

Optimization of the cropping pattern in Saudi Arabia using a mathematical programming sector model

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Abstract: A mathematical sector model has been formulated to optimize the cropping pattern in Saudi Arabia aiming at maximizing the net annual return of the agricultural sector in Saudi Arabia and ensuring the efficient allocation of the scarce water resources and arable land among the competing crops. The results showed the potential for Saudi Arabia to optimize its cropping pattern and to generate an estimated net return equivalent to about 2.42 billion US\$ per year. The optimized cropping pattern in Saudi Arabia has been coupled with about 53% saving in the water use and about 48% reduction in the arable land use compared to the base-year cropping pattern. Comparable weights was given to different crop groups by allocating about 48.4%, 35.4%, 13.1%, and 3.2% to grow cereals, fruits, forages, and vegetables, respectively. These findings were in line with the national strategy to rationalize the cultivation of water-intensive crops in favour of highly water-efficient crops.

Key words: maximum net return, efficient water allocation, LINGO optimizer modelling program

Agricultural sector is a key driver in the world-wide economic and social development. It plays a substantial role in achieving, among other, food security, economic diversification, poverty eradication, and human welfare. Its role is highly emphasized while the international community, in particular developing countries, is struggling to cope with the impacts of the climate change and the implementation of response measures in a sustainable manner. The adjustment of planting dates and crop variety, and crop re-allocation are among the selected planned adaptation actions in the agricultural sector (IPCC 2007).

The vulnerability of the agricultural sector to climate changes has driven Saudi Arabia to set up programs and policies heading towards maximizing the utilization of its limited resources, mainly, the irrigation water supply and arable land to produce high value crops such as fruits and vegetables. The 8th Development Plan of Saudi Arabia (Ministry of Economy and Planning 2004) emphasized the importance of rationalizing the cultivation of water-intensive crops, such as cereals and fodder, in favour of highly water-efficient crops, such as fruits and vegetables.

This research paper underlines some of the promising deliverables of a five-year research project (Al-Amoud et al., 2010) funded by the King Abdulaziz City for Science and Technology – Saudi Arabia

(<http://www.kacst.edu.sa>), to optimize the cropping pattern in Saudi Arabia using a mathematical sector model that would maximize the net annual return of the agricultural sector in Saudi Arabia and to ensure the efficient allocation of the scarce water resources and arable land among the competing crops.

Various modelling approaches have been applied to optimize the cropping pattern worldwide including the linear and nonlinear optimization models (Haouari and Azaiez 2001; Singh et al. 2001; Montazar and Rahimikob 2008; Kaur et al. 2010); deterministic linear programming and chance-constrained linear programming models (Sethi et al. 2006), the interactive fuzzy multi-objective optimization approach (Zhou et al. 2007), the goal program approach (Vivekanadan et al. 2009), the multi-objective fractional goal programming approach (Fasakhodi et al. 2010), and the genetic algorithm model (Karamouz et al. 2010).

MATERIALS AND METHODS

Fourteen cash crops grown in nine major cropping-production regions (study regions) in Saudi Arabia were considered to optimize the cropping pattern in accordance with the regional comparative advantage. The considered crops covered different crop groups, namely, forage including alfalfa and roadus grass;

cereals including wheat, sorghum, millet, and sesame; vegetables including tomatoes, potatoes; and fruits including dates, melons, olives, orange, mango and lemon. The market structure was visualized in this study as having two supply regions. Both regions compete to satisfy the national demand of the given commodity. These supply regions represent: (i) supply from the major cropping-production regions or study regions, and (ii) supply from the outside study regions or the rest of the nation. At the given price, supply from study regions would represent the difference between the quantity demanded and the quantity supplied from the outside study regions.

A mathematical sector model has been formulated to achieve the ultimate objective of this study using the LINGO optimizer modelling program (2008), popular and reliable software used for solving optimization models. The mathematical formulation of the formulated sector model comprised four key components: objective function, resource constraints, national commodity balance and national trade balance.

The *objective function* of the sector model was to determine the optimal one-year cropping pattern in accordance with the comparative advantage in the major cropping-production regions in Saudi Arabia. The model maximized the net annual return subject to the limited water supply and arable land, given the marketing and trade balance constraints.

$$Z^y = \sum_{j=1}^J f(W_j^y) - \sum_{r=1}^R C_{jr}^y X_{jr}^y - I_j^y + E_j^y \quad \text{for all } j, r \quad (1)$$

where:

- Z^y = net economic return, in terms of US \$ per year
- $f(W_j^y)$ = welfare function which measures the area under the excess demand equation for j^{th} crop in year y
- C_{jr}^y = average cost for the j^{th} crop in r^{th} study region, in terms of US \$ per ton
- X_{jr}^y = average yield for j^{th} crop in r^{th} study region, in terms of tons per hectare
- I_j^y = Net national imports for j^{th} crop in year y , in terms of tons
- E_j^y = Net national exports for j^{th} crop in year y , in terms of tons
- J = 1, 2, 3, ..., 13 crops
- R = 1, 2, 3, ..., 9 study areas

The *resource constraints* ensured that the amount of the limited resources used in the production process did not exceed the available levels of resources. Two key resource constraints were applied in the model: water supply and arable land. Water supply constraint was presented in two forms: a monthly water supply and an annual water supply. The monthly water supply was used to overcome the seasonality of production and to ensure that the irrigation water requirements of

all crops in the study areas did not exceed the available monthly water supply, while the annual water supply constraint ensured that the annual irrigation water requirements for the considered economic crops in the study areas did not exceed a specific quantity of water annually. The mathematical illustration of the resource constraints was presented as follows:

$$\sum_j a_{ijr}^t X_{jr}^y \leq b_{ir}^t \quad \text{for all } i, r \quad (2)$$

$$\sum_j a_{wjr}^y X_{jr}^y \leq w_r^y \quad \text{for all } r \quad (3)$$

where:

- a_{ijr}^t = input-output coefficients that states the amount of i^{th} resources required to produce one hectare of j^{th} crop in r^{th} study region in time t
- X_{jr}^y = annual yield for j^{th} crop in r^{th} study region in terms of ton per hectare
- b_{ir}^t = maximum amount of i^{th} resource available in r^{th} study region in time t
- a_{wjr}^y = irrigation water requirements (w) for j^{th} crop in r^{th} study region in year y
- w_r^y = maximum water supply in year y in r^{th} study region
- I = irrigation water requirement, and arable lands
- T = 1, 2, 3 ..., 12 months

For the given crop, the *national commodity balance* comprised three key elements. These were the average supply in the study areas (GS_{jr}^y), the net national import (NI_{jn}^y) or the net national export (NE_{jn}^y), and the excess national demand (Ed_{jn}^y). The national commodity balance for the net-imported crops aimed at ensuring that the sum of the study areas' supplies and the net national import were greater than or equal to the excess national demand. On the other hand, the national commodity balance for the net-exported crops aimed at ensuring that the sum of the regional supplies was greater than or equal to the excess demand plus the net national exports for the given crop. The national commodity balance was illustrated mathematically for the net-imported crops and for the net-exporting crops, respectively, as follows:

$$Ed_{jn}^y - NI_{jn}^y - GS_{jr}^y \leq 0 \quad (4)$$

$$Ed_{jn}^y + NE_{jn}^y - GS_{jr}^y \leq 0 \quad (5)$$

where:

- Ed_{jn}^y = excess national demand for the j^{th} crop in year y
- NI_{jn}^y = net national imports for the j^{th} crop in year y
- GS_{jr}^y = average production for the j^{th} crop in year y
- Ed_{dn}^y = excess national demand for exporting crops in year y
- NE_{dn}^y = net national exports for exporting crops (d) in year y
- GS_{dr}^y = average production of exporting crops (d) in year y

The *national trade balance* ensured that the net national import (NI_{jn}^y) for the given crop did not exceed a maximum limit for the net national imports (I_{jn}^y) annually, and the net national export (NE_{jn}^y) for the given crop did not exceed a maximum limit for the net national exports (E_{jn}^y) annually. The national trade balance could be illustrated mathematically as follows:

$$NI_{jn}^y \leq I_{jn}^y \quad (6)$$

$$NE_{jn}^y \leq E_{jn}^y \quad (7)$$

where:

NI_{jn}^y = net national imports for j^{th} crop in year y

I_{jn}^y = maximum limits for net national imports for j^{th} crop in year y

NE_{jn}^y = net national exports for j^{th} crop in year y

E_{jn}^y = maximum limits for net national exports for j^{th} crop in year y

The key input-output coefficients for the mathematical sector model include the average values of the following: yield, market price, production cost, CIF and FOB prices, crop water requirements and national demand for the considered cash crops.

More than 160 farms were field-surveyed and some statistical yearbooks were investigated to calculate the required input-output coefficients. Table 1 shows the input-output coefficients for the considered cash crops in Saudi Arabia.

RESULTS AND DISCUSSION

Optimizing the cropping pattern of the considered crops in Saudi Arabia in accordance with the regional comparative advantage using the mathematical sector model showed the great potential of Saudi Arabia to restructure its cropping pattern in accordance with its limited water resources and arable land and to generate a high net annual return equivalent to about 2.42 billion US\$/year. The optimized cropping patterns would provide Saudi Arabia with the opportunity to reduce the cropping areas by about 48%, from about 704 thousand hectares to about 364 thousand hectares, and the water supply by about 53%, from 8.84 million cubic meters a year to about 4.12 million cubic meters a year.

As shown in Figure 1, the optimized cropping patterns put comparable weights to different crop

Table 1. Mathematical programming sector model input-output coefficients in Saudi Arabia

	Crops	Average yield	Average market price	Average production costs	Average national demand	Import price (CIF)	Export price (FOB)	Average water requirements*
		(ton/ha)	(US \$/ton)	(US \$/ton)	(ton/year)	(US \$/ton)	(1000 cm/ha)	
Forage	alfalfa	15.33	202.39	3 364.63	1 739 895	188.54	183.85	4 102.09
	roadus	4.50	1 329.79	3 627.93	363 237	na	na	2 110.88
Cereals	wheat	4.57	258.24	1 692.82	2 658 716	211.73	623.18	2 203.79
	sorghum	2.59	894.95	1 179.26	244 396	208.50	634.08	646.73
	millet	1.44	944.15	403.99	15 566	205.80	578.71	9.62
	sesame	1.68	1 104.52	775.00	30 910	827.90	663.76	11.28
Vegetables	potatoes	22.64	331.38	3 283.78	389 734	261.81	202.74	64.09
	tomatoes	17.56	500.00	2 718.62	483 459	167.46	313.88	73.45
Fruits	dates	6.34	1556.12	3 107.45	889 296	412.79	667.50	928.31
	melon	13.20	361.97	2 081.12	306 367	346.30	261.28	127.38
	olives	12.19	262.77	2 173.14	15 266	2 936.32	731.30	494.31
	orange	18.33	310.37	2 147.07	297 565	379.22	479.43	7.13
	mango	7.29	1 263.30	4 265.73	52 604	607.74	438.87	9.88
	lemon	20.72	1 429.52	1 602.66	122 550	390.71	330.03	2.50

Sources: calculated from field survey collected data (2007), Ministry of Agriculture (2007), Ministry of Agriculture official website www.agrwat.gov.sa/public/portal, Food and Agriculture Organization www.fao.org

*Al-Amoud et al. (2010)

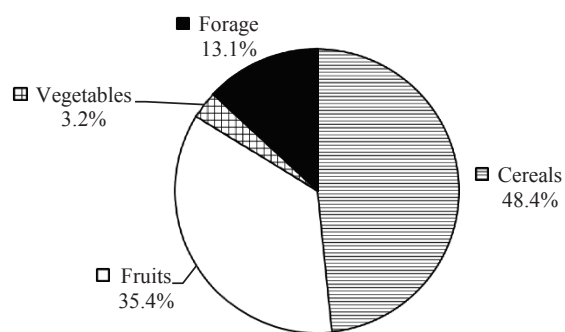


Figure 1. Optimized cropping pattern in Saudi Arabia using sector model

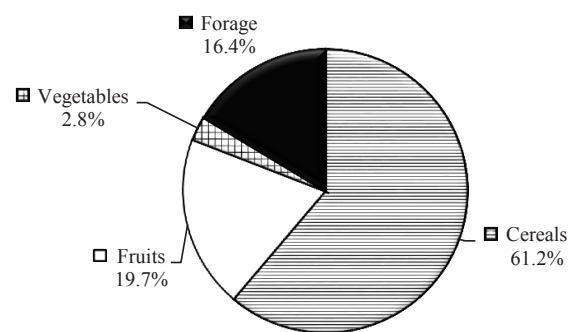


Figure 2. Base-year cropping pattern representing the average cropping areas in Saudi Arabia during 2003–2005

groups by allocating about 48.4%, 35.4%, 13.1%, and 3.2% to grow cereals, fruits, forages, and vegetables, respectively, while the base-year cropping patterns, which represent the average cropping areas in Saudi Arabia during 2003–2005, placed a higher weight to cereals by allocating more than 61.2% from the cropping areas to cereals and 19.7% to fruits, 16.4% to forages, and 2.8% to vegetables, as shown in Figure 2. These findings were in line with the national strategy to rationalize the cultivation of water-intensive crops, such as cereals and fodder, in favour of highly water-efficient crops, such as fruits and vegetables.

In terms of the allocated cropping area, the optimized cropping pattern was given the priorities from among the fourteen considered cash crops to grow wheat, dates and alfalfa, respectively, with an allocated area equivalent to about 89% of the total cropping area in Saudi Arabia. The allocated cropping area was different in the base year, the cropping pattern giving the priority to wheat, sorghum, dates, and alfalfa with a proximity allocated area equivalent to about 93% of the total cropping area. Table 2 compared the optimized cropping pattern versus the base year cropping pattern for each considered crop in Saudi Arabia.

Table 2. Optimized cropping pattern Vs. Base year cropping pattern in Saudi Arabia

Crops	Base-year cropping area	Relative importance of base year cropping area at a national level	Optimized cropping area	Relative importance of optimized cropping area at a national level
	(1000 ha)	(%)	(1000 ha)	(%)
Wheat	304.80	43.2	163.72	44.9
Sorghum	121.90	17.3	10.46	2.9
Dates	118.20	16.8	112.99	31.0
Alfalfa	110.70	15.7	47.61	13.1
Melon	18.06	2.6	13.70	3.8
Tomatoes	9.90	1.4	2.03	0.6
Potatoes	9.20	1.3	9.10	2.5
Roadus	4.80	0.7	0	0
Millet	2.40	0.3	0	0
Sesame	2.11	0.3	2.11	0.6
Orange	1.47	0.2	1.47	0.4
Mango	0.51	0.1	0.51	0.1
Lemon	0.38	0.1	0.38	0.1
Olives	0.35	0.1	0.35	0.1
Total	704.77	100.0	364.44	100.0

CONCLUSIONS

Saudi Arabia is among the most vulnerable countries regarding the impact of the climate change and the impact of the implementation of response measures. Optimizing the cropping pattern of the cash crops in accordance with the comparative advantage in the major crop production regions in Saudi Arabia would scale up the capability to adapt to climate change and its impacts and it would demonstrate what crops and where to grow, given the limited natural resources, and to bridge the gap between the national demand and supply through importing from the world market. The findings of this research project are significant and will be of a great interest not only to the researchers working in the field, but they will also appeal to the decision makers and to a broader public.

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