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Water resources in Saudi Arabia: trends in rainfall, water consumption, and analysis of agricultural water footprint

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Saudi Arabia is one of the most arid countries in the world. Thus, freshwater availability and consumption are of crucial importance for the fast-growing population subjected to an escalating heat stress from climate change. We provide an overarching view of water resources in Saudi Arabia, in terms of supply, demand, vulnerabilities, and the associated implications on food supply and security. To estimate the effects of climate change on natural water supply, we use ERA5 for the reliable and complete statistics of the long term-precipitation (1950-2021) trends across the Kingdom's territory. ERA5 is the latest generation of the reanalysis of global climate from the European Centre for Medium-Range Weather Forecasts. The average annual precipitation is about 50 mm/year and does not satisfy the freshwater needs of the country. Energy-intensive desalination, driven by fossil fuels, meets two thirds of municipal freshwater requirements, while non-renewable "fossil" groundwater addresses most of agricultural consumption needs. Total freshwater use has decreased in recent years due to a significant reduction of water use by agricultural sector. Nevertheless, this sector still accounts for 67% of the total freshwater consumption and provides a third of the country's food supply. To understand efficiency of freshwater use in the agricultural sector, we have developed a novel methodology that allowed us to estimate the country-scale water consumption associated with crop production. Results indicate that water requirements for crop cultivation in Saudi Arabia are up to three times the global average. Date and cereal production consumes almost two thirds of the total freshwater supply, while mass production is dominated by forage crops.

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INTRODUCTION

Saudi Arabia has one of the fastest rates of population growth, driven by a spur in economic development, wellbeing and access to cheap and abundant energy. Simultaneously, the demand for resources grows, including life-essential water. Freshwater resources are finite on the Earth, and of special significance for Saudi Arabia, where permanent water bodies are absent, replenishable reserves are small, and access to them extensively depends on the availability of fossil fuels, another finite and non-renewable resource. Freshwater production is energy-intensive in this arid region, consuming up to 9% of electricity in Saudi Arabia[1], which is generated entirely from oil and gas[2]. Water requires energy for pumping from deep aquifers and for desalination[3]. Paradoxically, in this water scarce environment[4], access to freshwater has been easy in modern Saudi Arabia. The government subsidizes water desalination, making it cheap and accessible to the population. Agricultural sector is also well-supported with low water tariffs[5]. Availability of water allows agriculture to play an important role in the country's economy, but sustainable water use practices are often lacking[6].

Current abundance of resources cannot persist into the future for an extensive period of time. Non-renewable fossil ("fossil" groundwater is confined in the sandstone and limestone formations up to 300 m thick, and 150–1500 m deep. Most of this fossil groundwater in Saudi Arabia is stored in principal aquifers in the eastern and central parts of the country. Fossil water aquifers are nonrenewable and were formed approximately 10–32 thousand years ago[7]) groundwater resources are decreasing[8], while the demand for water is escalating due to population increase along with the factors related to climate change. Saudi Arabia has one of the fastest rates of temperature increase[9], and heat extremes significantly intensify with each passing decade[10,11]. A warmer climate increases the demand for fresh water used in irrigation, heightens thermal stress and decreases crop yields[12,13] by 7–25% per each one-degree Celsius increase in temperature[14].

In order to develop policies aimed at improving sustainability of water supply, it is crucial to evaluate current state of water use at the national level and identify areas where efficiency can be improved. Several previous studies have reported water resources and consumption trends in Saudi Arabia[14–19]. It has been noted that the improvements of water resource use need to include a reduction in consumption by agriculture that accounted for 87% of the country's water use in 2010, with 31% of agricultural water use dedicated for forage crop cultivation[4]. Saudi Arabia's water sector is unique and different from other countries, where many studies exist. First, it is characterized by the nearly totally irrigated agriculture and by desalination of potable water. This uniqueness makes it hard to compare agricultural practices in Saudi Arabia with those in other countries. Second, lack of publicly available data complicates water use statistics.

An updated analysis is needed to account for significant changes in resource use, and the various incentives introduced by the government within the past few years[20,21]. In addition, new datasets on precipitation and water use have also been released[22,23], and inclusion of the most recent data is crucial to obtaining relevant results. To the best of our knowledge, there are no recent public reports that summarize countrywide water consumption in Saudi Arabia and focus on agricultural sector, which is responsible for two-thirds of freshwater use in the Kingdom[24].

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There are multiple publications that focus on evapotranspiration of crops in Saudi Arabia[25–27]. There are also studies that show the total water requirements of various crops, with the majority focused on date palms, the main non-forage crop. Estimates of date palm tree water requirements vary from roughly 53 m^3 year in Qatif[28], to 136 m^3 in Najran[29], and 195 m^3 in the central region (Qatif is a coastal city and oasis located 30 km north of Dammam. Najran is located in the south-western part of the country. It is also famous for its underground water resources and has a rich agricultural sector. The central region of Saudi Arabia is located in the geographic center of the country and encompasses the capital city, Riyadh (Fig. 2a))[30]. Assuming that a date palm tree produces roughly 50 kg of fruit per year[31], this translates into 1–4 m^3 of water per kg of produce. Water use depends on the geography, seasons and irrigation types. Date palm trees require nearly four times more water in August than in January[25]. The traditional surface irrigation method is more water intensive than the more recently developed techniques. Subsurface drip irrigation can decrease water use significantly, to less than 40 m^3/palm tree/year[32].

There are no available data on the average agricultural sector water intensity and water use per crop type in Saudi Arabia. Our work addresses this gap by inferring those estimates based on the available data on global water footprint of crops, and on water use by agricultural sector in Saudi Arabia. Moreover, we provide a detailed analysis of precipitation, water use per sector, and agricultural productivity in Saudi Arabia with the emphasis on food security.

METHODS

We extracted the precipitation data from ERA5, the latest generation of the reanalysis of global climate from the European Centre for Medium-Range Weather Forecasts (ECMWF)[22]. Reanalysis data provide the most complete picture currently possible of past weather and climate. It is a blend of observations with the past short-range weather forecasts rerun with modern weather forecasting models. While observations alone, either satellite- or ground-based, cannot provide a complete and accurate picture of the state of the regional climate system, reanalyses fill the gaps in the observational records and improve data quality. The ERA5 reanalysis datasets are globally complete, consistent in time, and often referred to as 'maps without gaps'[33,34]. The data are provided on a regular 0.25° latitude-longitude grid. The Saudi-specific data (Fig. 2b) average those satellite data points that fall within the boundaries of the country. We also corrected for the decreasing distance covered by one degree of latitude as one moves towards the poles. Finally, we compared the ERA5 data with the Ministry of Environment, Water and Agriculture (MEWA) data for 2010–2019, obtained via the General Authority of Statistics (GASTAT)[23].

We accessed historical crop production data for Saudi Arabia from MEWA's statistical reports in 2018 and 2020[24] for 2015–2020, excluding 2019, because no data were available for that year, and the Food and Agriculture Organization of the United Nations (FAO, ref. [35]) for 1961–2020. The MEWA and FAO statistics have one substantial difference – the FAO data do not include statistics of forage crops, while the MEWA data do. Total crop production in Saudi Arabia was reported as 6.1 million metric tons by the FAO as opposed to 10.9 million metric tonnes reported by MEWA in 2020. Forage is a major crop type produced in Saudi Arabia and accounted for 42% of mass production in 2020. Data on production of non-forage crops are similar yet not identical between the two reporting bodies. For further calculations we used the 2015-2020 MEWA data because they are the primary source.

Methodology to estimate water footprint of crops

We calculated both the theoretical and actual water consumption required to grow crops in Saudi Arabia for the period 2015–2020. The theoretical value (Eq. (1)) is based on the MEWA crop production data and the global average total water footprint (total footprint includes green, blue, and gray water footprint[36]) values for these crops. Hereafter, the water footprint, is obtained from Mekonnen and Hoekstra (2010, 2011)[36,37] (Fig. 1).

The summary tables that contain the MEWA data on crop production and the calculated theoretical water footprint values are in the Supporting Online Materials (Tables 1 and 2 for the years 2015–2018 and 2020, respectively). Actual water consumption for crop production is based on the MEWA data for agricultural water use. It is important to mention that total agricultural water use includes both regenerated and non-renewable water. The MEWA reports for 2010–2019 contain only the non-renewable water use. To obtain the total value, we assumed that the regenerated water accounts for 20% of total agricultural water use. This fraction was obtained from the 2020 data (Fig. 4, ref. [24]). Next, we factored out the water *not* used for crop production. This includes water for fish, meat, dairy, and egg production. KAPSARC (King Abdullah Petroleum Studies and Research Center)[4] estimated this figure to be 6% of total agricultural water use in 2012, or approximately 1320 million m^3. However, there are no publicly available equivalent data after this time, and therefore we have assumed this fraction to be constant.

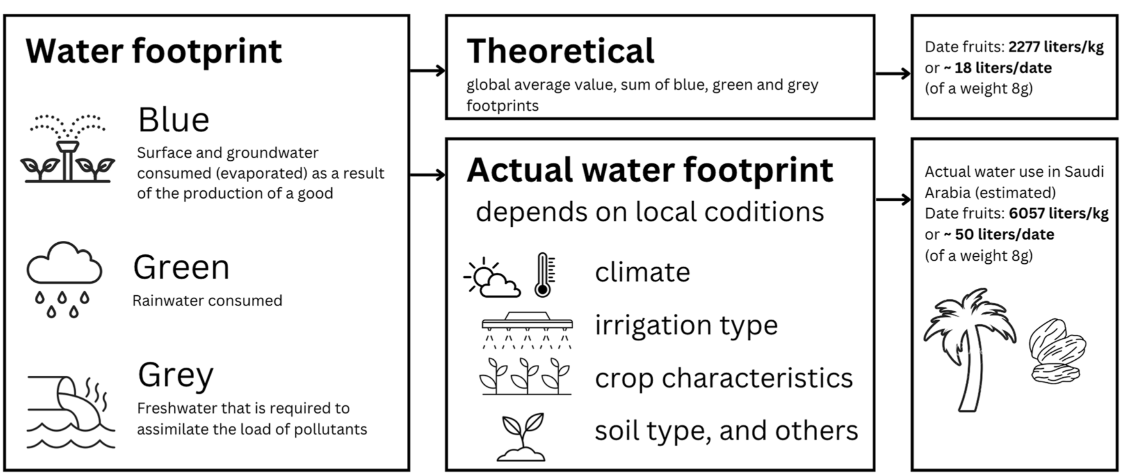

Fig. 1 Water footprint of crop production is based on the data from ref. [36] and estimates by the authors. Actual water footprint in Saudi Arabia comprises blue and grey water footprint, while the green one is neglected because of almost no rainfall.

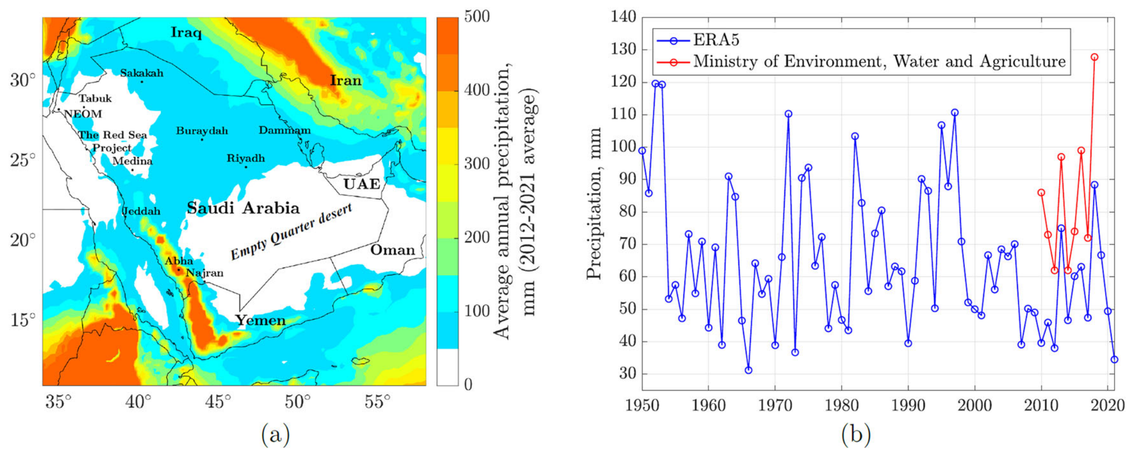

Fig. 2 The average annual precipitation and annual rainfall in Saudi Arabia. a The 2010–2019 average precipitation (ERA5). **b** The 1950–2020 annual precipitation in Saudi Arabia (ERA5, MEWA). Mean: 65 mm/year, standard deviation: 21.6 mm/year (ERA5 1950–2021 data).

Fig. 6b shows the obtained value of total agricultural water use associated with crop production. This value is also used to obtain the water use per unit mass of agricultural produce (Fig. 10a, red curve). Table 3 in the Supporting Online Materials summarizes agricultural water use for the years 2010–2020, based on the MEWA data and the assumptions mentioned above. This table includes total agricultural water consumption, non-renewable and renewable water use, water use in crop cultivation, and the water consumed for meat, fish, dairy and egg production.

We then compared the actual water consumed in Saudi Arabia for crop production with the average theoretical value. We assumed that it takes X times more water to grow crops in Saudi Arabia than the global average. This X is the same regardless of crop type, but it changes with time. To calculate X, we divided the annual domestic agricultural water use for crop production by the theoretical water footprint (Eq. (2)). Thus, X varies between 2.6 and 2.9 for the years 2015–2018 (Fig. 7b and Table 4 in the Supporting Online Materials).

$$\textit{cumulative global average water footprint of crops produced in Saudi Arabia, liters} = \sum_{i=1}^{N}(\textit{crop}_i \textit{ water footprint , liters/kg} \cdot \textit{annual production of crop}_i\textit{, kg}) \tag{1}$$

$$X = \frac{\textit{annual agricultural water use for production of crops in Saudi Arabia, liters}}{\textit{cumulative global average water footprint of crops produced in Saudi Arabia, liters}} \tag{2}$$

RESULTS AND DISCUSSION

Water resources

Saudi Arabia is one of the most arid regions of the world. Average annual precipitation is less than 100 mm per year across most of the country's territory, and varies from as low as 20 mm/year in the Empty Quarter desert to 500 mm/year in the mountainous regions in southern Saudi Arabia (Fig. 2a). Average annual precipitation over the past 71 years is shown in Fig. 2b. The change in precipitation over that period is insignificant, consistently with the previously reported results[14]. Between 2010–2019, average precipitation across Saudi Arabia varied from 40 to 90 mm/year based on the ERA5 data, and from 60 to 130 mm/year based on the MEWA data obtained via GASTAT[23]. The discrepancy between these two datasets is caused by the different calculation methodologies: ERA5 is the global reanalysis dataset and encompasses the entire territory of the country, including the vast Empty Quarter desert, whilst MEWA uses local data from the sparse meteorological stations located mostly near cities.

Water consumption

With almost no rainfall, there are no permanent swamps, rivers or lakes in the country, and the few wadis (wadi is the Arabic term traditionally referring to a river valley. It may refer to a wet riverbed with varied water level depending on the rainfall season[38]) and water dams cannot support the Kingdom's freshwater needs. Energy-intensive desalination driven by fossil fuels meets two thirds of municipal demand for freshwater, while non-renewable groundwater addresses 80% of agricultural consumption needs. Water use has been steadily growing since 2010 and peaked in 2015 at 24.8 billion m^3 (Fig. 3a), or 30 billion m^3, if regenerated water is included. Water use in 2015 was nearly 150% of the 2010 value. After 2015, the total consumption started to decline due to the substantial decrease of agricultural water use, particularly after 2019, following the initiation of the government program to decrease forage cultivation[24]. Although agricultural sector water use has been declining, the municipal and industrial demand accelerates each year due to the vast economic development and increase in population. The water use in Saudi Arabian municipalities has been increasing by 4.5% per year, while the volume of treated wastewater has been rising at a faster rate of 5.5% per year. However, in 2020, only half of the total volume of water used by municipalities was treated. The share of treated water was 52% of the total domestic consumption in 2020, compared with 45% in 2010 (Fig. 3b). It is important to emphasize that only 18% of treated wastewater is further reused (2020)[24].

Presently, the total amount of water consumed in Saudi Arabia is nearly 16 billion m^3 (2020), or 444 m^3 per person per year (assuming the population was 36 million people in 2020[39]) (1216 liters per person per day), with 67% attributed to agricultural consumption, 23% to municipal use, and the remainder used by industry (Fig. 4).

Agricultural water use, production, and efficiency

Despite the hot desert climate, Saudi Arabia has a strong agricultural industry, owing to the rich but non-renewable groundwater resources[40]. At present, agriculture accounts for 67% of the Kingdom's total water use, or 62% if the regenerated agricultural water is excluded (Fig. 3a). Eighty percent of agricultural water consumption, or 8.5 billion m^3/year, comes from nonrenewable groundwater resources (Fig. 4). The remaining 20% is regenerated water, or 2.2 billion m^3/year (2020)[24]. Prior to 2019, agricultural water use was nearly double the amount in 2020, and peaked at 24.8 billion m^3/year in 2015. This sector accounted for 84% of Saudi Arabia's total water use (excluding

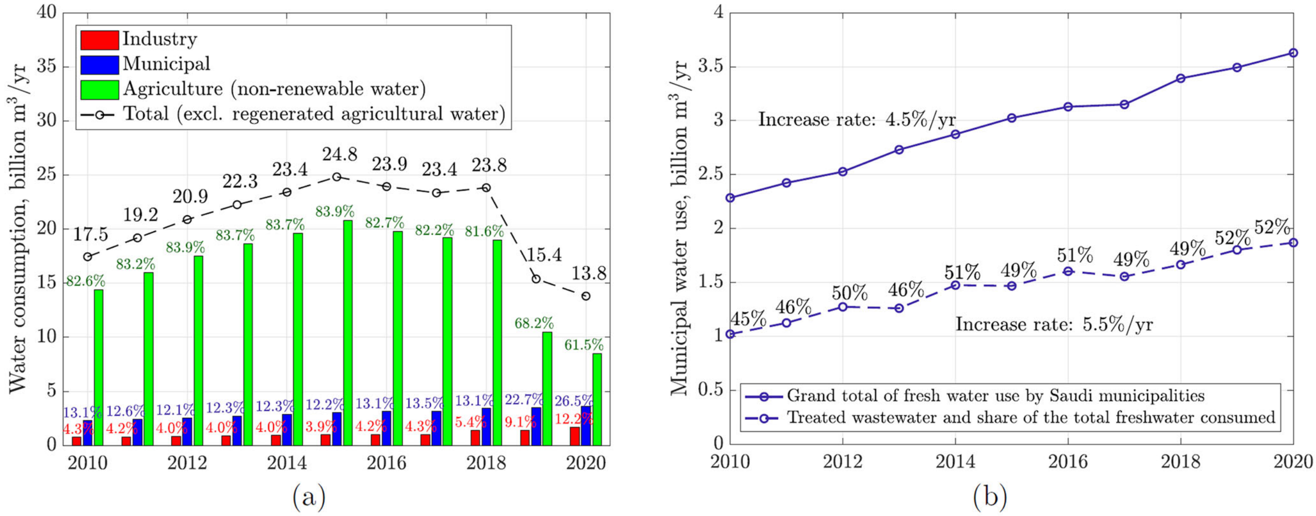

Fig. 3 Water consumption and treated wastewater share in Saudi Arabia between 2010 and 2020. a Water consumption by sector, excluding regenerated water use in agricultural sector. **b** Wastewater treatment share of total municipal water use. Data source: MEWA.

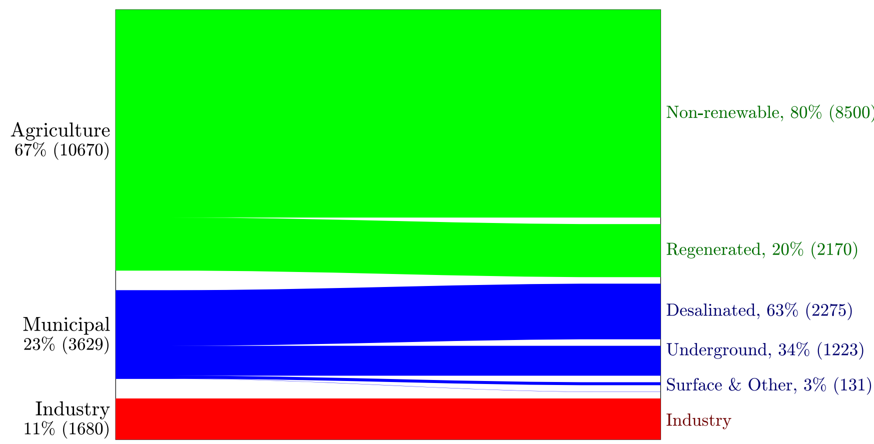

Fig. 4 Distribution of water uses in Saudi Arabia. Water use shares in Saudi Arabia, 2020. Total: 15979 million m^3 (MEWA)

regenerated water). The sharp decline in non-renewable water use is due to the program to decrease forage cultivation[24].

Agricultural production in Saudi Arabia started to grow rapidly since the early 1980s, peaked in 1994 at 8.2 million tonnes of non-forage crops, and was dominated by cereals (Fig. 5). After a decline in production, the second peak occurred in the mid-2000s, at approximately 7 million tonnes per year. Since the 2010s, the production of water-intensive cereals has declined in Saudi Arabia, while production of fruits and vegetables has simultaneously increased (Fig. 5). The year 2020 was the third historic peak in production of non-forage crops at 6.1 million tonnes - the highest value since 2005 - despite the abrupt decline in agricultural water use in the same year. Vegetables were the largest non-forage crop type in 2020, followed by dates, cereals and other fruits[24]. Forage was the main crop type, accounting for 42% of mass production (Figs. 6a and 7). However, mass production values do not represent water use per crop type, as different crops have different water footprints. For example, per unit of mass, forage has a smaller water footprint than non-forage crops, and accounts for only 12% of the total annual agricultural water use. By contrast, cereals and dates have a relatively high water footprint. Date production uses 38% of agricultural water and cereals account for 24%, while their shares in mass production are 14% and 12% respectively (Fig. 6b). Figures 8 and 9 summarize the top 15 crops grown in Saudi Arabia with the highest water footprint and total theoretical water use. The actual water consumption is higher than its predicted theoretical value because of the hot desert conditions. To calculate the actual water consumption, the theoretical value is multiplied by the X from Eq. (2) for a given year (Fig. 10b).

The calculated theoretical water footprint of the agricultural sector in Saudi Arabia, based on the global average values[36,37], was about 600 liters per kilogram of produce between 2015 and 2018. As previously discussed, the production of forage crops decreased in 2020, while the production of more water intensive fruits and vegetables increased. These changes in crop production led to an increase of the average water footprint value to 860 liters/kg in 2020 (Fig. 10a, blue curve). Actual water consumption, based on data for water consumption associated with agricultural production varied between 1450 and 1650 liters per kilogram of produce between 2015 and 2018 (Fig. 10a, red curve). The share of actual to theoretical water consumption, X, was between 2.6 and 3 over the same time period (Fig. 10b). Interestingly, the value of the actual water footprint drops significantly in 2020 based on MEWA's predicted value of actual agricultural water consumption. This may be due to an underestimation of actual water use in 2020 by MEWA (Fig. 3). We estimate the projected actual water footprint for 2020 as 2265 liters/kg based on the 2016–2018 average X value. For cereals that take a substantial proportion of agricultural production in Saudi Arabia, the estimated global average water footprint is 1644 m^3/ton, and it is 2991 m^3/ton for the Middle East (1.8 times the global average)[36]. Our estimate of this value for Saudi Arabia, 4274–4884 m^3/ton is based on our conclusion that it takes 2.6–3 times the global average of water consumption to produce crops in Saudi Arabia (2015–2018 data). We conclude that the local environmental factors play a role in this large discrepancy. Another contributing factors are water usage, water losses during transportation (factored in the data that we used), and lack of penetration of novel irrigation techniques.

IMPLICATIONS FOR FOOD SECURITY

Agricultural productivity is inextricably connected with food security. Small-scale agriculture might be sustainable[41], but in general modern industrial agriculture is thermodynamically unsustainable[42], regardless of water problems.

Despite a strong agricultural sector, the Kingdom's production volumes do not meet domestic demand. The share of local production in the mass food balance is 33%, while imports make up the remainder. The term 'food balance' in this context refers to the total amount of domestically produced and imported food. The domestic supply (locally consumed food) is 89%, with the remaining 11% exported.

Substitution of local production with imports is a contentious issue. On the one hand, food imports allow the preservation of non-renewable water resources and enable the population to access a varied diet. On the other hand, a strong reliance on imports jeopardizes the country's food security. This takes on particular significance during times of political unrest, droughts and flash flooding, which often disrupt global crop supplies[43]. These events are predicted to intensify with the accelerating climate change. Hence, even though the agricultural sector in Saudi Arabia has its own truly unique features such as high water intensity and reliance on depletable fossil water, its importance for food security in an arid region that hosts tens of millions of people is hard to overestimate. In this context, careful resource management is essential. This involves prioritization of local production of perishable crops, such as vegetables and fruits, optimization of irrigation water use, expansion of greenhouse environments,

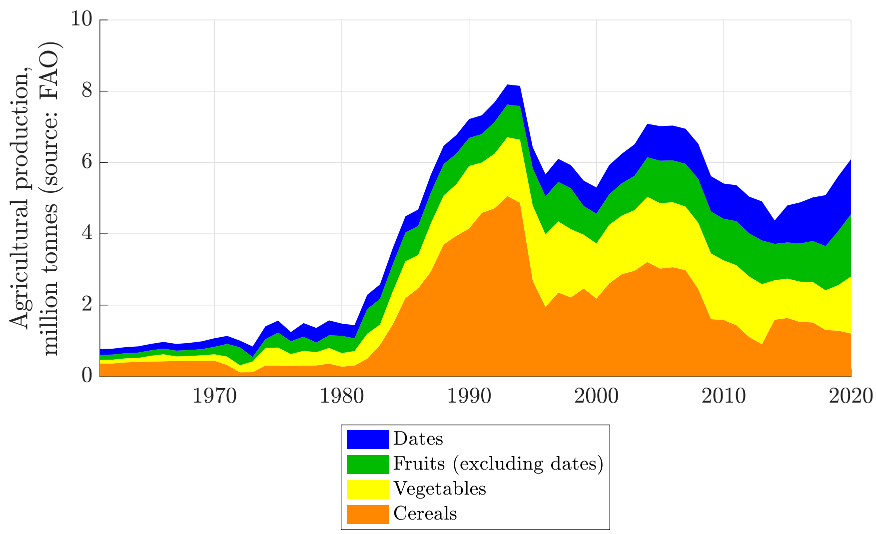

Fig. 5 Agricultural production from the FAO data (excluding forage crops). Cereal fraction includes minor quantities of seeds and pulses.

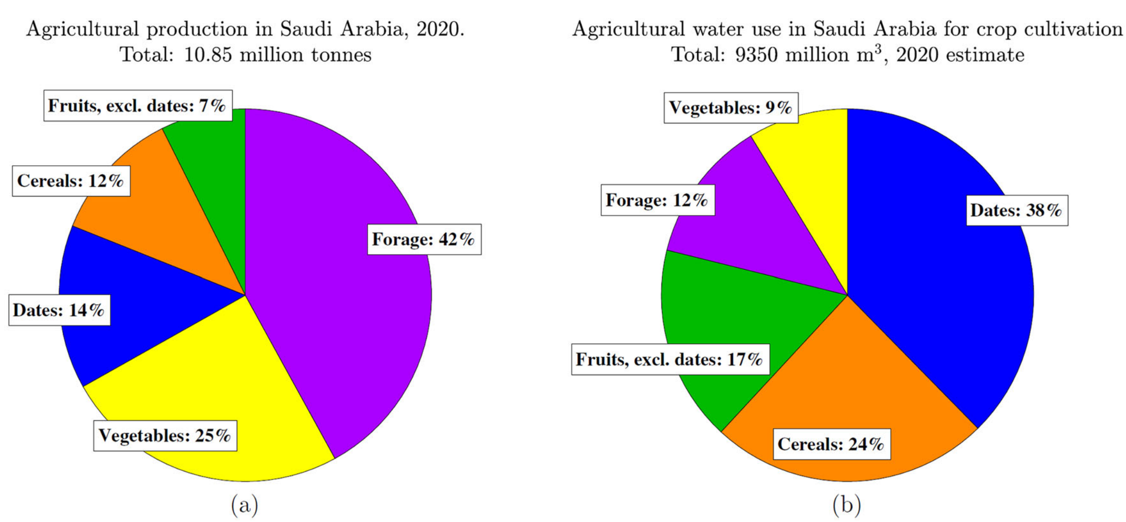

Fig. 6 Key crops and their water use shares in Saudi Arabia. Agricultural production (**a**) and water use (**b**), based on the MEWA data (including forage crops). Water use values are based on the footprint estimates from refs. [36,37].

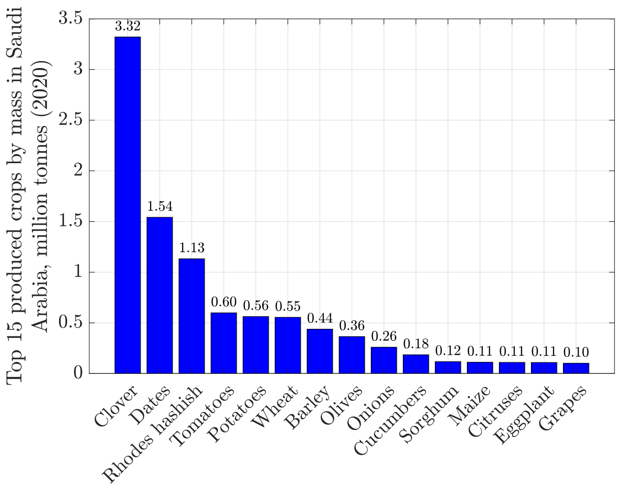

Fig. 7 Mass of the top 15 crops produced in Saudi Arabia. Clover and rhodes hashish are the two main forage crops grown in Saudi Arabia. Dates are the main non-forage crop by mass production. Based on MEWA 2020[24] data.

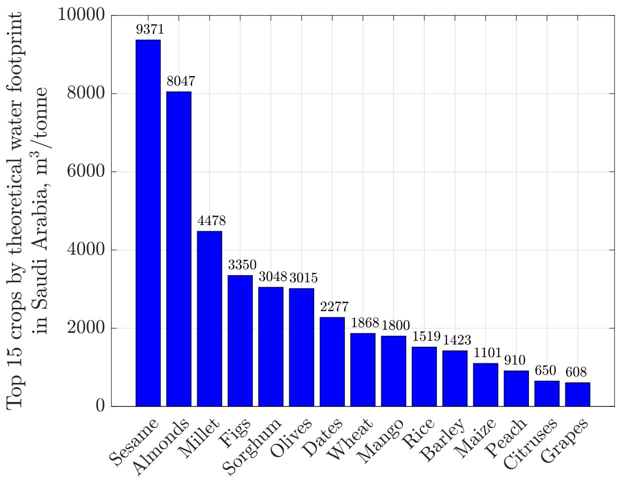

Fig. 8 Water footprint of the top 15 crops produced in Saudi Arabia, based on the MEWA 2020[24] data for crop production and the Mekonnen et al.[36] data on global footprint of crops. Note: values are for the theoretical water intensity based on global average values. Actual water intensity can be obtained by the multiplication by a factor of *X* for a given year, Fig. 10b.

substitution of water-intensive cereals with less water-demanding varieties (for example, a decrease of wheat cultivation in favor of less water intensive maize), diversification of imports, and outsourcing of forage production abroad as its importance for food security is lower than that of non-forage crops. These measures have been initiated in recent years[24].

Optimization of resources relies not only on the production side, but also on the side of consumers. In Saudi Arabia, the issue of food waste correlates with economic growth and increases in incomes. We estimate that the food supply in Saudi Arabia is 155% of what the population theoretically requires, or 3308 kcal/person/day, while the theoretical average is 2139 kcal/person/day (here we compare the calorific and mass values of food supply per capita in Saudi Arabia[44] to the theoretical average calorific requirements value per capita[45], which takes into account age distribution of the population of Saudi Arabia[46]). This equates to 483 kg/person/year and highlights that 35% of the total domestic

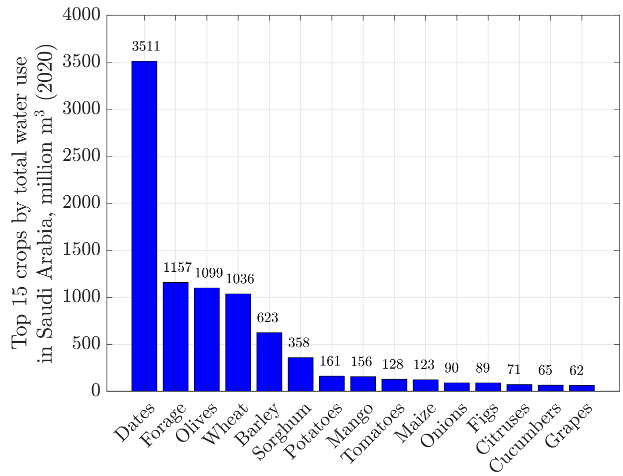

Fig. 9 Total theoretical water use by the 15 crops produced in Saudi Arabia. Based on the MEWA 2020[24] data for crop production and the Mekonnen et al.[36] data on global footprint of crops[23,35,36]. Note: values for theoretical water use are based on global average values. Actual water use can be obtained by the multiplication by a factor of *X* for a given year, Fig. 10b. Forage crops are lumped under one category, `Forage', because of the difficulties in estimation of individual forage crop footprint values.

food supply is wasted or misused. These estimates are calculated using the data from refs. [44–46].

CONCLUSION

This work presents an overarching review of water supply and consumption in Saudi Arabia – one of the most arid countries in the world. Our focus is the agricultural sector which consumes almost three times more water than the municipal sector and relies on non-renewable groundwater. Yet, agriculture provides only a third of the country's food supply. The MEWA data used in this paper were obtained from historical reports in Arabic that had not been previously published in English. Our findings reveal that on average (based on the 2015–2018 data), it takes 2.6–3 times more water to grow crops in Saudi Arabia than the global average. For example, nearly 50 liters of water are needed to produce one date with an average weight of 8 grams, and about 5.1 tonnes of water are required to produce 1 kg of wheat. The major agricultural product in Saudi Arabia by mass is forage, the fact that is largely unknown to the public. Forage is used to graze livestock and does not directly appear on kitchen tables. Its production by mass is three times the total production of dates in the country, the main non-forage crop. We stress that water conservation is not only about saving domestic water, but is also about reducing food waste (in particular, of animal origin), and optimization of agricultural water consumption. The municipal sector is the second largest consumer of water in the Kingdom, and its demand is steadily growing each year. We highlight that the share of regenerated water that is further reused was only about 10% of the total municipal water supply in 2020. Although this article mainly focuses on agricultural and municipal water use, industrial consumption is also important. Water use by the industrial sector increased by 70% between 2017 and 2020. However, lack of data restricts further analysis. In conclusion, freshwater resources are intrinsically linked to the Kingdom's current and future liveability and wellbeing. With the looming climate change, careful water consumption management is even more critical.

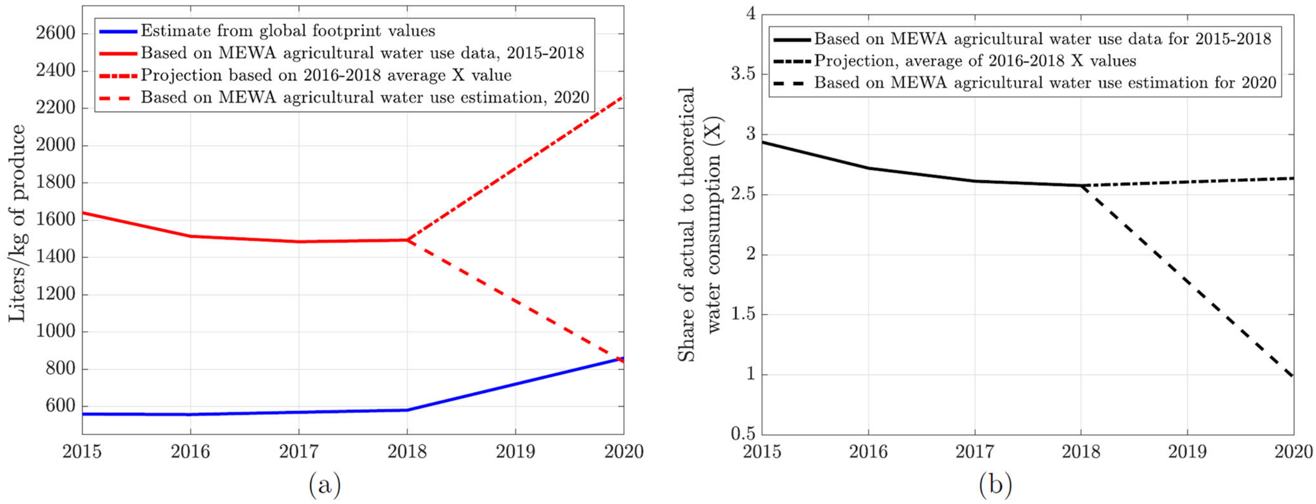

Fig. 10 Efficiency of agricultural sector in Saudi Arabia. a Water use per unit of agricultural produce, liters/kg; **b** Share of actual to theoretical water consumption. Data for 2019 are not available.

DATA AVAILABILITY

The final data used in this paper are summarized in the Supplementary Materials file. The data will be made available electronically upon request.

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AUTHOR CONTRIBUTIONS

T.W.P. conceived the project and supervised data analysis and creation of figures. N.O. gathered and analyzed the data, plotted them, and wrote the manuscript that was then edited by T.W.P. Both authors reviewed the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

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