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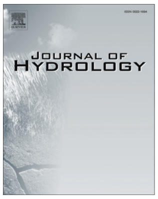

The impact of food and agricultural policies on groundwater use in Syria

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SUMMARY

During the last three decades, the expansion of irrigation using both surface water and groundwater resources has had an important positive impact on Syria's agricultural production. It is an example of success in achieving food policy objectives, but it has also introduced the challenge of groundwater sustainability. This paper examines the trends in groundwater abstraction for irrigation and the effect of government policies, including input subsidies – such as the diesel fuel subsidy and the crop procurement price support. The fuel subsidy is an important driving force in groundwater depletion and over-abstraction. This analysis examines the interaction between policy signals and the use and allocation of water by farmers. The rapid decline in groundwater resources shows the limitations of this agricultural development strategy and questions its sustainability unless policies change and the rate of abstraction is changed so as not exceed the recharge rate.

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1. Introduction

Water scarcity is globally recognized as a serious development constraint and a potential source of international and intra-national conflicts. Lack of water is already constraining agricultural production in many parts of the world (Biswas, 2010; FAO, 2009; Jhorar et al., 2009; Dhehibi and Telleria, 2012). The Middle East and North Africa (MENA) region is the most water scarce one in the world (World Bank, 2007). Worldwide, the average water available per person is about 7000 m^3/person/year; in the MENA region, it is only around 1200 m^3/person/year. In this region, the population is expected to grow from about 380 million today to about 500 million in 2025 (World Bank, 2007), while per capita water availability is expected to fall to 500 m^3/person/year by 2025 (UNOCHA, 2010).

The challenges of water scarcity are heightened by the increasing costs of developing new water resources, land degradation in irrigated areas, groundwater depletion, water pollution, and ecosystem degradation (Rosegrant and Cline, 2003). Unsustainable water management practices, which exceed the system's carrying capacity, impose direct significant costs, in terms of lost farm productivity, and indirect costs which are potentially enormous (Khan and Hanjra, 2008). Over-extraction of groundwater and aquifer depletion threatens many of the world's most important food-producing regions, including the North China Plain, the Indian Punjab, parts of Southeast Asia, large areas of MENA, and much of the western United States (Rosegrant and Cline, 2003; Postel, 1999). Results from recent climate change models suggest greater water stress from decreased precipitation in many arid and semi-arid regions worldwide, including parts of the Middle East, Africa, Australia, and the United States (Qureshi et al., 2010; Christensen et al., 2007). A fundamental shift in water and energy use is needed in food policy to avoid a severe food crisis in the future (Hanjra and Qureshi, 2010).

Excluding the Gulf region, agriculture is the largest consumer of water in the MENA region, taking an average 85% of the supply (Richards and Waterbury, 2008). Syria is located within the water-critical region. Agriculture accounts for 87% of the water withdrawn from Syria's aquifers, rivers, and lakes (FAO AQUASTAT, 2012). Renewable water resources in Syria are estimated at 808 m^3/capita/year (FAO AQUASTAT, 2012), which is below the water scarcity threshold of 1000 m^3/capita/year (Roudi-Fahimi et al., 2009). With a rate of population growth consistent with the UN's medium variant population projection (UN-DESA, 2011), the country will approach the absolute water scarcity threshold

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(500 m^3/capita/year) by 2050. However, both climate change and developments in neighboring countries are likely to reduce these resources even further, considering that half of Syria's annual renewable water resources originate from cross-border flow, with the majority of it flowing in from Turkey by way of the Euphrates.

Groundwater-based agriculture comprises 53% of the total irrigated land (MAAR, 2010). Expansion of the use of groundwater use in agriculture has had a positive effect on production so far, but it could have a considerable adverse effect on the availability of water resources in the long run. In effect, the sustainability of agricultural incomes and rural livelihoods are at stake. However, the effects of such expansion on the sustainability of water resources have received less attention than the effects on food and income security. Policy makers have only recently come to consider the issue of resource capacity (Salman and Mualla, 2008).

Energy, mainly diesel fuel, is used to power groundwater abstraction and currently constitutes the major component of the variable costs involved. Diesel prices in Syria increased with the world oil price surge in 2011. Yet, diesel fuel prices remain subsidized, and are reckoned to cost Syria around 5% of gross domestic product (GDP) a year (The Economist, 2011). Prior to the increase in these fuel prices, farmers did not consider the cost of pumping to be a critical production constraint, though this perception might change as a result of the higher diesel prices.

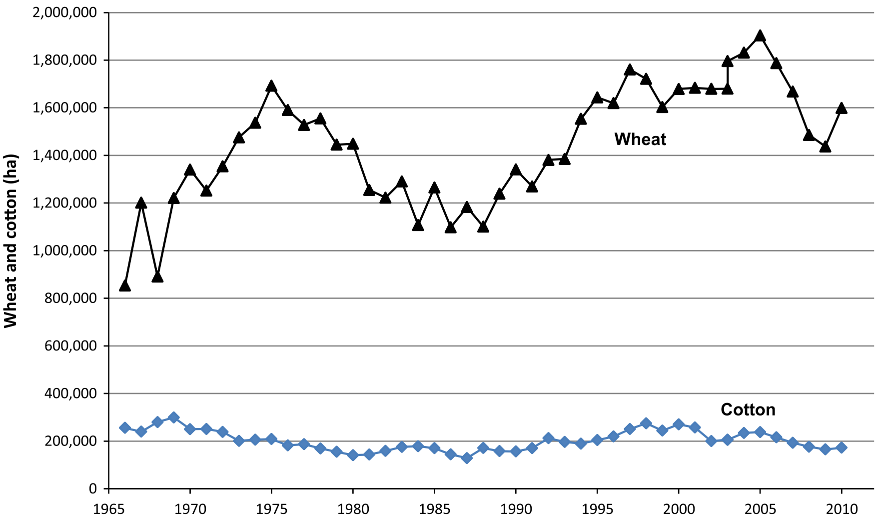
This study analyzes the effects of food and agricultural policies on groundwater use in Syria. The driving forces that have contributed to the high-intensity of groundwater use in Syria are examined and their effects on the development of groundwater-based irrigation are discussed, along with the potential consequences. The study evaluates the effects of changes in energy prices (i.e. through the removal of fuel subsidy) on the profitability of different crops. The study undertakes a simulation of how farmers might respond, in terms of crop choice and water use, to changes in energy policy. We argue that groundwater abstraction in the dry areas, if it continuously exceeds the recharge rate, resembles a mining process – extracting a limited resource, with its inevitable depletion and its economic, social, and environmental consequences.

2. Background on Syria's food and irrigation policies

Based on the overall government development policy objectives, the expansion in irrigated agriculture in Syria can be categorized into three broad phases. The first phase, from 1966 to 1984, was an expansion of irrigation systems as a result of policies to improve food security and agricultural and rural development (Wakil, 1993). Since the 1960s, wheat has covered more hectares than any other crop in Syria. By 1966 wheat cultivation was already above 800,000 ha, providing more than 550,000 tons of wheat (FAOSTAT, 2013). By 2005, wheat was covering almost 2 million ha and this decreased to about 1.5 million ha by 2010. In general, wheat cultivation has followed an up and down pattern, though the long-term trend was positive from 1966 to 2010 (Fig. 1). Cotton has been an important crop since the 1960s. It accounted for 60% of the irrigated land, or about 220,000 ha, in the period 1966–1969. The irrigated wheat and vegetable areas each occupied 14% of the irrigated land during the same period. During this period, the cotton area experienced a declining trend; it recovered a little through the 1990s, but again followed a downward trend from 2000 onwards.

The second phase marked the period between 1985 and 2000. To ensure that production targets were met in this period, agricultural production plans were drawn up every year for the country's main products and guaranteed prices were set for strategic crops, such as wheat and cotton. Farmers participating in the official production schemes would receive direct subsidies on farm inputs, such as seeds, fertilizers, farm equipment, and fuel. Farmer participation was used to facilitate the granting of well licenses, and sometimes these schemes took precedence over the observance of drilling restrictions. Farmers registered for government production schemes were given greater access to low-interest loans, which were, in turn, used to purchase inputs. In addition, to allow farmers to dig wells and purchase pumps, medium-term loans were provided at an interest rate of 5%, which was low in comparison with the official rate of 9%, while the informal market rate could be as high as 50%. (For a detailed description of the Syrian policy's specific measures that related to irrigation water in the 1990s, see Varela-Ortega and Sagardoy, 2001.)

As domestic diesel fuel prices did not fluctuate in line with international petroleum prices, the domestic diesel price in Syria used to be as low as 20% of the world market price. The difference was an explicit fuel subsidy. Of the various agricultural input subsidies provided during the 1990s (Table 1), the largest was applied to diesel fuel, constituting approximately 80% of the local purchase price. Thus, in Syria, approximately 75% of the groundwater pumps and well rigs and the equipment for drilling and deepening wells



Source: Authors' elaboration based on data from MAAR, Statistical Yearbook, 1980—2010.

Fig. 1. Wheat and cotton cultivation in Syria, 1966–2010.

were all powered by diesel motors supported by diesel subsidies (NAPC, 2003).

In response to subsidy policies, credit facilities, and crop price support, the most dramatic shift started in the late 1980s through the 1990s when groundwater-irrigated areas and the construction of wells expanded rapidly – at an average annual growth rate of 15% (Fig. 2). As a result, by 2000 the irrigated areas had expanded to about 1.2 million ha (double the area of 1984). The rapid growth in irrigated wheat and cotton cultivation coincided with the growth of fertilizer use and a rapid expansion in the exploitation of groundwater from the expansion in artesian wells. (For a discussion on the effects of irrigation on modern technology use for and livelihoods from wheat production, see Mazid et al., 2003.)

During the period of rapid groundwater development (1990–1997) the production of cotton rose from 160,000 tons to about 230,000 tons, at a rate of 6% a year. Similarly, wheat production increased from 1.6 million tons to over 4 million tons, a growth rate of around 15% a year. This implies that, during the period 1990–2000, a considerable portion of the country experienced a shift from rainfed farming to irrigated agriculture. More importantly, most of this shift took place within a relatively short period of time.

This expansion in irrigation and the changes in irrigated cropping patterns have had several important implications. First, the impact of policy on groundwater development was both clear and dramatic. Before 1988, both the number of wells and the groundwater-irrigated area were stable, with only about 53,000 wells being used to irrigate around 309,000 ha. By 1994, the number of wells had increased sharply, reaching around 124,000, while the area irrigated with groundwater had increased to over 700,000 ha, accounting for about 64% of the total irrigated area during the 1990s. Yet, between 2005 and 2009 the groundwater-irrigated area declined to 53% of the total irrigated area (CBS, 2010) for the reasons discussed below when examining the third phase.

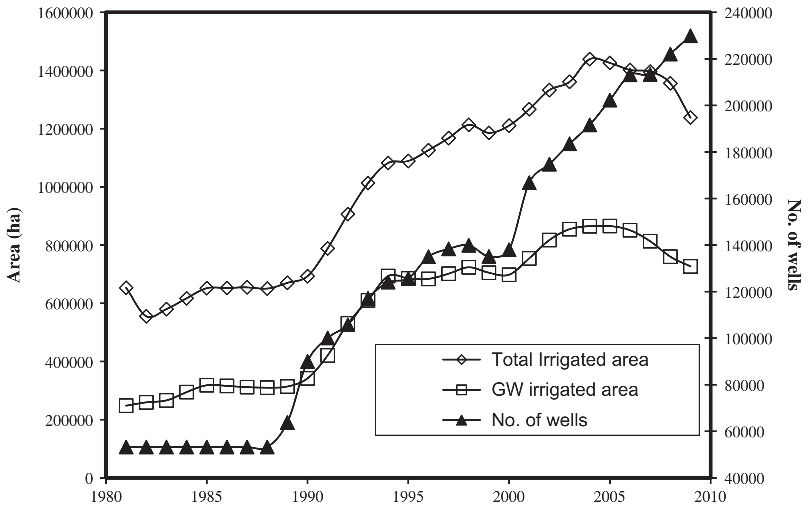
This expansion in the use of groundwater irrigation increased the incomes of those farmers who did not have access to canal irrigation, stabilizing and increasing their crop yields and allowing them to benefit from more secure livelihoods. Salkini and Ansell (1992) estimated wheat yield responses to supplemental irrigation to be 80% for high rainfall conditions, 125% for normal rainfall conditions and 390% for low rainfall conditions. Because the majority of the crops in the region are grown during the winter rainfall season (October to May), supplemental irrigation of winter crops has increased and stabilized yields, overcoming the problems caused by low and uncertain rainfall (Perrier and Salkini, 1991). Zhang and Oweis (1999) found that to harvest 6.6 t/ha of durum wheat grain, a farmer had to irrigate at a rate of 4500–5100 m^3/ha (510 mm) if 250 mm of rainfall (or 2500 m^3/ha) was received. These results supported the government's policy of expanding supplemental irrigation into rainfed areas, to increase productivity, reduce rural poverty, increase investment in agriculture, and slow down rural/urban migration.

The third phase (2001–2010) was characterized by the challenge of dealing with groundwater depletion while ensuring food security. The irrigation policy is still important in this phase to secure food for the 21 million people living in Syria. The population is growing fast – 2.9% in 2003 and 2.5% in 2010 (CBS, 2010). There is a

Table 1
Subsidies on major production inputs based on the 1999 exchange rate in Syria.

Commodity	Local prices (SYP)	World market prices (USD)	Border prices (SYP)	Input price subsidy (SYP)
Diesel fuel (L)	6.1	0.23	11.54	5.44 (47%)
N fertilizer (kg)	8.3	0.18	9.00	0.70 (8%)
P fertilizer (kg)	8.3	0.23	10.72	2.42 (23%)

Note: Border prices = Exchange rate x World market prices (International FOB prices + transport). Exchange rate has been almost fixed in Syria since 2000–2011, at SYP 50 per USD. (FOB = Free On Board).
Source: Authors' elaboration based on FAOSTAT (2013) data on international market prices.



Sources: Authors' elaboration based on FAOSTAT (2013); MAAR (2010), the Annual Agricultural Statistical Abstract for year 2010, Syrian Ministry of Agriculture and Agrarian Reform, Damascus, Syria.

Fig. 2. Total irrigated area, groundwater irrigated areas and number of wells in Syria, 1980–2010.

very large rural sector – 44% of the total population (FAOSTAT, 2013) – in which agriculture employs around 15% of the total labor force and accounts for 17% of total GDP (CBS, 2010).

As part of the strategy for economic development, major policy objectives continued to be the achievement of self-sufficiency in major food crops (particularly cereals), the stabilization of farm incomes through price-support measures, more rural employment through increased agricultural production, greater foreign exchange earnings, and a secure supply of raw materials for domestic industries (NAPC, 2006). In order to help achieve these objectives, the government devoted 70% of its total agricultural budget to irrigation subsidies (Haddad et al., 2008). By 2008 it was estimated that around 160 dams in Syria, with a total storage capacity of 14 billion m^3, were operating (Haddad et al., 2008). Despite favoring market-oriented policies in recent years, the government still plays a significant role in the purchase and trade of strategic agricultural commodities (wheat, cotton, tobacco, sugar beet, barley, lentils, and chickpeas), while the private sector has been left with the trading of fruits, vegetables, and livestock products (Haddad et al., 2008).

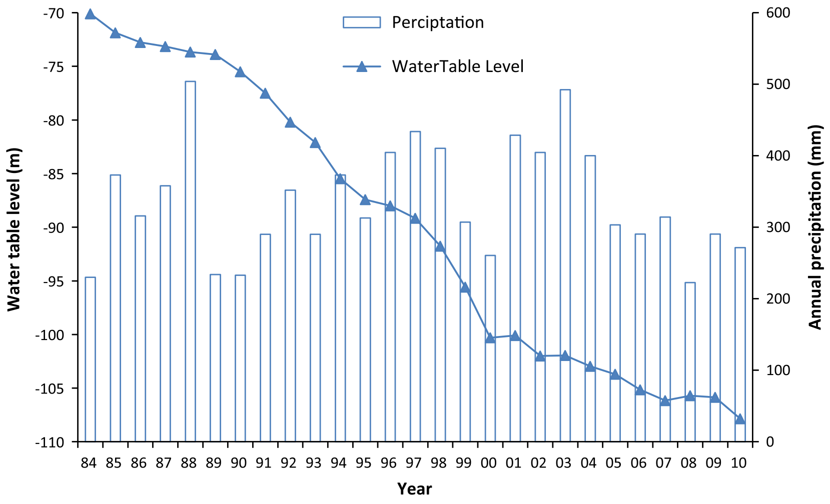
In this phase (Fig. 2) the number of wells grew steadily from 2001 to 2010, while the groundwater-irrigated areas were also increasing, but at an ever slower rate, reaching an inflexion point in 2005 when the actual groundwater-irrigated area started to decrease. This phenomenon means that the number of wells has been increasing based on producers' expectations that such investments would be profitable, while the decrease in the groundwater-irrigated area would suggest a drop in the productivity of wells and, hence, the groundwater supply. Profit, in turn, may be reduced as result of declining water levels and the need to deepen wells – thus increasing the cost of pumping – and the declining well yields failing to supply the required volume of water to the crops. Farmers' expectations are based on successful past experiences. These encourage them to make an investment today which will render benefits over the longer term. If a farmer digs a well and gets water he/she will immediately realize short-term benefits even if the overall aggregate groundwater supply is reduced. So, the rational expectation behavior (in the short term) and a decline in the groundwater supply (in the long run), as a consequence of overpumping, are compatible. Eventually there will be a point where producers correct their expectations and they will not see any more potential for investment in digging wells. But that would probably be late in coming, when the aquifer has been depleted, with substantial economic losses, including failed investments in irrigation infrastructure (pumps, pipes, sprinklers, drippers, etc.).

In fact, declines in water levels and dried-up wells have been reported throughout the country, such as in Zones 3 and 4 of Aleppo province, which are lower rainfall zones (Luijendijk and Bruggeman, 2008; Rida, 2003). The main water supply for Aleppo city is surface water conveyed by canal from the Euphrates. The aquifers in the area are predominantly limestone and chalky limestone formations of limited extent and with low hydraulic conductivities (Luijendijk and Bruggeman, 2008). Thus, any groundwater pumping in the urban area (which is very little) is not expected to affect the groundwater resources of the rural communities in the country side. At ICARDA's headquarters' research station (Tel Hadya, Syria), located in the agricultural areas 25 km south of Aleppo city, the groundwater level has fallen by 1.5 m/year over the last 25 years (Fig. 3). The wells at the research station tap the Neogene Helvetian limestone formation (Technoexport, 1966), which is an unconfined aquifer that is recharged from the surface, especially in rocky areas with shallow soils, and by local ephemeral streams (wadis). Even though erratic, the level of rainfall at Tel Hadya has shown neither an increasing nor a decreasing trend since 1984. Despite this, the water table at Tel Hadya has been found at incrementally deeper levels overtime, indicating that the water extraction is higher than the natural recharge of the aquifer and that eventually the aquifer might go dry. Hence, there is a need for policy measures that help prevent areas like Tel Hadya from suffering a complete depletion of groundwater.

3. Methodology

3.1. Theoretical framework

A farmer's allocation of groundwater to different crops is influenced by production factor costs, crop prices, and government policies. Groundwater abstraction cost is a function of well depth, fuel cost, and labor cost. The total factor cost of irrigation (*TFC*), was calculated for each crop from the total number of pumping hours, the amount of fuel used (in liters), the labor cost, and the cost of the fuel, using the farm-gate fuel prices in Syrian pounds (SYP) (USD



Source: Authors' elaboration based on ICARDA water table and pluviometry database, 1984 - 2010.

Fig. 3. Water table level and annual precipitation at Tel Hadya Research Station (Aleppo, Syria) for the period 1984–2010. Note: For more than 25 years. ICARDA, 1984 has been recording water table data and precipitation levels at its research station and headquarters in Aleppo, Syria. The data shows that the water table has been dropping at an average rate of 1.5 m/year.

1 = SYP 50 in 2000 and in 2011). Thus, a relation between the volume of groundwater abstracted from the aquifer (w) and the *TFC* (measured in SYP/ha) was developed for each crop by fitting the data to the quadratic equation below,

$$TFC = \beta_0 + \beta_1 w + \beta_2 w^2 \tag{1}$$

where β_0 is a constant (fixed cost of irrigation expressed in SYP/ha), w is the volume of groundwater abstracted from the aquifer (m^3), β_1 controls for the symmetry of the function, and β_2 is a parameter which controls the rate of increase of groundwater abstraction. The marginal irrigation cost (*MIC*) function was calculated from the *TFC* function as the first derivative with respect to w:

$$MIC = \frac{dTFC}{dw} = \beta_1 + 2\beta_2 w \tag{2}$$

The *MIC* measures the cost (SYP/m^3) for each additional unit of water pumped. Because there is a cost per unit of water pumped from an aquifer, we analyzed the farmer's groundwater use behavior using a quadratic production function concept (Carlson et al., 1993):

$$Y = \alpha_0 + \alpha_1 w + \alpha_2 w^2 \tag{3}$$

This yield function is presented in its generic form (displaying positive sign just for the summation), where empirical estimations of α_2 are negative reflecting the law of diminishing marginal returns. Y is crop yield (kg/ha), w the quantity of water applied (m^3), α_0, α_1 and α_2 are the parameters to be estimated. This quadratic function is based on two principles. The first is that after a certain level of irrigation has been applied to the crop, the output will be subject to the law of diminishing returns, i.e. as more water is applied, the increase in crop output will diminish. This is illustrated by the concept of marginal physical product (*MPP*), measured in kg/m^3, which increases until the total product reaches the flex point where the additional output per unit of water declines. From that point onwards total product increases, but at a decreasing rate, until it reaches a maximum when *MPP* becomes negative. This could be because excessive irrigation could cause water logging or leaching of nutrient from the root zone. The *MPP* is the first derivative of the quadratic production function with respect to the volume of water applied:

$$MPP = \frac{dY}{dw} = \alpha_1 + 2\alpha_2 w \tag{4}$$

MPP measures the amount of output obtained from each additional unit of water used. The second principle is that the per unit cost of irrigation increases as more and more water is pumped and applied to the crop. So higher water application levels are associated with higher per unit pumping costs of water and hence generate the upward sloping *MIC* curve for water. By multiplying the *MPP* (kg/m^3) by the crop price, P (SYP/kg), the value marginal product (*VMP*), measured in SYP/m^3, is obtained. The *VMP* is the value of the extra crop output per unit of water, and can be computed for each crop from a water-dependent production function and from output prices. The profit maximizing irrigation level is, therefore, determined by comparing the per unit water costs (*MIC*) and the *VMP* as derived from Eqs. (2) and (4):

$$w = \frac{(\beta_1 - P\alpha_1)}{2(P\alpha_2 - \beta_2)} \tag{5}$$

Applications of volumes of water, w, higher than the profit maximizing irrigation level will result in a net revenue loss for every additional unit applied, since the per unit cost of water is higher than its value. However, lower applications are suboptimal, as the net revenue per additional unit applied can be augmented by increasing the volume of water applied. The profit-maximization rule has several implications. First, the need to equate the *VMP* with the *MIC* of the water provides a benchmark to either reduce the quantity of water the farmer is using, or to use it optimally. Second, as water becomes more scarce and more valuable, and as the cost of pumping increases, the farmer would allocate water to crops with a higher *VMP*, which will reduce the amount of water allocated to relatively low-value crops that have a relatively high water consumption. Third, as water becomes scarcer and pumping more costly, producers could increase their net income by applying less water and cutting down pumping costs.

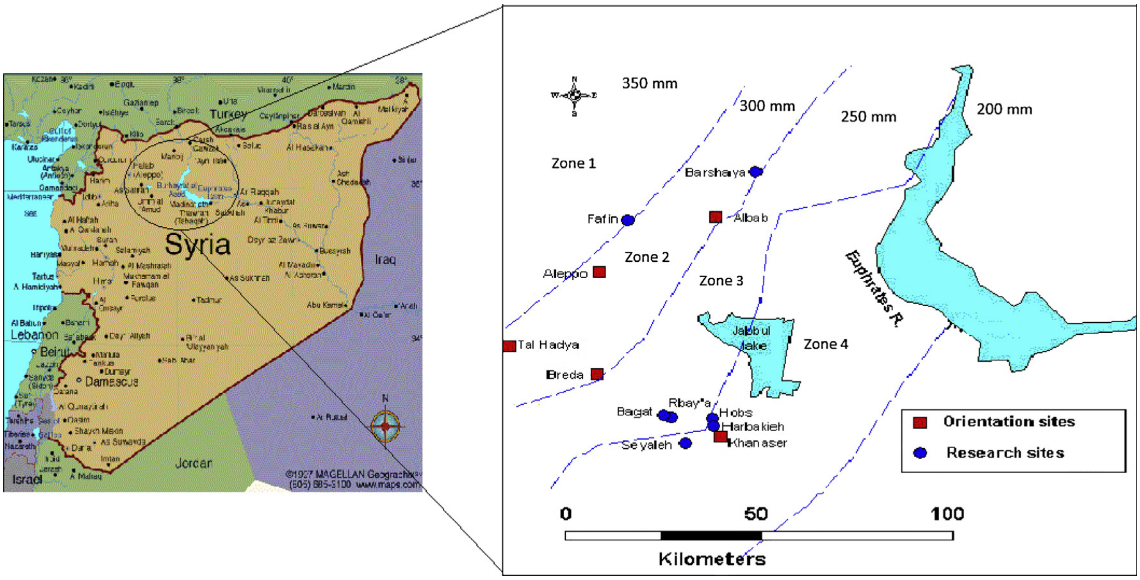
3.2. Data

The main objective of this study was to analyze the effects of food and agricultural policies on groundwater use in Syria. We used a results of a survey on sustainable groundwater use collected by ICARDA in 2003 (ICARDA, 2003), in which 30 farmers, located in five villages (Fafin, Barshaya, Rbay'a and Bagat, Harbakieh and Hobs, and Seyaleh) in four agro-climatic zones across northern Syria, were randomly selected (villages shown with blue dots in Fig. 4). The selected farmers in those villages owned several wells and participated in a water use monitoring scheme by measuring the number of irrigations and the amount of water applied for each crop and from each well. The number of data points collected for each crop in each village is determined by the number of wells and the number of crop plots irrigated from those wells. The reason for using a 2003 survey was to assess how farmers would be affected if the subsidies that the government provided in 2011 had been gradually removed. More specifically, we tested how the profitability of cotton, wheat, cucumber, and beans would be affected if the Syrian government had gradually removed the diesel subsidy that was current until 2011 (latest data available).

The government of Syria uses stability zones as a reference for agricultural planning. That is, cropping patterns in these zones are determined centrally by the government and based on local consultations and national objectives (NAPC, 2003). ICARDA selected these four agro-climatic zones as they provide good representation of the conditions of water scarcity in the region. There are no prospects of them gaining access to surface-water irrigation systems in the near future and intensive well drilling over the previous three decades has resulted in sharp drops in the groundwater tables.

The relatively small sample size (30 farmers) was determined by the farmers' willingness to participate and accept frequent visits to monitor pumping and irrigation practices and to measure and record water abstraction data. Many farmers were reluctant to participate in a study with this intensive data collection (ICARDA, 2003). However, it was decided that a sample of size 30 would be sufficient to determine independent random variables, which will be approximately normally distributed, and thus generating reasonably accurate parameters. Throughout the survey, the farmers also recorded all the costs associated with crop irrigation, including diesel, labor, and the amount of pumping time. The survey monitored water use and measured land attributes (such as total cultivated area, average holding size, and type of land holding – whether private or public), well characteristics (starting when the well was first used for irrigation, initial and current well depth, and depth of water intake), energy used in well operation (diesel and electrically powered irrigation systems), and water allocations to different crops.

We summarize these data in Table 2, which shows that in Zones 1 and 2, where precipitation levels are the highest in the sample, better soil conditions allow for crop diversification. Thus, cotton, wheat, and vegetables (such as cucumber and beans) are cultivated in all villages. In Rbay'a and Bagat, Harbakieh and Hobs, and Seyaleh, which correspond to Zones 3 and 4 with lower rainfall levels, only cotton and wheat are cultivated, presumably prompted by the



Note: Northern Syria is divided into four agricultural stability zones (NAPC, 2003), where each zone is defined in terms of the average annual rainfall, as follows:

- Zone 1: Fafin, annual rainfall of 350 mm and above
- Zone 2: Barshaya, annual average rainfall between 300 and 349 mm
- Zone 3: Rbay'a and Bagat, annual average rainfall between 250 and 299 mm
- Zone 4: Harbakieh, Hobs and Seyaleh, annual average rainfall less than 250 mm (average rainfall in these villages is 200 mm).

Source: Authors' elaboration based on NAPC (2003), and Magellan Geographix Maps (www.maps.com).

Fig. 4. Locations of the selected villages in northern Syria.

subsidy scheme explained in the background section. The average land holding fluctuates between 10 and 30 ha, and almost 100% of the land is privately owned. This is an interesting feature as it has encouraged private investment. Investments in wells for irrigation purposes have been made for many years – ranging from 50 to 20 years before 2003. When wells were established, water was found at depths of between 7 and 40 m, but 20–50 years later water was found at depths of between 50 and 120 m.

The survey also shows that all the farmers interviewed used diesel–fueled engines to pump water. This does not come as surprise given that Syria's policy to deliver food security consisted of heavily subsidizing the use of diesel for irrigation purposes, reaching a point where the domestic price of diesel in Syria was as little as 20% of the world market price. All farmers' wells tap unconfined, upper aquifer systems. These aquifers consist of Neogene and Paleogene limestone formations and a Pleistocene alluvial and proluvial formation in Seyaleh (Technoexport, 1966). Some of the limestone formations extend across the border with Turkey, but the hydraulic conductivities in these systems are so low that any cross-border effects will be very local and will not affect the study villages. The Qwayk River, a transboundary, ephemeral stream which passes near the village of Fafin, is dammed upstream from the village, on either side of the border. Drilled wells were by far the dominant type in these villages, which is mainly explained by the long-life of drilled wells as compared to Arabic (dug) wells. The life of drilled wells, like those in Barshaya (Zone 2) and Rbay'a and Bagat (Zone 3) villages, can easily reach 50 years. Low and highly variable levels of rainfall, averaging less than 400 mm/year (Table 2), have contributed to development of wells. Access to groundwater allows farmers to stabilize and increase the yields of their rainfed winter crops and to cultivate cotton and vegetables during the dry summers.

4. Estimation and results

4.1. Estimation procedure

We compared the value marginal product (*VMP*) with the marginal irrigation cost (*MIC*) in order to estimate the profit maximizing irrigation level for the major crops (cotton, wheat, cucumber, and beans). The gross margins per cubic meter for different crops were calculated using crop budget data collected by ICARDA (2003), and evaluated at the official prices for wheat and cotton, and the market prices for the other crops (cucumber and beans).

The water use (w) of each crop was computed from the total number of hours of irrigation and the measured discharge of each well. If no well discharge was measured, water use was estimated from the median irrigation depth for that particular crop in the village. The farmers' water use for irrigation was compared with the crop water requirements for optimal yields. The crop water requirements were computed from the farmers' planting and harvesting dates, crop coefficients and reference evapotranspiration, following the procedures of Allen et al. (1998). Reference evapotranspiration was computed using climate data from nearby ICARDA and government stations (Breda, Qurbatiyah, Aleppo). Finally, the irrigation water requirements were obtained by subtracting the observed rainfall. Although in each zone a farmer was supplied with a rain gauge, farmers in only one village (Barshaya in Zone 2) consistently measured daily rainfall. Therefore, for the other locations rainfall data from the above mentioned climate stations were used. The computed irrigation water requirements are referred to as technically recommended level. Policy impacts were assessed by analyzing the effects that changes in diesel fuel subsidy had on the relative profitability of different crops and on the farmers' choice of crops.

Table 2
Household characteristics of five villages in northern Syria.

Item	Fafin (Zone 1)	Barshaya (Zone 2)	Rbay'a and Bagat (Zone 3)	Harbakieh and Hobs, Seyaleh (Zone 4)	Total or average
Number of farmers surveyed[a]	6	6	6	12	30
Total cultivated land (ha)[a]	2500	600	1500	1200	5800
Crop yield (kg/ha)					
– Cotton	4250	3500	3625	2800	3544
– Wheat	3350	3950	4250	3150	3675
– Cucumber	20,000	23,200			21,600
– Beans	10,000	12,500			11,250
Average size of holding (ha)[a]	13	15	30	13	18
Type of land holding, private (%)[a]	100	95	100	100	–
Number of drilled wells[a]	70	10	80	35	195
Number of dug (Arabic) wells[a]	3	1	4	9	17
Number of shared wells[a]	0	0	0	0	0
Number of abandoned wells[a]	100	200	73	85	458
Beginning of well irrigation (years)[a]	35	50	50	25	–
Initial well depth (m)[a]	15	7	25	27	–
Current well depth (m)[a]	55–120	50	100	50	–
Depth of water intake (m)[a]	45–90	35	90	40	–
Diesel energy used for irrigation (%)[a]	100	100	100	100	–
Electricity energy used for irrigation (%)[a]	0	0	0	0	–
Elevation (m)[a]	416	461	362	400	409
Average precipitation (mm)[b]	350	300	265	230	275
Average evapotranspiration (mm)[c]	1500	1493	1544	1576	1537

[a] *Source:* Authors' elaboration based on survey data generated by ICARDA (2003).
[b] *Source:* Authors' elaboration based on data derived from ICARDA spatial datasets (De Pauw, 2001).
[c] *Source:* Authors' elaboration based on ICARDA (2003) farmer survey data and ICARDA climate data in Qurbatiyah and Breda stations (Syria).

4.2. Results: farmers' water application

By fitting the survey data to the total factor cost of irrigation (*TFC*) for cotton in Zone 1, the following functional relationship was obtained:

$$TFC\ (\text{cotton}) = 129,016 - 13.68w + 5\text{E}^{-4}(w^2); \quad R^2 = 0.64 \qquad (6)$$

The R^2 value (0.64) indicates that there is unexplained variance in the model, yet the estimated *TFC* values reflect reasonably well the reality in terms of irrigation costs in these villages (Table 3). By taking the first derivative of Eq. (6), the *MIC* function for cotton in Zone 1 was derived as follows:

$$MIC\ (\text{cotton}) = -13.68 + 1E^{-3}(w) \qquad (7)$$

The *MIC* of Eq. (7) represents the supply function for water withdrawn from an aquifer for any quantity above the minimum average variable cost. In other words, the water supply curve can also be considered as the cost per unit, or marginal factor cost, of water. As expected the sign of the water coefficient in Eq. (7) is positive, indicating that as more water is abstracted from the aquifer, the cost of pumping an additional unit of water (or *MIC*) increases. Data was fitted to the production function for all crops in all zones. For cotton the following relationship was obtained:

$$Y\ (\text{cotton}) = -25,230 + 3.2733w - 9E^{-5}(w^2); \quad R^2 = 0.66 \qquad (8)$$

The R^2 squared value (0.66) indicates some unexplained variance in the model, but the *Y* values are reasonably well explained by the quadratic function. The first derivative of Eq. (8) provides the *MPP* function for cotton in Zone 1 as follows:

$$\text{MPP}\ (\text{cotton}) = 3.2733 - 18E^{-5}(w) \qquad (9)$$

As expected the coefficient of *w* in the *MPP* equation is negative indicating that after a certain level of irrigation, the crop will be subject to diminishing returns. That is, as additional units of water are applied the extra output (measured in kg/ha) declines. Table 3 presents the coefficients for both the quadratic production and cost functions by crop and by zone.

Assuming farmers are maximizing their profits, they would pump water at the level where the *VMP* is equal to the *MIC*. Hence, by equating the *VMP* and *MIC* of water, the profit maximizing irrigation levels were computed for all crops in the different zones. In the case of cotton, the actual irrigation levels were in all cases higher (32% on average) than the technically recommended level, but the actual irrigation levels were much closer to the profit maximizing irrigation levels – on average 7% lower (Table 3). These results point to two important points. First, they imply that farmers' irrigation levels are close – within the margin of error – to the profit maximizing irrigation levels, indicating that, given the prevailing market signals and policy environment, farmers are within the norms of rational behavior consistent with the economic parameters of profit maximization. In this case, farmers were behaving with economic rationality in the short term given that they allocate a cheap resource, i.e. water cost artificially reduced by subsidy, to cotton that has a secured market and provides assurance in terms of livelihoods. Secondly, comparing only observed water applications with the technically recommended levels, without considering the farmer's response to price signals (either by market or by the state through price support and subsidies) we can conclude that farmers are over-irrigating. Apparently such analysis and conclusions are not fully informed and cannot provide policy guidance. A more complete analysis, taking into account farmers' responses to prices, costs, and subsidies is required to understand their behavior regarding groundwater use.

In the case of wheat, the actual irrigation levels for wheat were higher (from 13% in Zone 4 to almost 50% in Zone 1) than the technical recommendation level. Then a logical reading would point to over-irrigation. Yet, a more careful analysis shows that farmers were actually applying water in quantities that were close to, and in all cases less than, the irrigation levels which maximize profits. That is, by comparing the irrigation level which maximizes profits with the actual irrigation level (last column in Table 3), the famers were close to, but less than, the profit maximizing level (almost identical in Zones 2 and 3, and less than 23% lower in Zones 1 and 4). This is displaying a rational behavior in light of a subsidized

Table 3
Estimated values for VMP and MIC for different crops across Stability Zones 1–4.

Crop	Zone	Production functions		Cost functions		Actual irrigation level (m^3/ha)	Technical recommendation (m^3/ha)	Profit maximizing level (m^3/ha)	Actual irrigation level / Technical recommendation	Actual irrigation level/ profit maximizing level
		Y=	R2	TFC=	R2					
Cotton	1	$-25{,}230 + 3.2733w - 0.00009(w2)$	0.66	$129{,}016 - 13.684w + 0.0005(w2)$	0.64	16,541	12,500	17,461	1.32	0.95
	2	$-26{,}218 + 3.3791w - 0.00009(w2)$	0.68	$99{,}134 - 9.8349w + 0.0004(w2)$	0.73	16,394	12,500	17,912	1.31	0.92
	3	$-19{,}779 + 2.6135w - 0.00007(w2)$	0.73	$149{,}249 - 15.52w + 0.0005(w2)$	0.75	16,607	12,500	18,046	1.33	0.92
	4	$-13{,}082 + 1.8701w - 0.00005(w2)$	0.77	$177{,}879 - 17.285w + 0.0006(w2)$	0.76	16,557	12,500	17,443	1.32	0.95
Wheat	1	$-1946.8 + 2.3898w - 0.0002(w2)$	0.86	$3{,}532.5 + 1.4532w + 0.0003(w2)$	0.73	3728	2500	4775	1.49	0.78
	2	$+443.63 + 1.2512w - 0.00009(w2)$	0.83	$10{,}943 - 4.1544w + 0.0013(w2)$	0.89	3669	2500	3653	1.47	1.00
	3	$-4690.3 + 3.6822w - 0.0004(w2)$	0.87	$1763.8 + 1.386w + 0.0004(w2)$	0.78	3977	3000	3969	1.33	1.00
	4	$-8745.1 + 5.3027w - 0.0005(w2)$	0.89	$11{,}245 - 3.51w + 0.0012(w2)$	0.90	3945	3500	4494	1.13	0.88
Cucumber	1	$-19{,}811 + 7.0354w - 0.0003(w2)$	0.61	$14{,}677 - 1.2942w + 0.0002(w2)$	0.82	8651	8000	10,987	1.08	0.79
	2	$-21{,}892 + 7.4043w - 0.0004(w2)$	0.81	$24{,}727 - 4.2254w + 0.0004(w2)$	0.80	8977	8000	8759	1.12	1.02
Beans	1	$-109{,}638 + 32.679w - 0.0022(w2)$	0.88	$55{,}510 - 14.609w + 0.0012(w2)$	0.73	7559	7000	7358	1.08	1.03
	2	$-88{,}582 + 26.723w - 0.0018(w2)$	0.64	$38{,}454 - 9.1956w + 0.0008(w2)$	0.75	7364	7000	7352	1.05	1.00

Zone 1 = Fafin village, Zone 2 = Barshaya village, Zone 3 = Rbay'a & Bagat villages, Zone 4 = Harbakieh & Hobs, and Seyaleh villages.
Source: Own estimations based on ICARDA farmer survey data.

resource which substantially contributes to higher yields, and hence to more income.

In Syria, vegetables, such as cucumber and beans, are generally ruled by market forces, including the absence of price support, but still enjoy support through diesel subsidy to pump groundwater. For these crops the differences between actual irrigation levels, the profit maximizing levels, and the technically recommended levels were much narrower than for cotton and wheat. Our estimates of the profit maximizing irrigation levels for cucumber and beans were very close to the actual irrigation levels applied by farmers, being on average 10% lower in the case of cucumber, and almost identical in the case of beans.

This analysis shows that, in the short run, farmers allocate water to crops in an economically rational manner. We found that price support policies which benefit cotton and wheat tend to modify the profit maximizing benchmarks. In the case of cucumber and bean, this benchmark is much less exposed to direct government intervention, which leads to more consistent market-oriented profit maximizing estimations for the observed irrigation levels. Modifications in the maximizing parameters are made for several reasons:

- Dictated higher and fixed prices for cotton and wheat strongly encourage farmers to allocate more production inputs (including groundwater, which is fundamental in dry areas) to these crops.
- Farmers operate under lower risk by cultivating cotton and wheat as the prices are fixed and government procurement of the crops is guaranteed.
- Farmers have a lower incentive to focus on vegetable production because it entails greater risk; most vegetables need to be sold directly after harvest as vegetable prices fluctuate in line with market conditions.
- Farmers are aware that groundwater is a common resource, so saving water in summer does not necessarily mean an increase in the supply available in winter. They, therefore, can be tempted to use more water than necessary as they seek to satisfy their needs before their neighbors deplete the resource. This depletion process is explained by the theory of the 'tragedy of the commons' (Hardin, 1968), according to which individuals acting independently and rationally corresponding to self-maximizing interest behavior, collectively act contrary to the group's long-term most beneficial interests by depleting the common resource.
- Lack of accurate knowledge of either soil water conditions or crop water requirements during the different crop stages could lead to over- or under-irrigation.
- Groundwater abstraction continues to be over-abstracted in the presence of input subsidy policies, which tend to offset the cost of abstraction as water becomes scarcer.

The effect of racing, or the rule of capture (Koundouri, 2004), encourages farmers not to forego today's pumping and minimizes the opportunity for option value. But from the public perspective, option value or inter-seasonal allocation of groundwater should be an important policy consideration in groundwater management.

A conclusion that emerges from this analysis is that the behavior of farmers is not the issue, as they behave rationally in terms of maximizing benefits. The issue is government policies that create incentives for farmers to abstract groundwater at unsustainable levels that are greater than technically and economically required; but farmers do that by maximizing their profits in response to these policies and market signals. The adjustment to correct this problem of groundwater overuse has to mostly be solved from the policy side.

4.3. Fuel subsidy and crop choice

In this section we look at the level of subsidy for diesel relative to 2011 and test how the gradual elimination of this subsidy would affect the profitability of cotton, wheat, cucumber and beans. Changes in irrigation costs, as a result of changes in fuel costs, will have varying effects on the profitability of different crops being planted. To determine the effects of increased fuel costs on the profitability of these crops four scenarios, reductions of 25%, 50%, 75%, and 100% in fuel subsidy were simulated. Then, changes in gross margin for each crop and zone were estimated according to gradual lifting in diesel subsidy. In the analyses, other variable costs and government price supports were held constant, and the use of the surface irrigation method was assumed.

As a result of higher fuel costs to the farmers, the greatest decline in gross margins per hectare was estimated to be for crops cultivated in dryer conditions (villages located in Zones 3 and 4), which depend more on groundwater for irrigation (Table 4). The analyses show that cotton farming would not be profitable in the drier Zones 3 and 4 if the diesel subsidy is decreased by just 25%. Losses in these zones would further increase with decreases of 50%, 75%, and 100% in the diesel subsidy. Unprofitability occurs because wells are deeper and recharge is much lower, thus the cost of pumping becomes higher. Thus in Zones 3 and 4, farmers become losers if subsidies on diesel are removed. Unprofitable farming is not an intended output of the policy, particularly in the poorest areas. If the diesel subsidy is removed, the challenge consists of introducing compensatory measures which will ensure alternative sources of income to affected households. In Zones 1 and 2, which are the relatively less dry of the four zones, as the subsidy is gradually removed the profitability of cotton decreases. Our estimates show that farming cotton in Zone 2 could withstand up to 75% removal of the subsidy which, as expected, would result in smaller benefits. In Zone 1, where rainfall is more copious and consistent, cotton farming would stand a complete removal in diesel subsidy.

If the fuel subsidy was reduced by 25% or more in Zone 4, then wheat production would not be profitable. In Zones 1, 2 and 3, wheat production would be a loss-making activity if fuel subsidy would be completely removed. In Zones 1, 2 and 3, wheat faming could withstand up to 50% removal of the subsidy given that in Zones 1 and 2 particularly higher rainfalls allow farmers to use less groundwater in crop irrigation. The rainfall also makes the farmers less dependent on the subsidy to achieve profitability in crop production.

Cucumber and beans are grown in Zones 1 and 2 only. As the diesel subsidy is removed, the profitability of cucumber and beans (measured in gross margin per hectare) drops but not as much as cotton. This is because vegetables (including cucumber and beans) require less water than cotton, and hence drop in gross margin were much lower allowing for still profitable farming even in the face of complete discontinuation in diesel subsidy. These results suggest that removing the subsidy on diesel will have a greater negative effect on crops with a high consumption of water, such as cotton, because higher fuel prices will more seriously affect low water-productive crops, such as cotton, and less seriously affect high water productive crops, such as vegetables.

Hence, the government has a key role to play by adjusting the subsidy policy in such a way that subsidy support would not become an incentive to drill more wells in dry areas. Correcting the subsidy would reduce the intensity of groundwater pumping and it could induce farmers to shift to less water-demanding crops and/or adopt water-saving irrigation technologies. Bathla (1999), while examining the linkages between water demand and agricultural development in Central Punjab (India), similarly concluded that because of the 'public good' characteristics of water, the role of government, especially in setting agricultural policies, is critical

Table 4
Crops gross margin changes under different fuel prices scenarios.

Crop	Zone	Water cost (SYP/ha)	All other costs (SYP/ha)	Crop yield (kg/ha)	Total revenue (SYP/ha)	Current gross margin (SYP/ha)	Irrigation level maximizing profits (m^3/ha)	Gross margin per area unit (SYP/ha) under different scenarios			
								25% fuel subsidy removed	50% fuel subsidy removed	75% fuel subsidy removed	100% fuel subsidy removed
Cotton	1	41,817	45,949	4483	130,017	42,251	17,461	31,797	21,343	10,889	434
	2	44,163	42,839	4228	122,598	35,596	17,912	24,555	13,515	2474	−8567
	3	44,796	59,344	3972	115,192	11,052	18,046	−147	−11,347	−22,546	−33,745
	4	44,783	67,705	4239	122,936	10,448	17,443	−748	−11,944	−23,140	−34,336
Wheat	1	12,931	10,805	3842	34,581	10,845	4775	7612	4380	1147	−2086
	2	13,614	9921	3723	33,505	9970	3653	6567	3163	−240	−3644
	3	13,400	10,845	3745	33,709	9464	3969	6114	2764	−586	−3936
	4	17,210	12,020	3420	30,780	1550	4494	−2753	−7055	−11,358	−15,660
Cucumber	1	17,557	34,340	14,751	103,260	51,363	10,987	46,974	42,584	38,195	33,806
	2	18,609	17,018	14,340	100,380	64,753	8759	60,101	55,449	50,797	46,144
Beans	1	11,895	50,459	12,014	120,136	57,782	7358	18,768	15,794	12,820	9846
	2	12,507	28,932	11,935	119,350	77,911	7352	38,979	35,852	32,725	29,599

Zone 1 – Fafin village, Zone 2 – Barshaya village, Zone 3 – Rbay'a and Bagat villages, Zone 4 – Harbakieh and Hobs, and Seyaleh villages. *Source:* Crop budget data from the research survey.
Source: Authors' estimations based on ICARDA farmer survey data.

if sustainable water use is to be achieved. It is important to clarify that this analysis applies to four geographical zones in Aleppo Province. To analyze how subsidy removal/reduction would affect national production of wheat, cotton and vegetables (such as cucumber and beans), including balance in food production and water sustainability, national storage, imports, supply and trade, a general equilibrium approach would be needed. That approach, which is beyond the scope of this research, would be instrumental to get into a macro analysis of the trade-offs emerging from different policy scenarios and associated outcomes.

Farmers revealed that in areas where aquifer depletion was complete, farm households were no longer able to sustain themselves through rainfed cropping, and therefore tended to migrate, searching for jobs in urban centers or in irrigated areas, where they were able to work as laborers on summer crops (ICARDA, 2003). These are long-term outcomes which are contrary to the intended food policy/security objectives. Therefore, questions arise as to whether the groundwater-based agricultural production and food security induced by government food policies can be sustained. Unabated depletion of groundwater could ultimately reduce farm incomes and have a negative consequence for rural livelihoods.

The Syrian Government introduced a new policy strategy that consisted of rationalizing the use of groundwater and river water. This policy was operationalized through the Water Law No. 31 announced by the Ministry of Irrigation in 2005, but implemented as from 2008 until 2011 (discontinued due to the social unrest conflict in Syria). The policy consisted of rationalizing the use of groundwater by introducing a set of measures that aimed at controlling the amounts of groundwater abstracted. The main policy measures include:

- Banning the cultivation of summer crops on the steppe (limited level of compliance).
- Establishing irrigation fees. Issuing a license for drilling wells or installing pumping equipment, a fee of 5000 SYP as a lump-sum shall be collected from license holders (not enforced).
- Limiting the amount of groundwater extracted within the quantity limit of the water resources available in each basin (not enforced).
- Applying penalty fees to farmers exceeding the maximum groundwater allocation per hectare established by law, and removing groundwater license to recidivist farmers (not enforced). In fact, the government limits the amount of water through the construction of sized channels that do not allocate much water to fields.
- A program for installing flow meters in wells (not yet fully implemented).
- Linking-up well licensing to the adoption of modern irrigation practices (not enforced).
- Providing cheap credits to farmers to purchase agricultural inputs (barely started);
- Coordinating the agricultural plan and the growing of strategic crops with irrigation water availability (still in progress).
- Increasing extension efforts to raise farmers' awareness of efficient water use practices (in progress).
- Encouraging the creation of water user associations (in progress).
- Improving equity in river water distribution in favor of farmers that are at the end of water channels (in progress).
- Converting, through support program, traditional irrigation systems into modern irrigation schemes from 2011 to 2015 (did not start).
- Increasing the cost of groundwater pumping to adjust for the changes in world oil prices (diesel fuel prices increased from SYP 7.4 (USD 0.15) per liter in 2008 to SYP 20 (USD 0.40) per liter in 2011.

These measures are considered positive steps. However, the level of implementation of the regulations clearly needs to be improved if the policy measures are to be effective. In addition, complementary policies, such as gradual elimination of the diesel subsidies for groundwater abstraction, will provide incentives to earmark resources according to their real opportunity costs, and to allocate water to commodities that are more profitable to farmers. As discussed in Table 4, it could lead to allocating production resources to less water intensive crops. Complementary, technical advisory services and more supportive credit facilities in the form of low interest rates should be promoted such that farmers can easily adopt modern irrigation technologies, like sprinkler and drip irrigation systems. The government might also consider banning license renewals to replace dried-up wells. These agricultural policies listed above show that in Syria there is no shortage of policies, but a serious issue is that institutions are weak in their delivery of policies. The government might consider a long-term plan to reinforce institutions. The full impact of the various water-conservation policies are still to be evaluated, and will depend heavily on how effective the Syrian institutions are in driving their implementation.

5. Conclusions

The Syrian government's food and development policy has encouraged the rapid expansion of groundwater exploitation in the country over the last three decades. This policy was based on an expansion of the irrigated areas, which are supplied with both surface water and groundwater, but without consideration being given to the sustainability of the groundwater resources. Agricultural policies, such as the provision of subsidies for diesel and price support for strategic crops, which stimulated groundwater use, had positively affected input use and agricultural production. These improved food security and increased farm income. However, in the long term, the effects on sustainable groundwater use, particularly in the drier regions, could be negative because of declining well productivity and the falling water table levels of the aquifer. Therefore, it is possible that the carrying capacity of the groundwater aquifers will continue to decline to such an extent that there will not be adequate amounts of water to irrigate the areas currently serviced with groundwater.

The results show that the actual irrigation levels for cotton and wheat were higher than those technically recommended. These results could mean that farmers have been applying more irrigation water than is economically justified. However, from the profit maximizing perspective, the actual irrigation level for these crops were in general close to (but lower than) the profit maximizing irrigation. This implies that farmers actually took their decisions following rational economic behavior in the short term. That is, their actual irrigation levels were reasonably close to the irrigation levels which maximize profits, implying economic rationality in the use of a cheap resource (water) for crops which have secured markets (cotton and wheat) and provide assurance in terms of livelihoods. Our estimates of the profit maximizing irrigation levels for cucumber and beans were fairly close to the observed and technical requirement levels.

In the case of cotton and wheat, we observed that farmers were consistent with the profit maximizing criteria, but with distorted incentives. This has happened for several reasons:

- Dictated higher and fixed prices for cotton and wheat drive farmers to produce crops that are 'safe' in terms of securing household income.
- Having the government buying all the cotton and wheat produced at fixed prices encourages farmers to allocate more production inputs (including groundwater) to these two commodities.

- Farmers avoid focusing exclusively on vegetable production as this implies facing all the risks associated with the marketing of these commodities – selling quickly as they are perishable items, transportation costs, and the fluctuating prices for vegetables.
- Groundwater being a common resource means that saving water in summer does not necessarily increase water supply for winter crops; therefore farmers seek to satisfy their needs before their neighbors deplete the resource ('tragedy of the commons').
- Farmers do not always have accurate knowledge of soil water requirements, which could lead to over- or under-irrigation.

The results of the different scenarios modeled in this study show that a reduction in, or the removal of, the diesel fuel subsidy will affect the profitability of all crops. The decline in gross margins per hectare in cotton was estimated to be highest in the villages located in the drier areas (Zones 3 and 4). The analyses show that cotton farming would not be profitable in drier areas (Zones 3 and 4) if diesel subsidy would be reduced by just 25%. In Zone 2 if diesel subsidy would be completely removed then cultivating cotton would become unprofitable. Only in Zone 1 (most favorable area) cotton would be cultivated without fuel subsidy, but gross margins would be diminished. In the case of wheat, a 25% decrease in diesel subsidy would be enough to make it unprofitable in Zone 4, while in Zones 2 and 3 a 50% removal would make wheat production unprofitable. Wheat would be profitable in Zone 1 if at least 25% diesel subsidy is provided. More viability of cotton and wheat in Zones 1 and 2 can be explained by higher rainfalls in these zones that allow for less groundwater to be used for crop irrigation. In Zones 1 and 2, vegetables (cucumber and beans) remain profitable even when fuel subsidy is removed. These results suggest that as water becomes scarcer and pumping becomes more costly, farmers could increase water productivity by shifting from crops with high water consumption to those with a short growing season, such as vegetables.

From a macro perspective, this study shows that balancing short-term productivity growth with the long-term negative impacts of groundwater depletion is a challenge facing policy makers. In the drier areas, regular monitoring of groundwater levels, as well as of farming and irrigation practices, would provide the information needed to meet this challenge. The expansion in groundwater-based farming and the associated depletion of aquifers in the drier regions of Syria suggests that aquifers are subject to fast depletion. This supports the hypothesis that groundwater abstraction in the dry areas resembles the mining of limited resource. We showed that the process of groundwater mining seems to follow a pattern where there is an initial high quantity of groundwater for irrigation purposes, followed by a sharp decline within a short period of time. The decline, driven by excessive well drilling and over-abstraction, can lead to the exhaustion of groundwater.

The government should consider a gradual removal of the diesel subsidy for the pumping of water, while fostering a system that introduces measures to ensure alternative sources of income to affected households. Complementary policies, such as introducing credit facilities (so that farmers can easily adopt improved irrigation technologies), a regulated system that prevents over-pumping, and restricting license renewals through which new wells are drilled to replace dried-up ones, should be considered. Overall, policies should support new irrigation technologies associated with cropping patterns that will help limit the mining and absolute depletion of groundwater aquifers, and lead to a more economically sustainable use in the long term.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2014.03.043.

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