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An Economic-Based Evaluation of Maize Production under Deficit and Supplemental Irrigation for Smallholder Farmers in Northern Togo, West Africa

Agossou Gadedjisso-Tossou [1,2,*], Tamara Avellán [1] and Niels Schütze [2]

1 United Nations University Institute for Integrated Management of Material Fluxes and of Resources, Ammonstrasse 74, 01067 Dresden, Germany; avellan@unu.edu

2 Institute of Hydrology and Meteorology, Technische Universität Dresden, Bergstr. 66, 01069 Dresden, Germany; niels.schuetze@tu-dresden.de

* Correspondence: tossou@unu.edu; Tel.: +49-351-7999-3816

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Abstract: While the world population is expected to reach 9 billion in 2050, in West Africa, it will more than double. This situation will lead to a high demand for cereals in the region. At the same time, farmers are experiencing yield losses due to erratic rainfall. To come up with a sound and effective solution, the available but limited water should be used to achieve high yields through irrigation. Therefore, full and deficit irrigation management strategies were evaluated. The expected profit that can be obtained by a smallholder farmer under a conventional irrigation system in the short-term of investment was also assessed considering rope and bucket, treadle pump, and motorized pump water-lifting methods. The study focused on maize in northern Togo. The framework used in this study consisted of (i) a weather generator for simulating long-term climate time series; (ii) the AquaCrop model, which was used to simulate crop yield response to water; and (iii) a problem-specific algorithm for optimal irrigation scheduling with limited water supply. Results showed high variability in rainfall during the wet season leading to significant variability in the expected yield under rainfed conditions. This variability was substantially reduced when supplemental irrigation was applied. This holds for the irrigation management strategies evaluated in the dry season. Farmers'expected net incomes were US$ 133.35 and 78.11 per hectare for treadle pump and rope and bucket methods, respectively, under 10% exceedance probability. The motorized pump method is not appropriate for smallholder farmers in the short run.

Keywords: irrigation management strategies; cereals; smallscale producer; profit optimization; West Africa

1. Introduction

The West African population will increase from 350 million in 2015 to 450 million in 2030, and nearly 800 million in 2050 [1]. Liniger et al. [2] stated that food production in West Africa should increase by 70% by 2050 to meet the required food calories. However, several parts of the region are already being harmed by the lack of available water for agricultural production, the energy sector, and other forms of anthropogenic water consumption [3]. The change in the food diets in many West African countries has aggravated this problem and led to an increase in the consumers' demand for processed food and animal proteins [4].

The West African region is subject to frequent crop failures due to an erratic climate [5]. The Togolese Ministry of the Environment and Forestry (MERF) [6] reported that in northern Togo, a West African country, the wet season lasted for six months in the 70s, but now lasts only four or five months. Also, due to the lack of rainfall, there is no off-season agricultural activity during the dry season in northern Togo [7]. Togolese agriculture, which is predominantly rainfed, accounts for 38% of Togo's gross domestic product, provides over 20% of export earnings, and employs 70% of the active population [8,9].

Pereira [10] defined irrigation scheduling as the procedure of deciding when, where, and how much water to apply in irrigated farming. Djaman et al. [11] pointed out that deficit irrigation (DI), which is limited irrigation scheduling in agriculture, could be controlled or otherwise. Under rainfed conditions, DI is uncontrolled. When farmers under-irrigate a crop purposely and systematically, this represents a controlled deficit irrigation (CDI) system [12,13].

The variability of relevant climate factors such as rainfall, temperature, and soil parameters were ignored in many studies, which applied the simulation-based approach to evaluate DI strategies [14,15]. Specifically, Semenov [16], Brumbelow and Georgakakos [17], and others who studied probable impacts of climate change and variabilities on agriculture by means of process-based simulation models, considered only rainfed or nonirrigated sites or hypothesized full irrigation (FI). Schütze and Schmitz [18] evaluated limited irrigation systems and the impact of climate variability on crop-water production functions (CWPF). Moreover, Schütze and Schmitz [18] investigated in detail the CWPF concept and proposed a stochastic framework in the form of a decision-support tool for Optimal Climate Change Adaption Strategies in Irrigation (OCCASION) for yielding site-specific stochastic CWPF (SCWPFs). Gadédjisso-Tossou et al. [19] utilized a similar approach to assess the crop yield response to different irrigation management strategies using crop simulation models in West Africa. Crop yield response to water can be simulated using crop simulation models available in the literature. Most of these models show substantial complexities and require large amounts of data to run. They require a high number of parameters to run, and many of these parameters are not readily available in the field and need to be determined experimentally [20]. Remarkably, the AquaCrop model [21] uses a relatively small number of explicit and mostly intuitive parameters and input variables, requiring simple methods for their data collection [22].

There are few studies to date that have evaluated crop response to different irrigation management strategies in northern Togo [8]. Thus, the present study investigated the potential of full and deficit irrigation and their feasibility in northern Togo. Specifically, the study aims at (i) evaluating maize (*Zea mays* L.) response to supplemental, full, and deficit irrigation management strategies in northern Togo, and (ii) assessing the expected profit that a smallholder farmer could gain under a conventional irrigation system in the short run considering rope and bucket, treadle pump, and motorized pump water-lifting methods.

2. Materials and Methods

2.1. Study Area and Data Collection

This study was conducted in the Dapaong district, northern Togo (Latitude: 10°51′44.10″ N, Longitude: 0°12′27.43″ E, and Altitude: 330 m above sea level). Dapaong is located in the Southern-Guinea-Savannah agro-ecological zone [23]. The main cultivated rainfed crops include maize (*Zea mays*), sorghum (*Sorghum bicolor*), and pearl millet (*Pennisetum glaucum*). Vegetables and legumes, namely, okra (*Abelmoschus esculentus*), cowpea (*Vigna unguiculata*), and soybean (*Glycine max*), are grown together with the cereals mentioned above. Maize is the staple food in Togo, and it is consumed by more than 60% of the population [24]. The climate in Dapaong district is hot semi-arid (BSh) after Köppen–Geiger's climatic classification [25]. Northern Togo is characterized by a single wet season in a year ranging from May to October, which is equivalent to 1050 mm of rainfall [19]. Thus, farmers adopt intercropping to gain a variety of crops they need in the year for their food. Introducing irrigated crops in the dry season may be helpful to farmers to sustain their production. Most farmers are smallholders and cultivate less than 1.5 ha of land [26]. Crop yields are generally low due an erratic rainfall, adverse soil fertility, low-quality seeds, and inappropriate land preparation tools, among others.

Daily rainfall, maximum and minimum temperature, minimum and maximum humidity, and wind speed data from 1983 through to 2011 were supplied by the nearest climate station to the study area, located 5 km away. The solar radiation and sunshine hours data were retrieved from the prediction of the Worldwide Energy Resource dataset from the National Aeronautics and Space Administration project NASA-POWER [27]. In order to have a long-term time series climate dataset for the assessment, the Long Ashton Research Station Weather Generator (LARS-WG)—a stochastic weather generator—was used to generate a 100-year of near-future climate dataset [28]. The calibrated LARS-WG and parameters for northern Togo were presented in detail in Gadédjisso-Tossou et al. [19].

The soil physical characteristics and hydraulic properties data for Dapaong were derived from Gadédjisso-Tossou et al. [19]. The crop parameters data for TZEE-W, which is the maize variety used, were retrieved from the "Institut Togolais de Recherche Agronomique", ITRA [24], Didjeira et al. [29], and Worou and Saragoni [30]. These data were utilized to fine-tune the maize parameters to the local agronomic and management conditions of Dapaong. The detailed descriptions of the climate, crop, and soil data used in this study are given in Gadédjisso-Tossou et al. [19].

2.2. *Stochastic Optimization of Irrigation Management Strategies*

We studied a rainfed condition or no irrigation (NI), controlled deficit irrigation (CDI) for supplemental and conventional irrigation, and full irrigation (FI) under supplemental and conventional irrigation. When we combine these strategies with the growing seasons, the following five application scenarios were obtained and investigated: (i) NI for the wet season (WS-NI); (ii) CDI for the supplemental irrigation system in the wet season (WS-CDI); (iii) full irrigation for the supplemental irrigation system in the wet season (WS-FI); (iv) CDI for conventional the irrigation system in the dry season (DS-CDI); and (v) full irrigation for the conventional irrigation system in the dry season (DS-FI) (Table 1).

Table 1. The irrigation management strategies evaluated.

Irrigation Management Strategies		Type of Irrigation System		
		No Irrigation	Supplemental Irrigation	Conventional Irrigation
Limited supply	Uncontrolled	NI	–	–
	Controlled	–	CDI	CDI
Full supply	Controlled	–	FI	FI
Application scenarios	Wet season (WS)	x	x	–
	Dry season (DS)	–	–	x

CDI: Controlled Deficit Irrigation; FI: Full Irrigation; NI: No Irrigation (Adapted from Gadédjisso-Tossou et al. [19]).

The framework used in this study was described in detail in Gadédjisso-Tossou et al. [19]. It consists of (i) a weather generator for predicting long-term climate time series; (ii) the AquaCrop model [21], which was used to simulate the irrigation system during the growing season and the maize yield response to a given irrigation management strategy; and (iii) a problem-specific algorithm for optimal irrigation scheduling with limited water supply. The latter represents the Global Evolutionary Technique for OPTimal Irrigation Scheduling (GET-OPTIS), for more details, see [14]. A set of given amounts of water were provided, and a complete CWPF resulted. Then, the resulting CWPFs were analyzed, and the SCWPFs were derived by using descriptive statistics such as mean, median, and quantiles. The quantiles represent the exceedance probability at which a given yield can be achieved [15]. AquaCrop version 5.0 was used to simulate multiple projects for successive years.

2.3. *SCWPF Interpolation and Profit Optimization*

Each SCWPF obtained from the simulation is given as a number of sets Y_q of n discrete points P_{qj} [31]:

$$Y_q = \left\{P_{qj}\right\}_{1 \leq j \leq n}, \tag{1}$$

where P_{qj} represents the yield subject to the amount of irrigated water with a yield reliability $q = \{10\%; 50\%; 90\%\}$. We used the set of these discrete points corresponding to given yield reliability to generate interpolated points between the latter. This was done using SRS1 Cubic Spline for Excel (V2.5) (http://www.srs1software.com). By using this technique, we generated data between the discrete points of Y_q. Generally, the quadratic form of crop water production is used to describe the relationship between irrigation water and crop yield [12,32]:

$$Y(w) = a_0 + a_1 w + a_2 w^2, \tag{2}$$

where, $Y(w)$ is crop yield (Mg/ha), w is irrigation water (mm), and a_0, a_1, and a_2 are costants. In this study, we fitted the interpolated SCWPF to a quadratic form of the function to get the $Y(w)$. This was done by a robust regression technique.

The principal goal of farmers is to maximize the profit using the irrigation system. The profit function can be represented by the following equation [31]:

$$P(w) = A \times \left[(Y(w) - Y_d) \times P_c - (C_v + P_w) \times w - C_f \right], \tag{3}$$

where $P(w)$ represents the profit function ($/ha), $Y(w)$ is the continuous yield function (Mg/ha), Y_d is the average expected rainfed yield (Mg/ha), A is the cultivated area (ha), P_c is crop price ($/Mg), P_w is water price ($/m^3), C_v is the variable cost per unit water, and C_f is the fixed cost per unit area. The following list shows the different costs for irrigation water, which form the full economic cost of water and exclude environmental externalities [33,34].

- ➢ Operation and maintenance (O&M) cost: These are associated with the daily running of the supply system (e.g., electricity for pumping, labor, repair materials, input costs for managing and operating storage and distribution); they often include administrative and other direct costs (e.g., internalized environmental and resource costs). They stand for the variable costs.
- ➢ Capital costs: They include capital consumption (depreciation charges) and interest costs associated with infrastructure, reservoirs, and distribution systems. They represent fixed costs.
- ➢ Opportunity costs: These address the fact that by consuming water, the user is depriving another user of the water; if that other user has a higher value for the water, then there are some opportunity costs experienced by society due to this misallocation of the resource.
- ➢ Economic externalities: These include the positive or negative impacts of irrigation use upon other activities (e.g., pollution, salinization, upstream diversion, downstream recharge).

The first two costs mentioned above form the direct full financial costs. Tardieu and Préfol [35] suggested that these two be covered for sustainability purposes. This paper takes into account only the direct financial costs when computing the profit.

To determine the requested irrigation amount for the crop under a given irrigation system, we computed the first derivative of Equation (3) which is defined as in [31]:

$$\frac{dP(w)}{dw} = A \times \left(P_c \times \frac{dY(w)}{dw} - (C_v + P_w) \right), \tag{4}$$

where $\frac{dY(w)}{dw}$ is the derivative of the single quadratic function $Y(w)$. Then, we calculated the roots w_i^* by solving the Equation (4) equal to zero. For each of these roots, as well as the amount of water that would be used in case of each irrigation system, we calculated the corresponding profit $P_i^*\left(w_i^*\right)$ by using Equation (3). The maximum value of P_i^* leads to the irrigation amount, which is the most profitable, considering the conditions shown in Equation (3). The values marked by '*' represent the volumes of irrigation water that lead to the highest profit for every single SCWPF. The data about irrigation costs were derived from Perry [36]. The crop price at production level was derived from the "Direction des statistiques agricoles de l'informatique et de la documentation (DSID)" [37].

Three water-lifting options were assessed in this paper, considering profit estimation. These are the traditional rope and bucket method, the motorized pump, and the treadle pump. The principal advantage of traditional rope and bucket technology is its low cost. The treadle pump has some features which are different from other manual irrigation pumps. The primary benefits of motorized pumps are their substantial capacity compared to traditional water lifting means, making it possible to expand irrigated surface areas [36].

3. Results and Discussion

3.1. Evaluation of Irrigation Management Strategies

Figure 1a shows the results of the expected maize crop yields, which can be obtained under the rainfed cropping system. On average, the expected maize crop yield obtained in the wet season is 3.5 Mg/ha (Figure 1a). These results are in agreement with the findings by Didjeira et al. [29] who indicated the range of 3.5–5 Mg/ha as the expected yield for the TZEE-W variety used in this study. The amount of rainfall that occurred during the wet season in Dapaong ranged from 450 mm to 1100 mm. The highest frequency was observed between 600 mm and 900 mm (Figure 1b). Figure 1c,d show the detailed results of the expected yields at 100 mm and 350 mm of supplemental irrigation water. When supplemental irrigation (WS-CDI) was applied, the rainfed yield increased from 3.48 Mg/ha to 3.74 Mg/ha. Thus, rainfed maize crop yields may be improved in northern Togo by applying supplemental irrigation if water is available. In Figure 1e,f, detailed results of the expected maize yields at 200 mm and 600 mm under conventional irrigation water are given. The expected yield that can be obtained under the conventional irrigation system is 4.84 Mg/ha for 600 mm water applied (Figure 1f). The standard deviation of the expected yields obtained under rainfed conditions is higher compared to the case of irrigated maize, regardless of the volume of water applied (Figure 1a,e,f). These findings show that the variability as well as the uncertainty in the yields are higher under the rainfed conditions (WS-NI) than those in the dry season CDI and FI [19]. The high variability under rainfed conditions might be due to the erratic rainfall in the wet season [38].

The application of supplemental irrigation in northern Togo for maize crop cultivation will not only contribute to improving crop grain yield and enhancing food security [39–41] but will also help to improve farmers livelihood. However, supplemental irrigation alone cannot improve the rainfed yields significantly; there might be a need to combine it with other field management activities such as soil preparation and fertility, pests and diseases management, and the choice of suitable crop varieties. The DS-CDI strategy seems to save water with a slight reduction in the grain yield relative to full irrigation [42–47]. In conclusion, growing maize in the dry season in northern Togo might be achieved under CDI if water is available [19].

3.2. Profit Optimization

Figure 2 shows an example of a crop water production function with yield reliability of 90%. The blue dots represent the interpolated SCWPF when cubic splines are used. This method introduces an artificial maximum value of the gained yield for an irrigation amount of water between the green dots. As a result, we obtain a nearly continuous form of the curve. Similar results were found by Griessbach et al. [31].

Figure 3 shows the quadratic form of the SCWPF under conventional and supplemental irrigation. The general trend is similar for all the cases of irrigation management strategies investigated in this study. The yield increased with the applied water, peaked, and then declined. This means that a further increase in the applied water will result in a reduction in the yield (Figure 3). These results are similar to the findings of Kiani [32].

Table 2 shows the expected profit, which can be obtained under the conventional irrigation system for rope and bucket, treadle pump, and motorized pump methods. The results showed that the farmers' net expected income in the first year of activity is positive for rope and bucket and treadle pump, while the motorized pump method showed a negative profit. The highest expected net incomes obtained were US$ 133.35 and 78.11 per hectare for treadle pump and rope and bucket methods, respectively, for 10% of yield reliability (Table 2). These results can be explained by the fact that rope and bucket and treadle pump are fabricated from locally available materials resulting in a low cost of initial investment. However, the motorized pump requires high capital costs and high operation and maintenance costs (diesel-powered pumps or gasoline engines) [36]. The motorized pump method is not appropriate for smallholder farmers in the short run.

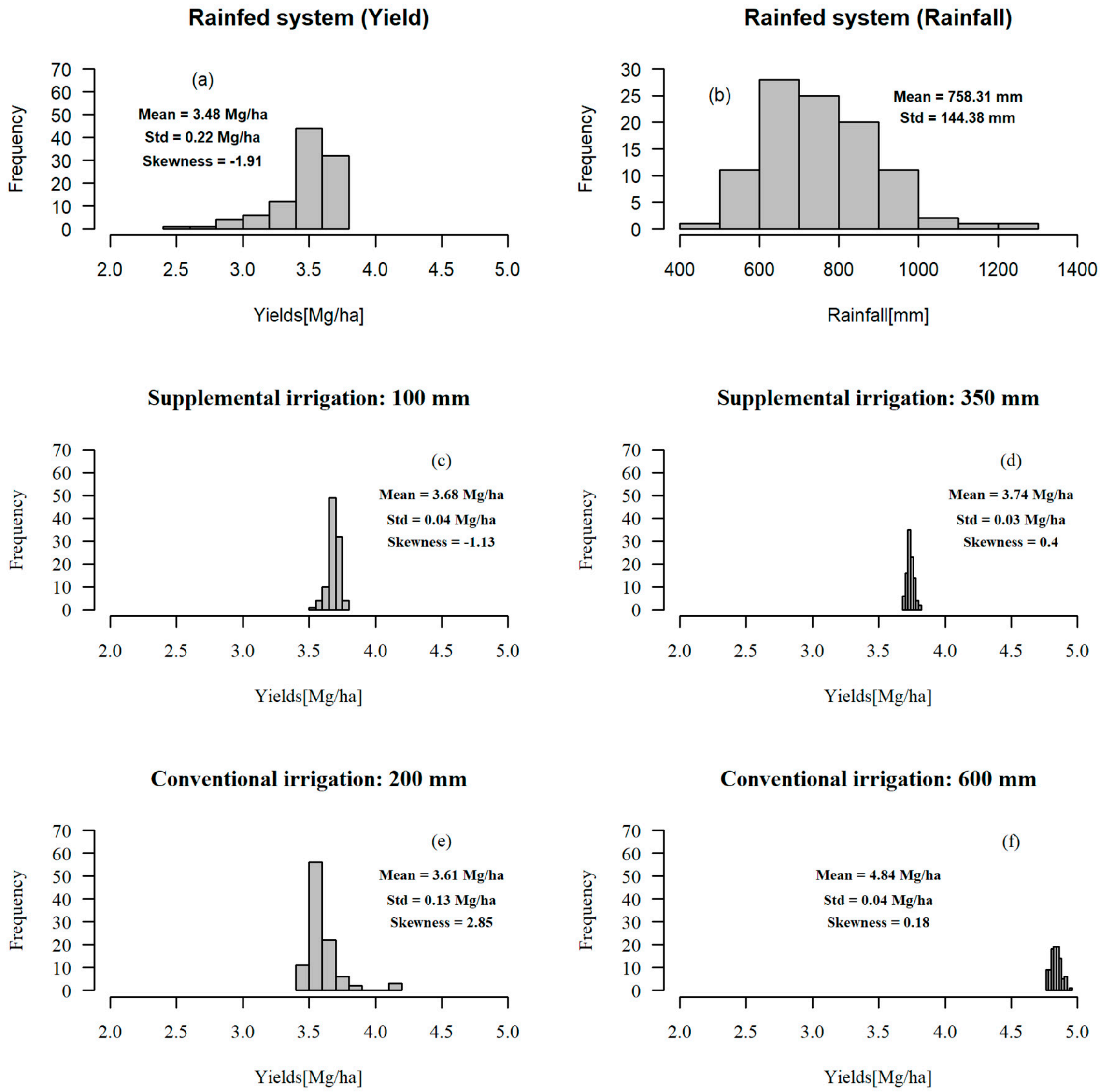

Figure 1. Histogram of distributions of (**a**) the expected yield of maize grown in a rainfed system (WS-NI) and (**b**) the rainfall during the wet season. The expected yield using (**c**) 100 mm (WS-CDI) and (**d**) 350 mm (WS-FI) of water for supplemental irrigation of maize in the wet season. The expected yield using (**e**) 200 mm (DS-CDI) and (**f**) 600 mm (DS-FI) of water for irrigation of maize in the dry season in Dapaong.

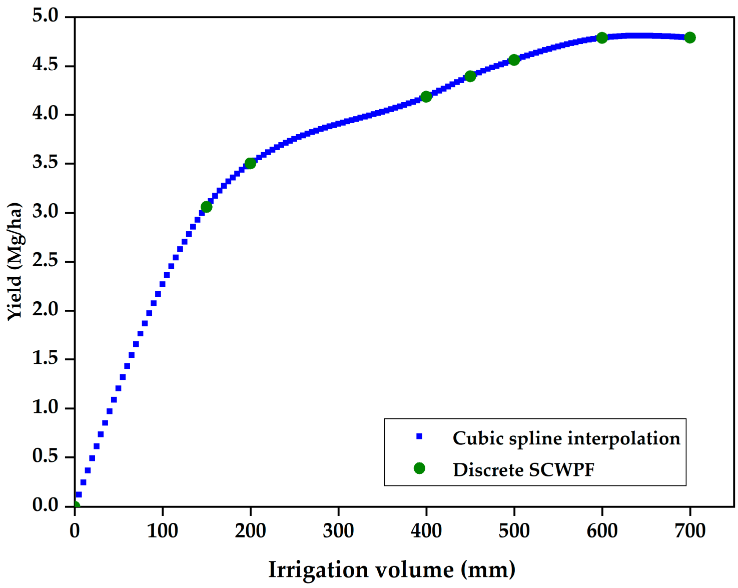

Figure 2. Cubic spline interpolation of discrete site-specific stochastic climate variability on crop-water production functions (SCWPFs) (90% yield reliability).

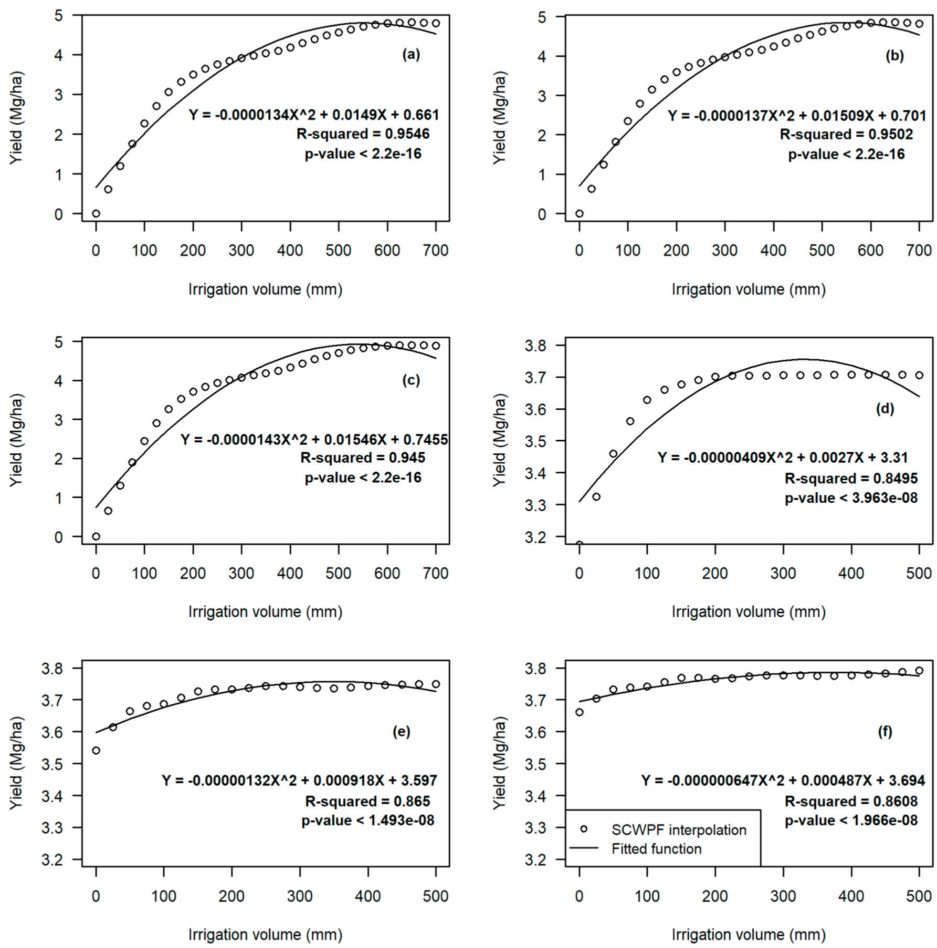

Figure 3. Continuous quadratic SCWPF of conventional irrigation at (**a**) 90% yield reliability, (**b**) 50% yield reliability, and (**c**) 10% yield reliability; supplemental irrigation at (**d**) 90% yield reliability, (**e**) 50% yield reliability, and (**f**) 10% yield reliability.

Table 2. Expected profit under the conventional irrigation system in the first year of investment.

Expected Profit (US$/ha)	Water Lifting Options		
	Rope and Bucket	Treadle Pump	Motorized Pump
90% yield reliability	38.07 *	95.09	−101.56
50% yield reliability	54.88	111.30	−84.47
10% yield reliability	78.11	133.35	−60.68

* US$ 1 = 0.87 € (Exchange rate of 19 October 2018).

4. Conclusions

The AquaCrop model was used to evaluate the potential of deficit and supplemental irrigation in northern Togo under climate variability. The results showed that the deficit irrigation water requirement varies from 0 to 600 mm. The maximum expected maize grain yield that can be reached under conventional irrigation is 4.84 Mg/ha with the TZEE-W local variety. The rainfed yield could be improved by applying supplemental irrigation. At the same time, the variability in the yield could be substantially reduced. This holds for the dry season irrigation management strategies evaluated. Farmers'expected net incomes were US$ 133.35 and 78.11 per hectare for treadle pump and rope and bucket methods, respectively, under 10% of yield reliability. The motorized pump method is not appropriate for smallholder farmers in the short run.

The variability in rainfall during the wet season (WS-NI) is high, inducing a substantial variability in the expected yield under rainfed conditions. The variability in the expected yields would decrease substantially when supplemental irrigation management strategies are applied (WS-CDI or WS-FI). At the same time, supplemental irrigation would improve the expected yields and contribute to the avoidance of crop failure. The dry season irrigation management strategies (DS-CDI and DS-FI) would increase yield potential and decrease the variability of expected yield simultaneously. Therefore, the application of supplemental or dry season irrigation management strategies investigated in this study would help to enhance food availability in the West African region.

Irrigation infrastructures would be needed to implement the irrigation management strategies investigated in this study in northern Togo. Moreover, the institutional arrangement—market and connectivity among farmers and other agents—should be enhanced. The framework used in this study may be applied to other areas in the West African region to develop regional water management strategies. Also, this framework could be extended by adding a soil variability component to it. The analysis could be made more comprehensive by considering farmers' socioeconomic characteristics.

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