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# A Bio-Economic Model for Improving Irrigated Durum Wheat Performance and Regional Profits under Mediterranean Conditions

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**Abstract:** Irrigated durum wheat is a staple food crop that occupies important areas in Tunisia. However, its performance remains weak, with an average national yield of no more than 7 tons $ha^{-1}$ and low profitability. Overall, on-farm wheat production will need to increase considerably to meet future demand and ensure minimum profitability for farmers. To this end, this study aims to identify the main levers for improving durum wheat crop performance. For this purpose, we have developed a regional bio-economic model by linking a biophysical model (CROPSYST) with an economic optimization model (MORBIT). CROPSYST was used to establish a database with a view to determining the relationships between farming practices, durum wheat yields, and water productivity within a context of high climate variability. The database was then integrated into a MORBIT model that analyzed the effects of farming practices on durum wheat performance and regional profits. Three scenarios related to irrigation control and the increase in durum wheat prices were developed. The results showed that reconciling irrigation practices with economic policies is the best alternative to improve durum wheat performance and increase profits at a regional level.

**Keywords:** durum wheat; profit; performance; bio-economic model; Tunisia

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## 1. Introduction

The inter-dependence of environmental and socioeconomic resources is an important feature of agricultural production systems. Consequently, applied agricultural system research will need to consider the relationships between the quality and quantity of natural resources such as soils, water and plant physiology, and farm production costs and profits [1]. Bio-economic modeling that integrates economics with agricultural science and ecology is the most widely recommended approach to studying the impact of political and technological changes on agriculture, the economy, and the environment [2]. Bio-economic models began to appear in the agricultural economic literature in the late sixties and early seventies [3,4]. Early examples of bio-economic models of plant-production systems include the Donaldson Harvest Machine Selection Model [3]. Over the past 20 years, with increased computer power and significant technical improvements for modeling biological processes, bio-economic models have become more sophisticated, more accurate, and more comprehensive in terms of the management alternatives and environmental situations that they can evaluate [4]. In recent years, there has been significant development of bio-economic models, especially those integrating biophysical models and economic mathematical programming models [5]. This development was enhanced by the conjunction of several factors, such as the multiplicity of objectives in innovative agricultural policies, the increase in demand for multi-disciplinary approaches for integrated assessment, and the call for more dialogue and cooperation between scientists from various disciplines [6].

In this context, a significant number of bio-economic agricultural models have been developed and tested in different agricultural systems and under different agro-ecological conditions [2]. They are mainly used to assess environmental issues at the farm level and to help agricultural producers to understand and manage their production systems. In order to assess the economic and environmental performances of farms, a bio-economic approach combining a biophysical and an economic model was explored [7]. The environmental impacts of crop management, such as the effect of water and nutrient management, were estimated using cropping system simulation models (CROPSYST). The outputs of the latter are then used to feed the economic farm model database [7]. However, this approach has failed to identify impacts at higher levels (e.g., region, country), which may be useful to policymakers. These limitations have led to the development of a regional model. When applied at a regional level, bio-economic models aim to optimize the profits of a specific region in relation to its technical options and economic and social aspirations [8–10]. One of the strengths of regional models is their capacity to take into account many technologies that can be used simultaneously, depending on the constraints associated with the availability of resources [11]. Regional models have varied widely depending on the systems involved, the questions being raised, and the policies being studied. Indeed, in order to analyze policy impacts on agriculture and, therefore, to provide suggestions for policy decisions, researchers first developed an aggregate regional model. In this model, the region is considered as a single farm [12]. Then, for assessing ex ante agro-environmental policies on a broad scale, a more detailed regional model was developed by dividing the region into sub-regions, each of which is considered a farm [13]. This new consideration makes it possible to develop models that represent the heterogeneity of soils and climates in the region. However, they fail to represent the diversity of farming systems and to consider decision-making processes at the farm level [14]. Hybrid bio-economic models address this issue by aggregating results from the farm level to higher levels [14]. In these models, the lowest level is the farm, and the highest one is the region. Decision-making and technical changes are represented at the farm level, while aggregated indicators can be calculated at a regional level. Thus, agro-economic policies are assessed at different levels by considering the diversity of farm types (e.g., crop, livestock), the heterogeneity of technology, and climate conditions in the region [15]. Hybrid models also provide the possibility of integrating the interactions and competitions between farms in the region when considering the possibilities of resource transfers between farms (e.g., water, labor, and land).

A rapidly growing number of research projects are using these models, and there is increasing interest in their application [15,16]. In Tunisia, hybrid bio-economic models are mainly used to address environmental policy questions [8]. In fact, the analysis of the impact of soil and water conservation policies [16] has contributed to the development of a dynamic Tunisian regional model. It combines the EPIC biophysical model with an economic mathematical programming model to assess the economic and ecological impacts of erosion control policies at the farm and regional levels. Furthermore, hybrid models are used to assess the impact of technological change on agricultural production. In fact, Jeder et al. [17] developed a regional agricultural model to assess the impact of the reallocation of water resources on income at the farm and regional levels. Results showed that this reallocation of water increases agricultural income by 2.12% and allows for a diversity of agricultural farms. Within the context of this study, we developed a bio-economic model integrating two-scale analysis, the farm frame as well as the regional level. In Tunisia, irrigated durum wheat (DW) indeed holds the most important place among irrigated cereal crops in terms of production and cultivated areas. It is grown on an average annual area of 48,700 ha, which represents two-thirds of the irrigated cereal crop area. The production reached an average of 180,000 tons, which represents around 20% of national DW production. However, the achieved DW yield only reached 3.6 tons ha$^{-1}$ against an expected yield of 7 tons ha$^{-1}$ [18]. This result also showed very low water productivity and economic performance [19]. Previous studies [20,21] assumed that the poor management of applied doses and irrigation timing are major factors that limit the agronomic performance of DW. Nevertheless, these studies were conducted in experimental plots without taking into account the intrinsic operating conditions of the farm.

The objective of this study is, therefore, two-fold. It aims firstly to draw up an operational diagnosis of irrigated cereal farms in Tunisia. The second objective is to highlight the main levers for improving the performance of the DW crop and regional profits.

Hence, the remainder of the paper is structured as follows. In Section 2, we displayed the study area and the method to gather and analyze the required data. We presented the different steps of our conceptual framework, particularly the modeling approach. We devoted Section 3 to presenting the results in terms of descriptive analysis and scenarios simulation. We discussed these results in Section 4. Finally, we presented some concluding remarks in Section 5, focusing on the main policy implications of the results and the limits of our research.

## 2. Materials and Methods

The general framework used in this paper to highlight the main levers for improving the performance of the DW crop and regional profits in Tunisia consists of three steps (Figure 1).

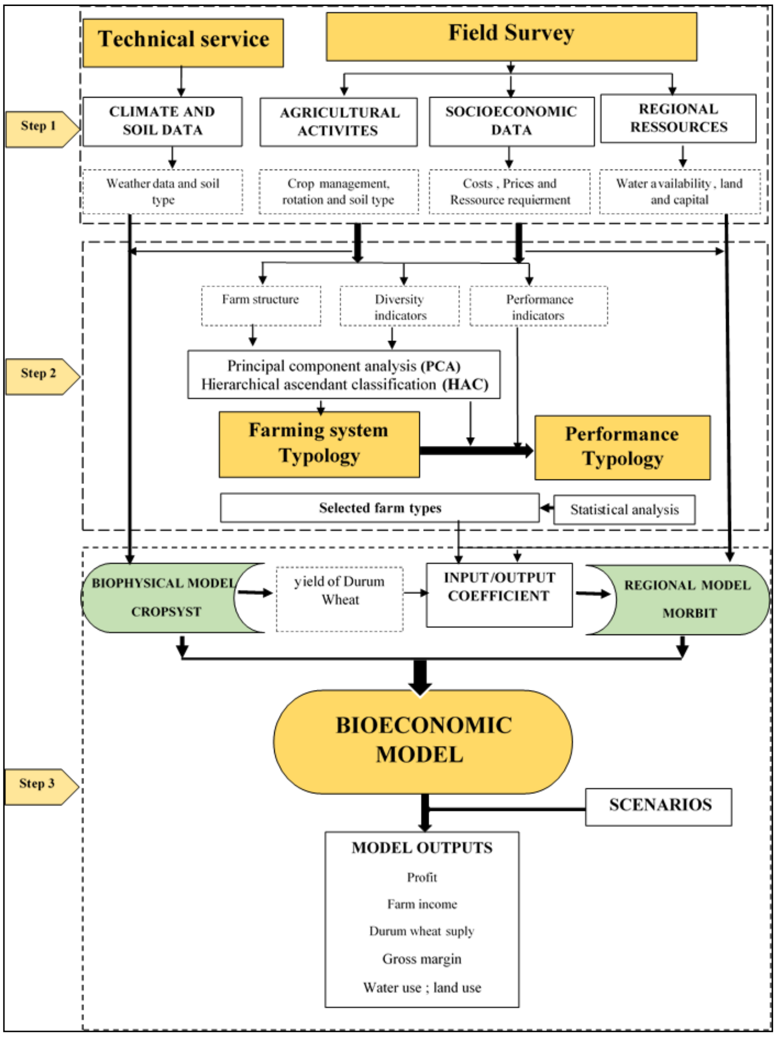


**Figure 1.** Framework of the analysis.

### 2.1. Study Area and Data Collection

This study was carried out in the governorates of Kairouan, Jendouba, and Siliana (Figure 2).

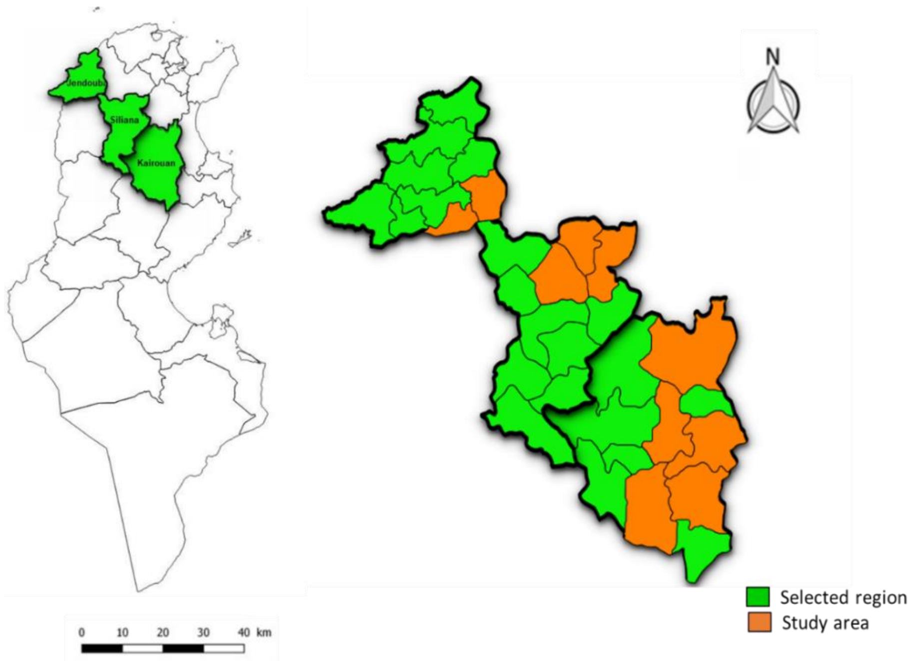


**Figure 2.** Location of the study area.

These regions represent the main area where irrigated DW is grown. The irrigated cereal crop area occupies 50% of the total cereal crop area.

DW is the most irrigated cereal crop, with an average area of 56% of the irrigated cereal crop area. This activity contributes an average of 54% of the total irrigated cereal crop production [22]. The region of Jendouba stands out with the rainiest climate in the country, with an average annual precipitation of 496 mm. The average temperature is 21 °C with a max of 46 °C. This very high temperature might negatively impact crops grown, worsened by high solar radiation (18 MJ $m^{-2}$ per day). Siliana is characterized by a continental climate with an average annual precipitation of about 486 mm and a mean temperature of 19 °C. The mean annual global radiation reached 17MJ $m^{-2}$ per day. Kairouan is characterized by a semi-arid climate with a mean annual rainfall is about 294 mm and a mean temperature of 24 °C. The mean annual global radiation of about can wait 20 MJ $m^{-2}$ per day. In the three regions, 60% to 80% of precipitation is recorded during the irrigated durum wheat crop cycle (November–June). The dominant soils are mainly clay to loam but differ in their water holding capacity (WHC).

In order to represent the diversity of farming systems and to analyze in depth the activity of growing irrigated DW, we attempted to select a representative sample. Indeed, we have collected an exhaustive list of farmers growing irrigated cereal crops (Wheat and barley) in the three regions. The total number of farms reached 8000. The cultivated area per farm varies between 0.5 and 60 ha, and the total area of the irrigated cereal crops accounts for 46,890 ha. Areas larger than 20 ha are mainly cultivated by the organized sector, such as the office of state land and companies of agricultural development. So in order to select a representative sample of private farms, we kept those with less than 20 ha, which cover 75% of the total area of irrigated cereals in the three regions. Then, we adopted the stratum sampling method by considering three strata ((0–5 ha), (5–10 ha), and (10–20 ha)) and fixing the sampling rate at 15% [23]. Thus, our sample reaches 905 cereal farmers, distributed between 563 (62%) in Kairouan, 269 (30%) in Jendouba, and 73 (8%) in Siliana (Figure 2). Hence, we carried out face-to-face surveys during the spring of 2016 to collect data on farm operations during the previous cropping year (2014–2015). We mainly focused on the characterization of the farms' structure (SAU, number of plots, access to water) and on the farming system (land use, livestock activity, irrigated activity, etc.). This makes it possible to gather detailed data regarding the technical management of cereal crops (seeds and sowing, tillage, fertilization, irrigation, treatment, labor, harvesting) as well as all the input and product prices. We also asked farmers about their perceptions regarding the constraints and prospects for the development of this activity, particularly in relation to the availability of the water resource. Finally, 904 farmers were interviewed. The analysis of these surveys showed that only 698 farms had grown the irrigated DW distributed as 386 (55%) in Kairouan, 245 (35%) in Jendouba, and 67(10%) in Siliana

### 2.2. Farm Typology

Given the wide diversity of agricultural systems, farm typology is an appropriate tool for identifying groups of farms with similarities in terms of farming practices. This is achieved by categorizing farms into groups with common characteristics [24]. Farm typology can also be used in modeling and simulation studies to assess the potential impacts of specific interventions on agricultural systems [17]. For this reason, to simulate the impact of cropping practices on the performance of DW while taking into account the heterogeneity of agricultural systems, we developed a farm typology. The methodological framework of the typology comprised the following two steps (Figure 1). First, we developed a typology based on the functioning of the agricultural system. All farms are grouped into coherent farm types according to (1) farm area, (2) the size of the irrigated cereal crop activity, (3) the diversification of the cropping system (H'), as well as (4) the technical-economic orientation. Once distinct farm types were established, we carried out a second classification that made it possible to identify the different levels of performance for each farming system by using agronomic and economic indicators [22].

In order to establish the typology, we used two multivariate statistical techniques, namely principal component analysis (PCA) and hierarchical ascending classification (HAC) (Figure 1). PCA is used to reduce the data set to uncorrelated constituents and HAC to partition the PCA output into clusters [25].

### 2.3. CROPSYST-MORBIT Modeling Chain

The modeling approach involves the development of a crop model using CROPSYST (Cropping Systems Simulation Model) and the MORBIT as an economic regional model (regional model of irrigated durum wheat in Tunisia) to assess the impact of agronomic and economic scenarios on DW performance and regional profits (Figure 1).

#### 2.3.1. CROPSYST

CROPSYST is a multi-year, multi-crop, daily time step crop growth simulation model [26]. It serves as an analytical tool to analyze the effect of cropping system management on crop productivity and the environment [26]. Based on daily weather data, such as solar radiation, maximum and minimum temperatures, rainfall, as well as soil characteristics, initial soil conditions, cultivar characteristics, and crop management, CROPSYST can simulate crop development, growth, yield, water, and nutrient uptake [27].

The choice of the CROPSYST model as the reference biophysical model is motivated by its low parameter requirement and its suitable predictive quality, even with succinct calibration, such as in Belhouchette et al. [27]. We want to avoid complex models, which are developed to be used for plot analysis with a large observed data set and therefore hardly compatible with a scenario-based approach in interaction with stakeholders dealing with innovation in cropping systems [7]. Starting from the idea that the degree of detail included in simulation models should much fit the specific research question addressed and data availability for calibration, the CROPSYST model should meet, given its modularity, parsimony, and measurability of a vast majority of its parameters, the main requirements for integration such addressed in this paper.

CROPSYST has been widely used in bio-economic modeling to assess agronomic indicators. This model has been applied to simulate several crops (maize, wheat, barley, soybean, sorghum, sugar beet, lupins, and forage crops) in different regions, generally with suitable results [28–32].

CROPSYST model was also used for the same climate and soil conditions, such as in this study, at least in two case studies. For both studies, the CROPSYST model was used respectively to feed the bio-economic model to assess (i) the resilience of mixed farming systems under climate uncertainty [33] and (ii) the performance of DW-based farms under different irrigation strategies [7]. The results indicated suitable confidence in simulating DW yield for a wide range of management practices [33].

In this study, CROPSYST is used to assess the impact of irrigation management alternatives on DW yield by taking into account climatic factors, previous crops, and soil characteristics. Four input data files are required to run the model. The climate file includes daily weather data in terms of maximum and minimum temperatures, maximum and minimum relative humidity, precipitation, solar radiation, and wind speed. These data were acquired from the National Institute of Meteorology (NIM) in Tunis (Table 1). The soil file characterizes the soil texture (% clay, % silt, % sand) and soil moisture (water content at field capacity, permanent wilting point). These data were collected from the Regional Agricultural Development Commissariat (CRDA). The management file describes the growing practices adopted by farmers during the physiological cycle of the crop, such as irrigation, fertilization, sowing, and harvest dates. The data were gathered from the field survey and validated by the technical experts of the CRDA. The crop file includes the phonological and morphological characteristics of the crop. These data were extracted from field research, which was adapted to the Tunisian context.

**Table 1.** Climate and soils description (average of campaigns 2014/2015 to 2016/2017).

| | T Max | T Min | T Mean | RH Max | RH Min | RH Mean | SRad | Clay | Silt | Sand |
|---|---|---|---|---|---|---|---|---|---|---|
| Kairouan | 48 | 2 | 24 | 100 | 7 | 85 | 20 | 56 | 30 | 14 |
| Jendouba | 46 | 6 | 21 | 100 | 4 | 68 | 18 | 39 | 28 | 33 |
| Siliana | 42 | 2 | 20 | 100 | 6 | 59 | 17 | 42 | 38 | 20 |

TMax = maximum temperature (°C), TMin = minimum temperature (°C), TMean = mean temperature (°C), RH = relative humidity (%), and SRad = solar radiation ($MJ/m^2$ /day).

### 2.3.2. MORBIT

MORBIT (regional model of irrigated DW in Tunisia) is a regional optimization model. It was developed by adapting the SARAS model (South African Regionalized Farm-level Resource Use and Output Supply Response) to Tunisian conditions [34]. The latter is a hybrid model that integrates farm and regional levels. Farm-level outputs are aggregated to the regional level by averaging the total output of each farm type. This model was also calibrated using positive mathematical programming (PMP) [35].

Furthermore, SARAS has a modular setup. This modularity makes it possible to activate and deactivate modules according to different objectives and modeling regions. The SARAS model also allows subsequent incorporation of additional modules that may be required to simulate activities not included in the existing version and the replacement of modules with other versions. Moreover, the main originality of SARAS lies in its ability to represent biophysical links between the field at the farm level and the regional level by using a technical coefficient. The latter is the ratio between the average yields obtained at a regional level and those achieved by a typical farm [34].

The adaptation of the SARAS model to meet our research purposes involves the following steps. Firstly, compared to SARAS, we did not consider livestock activities in this bio-economic modeling process because of the missing data. Secondly, we defined two different technologies according to the nature of irrigation resources (public, private). Thirdly, to develop the bio-economic model, we coupled the MORBIT with the CROPSYST by using a technical coefficient that represents the relation between the average wheat yields obtained at a regional level and those achieved by each farm type for each scenario. MORBIT aims to maximize regional profits subject to a set of resource constraints. The general mathematical formulation of MORBIT is as follows:

$$Maximize \prod = \sum_f \sum_t \sum_c ((\mathrm{PB}_{ftc} - (\alpha_{ftc} + 0.5\beta_{ftc})) * \mathrm{sup}_{ftc}) - \sum_f (\theta_f (\sum_t \mathrm{sup}_{ftc})' * \mathrm{covPB}_c (\sum_t \mathrm{sup}_{ftc})) \quad (1)$$

Subject to:

$$Nf \sum_f \sum_t \sum_c \mathrm{sup}_{ftc} \leq Disp_{Rterre} \quad (2)$$

$$\sum_t \sum_c \mathrm{sup}_{ftc} \leq Disp_{fterre} \quad (3)$$

$$Nf \sum_f \sum_t \sum_c Beseau_{ftc} * \mathrm{sup}_{ftc} \leq Disp_{Reau} \quad (4)$$

$$\sum_t \sum_c Beseau_{ftc} * Sup_{ftc} \leq Disp_{feau} \quad (5)$$

$$\sum_t \sum_c Besres_{ftc} * Sup_{ftc} \leq capital_f \quad (6)$$

$\prod$ is the regional profit; PB is the expected revenue from crop; $f$ is the vector of farm types; $t$ is the vector of technologies (public and private); $c$ is the vector of crop activities; $sup$ is the vector of land use; $Disp_{Rterre}$ is the available land at a regional level; $Disp_{fterre}$ is the amount of available land for each farm type $f$ (ha); $Beseau$ is the water requirement; $Disp_{Reau}$ is the amount of water available at a regional level; $Disp_{feau}$ is the amount of water available for each farm type $f$ ($m^3$); $Besres$ indicates the needs for financial means; $capital$ indicates the financial means available for each farm; $\theta$ is the risk coefficient; $Nf$ is the number of farming units in each farm type; and cov is the variance-covariance matrix of the selected farm.

The main technical and economic constraints are irrigable land, irrigation water, and financial means.

Equation (2) represents the land constraint at a regional level and means that the total land use of the region cannot exceed the available land.

Equation (3) represents the land constraint at the farm level and means that the total land cannot exceed the available one.

Equation (4) represents the water constraint at a regional level and indicates that the total water use of the region cannot exceed the amount of available water.

Equation (5) indicates that the total water use for each farm cannot exceed the amount of available water.

Equation (6) represents the capital constraint at the farm level.

### *2.4. Model Calibration*

#### 2.4.1. CROPSYST

CROPSYST was calibrated using the DW yields revealed by the surveys. The two most sensitive parameters were calibrated for simulation with CROPSYST, namely the biomass transpiration coefficient (KBT) and the radiation use efficiency (KLB) [27]. We adjusted these two parameters until a satisfactory balance between the observed and simulated yield was achieved [36]. For each farming system, we compared simulated DW yields with observed yields using the percent absolute deviation (PAD). The formula is as follows:

$$\mathrm{PAD}(\%) = 100 * [(\mathrm{V_{Si}} - \mathrm{V_{Oi}}) / \mathrm{V_{Oi}}]$$

where:

$V_{Oi}$ is the observed value of variable i; $V_{Si}$ is the simulated value of variable i.

To evaluate the performance of CROPSYST regarding the simulation of DW yield for each farming system, we considered different technical itineraries of DW performed by around 15% of different farms for each farming system. The goodness of fit between observed and simulated yield was calculated using the relative root mean squared error (RRMSE) [28].

#### 2.4.2. MORBIT

Just like the SARAS model, MORBIT was calibrated by using PMP and incorporating risk into the objective function. Indeed, The PMP is a common approach to avoid over-specialization in mathematical modeling and minimize the aggregation bias [37]. It has renewed the interest in mathematical modeling of agricultural and environmental policies [15]. This approach was implemented in two stages. In the first step, we added a number of calibration constraints to the model to ensure that the observed situation for the base year was reproduced. The objective is to calculate the shadow price of the binding calibration constraints. In the second step, the calibration constraints are taken out, and their shadow prices are used to calculate non-linear costs [38].

Then, to ensure the exact reproduction of the observed situation under Tunisian conditions, we adjusted the risk factor $\theta$ [39].

In order to evaluate the calibration of MORBIT, we compared the outputs of the model to the observed data in terms of total crop area, DW supply, and regional profits. To assess the difference between both values, we calculated the percent absolute deviation (PAD), which should be less than 15% at a regional level [15].

### *2.5. Definition of Scenarios and Indicators*

The operational diagnosis of DW activity makes it possible to define three alternative scenarios: irrigation management control, increased cereal prices, and a combination of the two previous scenarios

Irrigation management control (S1): By analyzing the irrigation schedules applied in the governorates of Siliana and Jendouba, results showed that the third irrigation dose was applied at the beginning of April. According to the volume of received rainfall and the level of recorded temperatures, the analysis of this irrigation schedule reveals that the third irrigation dose may not effectively contribute to plant growth [40]. Hence we hypothesized that an adequate calendar for irrigation scheduling could have an important impact on improving agricultural productivity in the regions. Following the work of Boughdiri et al. [40], this scenario suggests the application of a third irrigation dose in mid-March and not at the beginning of April.

Furthermore, studies showed that applying an adequate dose of irrigation to meet the right needs of crops allowed optimal yields [41,42]. In order to assess the effects of irrigation technical management on farm income and DW performance, the competent services of the INGC and field experts conducted an irrigation management trial during the 2015–2016 crop year on a plot of DW in the Kairouan region by using irrigation control methods. Results showed that by controlling irrigation doses, it is possible to optimize the yield and control water losses [41]. In addition, Hammami et al. [42] showed that the water supplies in Northern Tunisia irrigated districts (Siliana and Jendouba) did not always meet crop water requirements. The application of an irrigation dose in accordance with the crop's needs allowed farmers to achieve a DW yield of 5 tons ha$^{-1}$. Given these results, this scenario also aims to adjust the irrigation dose by taking into account the theoretical needs of the crop.

Increased cereal price (S2): The main problem facing farmers today is the decrease in their income due to low yields and rising costs. Maximizing profit is always the objective of farmers who try to reduce their production costs as much as possible. However, these production costs are constantly increasing due to the increase in the price of inputs (seeds, fungicides, mechanization, diesel, etc.). The economic aspect is of paramount importance in the introduction of cereal crops into the farming system. Indeed, minimum profitability should be guaranteed to farmers to encourage them to grow cereal crops. Therefore, increasing DW prices will improve the farmers' income. This scenario aims to analyze the impact of increasing cereal prices on the economic performance and supply of DW as well as on regional profits. We simulated three increased cereal price scenarios with different rates (10%, 15%, and 20%).

Mixed scenario (S3): The combination of all the previous scenarios was also explored by analyzing the possible positive or negative interactions between the effects of the management of irrigation and cereal prices.

In order to compare the performance of DW and the regional profits for the different scenarios, we calculated six indicators related to economic and agronomic aspects. We selected four agronomic indicators:

1. DW yield (tons $ha^{-1}$);
2. DW water productivity (kg $m^{-3}$ $ha^{-1}$) defined as follows:

$$\text{Water Productivity} = \frac{\text{DW Yield}}{\text{Water Consumption}}$$

$$\text{Water Consumption} = \text{Water Irrigation} + \text{Effective Rainfall}$$
$$\text{Effective Rainfall} = 0.7 * \text{Total Rainfall}$$

3. Total area of DW at a regional level (ha);
4. DW supply (tons).

In addition, two economic indicators were considered:

1. DW gross margin TND $ha^{-1}$ per farm;
2. Regional profit (TND).

DW yield was simulated using the CROPSYST model. Water productivity was calculated using CROPSYST output. The total area and supply of DW and economic indicators were calculated directly using the MORBIT model.

## 3. Results

### *3.1. Descriptive Analysis*

The results showed that the surveyed land covered 7345 ha. The average farm area reached 11 ha, ranging from 0.5 to 100 ha. Approximately 86% of surveyed crop areas are fully or supplementary-irrigated. The analysis of irrigated land use during cropping year 2014–2015 showed that the farming system is mainly based on irrigated cereal crops, which account for 58% of the total irrigated area. Irrigated DW is the main cultivated cereal crop and covers 3183 ha, with a significant difference between regions. In fact, in the Kairouan region, the irrigated DW area amounts to 1756 ha. However, it reaches 1148 ha in the Jendouba region and 279 ha in Siliana. Market gardening crops occupy an area of 1694 ha (28%). Fruits trees make up 9% of the irrigated area. While other crops, such as fodder crops and legumes, are cultivated in limited areas. In terms of rotation, results showed that the DW market gardening is one of the most common rotation types. In fact, DW-legume rotations are limited and are mainly carried out in the region of Jendouba. However, some farmers do cultivate DW in monoculture to benefit from governmental support in selling their harvest at relatively acceptable prices.

Regarding irrigation management, results showed that farms in the Kairouan region are supplied with water from surface wells and private boreholes. However, farmers in Siliana and Jendouba have access to water through the public network releasing water from the reservoirs. Even though DW is grown during the winter season, it receives complementary irrigation during early spring to ensure better yields. The water consumption of DW reached 2179 $m^3$ $ha^{-1}$ but presented high regional variability (3407 m $^{-3}$ $ha^{-1}$ in Kairouan, 813 $m^{-3}$ $ha^{-1}$ in Siliana, and 618 $m^3$ $ha^{-1}$ in Jendouba).

In terms of performance, results showed that the use of complementary irrigation allowed farmers to achieve an average DW yield of 3.9 tons $ha^{-1}$. There were also differences in DW yields across the different regions. In fact, in Jendouba, the DW yield reached 4.2 tons $ha^{-1}$, while it was only 3.9 tons $ha^{-1}$ for the others. Given this result, water productivity reached 0.76 kg $ha^{-1}$ $m^{-3}$, which is half of the potential level that should be reached according to agronomic studies [43]. Economic results showed that the gross margin of DW only reached 1696 $TNDha^{-1}$.

### *3.2. Farm Type Selection*

The farm typology revealed three distinct farming systems:

- The monocultural system: this farming system is based on DW crops. In fact, these farms occupied an average area of about 8.3 ha. They stand out as the least diversified cropping system with a Shannon-Wiener index (H') of 17% [22]. This group is characterized by the lowest water consumption, with an average of 1953 $m^3$ $ha^{-1}$. It also has the lowest income with an average of 1691 TND $ha^{-1}$. Cereal crops occupy 97% of the land area. They constitute the main source of income with a gross margin of 1500 TND $ha^{-1}$.
- The diversified cereal-oriented system: this farming system includes farms that predominantly cultivate cereal crops. In fact, these farms occupy an average area of 10 ha. They are characterized by a diversified cropping system (H' = 35%). However, cereal crops remain the most important activity in terms of area and income. Indeed, they occupy 56% of the cultivated area and provide approximately 51% of the total income. Horticultural crops only occupy 21% of the total area, and the other crops occupy about 23%. This group uses 2815 $m^{-3}$ $ha^{-1}$ of water irrigation per farm.
- The diversified market gardening-oriented system: this group of farms occupies an average area of 14 ha. It stands out as the most diversified cropping system with a Shannon–Wiener index (H') of 43%. Similarly, this farming system has the highest water consumption (4293 $m^3$ $ha^{-1}$) and the highest farm income (2907 TND $ha^{-1}$). Although vegetable crops only represent 39% of the total cultivated area, they provide 56% of the total income. Cereal activity, which occupies 49% of the area, only provides 26% of the total income.

The comparison of these three farming systems in terms of DW performance showed significant disparity. The typology of performances made it possible to distinguish two performance levels for each farming system and for each region. We thus identified 18 farm types.

In order to select farm types for the model, we carried out a two-step statistical analysis. In the first step, we assessed the regional effect on the performance of irrigated DW using the Kruskal–Wallis test [44]. Results showed that there are no significant differences between Siliana and Jendouba, while these two regions showed significant differences with the Kairouan region for some indicators [22]. In the second step, we conducted a spatial analysis to identify the dominant farm types by system and by region. The results of this analysis revealed that 50% of farmers in the governorate of Siliana opt for monocultural systems. In the governorate of Kairouan, 77% of farmers use diversified systems, 42% have a diversified system with a market gardening orientation, and 35% adopt diversified systems with a cereal orientation. While in the governorate of Jendouba, we found that the three systems have almost the same importance in terms of the number of farms (Figure 3).

Given these results, 10 dominant farm types stand out, depending on land use, the resource endowments available for each farm, and the performance of DW.

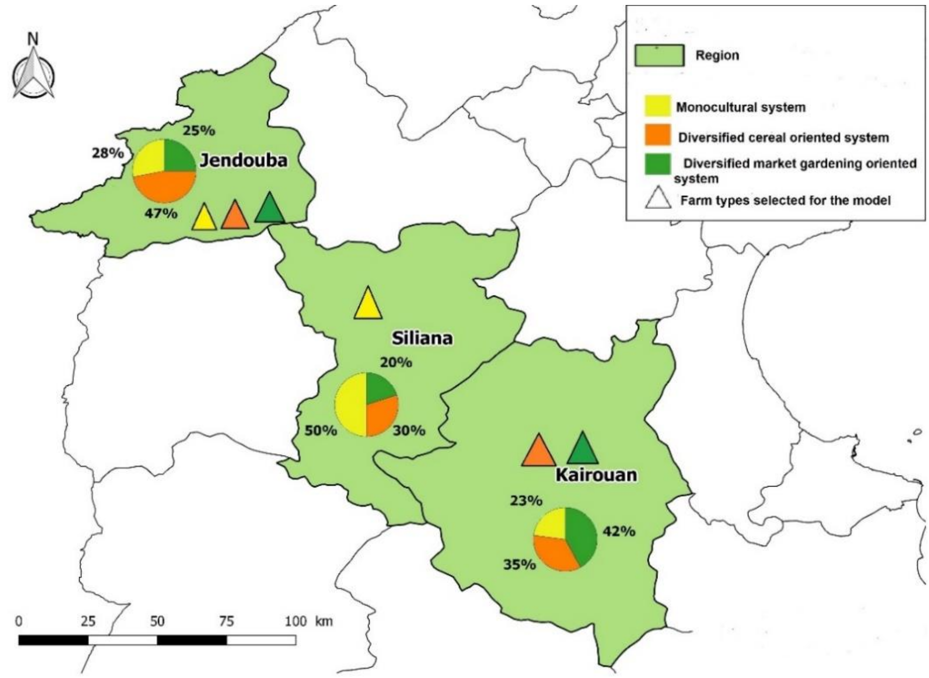


**Figure 3.** Distribution of farm types by region.

Table 2 defines these farms types and presents the resource endowment characteristics of each farm type, such as available land (%), crop area (%), and irrigation water availability ($m^3$).

**Table 2.** Data on the resource endowment of each farm type.

| | Definition of Each Farm Type | Total Area (ha) | Irrigable Area (ha) | Crop Area (%) | | | | Water Available ($m^3$) |
|---|---|---|---|---|---|---|---|---|
| | | | | Cereal Crops | Market Gardening | Fruits Trees | Others Crops | |
| MNNP | Monocultural system with a positive technical base in the North | 7.6 | 4.7 | 58 | 4 | - | 1 | 2525 |
| MNNN | Monocultural system with a negative technical base in the North | 5.9 | 4.8 | 79 | 0.04 | - | 4 | 2539 |
| CRPJ | Diversified cereal-oriented system with a positive technical base in the Jendouba region | 9.8 | 8.7 | 51 | 20 | 3 | 18 | 10,023 |
| CRNJ | Diversified cereal-oriented system with a negative technical base in the Jendouba region | 8.2 | 6.5 | 49 | 12 | 6 | 16 | 7380 |
| CRPK | Diversified cereal-oriented system with a positive technical base in the Kairouan region | 9 | 9 | 60 | 22 | 14 | 4 | 32,083 |
| CRNK | Diversified cereal-oriented system with a negative technical base in the Kairouan region | 8.9 | 8.9 | 56 | 25 | 15 | 4 | 31,109 |
| MRPJ | Diversified market gardening-oriented system with a positive technical base in the Jendouba region | 17 | 14 | 34 | 37 | 6 | 11 | 13,805 |
| MRNJ | Diversified market gardening-oriented system with a negative technical base in the Jendouba region | 9.7 | 8.3 | 43 | 44 | 3 | 2 | 12,871 |
| MRPK | Diversified market gardening-oriented system with a positive technical base in the Kairouan region | 14 | 13 | 43 | 35 | 8 | 4 | 38,051 |
| MRNK | Diversified market gardening-oriented system with a negative technical base in the Kairouan region | 12 | 11 | 43 | 26 | 12 | 2 | 47,152 |

### *3.3. Model Evaluation*

CROPSYST was calibrated by comparing the simulated and observed yields of DW for each farming system revealed by the field survey. Results of the calibration show that the PAD was below 10% (Table 3).

**Table 3.** Calibration of CROPSYST for each farming system.

| Farming System | Observed Yield (Tons ha$^{-1}$) | Simulated Yield (Tons ha$^{-1}$) | PAD (%) |
|---|---|---|---|
| Monocultural system in the Siliana region | 3.4 | 3.4 | 1.4 |
| Monocultural system in the Jendouba region | 4.2 | 4.4 | 4.7 |
| Diversified cereal-oriented system in the Jendouba region | 4.4 | 4.6 | 4.5 |
| Diversified cereal-oriented system in the Kairouan region | 3.7 | 3.9 | 6.4 |
| Diversified market gardening-oriented system in the Jendouba region | 4.5 | 4.6 | 3 |
| Diversified market gardening-oriented system in the Kairouan region | 4.3 | 4.2 | 2 |

Once calibrated, the model was evaluated by considering different technical itineraries of DW performed by different farms for each farming system. Results showed a significant correspondence between the simulated yields and those observed with an RRMSE lower than for all farming systems by 20% (Figure 4). Referring to previous studies [19,28], we concluded that the model is well calibrated and is able to simulate different scenarios.

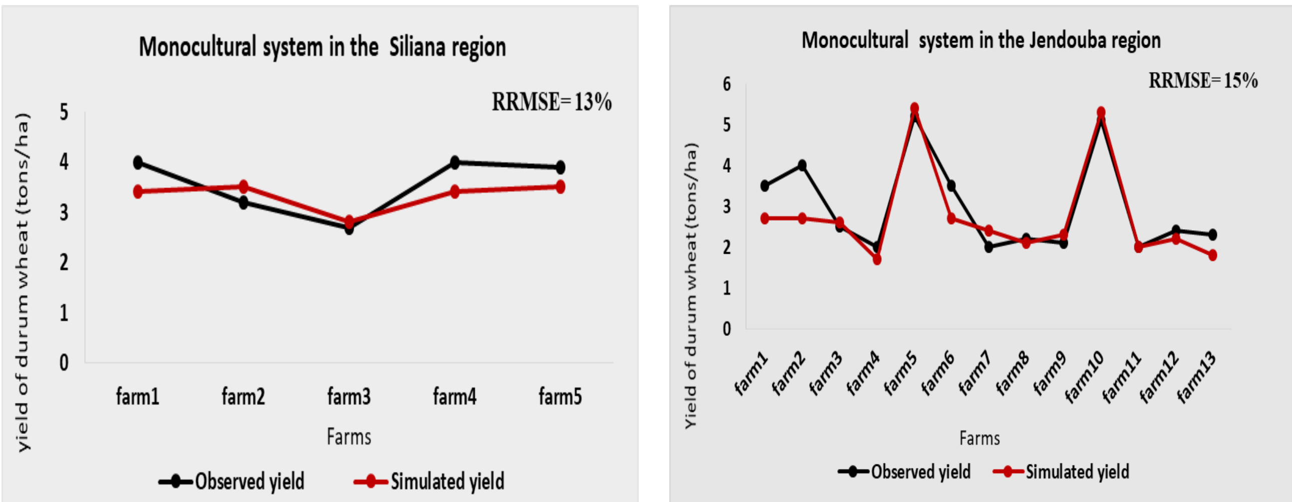


**Figure 4.** *Cont.*

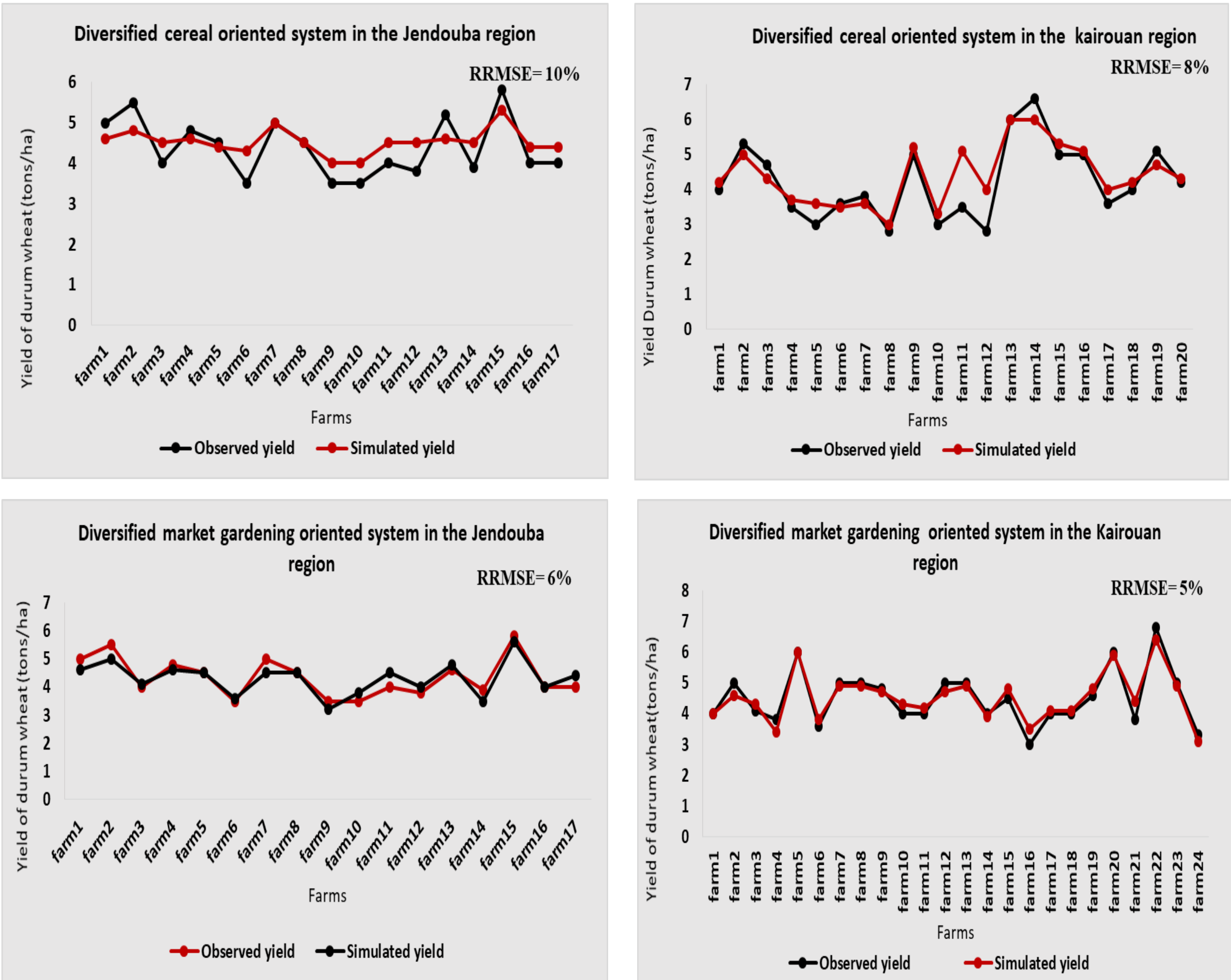


**Figure 4.** Validation of CROPSYST for each farming system.

Regarding the calibration of MORBIT, it has already been calibrated by the PMP, and we have just adjusted the risk aversion. By fixing the later coefficient at 1%, results confirm the suitable performance of the model with a PAD of 2% and 6% for DW supply and crop area, respectively (Table 4). Suitable results were also observed for a profit with a PAD of 0.4% [15]. The situation observed after the calibration represents the reference (Baseline situation-S0-) for the interpretation and analysis of the selected scenarios.

**Table 4.** Simulated regional level vs. observed indicators.

| Indicators | Observed Value | Simulated Value | PAD (%) |
|---|---|---|---|
| Crop area (ha) | 4327 | 4057 | 6 |
| Durum wheat supply (tons) | 9585 | 9367 | 2 |
| Profit (TND) | 202,229 | 201,480 | 0.4 |

### *3.4. Simulation Results*

#### 3.4.1. Irrigation Management Control (S1)

The operational diagnosis of DW management confirmed that the weak performance of irrigated DW could be attributed to the poor management of irrigation doses and to inadequate irrigation schedules. In fact, results showed that the water consumption of DW in monocultural farms (MNNP and MNNN) reached an average of 665 $m^3$ $ha^{-1}$. Taking into account the effective rainfall recorded during the 2014–2015 season, this volume is below the theoretical needs of DW crops, estimated at 3334 $m^3$ $ha^{-1}$. In addition, the results of the typology revealed the importance of water consumption in the Kairouan region, particularly in farms with a cereal orientation (CRNK) and those with a market gardening orientation (MRNK). The water consumption respectively amounts to 4004 and 4383 $m^3$ $ha^{-1}$ [22]. Hence, we have increased the irrigation dose by 25% for MNNP and MNNN farms. On the other hand, we have decreased the irrigation doses by 36% for CRNK farms and by 42% for MRNK farms. According to this adjustment of irrigation doses and after applying the third irrigation in mid-March instead of the beginning of April, the results of CROPSYST showed that the linking of irrigation practices with the adoption of an adequate irrigation schedule and the control of irrigation doses (S1) allows farmers to obtain an average yield of 4.97 tons $ha^{-1}$, which was 27% higher than the observed situation (S0) (Table 5). Maximum yields were reached with 74% for the MRNJ farm, while the MNNN farm showed the lowest yields with an average of 3.7tons $ha^{-1}$, which was 7% higher compared to the baseline situation (3.4 tons $ha^{-1}$) (Table 5). The irrigation management scenario also allowed farmers to achieve an average water productivity of 0.97 kg $m^{-3}$ $ha^{-1}$, which entailed an increase of 29% compared to the baseline situation (S0) (Table 5). The improvement of water productivity is important for all farm types. The farms with low performance were most affected by this improvement. Indeed, in the MRNK farm type, this scenario led to water productivity that was 108% higher than the baseline situation.

**Table 5.** Variation in yields and water productivity of DW by farm type and scenario.

| Farm Type | Yield (tons $ha^{-1}$) | | | Water Productivity (kg $m^{-3}$ $ha^{-1}$) | | |
|---|---|---|---|---|---|---|
| | S0 | S1 | Difference (%) | S0 | S1 | Difference (%) |
| MNNP | 4.6 | 4.9 | 7 | 0.87 | 0.88 | 1 |
| MNNN | 3.4 | 3.7 | 9 | 0.73 | 0.75 | 3 |
| CRPK | 4.4 | 5.5 | 25 | 1 | 1.1 | 10 |
| CRNK | 3.4 | 5.5 | 62 | 0.54 | 1.1 | 104 |
| CRPJ | 4.7 | 5.4 | 15 | 0.9 | 0.9 | 0 |
| CRNJ | 3.4 | 4.5 | 32 | 0.62 | 0.83 | 34 |
| MRPK | 4.3 | 4.7 | 9 | 0.9 | 0.94 | 4 |
| MRNK | 3.3 | 4.7 | 42 | 0.48 | 1 | 108 |
| MRPJ | 4.8 | 5.4 | 13 | 0.9 | 0.9 | 0 |
| MRNJ | 3.1 | 5.4 | 74 | 0.59 | 1 | 69 |
| Average | 3.9 | 4.97 | 27 | 0.75 | 0.97 | 29 |

S0: Baseline situation; S1: Irrigation Management Control.

In order to evaluate the effects of the irrigation management scenario (S1) on yields and water productivity, we carried out a statistical analysis using the SPSS software. We thus used the Student's t-test at a 5% level to find any significant differences between simulated and observed results [45]. The results obtained in both scenarios are presented in Table 6 and show a significant difference between observed and simulated indicators.

**Table 6.** Comparison of the means of yields, water productivity, and gross margins of DW using a Student's *t*-test.

| Scenarios | Yield (tons ha$^{-1}$) | | Water Productivity (kg m$^{-3}$ ha$^{-1}$) | | Gross Margin (TNDha$^{-1}$) | |
|---|---|---|---|---|---|---|
| | Mean Standard Error | *t* | Mean Standard Error | *t* | Mean Standard Error | *t* |
| S0–S1 | 2.276 | −4.526 *** | 0.722 | −2.632 *** | 21.654 | −3.36 *** |
| S0–S2$_{10\%}$ | - | - | - | - | 12.950 | −1.102 *** |
| S0–S2$_{15\%}$ | - | - | - | - | 1 9.193 | −1.453 *** |
| S0–S2$_{20\%}$ | - | - | - | - | 25.519 | −1.576 *** |
| S0–S3$_{20\%}$ | 2.276 | −4.526 *** | | | 22.639 | −5. 053 *** |
| S1–S3$_{20\%}$ | - | - | - | - | −49.651 | −2.759 *** |
| S2$_{20\%}$–S3$_{20\%}$ | - | - | - | - | 24.637 | −3.011 ** |

*** Significant at 1%; ** significant at 5%.

Given these results, we can conclude that the adoption of adequate irrigation technology, with the adjustment of irrigation doses and the appropriate management of irrigation schedules, constitutes an alternative for increasing the agronomic performance of DW. What, then, is the impact of this scenario on the gross margin and supply of DW and regional profits, as well as the availability of resources (water, land)?

To deal with this issue, the yields simulated by the CROPSYST model were fed into the MORBIT model using multiplier coefficients. The simulation results showed that the management irrigation scenario (S1) implied a slight increase in the total area of DW, which reached 2369 ha (Table 7).

**Table 7.** Variation in DW area, DW supply, and profits under different scenarios.

| Scenarios | Definition | D W Area (ha) | DW Supply (Tons) | Profit (TND) |
|---|---|---|---|---|
| $S_0$ | Baseline situation | 2329 | 9367 | 201,480 |
| S1 | Irrigation management control | 2369 | 11,419 | 219,910 |
| S2$_{10\%}$ | Increasing durum wheat prices by 10% | 2356 | 9464 | 205,650 |
| S2$_{15\%}$ | Increasing durum wheat prices by 15% | 2380 | 9543 | 209,780 |
| S2$_{20\%}$ | Increasing durum wheat prices by 20% | 2402 | 9614 | 213,530 |
| S3$_{10\%}$ | Combination of S1 and S2$_{10\%}$ | 2373 | 11,432 | 221,970 |
| S3$_{15\%}$ | Combination of S1 and S2$_{15\%}$ | 2373 | 11,432 | 226,760 |
| S3$_{20\%}$ | Combination of S1 et S2$_{20\%}$ | 2376 | 11,453 | 231,090 |

MRNK farms showed the greatest improvement with an increase in DW area of 38% compared to the baseline situation (S0). This increase in crop yield and total area led to a wheat supply (11,419 tons) that was 3% higher than the baseline situation (9367 tons). Simulation results also revealed higher economic performances than those obtained in the baseline scenario (S0) (Table 8). Indeed, under this scenario (S1), the gross margin (1173 TNDha$^{-1}$) doubled compared with the baseline situation. This gross margin varied among farm types. The MRNJ farm type thus showed the best improvements with a gross margin of 1820 TNDha$^{-1}$, which was 420% higher than the baseline situation, while the MRNK farm type showed the lowest gross margin with an average of 494 TNDha$^{-1}$ but was 65% higher than the baseline situation (Table 8). Given these results, the profit reached 219,910 TND, which was 1% higher than the baseline situation (Table 7).

**Table 8.** Variation of DW gross margin, shadow price of water, and shadow price of capital by farm type and scenario.

| Farm Type | Gross Margin (TNDha$^{-1}$) | | | | | | | | Shadow Price of Water (TNDm $^{-3}$) | | | | Shadow Price of Capital (TND/TND) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Scenarios** | **S0** | **S1** | **S2$_{10\%}$** | **S2$_{15\%}$** | **S2$_{20\%}$** | **S3$_{10\%}$** | **S3$_{15\%}$** | **S3$_{20\%}$** | **S1** | **S2$_{10\%}$** | **S2$_{15\%}$** | **S2$_{20\%}$** | **S1** | **S3$_{10\%}$** | **S3$_{15\%}$** | **S$_{20\%}$** |
| MNNP | 1563 | 1730 | 1729 | 1887 | 2031 | 1903 | 2073 | 2227 | 2.5 | 2.7 | 2.7 | 3 | - | - | - | - |
| MNNN | 547 | 694 | 673 | 791 | 897 | 824 | 951 | 1066 | 1.4 | 1.6 | 1.8 | 2 | - | - | - | - |
| CRPK | 623.6 | 1137 | 802 | 955 | 1093 | 1331 | 1520 | 1692 | - | - | - | - | - | - | - | - |
| CRNK | −729.9 | 1049 | −671 | −556 | −453 | 1242 | 1430 | 1601 | - | - | - | - | - | - | - | - |
| CRPJ | 1468.5 | 1517 | 1685 | 1850 | 2000 | 1685 | 1850 | 2000 | - | - | - | - | - | - | - | - |
| CRNJ | 549.6 | 1254 | 676 | 794 | 901 | 1412 | 1568 | 1709 | - | - | - | - | - | - | - | - |
| MRPK | 297.7 | 494 | 445 | 593 | 728 | 660 | 823 | 970 | - | - | - | - | - | - | - | - |
| MRNK | −951.3 | 588 | −827 | −713 | −609 | 754 | 917 | 1064 | - | - | - | - | 0.355 | 0.375 | 0.425 | 0.525 |
| MRPJ | 1439 | 1452 | 1591 | 1756 | 1905 | 1591 | 1756 | 1905 | - | - | - | - | - | - | - | - |
| MRNJ | 349.9 | 1820 | 485 | 592 | 689 | 2010 | 2196 | 2365 | - | - | - | - | - | - | - | - |
| Average | 515.8 | 1173 | 658.8 | 794.9 | 918.2 | 1341.2 | 1508.4 | 1659.9 | - | - | - | - | - | - | - | - |

However, the adoption of this scenario had huge impacts in terms of the cultivated area of DW on both monocultural systems and diversified market gardening-oriented systems. Indeed, following the adjustment of irrigation doses, the model reduced the DW area by 31% and 35%, respectively, for the MNNP and MNNN farm types due to the constraint of water irrigation at the farm level (Figure 5).

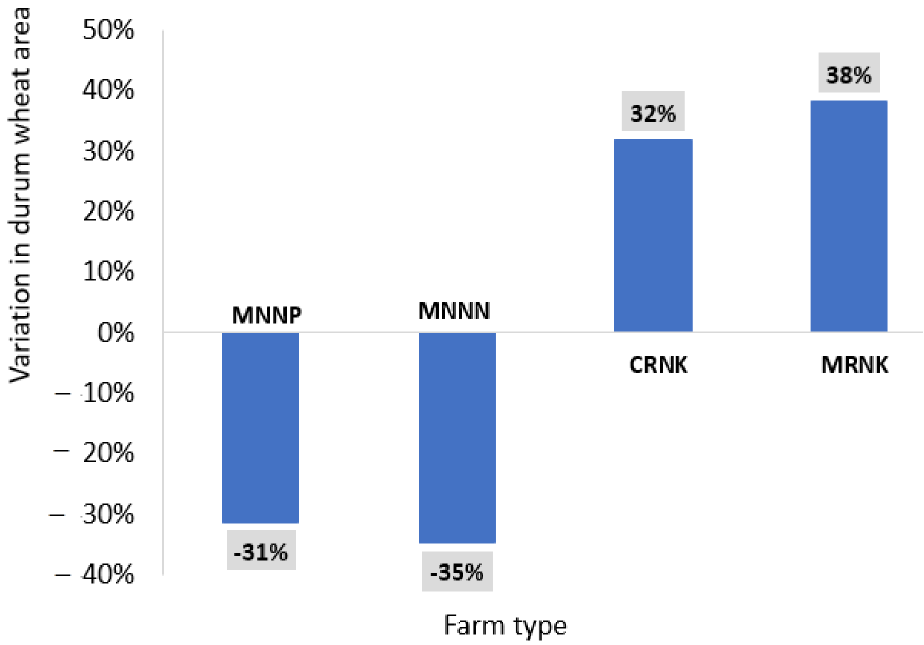


**Figure 5.** Variation in durum wheat area by farm type as a function of (S1).

The limited quantity of water led to a shadow price of 2.5 TNDm$^{-3}$ for MNNP farms and 1.3 TNDm$^{-3}$ for MNNN farms, which was higher than the irrigation water price paid by farmers (0.065 TNDm$^{-3}$). A total of 40% of the farmers who irrigate from reservoirs reported that the non-availability of water due to an old and defective irrigation network did not make it possible to meet the requested needs.

On the other hand, in diversified cereal-oriented systems and diversified market gardening-oriented systems, the adjustment of water irrigation increased the DW area by 32% and 38%, respectively, for CRNK and MRNK farms (Figure 5).

### 3.4.2. Cereal Price Scenario (S2)

The descriptive analysis showed that the management of irrigation could not be the sole factor limiting the agronomic and economic performance of the irrigated DW systems. Indeed, 50% of the farmers surveyed stated that the selling price of DW is low compared to the cost of production. Given these results, we simulated three increased cereal price scenarios with different rates (10%, 15%, and 20%) on DW performance and regional profits.

The simulations results showed that the yields and water productivity of DW remained constant while the total area and supply of DW and economic indicators were higher at different rates (10%, 15%, and 20%) than in the baseline situation. Indeed, results showed that the 10% increase in DW price ($S2_{10\%}$) implied a slight improvement in the DW area (1%) (Table 7). This improvement particularly concerned farms in the Kairouan region. In fact, the CRNK and MRNK farms were most affected by this improvement (5%), while the effect on MRPK farms only reached 1% (Figure 6). However, the adoption of this scenario has no effect on the DW area of farm types in the Jendouba and Siliana regions.

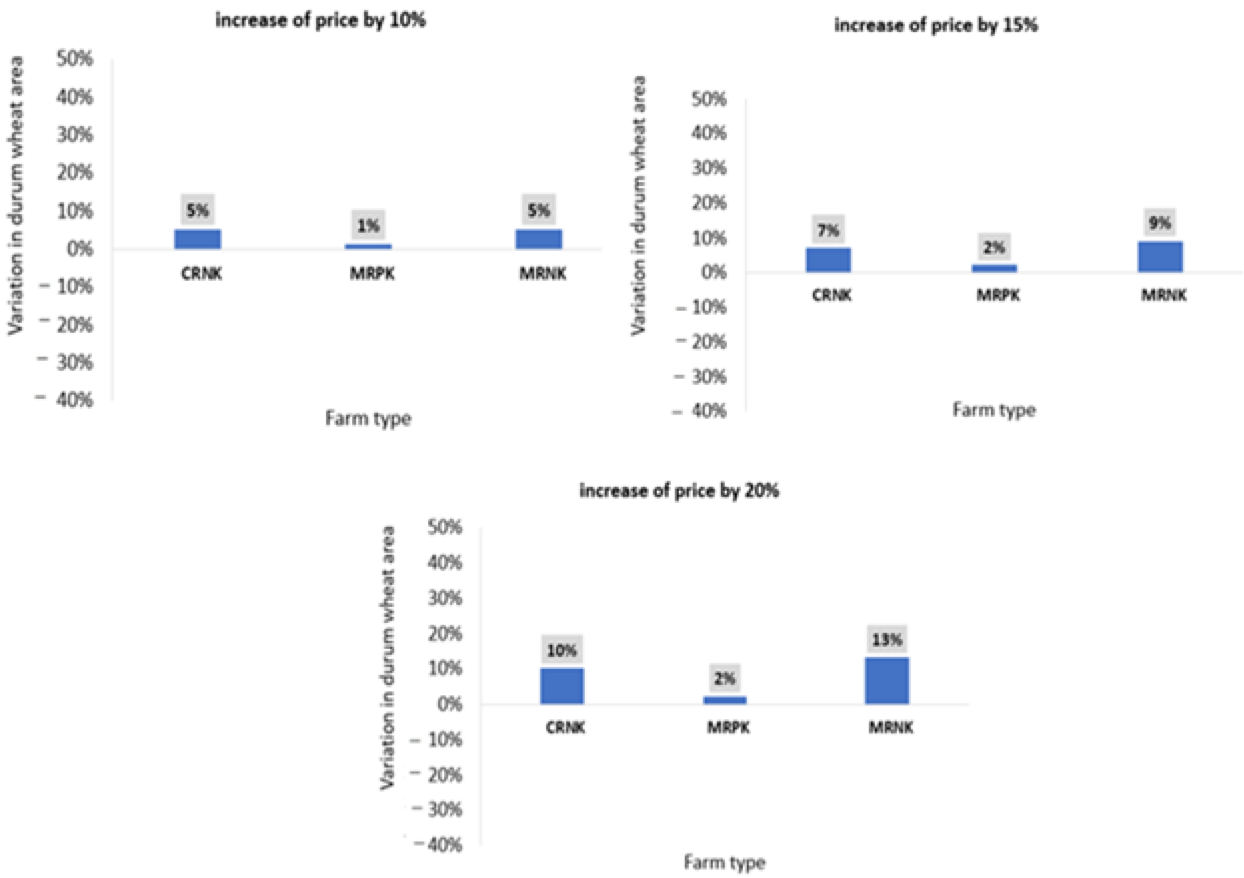


**Figure 6.** Variation in durum wheat area under increased cereal price scenario (S2).

Despite the area increase, the supply of DW reached 9464 tons, which was 17% lower than the management irrigation scenario (S1) and just 1% higher than the baseline situation. Compared to the baseline situation, this scenario (S210%) implied an improvement in the gross margin up to 28% (659 $TNDha^{-1}$). The highest gross margin difference (49%) was obtained by MRPK farms (Table 8). This scenario also made it possible to achieve a high level of profit (205,650 TND), which was 2% higher than the observed situation (Table 7).

Therefore, with the increase in cereal prices by 20%, the DW area reached 2402 ha, which was just 1% higher than $S2_{10\%}$ and 3% higher than the baseline situation. The CRNK and MRNK farms showed the best improvement with an increase of 10% and 13%, respectively (Figure 6). Given this improvement, the supply of DW reached 9614 tons, which was just 2% higher than the baseline situation (S0) and 15% lower than the irrigation management scenario (S1). This scenario ($S2_{20\%}$) also showed lower gross margins (918.2 $TNDha^{-1}$) and profits (213,530 TND) than the irrigation management scenario (S1) but was quite different from the baseline situation (S0). Given these results, we observed that the increased cereal price scenario (S2) was an interesting economic proposition for improving the economic performance of DW and increasing regional profits. Notwithstanding, this scenario had no effect on agronomic performance, which remained constant.

#### 3.4.3. Mixed Scenario (S3)

Simulation results revealed that the combination of all the previous scenarios had a strong impact on both agronomic and economic indicators. In fact, in terms of agronomic performance, this scenario showed an improvement in DW yields and water productivity comparable to that obtained by the simulation of the scenario (S1).

In terms of economic performance, results showed that the $S3_{10\%}$ and $S3_{15\%}$ scenarios increased DW area by 1% and consequently improved DW supply and regional profits. However, the simulation of the scenario ($S3_{20\%}$) proved that matching water intakes and increasing DW prices by 20% constitutes a relevant pathway to ensure better economical performances and regional profits. In fact, this scenario ($S3_{20\%}$) made it possible to increase DW areas up to 2376 ha (Table 7). However, the implementation of this scenario requires the mobilization of financial means, particularly in the case of diversified market gardening-oriented systems. In fact, due to the constraint of available financial means, the DW area for MRNK farms only increased by 39%, and the model further increased the shadow price of capital by 48% compared to the management scenario (0.355 TND). This improvement in terms of yield and durum wheat area allowed farms to achieve a higher supply of 11,453 tons, which was 22% higher than the baseline situation. The adoption of this scenario also ensured the best economic performance (Table 8). Indeed, the gross margin difference between this scenario ($S3_{20\%}$) and the baseline situation increased to 222%. This difference was well confirmed for all farms with a significant disparity. The MRNJ farm type was the most affected by this improvement (+576%), and the CRNK farm type was the second most affected (+319%), while the gross margin difference between S0 and $S3_{20\%}$ for the MRPJ farm type was only 32% (Figure 7).

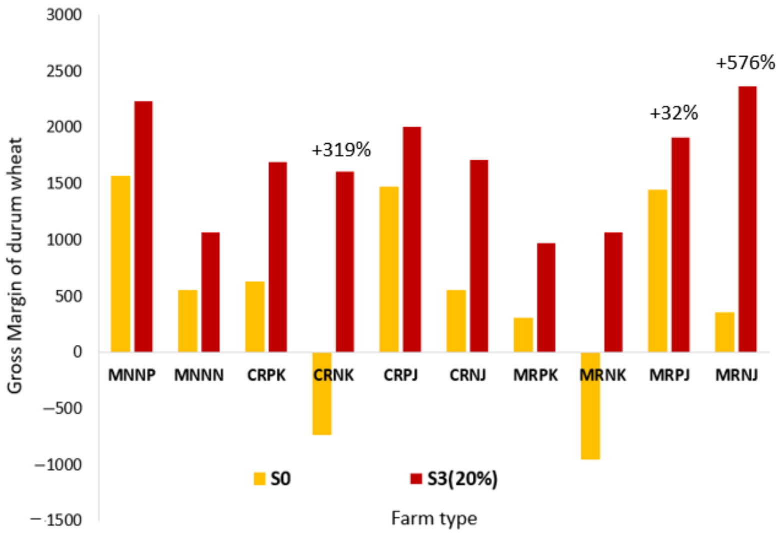


**Figure 7.** Gross margin difference between S0 and $S3_{20\%}$.

This improvement in terms of agronomic and economic performance made it possible to achieve better profits (231,090 TND), which were 15% higher than the baseline situation (Table 7). Regarding the valorization of water, this scenario led to a better value of irrigation water in monocultural systems, with a shadow price of 3 $TNDm^{-3}$ for the MNNP farm type and 2 $TNDm^{-3}$ for the MNNN type.

## 4. Discussion

The investigation of growing irrigated DW in the regions of Kairouan, Siliana, and Jendouba stressed the issue of the lower performance of irrigated DW and regional profits. The operational diagnosis of crop management revealed shortcomings in farming practices related to the farmers' financial capacity and the poor management of irrigation practices. In fact, simulation results showed that the optimization of DW yields and water productivity can be achieved by adopting best agricultural practices mainly related to irrigation doses and schedules (S1) (Table 5).

This scenario (S1) also showed slightly higher gross margins and profits than the baseline situation (Table 7). The results are consistent with other studies. As reported by Rezgui et al. [46], the linking of soil potentialities and irrigation practices is often recommended for increasing crop yields and water productivity. Ben Nouna et al. [19] also reported that the use of appropriate irrigation schedules in semi-arid regions increases durum wheat yields from 1.7 to 3.4 tons $ha^{-1}$ and improves water-use efficiency by 8% [20].

Furthermore, by showing the impact of irrigation schedules on the yields and gross margins of maize crops in Albacete (Spain) [47] highlighted that the adoption of optimal irrigation schedules increased yields and gross margins by 6.8% and 10.7%, respectively.

This scenario (S1) confirms that technical support for farmers in terms of irrigation, particularly in the Kairouan region, is recommended to improve the performance of DW and obtain high profitability at a regional level (Table 7). In a study conducted in the Kairouan region, Frija et al. [48] confirmed that farmers do not resort to appropriate practices with respect to irrigation scheduling and irrigation doses. In fact, 31.7% of the farmers applied water volumes above the economic optimal volume in order to guarantee maximum production and minimize the risks of yield loss, while 50% of farmers applied less irrigation water than this optimal volume. For these farmers, using less than the optimal volume of water allows them to carry out other complementary irrigation and obtain more benefits. Similarly, other studies [49] mentioned that irrigation schedules in Tunisia are implemented without considering crop water needs and timing, and they are usually based on simple observations of weather conditions. Given these results, a strategy for the rational and efficient management of irrigation urgently needs to be developed. Nevertheless, the implementation of this approach is a complex issue that requires a large amount of accurate information and technical support for farmers [21].

However, the adoption of the irrigation management scenario (S1) requires a concerted reflection between stakeholders in order to put forward suitable strategies for the renewal of collective irrigation networks in the Siliana and Jendouba regions.

By analyzing the performance of irrigated sectors in Tunisia, El Atiri [50] showed that the collective irrigation networks have become obsolete and are subject to frequent collapses and breakdowns that generate significant water losses and low efficiency. Lebdi [51] also proved that collective networks often operate on a water tower basis with insufficient residual pressure at the terminal, which does not allow the adoption of adequate irrigation.

Simulation results also showed that the availability of irrigation water could not be the sole factor limiting economic performance, irrigated DW production, and regional profits. Under water shortage, increasing DW prices by important rates could be viewed as a way to encourage farmers to produce more (Figure 6) and improve the competitiveness of this crop, mainly for diversified systems in the Kairouan region [52]. By analyzing the effects of agricultural policies applied to DW in Turkey, Cevher et al. [53] argue that 66.7% of surveyed producers in the region stated that the net income from DW production would need to be higher than the net income from other crops in order to increase DW areas. These findings corroborated the results of previous studies [54], which indicated that the increase in cereal prices improved DW areas by 3.4% and the total production by 2%. On the other hand, this has resulted in a significant decrease in the area dedicated to barley and to oats by 5.1% and 1.4%, respectively.

In addition, the scenario ($S2_{20\%}$) mainly increased economic performance in the Kairouan region and led to a significant improvement in DW supply and regional profits. By analyzing the cereal system in Morocco, El Khansa [55] thus reported that significant financial support for farmers is one of the key factors toward improving regional income by 16%. However, this scenario has no impact on the agronomic performance of DW. The combination of the two previous scenarios ($S3_{20\%}$), therefore, was an interesting proposition, as the agronomic performance of DW largely increased, and irrigation water was properly valorized. Furthermore, from an economic point of view, this scenario showed a higher gross margin and a significant improvement in DW supply and regional profits compared to the other scenarios (Table 7). However, this scenario was more constrained by the financial endowment of farms. As reported by El Ansari [56], the promotion of cereal production will not only be achieved by the improved management of irrigation but also through the implementation of policy measures that allow for an increase in direct support to farmers. Thus, by analyzing the cereal system in arid regions, other studies [57] emphasized that increasing direct support to cereal production and increasing water availability were efficient levers for improving farm income. Given these results, we concluded that the improved management of irrigation and increasing DW prices could enhance existing system efficiency while simultaneously yielding high agronomic output and economic benefits. This change is facilitated by supportive agricultural policies.

## 5. Conclusions

This study made it possible to highlight the main levers for improving the performance of the DW crop and regional profits under Tunisian conditions. In order to deal with this issue, a field survey was carried out among a sample of 698 farmers belonging to the Jendouba, Siliana, and Kairouan regions, which produce over 50% of the irrigated durum wheat crop in Tunisia. The data collected made it possible to develop a farm typology. The typological analysis helped to highlight the relationship between cropping systems and the performance of the irrigated DW crop. Several studies have analyzed DW performances. Our results, nevertheless, allowed the farmers and policymakers to categorize existing systems in terms of their performance. Furthermore, this analysis led to the identification of shortcomings in the economic policies that could impact the agronomic and economic performances of irrigated DW and regional profits negatively. In addition, the development of a bio-economic model linking a biophysical model (CROPSYST) with an economic regional model (MORBIT) and different scenario simulations allows guiding farmers as well as decision makers toward alternatives in terms of best practices and adequate policies to improve DW production and regional profits. The simulation results made it possible to identify the main levers related to (i) the control of irrigation and (ii) the increase in cereal prices for improving DW performance and regional profits.

The results of the present study may serve as a basis for discussions with policymakers, governmental and non-governmental development organizations, and extension personnel in order to put forward suitable strategies according to the context under study, the availability of biophysical and monetary resources, and the current income levels of each farm type.

Given the lack of data, our approach is limited to the analysis of the functioning of the crops' activities and does not take into account the animal component, the rotation. In future research, anticipating our results, it seems interesting to improve the structure of our model by integrating animal components and equations related to crop rotation. In addition, the presented model chain (CROPSYST—MORBIT) was used to set up assess the regional profit for a wide range of (i) biophysical conditions (soil, weather), (ii) types of water resources (public, private), and (iii) types of farming system with a special focus on irrigated crops mainly the durum wheat. However, Tunisia is considered one of the countries most exposed to climate change in the Mediterranean [58]. These risks have already caused decreases in crop yields, mainly wheat, barley, and irrigated potatoes [58]. Moreover, with climate change, there will not be enough surface water to meet farmers' irrigation needs, especially in the arid zones of the country. As a result, water shortage y may force agri-food actors and farmers to make crop choices with important trade-offs.

Therefore, this bio-economic approach can also be adapted to assess the impact of climate change on crop productivity and regional profit and to identify these current "best" practices as well as future adaptation strategies. The flexibility of the bio-economic approach in assessing climate change and technological innovation scenarios has already been confirmed by many studies [59].

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