space Flight Center (available here). All regions in grey indicate non-arable land.

and temporal coverage. In recent decades, remote sensing has enabled scientists to quantify water resources with unprecedented scale and scope. Perhaps most importantly, the Gravity Recovery and Climate Experiment (GRACE) uses satellite measurements of small changes in the earth's gravitational pull at each grid cell to provide a monthly measure of local changes in "total water storage" (ΔTWS), defined as the aggregate volume of water in a location, including groundwater, soil moisture, surface water, snow, and ice (Tapley et al., 2004). A substantial body of scientific literature validates the water volume interpretation of GRACE data, and also highlights important measurement limitations. We discuss these further in Appendix A.

Figure 1 plots the trend in TWS recovered by GRACE over the satellite record period of 2003-2022 for all arable land at the level of equal-area grid cells that measure $1^\circ \times 1^\circ$at the equator. We define arable land as any GRACE grid cell containing either cropped area or pasture land as estimated by Monfreda, Ramankutty and Foley (2008). The data show tremendous heterogeneity throughout the world, at both regional scales—with broad patterns of loss or gain across regions such as Europe and the Middle East—and at more local scales—with diverging subnational patterns within countries such as the U.S., India, and Australia.

We calculate that water losses and gains on arable land are in near perfect balance. Over the satellite record, 51.2% of arable acreage lost water, while 48.8% gained. Total losses slightly exceeded total gains, such that global arable land lost 105 km^3 per year, or 9 m^3/ha per year. For context, this rate of net loss amounts to 0.1% of average annual rainfall on arable land, or 1.2% of the estimated total water used in global crop production.

Note that this paper does not examine the relative contributions of various natural and anthropogenic factors driving observed trends, nor do we infer whether they are likely to continue in the future. Each of these topics is the subject of a growing scientific literature.

II. Regional Trends and Existing Scarcity

While water resources on arable land appear to be stable on average in recent decades, Figure 1 shows substantial losses in many regions. To the extent that the marginal value of water depends on its scarcity, such declines are likely to be most consequential for welfare in locations with low baseline water availability. To investigate the correlation between water losses and water scarcity, Figure 2a and Appendix Figure A1 map changes in total water storage against gridded estimates of groundwater table depth, rainfall, and surface water prevalence. The

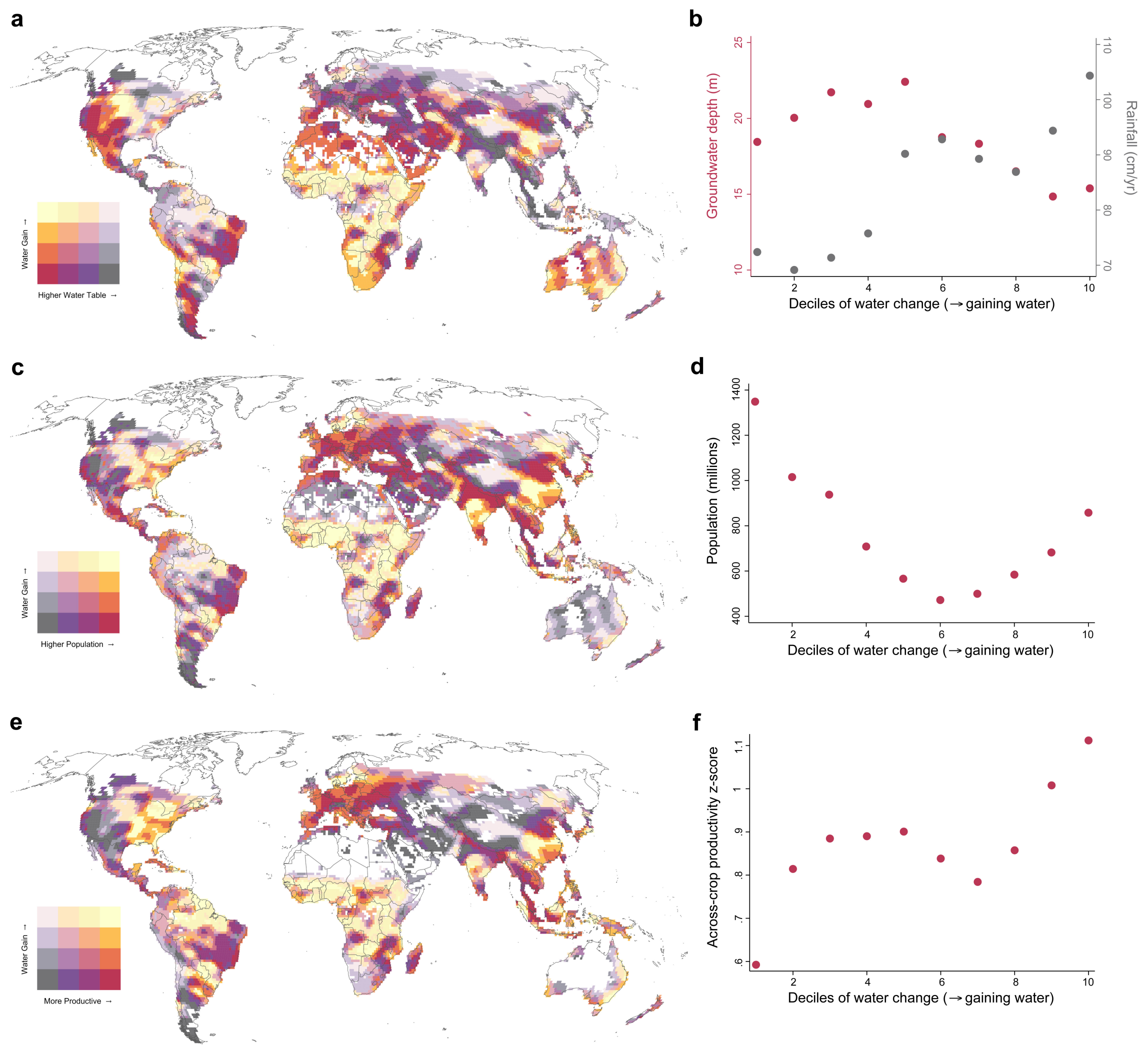

FIGURE 2. ECONOMIC CORRELATES OF WATER LOSS AND GAIN ON ARABLE LAND

Note: Maps show trends in total water storage from Figure 1 against: **a,** depth to groundwater from Fan, Li and Miguez-Macho (2013); **c,** total population from the Global Human Settlement Layer produced by the European Commission; and **e,** average agricultural productivity, assembled from GAEZ. Scatter plots show the following variables for each decile of total water storage trends: **b,** average depth to groundwater (pink) and average annual rainfall from the European Centre for Medium-Range Weather Forecasts Reanalysis v5 (grey); **d,** total population; and **f,** average across-crop agronomic productivity.

corresponding graphs to the right of each map plot each of these measures of water availability against deciles of trends in ΔTWS across global arable land on the x-axis. For context, regions in the leftmost decile are depleting water each year at a rate equivalent to 2-5% of the amount needed to grow barley, a relatively low water-intensity crop, on each arable hectare.

Together, the figures show some evidence that regions suffering rapid water declines are those that are already water scarce. Regions losing water fastest are those with the lowest annual average rainfall and prevalence of lakes, rivers, and streams. The pattern for groundwater table depth is more nuanced. Regions with the lowest water tables (furthest from the surface, and thus least easily accessible) are losing water on average, but the most extreme water losses are concentrated in places with average water table depth. Overall, we calculate that just 6.8% of the world's arable land is in the bottom quartile of both groundwater availability and trends in water resources. These regions with low existing stocks and rapid depletion, which include large parts of the Middle East, the southwestern United States, northern China, eastern Brazil, and southern Argentina, are likely those that suggest the greatest cause for concern.

III. Population Exposure to Water Trends

Water depletion also has more serious welfare implications if it affects more people. Figures 2c–d show the global population's exposure to water resource trends by overlaying trends in the GRACE data with gridded population estimates. The results show an extreme concentration of the global population in the parts of the world losing water most rapidly, along with a moderate concentration in regions gaining water. Over 1.3 billion people live in the most rapidly depleting decile of the world's arable land, nearly three times as many as in deciles with stable water resources. The map shows that this pattern is driven largely by parts of northern India and northeastern China, some of the most densely populated locations on earth.

Encouragingly, employment in these rapidly depleting regions is not especially concentrated in agriculture, by far the most water-dependent sector of the economy. Using country-level data from the FAO, we calculate that the average agricultural employment share for grid cells in the bottom decile of ΔTWS is 24%, below the global average and far below the 36% share in grid cells gaining water fastest. Moreover, Appendix Figure A2 shows that the world's population is disproportionately concentrated in arable regions with more rainfall and shallow groundwater tables, suggesting population density correlates differentially with static versus dynamic measures of water availability.

IV. Agricultural Exposure to Water Trends

Given that the overwhelming majority of human water consumption occurs in agriculture, the welfare consequences of global depletion depend on the degree to which it is concentrated in especially agriculturally productive regions. To investigate this, Figures 2e-f overlay trends in the GRACE data with gridded estimates of potential crop productivity from the FAO's Global Agro-Ecological Zones (GAEZ) database. We construct an aggregate index across the 38 crops in GAEZ that computes the z-score of each crop's productivity in each grid cell relative to the global distribution, and then takes the average across crops weighting by cropped area estimates from Monfreda, Ramankutty and Foley (2008).

The results in Figure 2f show a clear pattern in which the parts of the world losing water fastest have the lowest potential crop yields. The map shows that these relatively unproductive agricultural regions with rapid depletion include Iran, Saudi Arabia, Tibet, and northwestern China. Further, Appendix Figure A4 shows that a similar pattern of low productivity in depleting regions also holds for rice, but not for wheat, which are two of the most water-intensive staple crops. However, potential productivity and realized production can differ substantially; we use gridded GAEZ estimates of actual production to calculate that the decile of most rapid water loss currently grows 19% of global cereal tonnage, suggesting that current production patterns may need to shift to address possible future water shortages (see Appendix Figure A7).

V. Water Scarcity and Virtual Water Trade

The consequences of the evolving local water scarcity documented above are likely to depend critically on the degree to which water can be sourced from abroad. Although water itself is rarely traded because of its low value-to-weight ratio, its service as a factor of agricultural production can be exchanged indirectly through trade in agricultural goods. The scientific literature typically refers to this as "virtual water trade" following Allan (1998).

Figure 3a maps country-level net virtual water imports from crops and crop-derived food commodities in 2009. Most of Africa and the Middle East are net importers of virtual water, but the largest net importers are concentrated in East Asia (China, Japan, South Korea) and Central Europe (the Netherlands, Germany, Italy). The largest net exporters are the U.S. and Brazil, both major agricultural producers, followed by other large producers in the Americas (Argentina and Canada) and South Asia (India).

In the driest regions, virtual water imports seem to play an indispensable role in offsetting local water scarcity. Figure 3b shows that, on average, regions with the lowest rainfall rely most on imports for their water-intensive consumption. But, in general, water does not necessar-

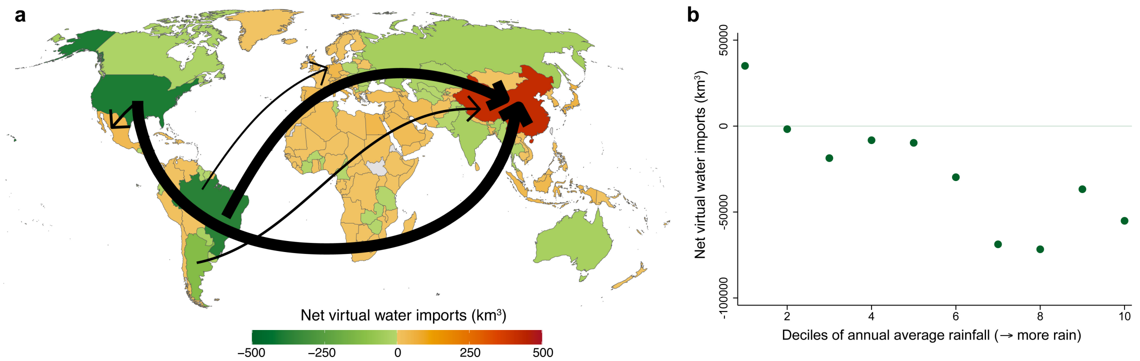

FIGURE 3. GLOBAL VIRTUAL TRADE IN AGRICULTURAL WATER

Note: Map colors in **a** show estimates of imports minus exports of agricultural "virtual water", or water consumed in the production process of agricultural goods. Positive values indicate imports of water embedded in traded agricultural goods that exceed exports. The five largest bidirectional flows are shown with arrows, where arrow width indicates flow magnitude. Plot in **b** shows average net virtual water imports for each decile of annual average rainfall over arable lands.

ily flow from water-abundant to water-scarce regions. Differences in relative agricultural productivity and relative arable land endowments can cause virtual water to flow from scarce regions to abundant ones. How exactly trade can exacerbate or mitigate these regional inequities in water resources is an important topic we study in Carleton, Crews and Nath (2023).

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