sustainability

MDPI

Article

# Effects of Biochar on Irrigation Management and Water Use Efficiency for Three Different Crops in a Desert Sandy Soil

**Giorgio Baiamonte** *, **Mario Minacapilli** and **Giuseppina Crescimanno**

Department of Agricultural, Food and Forest Sciences (SAAF), University of Palermo, Viale delle Scienze, Bldg. 4, 90128 Palermo, Italy; mario.minacapilli@unipa.it (M.M.); giuseppa.crescimanno@unipa.it (G.C.)
* Correspondence: giorgio.baiamonte@unipa.it; Tel.: +39-091-23897054

Received: 5 August 2020; Accepted: 15 September 2020; Published: 17 September 2020

**Abstract:** This paper aimed at investigating if the application of biochar (*BC*) to desert sand (*DS*) from the United Arab Emirates (UAE), characterized by a very poor soil-water retention (*SWR*) and by a very low value of the maximum water available for crops ($AW_{max}$), could positively affect soil water balance, by reducing the irrigation needs ($V_{IRR}$) and improving the irrigation water use efficiency (*IWUE*) and the water use efficiency (*WUE*). The analysis was performed for three crops, i.e., wheat (*Triticum aestivum*), sorghum (*Sorghum vulgare*) and tomato (*Lycopersicon esculentum*). *BC* was applied to the *DS* at different fractions, $f_{BC}$ ($f_{BC}$ = 0, 0.091, 0.23 and 0.33). Drip irrigation was adopted as a highly efficient water saving method, which is particularly relevant in arid, water-scarce countries. Soil water balance and irrigation scheduling were simulated by application of the AQUACROP model, using as input the *SWR* measured without and with *BC* addition. The effect of *BC* was investigated under either a no-water stress (*NWS*) condition for the crops or deficit irrigation (*DI*). The results showed that the application of *BC* made it possible to reduce the predicted $V_{IRR}$ and to increase the *IWUE* under the *NWS* scenario, especially for wheat and sorghum, with less evident benefits for tomato. When a deficit irrigation (*DI*) was considered, even at the lowest considered $f_{BC}$ (0.091), *BC* counterbalanced the lower $V_{IRR}$ provided under *DI*, thus mitigating the yield reduction due to water stress, and improved the *WUE*. The influence of *BC* was more pronounced in wheat and tomato than in sorghum. The results evidenced that the application of *BC* could be a potential strategy for saving irrigation water and/or reducing the effects of drought stress in desert sand. This means that biochar could be used a management option to promote local production and reduce the dependency on food import, not only in the UAE, but also in other countries with extremely arid climatic conditions and large extensions of sandy soils similar to the considered *DS*.

**Keywords:** biochar; desert sand; AQUACROP; irrigation management

## 1. Introduction

Fresh water is an indispensable natural resource, which plays a vital role in the development of any country. Water scarcity originates not only from the physical constraints of available fresh water, but also from competition between different uses and from inefficient use and poor management (FAO, 2008). As a result, water allocation has become one of the most vexing problems faced by policy makers.

Agriculture accounts for roughly 70% of total freshwater withdrawals and for over 90% in the majority of the least developed countries [1]. Without improved efficiency strategies, agricultural water consumption is expected to increase by about 20% by 2050 [2]. As a consequence, the world could face a 40% global water deficit by 2030 under a business-as-usual scenario [3]. Water withdrawal for agricultural purposes accounts for about 75% of all usages in developing countries, and irrigation is widely criticized as a wasteful user of water, especially in the water-scarce regions [4]. Under these critical water availability conditions, a rational management of water is essential to enhance water productivity, i.e., the ratio between the agricultural benefit and the water supplied [5].

Drip irrigation has been increasingly preferred to other irrigation systems in order to save water, especially in arid and water-scarce countries. Drip irrigation makes it possible to increase crop yield ($Y$) per any drop of water supplied [6,7], thus maximizing the irrigation water use efficiency (*IWUE*), i.e., the ratio between $Y$ and the supplied irrigation volume ($V_{IRR}$) [8].

Deficit irrigation (*DI*), i.e., application of water below the maximum crop transpiration ($T_c$) or evapotranspiration ($ET_c$) requirements, has been proposed as a valuable strategy when water availability represents the factor limiting the crop cultivation and yield [9]. The main goal of *DI* is to increase crop water productivity by reducing the amount of water applied to the crop [10]. *DI* makes it possible to reduce the irrigation needs and to divert the water saved for alternative uses, especially if practiced with a proper irrigation scheduling, i.e., with irrigation timings and amounts of irrigation water determined taking into account the processes occurring in the soil-plant-atmosphere (*SPA*) system. *DI*, in combination with drip irrigation, can be proposed as an irrigation strategy saving water, further improving crop productivity and water use efficiency [6,7].

A number of models simulating water transport and energy exchanges in the *SPA* system have been developed [11–14] and applied to assess irrigation scheduling under limited water availability conditions [15–19]. The application of these models makes it possible to obtain reliable irrigation and management scenarios if accurately measured soil hydraulic parameters are used as input [17]. Comparing the performance of the different simulated scenarios and selecting those providing the best results may help to save the time, the costs and the efforts needed to implement experimental investigations, and can be considered preliminary to field experiments aimed at further evaluating the simulated options and scenarios [17].

AQUACROP [20,21] is a crop growth model developed by the FAO Land and Water Division to address food security and to assess the effect of environment and management on crop production. The water-driven crop growth model used in AQUACROP assumes a linear relationship between yield ($Y$) and actual evapotranspiration ($ET$) [22,23]. One of the major advantages of the water-driven module is the opportunity to normalize the water use efficiency (*WUE*), i.e., the ratio between $Y$ and $ET$ for differences in climate, thus providing a wider applicability for a number of locations characterized by spatial and temporal variability [23,24]. Being a water-driven crop model, crop biomass and harvestable yield are simulated in response to available water (soil moisture and irrigation). Although constructed upon basic and complex biophysical processes, only a relatively small number of parameters are needed to adapt AQUACROP to different cases and crops. Often the integrated default input variables are sufficient and do not require additional fitting [25]. When additional variables are needed, they are mostly intuitive and can easily be determined using simple methods [11,13].

This robust field crop-water balance has been successfully tested for a wide range of crops and regions, and its database is still expanding through worldwide contributions. The crop parameters enclosed in AQUACROP as a result of validation and calibration in a number of water-scarce countries of the world are relative to: (i) irrigated winter wheat canopy cover, biomass and grain yield in the North China Plain [26], in Iran [27], in Italy [28] and in Morocco [29]; (ii) maize yield under variable irrigation in India [30], in Colombia [31] and in Iran [32]; (iii) deficit and full irrigation of tomato in Ghana [33], in Tunisia [28] and in Southern Italy [34]; (iv) drip irrigated cotton grown under full and deficit irrigation in Syria [35]; (v) irrigated cabbage in India [36]; (vi) irrigated potato in Spain [37]; (vi) quinoa in Bolivia [38]; (vii) sunflower in Southern Italy [39]; (viii) sugar beet under climate change conditions in Serbia [40]; (ix) sorghum in Kenia [41] and in Oman [42].

Biochar (*BC*) is a *C*-rich organic material, which is produced by the thermal decomposition of plant-derived biomass in partial or total absence of oxygen. Addition of *BC* to the soil has the potential to improve soil quality and *C* sequestration, mitigating the excess of *C* dioxide in the atmosphere [43]. Previous investigations proved that the addition of *BC* to sandy soils increased soil organic *C* [44] and had positive effects on soil physical properties such as porosity ($\theta_s$), soil water retention and the maximum water available for crops, $AW_{max}$ [44,45]. Several studies also showed that the application of *BC* was effective in reducing salinity stress by improving the soil's physico-chemical and biological properties directly related to Na removal, Na adsorption ratio and electrical conductivity [46].

Sandy soils lacking sufficient organic matter to sustain microbial activity are widespread in various arid and semi-arid regions of the world, including India, Tunisia and Saudi Arabia, as well as the United Arab Emirates (UAE) [47–49]. These soils have a low capacity of water retention [50] and low values of the maximum water available for crops, $AW_{max}$, i.e., the difference between field capacity ($\theta_{fc}$) and wilting point ($\theta_{wp}$). Without any amendment, the agricultural production capacity of these soils is weak, and therefore a considerable amount of irrigation water is necessary to meet the crop water requirements.

Baiamonte et al. [51] found that the application of *BC* to desert sand (*DS*) from the UAE (Al-Foah area, border with Oman) increased soil porosity and enhanced the formation of textural and structural pores, especially increasing the amount of storage pores (pores with diameter $D$ = 9.09 μm). *BC* also modified the portion of the soil pore size distribution associated with aggregation [52], increasing the soil aggregate stability [53,54]. The specific surface area (SSA) measured by Nitrogen adsorption measurements confirmed that *BC* modified the internal soil pores' structure, increasing the number of structural, connected pores [55]. As a consequence, *BC* increased the values of saturated volumetric water content, $\theta_s$, field capacity, $\theta_{fc}$, and wilting point, $\theta_{wp}$, enhancing the soil water retention and increasing the $AW_{max}$ from a value of 19 mm/m for the *DS* without *BC* to values of 62, 103 and 109 when *BC* fractions, $f_{bc}$, equal to 0.091, 0.23 and 0.33, respectively, were mixed with the *DS*.

These results suggested that the application of *BC* could be a management option improving the soil's structural and retention characteristics, as well as the $AW_{max}$ of the *DS*. This could be of considerable potential interest not only for the Al-Foah area but also for other arid and/or semi-arid regions characterized by large extensions of sandy soils similar to that considered, with poor structural and retention characteristics.

The objective of this paper was to explore the hitherto little investigated application of *BC* to *DS*, as an amendment option improving soil water balance and irrigation management for three different crops, i.e., wheat (*Triticum aestivum*), sorghum (*Sorghum vulgare*) and tomato (*Lycopersicon esculentum*). Soil water balance and irrigation scheduling were simulated by AQUACROP using as input the soil's hydrological parameters previously measured at $f_{bc}$ = 0, 0.091, 0.023 and 0.33 [51]. The specific objective was to investigate if under drip irrigation, the application of *BC* to *DS* improved the irrigation water use efficiency (*IWUE*) and water use efficiency (*WUE*), under conditions of no water stress (*NWS*) for the crops and under deficit irrigation (*DI*).

## 2. Materials and Methods

### 2.1. Study-Area and Soil Characteristics

The sandy soil was taken from the dunes near Al Foah (long 55°50′E and lat 24°30′N), located north of Al Ain, a city in the Eastern Region of the Emirate of Abu Dhabi, which is one of the seven States of the UAE, with an area of about 64,000 km$^2$, most of which covered by Aeolian sand. Agricultural development is limited to a few small-scattered oases, such as the Liwa group and those at Al Ain. The latter, seven in Abu Dhabi State and two, including Buraimi, in Muscat territory, have always been the most important centers of agriculture in the region.

Climate is arid, with very high summer temperatures. The interior desert region has hot summers with temperatures rising up to about 50 °C. Annual rainfalls are very scarce and vary between 15 mm and 78 mm, with January and February being the rainy months.

The desert sand (*DS*) considered in the AQUACROP application was characterized by a content in clay, silt and sand equal to 2.6, 1.9 and 95.6%, respectively, a low organic matter content (0.54 g/kg) and a Ca and Mg content equal to 12 and 4 mg/kg, respectively. A weak structural development was observed, as usual in single grained sandy soils. The *DS* was classified as Aridisol according to the USDA [56,57].

## 2.2. Model Description

The AQUACROP model, developed by the FAO Land and Water Division, is a water-driven model that can be used as a planning and support tool for management decisions in both irrigated and rainfed agriculture [20,58]. The model computes the soil water balance in the root zone according to Allen et al. [59,60], calculating the root zone depletion, $D_r$, at the end of every day, as:

$$D_{r,i} = D_{r,i-1} - (R - RO)_i - V_{IRR} - CR_i + ET_i + DP_i \quad (1)$$

where the subscripts $i$ and $i - 1$ refer to the current day and to the previous day, respectively, $R$ (mm) is the rainfall depth, $RO$ (mm) is the runoff, $V_{IRR}$ (mm) is the irrigation depth, $CR$ (mm) is the capillary rise, $ET$ (mm) is the actual crop evapotranspiration and $DP$ (mm) is deep percolation. The parametric equations described by Liu et al. [61] are used to calculate $CR$ and $DP$. The water balance is highly affected by runoff, $RO$, [62], which in turn is highly influenced by the soil's hydrological characteristics [63,64]. AQUACROP estimates $RO$ by using the curve number approach [65], and splits the maximum $ET$ component, $ET_c$, in maximum soil evaporation, $E_s$ (mm), and maximum crop transpiration, $T_c$ (mm), which are estimated as:

$$E_s = K_r(1 - CC)K_e ET_0 \quad (2)$$

$$T_c = CC\ K_{cTr} ET_0 \quad (3)$$

where $ET_0$ (mm) is the reference evapotranspiration [59], $CC$ (%) is the crop development value, $K_e$ is the maximum soil evaporation coefficient (dimensionless), $K_r$ is the evaporation reduction coefficient (0–1) and $K_{cTr}$ is the standard crop transpiration coefficient (dimensionless) when $CC$ = 100%. The actual transpiration, $T_a$ (mm), is calculated as:

$$T_a = CC\ K_s K_{cTr} ET_0 \quad (4)$$

where $K_s$ is a water stress coefficient ranging between 0 and 1 [59,66]. Further details on calculating $T_a$ and $E_s$ are provided by Raes et al. [67].

In AQUACROP the ground dry biomass, $B$ (kg ha$^{-1}$), is computed as the product of the season-cumulated ratio $T_a/ET_0$ and the adjusted biomass (water) productivity $BWP^*$ (g m$^{-2}$), that takes into account the actual atmospheric $CO_2$ concentration [67], whereas the crop yield, $Y$ (kg ha$^{-1}$), is predicted by $B$ as:

$$Y = f_{HI}\ HI_0 B \quad (5)$$

where $HI_0$ is the reference harvest index, which indicates the harvestable proportion of biomass, and $f_{HI}$ is an adjustment factor computed by the model and related to five water stress factors, i.e., inhibition of leaf growth, inhibition of stomata, reduction in green canopy duration due to senescence, reduction in biomass due to pre-anthesis stress and pollination failure.

The main input data required by AQUACROP are:

*Climatic data*—daily maximum and minimum air temperature, $T_{max}$ (°C) and $T_{min}$ (°C), daily rainfall ($R$), reference evapotranspiration ($ET_0$) and mean annual $CO_2$ (ppm) concentration in the atmosphere.

*Crop data*—crop calendar with reference to the emergence, maximum coverage, maturity and senescence stages; maximum value of $K_{cTr}$; minimum and maximum root depths and roots expansion shape factor; the parameters of the canopy cover ($CC$) curve; the canopy growth coefficient $CGC$ (% degree day$^{-1}$) and the canopy decline coefficient $CDC$ (% degree day$^{-1}$); the parameters used to compute yield, $BWP^*$ and $HI_0$ defined above; the water stress coefficients relative to canopy expansion, stomatal closure, early canopy senescence and aeration stress due to water logging.

*Soil data*—number of layers (maximum 5) and soil layer depth, *d* (m), and for each layer volumetric water content at saturation, $\theta_s$ ($m^3$ $m^{-3}$), field capacity, $\theta_{fc}$, and wilting point, $\theta_{wp}$.

*Irrigation*—irrigation system; scheduling parameters (time and depth criteria), in case of irrigation scheduled by the model, or time and volume of each water supply in case of user-imposed irrigation depth. The irrigation system can be selected as "sprinkler", "surface" or "drip". In the latter case, an adjustment coefficient (%) for partial soil wetting can be used to take into account the actual irrigated area.

*Field and management data*—salinity, soil fertility, mulching and runoff reduction practices.

### 2.3. Data Collection and Simulation Scenarios

Daily rainfall (*R*) and daily maximum and minimum air temperature ($T_{max}$ and $T_{min}$), recorded from 1 Jan 2006 to 31 Dec 2007 at Al Buraimi weather station (24.233° lat, 55.783° long, 299 m a.s.l.), were used to calculate the reference evapotranspiration $ET_0$ [60], using the Hargreaves equation [68], and to carry out the AQUACROP simulations. Al Buraimi is located in Oman at the border with the UAE, and is near to the Al Foah area. Data from the Al Buraimi weather station were used because they fully covered the investigated period. Figure 1 illustrates *R* and $ET_0$, characterizing the climatic conditions of the study-area, where only a small number of rainfall events occurred in 2006 (114 mm with 26 rainfall events) and in 2007 (58 mm with 15 rainfall events), and reference evapotranspiration values that achieved about 9 mm/day in the summer season.

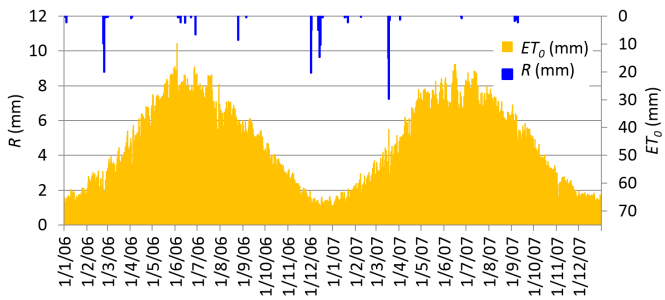


**Figure 1.** Rainfall, *R*, and reference evapotranspiration, $ET_0$, at Al Buraimi weather station, in the investigated period (1 January 2006–31 December 2007).

Biochar, *BC*, from forest biomass (*Abies alba M.*, *Larix decidua Mill.*, *Picea excelsa L.*, *Pinus nigra A.* and *Pinus sylvestris L.*, mixed in equal relative proportions), pyrolyzed at 450 °C for 48 h, had been used to amend the *DS* and to measure the soil water retention [51]. The *BC* fractions considered by Baiamonte et al. [51] were: $f_{BC}$ = 0.0 (soil only), $f_{BC}$ = 0.091, 0.23, 0.33 and 1.00 (*BC* only), with the biochar fraction, $f_{BC}$, defined as:

$$f_{BC} = \frac{P_{BC}}{P_s + P_{BC}} \tag{6}$$

where $P_{BC}$ (g) and $P_S$ (g) are the *BC* and *DS* weights, respectively.

Table 1 reports the saturated water content, $\theta_s$, together with the $\theta_{fc}$ and $\theta_{wp}$ values previously measured for the *DS* without *BC* and with *BC* addition [51] and used as input to simulate the soil water balance and irrigation scheduling under drip irrigation. These hydraulic parameters were determined by the High Energy Moisture Characteristic (HEMC) technique [69,70], and therefore took into account the structural changes occurring in the soil-BC mixtures after *BC* addition. The importance of using hydraulic parameters determined with measurement techniques detecting even small structural changes as input to physically-based simulation models, in order to obtain reliable model predictions, has been evidenced in previous investigations (17). This also means that the *ET* values predicted by AQUACROP using these hydraulic parameters can be considered reliable.

**Table 1.** Experimental soil hydrological parameters [51].

| Soil | Layer Depth, Z (m) | $\theta_s$ ($cm^3\ cm^{-3}$) | $\theta_{fc}$ ($cm^3\ cm^{-3}$) | $\theta_{wp}$ ($cm^3\ cm^{-3}$) | $AW_{max}$ ($mm\ m^{-1}$) |
|---|---|---|---|---|---|
| $f_{BC} = 0$ | 0.4 | 0.409 | 0.046 | 0.027 | 19 |
| $f_{BC} = 0.091$ | - | 0.559 | 0.098 | 0.036 | 62 |
| $f_{BC} = 0.23$ | - | 0.675 | 0.152 | 0.049 | 103 |
| $f_{BC} = 0.33$ | - | 0.724 | 0.163 | 0.054 | 109 |

The crops chosen for the simulations were wheat, sorghum and tomato, which are of economic interest for many countries all over the world. Production of wheat is negligible in the UAE due to extreme heat, low rainfall and barren desert soil, but increasing the local production could be of interest for the UAE. Abu Dhabi has two large wheat farms at Al Ain, and experimental farms at Rawaya and Mazaid (near Al Ain) were designed to encourage local Bedouins to take up settled farming. As part of a research project, about 100 varieties of wheat used for the production of flour to make bread were cultivated in Al Ain in 2013, and the initial results were positive [68,71].

Sorghum is predominantly grown in semi-arid and arid agro-ecological areas and is considered one of the crops that can also be cultivated for large-scale production, despite the harsh climate conditions of the UAE. Sorghum cultivation is being investigated on a trial basis at the experimental farms of UAE University. Tomato is one of the most widely cultivated crops in the world, including UAE, where the government policies are supporting tomato cultivation, enhancing locally-grown production for the UAE consumers [71].

Table 2 reports the main default parameters implemented in AQUACROP and used as inputs to carry out the simulations for the three considered crops.

**Table 2.** Crop parameters considered in ACQUACROP.

| Parameter Description | Units | Crops | | |
|---|---|---|---|---|
| | | Wheat | Sorghum | Tomato |
| Time from sowing/transplanting to emergence | days | 9 | 6 | 5 |
| Time from sowing/transplanting to maximum rooting depth | days | 51 | 65 | 65 |
| Time from sowing/transplanting to start senescence | days | 94 | 69 | 111 |
| Time from sowing/transplanting to maturity | days | 126 | 79 | 119 |
| Time from sowing/transplanting to flowering | days | 71 | 60 | 40 |
| Base temperature below which crop development does not progress | °C | 0 | 8 | 7 |
| Upper temperature above which crop development no longer increases temperature | °C | 26 | 30 | 32 |
| Soil water depletion factor for canopy expansion (Upper threshold) | - | 0.2 | 0.15 | 0.15 |
| Soil water depletion factor for canopy expansion (Lower threshold) | - | 0.65 | 0.7 | 0.55 |
| Soil water depletion fraction for stomatal control (Upper threshold) | - | 0.65 | 0.75 | 0.5 |
| Soil water depletion factor for canopy senescence (Upper threshold) | - | 0.7 | 0.7 | 0.7 |
| Minimum air temperature below which pollination starts to fail | °C | 5 | 10 | 10 |
| Maximum air temperature above which pollination starts to fail | °C | 35 | 40 | 40 |
| Crop coefficient when canopy is full but prior to senescence | % | 1.1 | 1.07 | 1.1 |
| Minimum effective rooting depth (m) | m | 0.1 | 0.1 | 0.15 |
| Maximum effective rooting depth (m) | m | 0.4 | 0.4 | 0.4 |
| Building up of Harvest Index starting at flowering | days | 54 | 19 | 63 |

The length of crop development stages, $T_{LCD}$ (day), i.e., the time from sowing/transplanting to emergence, to maximum rooting depth, to the beginning of senescence and to maturity, were adjusted in order to take into account the site-specific conditions [59].

For each crop, a soil water balance was performed daily by using a simulation period between sowing/transplanting and the end of maturity. Since the accuracy of the soil water balance depends on the soil water content ($\theta$) at the starting day, information not available, the first rainy day following sowing/transplanting, characterized by a rainfall depth > 15 mm, was chosen as starting date. This made it possible to start the simulations for all the crops from the same initial soil conditions at the field capacity, $\theta_{fc}$.

Simulations were carried out in order to investigate the effects (i) of the different $f_{BC}$, and (ii) of the different options of *BC* incorporation into soil layers of different depths, ($Z_{DS+BC}$), on soil-water balance, on irrigation efficiency and on the crop response to water.

Incorporation of *BC* into the soil was assumed to be technically feasible if carried out with plowing, before sowing, as also shown by Moiwo et al. [72].

Although values of $Z_{DS+BC}$ equal to 30 or 40 cm are likely to be non-sustainable possibilities, because of the considerable amounts of *BC* that should be used to amend the soil with these options, these values were also considered as a theoretical possibility of incorporating *BC* into the deepest soil layers. In case of low-cost *BC* obtained in farms by waste residues, this incorporation could be done during tillage before sowing when soil preparation is carried out, and could be justified by the benefits in terms of the increase in soil fertility and related crop productivity, in the long term [49].

Simulations were carried out by assuming drip irrigation [8,73] under two different management scenarios. In the first scenario, a condition of "no water stress for the crop" (*NWS*) was simulated by an irrigation scheduling bringing the soil water content at $\theta_{fc}$, when 65% of the readily available water (*RAW*) was depleted from the soil. *RAW* was calculated as a *p* fraction of $AW_{max}$ equal to 0.65 [59]. Therefore, for each crop, this scenario determined $T/T_{max}$ ratios equal to 1, evidencing the effect of *BC* on the predicted irrigation water needs ($V_{IRR}$) and on the irrigation scheduling when the objective was to avoid any water stress for the crop, obtaining the maximum yield, *Y*.

Instead, the second scenario simulated a condition of water stress for the crops by scheduling a deficit irrigation (*DI*), supplying the soil-crop system with a total amount of irrigation water, $V_{IRR}$, restoring 70% of the maximum crop evapotranspiration, $ET_C$. Under this *DI* condition, $V_{IRR}$ did not vary, for the same crop, at changing $f_{BC}$ and $Z_{DS+BC}$, and the effect of *BC* on crop yield, *Y*, and on the *WUE* could instead be evaluated for each crop.

Table 3 reports some information related to the simulated scenarios. The *DS* option refers to soil water balance simulations carried out for the soil without *BC*, whereas the "$Z_{BC+DS}$" and $Z_{DS}$ are the different options of incorporating the three *BC* fractions ($f_{BC}$ = 0.091, $f_{BC}$ = 0.23 and $f_{BC}$ = 0.33) into soil layers of different depths.

The performance of each scenario, with the options of *BC* incorporation, on the soil-crop system and on irrigation management, was assessed by considering the outputs provided by AQUACROP, as well as by calculating the irrigation water use efficiency index, *IWUE* (kg m$^{-3}$), as:

$$IWUE = 100\frac{Y}{V_{IRR}} \tag{7}$$

where *Y* (t ha$^{-1}$) is the crop yield and $V_{IRR}$ (mm) is the total irrigation volume.

For the *NWS* scenario, the dimensionless ratios $V_{IRR}/V_{IRR,DS}$ and $N_{IRR}/N_{IRR,DS}$, obtained by dividing the total irrigation volumes, $V_{IRR}$, and the number of irrigations, $N_{IRR}$, by the corresponding values obtained simulating only sand without *BC*, were considered.

**Table 3.** Simulation scenarios for the three considered crops.

| Simulation Scenarios | Wheat (*T. aestivum*) | Sorghum (*Sorghum vulgare*) | Tomato (*Lycopersicon esculentum*) |
|---|---|---|---|
| *Date of planting/seeding* | 1 December 2006 | 24 February 2006 | 15 January 2006 |
| *Start date of simulation* | 2 December 2006 | 25 February 2006 | 24 February 2006 |
| *End date of simulation* | 6 April 2007 | 14 May 2006 | 13 May 2006 |
| *Length of Crop Development stage, $T_{LCD}$ (days)* | 126 | 79 | 119 |
| *Desert sand (DS) and Biochar (BC) depths* | | | |
| *DS* (cm) | 40 | | |
| $Z_{DS+BC}$ (cm) | 40 30 20 10 | | |
| $Z_{DS}$ (cm) | 0 10 20 30 | | |
| *Irrigation management scenarios* | | | |
| Deficit irrigation, *DI*, (Number-Depth in mm) | 38-5 | 33-8 | 37-8 |
| No water stress, *NWS*, (Time and Depth Criteria) | 65% of RAW depleted, irrigation depth back to the field capacity | | |

For the *DI* scenario, the ratios between the actual transpiration, *T*, the maximum transpiration, $T_{max}$, the yield, *Y*, the maximum yield, $Y_{max}$, the irrigation water use efficiency, *IWUE*, and the water use efficiency, *WUE*, were analyzed.

## 3. Results and Discussion

With reference to the three crops and to the *NWS* scenario, for each of the considered $f_{BC}$ ($f_{BC}$ = 0.091, 0.23 and 0.33), The main outputs of the soil water balance simulated by AQUACROP for the different $Z_{DS+BC}$, including the results obtained for the *DS*, without *BC*, are reported in Table 4. The reference evapotranspiration, $ET_0$ (mm), during the simulation period, the total irrigation volume, $V_{IRR}$ (mm), predicted by the model, the actual crop transpiration, *T* (mm), which was equal to the maximum ($T = T_{max}$), the actual soil evaporation, *E* (mm), the number of irrigations, *#IRR*, and the average irrigation water volume, $h_{IRR}$ (mm), the crop biomass, $B_{mass}$ (t ha$^{-1}$), the cumulative Harvest Index, $H_i$ (%), the crop yield, *Y* (t ha$^{-1}$), the water use efficiency, *WUE* (kg m$^{-3}$), and the irrigation water use efficiency, *IWUE* (kg m$^{-3}$), with the latter calculated per Equation (7), are also reported in Table 4.

As can be seen in Table 4, *BC* positively affected the soil water balance, by decreasing the amount of $V_{IRR}$ necessary to fully meet the crop water requirement and to obtain the maximum *Y*, with $V_{IRR}$ values that decreased at increasing $f_{BC}$ and $Z_{DS+BC}$, compared to *DS*.

The positive effects of *BC* on soil water balance were the consequence of the improved retention characteristics, which in turn were the consequence of the improved structural and aggregation soil properties due to *BC* addition. *BC* increased the number of pores with diameter = 9.09 µm (storage pores), improved the aggregate stability and increased the number of internal pores [51]. Since $AW_{max}$ increased at increased $f_{BC}$, indicating a greater ability of the soil to store water as a consequence of *BC* addition, this explains why lower $V_{IRR}$ values were predicted when *BC* was applied at higher $f_{BC}$ and application depths ($Z_{DS+BC}$).

These results indicated that the addition of *BC* to the *DS* can be considered a water saving strategy. The decrease in the $V_{IRR}$ values was the consequence of the increase in soil porosity and water retention due to *BC* [51], as can be illustrated by analyzing the temporal variation of the volumetric water content, θ, and of the irrigation scheduling obtained by AQUACROP for the *DS* without *BC* and after *BC* addition.

Figure 2a–c shows that, for the three crops, when the soil water balance was simulated for the *DS*, without *BC*, θ was almost constant during the entire simulation period and close to the value of 0.046, corresponding to the *DS* field capacity, $\theta_{fc}$ (Table 1). Instead, when *BC* was applied to the *DS* at $f_{BC}$ = 0.23 and $Z_{DS+BC}$ = 30 cm (Figure 2d–f), a larger variability occurred in the θ values predicted before and after irrigation. This was the consequence of the increased field capacity, $\theta_{fc}$ (from 0.046 to 0.152 cm$^3$), wilting point, $\theta_{wp}$ (from 0.027 to 0.049 cm$^3$), and $AW_{max}$, determined by the *BC* application (Table 1).

The increase in $AW_{max}$ from 19 mm/m to 103 mm/m after *BC* addition at $f_{BC}$ = 0.23 indicated a considerably enhanced soil ability to act as a reservoir for water and to provide a higher amount of water to the crops. This explains why the simulation carried out with $AW_{max}$ = 103 mm/m, compared to that carried out with $AW_{max}$ = 19 mm/m, determined an irrigation scheduling predicting an amount of $V_{IRR}$ equal to 224.4 mm, for wheat, against the $V_{IRR}$ of 251.3 mm obtained for the *DS*. For sorghum, the predicted $V_{IRR}$ was equal to 308.8 mm, against the value of 343.8 mm, and for tomato the predicted $V_{IRR}$ was equal to 367.0 mm, against the value of 394.3 mm. Thus, for the *NWS* scenario, and for $f_{BC}$ = 0.23 and $Z_{DS+BC}$ = 30 cm, the reductions in the $V_{IRR}$ values were equal to 10.7%, 10.2% and 6.9% for wheat, sorghum and tomato, respectively, with the minimum effect on tomato and comparable effects on wheat and sorghum. These results indicated that, under the climatic conditions explored in this investigation, the addition of *BC* to the *DS* made it possible to save water, showing the positive role of *BC* in improving irrigation management for the considered *DS* and for the three crops.

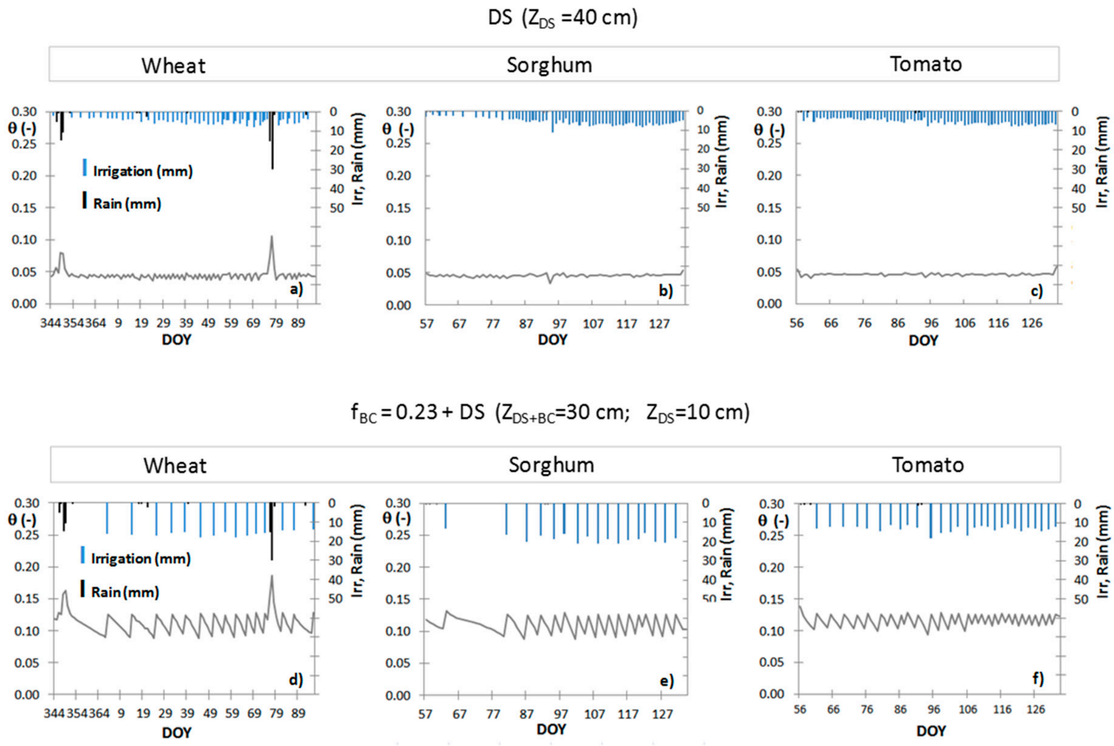


**Figure 2.** Temporal variation of the average soil water content, θ, scheduled by AQUACROP under the no water stress (*NWS*) scenario. (**a**–**c**) refer to the simulations for which no biochar application was considered (*DS*), whereas (**d**–**f**) refer to the case of a biochar fraction $f_{BC}$ = 0.23, applied in the first 30 cm of the soil ($Z_{DS+BC}$ = 30 cm).

A further positive effect of *BC* was the reduction in the number of the irrigation events scheduled by the model, #*IRR* (14 against 54 for wheat, 17 against 63 for sorghum and 28 against 75 for tomato), with these results indicating that a certain amount of energy can be saved when irrigation is carried out after *BC* application.

For wheat, similar $V_{IRR}$ values were obtained, for the same $Z_{DS+BC}$ (30 cm), with $f_{BC}$ = 0.091 ($V_{IRR}$ = 226.0 mm) and $f_{BC}$ = 0.33 ($V_{IRR}$ = 220.0 mm). Other options implying lower $f_{BC}$ and $Z_{BC+DS}$ values also determined reductions in the $V_{IRR}$ and #*IRR* values (Table 4). However, also in these other cases, reductions in the $V_{IRR}$ and #*IRR* values due to *BC* addition were always maximal for wheat, followed by sorghum and by tomato. For wheat, the reductions in $V_{IRR}$ ranged from 18% (for $f_{BC}$ = 0.33 and $Z_{DS+BC}$ = 40 cm) to 3.1% (for $f_{BC}$ = 0.091 and $Z_{DS+BC}$ = 10 cm), for sorghum from 13.5% ($f_{BC}$ = 0.33 and $Z_{DS+BC}$ = 40 cm) to 3.7% ($f_{BC}$ = 0.091 and $Z_{DS+BC}$ = 10 cm) and for tomato from 7.5% ($f_{BC}$ = 0.33 and $Z_{DS+BC}$ = 40 cm) to 2.8% ($f_{BC}$ = 0.091 and $Z_{DS+BC}$ = 10 cm). These results indicated that (i) the maximum *BC* benefit was found at the maximum considered depth of 40 cm, agreeing with the experimental results of Moiwo et al. [72], who found an increasing *BC* benefit with increasing application depth, (ii) wheat was the crop showing the maximum benefit from *BC* application and tomato the crop having the minimum benefit, with sorghum in the middle, and (iii) for wheat, lower $f_{BC}$ than those required for sorghum and tomato would be enough to obtain comparable $V_{IRR}$ reductions, indicating that *BC* was more efficiently used by wheat.

*BC* increased the irrigation water use efficiency (*IWUE*) for the three crops, with the maximum *IWUE* obtained for $f_{BC}$ = 0.33 and $Z_{DS+BC}$ = 40 cm (Table 4). However, the effect of *BC* on *IWUE* was maximal for wheat (from 2.77 kg m$^{-3}$ to 3.38 kg m$^{-3}$) and negligible for sorghum and tomato. This result is in agreement with the previously observed maximum effect of *BC* on the $V_{IRR}$ values observed for wheat.

For each crop and for the different $f_{BC}$ and $Z_{DS+BC}$ options, Figure 3 illustrates the dimensionless ratios $V_{IRR}/V_{IRR,DS}$ (Figure 3a–c) and $\#IRR/\#IRR_{DS}$ (Figure 3d–f), obtained by dividing the $V_{IRR}$ and the $\#IRR$ by the corresponding *DS* without *BC*, as a function of the considered $Z_{DS+BC}$. The lowest $V_{IRR}/V_{IRR,DS}$ and $\#IRR/\#IRR_{DS}$ indicate more efficient water and energy saving solutions, either in terms of $f_{BC}$ or of $Z_{DS+BC}$. These figures can be useful to select different possible $f_{BC}$ and $Z_{DS+BC}$ options even for $f_{BC}$ and $Z_{DS+BC}$ values not explored in the simulations.

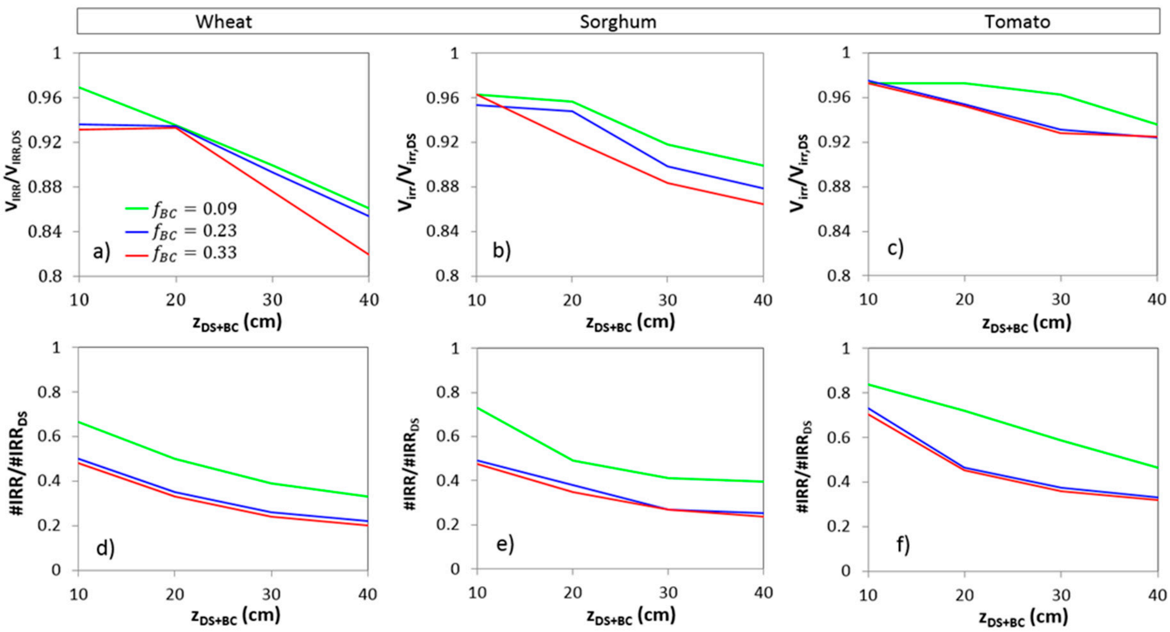


**Figure 3.** For each *BC* fraction, $f_{BC}$, and for the three considered crops, (**a**–**c**) ratios between the total irrigation volume, $V_{IRR}$, obtained at the three considered *BC* and the irrigation volume, $V_{IRR,DS}$, obtained for the *DS* without *BC*, vs. the depth of *BC* application, $Z_{DS+BC}$, up to the maximum depth of 40 cm. For the three crops, (**d**–**f**) ratios between the number of irrigations, $\#IRR$, and the number of irrigations $\#IRR_{DS}$, obtained for the *DS* without *BC*, versus $Z_{DS+BC}$.

The $f_{BC}$ and $Z_{DS+BC}$ options could be further considered in terms of feasibility and sustainability according to cost-benefit analyses taking into account site-specific factors, such as the cost and the availability of *BC*, the cost of water and of energy needed for irrigation, as well as the benefits of amending the *DS* by *BC* in terms of $V_{IRR}$, $\#IRR$ and *IWUE*.

In the UAE, the addition to sandy soils of BC obtained from palm dates significantly improved plant growth in maize and soil productivity [74], since there are about 40 million palm trees and each tree generates annually about 15 kg of biomass waste, with a total of 600 million kg of green waste. The use of on-farm produced *BC* as amendment could be a sustainable practice enhancing the soil water retention [75] and increasing the *IWUE* [76], thus helping to save water.

If *BC* can be produced from locally abundant feedstock, the low cost of *BC* could justify the amount of *BC* to be used to amend the soil with higher $f_{BC}$ and/or $Z_{DS+BC}$. An example of the use of *BC* from date palms as a strategy improving the soil water retention of desert sand in Saudi Arabia, increasing the yield of wheat, was recently reported by Alotaibi and Shoenau [49].

Figure 3 also shows that, in general, similar $V_{IRR}/V_{IRR,DS}$ and $\#IRR/\#IRR_{DS}$ ratios were obtained for $Z_{DS+BC}$ = 10, 20 cm, indicating that the application of *BC* into the first 10 cm could be sufficient in order to gain some benefits, except for wheat (at $f_{BC}$ = 0.091), sorghum (at $f_{BC}$ = 0.33) and tomato (at $f_{BC}$ = 0.23 and 0.33), for which $Z_{DS+BC}$ = 20 cm was necessary to further reduce $V_{IRR}$.

For the three crops, Table 4 also shows that in the *NWS* scenario, no effects of *BC* occurred on the biomass, $B_{mass}$, on the $H_i$ index or on the crop yield, *Y*. These expected results are due to the fact that no water stress was induced on the crops, and as a consequence the yield, $Y$, was always maximal. Therefore, negligible effects were also observed on the $WUE$, because of the slight influence of the evaporation component, $E$ (Table 4), on $ET$, obtained by varying $f_{BC}$ and $Z_{DS+BC}$.

With reference to the "deficit irrigation", $DI$, Table 5 reports the main outputs of the soil-water balance simulated by AQUACROP for the three considered crops and for the previously considered $f_{BC}$ and $Z_{DS+BC}$ values.

In particular, $DI$ was applied by supplying to each crop an irrigation volume, $V_{IRR}$, calculated as 0.7 $ET_C$, and setting a number of irrigations (#$IRR$) of fixed depth, $h_{IRR}$ (mm), uniformly distributing $V_{IRR}$ in the simulation period. According to this irrigation scheduling (Table 3), the pairs (#$IRR$, $h_{IRR}$) satisfying the values of the pre-calculated $V_{IRR}$ were equal to (38, 5), (33, 8) and (37, 8) for wheat, sorghum and tomato, respectively. The supplied $V_{IRR}$ were equal to 190 mm, 264 mm and 296 mm for wheat, sorghum and tomato, respectively.

As can be seen in Table 5, the application of $BC$ increased the $T/T_{max}$ ratio, at increasing $f_{BC}$ and $Z_{DS+BC}$, with the $T/T_{max}$ calculated by considering only the $T/T_{max} < 1$ values. The lowest $T/T_{max}$ were obtained for wheat (average of all the values equal to 0.356), and the highest for sorghum (0.614), with tomato in the middle (0.595). These results indicated that a greater water stress ($WS$) condition occurred for wheat compared to sorghum and tomato.

For the three crops, the productivity parameter, $B_{mass}$, increased at increasing $f_{BC}$ and $Z_{DS+BC}$, with the highest $B_{mass}$ obtained for sorghum, followed by wheat and tomato. However, the $H_i$ values were maximum for tomato ($H_i$ between 61.8% and 54.6%), followed by wheat (between 46.2% and 25.7%). Instead, for sorghum, $H_i$ values were much lower (between 26.2% and 18.1%) than those obtained for wheat and tomato, thus indicating that the effect of water stress ($WS$) negatively impacted sorghum in terms of $H_i$.

The low $H_i$ values obtained for sorghum can be explained by the shorter $H_i$ building up period (Table 2), during which $T/T_{max}$ lower than 1 occurred with a higher frequency than for wheat and tomato, as can be seen by considering the ratio ($t_{ws}/t_{LCD}$) between the number of days, $t_{ws}$, during which $T/T_{max} < 1$, with respect to the length of the crop development stage, $t_{LCD}$ (Table 2). Indeed, as reported in Table 5, the $t_{ws}/t_{LCD}$ ratios obtained for sorghum were higher than those for wheat and tomato, thus explaining the lowest $H_i$ and $Y$ values obtained for sorghum, compared to wheat and tomato, notwithstanding its highest $T/T_{max}$.

As can be seen in Table 5, for the three crops, the maximum positive effect of $BC$ occurred when $BC$ at $f_{BC} = 0.33$ was considered to be applied up to the maximum considered depth, $Z_{DS+BC} = 40$ cm. In this case, for wheat, $Y$ increased from 1.5 t/ha (for the $DS$) to 6.1 t/ha, with this latter value being comparable to that of the $NWS$ scenario ($Y = 6.96$ t/ta) and indicating that $BC$ mitigated the yield reduction due to water stress. For tomato, $Y$ increased from 4.3 t/ha (for the $DS$) to 7 t/ha, against a value of 7.84 t/ha for the $NWS$ condition, indicating a similar beneficial effect of $BC$ application. Instead, for sorghum, $Y$ increased from 1.4 t/ha (for the $DS$) to 3.9 t/ha, against a value of 7.1 t/ha for the $NWS$ scenario, indicating less benefits of $BC$ application than for wheat and for tomato.

Figure 4a–c illustrate the ratios $Y/Y_{max}$, as a function of $Z_{DS+BC}$. For wheat (Figure 4a), $BC$ increased the $Y/Y_{max}$ values at increasing $f_{BC}$ and $Z_{DS+BC}$, thus decreasing the $Y$ reduction ($1-Y/Y_{max}$) from 78.4% for the $DS$ to values ranging between 12.3% (for $f_{BC} = 0.33$ and $Z_{DS+BC} = 40$ cm) and 58.3% (for $f_{BC} = 0.091$ and $Z_{DS+BC} = 10$ cm).

For sorghum (Figure 4b), the $Y/Y_{max}$ values were lower than those obtained for wheat, with reductions in $Y$ decreasing from 80.3% for the $DS$ to values ranging between 45.1% (for $f_{BC} = 0.33$ and $Z_{DS+BC} = 40$ cm) and 69.0% (for $f_{BC} = 0.091$ and $Z_{DS+BC} = 10$ cm).

Tomato (Figure 4c) was the crop less affected by water stress under $DI$ conditions, with a reduction in $Y$ equal to 45.1% for the $DS$, compared to the $NWS$ scenario, much lower than those obtained for wheat (78.4%) and for sorghum (80.2%). For tomato, $1-Y/Y_{max}$ decreased from 45.1% ($DS$) to 10.7% (for $f_{BC} = 0.33$ and $Z_{DS+BC} = 40$ cm) and to 26.0% (for $f_{BC} = 0.091$ and $Z_{DS+BC} = 10$ cm). These results demonstrated that with reference to the mitigating effect of $BC$ on the Y reductions, wheat was the crop receiving the maximum benefits from *BC* application, followed by tomato, with sorghum showing the lowest benefits.

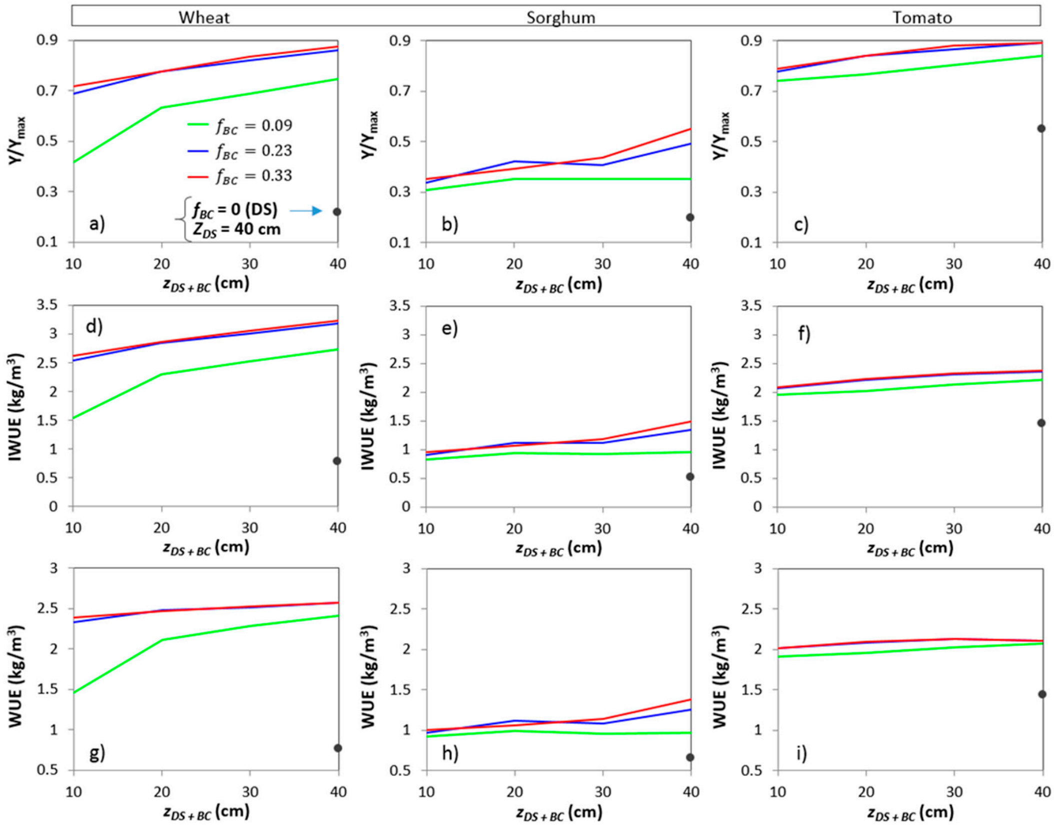


**Figure 4.** For each *BC* fraction, $f_{BC}$, and for the three considered crops, (**a**–**c**) ratio between the yield and the maximum yield, $Y/Y_{max}$, (**d**–**f**), the irrigation water use efficiency, *IWUE*, and (**g**–**i**) the water use efficiency, *WUE*, versus the depth of *BC* application, $Z_{DS+BC}$.

Figure 4d–f illustrates *IWUE* as a function of $Z_{DS+BC}$. The figures can be useful to check the effect of the different $f_{BC}$ and $Z_{DS+BC}$ values on the considered *IWUE*, which depends on *Y* and on $V_{IRR}$. The maximum *IWUEs* were obtained for wheat, followed by tomato, with lower *IWUEs* for sorghum even at the highest $f_{BC}$ and $Z_{DS+BC}$.

When the *WUE* was considered (Table 5, Figure 4g–i), the maximum *WUE* was obtained for wheat and tomato, and the minimum for sorghum. These results depended on the lower actual *ET* predicted for wheat (average value 209.5 mm) compared to tomato (average value 309.8 mm) and to sorghum (average value 257.1 mm), with maximum *Y* obtained for tomato, followed by the minimum for sorghum. These results confirmed that, under *DI*, wheat was the crop providing the maximum *WUE*, and tomato the second possible best option, while cultivation of sorghum slightly benefited from *BC* application and could be inadvisable under deficit irrigation.

These outcomes could be of interest considering the economic importance of cultivating wheat and tomato in the UAE and in many other countries of the world.

For the three crops, Figure 5a,b illustrate the comparison between the *WUE* and *IWUE* obtained with the *DI* and *NWS* scenarios, either without *BC* and after *BC* addition, at $f_{BC}$ = 0.091 and $Z_{DS+BC}$ = 10 cm, which is the option among those explored, involving the minimum amount of *BC*. Values of $f_{BC}$ lower than 0.091 were not explored in the simulations because the results previously obtained showed no effects on porosity, soil water retention and $AW_{max}$ of the *DS* when $f_{BC}$ = 0.014 was tested [51].

For the three crops, when the *NWS* scenario was considered, the effect of this $f_{BC}$ and $Z_{DS+BC}$ on *IWUE* and on *WUE* was negligible. Instead, under *DI*, *BC* increased the *WUE* and the *IWUE*, compared to the values obtained for the *DS* without *BC*, counterbalancing the lower irrigation amount, $V_{IRR}$, supplied with the *DI*. The maximum increase in *IWUE* and *WUE* as an effect of *BC* addition was found for wheat, with lower effects on tomato than on wheat, and negligible effects on sorghum.

These results showed that even at the lowest considered $f_{BC}$, among those considered, *BC* addition could be a useful strategy when *DI* is practiced for cultivation of wheat and tomato, under the extremely arid conditions of the considered study area and/or similar climatic areas. Our results agree with those obtained by Bagheri et al. [77] in Iran, indicating that the use of biochar can be a successful strategy for improving water use efficiency and reducing the effects of drought stress under extremely arid climates and for soils characterized by very poor soil water retention, as the desert sand considered in this investigation.

Although these results could be considered reliable, because based on accurately measured hydraulic properties as input of the hydrological AQUACROP component, and on suitable crop parameters, a field investigation aimed at validating some of the best options provided by the model should be the next step to be pursued.

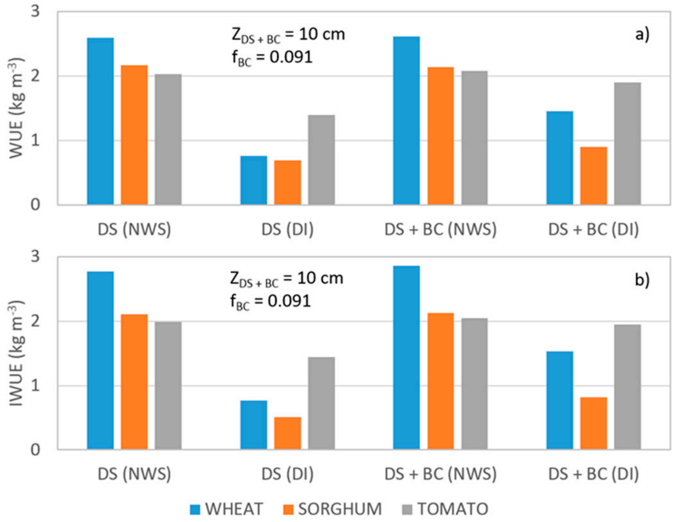


**Figure 5.** For the three considered crops, for *BC* fraction, $f_{BC}$ = 0.091, and for the depth of *BC* application, $Z_{DS+BC}$ = 10 cm, (**a**) water use efficiency, *WUE*, and (**b**) irrigation water use efficiency, *IWUE*, for the two considered irrigation management scenarios, no water stress (*NWS*) and deficit irrigation (*DI*), without *BC* (*DS*) and by *BC* application to *DS* (*DS* + *BC*).

**Table 4.** Soil layering for different biochar fractions, $f_{BC}$, and main outputs obtained using AQUACROP for the three considered crops. Data refer to a soil-water balance simulation with a "no water stress irrigation" management (*NWS*).

| Soil Layer | $Z_{DS+BC}$ (cm) | $Z_{DS}$ (cm) | $ET_0$ (mm) | $V_{IRR}$ (mm) | $T$ (mm) | $E$ (mm) | $T/T_{max}$ (-) | $\#IRR$ (-) | $h_{IRR}$ (mm) | $B_{mass}$ (t/ha) | $H_i$ (%) | $Y$ (t/ha) | $WUE$ (kg/m$^3$) | $IWUE$ (kg/m$^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Wheat** | | | | | | | | | | | | | | |
| *DS* | - | 40 | | 251.3 | | 20.3 | | 54 | 4.7 | | | | 2.59 | 2.77 |
| $f_{BC}$ 0.091 | 40 | - | | 216.4 | | 16.3 | | 18 | 12.8 | | | | 2.64 | 3.22 |
| | 30 | 10 | | 226.0 | | 16.9 | | 21.0 | 10.8 | | | | 2.63 | 3.08 |
| | 20 | 20 | | 235.1 | | 18.8 | | 27 | 8.7 | | | | 2.61 | 2.96 |
| | 10 | 30 | | 243.5 | | 19.8 | | 36 | 6.8 | | | | 2.61 | 2.86 |
| $f_{BC}$ 0.23 | - | 40 | 299.6 | 214.6 | 240.9 | 17.6 | 1 | 12 | 19.5 | 14.5 | 48 | 6.96 | 2.62 | 3.24 |
| | 30 | 10 | | 224.4 | | 16.9 | | 14 | 16.0 | | | | 2.62 | 3.10 |
| | 20 | 20 | | 234.9 | | 20.3 | | 19 | 12.4 | | | | 2.59 | 2.96 |
| | 10 | 30 | | 235.2 | | 19.6 | | 27 | 8.7 | | | | 2.60 | 2.96 |
| $f_{BC}$ 0.33 | 40 | - | | 205.8 | | 17.8 | | 11 | 20.4 | | | | 2.62 | 3.38 |
| | 30 | 10 | | 220.0 | | 18.8 | | 13 | 16.9 | | | | 2.61 | 3.16 |
| | 20 | 20 | | 234.4 | | 20.0 | | 18 | 13.0 | | | | 2.59 | 2.97 |
| | 10 | 30 | | 234.1 | | 20.0 | | 26 | 9.0 | | | | 2.60 | 2.97 |

**Table 4.** *Cont.*

| Soil Layer | $Z_{DS+BC}$ (cm) | $Z_{DS}$ (cm) | $ET_0$ (mm) | $V_{IRR}$ (mm) | $T$ (mm) | $E$ (mm) | $T/T_{max}$ (-) | $\#IRR$ (-) | $h_{IRR}$ (mm) | $B_{mass}$ (t/ha) | $H_i$ (%) | $Y$ (t/ha) | $WUE$ (kg/m$^3$) | $IWUE$ (kg/m$^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sorghum** | | | | | | | | | | | | | | |
| *DS* | - | 40 | | 343.8 | | 43.7 | | 63 | 5.5 | | | | 2.17 | 2.11 |
| $f_{BC}$ 0.091 | 40 | - | | 309.2 | | 27.2 | | 25 | 12.9 | | | | 2.20 | 2.27 |
| | 30 | 10 | | 315.8 | | 28.8 | | 26 | 12.1 | | | | 2.19 | 2.21 |
| | 20 | 20 | | 328.9 | | 33.6 | | 31 | 10.6 | | | | 2.18 | 2.15 |
| | 10 | 30 | | 331 | | 35.8 | | 46 | 7.2 | | | | 2.14 | 2.13 |
| $f_{BC}$ 0.23 | 40 | - | 402.5 | 302.3 | 293 | 25.7 | 1 | 16 | 20.1 | 17.1 | 45 | 7.10 | 2.22 | 2.32 |
| | 30 | 10 | | 308.8 | | 25.7 | | 17 | 18.2 | | | | 2.18 | 2.24 |
| | 20 | 20 | | 326 | | 29.8 | | 24 | 13.6 | | | | 2.19 | 2.15 |
| | 10 | 30 | | 327.8 | | 36 | | 31 | 10.6 | | | | 2.14 | 2.14 |
| $f_{BC}$ 0.33 | 40 | - | | 297.3 | | 26.4 | | 15 | 21.2 | | | | 2.20 | 2.35 |
| | 30 | 10 | | 303.8 | | 27.4 | | 17 | 19.0 | | | | 2.22 | 2.32 |
| | 20 | 20 | | 316.9 | | 29.4 | | 22 | 14.4 | | | | 2.18 | 2.21 |
| | 10 | 30 | | 331.1 | | 36.8 | | 30 | 11.0 | | | | 2.14 | 2.11 |
| **Tomato** | | | | | | | | | | | | | | |
| *DS* | - | 40 | | 394.3 | | 44.3 | | 75 | 5.3 | | | | 2.03 | 1.99 |
| $f_{BC}$ 0.091 | 40 | - | | 369.0 | | 28.7 | | 35 | 10.54 | | | | 2.11 | 2.13 |
| | 30 | 10 | | 379.4 | | 33.3 | | 44 | 8.62 | | | | 2.09 | 2.07 |
| | 20 | 20 | | 383.5 | | 35.4 | | 54 | 7.10 | | | | 2.07 | 2.05 |
| | 10 | 30 | | 383.4 | | 35.0 | | 63 | 6.09 | | | | 2.08 | 2.05 |
| $f_{BC}$ 0.23 | 40 | - | 397.1 | 364.3 | 343.5 | 25.8 | 1 | 25 | 14.57 | 12.4 | 63 | 7.84 | 2.13 | 2.15 |
| | 30 | 10 | | 367.0 | | 27.5 | | 28 | 13.11 | | | | 2.12 | 2.14 |
| | 20 | 20 | | 376.2 | | 30.6 | | 35 | 10.75 | | | | 2.10 | 2.09 |
| | 10 | 30 | | 384.6 | | 37.2 | | 55 | 6.99 | | | | 2.07 | 2.04 |
| $f_{BC}$ 0.33 | 40 | - | | 364.6 | | 25.5 | | 24 | 15.19 | | | | 2.13 | 2.15 |
| | 30 | 10 | | 366.0 | | 26.9 | | 27 | 13.56 | | | | 2.12 | 2.14 |
| | 20 | 20 | | 375.4 | | 30.7 | | 34 | 11.04 | | | | 2.10 | 2.09 |
| | 10 | 30 | | 383.5 | | 36.2 | | 53 | 7.24 | | | | 2.07 | 2.05 |

**Table 5.** Soil layering for different biochar fractions, $f_{BC}$, and main outputs obtained using AQUACROP for the three considered crops. Data refer to a soil-water balance simulation with a "deficit irrigation" management (*DI*).

| Soil Layer | $Z_{DS+BC}$ (mm) | $Z_{DS}$ (cm) | $ET_0$ (mm) | $V_{IRR}$ (mm) | $T$ (mm) | $E$ (mm) | $T/T_{max}$ (-) | $t_{ws}/t_{LCD}$ (-) | $\#IRR$ (-) | $h_{IRR}$ (mm) | $B_{mass}$ (t/ha) | $H_i$ (%) | $Y$ (t/ha) | $WUE$ (kg/m$^3$) | $IWUE$ (kg/m$^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Wheat** | | | | | | | | | | | | | | | |
| *DS* | - | 40 | | | 170.5 | 17.4 | 0.185 | 0.20 | | | 11.1 | 13.2 | 1.5 | 0.76 | 0.77 |
| $f_{BC}$ 0.091 | 40 | - | | | 191.7 | 17.9 | 0.321 | 0.14 | | | 12.3 | 42.3 | 5.2 | 2.41 | 2.74 |
| | 30 | 10 | | | 186.5 | 18.2 | 0.347 | 0.17 | | | 12.0 | 40.1 | 4.8 | 2.28 | 2.53 |
| | 20 | 20 | | | 181.9 | 18.4 | 0.345 | 0.18 | | | 11.7 | 37.2 | 4.4 | 2.11 | 2.30 |
| | 10 | 30 | | | 176.2 | 18.3 | 0.349 | 0.21 | | | 11.4 | 25.7 | 2.9 | 1.46 | 1.54 |
| $f_{BC}$ 0.23 | 40 | - | 299.6 | 190 | 209 | 18.6 | 0.375 | 0.10 | 38 | 5 | 13.2 | 45.9 | 6.0 | 2.57 | 3.18 |
| | 30 | 10 | | | 201.2 | 19.1 | 0.374 | 0.13 | | | 12.8 | 44.8 | 5.7 | 2.52 | 3.01 |
| | 20 | 20 | | | 190.2 | 20.6 | 0.350 | 0.15 | | | 12.2 | 44.2 | 5.4 | 2.48 | 2.85 |
| | 10 | 30 | | | 181.3 | 18.7 | 0.345 | 0.18 | | | 11.7 | 41.3 | 4.8 | 2.33 | 2.54 |
| $f_{BC}$ 0.33 | 40 | - | | | 212 | 18.7 | 0.435 | 0.10 | | | 13.3 | 46.2 | 6.1 | 2.57 | 3.23 |
| | 30 | 10 | | | 202.7 | 19.6 | 0.367 | 0.12 | | | 12.9 | 45.2 | 5.8 | 2.53 | 3.06 |
| | 20 | 20 | | | 192.4 | 20.3 | 0.333 | 0.14 | | | 12.3 | 44.1 | 5.4 | 2.47 | 2.86 |
| | 10 | 30 | | | 182.2 | 19.9 | 0.330 | 0.17 | | | 11.7 | 42.5 | 5.0 | 2.39 | 2.62 |
| **Sorghum** | | | | | | | | | | | | | | | |
| *DS* | - | 40 | | | 171.7 | 37.3 | 0.394 | 0.49 | | | 9.8 | 13.9 | 1.4 | 0.65 | 0.52 |
| $f_{BC}$ 0.091 | 40 | - | | | 226.6 | 32.5 | 0.619 | 0.35 | | | 13.8 | 18.3 | 2.5 | 0.97 | 0.96 |
| | 30 | 10 | | | 223.1 | 32.5 | 0.600 | 0.35 | | | 13.6 | 18.1 | 2.5 | 0.96 | 0.93 |
| | 20 | 20 | | | 217.4 | 33 | 0.609 | 0.37 | | | 13.1 | 18.9 | 2.5 | 0.99 | 0.94 |
| | 10 | 30 | | | 199.9 | 35.4 | 0.592 | 0.39 | | | 11.9 | 18.2 | 2.2 | 0.92 | 0.82 |
| $f_{BC}$ 0.23 | 40 | - | 402.5 | 264 | 245.1 | 35.1 | 0.643 | 0.29 | 33 | 8 | 14.8 | 24.0 | 3.5 | 1.26 | 1.34 |
| | 30 | 10 | | | 236.7 | 35.1 | 0.586 | 0.29 | | | 14.4 | 20.5 | 2.9 | 1.08 | 1.11 |
| | 20 | 20 | | | 228.4 | 35.7 | 0.599 | 0.33 | | | 13.8 | 21.4 | 3.0 | 1.12 | 1.12 |
| | 10 | 30 | | | 208.7 | 36.7 | 0.632 | 0.38 | | | 12.5 | 19.1 | 2.4 | 0.97 | 0.90 |
| $f_{BC}$ 0.33 | 40 | - | | | 248.1 | 36.1 | 0.646 | 0.28 | | | 15.0 | 26.2 | 3.9 | 1.38 | 1.48 |
| | 30 | 10 | | | 239.2 | 36.1 | 0.593 | 0.27 | | | 14.5 | 21.6 | 3.1 | 1.14 | 1.18 |
| | 20 | 20 | | | 228.6 | 36.5 | 0.612 | 0.34 | | | 13.9 | 20.3 | 2.8 | 1.06 | 1.07 |
| | 10 | 30 | | | 209.3 | 36.9 | 0.634 | 0.38 | | | 12.6 | 19.9 | 2.5 | 1.01 | 0.95 |

**Table 5.** *Cont.*

| Soil Layer | $Z_{DS+BC}$ (mm) | $Z_{DS}$ (cm) | $ET_0$ (mm) | $V_{IRR}$ (mm) | $T$ (mm) | $E$ (mm) | $T/T_{max}$ (-) | $t_{ws}/t_{LCD}$ (-) | $\#IRR$ (-) | $h_{IRR}$ (mm) | $B_{mass}$ (t/ha) | $H_i$ (%) | $Y$ (t/ha) | $WUE$ (kg/m$^3$) | $IWUE$ (kg/m$^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Tomato** | | | | | | | | | | | | | | | |
| *DS* | - | 40 | 397.1 | 296 | 273.1 | 24.1 | 0.557 | 0.24 | 37 | 8 | 10.3 | 41.6 | 4.3 | 1.44 | 1.45 |
| $f_{BC}$ 0.091 | 40 | - | | | 292.1 | 25.2 | 0.642 | 0.22 | | | 11.0 | 59.9 | 6.6 | 2.07 | 2.22 |
| | 30 | 10 | | | 286.1 | 23.4 | 0.563 | 0.19 | | | 10.9 | 58.0 | 6.3 | 2.03 | 2.13 |
| | 20 | 20 | | | 280.7 | 23.5 | 0.604 | 0.24 | | | 10.7 | 55.9 | 6.0 | 1.96 | 2.02 |
| | 10 | 30 | | | 276.8 | 23.6 | 0.579 | 0.24 | | | 10.6 | 54.6 | 5.8 | 1.91 | 1.95 |
| $f_{BC}$ 0.23 | 40 | - | | | 305.3 | 26.4 | 0.663 | 0.18 | | | 11.3 | 61.7 | 7.0 | 2.11 | 2.36 |
| | 30 | 10 | | | 295.7 | 24.8 | 0.557 | 0.16 | | | 11.1 | 61.4 | 6.8 | 2.13 | 2.31 |
| | 20 | 20 | | | 287.9 | 24.8 | 0.557 | 0.18 | | | 10.9 | 60.1 | 6.6 | 2.09 | 2.22 |
| | 10 | 30 | | | 279.3 | 24.2 | 0.595 | 0.24 | | | 10.6 | 57.3 | 6.1 | 2.01 | 2.06 |
| $f_{BC}$ 0.33 | 40 | - | | | 306.3 | 26.9 | 0.656 | 0.17 | | | 11.4 | 61.8 | 7.0 | 2.11 | 2.38 |
| | 30 | 10 | | | 297.3 | 25.7 | 0.570 | 0.16 | | | 11.2 | 61.5 | 6.9 | 2.13 | 2.33 |
| | 20 | 20 | | | 288.6 | 25.7 | 0.563 | 0.18 | | | 10.9 | 60.5 | 6.6 | 2.1 | 2.23 |
| | 10 | 30 | | | 279.7 | 24.4 | 0.598 | 0.24 | | | 10.7 | 57.7 | 6.2 | 2.02 | 2.08 |

## 4. Conclusions

This investigation showed that the application of biochar to a desert sand for three crops, i.e., wheat, sorghum and tomato, positively affected the soil water balance and the irrigation scheduling simulated by the AQUACROP model, using as input accurately measured soil hydraulic parameters representing the physical and structural condition of the soil without and with *BC* addition.

The results indicated that the application of biochar could be proposed as a strategy mitigating water and energy saving consumptions when no water stress conditions were considered, in order to obtain the maximum crop yield. Wheat was the crop showing the maximum benefits from biochar application in terms of reduction in the amount of irrigation volume, of increase in the irrigation water use efficiency and of decrease in the number of predicted irrigations. Biochar showed beneficial effects also for sorghum and tomato but to a lesser extent than for wheat.

When a deficit irrigation was simulated, the application of biochar counterbalanced the lower amount of irrigation volume supplied under deficit irrigation, partially mitigating the crop yield reduction due to the water stress conditions, especially for wheat and for tomato, with a less pronounced effect for sorghum. Under deficit irrigation, the application of biochar could also be a useful management option to promote the cultivation of wheat and tomato in the UAE, as well as in other countries with similar climatic and soil conditions. This could help to increase the local production, thus reducing the impact of water shortage on food security and the dependency on food import.

**Author Contributions:** Conceptualization, G.B., M.M. and G.C.; methodology, G.B., M.M. and G.C.; validation, G.B., M.M. and G.C.; investigation, G.B., M.M. and G.C.; data curation, G.B. and M.M.; writing—original draft preparation, G.B., M.M. and G.C.; writing—review and editing, G.B. and G.C.; visualization, G.B.; supervision, G.B. and G.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Acknowledgments:** The authors wish to thank Mushtaque Ahmed, Sultan Qaboos University|SQU Department of Soils, Water and Agricultural Engineering, for providing climatic data of the Al Buraimi weather station.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. . Available online: FAO. *The State of the World's Land and Water Resources: Managing Systems at Risk*; Earthscan: London, UK, 2011. Available online: http://www.fao.org/docrep/017/i1688e/i1688e.pdf (accessed on 31 December 2011).
2. WWAP. UNESCO World Water Assessment Programme. The United Nations World Water Development Report 2020: Water and Climate Change. Available online: https://unesdoc.unesco.org/ark:/48223/pf0000372985.locale=en (accessed on 1 July 2020).

3. WRG. 2009 Charting Our Water Future. Economic Frameworks to Inform Decision-Making. The 2030 Water Resources Group. Available online: https://www.2030wrg.org/wp-content/uploads/2012/06/Charting_Our_Water_Future_Final.pdf (accessed on 31 December 2009).
4. FAO. *The State of Food Insecurity in the World, 2008*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2008.
5. Cook, S.; Gichuki, F.; Turral, H. *Estimation at Plot, Farm and Basin Scale. International Water Management Institute (IWMI)*; Basin Focal Project Working Paper No. 2; Challenge Program Secretariat: Colombo, Sri Lanka, 2006.
6. English, M.J.; Musick, J.T.; Murty, V.V. Deficit irrigation. In *Management of Farm Irrigation Systems*; Hoffman, G.J., Towell, T.A., Solomon, K.H., Eds.; ASAE: St. Joseph, MI, USA, 1990.
7. Akhtar, S.S.; Li, G.; Andersen, M.N.; Liu, F. Biochar enhances yield and quality of tomato under reduced irrigation. *Agric. Water Manag.* **2014**, *138*, 37–44. [CrossRef]
8. Baiamonte, G. Explicit Relationships for Optimal Designing of Rectangular Microirrigation Units on Uniform Slopes: The IRRILAB Software Application. *Comput. Electron. Agric.* **2018**, *153*, 151–168. [CrossRef]
9. Pereira, L.S.; Oweis, T.; Zairi, A. Irrigation management under water scarcity. *Agric. Water Manag.* **2002**, *57*, 175–206. [CrossRef]
10. Fereres, E.; Soriano, M.A. Deficit irrigation for reducing agricultural water use. *J. Exp. Bot.* **2007**, *58*, 147–159. [CrossRef]
11. Feddes, R.A.; Kowalik, P.J.; Zaradny, H. *Simulation of Field Water Use and Crop Yield*; Pudoc (Centre for Agricultural Publishing and Documentation): Wageningen, The Netherlands, 1978; 189p.
12. van Dam, J.C.; Huygen, J.; Wesseling, J.G.; Feddes, R.A.; Kabat, P.; van Walsum, P.E.V.; Groenendijk, P.; van Diepen, C.A. *Theory of SWAP Version 2.0. Simulation of Water Flow, Solute Transport and Plant Growth in the Soil-Water-Atmosphere-Plant Environment*; Technical Document 45; Wageningen Agricultural University and DLO Winand Staring Centre: Wageningen, The Netherlands, 1997.
13. Droogers, P.; Bastiaanssen, W.G.M.; Beyazgul, M.; Kayam, Y.; Kite, G.W.; Murray-Rust, H. Distributed agro-hydrological modeling of an irrigation system in western Turkey. *Agric. Water Manag.* **2000**, *43*, 183–202. [CrossRef]
14. Bastiaanssen, W.G.M.; Allen, R.G.; Droogers, P.; D'Urso, G.; Steduto, P. Inserting man's irrigation and drainage wisdom into soil water flow models and bringing it back out: How far have we progressed? In *Unsaturated-Zone Modeling: Progress, Challenges and Applications*; Feddes, R.A., de Rooij, G.H., van Dam, J.C., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherland, 2004; pp. 263–299.
15. Vanclooster, M.; Viane, P.; Diels, J.; Christiens, K. *WAVE: A Mathematical Model for Simulating Water and Agrochemicals in the Soil and Vadose Environment: Reference and User's Manual (release 2.0)*; Institute for Land and Water Management, Katholieke Universiteit Leuven: Leuven, Belgium, 1994.
16. Ragab, R. A holistic generic integrated approach for irrigation, crop and field management: The SALTMED model. *Environ. Model. Softw.* **2002**, *17*, 345–361. [CrossRef]
17. Crescimanno, G.; Garofalo, P. Management scenarios optimizing irrigation with saline water in cracking clay soils. *Soil Sci. Soc. Am. J.* **2006**, *70*, 1774–1787. [CrossRef]
18. Liu, J.; Wiberg, D.; Zehnder, A.; Yang, H. Modeling the role of irrigation in winter wheat yield crop water productivity, and production in china. *Irrig. Sci.* **2007**, *26*, 21–23. [CrossRef]
19. Pereira, L.S.; Allen, R.G.; Smith, M.; Raes, D. Crop evapotranspiration estimation with FAO56: Past and future. *Agric. Water Manag.* **2015**, *147*, 4–20. [CrossRef]
20. Steduto, P.; Hsiao, T.C.; Raes, D.; Fereres, E. AquaCrop—The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agron. J.* **2009**, *101*, 426–437. [CrossRef]
21. Raes, D.; Steduto, P.; Hsiao, T.C.; Fereres, E. AquaCrop-The FAO crop model to simulate yield response to water: II. Main algorithms and software description. *Agron. J.* **2009**, *101*, 438–447. [CrossRef]
22. Tanner, C.B.; Sinclair, T.R. Efficient water use in crop production: Research or re-search. In *Limitations to Efficient Water Use in Crop Production*; Taylor, H.M., Jordan, W.R., Sinclair, T.R., Eds.; American Society of Agronomy: Madison, WI, USA, 1983; pp. 1–28.
23. Steduto, P.; Albrizio, R. Resource use efficiency of field-grown sunflower, sorghum, wheat and chickpea: II. Water use efficiency and comparison with radiation use efficiency. *Agric. For. Meteorol.* **2005**, *130*, 269–281. [CrossRef]
24. Steduto, P.; Hsiao, T.C.; Fereres, E. On the conservative behavior of biomass water productivity. *Irrig. Sci.* **2007**, *25*, 189–207. [CrossRef]

25. Wellens, J.; Raes, D.; Tychon, B. On the use of decision-support tools for improved irrigation management: AquaCrop-Based applications. In *Current Perspective on Irrigation and Drainage*; Kulshreshtha, S., Elshorbagy, A., Eds.; Books on Demand: Pasig, Philippines, 2017. [CrossRef]
26. Jin, X.-L.; Feng, H.-K.; Zhu, X.-K.; Li, Z.-H.; Song, S.-N.; Song, X.-Y. Assessment of the AquaCrop Model for Use in Simulation of Irrigated Winter Wheat Canopy Cover, Biomass, and Grain Yield in the North China Plain. *PLoS ONE* **2014**, *9*, e86938. [CrossRef]
27. Rezaverdinejad, V.; Khorsand, A.; Shahidi, A. Evaluation and comparison of aquacrop and FAO models for yield prediction of winter wheat under environmental stresses. *J. Biodivers. Environ. Sci.* **2014**, *4*, 438–449.
28. Bird, D.N.; Benabdallah, S.; Gouda, N.; Hummel, F.; Koeberl, J.; Jeunesse, I.L.; Meyer, S.; Prettenthaler, F.; Soddu, A.; Susanne, W.G. Modelling climate change impacts on and adaptation strategies for agriculture in Sardinia and Tunisia using AquaCrop and value-at-risk. *Sci. Total Environ.* **2016**, *543*, 1019–1027. [CrossRef]
29. Toumi, J.; Er-Raki, S.; Ezzahar, J.; Khabba, S.; Jarlan, L.; Chehbouni, A. Performance assessment of AquaCrop model for estimating evapotranspiration, soil water content and grain yield of winter wheat in Tensift Al Haouz (Morocco): Application to irrigation management. *Agric. Water Manag.* **2016**, *163*, 219–235. [CrossRef]
30. Abedinpour, M.; Sarangi, A.; Rajput, T.B.S.; Singh, M.; Pathak, H.; Ahmad, T. Performance evaluation of AquaCrop model for maize crop in a semi-arid environment. *Agric. Water Manag.* **2012**, *110*, 55–66. [CrossRef]
31. Javier Garcia, A.; Fischer, G.; Nestor Riaño, H. Effect of fertilization level onwater use and production of corn (*Zea mays* L.) in a cereal producing area in Colombia—A modeling exercise using AquaCrop-FAO. *Agron. Colomb.* **2017**, *35*, 68–74. [CrossRef]
32. Salemi, H.; Soom, M.A.M.; Mousavi, S.F.; Ganji, A.; Lee, H.; Yusoff, M.K.; Verdinejad, V.R. Irrigated Silage Maize Yield and Water Productivity Response to Deficit Irrigation in an Arid Region. *Pol. J. Environ. Stud.* **2011**, *20*, 1295–1303.
33. Darko, R.O.; Shouqi, Y.; Haofang, Y.; Junping, L.; Abbey, A. Calibration and validation of AquaCrop for deficit and full irrigation of tomato. *Int. J. Agric. Biol. Eng.* **2016**, *9*, 104–110.
34. Rinaldi, M.; Garofalo, P.; Rubino, P.; Steduto, P. Processing tomatoes under different irrigation regimes in Southern Italy: Agronomic and economic assessments in a simulation case study. *Ital. J. Agrometeorol.* **2011**, *3*, 39–56.
35. Hussein, F.; Janat, M.; Yakoub, A. Simulating cotton yield response to deficit irrigation with the FAO AquaCrop model. *Span. J. Agric. Res.* **2011**, *9*, 1319–1330. [CrossRef]
36. Pawar, G.S.; Kale, M.U.; Lokhande, J.N. Response of AquaCrop Model to Different Irrigation Schedules. *Agric. Res.* **2017**, *6*, 73–81. [CrossRef]
37. Montoya, F.; Camargo, D.; Ortega, J.F.; Córcoles, J.I.; Domínguez, A.; Clothier, B.E. Evaluation of Aquacrop model for a potato crop under different irrigation conditions. *Agric. Water Manag.* **2016**, *164*, 267–280. [CrossRef]
38. Geerts, S.; Raes, D.; Garcia, M. Using AquaCrop to derive deficit irrigation schedules. *Agric. Water Manag.* **2010**, *98*, 213–216. [CrossRef]
39. Todorovic, M.; Albrizio, R.; Zivotic, L.; Abi Saab, M.T.; Stöckle, C.; Steduto, P. Assessment of AquaCrop, CropSyst, and WOFOST models in the simulation of sunflower growth under different water regimes. *Agron. J.* **2009**, *101*, 509–521. [CrossRef]
40. Stričević, R.; Dželetović, Z.; Djurović, N.; Cosić, M. Application of the AquaCrop model to simulate the biomass of Miscanthus x giganteus under different nutrient supply conditions. *GCB Bioenergy* **2015**, *7*, 1203–1210. [CrossRef]
41. Mwangi, P.; Karanja, F.; Mwende, J.; Ogara, W. Application of Aquacrop Model for Sorghum Yield Projections and Scenarios Development under Rainfed Farming at Wiyumiririe Laikipia County, Kenya. *East Afr. Sch. J. Agric. Life Sci.* **2019**, *2*, 420–432.
42. Country Reports. The State of Oman's Biodiversity for Food and Agriculture. Available online: http://www.fao.org/3/CA3513EN/ca3513en.pdf (accessed on 1 July 2020).
43. McHenry, M. Agricultural bio-char production, renewable energy generation and farm carbon sequestration in Western Australia: Certainty, uncertainty and risk. *Agric. Ecosyst. Environ.* **2009**, *129*, 1–7. [CrossRef]
44. Busscher, W.I.; Novak, J.M.; Evans, D.E.; Watts, D.W.; Niandou, M.A.S.; Ahmedna, M. Influence of pecan biochar on physical properties of a Norfolk loamy sand. *Soil Sci.* **2010**, *175*, 10–14. [CrossRef]

45. Basso, A.S.; Miguez, F.E.; Laird, D.A.; Horton, R.; Westgate, M. Assessing potential of biochar for increasing water holding capacity of sandy soils. *GCB Bioenergy* **2013**, *5*, 132–143. [CrossRef]
46. Saifullah, S.D.; Naeem, A.; Rengel, Z.; Naidu, R. Biochar application for the remediation of salt-affected soils: Challenges and opportunities. *Sci. Total Environ.* **2018**, *625*, 320–335. [CrossRef]
47. Sehgal, J.; Abrol, I.P. *Soil Degradation in India: Status and Impact*; Oxford and IBH: New Delhi, India, 1994.
48. Karbout, N.; Gasmi, I.; Moussa, M.; Bousnina, H. Effect of clay amendment on the conservation of moisture in sandy soils of South East Tunisia. *J. Res. Environ. Earth Sci.* **2016**, *4*, 125–131.
49. Alotaibi, K.D.; Schoenau, J.J. Addition of Biochar to a Sandy Desert Soil: Effect on Crop Growth, Water Retention and Selected Properties. *Agronomy* **2019**, *9*, 327. [CrossRef]
50. Lesschen, J.P.; Kok, K.; Verburg, P.H.; Cammeraat, L.H. Identification of vulnerable areas for gully erosion under different scenarios of land abandonment in Southeast. *Catena* **2007**, *71*, 110–121. [CrossRef]
51. Baiamonte, G.; Crescimanno, G.; Parrino, F.; De Pasquale, C. Effect of biochar on the physical and structural properties of a desert sandy soil. *Catena* **2019**, *175*, 294–303. [CrossRef]
52. Downie, A.; Crosky, A.; Munroe, P. Physical properties of biochar. In *Biochar for Environmental Management: Science and Technology*; Lehmann, J., Joseph, S., Eds.; Earthscan: London, UK, 2009.
53. Assi, A.T.; Blake, J.; Mohtar, R.H.; Braudeau, E. Soil aggregates structure-based approach for quantifying the field capacity, permanent wilting point and available water capacity. *Irrig. Sci.* **2019**, *37*, 511–522. [CrossRef]
54. Braudeau, E.F.; Assi, A.T.; Boukcim, H.; Mohtar, R.H. Physics of the soil medium organization part 1: Thermodynamic formulation of the pedostructure water retention and shrinkage curves. *Front. Environ. Sci.* **2014**, *2*, 4. [CrossRef]
55. Brantley, S.L.; Mellott, N.P. Surface area and porosity of primary silicate minerals. *Am. Mineral.* **2000**, *85*, 1767–1783. [CrossRef]
56. Soil Survey Staff. *Soil Survey Manual*; U.S. Dept. Agriculture Handbook No. 18; Lulu Press: Morrisville, NC, USA, 1951; 503p.
57. Soil Survey Staff. *Keys to Soil Taxonomy*, 8th ed.; SMSS Technical Monograph N. 19; Pocahontas Press Inc.: Blackbourg, VA, USA, 1992; 556p.
58. Hsiao, T.C.; Heng, L.; Steduto, P.; Rojas-Lara, B.; Raes, D.; Fereres, E. AquaCrop-The FAO crop model to simulate yield response to water: III. Parameterization and testing for maize. *Agron. J.* **2009**, *101*, 448–459. [CrossRef]
59. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration*; FAO Irrigation and Drainage Paper 56; Food and Agricultural Organization of the United Nations: Rome, Italy, 1998; 300p.
60. Allen, R.G.; Wright, J.L.; Pruitt, W.O.; Pereira, L.S.; Jensen, M.E. Water requirements. In *Design and Operation of Farm Irrigation Systems*, 2nd ed.; Hoffman, G.J., Evans, R.G., Jensen, M.E., Martin, D.L., Elliot, R.L., Eds.; ASABE: St. Joseph, MI, USA, 2007; pp. 208–288.
61. Liu, Y.; Pereira, L.S.; Fernando, R.M. Fluxes through the bottom boundary of the root zone in silty soils: Parametric approaches to estimate groundwater contribution and percolation. *Agric. Water Manag.* **2006**, *84*, 27–40. [CrossRef]
62. Baiamonte, G.; Singh, V.P. Overland Flow Times of Concentration for Hillslopes of Complex Topography. *J. Irrig. Drain. E-ASCE* **2016**, *142*, 04015059. [CrossRef]
63. Cullotta, S.; Bagarello, V.; Baiamonte, G.; Gugliuzza, G.; Iovino, M.; La Mela Veca, D.S.; Maetzke, F.; Palmeri, V.; Sferlazza, S. Comparing different methods to determine soil physical quality in a Mediterranean forest and pasture land. *Soil Sci. Soc. Am. J.* **2016**, *80*, 1038–1056. [CrossRef]
64. Baiamonte, G.; Bagarello, V.; D'Asaro, F.; Palmeri, V. Factors influencing point measurement of near-surface saturated soil hydraulic conductivity in a small Sicilian basin. *Land Degrad. Dev.* **2017**, *28*, 970–982. [CrossRef]
65. Baiamonte, G. SCS—Curve Number & Green-Ampt infiltration models. *J. Hydrol. E-ASCE* **2019**, *24*, 04019034. [CrossRef]
66. Allen, R.G.; Pereira, L.S.; Smith, M.; Raes, D.; Wright, J.L. FAO-56 Dual crop coefficient method for estimating evaporation from soil and application extensions. *J. Irrig. Drain. Eng.* **2005**, *131*, 2–13. [CrossRef]
67. Raes, D.; Steduto, P.; Hsiao, T.C.; Fereres, E. Reference Manual AquaCrop (Version 4.0). 2012. Available online: http://www.fao.org/nr/water/aquacrop.html (accessed on 31 December 2013).
68. Ali, H.G.; Alkhamisi, S.A.; Nadaf, S.K.; Al-Bakri, A.N. Forage Productivity of Three Introduced Sorghum × Sudan grass Hybrids under Irrigation in three Arid Areas in Oman Jordan. *J. Agric. Sci.* **2014**, *10*, 716–724.

69. Pierson, F.B.; Mulla, D.J. An improved method for measuring aggregate stability of a weakly aggregated loessial soil. *Soil Sci. Soc. Am. J.* **1989**, *53*, 1825–1831. [CrossRef]
70. Crescimanno, C.; Provenzano, G.; Iovino, M. Influence of Salinity and Sodicity on Soil Structural and Hydraulic Characteristics. *Soil Sci. Soc. Am. J.* **1995**, *59*, 1701–1708. [CrossRef]
71. ADFCA. Abu Dhabi Food Control Authority. Available online: https://gulfnews.com/uae/environment/abu-dhabi-explores-wheat-cultivation-in-the-emirate-1.1136891 (accessed on 31 December 2013).
72. Moiwo, J.P.; Wahab, A.; Kangoma, E.; Blango, M.M.; Ngegba, M.P.; Suluku, R. Article Effect of Biochar Application Depth on Crop Productivity Under Tropical Rainfed Conditions. *Appl. Sci.* **2019**, *9*, 2602. [CrossRef]
73. Baiamonte, G. Advances in designing drip irrigation laterals. *Agric. Water Manag.* **2018**, *199*, 157–174. [CrossRef]
74. ICBA. On-Farm Biochar Production System. International Center for Biosaline Agriculture. 2016. Dubai. Available online: https://www.biosaline.org/sites/default/files/technology_innovation_biochar_production_system_web.pdf (accessed on 31 December 2016).
75. Jouiad, M.; Al-Nofelib, N.; Khalifab, N.; Benyettouc, F.; Yousef, L.F. Characteristics of slow pyrolysis biochars produced from rhodes grassand fronds of edible date palm. *J. Anal. Appl. Pyrolysis* **2015**, *111*, 183–190. [CrossRef]
76. Fischer, B.M.C.; Manzoni, S.; Morillas, L.; Garcia, M.; Johnson, M.S.; Lyon, S.W. Improving agricultural water use efficiency with biochar—A synthesis of biochar effects on water storage and fluxes across scales. *Sci. Total Environ.* **2019**, *657*, 853–862. [CrossRef]
77. Bagheri, S.; Hassandokht, M.R.; Mirsoleiman, A.; Mousavi, A. Effects of Palm Leaf Biochar on the Availability of Soil Nutrients, Leaf Nutrient Concentration, and Physiological Characteristics of Melon Plants (*Cucumis melo* L.) Under Drought Stress. *Acta Agrobot.* **2020**, *73*, 7311. [CrossRef]