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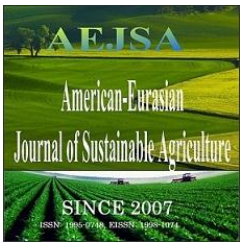

Optimizing Returns and Labour in a Situation of Extreme Aridity: the Case of South Khorasan, Iran

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ABSTRACT

Agriculture is the major consumer of water worldwide. Competition for water is growing, as well as aridity and desertification. The improvement of water allocation is consequently a must, with and without hard and soft innovations. This paper presents an innovative econometric approach for optimal irrigation water allocation, within the current technological asset, in a very arid situation. It shows a Multiple Criteria Decision Making (MCDM) procedure, where two types of models have been implemented: the single Fractional Programming (FP) model and the Multiple Objectives Fractional Programming (MOFP) model. The models have been applied to identify the optimal cropping plans maximizing net income and labour, per unit of water used in a situation of extreme scarcity of groundwater. 237 farmers were interviewed in August 2017, in the South Khorasan province of Iran, with a questionnaire containing 92 questions about technical and socio-economic aspects. The MOFP model indicates that the economic returns and the labour, per unit of water demanded, could improve respectively by 134.3% and 24.5%, on average, on the entire sample. Such results could be achieved with proper collection of agronomic and economic data, followed by fast data processing and farmer-specific advice, to support the producers in land use and crop choice design.

KEYWORDS: Optimization; Irrigation; Mathematical Programming; Advisory Service

INTRODUCTION

Agriculture is globally the main user of freshwater: about 70% of the total availability [1]. Irrigation is needed for several crops: some for direct human consumption (wheat, rice, maize, soybean), others (alfalfa, other forage crops, the same maize and soybean) are used for feeding animals (cows, pigs, sheep, goats) which then produce meat, eggs, milk, and other products for the growing human population ([2]. Water availability varies enormously between regions and countries: the MENA region, Middle East, and North Africa already use 58 percent of their water resources for agriculture [1]. The demand for different crops and entire farming systems, also called "water footprint," has been studied by many authors [3], who underline – among several factors - the variability due to the irrigation systems implemented by the farmers, even within the same climatic region. Furthermore, the water is generally perceived as a common good [4], a gift from nature, subject to traditional and sometimes archaic rules, hard to modify. In the last

decades, but with a worrying acceleration in the most recent years, there has been a decreasing availability of fresh water in many countries, the competition for industrial and civil utilization has increased, rains are becoming scarce and erratic, desertification is expanding [5]. By 2025, about 1.8 billion people will be living in regions with absolute water scarcity, and two-thirds of the world population will experience water stress conditions. For the future, the Food and Agriculture Organization of the United Nations ([6] has proposed five principles for sustainable agriculture:

a) Improved efficiency in the use of resources
b) Direct action to conserve, protect and enhance natural resources
c) Protection and improvement of rural livelihood and social well-being
d) Enhanced resilience of people, communities, and ecosystems
e) Responsible and effective governance mechanism.

Implementing such measures is needed to reach several of the Sustainable Development Goals defined by the United Nations for 2030 [7].

Several strategies, soft and hard ones, can be implemented for improved efficiency of irrigation water [8] [9] [10]: better education and training for the operators, better and more localized advice, new types of farmers' organizations (like the Water Users' Associations), more advanced technologies (from drip irrigation to drones), lower use of fertilizers (which usually impose a higher quantity of water), new varieties demanding less water, new aridity resistant crops, total change and re-design of more resilient production systems, the introduction of meters and pricing of water, landscaping.

In Iran [11] [12] [13], the situation was and still is particularly difficult, with several parts of the country severely affected by drought and water scarcity, made even worst by inefficiencies of the water distribution and irrigation systems. The Authors cited before have realized detailed studies of different nature (technical, economic, sociological) and meaningful contributions have been produced to define policies aiming to improve agriculture's sustainability.

This article focuses on the results that could be achieved, thanks to an innovative econometric approach, in terms of two selected sustainability indicators (net return /water demand and labour /water demand), without any heavy investment, but with some modifications to the area allocation among six crops, thanks to the utilization of a decision-making tool based on a mathematical programming technique.

In the last decades, various methodological approaches have been proposed to assess agricultural systems' sustainability regarding economic, social, and environmental aspects. Most of the simulation models are based on mathematical programming techniques [14] [15] [16] [17], which optimize a result (objective function) within a particular context (such as maximizing income or minimizing cost), subject to constraints due to the resources available in the considered system.

Among the mathematical programming techniques, Fractional Programming (FP) and Multi-Objective Fractional Programming (MOFP) have been commonly adopted to optimize the efficiency of several decision-making units, thanks to their suitability to deal with the optimization of ratio problems. As an objective function, such issues include the quotient of two parts: cost/time, cost/profit, or output/input, which are linear combinations of decision variables ([18]. Consequently, FP has been widely used in several sectors, from economics and finance to engineering and transports, to assess the performances of many productive processes by calculating applicable quality and efficiency indicators [19] [20]. The success of its application is mainly due to two main advantages. The first one is its adaptability to different operational contexts, allowing to evaluate system efficiency of various management problems [21] [22]. Another advantage is represented by its capability to compare and balance, based on their original magnitudes, conflicting objectives to provide a full performance measure [23]. In this perspective, FP represents a valuable tool to address the challenges related to the sustainability of the production systems, allowing for the inclusion in the objective function of economic, environmental, and social goals [22]. Since

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the short term economic objectives are generally conflicting with the environmental and social ones (e.g., maximizing labour demand), trade-offs arise between these different aspects, requiring the identification of the best compromise solutions, or Pareto's optimal solutions, to achieve higher and whole sustainability level [24].

Only a few studies have used these techniques to assess the sustainability of agricultural water management within a multi-objective framework [18] [25]. In our case, this Multiple Criteria Decision Making (MCDM) approach, such as the MOFP model, has been implemented to identify the best cropping plans for 237 farmers in the Iranian Province of South Khorasan, which simultaneously optimize two objectives, belonging to different dimensions of sustainability.

MATERIALS AND METHODS

Study area

The survey has been realized in South Khorasan (Khorasan-E- Jonobi), one of the 31 provinces of Iran. Three different climatic zones (cold desert, hot desert, cold semi-arid) can be defined, where only groundwater is a liable resource for agriculture and domestic uses. Still, nowadays, more than 90 percent of this water is used for agriculture, with very traditional distribution methods. Most families have less than two hectares, fragmented in several separated small plots. A detailed description of the area and of the present farming system can be found in [26].

Sampling and data collection

Data collection was performed through a sample survey based on a structured questionnaire administered to 237 farmers during 2017. The sample includes producers in seven of the 11 counties of South Khorasan, who share wells as the only water source for irrigating their fields. Within much more extensive research that has also included both technical and socio-economic aspects, out of a total population of 49,685 well operators, according to the Cochran formula, 380 had to be interviewed, but for various reasons, it was possible to contact only 237 persons. A detailed description of the sampling methodology and of the data collection procedure (direct interviews) can be found in [27].

Fractional Programming (FP) and Multi-Objective Fractional Programming (MOFP) models

Following [18] and [25], this study uses FP and MOFP to assess water management sustainability in 237 Iranian farms by identifying the optimal cropping patterns to maximize both the economic and social objectives in a context where the scarce water is precious.

The former relates to the maximization of the farm net return, while the social one refers to maximizing the farm labour requirements. To include the environmental dimension, the water consumption was considered and included, as the denominator, in the following two ratios identified as sustainable indicators for the objectives mentioned above: "net return/water demand" and "labour/water demand". These ratios represent the two fractional objectives of the two implemented single-objective FP models, while a MOFP model was developed for their simultaneous optimization.

The six main and most widely cultivated crops in the study area have been considered: wheat, barley, canola, cucurbits, sugar beet, and forage corn. The cultivated areas associated to each crop represent the decision variables. The three models were formulated considering constraints related to the resources' availabilities and some agronomic aspects, as illustrated in the next paragraph. Each of the three modelswas solved separately for each farm in a General Algebraic Modeling System (GAMS) environment for a total of 711 run models.

A general single objective FP model with m constraints and n decision variables can be formulated as follows [28]:

$$\text{Max } f = \frac{a^T x + \alpha}{b^T x + \beta} \qquad (1)$$

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Subject to:

$Ax \leq c$

and

$x \geq 0;$

where a, b $\in R^n$, $c \in R^m$, α, β ∈ R, and T refers to transposition.

Both the numerator and the denominator are real functions defined on R^n, x is an n-dimensional vector of decision variables, a, b are technical coefficients n-dimensional vectors, α, β are scalar constants, A is a mxn technical coefficients real matrix and c is the m-dimensional right-hand side (RHS) vector. According to [21], if the denominator is strictly positive in a sign for all x on the feasible set of solutions, the FP model could be transformed in a linear programming problem, by introducing a new n-dimensional vector y defined as follows:

$$y = x \cdot t, \; t = \frac{1}{b^T x + \beta} \qquad (2)$$

Through this transformation, the original fractional problem (1) can be optimized by solving the following linear programming problem, using an additional constraint:

$$Max\ g = c^T y + \alpha \qquad (3)$$

Subject to:

$Ay - ct \leq 0$

$b^T y + \beta t = 1$

$y, t \geq 0;$

From the optimum solution of the above linear problem $(y^*, t^*)^T$ it is possible to find the optimal solution of the original fractional problem as follows:

$$x^* = \frac{y^*}{t^*}$$

The two single objective fractional models aim to maximize the ratio "net return/water demand" and the ratio "labour/water demand". Based on the above-illustrated equations (1) and (2), the two objectives can be formulated as follows:

$$\text{Max } \frac{\sum_i^I NR_i \cdot x_i}{\sum_i^I W_i \cdot x_i} \quad (4)$$

$$\text{Max } \frac{\sum_i^I LE_i \cdot x_i}{\sum_i^I W_i \cdot x_i} \quad (5)$$

Both objectives are subject to the following constraints:

$$\sum_i^I x_i \cdot Land_{i,s} \leq AL \quad \forall\, s \in S \qquad (6)$$

$$\sum_i^I x_i \cdot W_i \leq AW \qquad (7)$$

$$\sum_i^I x_{i(k1)} \leq \sum_i^I x_{i(k2)} \qquad (8)$$

$$x_i \geq 0\,; \qquad (9) \quad (i = 1, \dots, I), (s = 1,\dots,S)$$

Where:

i = Crop index referred to the I available crops (wheat, barley, canola, cucurbits, sugar beet, forage corn)

s = Month index referred to the S available months (January through December)

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k1 = Winter crop index (wheat, barley, canola)

k2 = Spring crop index (cucurbits, sugar beet, forage corn)

xi = Allocated land to ith crop (ha)

NRi = Net return of ith crop (Toman[1]/ha)

LEi = Labour requirement during the cropping season for ith crop (h/ha)

AL = Total cultivable area in the farm (ha)

AW = Available water for irrigation in the farm (m3)

ci = Per unit area cost of production for ith crop (Toman/ha)

$Land_{i,s}$ = Land use requirement for ith crop during the sth month

Wi = Net irrigation water requirement for ith crop during the cropping season (m3/ha)

The MOFP model relates to the simultaneous maximization of the labor per unit of water and the net return per unit of water. This approach allows for more information about irrigation water management's sustainability performances, allowing to obtain better results than maximizing the net return or the labour, or minimizing the water consumption separately. Mathematically, such a model can be formalized as follows:

$$\text{Max} \left\{ \frac{\sum_i^I NR_i \cdot x_i}{\sum_i^I W_i \cdot x_i}, \frac{\sum_i^I LE_i \cdot x_i}{\sum_i^I W_i \cdot x_i} \right\} \quad (10)$$

Subject to the constraints seen in equations (6) (7) (8) and (9).

Consequently, based on the optimal values of the two fractional goals obtained by solving the single objective fractional models, the deviational variables measuring the slack between the optimal values and the obtained results are introduced in a fractional goal programming model [19], which can be transformed in the following equivalent linear Goal Programming Model, used in this study, according to [19] and [25]:

$$\text{Min } (r_1 + r_2) \quad (11)$$

Subject to:

$$\sum_i^I NR_i \cdot x_i - \mu_{g1} \cdot (\sum_i^I W_i \cdot x_i) + r_1 - q_1 = 0$$
$$\sum_i^I LE_i \cdot x_i - \mu_{g2} \cdot (\sum_i^I W_i \cdot x_i) + r_2 - q_2 = 0$$

(6) – (9)

$r_1, q_1, r_2, q_2 \geq 0$

Where:

r_1, q_1 = negative and positive deviational variables, respectively, measuring the difference between the economic objective in (4) and its optimal value obtained in the respective single objective FP models

μ_{g1} = optimal value for "net return/water demand" obtained from the respective single objective FP model

[1] The exchange rate between the Iranian currency (1 Toman = 10 rials) and the Euro was about 12,000 Toman per Euro. Due to the rapid exchange rate fluctuations and the strong two-digits inflation characterizing the last years, the Authors have preferred to use the local currency without converting into Euro or US dollar. Therefore, the economic values must be considered indicative for the period of the survey.

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μ_{g2}= optimal value for "labour/water demand" obtained from the respective single objective FP model

r_2, q_2 = negative and positive deviational variables, measuring the difference between the social objective in (5) and its optimal value obtained in the respective single objective FP model.

RESULTS AND DISCUSSION

Table 1 shows the technical coefficients referred to the objective functions and constraints included in the models, as they were calculated from the data supplied by the farmers. The net return for each crop has been calculated as the difference between the total revenue (crop yield x market price) and the total production costs. Labour data were estimated by considering all the cultivation phases, such as soil preparation, seeding, crop protection, weeding and harvesting.

Table 1 – Matrix of technical coefficients

Technical data	Wheat	Barley	Canola	Sugar beet	Cucurbits	Forage corn
Net return (000Toman/ha)	639	-319	487	26,323	5,127	3,088
Irrigation water required (m3/ha)	7,5	7,3	7,5	14,0	10,3	12,0
Labour demand (h/ha)	90	76	95	364	270	114
Rotation	1	1	1	-1	-1	-1

Note: 1 indicates main winter crops, -1 secondary crops

Rotations between spring and winter crops are included as the standard crop management applied in the study area. The local extension service supplied the irrigation water requirements for each crop during the entire crop cycle. From the solution of the three models described in the previous section, for each one of the 237 considered farms, the optimal cropping patterns for economic, social, and whole sustainability objectives have been identified (these results are not reported here). Considering the FP model aimed only at maximizing the ratio "net return/water demand" for all the regarded farms, the optimal solution for crops is wheat and sugar beets alternated in a biennial rotation. Indeed, these two crops show higher benefits in economic terms and ensure lower water needs. No other crops enter the optimal solutions for this model.

Referring to the social objective FP model, dealing only with the maximization of "labour/water demand", the results obtained are quite different. In this case, the optimal solutions designed by the model for the entire sample are canola, which replaces wheat as a winter crop, and sugar beet, which remains in the efficient solutions set in terms of social performances due to its high labour intensity concerning water consumption. When both objectives are taken into consideration, the MOFP model for the simultaneous optimization of 'net return/water demand' and 'labour/water demand' leads to the same optimal cropping pattern identified with the single optimization of the economic objective, thus resulting in no gains in terms of real sustainability, when considering both economic and social aspects. Table 2 contains the average values for the entire sample.

According to [25], the two single objective FP models allow achieving more efficient solutions for both sustainability indicators considered when compared to the current agricultural pattern. As expected, the "net return/water demand" ratio reaches the highest value (1,254 Toman/m3) in the single economic objective model. This indicator shows only a little decrease moving to the social objective model, whose cropping pattern results in 1,245 Toman/m3. Also, in terms of "labour/water demand," the FP and MOFP solutions dominate the current situation, with values ranging from 0.02135 hours/m3 for the social objective model, to 0.2112 for both economic and multi-objective models. In this case, the two objectives show a very low conflicting degree, as the proximity of the extreme points suggests

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Table 2 – Sustainability indicators resulting from optimal cropping patterns obtained from single and multi-objective fractional models (average values per farm).

	Net return (10^6 Toman)	Labour (h)	Water consumption (m^3)	Net return/water demand (Toman/m^3)	Labor/water demand (h/m^3)
Present situation	48.67	1,337	75,186	535	0.01696
Economic objective	103.02	1,735	82,155	1,254	0.02112
Social objective	102.45	1,754	82,155	1,245	0.02135
Both objectives	103.02	1,735	82,155	1,254	0.02112

To compare the economic and social benefits deriving from the FP and MOFP optimal cropping patterns, Table 3 shows the potential increase of the sustainability performances compared to the present situation. As the results indicate, the farms show high potential for both the sustainability indicators considered in the study, especially in terms of "net return/water demand", thus evidencing the low performances of the actual water management system. More specifically, adopting the crop pattern identified with the individual optimization of the economic objective, both sustainability indicators "net return/water demand" and "labour/water demand" could increase, respectively, by 134.3% and 24.5%, on average among all the farms.

Table 3 – Sustainability indicators are resulting from optimal cropping patterns obtained from single and multi-objective fractional models (average values per farm).

Objectives	Δ [(optimal net return/water demand) / (current net return/water demand)]	Δ [(optimal labour /water demand) / (current labor /water demand)]
Economic objective	134.3%	24.5%
Social objective	132.7%	25.8%
Both objectives	134.3%	24.5%

Quite similar is the improvement achievable by considering the optimal solutions suggested by the social objective fractional model, corresponding to a potential increase, on average, of 132.7% and 25.8%, respectively for the two ratios. As already mentioned, since the efficient solutions indicated by the MOFP model coincide with the objective economic ones, no differences can also be found in terms of potential increase of the sustainability indicators.

To this regard, Table 4 shows the comparison between the solutions of the MOFP model and those of to the single FP models. In terms of Pareto's optimality, no dominance relationships of the multi-objective solutions could be identified over the single objective ones. Concerning the economic objective, the multi-objective solutions are equivalent, whereas compared to the social ones, they are better for one indicator (net return/water demand), but worse for the second one (labour/water demand).

Table 4 - Comparison between the farm sustainability indicators (average values) from the multi-objective and the single objective solutions.

Objectives	Δ [(optimal MOFP net return/water demand)/(optimal FP net return/water demand)]	Δ [(optimal MOFP labour/water demand)/(optimal FP labour/water demand)]
Multiple objectives / Economic objective	0.00%	0.00%
Multiple objectives / Social objective	1.20%	-5.03%

CONCLUSIONS

This paper demonstrates that the implementation of a decision support system, based on a mathematical programming model, the single Fractional Programming (FP) and on a Multiple Objectives Fractional Programming (MOFP) model, could represent an effective strategy to increase the efficiency of the irrigation groundwater, in terms of net income and labour requirement per cubic meter, as also indicated by [25]. These two indicators are significant for all smallholders worldwide, producing in a situation of extreme aridity, who usually live near the poverty line and have labour available as an internal family resource. Such results fit perfectly into the UN Sustainable Development Goals [7] set for 2030, especially those dealing with poverty eradication and natural resource management.

This can be done if the local extension services, either public or private, collect and process some basic farm management data (yields, cost of production, water demand, rotations, labour requirements), related to the most cultivated crops and then, with a MOFP model, advice the producers about their optimal land distribution. We are not talking about generic blanket recommendations, with some general guidelines standard for all farmers and situations, but about tailor-made advice, locally specific, for each farmer. As written by several authors [11] [27], in Iran, this cannot be done without the strengthening, at the field level, of the public extension service, which requires more technicians, adequately qualified, and more means to reach all farmers, in all villages.

However, the implementation of such individualized advice should not prevent the search for other types of soft and hard innovations [29], such the ones listed before: new kinds of farmers' organizations (like the Water Users' Association), more advanced technologies (from drip irrigation to drones), the introduction of meters and pricing of water, lower use of fertilizers, new - less water demanding - varieties, new more aridity resistant crops, landscaping for water catching and better water distribution, re-design of more resilient production systems.

Finally, further research is needed to apply the FP and the MOFP models to different farming systems, including orchards and animal productions, where adaptation could be more complex and time-demanding.

AUTHORS' CONTRIBUTION

Azadeh Bakhshi has been responsible for the conceptualization, field survey coordination, data entry and elaboration; Lucio Cecchini was the main responsible for data control, validation and econometric elaboration, while Fabio Maria Santucci was in charge for supervision, coordination, writing and editing. All authors cooperated for the discussion and conclusions.

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There is no conflict of interest

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