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Toward A Sustainable Agriculture Sector: Policy Options for Reducing Water Use in Abu Dhabi's Agriculture Sector

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Key Points

Water scarcity is a serious challenge for the Gulf Cooperation Council (GCC) countries and could undermine their security. It is estimated that Abu Dhabi's groundwater will be depleted in 55 years if current consumption trends continue.

Agriculture consumes about 70% of worldwide water withdrawals, 60% of which is met by non-renewable groundwater.

This paper attempts to answer the question, How can Abu Dhabi optimize the water used in its agriculture sector while meeting its demand for agricultural products?

A water and agriculture optimization model is developed to determine the optimal crop portfolio for a given water consumption budget for the emirate of Abu Dhabi on an annual basis. The model finds the least-cost mix of crops that stays within the emirate's water budget, while satisfying given demand without compromising food security or aggregate farmer revenues.

Key stakeholders in Abu Dhabi can use insights from the model to decide which water uses could be curtailed or maintained to keep water consumption within the limits of its sustainable water budget. This would involve a shift toward water-productive crops to create sustainable water use.

In some scenarios, using more restricted water budgets for Abu Dhabi can prolong the life of the emirate's groundwater from 22 years to over a millennium.

The model's results show different crop portfolios for different production and import scenarios under a variety of water budgets. These budgets focus on locally produced, low water-intensive crops and imported highly water-intensive crops.

Summary

Water shortages are a global challenge, with one third of the world's population still without access to clean water. Gulf Cooperation Council (GCC) countries face a scarcity of water resources due to their dry climates. The United Arab Emirates' (UAE's) renewable water resources are below the United Nations' water scarcity threshold, and its water usage far exceeds the natural recharge rate by as much as 26-fold. This study investigates the water-agriculture nexus in the emirate of Abu Dhabi and provides policy options for reducing water use in the agriculture sector to sustainable levels.

Agriculture consumes about 70% of water withdrawals in the UAE, mainly from groundwater – a non-renewable water resource that has accumulated over thousands of years in a desert area with low precipitation. It is estimated that the UAE's remaining groundwater will be exhausted in 55 years if current consumption trends continue. Despite the emirate's water scarcity, its consumption of water resources is high. There are around 25,000 farms in Abu Dhabi, which primarily produce date palms, field crops and vegetables. Dates and field crops are among the most water-intensive crops and are produced in the UAE in large quantities.

This paper attempts to answer the question, How can Abu Dhabi optimize the water used in its agriculture sector while meeting its demand for agricultural products? To answer this question, we constructed a linear programming stylized model to maximize the water productivity of Abu Dhabi's agriculture sector, i.e., extracting the most value from water. The purpose of the model is to determine the optimal crop portfolio for a given water consumption budget in Abu Dhabi on an annual basis. The model finds the least-cost mix of crops that stays within the emirate's water budget while satisfying the emirate's given demand, using key factors such as the water intensity of crops, to generate an optimal output of crops produced.

We examine four scenarios with increasingly stringent water budgets and varying quantities of imported and locally produced crops to determine the optimal policy option for increased water productivity. The scenarios give insightful results that offer policy recommendations to enable Abu Dhabi to focus on high-value low water-intensive crops.

This is a joint research project between the King Abdullah Petroleum Studies and Research Center (KAPSARC), the Environment Agency-Abu Dhabi (EAD) and the Abu Dhabi Food Control and Water Authority (ADFCA).

Introduction

One third of the world's population remains without access to clean water. The global water crisis is a major challenge for the future of humanity. Access to clean water is one of the United Nations' (U.N.'s) Sustainable Development Goals (U.N. 2019). Water is a finite resource, with 97.5% of the 70% of water that covers the Earth's surface saline water. Of the remaining 2.5%, 2% is trapped in glacier ice and only 0.5% is freshwater (USGS 2019). The available freshwater is distributed unequally between regions, leaving some regions water stressed due to the physical scarcity of water, or sometimes because of economic scarcity, i.e., a lack of infrastructure.

Agriculture is by far the largest use for Earth's available freshwater, accounting for 70% of total water withdrawals worldwide, 80% in Africa and Asia, and 90% in South Asia (Global Agriculture 2019). Global water productivity – the crop yield per cubic metre of water consumption – is currently about half its potential obtainable under optimal agricultural management (U.N. 2019).

According to the U.N., an area experiences water stress when annual water supplies drop below 1,700 cubic meters (m^3) per person. When they drop below 1,000 m^3 per person, the population faces water scarcity, and "absolute scarcity" when they are below 500 cubic metres (UNESCO 2012; U.N. 2014; UNDP 2006). According to this definition, the Gulf Cooperation Council (GCC) countries are indeed water scarce, facing acute water resource availability due to their dry climates, with some experiencing absolute scarcity.

The United Arab Emirates' (UAE's) renewable water resources are below the U.N.'s scarcity threshold. However, in addition to its physical scarcity of water, groundwater in Abu Dhabi is used at around 26 times the rate at which it is naturally recharged (EAD 2012). If the UAE continues its current patterns of groundwater use for agriculture and forestry, it may deplete its usable groundwater in a few decades and have to replace it with desalinated water.

Therefore, the government of Abu Dhabi is required to ensure that the emirate will meet its future water demand by reducing groundwater use to sustainable levels. Reducing groundwater use could be achieved by substituting water-intensive, low-value-added crops with water-productive, high-value-added crops.

To achieve this, the Environment Agency – Abu Dhabi (EAD) proposed the adoption of a water budget in 2015, which will allow for the sustainable allocation of the water budget to optimize water use. A water budget calculates the water resources within a given area for a specific period. It includes the sources and quantities of water inflows (i.e., rain and groundwater), the water savings (storage) and the water outflows (water uses). A sustainable water budget allows for an amount of water to be allocated for different uses in a manner that achieves economic efficiency, social equity and environmental sustainability.

The sustainable use of groundwater in Abu Dhabi will reduce the need for desalination. This could offer environmental, social and economic co-benefits, such as energy savings, reducing the emissions from air pollutants and greenhouse gases, and limiting the discharge of brine and treated sewage into the Arabian Gulf. It could also offer the economic benefits of reducing capital and operational expenditures in costly infrastructure products and gas imports.

Water Resource Management in Abu Dhabi

Historically, wells provided the main sources of water in the UAE, which ultimately determined the location of settlements (McDonnell 2014). Following the independence from the United Kingdom of the seven sheikhdoms that now form the UAE, each emirate encouraged the expansion of agricultural activities to solidify their settlements:

"In these early nation-building days, the emirate [of Abu Dhabi] provided water, pumps and fuel to bedu people free of charge in order to encourage agricultural production as a strategy to support their settlement." (McDonnell 2014)

With the discovery of oil, a growing population, urbanization and increased economic activity, the demand for water in Abu Dhabi also increased. This demand could not be met by groundwater resources alone, leading to the development of a growing desalination market (McDonnell 2014).

Since the construction of the first desalination plant in the 1960s, Abu Dhabi's water policy has been largely based on supply-side management, always matching capacity with demand. Hence, the planning assumption today is that Abu Dhabi will meet its future water demand by increasing supply. However, there are environmental, technological and economic limits that discourage this approach.

Article 23 of the UAE's constitution of 1971 declared all natural resources to be the property of each emirate. Today, the government of Abu Dhabi is charged with ensuring that demand for water in the emirate is served:

> Law No. 2 of 1998 Concerning the Regulation of the Water and Electricity Sector establishes that water companies should provide sufficient production capacity to ensure that, at all times, all reasonable demand for water in the emirate is satisfied.

> Law No. 5 of 2016 concerning groundwater establishes that the emirate of Abu Dhabi owns groundwater, with its extraction and use governed by rules, standards and conditions set by the EAD. This law is expected to help manage the demand for groundwater in Abu Dhabi and ensure its long-term conservation.

Three main institutions are involved in the management of Abu Dhabi's water resources: (1) the Ministry of Energy and Industry, which is responsible for protecting and sustaining water resources; (2) the Department of Energy, which is in charge of proposing strategic and executive plans for the management of water resources; and (3) the EAD, which is responsible for the conservation of groundwater resources.

Abu Dhabi is the largest of the UAE's seven emirates, with a total area of 67,340 square kilometers (km^2), 84% of which is land (UAE 2019). Its agricultural activities have been mostly concentrated around two of its islands, Al-Ain and Liwa. The emirate has always been an important center of agriculture in the region (Stevens 1970), supporting the livelihoods of its increasing inhabitants, estimated at around 3 million people today (World Population Review 2019; SCAD 2018). Abu Dhabi has the highest cultivated area in the UAE, albeit with limited potential for agricultural expansion, since 80% of its land is desert (AQUASTAT 2008).

Located in a hyper-arid region with an average precipitation rate of 60.7 millimeters per year (SCAD 2017), Abu Dhabi, along with the UAE and other

GCC countries (Bushnak 1990), is one of the most water-scarce regions in the world (Saif, Mezher, and Arafat 2014). Abu Dhabi's current annual water use is 26 times larger than its annually renewable natural water resources (Mohamed 2006). It suffers from serious water scarcity that threatens its economic prosperity and remaining water resources (Murad 2010), which it is estimated will be exhausted in 55 years if current trends continue (Baker and Van Houtven 2015; OBG 2015; The National 2018; Gulf News 2015). Abu Dhabi has only negligible surface water, with groundwater as the only natural water resource. Its limited recharge rate makes water a non-renewable resource (EAD 2017) (Table 1).

Abu Dhabi's estimated renewable water resource is 723m^3 per person per year (calculations, data from EAD [2017]). Its very high extraction rate exceeds the natural recharge rate of aquifers, resulting in depletion. The renewable water resource falls short of the threshold of water scarcity, making the UAE a water scarce country that must manage its water resources carefully and sustainably.

Figure 1 shows a chart of the water supply in Abu Dhabi by source. The majority of the supply is from groundwater (60%), followed by desalination (35%) and recycled water (5%). Using groundwater is unsustainable as it is essentially a non-renewable resource that has been accumulated over thousands of years in an area of low precipitation. It is used mainly for agriculture and forestry, while desalinated seawater is used for domestic, commercial and industrial uses. All water used for irrigation is groundwater. However, the use of groundwater is limited due to the salinity of Abu Dhabi's aquifers, containing only 3% fresh water.

The Total Water Supply in the Emirate of Abu Dhabi = 3,338 Mm^3 (MCM) per year (EAD 2019).

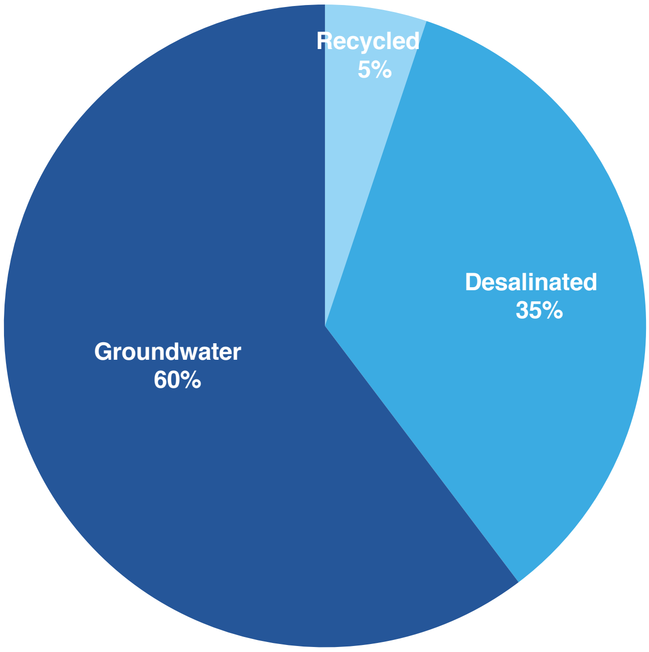
The challenge of using groundwater is made worse by scanty rainfall and over-pumping, depleting it and affecting its quality, which deteriorates over time (Murad 2010). The decline in groundwater levels, increased salinity and pollution are forcing farmers to reduce groundwater extraction and increasing the demand for desalinated and treated sewage effluent. Groundwater deficits are countered by desalinated seawater and brackish water. Desalination is no longer seen as a nonconventional resource by GCC countries, as most of their cities remain heavily reliant on desalinated water (Ghaffour 2013). Saudi Arabia, Kuwait, and the UAE are the largest

Table 1. Water resources in the UAE.

Renewable freshwater resources			Source
Precipitation (long-term average)	120	mm/yr	UAE Water Conservation Strategy 2010
Internal renewable water resources (long-term average)	0.15-0.2	10^9 m^3/yr	UAE Water Conservation Strategy 2010
Total actual renewable water resources	0.15-0.2	10^9 m^3/yr	UAE Water Conservation Strategy 2010
Total actual renewable water resources per inhabitant	48	m^3/yr	Water Security Strategy 2036
Total dam capacity	130	10^6 m^3	Dams Department, MOEI

Note: mm = millimeters; m^3 = square meters; yr = year; MOEI = Ministry of Energy and Industry.

Figure 1. Water supply in Abu Dhabi by source.



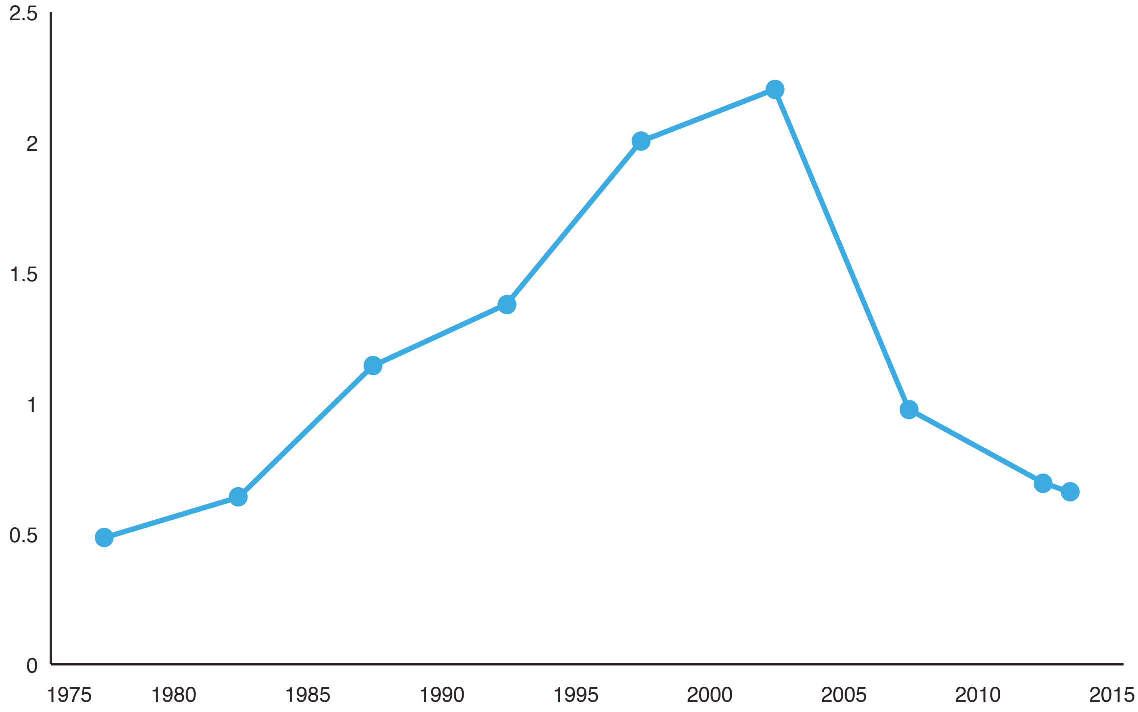
Source: EAD 2019.

markets in the GCC for desalination (Sommariva and Syambabu 2001; Rizk and Alsharhan 2003). Murad (2010) shows that groundwater availability is negatively correlated with population growth, and water desalination production is positively correlated with population growth (Murad 2010, 187). In other words, groundwater diminishes as populations grow, and desalination increases according to demand. Therefore, groundwater will continue to diminish as populations rise if there are no policies to manage the resource sustainably.

In spite of water scarcity, water consumption levels are high. From 1973, there was a dedicated effort to expand agricultural activities in Abu Dhabi, aiming to provide amenity and fodder for animals (Wood, Willens, and Willens 1975). Figure 2 shows the contribution of the UAE's agriculture sector to its gross domestic product (GDP). From 1975 to 2015, its population grew by a factor of 14, from 197,000 to 2,785,000, respectively (SCAD 2017). During the same period, the UAE's desert greening policies resulted in the expansion of its agriculture sector, planted forests and extensive landscape vegetation. The area used for agriculture increased from 22.377 km^2 in 1971 to to 749.868 km^2 in 2016 (EAD 2017), as reflected in Figure 3 below.

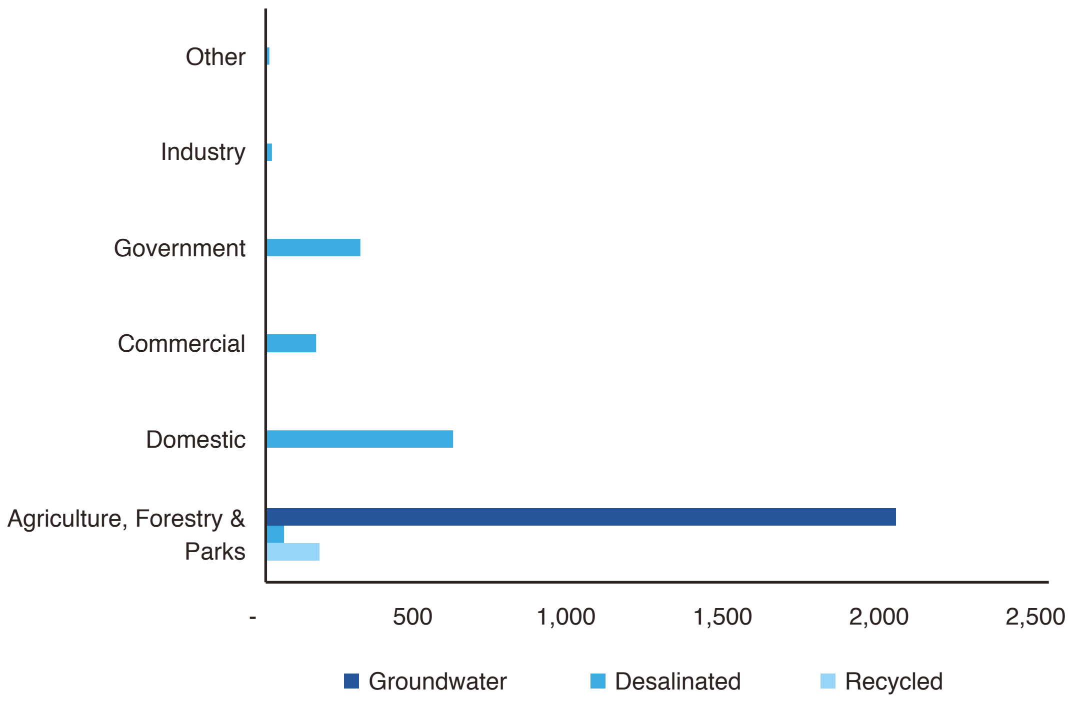
As Figure 3 shows, the contribution of the agriculture sector to the UAE's GDP peaked between 2000-2005. As a result of this agricultural expansion, the use of groundwater to irrigate the production of crops dropped significantly, especially during these years. Groundwater was used in the agriculture, forestry and parks sector. Agriculture alone has accounted for between 70%-80% of total water withdrawals (Figure 3).

Figure 2. Contribution of UAE's agriculture sector to its GDP (% GDP).



Source: AQUASTAT (2018).

Figure 3. Water usage in Abu Dhabi.



Source: EAD 2017.

Table 2 shows Abu Dhabi's irrigation water requirements, estimated at 1,470 MCM in 2014 and 1,574 in 2015. This will guide the assumed water budget in the model.

Since the 1970s, agricultural activities have been encouraged in Abu Dhabi, and they have expanded significantly, reaching a total of 24,394 farms today. They primarily cultivate date palms, fodder and vegetable crops (ADFCA 2011). Despite efforts to support the agriculture sector through centers dedicated to improving local production and increasing the market share of local produce, international food supplies dominate the domestic market, with 87% of all food imported (AGEDI 2015).

The government provides services to farm owners, including the provision of subsidies for well drilling and energy, a monthly payment for eligible recipients, dedicated interest free loans and the opportunity to sell their harvests at guaranteed prices. The market distortions this has created, and the absence of a pricing mechanism for groundwater, has resulted in inefficient irrigation, water-intensive crop portfolios and underinvestment in technologies.

Moreover, the price of water in Abu Dhabi does not reflect its economic value. Desalinated water is subsidized, and groundwater is not priced for UAE nationals. Well owners receive all the benefits of groundwater use but only pay part of the costs, mainly the capital cost of the well's construction and the operational cost of pumping water; the latter is increasing as water tables drop. As a result, the cost for well owners of using groundwater is very low, leading to its inefficient use.

In addition, the agriculture sector provides low value added to the local economy and few jobs. The challenge is to develop the sector in a way that can achieve the UAE's ambitious target of increasing the domestic market share of its local production to 40% (FSCAD 2018). This will require innovative policy solutions to manage the overexploited water resources used in agriculture. The UAE is a food secure country, ranked 33 out of 113 countries on the global food security index (EIU 2017), which considers the availability, affordability, quality and safety of food.

Greenhouse hydroponics

Greenhouse hydroponics is the technology used for growing plants without using soil in mineral nutrient-enriched water. Depending on the crop, the technology offers water saving opportunities.

Table 2. Estimated annual irrigation water requirements for Abu Dhabi.

Irrigation water requirements Million cubic meters (MCM) per annum	**Year**
1,470	**2014**
1,574	**2015**

* The above figures are the estimated irrigation requirements NOT the actual irrigation water consumed.

Source: EAD.

Compared with traditional farming, in some cases hydroponics results in up to 90% more efficient use of water, between three to 10 times as much production, half the production time, and eliminates the need for weed and pest control (Green Our Planet 2019).

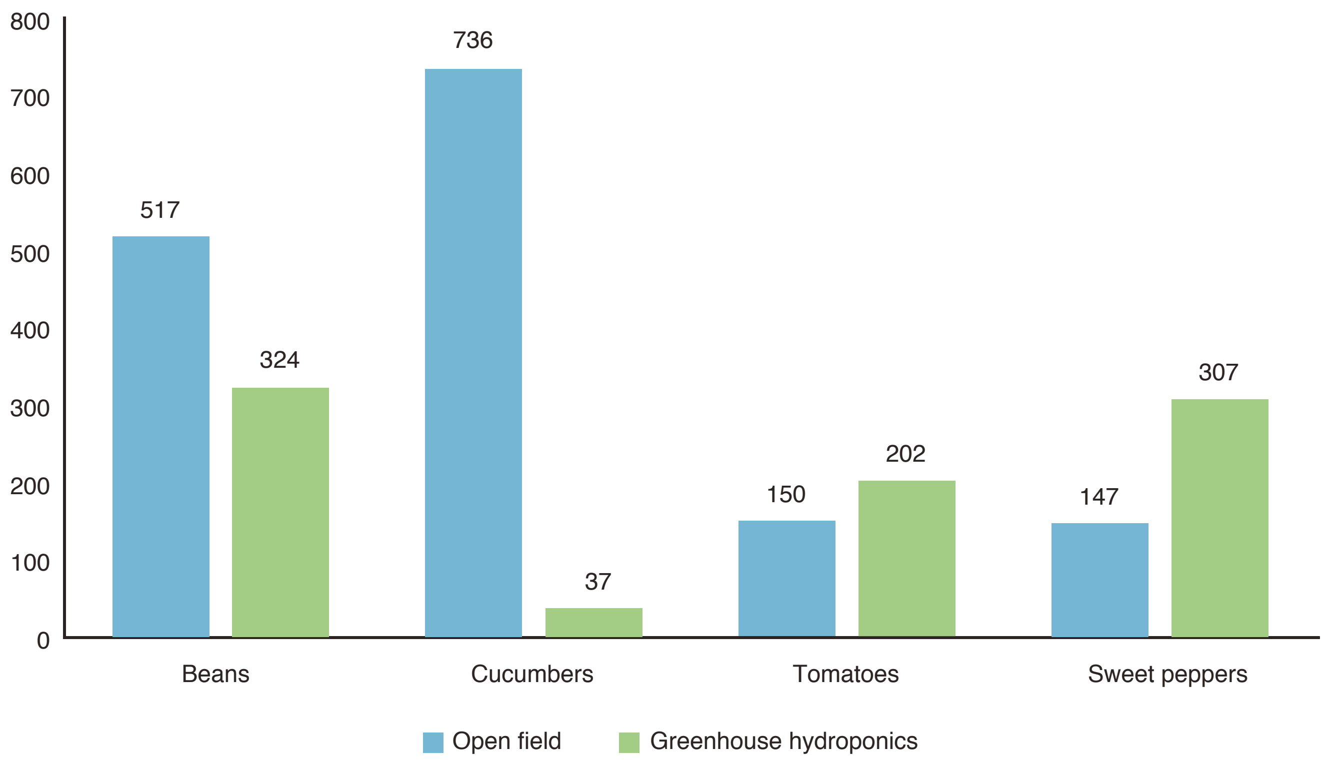
Figure 4 shows the differences between the water intensity of greenhouse hydroponics and traditional open field farming in the UAE.

Greenhouse hydroponics promises to reduce the overall use of water for crop irrigation. However, Figure 4 shows that the technology does not always reduce water intensity. It helped reduce the quantity of water required for beans from 517 m^3 per tonne to 324 m^3 per tonne. It drastically reduced the quantity of water needed to grow cucumbers, from 736 m^3 to only 37 m^3 per tonne. However, the results for tomatoes and sweet peppers show the opposite. The water intensity of tomatoes increased with the use of the technology from 150 m^3 to 202 m^3, and sweet peppers from 147 m^3 to 307 m^3.

According to a hydroponics study in the UAE (Hirich and Choukr-Allah 2017), the water used to grow crops, including tomatoes and sweet peppers, is mostly directed at cooling more than irrigation. Although greenhouse farming produces higher crop yields, irrigation water productivity and crop quality, the study concluded that the need for excessive cooling due to the UAE's desert environment, especially during summer months, made hydroponics unsustainable for agricultural use in the UAE.

Although hydroponics used more water than traditional farming, the former confers benefits not

Figure 4. Water intensity of crop production (m^3 per tonne).



Source: EAD 2017.

typically captured in water minimization modeling. An experiment in Mexico in 2018 (Horti Daily 2018) compared the production of tomatoes and sweet peppers grown in open fields and hydroponic greenhouses. Hydroponics produced more crops of a higher quality, including healthier, less diseased, plants containing fewer insects. It enabled a more controlled use of fertilizers and a controlled environment that allowed for the optimization of nutrients. Soil use, on the other hand, showed many production limitations.

Hydroponics offers substantial water savings for some crops and could be used in Abu Dhabi for the efficient production of cucumbers and beans. Given the challenges of water resource management in Abu Dhabi, water use in the agriculture sector needs to be reduced to sustainable levels through improving water productivity and increasing the efficiency of water use. The next section presents a model that attempts to do that.

Data and Model

This section presents the data used to develop the model, along with the model itself. The model aims to determine the optimal crop portfolio for a given water consumption budget for Abu Dhabi on an annual basis. It finds the least-cost mix of crops that stay within the water budget while satisfying the given demand. It uses key factors such as the water intensity of crops to identify the quantities of crops that can be produced within the water budget.

Linear programming

The model is developed using the General Algebraic Modeling System (GAMS 2019), “which is a high-level modeling system for mathematical programming and optimization. It consists of a language compiler and a high-performance solvers. It is tailored for complex, large-scale modeling applications, and it is specifically designed for modeling linear, nonlinear and mixed integer optimization problems.”

The model is a linear program (LP), an optimization method to determine the best possible outcome from a given set of parameters, such as profit maximization or cost minimization. It is a mathematical technique for optimizing a linear objective function, a model for the analysis of optimum decisions, subject to certain constraints in the form of linear relationships. LPs are used in various fields but more extensively in energy, transportation, telecommunications and manufacturing. The basic components of an LP include an objective function, decision variables, constraints and data. An LP is one of the simplest ways to perform optimization.

This model benefits from a previous water optimization model developed for Saudi Arabia’s agriculture sector (Napoli, Wise, Wogan, and Yaseen 2018; Napoli 2016). We modified this model’s linear program for this paper.

An alternative method to an LP is a mixed complementarity problem (MCP) that includes complementarity relationships. The model developed in this paper is a stand-alone LP, but constructed so it can be converted to an MCP and incorporated into the broader ‘mother’ model, the KAPSARC Energy Model for the GCC (KEM-GCC). KEM-GCC is a partial equilibrium model focused on the GCC countries (Wogan, Murphy, and Pierru 2019), covering three main industrial sectors: oil and gas, power and water. KEM-GCC follows the original KEM model developed for Saudi Arabia, KEM-KSA (Murphy and Pierru 2016; Matar, Murphy, and Pierru 2017).

Data description

The model finds the least-cost mix of crops that enables the emirate to stay within its water budget while satisfying demand without compromising food security or aggregate farmer revenues. Data for these components are readily available at the emirate level and provide sufficient insights into the effect of different crop production mixes versus water consumption.

Data used in the model is provided by EAD and includes the following:

- Crops produced (30 crops)
- Crop type (three crop types)
- Production costs for each crop (Emirati dirham [AED] per tonne)
- Cost of imported crops (AED per tonne)
- Prices paid by the single buyer for each crop (AED per tonne)
- Demand for crops (initial production in tonnes)

- Crop water intensity (m^3 per tonne)
- Desired water budgets (MCM per year)
- Production (tonnes) of crops (single year)

For more details, see Appendix A.

Technical description of the model structure

This section includes a detailed account of the technical description of the model structure, describing and analysing the equations and the data used.

The objective function is the main equation at the heart of the model. It is set to minimize the total cost of producing crops, consuming water, and importing crops, and maximize the net revenues from selling products:

Equation 1. Objective function

$$obj..\min Obj \sum_i \{AGcp_i * (AGq_i + AGm_i)\} - \sum_i \{(AGCimport_i * AGm_i) + AGc_i * AGq_i\}$$

Where *i* is each crop produced, *AGcp* is the consumer price of crops, *AGq* is the quantity of crops produced, *AGm* is the quantity of crops imported, and *AGCimport* is the price of imported crops.

The import balance equation calculates the cost of importing crops, where *AGCimport*Total is the total cost of production, AGm_i is the quantity of imports by crop *i*, and $AGCimport_i$ is the cost of importing crop *i*:

Equation 2. Import balance

$$import\ balance.. \sum_i \{AGm_i * AGCimport_i\} - AGCimportTotal \geq 0$$

The production balance equation calculates the total cost of producing crops (AGCproductionTotal), where AGC_i is the cost of producing crop *i*, and AGq_i is the quantity of crop *i* produced:

Equation 3. Production balance

$$production\ balance.. \sum_i \{AGq_i * AGC_i\} - AGCproductionTotal \geq 0$$

Agricultural products are purchased by a single buyer and then sold to end consumers at subsidized prices. The revenue producers receive (AGrevenue) is a function of the quantity of crop *i* (AGq_i) produced and the price the single buyer pays for crop *i* (AGp_i):

Equation 4. Revenue balance

$$revenue\ balance.. \sum_i \{(AGq_i + AGm_i) * AGp_i\} - AGrevenue \geq 0$$

The water balance equation calculates the total water consumed by all crops produced. Where AGWtotal is the total water consumed by all crops produced, AGq_i is the quantity of crop *i* produced, AGw_i is the amount of water consumed by each crop *i*. Water consumption is captured as follows:

Equation 5. Water balance

$$water\ balance.. \sum_i \{AGq_i * AGw_i\} - AGWtotal \geq 0$$

Water consumption can be constrained by exogenously setting (*AGWtotal*) to a desired water budget (*AGWbud*). Note that the water budget will constrain the possible total level of production. Water intensity (AGw_i) is the volume of water consumed to produce a tonne of crop *i*. The primary policy parameter, the water budget, can be examined to illustrate how the optimal mix of crop production varies by budget.

The water budget is calculated by assuming that the total water consumption by all crops produced (*AGWtotal*) is less than or equal to the water budget (*AGWbud*):

Equation 6. Water budget

$$\begin{gathered}water\ budget..\\ AGWtotal \leq AGWbud\end{gathered}$$

The supply balance equation aggregates the supply of crop type *j* (AGt_j), where AGq_i is the quantity of crop *i* produced and AGm_i is the quantity of imports by crop *i*. Supply can be met by domestic production or imports, whichever costs less. This ensures that production (or imports) is non-negative but allows enough slack for multiple crop portfolios:

Equation 7. Supply balance

$$\begin{gathered}supply\ balance..\\ \sum_{i,j}\{AGq_i + AGm_i\} - AGt_j \geq 0\end{gathered}$$

We represent demand in a more robust way than the aforementioned Saudi Arabia water and agriculture study did (Napoli et al. 2016). The latter considered aggregate demand that could be met by any portfolio of crops. This method required limits to be set on the degree to which crop production could change, to prevent trivial solutions such as producing only one crop – or no crops at all. That approach only looked at aggregate tonnage and revenue, without ensuring a reasonably balanced mix of production.

The modified approach used for the UAE provides a more accurate reflection of reality, where demand is met by all crops. The portfolio of crops can change according to the water budget. We assume exogenous demand for products.

The demand balance equation is calculated by assuming that the supply of crop type *j* (AGt_j) is equal to the demand for crop type *j* (AGd_j).

Equation 8. Demand balance

$$\begin{gathered}demand\ balance..\\ AGt_j - AGd_j \geq 0\end{gathered}$$

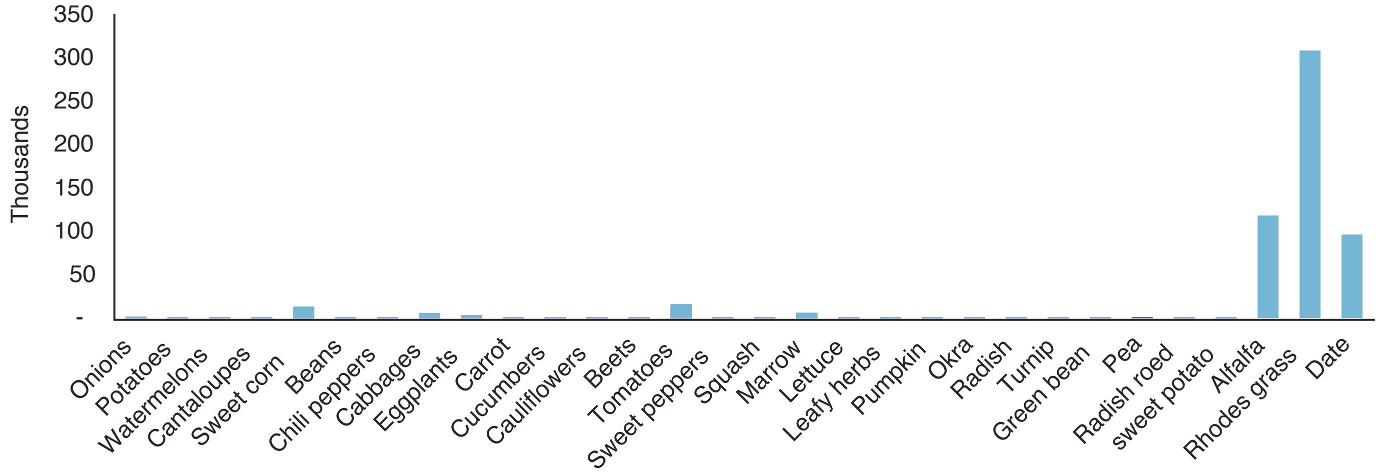
Figure 5 shows the production of crops in tonnes for Abu Dhabi. We considered 30 crops (for the full data, see Appendix A). In terms of tonnage, field crops are shown to have the maximum production, with Rhodes grass and alfalfa the most produced crops, followed by dates.

For more details, see Appendix A.

Figure 4 shows the initial crops produced, and Table 3 shows the initial production grouped by type. The total initial production of all crops is 517,722 tonnes. As we can see, the production of fruit exceeds that of vegetables, by almost a factor of four, and almost four times as many field crops are produced than fruit. Field crops and dates together make up around 90% of crop production.

Figure 5 shows the water intensity level for each crop. As we can see, dates have the highest water intensity, at nearly 3,000 m^3/tonne. Peas are also very water-intensive, at nearly 2,500 m^3/tonne.

Figure 5. Production of crops (tonnes) in Abu Dhabi.



Source: EAD 2017.

Table 3. Initial production of crops by type (tonnes) in Abu Dhabi.

Crop type	Initial production (tonnes)
Fruit	117,302
Vegetables	30,018
Field crops	426,402
Total	573,722

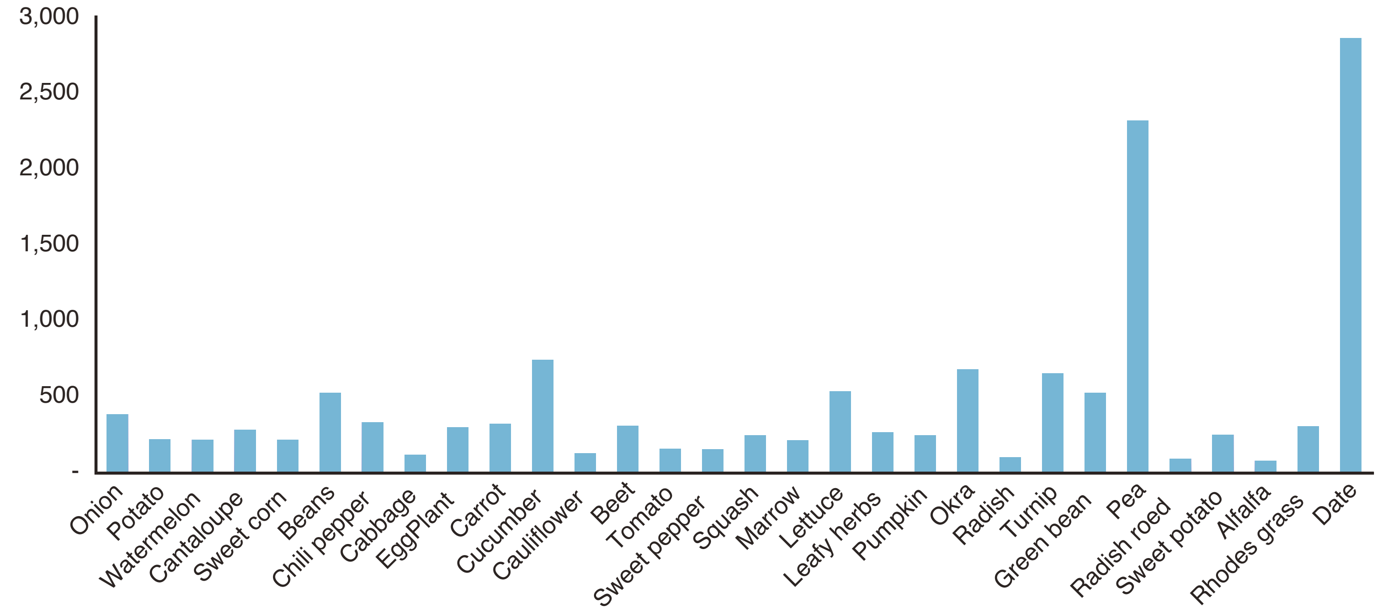
Source: EAD.

Figure 6 shows the aggregate water volume used by crops in m^3. Dates, which have the highest water intensity per crop (Figure 5) and are the third most produced crop in Abu Dhabi (Figure 4), have the highest aggregate water consumption of nearly 300 million m^3. Rhodes grass and alfalfa are not as water-intensive but are produced in large quantities. Because of their water intensity, neighbouring Saudi Arabia has banned all forage crop production in 2019. Peas, which are more water-intensive than field crops, do not appear as water-intensive in aggregate water consumption due to their low overall production of only one tonne. In fact, peas are shown to be the least water-intensive on aggregate, at only 2,000 m^3.

Figure 7 shows the aggregate cost of crop production. It compares the price of crops paid by the single buyer, the cost of producing crops, and the price of importing crops.

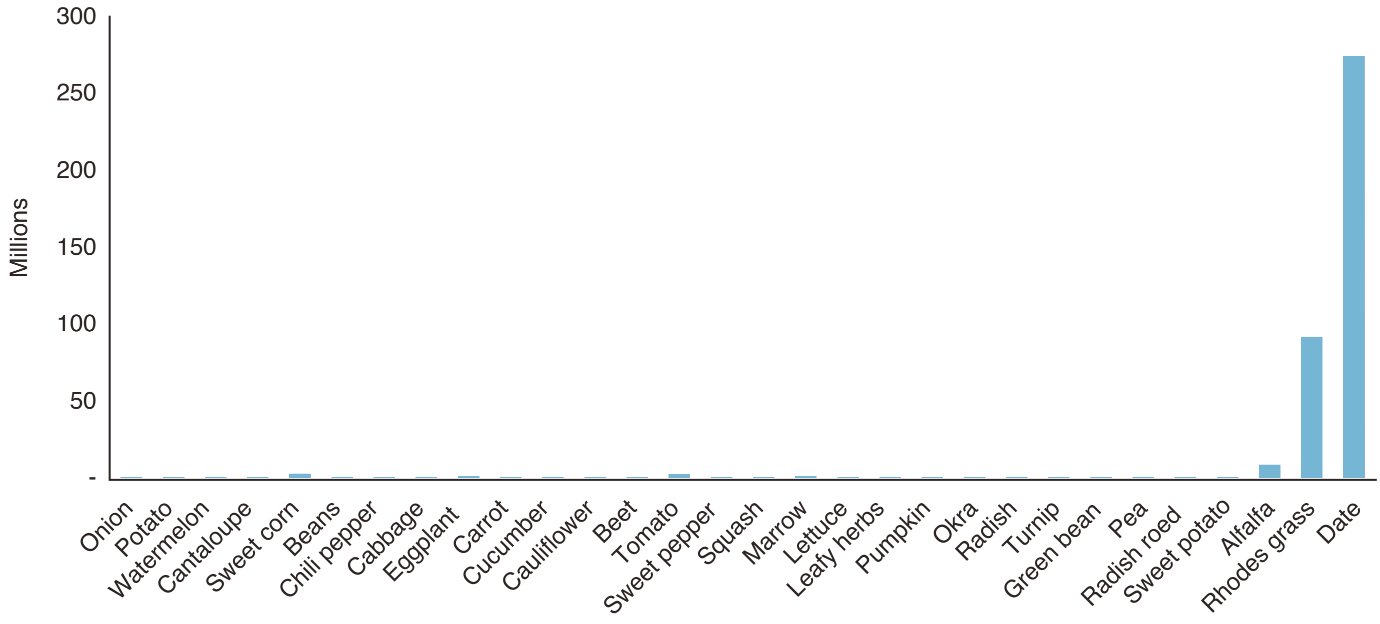
Dates are clearly the most expensive crop produced in Abu Dhabi. Their cost of production far exceeds their import cost by a factor of five, and they are sold at a loss locally. Peas are the second most expensive crop to produce, mostly because of their water intensity, followed by cucumbers and okras. Chili pepper is the most expensive crop to import. Its production cost is much lower than its import cost, so it is most likely more economical to produce it locally. Similarly, the cost of importing sweet corn, cucumber, squash and pumpkin is higher than their local cost of production, so it is cheaper to produce them locally.

Figure 6. Water intensity of crops in Abu Dhabi (m³/tonne).



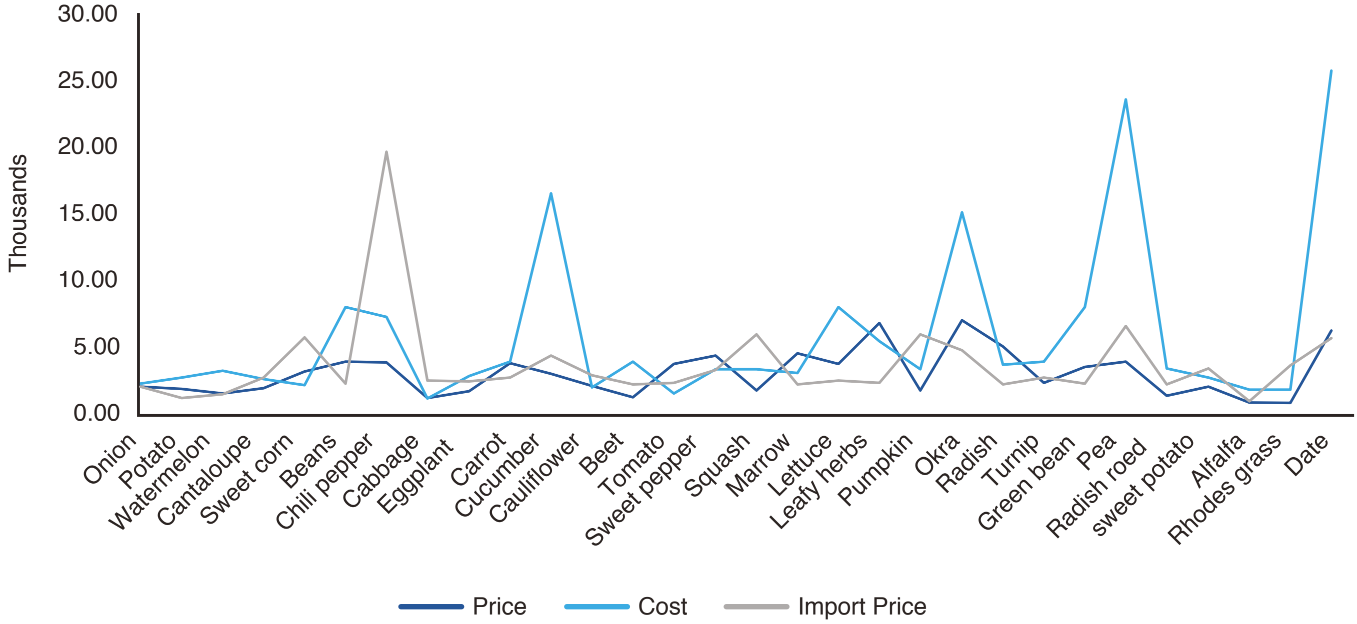
Source: EAD 2017.

Figure 7. Aggregate water consumption by crop in Abu Dhabi (m³).



Source: EAD 2017.

Figure 8. Cost of producing crops in Abu Dhabi (AED per tonne).



Assumptions and limitations

The model assumes no transportation cost. When a water budget is applied, the assumed water budget in the baseline scenario is 1,500 MCM, with other scenarios assuming more restrictive water budgets of 1,000 MCM and 50 MCM. The price of water is embedded in the cost of production. The model also assumes that demand is satisfied by production and imports and assumes no crop exports.

There are inherent limitations to adopting quantitative research methods (Chetty 2016). These include improperly representing the target population, a lack of resources for data collection, the inability to control the environment, the limited outcomes of quantitative research, its expense and time, and the difficulty of data analysis.

In addition, an LP, as the name suggests, deals with linear problems, which is limiting since many of the real world problems are non-linear. Defining an objective function limits the understanding and scope of the problem. Also, defining a set of constraints may not be directly expressible in linear inequalities. And more importantly, an LP is built on many assumptions that are not reflective of the real world. For example, it assumes a linear relationship between inputs and outputs, perfect competition, and constant (instead of diminishing or increasing) returns.

One of the main difficulties in data collection for this model was the lack of data, especially for the water and agriculture sector, for which data has not traditionally been archived, and water use for agriculture was not metered for many years. The EAD was able to provide the required data, albeit with assumptions. For example, an inherent assumption of the EAD data was that the cost of crop production is the same for all crop types, which does not reflect reality and affects the model's results.

Finally, the model treats all crops as equal and distinguishes between them by cost and water intensity only. However, not all crops are equal. Dates, for instance, the third most produced and highest water intensity crop in Abu Dhabi, are not necessarily equal in value to other crops. Other factors that are not considered include calorific value and the cultural significance of certain crops.

Other factors could be used to determine production, such as calorific values, area of land cultivation, soil fertility, crop yields, and seed generations. For example, Farid and Lubega (2014) looked at agricultural capacity planning using the Systems Modeling Language (SysML) (Abdelfattah 2013), another study examined soil fertility and the overall suitability and potential for agricultural expansion to optimize crop production in Abu Dhabi (Shahid and Abdelfattah 2008).

Different factors will have different sets of assumptions and limitations, especially given an LP is limited to linear relationships and the inherent limitations of quantitative methods, as discussed earlier.

Results

In this section, we look at the results of the model using different scenarios. Table 4 lists the scenarios developed.

To develop the scenarios, we introduced two main constraints: imports and a water budget of 1,500 MCM (the irrigation water requirements in Abu Dhabi from Table 2). We also introduced more restrictive water budgets of 1,000 MCM and 50 MCM, to prolong the life of the groundwater.

Table 4. Scenarios developed.

	Scenario	Profit (million AED)	Aggregate water volume (MCM – million m³)
S0	Baseline (allow imports, no water budget)	2,712.81	122.34
S1	No imports (large water budget = 1,500 MCM)	-1,004.16	592.15
S2	Allow imports (large water budget = 1,500 MCM)	2,712.81	122.34
S3	No imports (restrictive water budget = 1,000 MCM)	-1,004.16	592.15
S4	Allow imports (restrictive water budget = 1,000 MCM)	2,712.81	122.34
R1	Allow imports (restrictive water budget = 50 MCM) Fix dates Field crop production is restricted by 50%	2,295.67	50.00

Source: EAD.

In Table 4, scenario S0 reflects the reference case (business as usual) before any policy changes. Under this scenario, imports are allowed and no water budget constraint is applied. In scenario S1, no imports are allowed and we impose a water budget of 1,500 MCM. In scenario S2, we allow imports and impose a water budget of 1,500 MCM. In scenario S3, we do not allow imports and impose a restrictive water budget of 1,000 MCM. In scenario S4, we allow imports but keep a restrictive water budget of 1,000 MCM, and in scenario R1, we cut the field crop production by half, and apply a very restrictive water budget of 50 MCM, while allowing imports. The results show different crop portfolios under different constraints (figures 9-14).

Figure 9 shows scenario 0, which allows imports and has no water budget constraint. The results show a broad range of crops, led by alfalfa, with Rhodes grass the most produced field crop, and tomatoes the most produced vegetable.

Figure 10 shows scenario 1, which does not allow imports and has a large water budget of 1,500 MCM. The model produces all crops locally.

Figure 11 shows scenario S2, which allows imports and has a large water budget of 1,500 MCM. Highly water-intensive crops such as alfalfa and dates are imported, while low water-intensive crops are produced locally, such as Rhodes grass and tomatoes.

Figure 12 shows scenario S3, which does not allow imports and has a restrictive water budget of 1,000 MCM, similar to scenario S1.

Figure 13 shows scenario S4, which allows imports and has a restrictive water budget of 1,000 MCM, similar to scenario S2.

Figure 9. Scenario 0 crop portfolio.

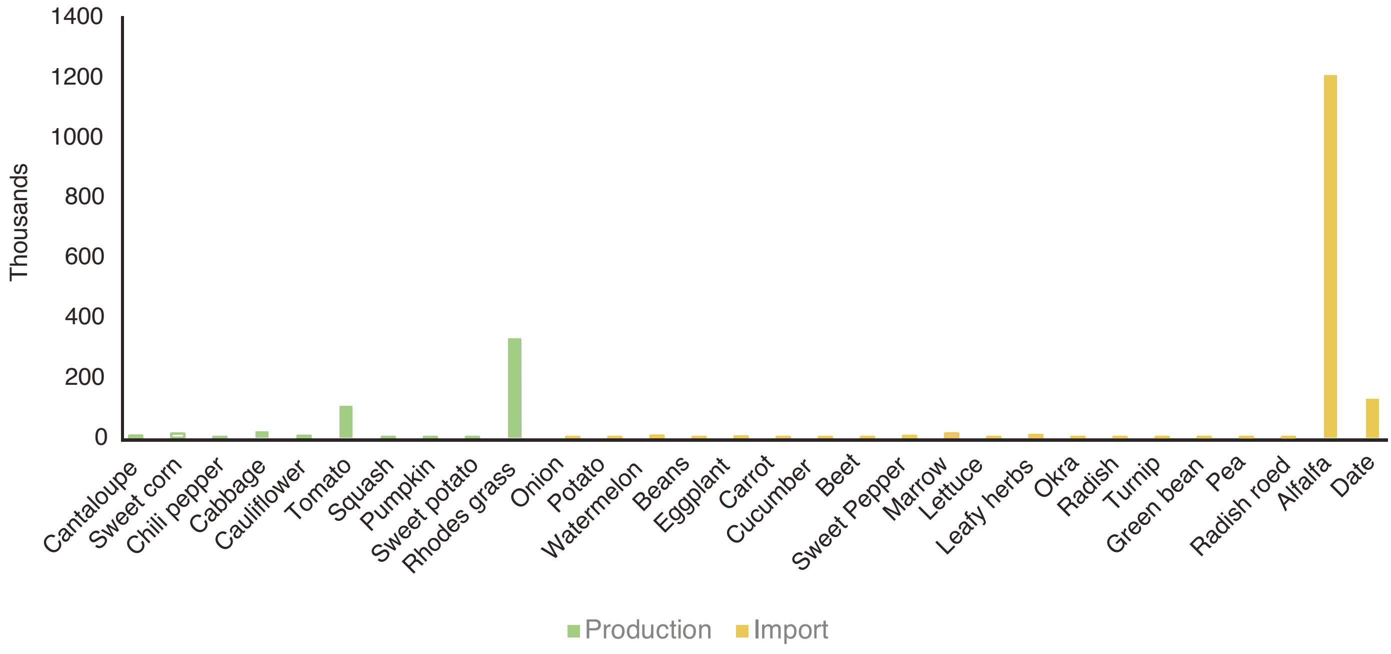


Figure 10. Scenario 1 crop portfolio.

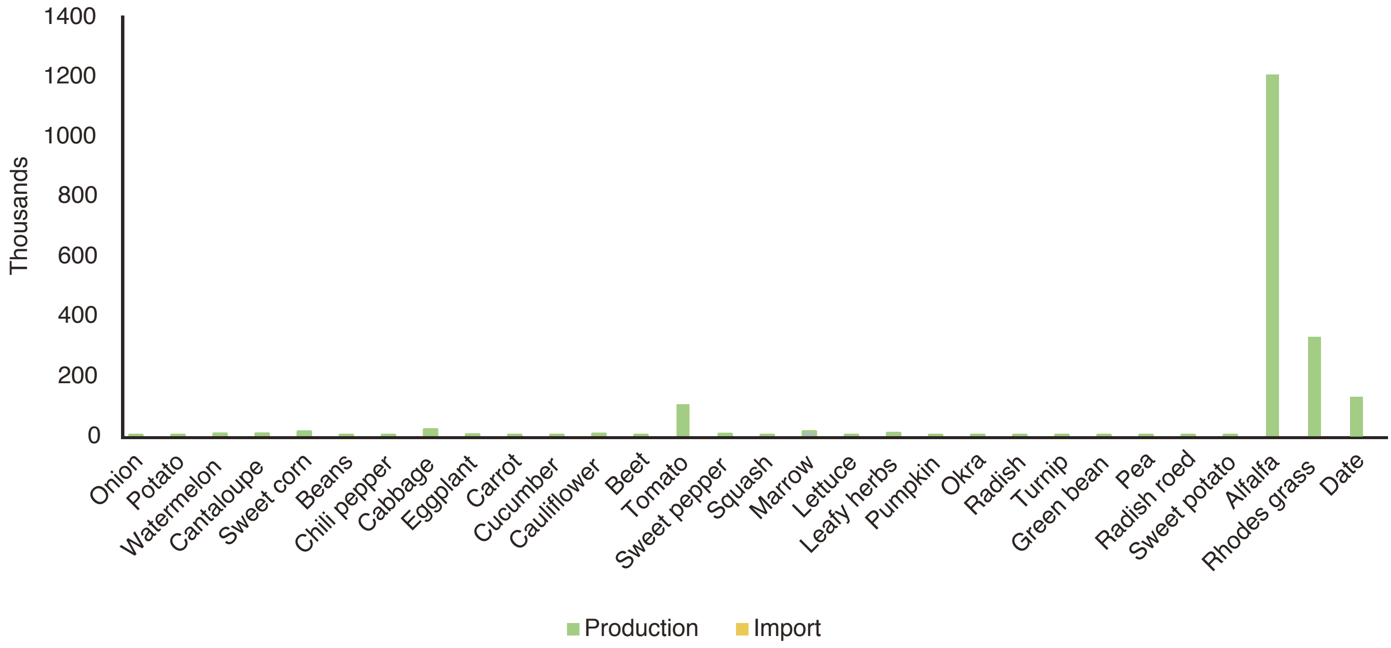


Figure 11. Scenario S2 crop portfolio.

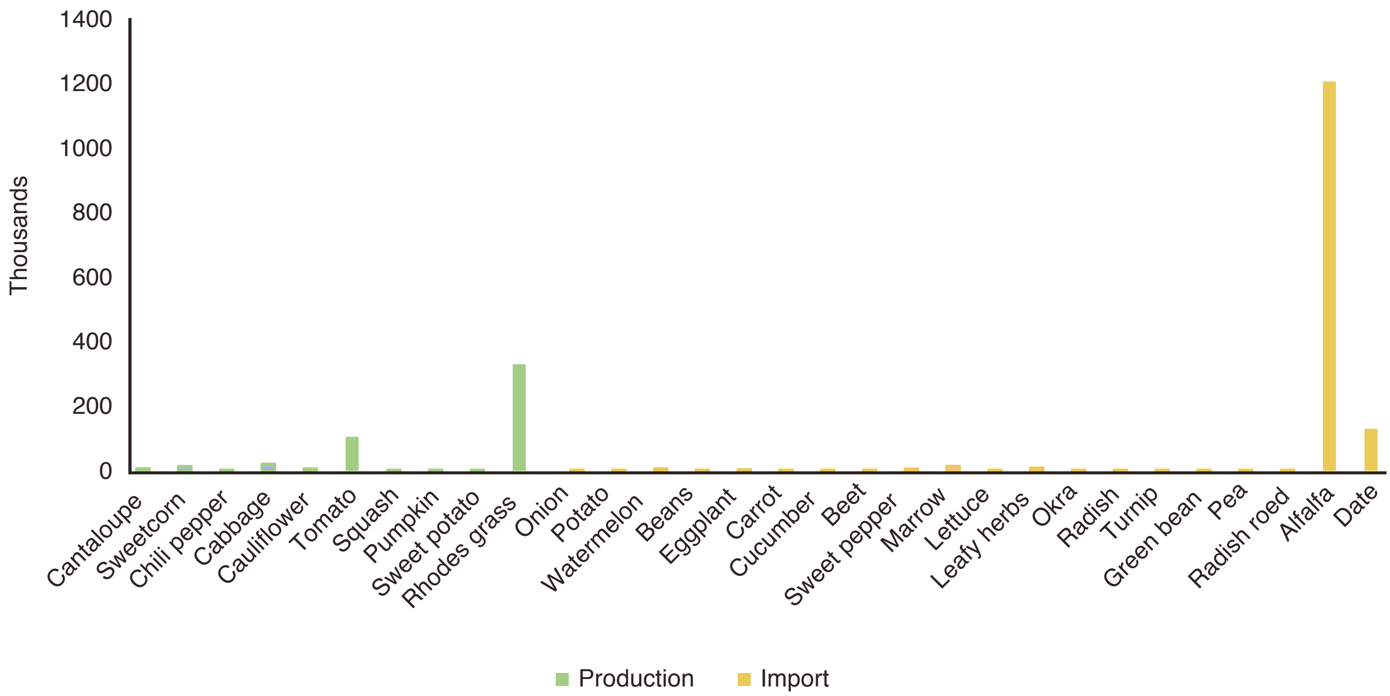


Figure 12. Scenario S3 crop portfolio.

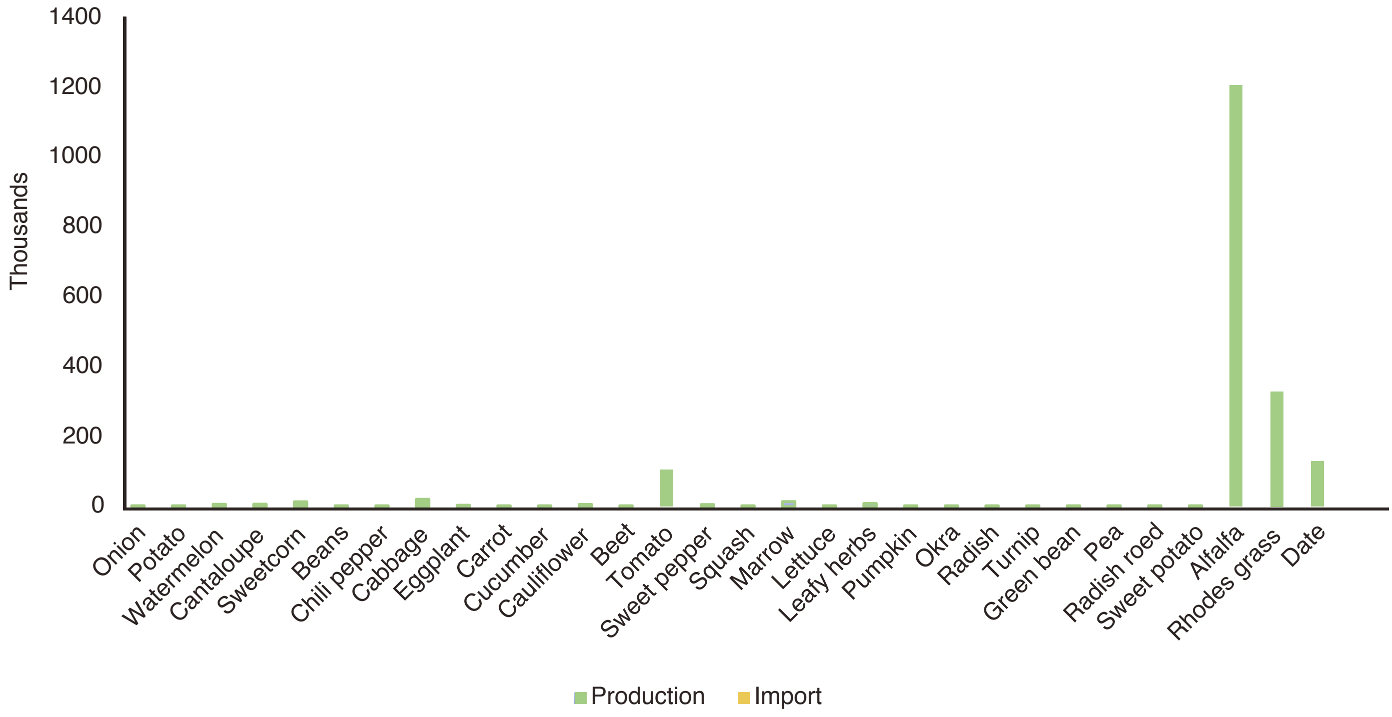


Figure 13. Scenario S4 crop portfolio.

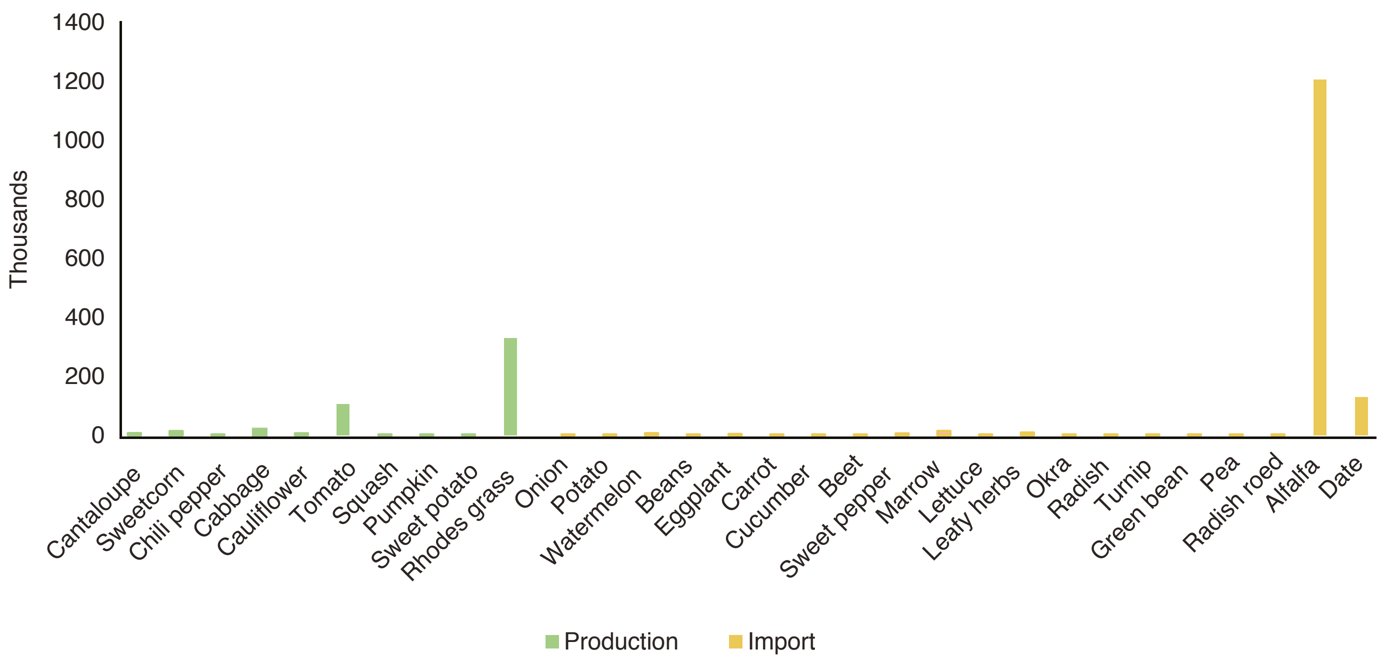
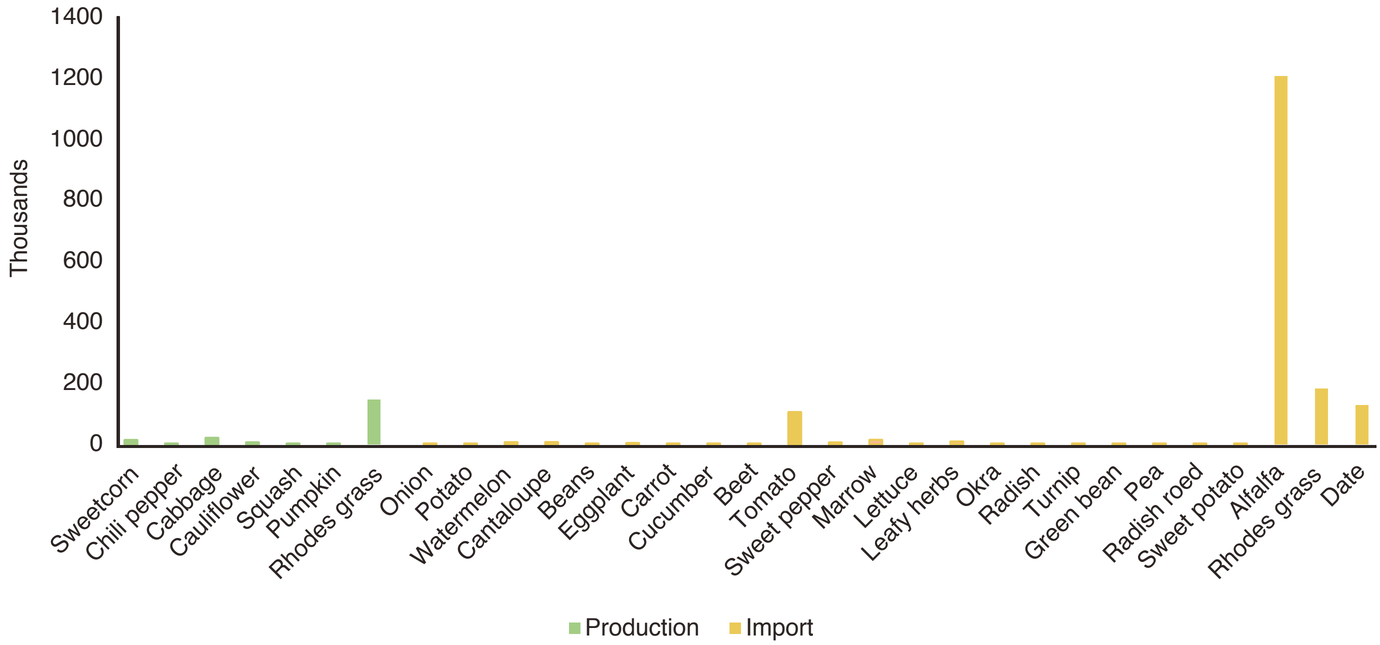


Figure 14 shows scenario R1, which allows imports, has a very restrictive water budget of 50 MCM, and reduces crop production by 50%.

Scenarios S1 and S3 operate at a loss, as shown in Table 4, while scenario R1 reduces the water budget to 50 MCM and halves crop production, which does not meet the demand for crops. Scenario S4 presents the most plausible and feasible option in reducing the water budget to 1,000 MCM while operating at a profit and meeting demand.

The results show how crop production can be optimized to meet water constraints while meeting consumer demand. The model decided when to import (when allowed) and when it was cheaper to import than to produce locally. It optimized the production of its crop portfolio to stay within a given water budget. The insights produced by this model allow policymakers to differentiate between low and high value crops that satisfy demand. This model can be replicated and modified further as needed.

Figure 14. Scenario R1 crop portfolio.



Policy Implications and Future Work

This paper offers insights for policymakers on how to optimize water use in Abu Dhabi, and therefore prolong the available groundwater resources, to make Abu Dhabi's agriculture sector more sustainable.

As discussed, Abu Dhabi currently uses 3,338 MCM of water per year, 60% of which is groundwater (2,000 MCM). It is estimated that this resource will last only 55 years, or 110,000 MCM. Seventy percent of this, around 77,000 MCM, will be used by agriculture at a rate of 1,400 MCM per year.

Under the model's restrictive water budget of 1,000 MCM in scenarios S3 and S4, Abu Dhabi's groundwater reserve is prolonged by 22 years to 77 years. Scenario S3, which did not allow imports, operated at a loss. Whereas scenario S4, which allowed imports, made a profit. Therefore, the authors' recommend scenario S4 as a plausible option.

Under the very restrictive water budget of 50 MCM (scenario R1), groundwater can be prolonged by 1,540 years. However, this scenario fixes the production of dates and halves field crop production, which together make up nearly 90% of all crop production (Table 3). This may not be a plausible option because it might not meet current demands. However, importing dates and fodder (and livestock) rather than growing them locally will significantly reduce Abu Dhabi's water use to sustainable levels.

Dates, which are currently produced locally in Abu Dhabi, have a very high cost of production and a very high water intensity. They are responsible for about 70% of all water used in Abu Dhabi's agriculture sector. They are also sold at a loss and can be imported at one fifth of the cost of locally produced dates. Policymakers should consider the option of reallocating capital away from the production of dates to more productive sectors of the economy.

Alfalfa and Rhodes grass, field crops used as fodder for livestock, are both sold at a loss. While imported Rhodes grass is more expensive than Rhodes grass produced locally, imported alfalfa is cheaper than that produced locally.

Rhodes grass is four times as water-intensive as alfalfa. There is also three times as much Rhodes grass as alfalfa produced. Overall there is ten times as much water used for the production of Rhodes grass as for alfalfa.

Therefore, policymakers should consider reducing or halting the production of Rhodes grass and satisfying the demand for livestock fodder by using imported alfalfa, as needed.

Moreover, as discussed earlier, technology can be used to save water. Cucumbers and beans grown using hydroponics use less water and therefore cost less than when grown in open fields. Since both cucumbers and beans are produced locally in Abu Dhabi, policymakers should consider growing these crops using hydroponics.

Finally, as discussed earlier, the model assigns equal value to all crops. Future studies could investigate other factors that might affect the value of crops, such as their calorific values, the area of land needed to grow them, soil fertility, crop yields, seed generations and their cultural significance.

In conclusion, the model developed combines relevant water and economic parameters into a linear optimization model that can be used to optimize groundwater management in Abu Dhabi's agricultural sector. The model has limitations, as discussed, and therefore offers space for improvement. However, the results from the model highlight a few critical areas for policymakers to consider while focusing on high-value low water-intensity crops and meeting demand.

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Technical Appendix

Appendix A: Crop production

3135.038	2124.913	773.14	5727.803503	SCAD, Statistical Yearbook Of Abu Dhabi 2017
3908.018	7983.914	350.5966	2256.871549	SCAD, Statistical Yearbook Of Abu Dhabi 2017
3812.5	7257.746	59.699	19640.731	ADFSC, Purchase price for agriculture product week (22)
1153.236	1131.054	15454.56	2472.014784	SCAD, Statistical Yearbook Of Abu Dhabi 2017
1685.173	2791.441	668.696	2409.987498	SCAD, Statistical Yearbook Of Abu Dhabi 2017
3803.882	3877.901	1488.297	2716.681206	SCAD, Statistical Yearbook Of Abu Dhabi 2017
3000	16494.88	400.948	4331.993176	ADFSC, Purchase price for agriculture product week (22)
2094.151	1938.951	5326.027	2873.999888	SCAD, Statistical Yearbook Of Abu Dhabi 2017
1242.268	3877.901	576.7937	2191.969627	SCAD, Statistical Yearbook Of Abu Dhabi 2017
3700	1512.03	89545.14	2301.368514	ADFSC, Purchase price for agriculture product week (22)
4375	3298.975	5715.618	3260.035048	ADFSC, Purchase price for agriculture product week (22)
1750	3298.975	354.6541	5952.452475	ADFSC, Purchase price for agriculture product week (22)
4500	3016.145	8526.905	2214.307536	ADFSC, Purchase price for agriculture product week (22)
3707.895	7983.914	236.4165	2472.014784	SCAD, Statistical Yearbook Of Abu Dhabi 2017
6770	5429.062	7805.579	2321.716557	SCAD, Statistical Yearbook Of Abu Dhabi 2017
1750	3298.975	15.52294	5952.452475	ADFSC, Purchase price for agriculture product week (22)
7000	15120.3	66.817	4740.814463	ADFSC, Purchase price for agriculture product week (22)
5004.255	3667.191	382.5957	2191.969627	SCAD, Statistical Yearbook Of Abu Dhabi 2017
2329.825	3877.901	1063.461	2716.681206	SCAD, Statistical Yearbook Of Abu Dhabi 2017
3500	7983.914	7.983427	2256.871549	ADFSC, Purchase price for agriculture product week (11)
3908.018	23552.55	332.869	6569.022649	SCAD, Statistical Yearbook Of Abu Dhabi 2017
1350	3393.163	310.9625	2191.969627	ADFSC, Purchase price for agriculture product week (8)
2000	2714.531	512.611	3404.30853	ADFSC, Purchase price for agriculture product week (22)
806.1334	1784.18	1088077	924.5284108	SCAD, Foreign Trade Statistics, 2017
800	1783.975	21168.16	3602.423876	SCAD, Foreign Trade Statistics, 2017
6249.133	25725.12	33351.53	5650.755474	SCAD, Statistical Yearbook Of Abu Dhabi 2017

Notes

Notes

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About the Project

This is a joint research project between the King Abdullah Petroleum Studies and Research Center (KAPSARC), the Environment Agency-Abu Dhabi (EAD) and the Abu Dhabi Food Control and Water Authority (ADFCA).

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