Sustainability of Irrigating Winter Wheat in the East of England—Adaptation at What Cost?

Daniel El Chami and André Daccache

Abstract: Climate change is "the challenge" of our times and for the next upcoming decades. The biggest impacts are likely to affect the sustainability of agricultural and food systems; both highly vulnerable to continuously changing climatic patterns. Wheat is a strategic crop for food security. It is widely grown worldwide as a rainfed (unirrigated) crop; but the latest research shows that recent world wheat price increases and increasing weather variability are making supplemental irrigation marginally profitable. The proposed study combines the outputs from a general circulation model (GCM), the Food and Agriculture Organization of the United Nations (FAO) crop growth model (AquaCrop), and economic modelling to assess the sustainability of irrigated wheat production compared to rainfed crop production both under current climate conditions and in the future under different climate scenarios. The AquaCrop model has been calibrated and validated for winter wheat grown on a sandy loam soil in the East of England (Bedfordshire). Long-term observed climate data (1970–2006) in Cambridge (Cambridgeshire) were used to validate the projected climate data from the GCM. Structural characteristics of the case study were representative of a typical farm of the area, and irrigation costs and wheat prices for the economic model were calculated assuming current market prices. In the longer term, a sensitivity analysis was used to assess the expected variations due to the increase in world wheat prices and the energy costs involved. Results of the study show that the impacts of climate change on winter wheat grown in the East of England would be a reduction in the rainfed yield (between -5.4% and -32.9%) and that the projected economic losses from rainfed winter wheat production would be expected to range between -24.3% and -36.0%. Irrigation, which does not seem to be an economic option under the current climate conditions, could be a future adaptation measure for yield increase (3.9–6.1 $\text{t}\cdot\text{ha}^{-1}$) and to improve the financial appraisal of irrigation investment, which would raise between 41 and 519 $£\cdot\text{ha}^{-1}$. However, negative externalities are increasing pressures on water and air resources, for example, an increase of the irrigation water requirements between 25.0% an 39.1% and global warming potential increases between 2.5% and 21.5%. Finally, the study suggests further research to incorporate a life cycle assessment model into the framework for an integrated and comprehensive approach for sustainability assessment of wheat in particular and agricultural systems in general.

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1. Introduction

The sustainability of world agricultural and food systems is highly endangered by the impacts of climate warming due to the high vulnerability of these systems to continuously changing climatic patterns [1] (p. 976). At the global scale, climate impacts are expected to further decrease world crop yields [2]. However, heterogeneous results are expected at regional levels due to local variations in agro-climatic conditions [3].

Wheat is the most important crop grown worldwide for food provision and feed for livestock [4,5]. Given its high adaptability to different climate conditions, it is grown under very diverse agro-climates extending from Russia to the tropics and sub-tropics [6]. In many areas, wheat is grown as a rainfed crop, but irrigation occurs in some areas such as sub-tropics [7].

Literature on the impacts of climate change on wheat production is abundant but contradictory. Parry et al. [2] adopted statistical analyses to derive agro-climatic regional yield transfer functions from site-level results under different Special Report on Emission Scenarios (SRES) and showed that wheat, amongst other cereal crops (wheat, rice maize, and soybean), is subject to potential yield changes at global levels, which would expose the global food security to high risks and result in security consequences [8]. Contrarily, Wilcox and Makowski [9] contradicted the previous results showing in a meta-analysis that the effects of high CO_2 concentrations would outweigh the effects of increasing temperature and the decline in precipitation leading to increasing yields depending on the geographical location. However, Supit et al. [10] used outputs from three general circulation models (GCMs) and a crop growth monitoring system in combination with a weather generator to demonstrate that crops planted in autumn and winter, such as winter wheat in Europe, may benefit from the increasing CO_2 concentration in the short run, but if the CO_2 increase lessens or stagnates, yield reductions may occur after 2050.

At localized levels, literature assessing the impacts of climate change on wheat crop tackled single aspects (e.g., impact on yield and/or water use) and results are site-specific [11–13]. However, Falloon and Betts [14] recommended an integrated approach to deal with climate change research, which is lacking so far.

Therefore, the aim of this study is to assess the sustainability of winter wheat production at the farm level, adopting irrigation for adaptation to climate change in a typical temperate climate in the East of England (UK). It will adopt an integrated modelling approach to estimate potential trade-offs between water savings, energy consumption (greenhouse gas (GHG) emissions), and economic benefits under current and future climate scenarios. This integrated approach makes a significant contribution to the carbon accounting of crop production in general and the impacts of intensification through irrigation in particular, and it could be easily replicated with different case studies and other crops.

2. Material and Methods

The study was divided into the following stages:

1. Defining a typical wheat-growing farm for modelling assessment.
2. Selecting the baseline climate data from a local weather station and downscaling the data according to different scenarios.
3. Quantifying the irrigation water requirements (depths applied) under current climate conditions and estimating the yield response and yield benefits from irrigation.
4. Assessing sustainability of the rainfed and irrigated winter wheat using a selection of financial, environmental, and social indicators under current climate conditions and future scenarios.
5. Undertaking a sensitivity analysis to assess the effects of variation in costs and market prices.

2.1. Selection of a "Typical" Farm

The case study farm was selected to reflect the regional farm characteristics in the East of England (Table 1). Therefore, we assumed that the farm was 200 ha, practicing rotational agriculture with winter wheat occupying 50 ha annually. The on-farm irrigation system was a hose reel fitted with either a raingun or boom, the most common method of irrigation in the UK according to Department for Environment, Food and Rural Affairs (DEFRA) [15], using an all year abstraction license from a nearby river and a diesel pump. We modelled irrigation needs assuming a deep uniform sandy loam soil, with a soil depth of 4 m and a total available water of 120 mm/m, as irrigation in England is more likely to be used on the lighter, droughtier soils (e.g., [16]); we considered, however, a deep uniform silty clay loam soil with a depth of 4 m and a total available water of 210 mm/m, which is a heavier soil given that most wheat is currently grown on heavier soils.

Table 1. Wheat production summary statistics for England and the East of England for 2011 [17,18].

Indicator	England	East of England	East of England/England (%)
Farmed area ($\times 10^6$ ha) *	8.89	1.38	15.5
Total number of farms *	53,090	8147	15.0
Wheat area ($\times 10^6$ ha) *	1.79	0.50	28.0
Wheat yield ($t \cdot ha^{-1}$)	7.73	7.21	93.3
Average farm size (ha) *	153.3	195.4	127.5
Wheat production (Mt)	13.8	3.6	26.1
Wheat output (Million £)	1984.64	573.51	28.9
Total crop output (Million £)	7724.42	1,979.58	25.6

* Data relates to 2010.

2.2. *Climate Data and Climate Scenarios*

The observed climate dataset used in this study was daily data (1970 to 2006) from a meteorological weather station located at Cambridge, Cambridgeshire (52.24° N, 0.10° W). Data included rainfall, reference evapotranspiration (ET_0), and maximum and minimum temperature for the historical baseline period (Figure 1).

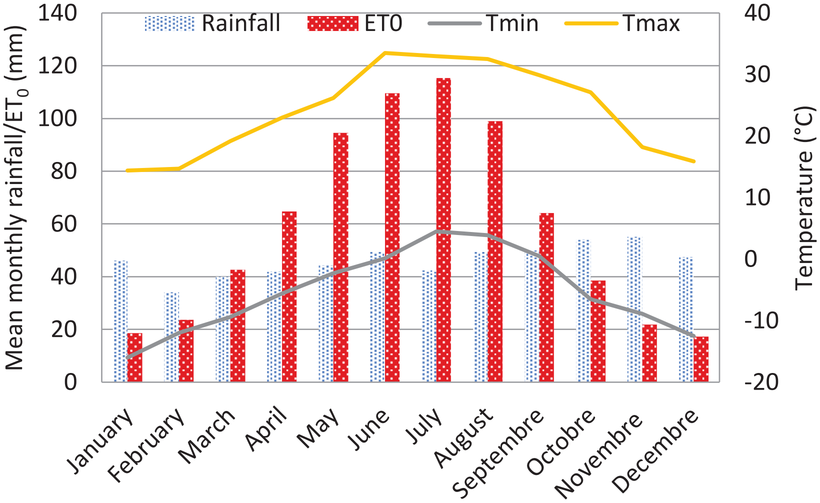

Figure 1. Monthly observed climate dataset at Cambridge.

To generate the future weather dataset, a LARS-WG stochastic weather generator was used [19,20] to produce daily weather from GCM outputs at a single site. The HadCM3 was chosen for this study since it was one of the major GCMs used in the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report [21], and has been widely used in the literature for climate impacts assessment (e.g., [22,23]).

The emissions scenarios used are those developed by the IPCC [24] and known as SRES (Special Report on Emission Scenarios), in which each scenario combines two sets of divergent tendencies: one set varies between strong economic values and strong environmental values, the other set between increasing globalization and increasing regionalization [25]. The scenarios are commonly known as A1 (economic-global), B1 (environmental-global), A2 (economic-regional), and B2 (environmental-regional). For this research A1 and B1 emissions scenarios were used; both are characterized by a rapid economic growth and a global population that reaches nine billion in 2050 and then gradually declines. The A1 scenario characterizes a future with energy technology balanced between fossil and non-fossil fuel, whilst the B1 scenario reflects global efforts to control GHG emissions through the introduction of clean and resource-efficient technologies (Table 2).

Table 2. Characteristics of climate change scenarios for the 2050s (A1 and B1) according to selected scenarios of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) [25].

Characteristics	IPCC Scenarios	
	Scenario A1	Scenario B1
Population growth (billion)	8.7 (Low)	8.7 (Low)
World GDP (10^{12} 1990 USD/yr)	164–187 (Very High)	136 (High)
Energy use (10^{18} J/yr)	1213–1431 (Very High)	813 (Low)
Global CO_2 emissions (GtC)	13.5 (Medium)	4.2 (Low)
Land-use changes	Low	High
Resource availability	Medium–High	Low
Technological change	High	Medium
Change favoring	Coal-Balanced Non-Fossils	Efficiency and Dematerialization

2.3. Irrigation Water Requirements (IWR) and Yield Response

The historical baseline and downscaled future climate datasets for Cambridge were used as inputs for the crop growth modelling. The Food and Agriculture Organization of the United Nations (FAO) crop model AquaCrop was used to simulate potential yield as a function of water consumption. AquaCrop has been previously tested under similar climate conditions (e.g., [26,27]). Further, El Chami et al. [26] have calibrated and validated AquaCrop for winter wheat crop in the East of England against experimental yield data obtained from the Broadbalk wheat experiment at Rothamsted Experimental Research Station (Harpenden, UK).

In this study, the same irrigation schedule adopted by El Chami et al. [28] was set (irrigation period between 1 April and 1 June applying 25 mm at a 50 mm soil moisture deficit), to maintain a small deficit in the rootzone to maximize the effective use for rainfall. Indeed, under typical UK climate conditions, irrigation on winter wheat is not generally needed before April, and should stop before the beginning of June with the initiation of flowering [29,30]. Furthermore, experimental studies in the East of England in the 1990s showed that irrigation on cereals after flowering would increase the risk of logging [31].

2.4. Sustainability Assessment

To date, considerable efforts have been made to identify appropriate indicators for agricultural sustainability [32,33], because indicators are one of two basic approaches to sustainability assessment [30]. Indicators can be divided into the multi-dimensional components of sustainability (economic, environmental, and social).

To evaluate the economic efficiency of winter wheat production, a cost-benefit analysis (CBA) was a key component of the integrated framework for the financial investment appraisal (FIA) of different options. The net present values (NPVs) were calculated to assess the economic viability over the life cycle of the project. Other economic indicators were also selected for this same purpose: the internal rate of returns (IRRs) to measure the capacity of the net revenues to remunerate the investment cost, and the benefit-cost ratios (BCRs) to summarize the relative size of the present benefits with respect to the present costs.

To estimate the economic model parameters, we consider a six-year average wheat price (2007–2012) as reported by Home-Grown Cereal Authority (HGCA) [34] for milling wheat. The production costs of the typical rainfed winter wheat farm in the UK are based on an integration of figures for the 2012 harvest year from Agro Business Consultants (ABC) [35] and from survey data from Nix [36]. The abstraction charge calculations are based on Environment Agency charges for 2013/14 [37]. The capital cost of the irrigation system calculations are based on updated market figures for similar equipment from a major local equipment supplier (Briggs Irrigation UK), whilst the variable elements of irrigation costs (labor, fuel, machinery) are based on an updated analysis of detailed irrigation costs by Morris et al. [38].

The social cost of carbon (SCC) was also calculated. It is defined as the estimated price of the damages caused by each additional ton of carbon dioxide (CO_2) released into the atmosphere [39], accounting also for the other GHG using carbon dioxide equivalents. The social cost of irrigation systems was included in the appraisal converting the volume of diesel used in the operation into global warming potential (GWP) [40] and multiplying it by a ten-year average of non-tradable prices of carbon obtained from Department of Energy & Climate Change (DECC) [41]; the average of the baseline was from 2008 to 2017 and the projected average of the future scenarios was from 2041 to 2050.

A selection of water related indicators and CO_2 emission indicators were used to assess the environmental effectiveness of wheat production on water and air resources. The first indicator is the GWP (tCO_2e per hectare) defined as a unit of measurement that allows the effect of different GHGs and other factors to be compared using CO_2 as a standard unit of reference. Three water related indicators were selected according to the data available to calculate them: (1) the surface water withdrawals (WWs), which in this case is the volume of irrigation water applied on the farm per unit area. This has been introduced by FAO as a key environmental integrity indicator of water resources [32] and it could be a good indicator to compare the water savings per hectare between different on-farm practices. (2) The irrigation use efficiency (IUE) used in the literature as an indicator to maximize water productivity and sustainably allocate resources [42] and defined in our case as the ratio of yield increment ($t{\cdot}ha^{-1}$) due to the irrigation water requirement ($m^3{\cdot}ha^{-1}$). (3) The added value of water (AVW), which is the extra benefit of irrigation generated per unit volume of water which shows in economic terms how water contributes to the production value.

To assess the social dimension in this research, we adopted the food security indicator classified under the safety indicators described by the FAO [30], which could support shocks and increase human well-being. In this case, food security was measured through the yield increase (YI). It is also to be noted that income increase could also be considered as a social indicator, because the extra money generated could be spent on farmers' well-being.

2.5. Sensitivity Analysis

Whilst analysts ascribe the current drop in oil prices to political drivers and objectives [43] similar to those described by Stevens [44,45] behind the non-regulation of the supply curve to reach a Pareto optimal price, oil prices are, however, expected to continue their upward trend. Previous estimates suggest that the price of oil is expected to rise by up to 60% by 2035 with prices of USD 250 per barrel forecasted [46]. This affects farmers, because fuel price is one of the major factors influencing operating costs for irrigated crops [47]. Further, the cereal price index has been generally increasing since 2000 and prices by 2022 are projected to be between 12% and 27% above those of the previous decade [48–51]. Therefore, a sensitivity analysis was carried out to find out how the added value of winter wheat would respond to price fluctuations and variations in the total costs of production.

3. Results and Discussion

This section first describes the results of simulated yields and the irrigation water requirements, then the sustainability indicators will be assessed for rainfed and irrigated production in different soils for the baseline climate and under different scenarios. Finally, the sensitivity analysis will estimate the variation of the indicators for wheat price change and for oil prices.

3.1. Yields and IWR Estimates

Under current climate conditions (baseline scenario), the results show that rainfed winter wheat crops grown on lighter soils (sandy loam) produce 14% less yield than heavier ones (silty clay loam). The results partially agree with He et al. [52] who showed that heavier soils have higher water use (WU), hence, wheat grown on lighter soil textures have good growth and high yields providing there is sufficient summer rains to replenish soil water.

In the future, rainfed yield is expected to be negatively affected by climate warming (between −5.4% and −32.9% depending on the scenario and the soil type) (Figure 2), which confirms the findings of Semenov and Shewry [53] who warned that a warming climate would have negative impacts on UK wheat; it endorses as well the results of other studies in similar climate conditions expecting negative impacts of climate change on winter wheat (e.g., [3,54]). Conversely, the results contradict the conclusions of Richter and Semenov [55], who predicted a yield increase for winter wheat of 15%–23% by the 2050s. This could be due, according to Kersebaum and Nendel [54], to site-specific conditions, as they noted a difference in simulated yield even within regions as site conditions had a strong influence on crop growth.

It should be noted that the yield variability of rainfed winter wheat under climate change scenarios is higher than the baseline scenarios (±2.4 for sandy loam soil and ±1.2 for silty clay loam soil), which has been abundantly stressed in the literature (e.g., [56,57]). However, irrigation (as discussed in the introduction) could be an efficient technique for adaptation to climate change as it reduces uncertainties and increases yields for a future food insecure population (Table 3). However, this adaptation measure comes at a cost. For the same irrigation schedule, a higher IWR is required in the future (25%–39% higher) compared to the current conditions (Figure 3), which is in line with the conclusions of Weatherhead and Knox [58] who predicted a future rise in irrigation water requirements in England and Wales.

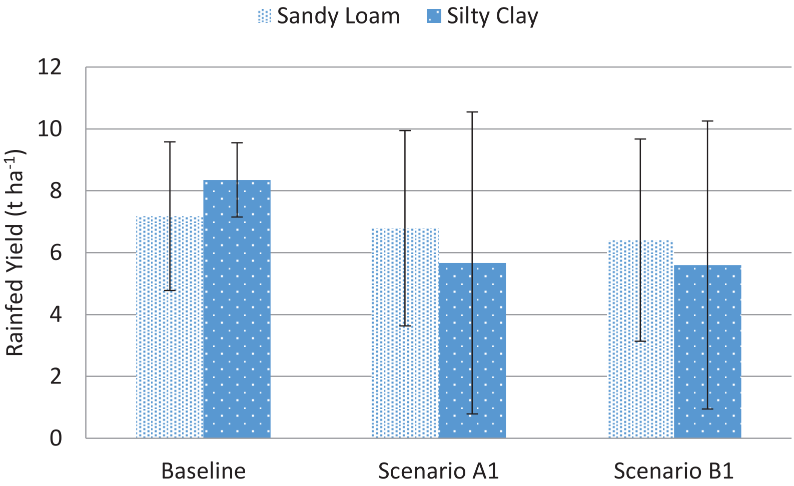

Figure 2. Simulated yield (t·ha^{-1}) at Cambridge for baseline and selected IPCC SRES scenarios [25].

Table 3. Rainfed and irrigated yields for different soil types and under baseline and selected IPCC SRES scenarios [25].

Soil Type	**Sandy Loam Soil**		**Silty Clay Loam Soil**	
Yield (t·ha^{-1})	**Rainfed**	**Irrigated**	**Rainfed**	**Irrigated**
Baseline	7.2 ± 2.4	8.7 ± 0.9	8.4 ± 1.2	9.2 ± 0.8
Scenario A1	6.8 ± 3.2	10.7 ± 0.7	5.7 ± 4.9	11.8 ± 0.7
Scenario B1	6.4 ± 3.3	10.5 ± 1.0	5.6 ± 4.7	11.7 ± 0.7

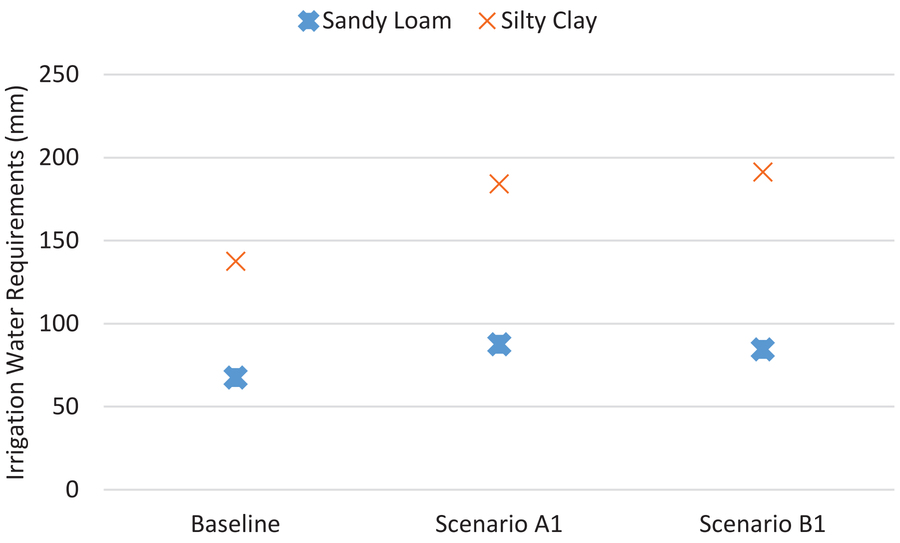

Figure 3. Irrigation water requirements (IWRs) for the same irrigation schedule under baseline and selected IPCC SRES scenarios [25].

3.2. Sustainability Assessment

Currently, under the baseline scenario rainfed winter wheat produced in sandy loam soils generate 23% more benefits than in silty clay soils; further, irrigation is not a beneficial option to farmers and generates environmental externalities in terms of CO_2 emissions and added value of water (Table 4).

Table 4. Sustainability assessment of agricultural practices for different soil types, under baseline and selected IPCC SRES scenarios [25].

Soil	**Sandy Loam Soil**						**Silty Clay Loam Soil**					
Scenario	**Baseline**		**Scenario A1**		**Scenario B1**		**Baseline**		**Scenario A1**		**Scenario B1**	
	Boom	**Raingun**	**Boom**	**Raingun**	**Boom**	**Raingun**	**Boom**	**Raingun**	**Boom**	**Raingun**	**Boom**	**Raingun**
FIA	−93.9	−184.4	260.1	104.5	294.1	144.9	−354.5	−535.4	429.4	67.4	417.9	41.0
NPV	10278.6	9770.2	12858.5	12108.3	12585.5	11868.5	10432.0	9171.0	13570.6	11748.0	13416.6	11516.5
IRR	83%	83%	101%	99%	99%	99%	84%	84%	107%	105%	105%	105%
BCR	6.7	4.3	7.6	4.5	7.5	4.5	5.5	2.6	6.1	2.6	5.9	2.5
WW	680	680	880	880	850	850	1380	1380	1850	1850	1920	1920
IUE	0.013	0.013	0.012	0.012	0.012	0.012	0.007	0.007	0.006	0.006	0.006	0.006
AVW	0.38	0.24	0.52	0.34	0.50	0.33	0.14	0.01	0.24	0.04	0.22	0.02
GWP	0.1	0.4	0.1	0.5	0.1	0.5	0.2	0.8	0.3	1.2	0.3	1.1
YI	1.6	1.6	3.9	3.9	4.1	4.1	0.9	0.9	6.1	6.1	6.1	6.1

FIA = Financial Investment Appraisal; NPV = Net Present Value; IRR = Internal Rate of Return; BCR = Benefit-Cost Ratio; WW = Water Withdrawal; IUE = Irrigation Use Efficiency; AVW = Added Value of Water; GWP = Global Warming Potential; YI = Yield Increase.

Under climate change scenarios, the yield reduction for rainfed winter wheat would cause a benefit loss to farmers between −24.3% and −36.0% on a sandy loam soil. On a silty clay loam soil farmers would not generate any benefit. These figures agree with El Chami et al. [28] who suggested that currently the yield benefits do not justify the investment in new irrigation systems for winter wheat grown in the UK. However, using existing on-farm unused equipment available between April and June could be beneficial.

Therefore, irrigation improves the farm economic performances and the added value of water is higher (Table 4), but this might increase CO_2 emissions between 2.5% and 21.5% according to the SRES scenario [25] selected, the soil type, and the irrigation system adopted. This range is not as wide as the results of Niero et al. [59] who assessed the life cycle of spring barley in Denmark under seven alternative future scenarios and found a GWP variation between −31% and 50% compared to baseline.

In general, irrigating winter wheat grown in heavier soils might generate higher incomes, but would require more water (two folds higher) and therefore the CO_2 emissions would be higher (Table 4). Further, results under all scenarios show that raingun systems are not a sustainable on-farm option to adopt; the global warming potential associated with the use of a raingun system is between 40% and 92.2% higher compared to the boom systems and the AVW is between 5.4% and 95.4% lower for rainguns (Table 4). Even though the capital cost of a raingun is cheaper than a boom, the variable costs and the social cost of carbon are relatively high, which makes them an expensive option with high pollution related impacts.

Under climate change scenarios, investing in irrigation systems becomes noticeably profitable and necessary to increase food security (YI: 3.9 to 6.1 $t \cdot ha^{-1}$). The higher benefits are observed on a silty clay loam soil and for the high emission scenario (Scenario A1). However, the highest economic benefits consume the highest amount of water (WW 1850–1920 $m^3 \cdot ha^{-1}$) and generate a lower AVW accompanied with the highest GWP, which could be two times higher in silty clay loam soils than in lighter soils (Table 4).

3.3. Sensitivity Analysis

According to the sustainability assessment, the most sustainable practice in the future to grow winter wheat would be on lighter soils, and given that irrigation activity would likely be affected by the components assessed in the sensitivity analysis (e.g., market wheat price and oil price), the sensitivity analysis was performed on the sandy loam soil and considered the AVW, which is a good indicator to show in economic terms how water contributes to the production value.

In general, the results of this analysis showed that the AVW is more sensitive to market price fluctuations than to variations in oil prices (Table 5). However, it is well noted that sensitivity of the AVW when using a hose reel fitted with boom (Table 5a) is less elastic than when using a raingun (Table 5b), hence a change in oil price would have higher impacts on the AVW when using a raingun.

Table 5. Sensitivity of Added Value of Water (£·m^{-3}) to market price of wheat (£·t^{-1}) and diesel price (£·L^{-1}) when using **(a)** a hose reel fitted with boom or **(b)** a raingun.

(a)									
Sandy Loam Soil—Boom									
	Baseline			**Scenario A1**			**Scenario B1**		
	−30%	165.9	+30%	−30%	165.9	+30%	−30%	165.9	+30%
−60%	−0.24	0.40	1.04	−0.06	0.54	1.15	−0.09	0.53	1.14
0.7	−0.26	**0.38**	1.02	−0.09	**0.52**	1.13	−0.11	**0.50**	1.12
+60%	−0.29	0.35	0.99	−0.11	0.50	1.10	−0.14	0.48	1.10
(b)									
Sandy Loam Soil—Raingun									
	Baseline			**Scenario A1**			**Scenario B1**		
	−30%	165.9	+30%	−30%	165.9	+30%	−30%	165.9	+30%
−60%	−0.30	0.34	0.98	−0.16	0.44	1.05	−0.19	0.43	1.04
0.7	−0.40	**0.24**	0.88	−0.26	**0.34**	0.95	−0.29	**0.33**	0.94
+60%	−0.50	0.14	0.78	−0.36	0.24	0.85	−0.36	0.23	0.84
Bold values = Central values									

4. Methodological Limitations

Certainly, the integration of different modelling approaches adopted in this study has numerous limitations. The crop growth modelling was based on one GCM (HadCM3), two scenarios (A1 and B1), one time-slice (2050s), two irrigation systems (hose reel fitted with boom and with raingun), and two soil types (Sandy loam and silty clay loam). A more detailed assessment would need to consider the entire range of projections and different soil types and irrigation systems in order to better quantify modelling errors and uncertainties [60].

Even though the irrigation systems used are both sprinklers with the same theoretical efficiency, the on-site application efficiency might vary from one system to another and abstraction efficiency might also be different. The study did not account for application and abstraction efficiency, which may have reduced the accuracy to estimate the applied IWRs and the ground and surface WW to assess the water related indicators.

Finally, the research accounted only for the GHG emissions generated from irrigation pumping and did not include the total emissions of the production generated through the life cycle of the wheat crop. This might have led to an underestimation in the results for the generated indicators.

5. Conclusions

This study confirmed that climate change would have negative impacts on winter wheat production in the East of England. These impacts are site-specific and highly depend on the agro-climatic conditions of the farm. Climate change impacts are also extremely dependent on soil types. The rainfed yields would be reduced by between −5.4% and −32.9% according to the soil type.

In economic terms, rainfed winter wheat under climate change would cost farmers between −24.3% and −36.0% of the benefit margin. However, irrigation could be a beneficial adaptation measure for farmers to increase future yields (YI between 3.1 and 6.1 $\text{t}\cdot\text{ha}^{-1}$) and reduce yield uncertainties. It could generate economic benefits that vary depending on the irrigation systems selected (FIA between 41 and 519 $£\cdot\text{ha}^{-1}$), the SRES scenario [25] adopted, and the soil type.

Irrigation might generate environmental externalities and might increase pressure on water and air resources as the irrigation water requirements increase between 25.0% and 39.1% compared to the baseline scenario, and the global warming potential increases between 2.5% and 21.5%. However, the selection of irrigation systems with low energy consumption would limit the environmental impacts to a minimum. As such, hose reels fitted with boom compared to hose reels fitted with raingun showed to be a more sustainable option which should be considered in the future in order to increase food security.

Finally, this research has attempted to integrate different modelling approaches to assess the sustainability of a wheat production system in a humid climate. However, for a comprehensive framework to be adopted and replicated in different agro-climatic conditions, different crops and a bigger range of SRES scenarios, a life cycle assessment model should be incorporated into the framework for wheat in particular and agricultural systems in general.

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