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Christian Siderius^{1,2,6} , Declan Conway¹, Mohamed Yassine³, Lisa Murken⁴, Pierre-Louis Lostis¹ and Carole Dalin⁵

¹ Grantham Research Institute on Climate Change and the Environment, London School of Economics, Houghton Street, WC2A 2AE, London, United Kingdom

² Uncharted Waters Research, Sydney, Australia

³ School of Sciences and Engineering, the American University in Cairo, P.O. Box, New Cairo 11835, Egypt

⁴ Potsdam Institute for Climate Impact Research (PIK), P.O. Box 60 12 03, D-14412, Potsdam, Germany

⁵ Institute for Sustainable Resources, University College London, London, United Kingdom

⁶ Author to whom any correspondence should be addressed.

E-mail: christian.siderius@unchartedwatersresearch.org

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Abstract

We quantify the heavily oil-dominated WEF nexus in three Gulf Cooperation Council (GCC) countries (Kuwait, Qatar and Saudi Arabia) across spatial scales and over time, using available empirical data at the national level, and explore the exposure to nexus stresses (groundwater depletion) in other countries through virtual water trade. At the domestic scale, WEF trade-offs are fairly limited; while all sectors require considerable amounts of energy, the requirements for water and food production are modest compared to other uses. At the international scale, revenues from oil exports in the GCC allow the region to compensate for low food production and scarce water availability. This dependency is dynamic over time, increasing when oil prices are low and food prices are high. We show how reducing domestic trade-offs can lead to higher exposure internationally, with rice imports originating in regions where groundwater is being depleted. However, Saudi Arabia's increased wheat imports, after reversing its food self-sufficiency policy, have had limited effects on groundwater depletion elsewhere. Climate change mitigation links the WEF nexus to the global scale. While there is great uncertainty about future international climate policy, our analysis illustrates how implementation of measures to account for the social costs of carbon would reduce the oil and gas revenues available to import food and desalinate water in the GCC.

1. Introduction

Despite the economic prosperity that the six states of the Gulf Cooperation Council (GCC¹) enjoy [1], economic challenges as a result of recent fluctuations in oil prices [2, 3] have exposed strategic risks, including securing long-term sustainable access to and use of water and food resources [4]. The GCC states rank among the lowest in the world in terms of per capita freshwater resources [5] and soil fertility [6], but among the highest in domestic water [7], energy consumption—mainly for cooling—and CO₂ emissions [8]. The decrease in crude oil prices led to significant budget deficits in recent years in several

GCC states (8% of GDP in Saudi Arabia in 2017, 17% of GDP in Kuwait in 2016 and 20% in GDP in Oman in 2016) [1].

None of the GCC states is self-sufficient in food and water; all rely heavily on imports (food products and virtual water in food products) from other countries [9] and seawater desalination [5] to sustain their needs. Harsh climatic conditions and scarce water resources have been major impediments for the development of the agriculture and water sectors. None of the GCC states have renewable water resources greater than 500 m³/capita [1], far below the widely used 'water scarce' threshold of 1000 m³/capita-year [10]. To meet their freshwater needs, GCC states have developed into world leaders in the application of seawater desalination technology with an installed desalination capacity in 2012 of 18 million m³ of

¹ Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates.

water per day [planned to expand 40% by 2020 [11]]. Desalination is, in turn, highly energy intensive [12] and a costly process [13].

Food security through conventional domestic agriculture has been deemed unsustainable and an unattainable goal due to environmental and water resource constraints [14–16]. Excluding Saudi Arabia and Oman, any meaningful attempt to support domestic agricultural production is thus strongly dependent on the availability of energy (i.e. burning more oil, and in future possibly solar) to desalinate seawater and brackish groundwater water for irrigation, to treat and reuse domestic waste water or using highly controlled environmental conditions in closed agricultural systems [5], but these techniques are currently too expensive to be used for staple crops [17]. GCC states therefore secure food resources by importing food from international markets, made possible by revenues from oil exports. This risks aggravating nexus trade-offs in food exporting countries, with unsustainable use of groundwater in these countries one of the major concerns [18, 19].

The deep interlinkages between the availability of water, energy, and food resources have been termed the water-energy-food (WEF) nexus [20]. Nexus debates are fundamentally about scarcity in natural resources and the recognition that water, energy, food, and other resources are interdependent [21, 22] at multiple spatial and temporal scales [23–25].

To date, the nexus interlinkages for the GCC states have received limited attention with the concept not widely used [26]; one likely reason being the abundance of oil which obscures any shortages in other sectors. Abulibdeh, Zaidan [27] sketch the main drivers of change in the region's WEF nexus. Siddiqi and Anadon [12] illustrate the water requirements of oil production and energy generation, and the energy need for water pumping and desalination. Keulertz and Woertz [28] explicitly address the importance that energy exports had for directing the GCC countries towards food imports, as an alternative to improving their WEF resource management. The trade dimension of the nexus, mainly in the form of virtual water as a solution to domestic nexus challenges, receives more attention in the Middle East literature compared to the global WEF nexus literature [16, 29, 30]. Pioneering work by Allan [31], and subsequently many others, has greatly refined understanding of quantitative elements of virtual water (water footprinting [32]) and the wider political economy of water and food security in the Middle East [26, 28]. Some (e.g. [33]), have suggested that a shift to renewables, as part of the climate mitigation response, might significantly affect the income sources that most of the Gulf States rely on and their capacity to mask domestic WEF nexus trade-offs through oil exports and food imports.

Previous methodologies applied to the nexus in the Middle East use comparatively more qualitative approaches and discuss the nexus conceptually (including policy papers), for instance [28, 29, 34–38]. Data requirements of nexus models are difficult to satisfy [39] and their compatibility can pose problems [40]. The few studies that use time-series data are primarily descriptive [41, 42]. Where quantitative methods are applied, it is often a quantification of two sector linkages [12, 43]. This mirrors the general nexus literature, where most nexus studies synthesize dual connections of water-food, energy-water and food-energy, or only conceptually address the complete WEF nexus [44–50]. More elaborate quantitative analyses include a life cycle analysis (LCA) model of food production systems [51, 52] and a scenario-based, integrated framework tool [53], both tested for Qatar. Grindle, Siddiqi [54] use a water footprint approach with energy input analysis, combined with assessments of virtual water trade and foreign direct investment for food production.

There are significant knowledge gaps in the way the WEF nexus of each state in the GCC is domestically dependent on its economic performance, regionally interdependent on each other's WEF nexus, and globally affected by the impact of climate variability and change on the world's food producers. The aim of this paper is to characterise in a quantitative fashion the multiple scales of the WEF nexus for the GCC, using three characteristic GCC states as examples; Kuwait, Qatar and Saudi Arabia, covering the largest and most populous GCC state (Saudi Arabia) with a considerable agriculture sector, a city state depending on oil exports (Kuwait) and a city state with a more diverse economy but still high dependence on gas exports (Qatar). We examine the nexus at three scales and their dynamics through time: the domestic nexus, which involves internal dependencies, trade-offs, and co-benefits amongst WEF nexus resources within the country; the international nexus, with exports and imports linking a country's domestic nexus to those in the countries it imports from, and, finally; the global scale through an illustrative example of the extent to which climate change mitigation policy might impact oil revenues.

2. Methodology

2.1. Approach

The analysis uses open-source data from international databases on resources interdependencies supplemented with national reports and an analysis of trade flows. One common problem with quantifying the nexus, and with many nexus studies, is that the sectors are measured in different units and are to some extent incommensurate and therefore rarely compared directly. To address this issue we convert and present the nexus flows in comparable units—million barrel of oil equivalents (MBOE). For nexus

linkages that could not be expressed in MBOE, their relative importance is presented. We consider the period between 2000 and 2016, for which the most comprehensive and complete data were available (see below).

2.2. Domestic nexus

Our model of the domestic nexus is similar to the simplest form of an input-output analysis, e.g. an assessment of the amount of oil (i.e. energy) used to desalinate water and, vice versa, the amount of water needed to produce oil which includes both extraction and processing. Resource use was either quantified, for those linkages that could be expressed in MBOE compared to total oil produced, or visualized and discussed in relative terms, such as water use compared to total renewable water resources.

Energy usage by sector and disaggregated by energy source was taken from the International Energy Agency (IEA) World Summary Energy Balance [55]. Domestic agriculture's energy consumption is split in on-farm energy use such as for traction, heating and power, and energy use via the energy-for-water linkage providing irrigation water through groundwater pumping and waste water treatment. The agricultural sectors in Kuwait and Qatar are too small for the IEA to report their final energy consumption; we assumed their energy intensity of agriculture to be the same as Saudi Arabia's. Energy requirements for irrigation were computed from energy intensities for groundwater pumping in Abderrahman [56] and average agricultural water withdrawals [5]. To explicitly calculate energy use for domestic water supply, we used reported estimates of energy intensities for groundwater pumping [56], waste water treatment [12] and desalination [57]. As energy intensity varies by desalination technique, a country-specific average energy intensity for desalination was derived by weighting intensity by installed capacity of each technique.

Water use data for household and agricultural purposes were taken from AQUASTAT, the UN Food and Agriculture Organization's (FAO) global information system on water resources and agricultural water management [5], though, because it is survey-based, frequent data gaps mean it is difficult to build continuous time series. We linearly infilled missing data over the study period, under the assumption that these data change incrementally [5]. Regarding desalination, the website Mordorintelligence.com, a market advisory firm, has biennial data on total production of desalination plants for Kuwait, Qatar and Saudi Arabia. Net water use estimates for the oil sector are rare, so we used water use per barrel of oil intensity estimates from the Kuwait Institute for Scientific Research for Kuwait [58] and reported values from Siddiqi and Anadon [12] for Saudi Arabia and Qatar, multiplied by the annual amount of oil produced, to calculate the total water need of energy production.

None of the three countries use significant land areas for the production of biofuels [55] and the limited area under agricultural use is unlikely to greatly affect runoff in this (semi-)arid region, making the food (i.e. land use)-to-water and food-to-energy linkages marginal.

2.3. International nexus

Limited domestic food production is compensated by imports, financed by oil (i.e. energy) exports. Annual oil and gas exports, measured in physical quantities, were taken from the IEA's World Summary Energy Balance [55]. Oil spot prices, the current market price at which oil is bought or sold for immediate payment and delivery, come from the Organization of Oil Producing Countries, OPEC. Countries spend a share of their oil export revenues on food imports. To estimate the quantity of oil that must be exported to meet food import demand, the value of total agricultural imports was divided by the price of oil. Resource Trade Earth data [59] were used to estimate agricultural imports and export. These are based on the United Nation's trade database, UN Comtrade [60], a repository of official international trade statistics, and provide aggregated figures on the value of total agricultural imports by country.

The reliability of food imports, and their price, depends to some extent on sustainable management of the water, energy and land resources that underpin the production of these food crops. Importing food thereby generates exposure to nexus trade-offs elsewhere. As an indicator of this exposure, we use the amount of groundwater depletion for irrigation (GWD) embedded in international food trade [18]. GWD is defined as the volume of groundwater that is abstracted for irrigation use in excess of the natural recharge rate and irrigation return flow, accounting for environmental flow requirements, and thus corresponds to an unsustainable use of groundwater for crop production. GWD contributed approximately 20% to the global gross irrigation water demand for the year 2000 and is largest in the Indo-Gangetic plain, followed by the United States, Iran, China, Mexico and Saudi Arabia [19]. Most of the crops grown with it are locally consumed, but some are exported.

We used data from Dalin *et al* [18] on global, country-specific GWD intensities for wheat and rice, staple food crops for this region and the two crops contributing most to global GWD transfers [18]. We also analysed the GWD of barley, one of the main feed crops both in the GCC and globally, but since barley is grown mainly under rainfed conditions and is relatively low (water) input intensive, GWD is low and we do not further report on it. We then multiplied the bilateral trade flows of these commodities (based on FAOSTAT, FAO's repository for food and agriculture data most of which is provided by national statistics offices [14], with trade data corrected for

re-export following Kastner [61] to link consumption patterns to the origin of primary products), by the GWD intensity of each commodity in the country of export to obtain the GWD volume embedded in food trade. GWD intensities were based on the average of the years 2000 and 2010, the two years for which these data have been compiled. Using either GWD intensities based on 2000 or 2010 gave only minor differences in total GWD imports to the three GCC countries (on average within 4% for rice and 12% for wheat), suggesting that simulated GWD is fairly constant.

Bilateral trade-flows are more dynamic and data for 2000 to 2016 were used to follow the evolution of trade and embedded GWD over time. A general decline in the overall quality and availability of agricultural statistics on production and trade has been a cause of concern, with the response rate to FAO's questionnaire in the Middle East among the lowest globally [62], and with collection methods, statistical expertise and harmonization of data varying between countries [62, 63]. We checked for consistency, eliminating countries from our trade matrices that had negative consumption, with exports exceeding production plus imports, due to either missing or incorrect data (this affected on average, in a year <5% of countries, and in almost all cases small, or island states). Country imports should be similar to exports as reported by exporting countries, with small differences possible due to different reporting methods for imports and exports [60]. Export data were used to supplement three years of missing import data for Kuwait and Qatar.

2.4. Global nexus

Climate change, among other things, links each country's and the region's nexus to the global scale. Given the dominant importance of oil revenues in the region and their contribution to global climate change we explore what mitigation policy might mean for revenues in relation to food import costs. Attempts to reduce greenhouse gas emissions in order to achieve the ambitions to combat climate change as expressed in the Paris Agreement or to account for the social cost of carbon (SCC) may influence demand for oil—and/or its price. Using common estimates on the cost of impacts and the emissions from a barrel of oil we estimate the exposure of the nexus to policies that are likely to affect the volume or price of oil exported. We use two types of SCC estimates. First, among the state-of-the-art contemporary estimates of the SCC are those provided by the US Environmental Protection Agency [64] for the period 2010 to 2050. Running three Integrated Assessment Models (IAM) they calculated impacts of carbon emissions on agricultural productivity, energy demand, human health, property damages from increased flood risk and the value of ecosystem services, among other things. We use the midrange estimate (at a 3% discount rate)

of 42 USD/tCO₂ in the year 2020 which, combined with 0.43 tCO₂ per barrel, gives a SCC estimate of 18 USD per barrel. Second, a more robust estimate is considered the marginal cost of carbon, the cost required to make a transition to reach a certain carbon limit and temperature rise below a certain temperature level, expressed as a price of carbon. Using an agreed target reduces the uncertainty inherent in the range of IAM impact estimates and leaves room to consider impacts that might not be so easily quantified. For this we draw from Dietz *et al* [65], who provide the marginal cost of carbon for 2020 and the decades up to 2100. All values used are in 2007 USD. Illustratively, we then compare the costs to the revenues of oil (at 61 USD per barrel, averaged over the 2000–2016 period) to show how much of export income could be affected by policies aiming to incorporate the SCC (i.e. mitigation policy could lead to a tax on carbon that reduces revenue to exporters).

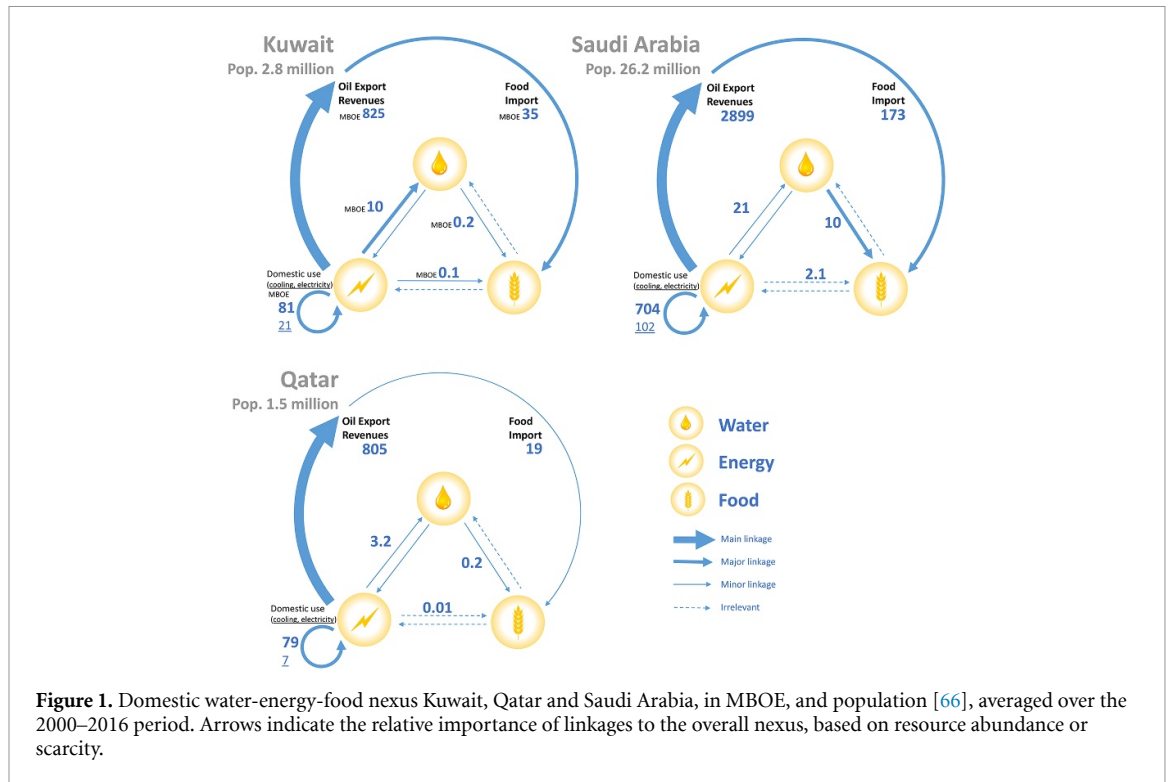
Compiling data from various sources, often collected by individual countries, leads to varying levels of accuracy [62], even though these databases are widely used by researchers, state-of-the art and with continuously updated data quality checks. Use of times series reduces this uncertainty to some extent as outliers in individual years can be detected, nevertheless our estimates of the domestic, international and global nexus should be considered illustrative.

3. Quantifying the water-energy-food nexus

3.1. The domestic WEF nexus of Kuwait, Qatar and Saudi Arabia

The GCC states rank among the world's highest energy consumers on a per capita basis [8]. In our three case study states, domestic consumption ranges from 9% to 20% of total oil and gas produced (figure 1 and table 1). Kuwait particularly has high water-related energy use, mostly for desalination and a small fraction to pump groundwater or treat waste water. This requires a significant amount of oil, about 10 MBOE/year with 81 MBOE for other uses. Cooling and electricity are other important energy users in Kuwait. At 21 MBOE this comprises about 23% of total domestic energy use (in Saudi Arabia 14% and in Qatar 8%). Considerably less energy is used for food production, reflecting the small domestic agricultural sector in Kuwait and Qatar. Only in Saudi Arabia, with its larger agriculture sector, is energy use for food (directly, and indirectly via water-for-food) a similar order of magnitude as energy use for water by households (table 1).

In Saudi Arabia, nexus trade-offs between food and water have been substantial, with massive over-exploitation of fossil groundwater reserves to sustain food production threatening future water security [15, 67, 68]. Of the roughly 23 BCM of water used annually, 85% was for irrigation, with only 10%



of total use supplied by renewable water resources. While the Arabian aquifer system underlying Saudi Arabia is vast [69], only a fraction is economically useable with most too deep to be abstracted or too saline to be directly used [67]. This situation led to the realisation that remaining water resources should be preserved for higher valued industrial and domestic uses, which promoted a policy shift away from food self-sufficiency after 2006 towards greater reliance on imports. The remaining irrigation is now primarily targeted at high value crops [15, 70]. While this has reduced overexploitation of groundwater it has not eliminated it [15].

In the smaller, highly urbanized city states, Kuwait and Qatar, there is no conflict between land used for food production and for water harvesting or energy generation. Production of biofuels is non-existent. Using land to harvest water is equally rare in the desert. While renewable water resources are obviously very limited, and there is clearly a challenge to use less and reuse more, overall nexus trade-offs between domestic sectors are small. Kuwait for example, has minimal annual renewable water resources, mostly consisting of groundwater inflow from Saudi Arabia, estimated at about 20 million cubic meter (MCM) according to AQUASTAT to 45 MCM [71] per year. Kuwait's groundwater extraction exceeds the aquifer's capacity almost tenfold resulting in poor quality of extracted water [71]. However, these volumes are small compared to an estimated desalination capacity of almost 1400 MCM in 2016, which fulfils Kuwait's domestic drinking water demand. Irrigation water use amounts to an estimated 200–500 MCM of water

per year, part brackish groundwater and part reuse of domestic waste water (~275 MCM); indicating a nexus synergy rather than a trade-off. Net water use estimates for the oil sector are rare, but using the water use per barrel of oil intensity estimates from Kuwait, a range of 30 MCM to 180 MCM per year is derived, only part groundwater, part seawater and an unknown part recycled. Most cooling of thermal power plants is done using seawater [12] thereby avoiding trade-offs with other water uses.

3.2. Exports, imports and the nexus

More important is the 'International Nexus', in which limited domestic food production is compensated for by imports financed by oil and gas (i.e. energy) exports that dominate the nexus (figure 1). In Kuwait, food imports represent a value of 35 MBOE which, at 4% of total oil export revenue, is relatively small. In years with low oil and high food prices, however, the food import-oil export proportion increases, becoming as high as 8% in 2014. Similarly, for Qatar the food import-oil export proportion is less than 3% on average, but it peaked at 7% in 2002. Saudi Arabia reported the highest proportion, on average 6%, but 10% in 2015.

Imported food requires land, water, energy and nutrient resources in other parts of the world. The availability of food for import and its price is subject to local WEF nexus interactions, which means that importing food increases vulnerability to nexus trade-offs elsewhere. Figure 2 shows annual imports from major exporting countries to Kuwait, Qatar and Saudi Arabia, for rice and wheat. Saudi Arabia's

Table 1. Summary of domestic water-energy-food nexus dependency for Kuwait, Qatar and Saudi Arabia averaged over the 2000–2016 period.

Domestic nexus dependencies	Kuwait			Qatar			Saudi Arabia		
	Total (M BOE/year)	Per capita* (BOE/capita-year)	Fraction of energy use (%)	Total (M BOE/year)	Per capita (BOE/capita-year)	Fraction of energy use (%)	Total (M BOE/year)	Per capita (BOE/capita-year)	Fraction of energy use (%)
Energy-for-water (household)	9.8	3.5	11%	3.0	2.1	4%	11	0.4	2%
Pumping water and desalination									
Energy-for-food	0.1	0.0	0%	0.01	0.0	0%	2.1	0.1	0%
Direct energy use in agriculture									
Pumping water and treating waste water	0.2	0.1	0%	0.2	0.1	0%	10	0.4	1%
Energy-for-other-sectors									
Cooling buildings and providing electricity	21	7.4	23%	7	4.5	8%	102	3.9	14%
Industry and transport	60	21.1	66%	73	49.6	88%	603	23.0	83%

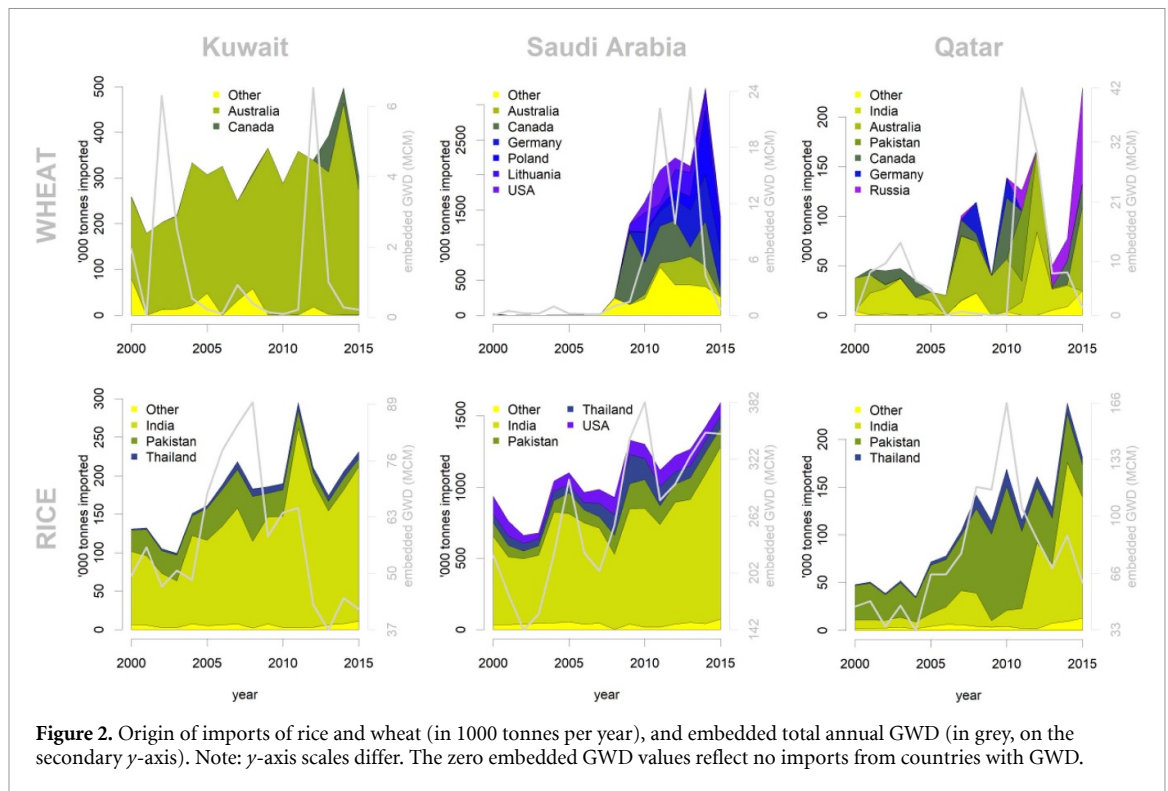


Figure 2. Origin of imports of rice and wheat (in 1000 tonnes per year), and embedded total annual GWD (in grey, on the secondary y-axis). Note: y-axis scales differ. The zero embedded GWD values reflect no imports from countries with GWD.

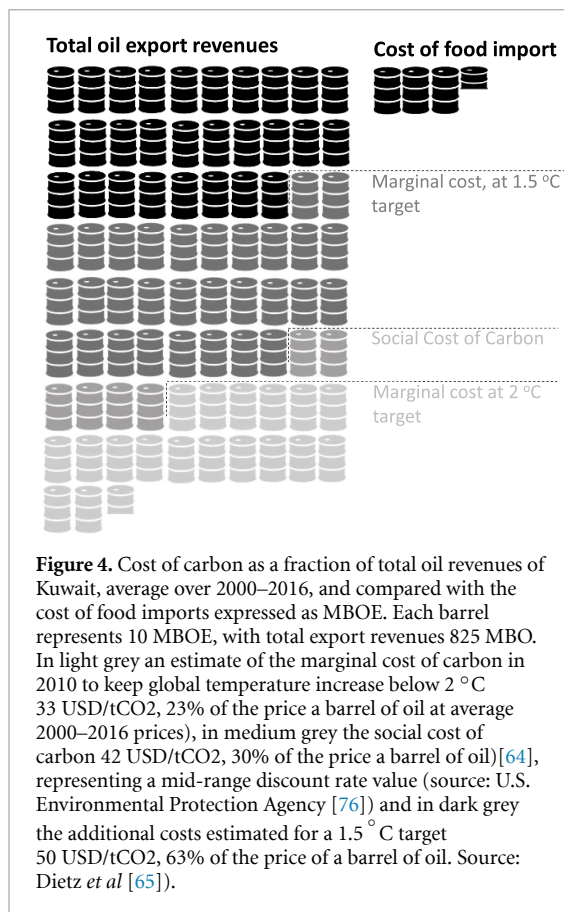
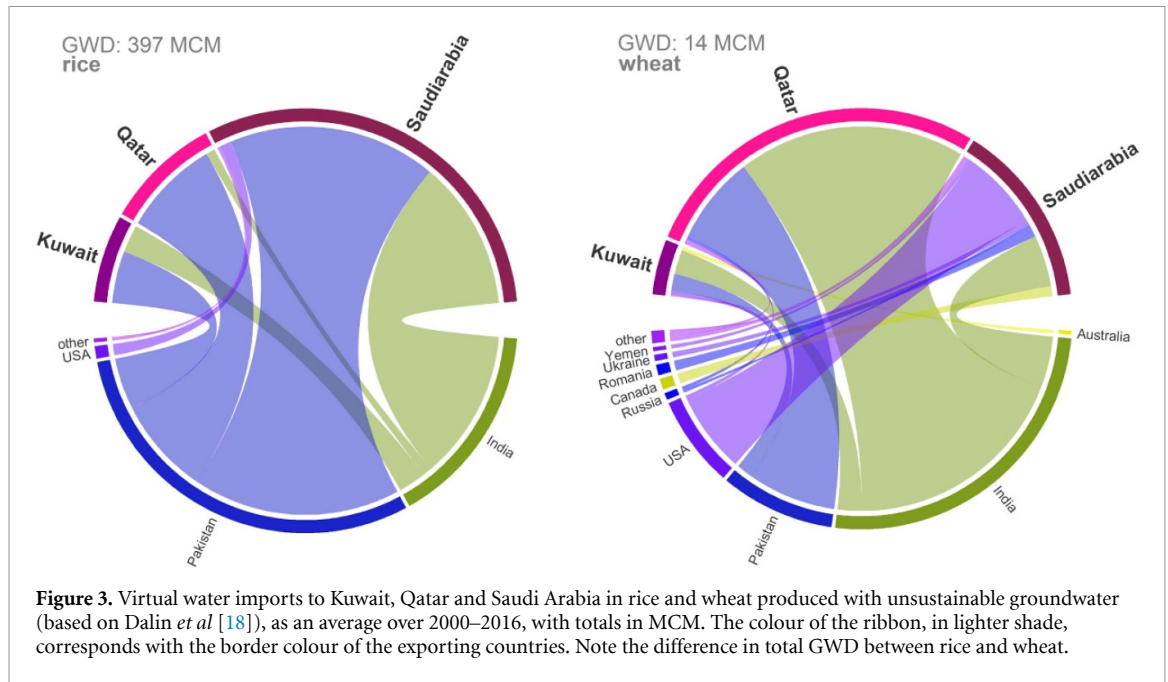
abandonment of its wheat self-sufficiency policy around 2006 is clearly visible in its increased import volumes. Wheat imports are dominated by Australia and Canada, two countries with—in normal years—a large food surplus from crops grown mainly under rainfed conditions. Threats to imports from nexus trade-offs play less of a role here, though changes in global demand—i.e. reduced production elsewhere—might affect future prices. In addition, there are a range of other countries exporting wheat. Rice imports mainly come from India. Qatar relies strongly on imports from Pakistan. Both India and Pakistan are countries that have abundant water resources seasonally, but that suffer from declining groundwater levels due to over-abstraction especially in rice growing areas like the Punjab [72–75].

The shift away from food self-sufficiency in Saudi Arabia to a higher reliance on wheat imports after 2006 has had a marginal effect on imported GWD (figure 2). GWD embedded in wheat rose slightly to 24 MCM in 2013, mainly because of increased imports from the USA, before decreasing again, with imports then originating mainly from Europe where wheat is grown mostly rainfed or in areas where groundwater use is sustainable. Fluctuations in GWD reflect both fluctuations in total imports as well as shifts in the origin of imports and thereby the GWD contained in those imports. An upward trend in GWD embedded in rice imports to Saudi Arabia, reflecting an increase in demand as result of population growth. Both Kuwait and Qatar reduced their imports from Pakistan in recent years, so that GWD declined even though total rice imports increased.

Figure 3 shows the amount of embedded GWD in food trade links. This highlights food imports that contribute to groundwater depletion in export countries, mostly Pakistan and India. We use the approach and data from Dalin, Wada [18], who estimated a total global exported GWD of 25.6 BCM for 2010. While Saudi Arabia's rice imports embed the largest share of GWD, Qatar's per capita embedded GWD (not shown) is higher because of its reliance on rice imports from Pakistan. Although these three countries have a total population of just 30 million, less than half a percent of the global population [66], the GWD embedded in their rice imports accounts for almost 2% of the global total GWD of all crops. The GWD embedded in wheat imports is minor.

3.3. Climate change; adding the cost of carbon to the nexus

Climate change strongly links the nexus of GCC countries to the global scale. Figure 4 illustrates the social costs of carbon (SCC) as a percentage of the total oil export revenues, according to the midrange estimate of the SCC as used by the US Environmental Protection Agency (42 USD/tCO₂), and alternative marginal cost estimates with a median marginal cost price of 33 USD/tCO₂ in 2020 as reported by Dietz *et al* [65] to stay within the 2 °C limit. A more ambitious maximum 1.5 °C temperature level, considered safer would raise this price to 50 USD/tCO₂ in 2020 [65]. The cost of food imports in Kuwait as a percentage of total cost of carbon-corrected oil revenues under the 1.5 °C limit would rise to an average of 17%, in Qatar 9% and in Saudi Arabia as high as 24%.



However, the price of carbon will not be constant, for example, it needs to rise steeply to drive further mitigation and maintain temperatures within 2 °C or 1.5 °C. This would imply an even larger impact on oil revenues.

With global progress on international commitments to reduce fossil fuel use slow, and carbon

prices still very low in those countries that have implemented emission trading schemes, the SCC values derived through modelling studies are highly uncertain [65]. Therefore, the comparison in figure 4 should only be considered as illustrative of the magnitude of potential impact. Moreover, a price on carbon cannot be translated one-on-one into a future reduction in revenues as demand is not fully elastic. And reduced demand will not impact producers equally; GCC countries have a comparative cost advantage, with large reserves easily exploitable. Any reduction in demand is likely to first reduce production from more costly sources. Commitment to a 2 °C maximum increase in temperature above pre-industrial levels, globally, would require over 430 billion barrels of oil and 95 trillion cubic metres of gas, currently classified as reserves, remain unburned by 2050 [77]. The Middle East possesses over half of the unburnable global oil (and gas) reserves leaving over 260 billion of barrels in the ground, almost 40% of its oil reserves [77], but with coal and oil production in other regions being phased out first—assuming that countries and consumers behave in an economically rational fashion.

Apart from costs, timing is important. The 1.5 °C ambition requires a decarbonisation of energy supply that is more rapid and profound than in 2 °C-consistent scenarios. Dietz *et al* [65] indicate that an energy-system transformation with about 50% additional decarbonisation compared to a 2 °C scenario is needed, starting sooner. Early CO₂ reductions in 1.5 °C-consistent scenarios are achieved through reductions in the power sector [78], but by 2050 most of the supply-side mitigation potential is already used—also when aiming to keep warming to 2 °C. Moving to 1.5 °C relies on much

stronger emission reductions on end-use sectors such as industry, transport and buildings [78], and, thus, those sectors consuming most oil. Again, this suggests there is some time left to adjust Saudi Arabia, Qatar and Kuwait's economy to changes in oil and gas demand, but with a 1.5 °C target, impacts will be felt sooner.

Finally, climate change will have an impact on the amount of food produced elsewhere—e.g. in Australia's grain belt [79] or rice production in the Indo-Gangetic plain [80], affecting global food availability and prices. Not only will gradual changes in production matter, but also their volatility; major food price spikes in 2007/8 illustrate that even a perceived shortage due to compounding climate impacts in multiple food producing regions can lead strong responses in restrictions on trade with impacts on prices [81]. Compared to poorer importing countries, e.g. in sub-Saharan Africa, the GCC states are still well endowed to buffer any shocks, but lack of alternative sources of food production means the region remains exposed.

4. Discussion and conclusion

This paper advances understanding of the nexus—taking three GCC states as examples—by studying the interconnections between three nexus elements, over multiple scales and using comparable units (BOE) to address issues of incommensurate units. At the domestic scale, WEF trade-offs are generally modest, dominated by energy and while there are issues of water scarcity, trade-offs between sectors at this level are relatively small because water scarcity limits agricultural production and surplus fossil fuel resources compensate through desalination and food trade. Partial analysis of the nexus can obscure important linkages; while the dependence of water use on oil has been well illustrated [12], we show that the water-food linkage, through oil exports and food imports, is of a considerably higher magnitude. Moreover, dependency on food imports in terms of export revenue is dynamic over time, fluctuating from about 4% on average up to 10% for Saudi Arabia in 2015, when oil prices were low. While high oil export revenues shield GCC states from the immediate impacts of higher prices, they would not fully buffer exposure to sudden export restrictions in exporting countries.

At the International scale, nexus analysis highlights more significant resource interdependencies, which play out both inwards, as a domestic challenge (e.g. an increasing part of the budget is spent on food imports) and outwards, affecting sustainable use of resources in source countries. Saudi Arabia's shift in 2006 to importing wheat appears to have resolved a domestic nexus stress without increasing nexus stress elsewhere. Importing rice, however, partly relies on areas abroad with high nexus stresses (e.g. Pakistan and India). Groundwater depletion is continuing, especially in the Indus basin, covering

most of Pakistan, and the Indian part of the Punjab, a major rice and wheat growing area where climate change and increased domestic demand is expected to lead to further water stress [80, 82]. At the same time, exports to the GCC provide valuable foreign currency for poorer exporting countries that have sovereignty in choosing with whom to trade. More investment in better agricultural water management in exporting countries, e.g. to increase efficient use of water without negatively affecting downstream users, often a complex trade-off [83], can help maintain export revenues while reducing water stress.

At the global scale, while uncertainty remains about future international climate policy and its implications for oil and gas revenues, our exploratory analysis suggests that implementation of measures to account for the SCC, assuming the costs were to be applied as a tax, would significantly impact export revenues. There is some, although limited, time to adjust the WEF nexus to the changes in demand for fossil fuels. These findings are illustrative as they rely on the major assumption that countries and consumers behave in an economically rational fashion in which coal and oil production in most costly regions will be phased out first. Our analysis of the SCC is a kind of 'stress test' of the countries' reliance on oil revenue to subsidise other nexus sector requirements. Here we use scenarios of global climate change mitigation policy. Additional scenarios might include price shocks in oil or price and availability shocks in food for other reasons.

Several linkages were not taken into account in this assessment. High rates of groundwater pumping will affect ecosystem functioning. Salinization and increased temperatures of coastal zones, due to the discharge of cooling water, desalination and drainage of irrigation and domestic return flows in the sea is another concern [84]. Transboundary dimensions, e.g. Kuwait and Qatar sharing groundwater reserves with neighbouring Saudi Arabia, were not addressed. Furthermore, the expansion of renewables could potentially replace a large proportion of current domestic energy demand [85, 86]. In addition to embedded GWD in food trade, excessive surface water extractions affecting environmental flows could be taken into account [87, 88]. Finally, issues with data consistency and missing values underscore the need for caution in the interpretation of absolute values presented here.

While the abundance of fossil fuels in combination with an arid climate creates a specific nexus in the countries studied, we are cautious about generalising from our findings. Comparability of the three countries lies in the reliance on a dominant export commodity to sustain an increasingly urbanized population with an energy intensive lifestyle. Though other countries within the GCC and the broader Middle East and Northern Africa region are more populous and/or with more diverse economies, a strong reliance

on fossil fuel exports to provide basic commodities and services in most cases still holds true. The value of a nexus analysis dominated by a single sector (commodity), in this case energy (oil), lies in revealing the nexus trade-offs it obscures, which, as we show, appear when moving beyond the domestic scale.

In terms of policy implications, a multitude of institutions are responsible for managing (parts of) the nexus in Arab countries, with so far little cooperation and overlapping competencies, and silo-thinking [89]. El Hajj *et al* [68] recommend a set of actions to improve regional cooperation on the nexus, for instance through increased knowledge building and sharing, private sector mobilisation for financing and integration of existing institutions. Al-Saidi and Elagib [50] identify different concrete institutional arrangements for implementing the nexus, with differing levels of comprehensiveness and actors involved. However, the political situation in the GCC strongly determines nexus resource allocations within sectors and society, and skews the political-economy of decision making [90]—GCC states operate a political-economy as ‘super rentier states’ [90], where the economy relies predominantly on rents from oil extraction and both taxation and political representation are largely absent. The role of resource subsidies in the social contract (cheap water, energy and food) in legitimising non-democratic governance therefore greatly constrains the political incentives and decision-making space for WEF choices.

While the political route maybe more challenging in GCC states than in other regions, quantitative assessments such as this may provide some entry points for further action. Greater understanding of nexus interlinkages at different scales can help characterise risks to resource security and clarify the range of actors involved in and affected by decisions, and the relevant institutional levels for response. In particular, our analysis highlights areas of risk relating to dependency on food imports with costs that can vary considerably and unpredictably over time and importantly in some cases with significant environmental externalities in source regions. Furthermore the global framing in terms of measures to account for the social costs of carbon highlights the potential significance for export revenues. A WEF nexus approach captures interdependencies that bring risks to supply security such as environmental externalities in key imports that would be missed in a less comprehensive analysis. As our analysis of the potential impact of climate mitigation shows, energy dominance in the GCC might wane. As a result, the governance system which relies predominantly on rents from oil extraction would come under increasing strain. Nexus analyses can help evaluate the multi-sectoral consequences of and responses to such shifts.

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Data availability

The data that support the findings of this study are openly available.

ORCID iD

Christian Siderius  <https://orcid.org/0000-0002-2201-9728>

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