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Opportunities for Green Energy through Emerging Crops: Biogas Valorization of *Cannabis sativa* L. Residues

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Abstract: The present work shows the experimental evidence carried out on a pilot scale and demonstrating the potential of *Cannabis sativa* L. by-products for biogas production through anaerobic digestion. While the current state-of-the-art tests on anaerobic digestion feasibility are carried out at the laboratory scale, the here described tests were carried out at a pilot-to-large scale. An experimental campaign was carried out on hemp straw residues to assess the effective performance of this feedstock in biogas production by reproducing the real operating conditions of an industrial plant. An organic loading rate was applied according to two different amounts of hemp straw residues (3% wt/wt and 5% wt/wt). Also, specific bioenhancers were used to maximize biogas production. When an enzymatic treatment was not applied, a higher amount of hemp straw residues determined an increase of the median values of the gas production rate of biogas of 92.1%. This reached 116.6% when bioenhancers were applied. The increase of the specific gas production of biogas due to an increment of the organic loading rate (5% wt/wt) was +77.9% without enzymatic treatment and it was +129.8% when enzymes were used. The best management of the biodigester was found in the combination of higher values of hemp straw residues coupled with the enzymatic treatment, reaching 0.248 $Nm^3 \cdot kg_{volatile\ solids}{}^{-1}$ of specific biogas production. Comparisons were made between the biogas performance obtained within the present study and those found in the literature review coming from studies on a laboratory scale, as well as those related to the most common energy crops. The hemp straw performance was similar to those provided by previous studies on a laboratory scale. Values reported in the literature for other lignocellulosic crops are close to those of this work. Based on the findings, biogas production can be improved by using bioenhancers. Results suggest an integration of industrial hemp straw residues as complementary biomass for cleaner production and to contribute to the fight against climate change.

Keywords: renewable energy technologies; sustainability; clean energy; bioenergy; biogas; industrial hemp; anaerobic digestion

1. Introduction

Industrial hemp (*Cannabis sativa* L.) is a valuable crop, and all parts of the plant can be used in many ways. Recent surveys carried out in the past few years (e.g., [1,2]) suggested that industrial hemp is a niche crop of increasing interest for its properties and versatility. New uses and innovative products appear on the market (more than 25,000 products have been discerned [3]), thus *Cannabis sativa* L. is becoming a very attractive crop on a global scale.

In Europe, hemp cultivation is mainly a multi-purpose crop. The market interest for hemp seeds and the need for attaining maximum economic viability of the related supply chains are stimulating a progressive shift of interest from traditional stem fiber use (textile, pulp or paper) towards multi-purpose cultivations. Indeed, in recent years, an increasing interest for new products obtainable as food or feed from seeds and for phyto-based cosmetics from inflorescence is emerging [4].

Hemp is a crop with fast growth, high biomass production at low inputs (fertilisers/pesticides), good CO_2 capture per hectare (about 2.5 t/ha), and soil protection due to the length of its roots, suitable for many industrial processes [5,6]. Appropriate soils for hemp are deep, show pH between 6.0 and 7.5, and have a good availability of nutrients and water holding capacity [7]. Moreover, hemp requires proper preparation of the seedbed, especially on clay soils, for a homogenous emergence due to its particular sensitivity to waterlogging. Sandy soils are less suitable for this cultivation, because of its poor water holding capacity determining greater water requirements [8]. It depends on climatic conditions. Indeed, in the South Mediterranean environment, higher irrigation volumes are required, with respect to the North Mediterranean one [9,10], but hemp water requirements are lower [11] compared to other specialized and common crops, such as maize, which are also cultivated for biogas production in Europe.

Industrial hemp cultivation is growing over time. A great increase was recorded from 2013 to 2017 in Europe [2], because of the introduction of policies and local incentives to the hemp industry [12].

As a result of the Italian Regulation [13], industrial hemp cultivation and processing assumed an increased national relevance. The regulation supports (also by including economic incentives) and promotes the development of integrated supply chains valuing research findings and pursuing local integration, as well as effective environmental and economic sustainability.

During the first decades of the 20th century, Italy was one of the most important producers on a global scale. In 1940, cultivated areas exceeded 100,000 ha, corresponding to more than 80,000 tons of hemp fibers [14].

The extension of the cultivated areas in Italy from 1961 to 2017 are reported in Figure 1 (sources of data: [15–17]).

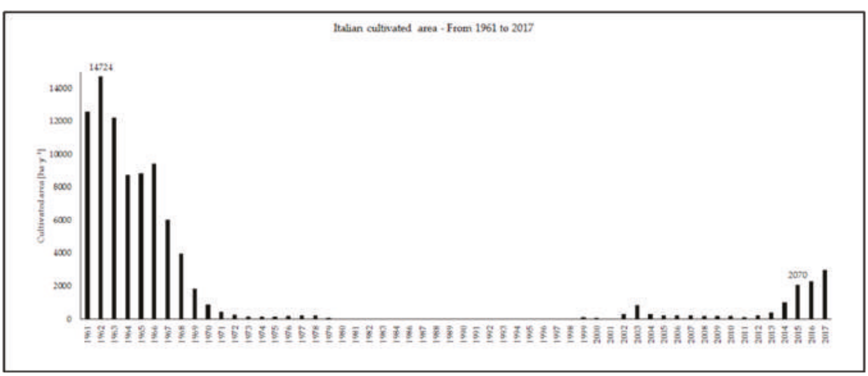


Figure 1. Hemp harvested areas (hectares by year) in Italy, from 1961 to 2017 (source of data: [15–17]).

Cultivated areas were significant during the 1960s and 1970s, and cultivations stopped in the 1980s and 1990s, mainly due to strict policies and regulations against the use of narcotic and psychotropic drugs. From 1999 to 2018, a new interest in hemp cultivation was developed, supported by national and European funding (the Italian Ministry of Agricultural Food and Forestry Policies financed a project to promote industrial hemp supply chains; during the same period, the European Union funded 3-year projects to reintroduce this feedstock for multiple purposes and to differentiate crops).

Due to the global resurgence of hemp cultivation needed to meet the requirements of the hemp sectors widespread today (building construction, food/animal feed, pharmaceutical, paper, textile, etc.), the recovery of hemp fiber and hurd residues should be addressed.

In this regard, some research and development projects funded by the European Union, such as MultiHemp [18] and GRACE [19], were already developed to demonstrate the sustainability of hemp-derived products according to the biorefinery concept.

However, another possible recycling path, aimed at increasing the economic and environmental benefits in a circular economy perspective, is the conversion of the agro-industry by-products into energy carriers.

Despite its thousands of uses, hemp by-products' potential as an energy feedstock is yet to be examined in depth. To date, few works have identified industrial hemp as an energy crop (for instance, a potential energy crop to produce bioenergy in [20]; ethanol production in [21,22]; methyl ester production in [23]; pyrolysis feedstock in [24]; biomass for thermochemical processes in [5]; combustion in [25,26]; co-firing in coal and peat power stations in [27]; and gasification or co-firing in [28]).

A few scientific works related to industrial hemp as a potential energy crop for biogas production can be found in the literature, going from 1990 to 2014. Rehman et al. [29] give an overall perspective of using hemp as a bioenergy crop in Pakistan, including biogas production.

Kreuger et al. [30], Heiermann et al. [31], Adamovics et al. [32], Mallik et al. [33] and Kaiser [34] provided data from anaerobic digestion trials carried out on a laboratory scale (a few liters-capacity reactors) (Table 1). As a pre-treatment, hemp was ground to a few mm or powder size. Since the grinding size influences the digestion kinetics [35] and, more generally, particle size affects the hydrolytic phase of the biodegradation of lignocellulosic feedstock [36], this factor should be considered when analyzing and comparing studies based on a laboratory scale. However, fine grinding is not reasonably achievable and economically affordable in industrial applications processing huge amounts of biomass.

Table 1. Main experimental conditions and information related to the scientific works found in the literature on anaerobic digestion of hemp, based on a laboratory scale.

Experiment	Hemp Cultivar	Country	Thermal Conditions	HRT	Specific Biogas Yield	Specific Methane Yield	Methane Content
[30]	Futura75	Sweden	50 °C	30 days	-	234 ± 35 $m^3 \cdot t^{-1}$ VS (mean ± std.dev. [1])	-
[31]	Fedora19	Germany	35 °C	35 days	453 ÷ 567 $L_N \cdot kg^{-1}$ VS	259 ÷ 301 $L_N \cdot kg^{-1}$ VS [2]	53 ÷ 57 (%vol)
[32]	Futura75 (among other cultivars)	Latvia	38 ± 1 °C	53 days	0.357 ÷ 0.370 $L \cdot g^{-1}$ VS (coarse particles); 0.470 ÷ 0.530 $L \cdot g^{-1}$ VS (fine particles)	0.172 ÷ 0.185 $L \cdot g^{-1}$ VS (coarse particles); 0.240 ÷ 0.270 $L \cdot g^{-1}$ VS (fine particles)	-

[1] std.dev. means "standard deviation"; [2] N means "normal", VS means "volatile solids".

For the present work, the study of Mallik et al. [33] was excluded from the comparison reported in Table 1, because of a lack of information about biogas production/methane production performance. In [34], experiments conducted in a batch digester were presented, where industrial hemp was co-digested with other vegetable wastes and poultry litter. These three types of biomass, fed to 10-L reactors, had the same size (2 cm), which did not allow the authors to consider the relationships between chemical composition and size, and how they influenced anaerobic digestion. It was difficult to assign biogas/methane production performances to each biomass making up the admixtures (with attention to hemp) to make comparisons with the results obtained in the present study.

The present work goes beyond the past research approaches to anaerobic digestion of hemp. It focuses on assessing actual opportunities of a large-scale use of industrial hemp straw residues. Indeed, in the south of Italy, hemp is primarily cultivated for seed production while hemp straw residues are ordinarily left in the field, due to their scarce economic value as well as to the limited industrial interest and knowledge about this by-product. This study aimed to provide a more comprehensive knowledge of this residual lignocellulosic biomass.

The screening carried out on hemp straw residues for biogas generation completes the major gaps identified in the related state-of-the-art, by offering in-depth knowledge of the effective performance of *Cannabis sativa* L. residues in biogas production.

This work considers an alternative use of hemp straw residues with respect to the already developed market sectors (see, for instance, [29]) and, consequently, it suggests new market opportunities for hemp-derived products. The outcomes show the effective potential of developing a new supply chain, based on an emerging lignocellulosic crop for biofuel production. These aspects will be economically relevant both for farmers and contractors in biogas/biomethane sectors.

As pointed out by [37], lignocellulosic crops are not a common source of biomass for biogas production. The authors emphasize that the most significant constraints to hemicellulose/cellulose digestion are related to the lignin content, crystallinity of cellulose, and particle size. These limits may be reduced through optimization of the methodologies and technologies supporting biogas and subsequent biomethane production, for more sustainable use of crop residues for energy purposes. Among other techniques, the use of specific enzyme systems should be considered to reduce the lignocellulose's recalcitrance to anaerobic digestion. An in-depth presentation of the chemical and biological mechanisms between recalcitrant biomass and enzymes was provided by [38].

As reported by [39], commercial bioenhancers are not thoroughly characterized, but the positive results provided by the recent literature (+30% increase circa, as reported by [40]) related to biogas production from biomass with a complex lignocellulosic structure stimulate further applications and studies.

This work includes treatment with a commercial preparation of bioenhancers developed to improve biogas production through anaerobic digestion of cellulose and hemicellulose in lignocellulosic crops, like *Cannabis sativa* L. residues, to contribute to an advance in the field.

Additionally, by assessing the current state of industrial hemp usage and deployment, it emerged that a synergistic approach along the entire supply chain should be adopted, by integrating high-value components of hemp and other parts of the plant into a well-designed biorefinery, in order to support the local economy in a more sustainable way.

2. Materials and Methods

In 2017, an experimental hemp crop on the *Cannabis sativa* L. cultivar "Futura75" was carried out at San Giovanni Suergiu (pilot site located in the south-western side of the Sardinian Island, Italy). This trial is part of the CANOPAES project (the Italian acronym for "CANapa: OPportunità Ambientali ed Economiche in Sardegna", focused on the environmental and economic opportunities of hemp in the Sardinian Island).

Futura75 was chosen for its diffusion in Europe and its ability to produce both seeds and biomass.

According to the available long-term data, the San Giovanni Suergiu's climate is typically the Mediterranean. During the crop cycle, the thermopluviometric trend was characterized by maximum temperatures above the average, and rainfall was equal to about one-third of the seasonal average. Hemp was sown at a density of 120 plants$\cdot$m^{-2} and at a depth of 0.02 m.

In addition, 60 kg$\cdot$ha^{-1} as urea were top-dressed at about one month after emergence. Irrigation was performed by sprinklers with 75% ETm (maximum evapotranspiration) restitution and no weed control was required. Hempseeds were harvested by an ordinary combine. After that, the by-product straw naturally dried on the field (moisture <15% on a wet basis). Then, straw was raked and baled for transportation to the pilot plant. The green biomass yield was about 20 t$\cdot$ha^{-1} while naturally dried straw was about 3.7 t$\cdot$ha^{-1}.

Based on the assumption that different uses of hemp straw can coexist, though the specific features of the local market drive the types of use (as stated by [6] and [7], the dual-purpose oil-fiber of *Cannabis sativa* L. is dominant in the European territory), this work assumed a hypothetical scenario made of a dual-purpose supply chain: Hempseeds were harvested by a combine, to be used for oil extraction, while residues were processed for energy carrier generation (specifically, biogas).

Then, single-step digestion was performed in the pilot plant described below. The duration of the experiment was of 423 days (from March 2018 to June 2019).

2.1. Feedstock Characterization and Pre-Treatment, Admixture Preparation, and Pilot Plant

Since the chemical composition and physical characteristics (e.g., moisture content M) were used to define the admixtures proportion, to manage the process stability and to optimize anaerobic digestion, proximate analysis and ultimate analysis of hemp straw residues were performed.

Samples were prepared by drying hemp straw at 105 ± 2 °C in a thermostatic oven (Memmert GmbH, Schwabach, Germany), and by shredding and mixing the material through a cutter.

The proximate analysis was conducted using a thermogravimetric analyzer (TGA701, LECO Corporation, St. Joseph, MI, USA) following [41], to determine the moisture content (M), volatile solids on a dry basis ($VS_{d.b.}$), ash content, and fixed carbon (FC) (reported as percentage by mass [%wt]).

Total carbon, hydrogen, total nitrogen, and sulphur were determined by conducting the ultimate analysis through a CHNS analyzer (Truspec, LECO Corporation, St. Joseph, MI, USA) in accordance with [42].

Fiber composition (ADF: Acid detergent fiber, NDF: Neutral detergent fiber, ADL: Acid detergent lignin) of the lignocellulosic feedstock was used to determine the daily intake of enzymes (see Section 2.2). Values were obtained by using a fiber analyzer ANKOM 2000 (ANKOM, Macedon NY, USA), following the Van Sœst methodology [43–46]. Concerning the hemicellulose and cellulose contents, those values were estimated by subtracting ADF from NDF and ADL from ADF [47,48].

Chemical and physical characteristics (with their standard deviations) of hemp residues are listed in Tables 2–4.

Table 2. Proximate analysis of hemp residues. The cultivar "Futura 75".

	Proximate Analysis [%wt]
$M^1_{d.b.}$	7.71 ± 0.01
$VS^2_{d.b.}$	81.37 ± 0.08
$Ash_{d.b.}$	2.50 ± 0.25
$FC^3_{d.b.}$	16.13 ± 0.35

[1] M means "moisture"; [2] VS means "Volatile Solids"; [3] FC means "Fixed Carbon".

Table 3. Ultimate analysis of hemp residues. The cultivar "Futura 75".

	Ultimate Analysis [%wt]
$Carbon_{d.b.}$	47.41 ± 0.04
$Hydrogen_{d.b.}$	6.52 ± 0.10
$Nitrogen_{d.b.}$	1.64 ± 0.02
$Sulphur_{d.b.}$	0.18 ± 0.00

Table 4. Fiber composition (mean values, [% dry matter]) of hemp residues. The cultivar "Futura 75".

Chopped Hemp, Reproductive Stage		
ADL [1] [%wt]	**NDF [2] [%wt]**	**ADF [3] [%wt]**
7.87	59.16	44.40

[1] ADL means "Acid detergent lignin"; [2] NDF means "neutral detergent fiber; [3] ADF means "acid detergent fiber"

The feedstock characterization did not include parameters, such as starch and sugar contents, because of the composition of hemp straw residues mainly characterized by the lignocellulosic structure.

The anaerobic digester used in the present work was a tubular, horizontal reactor of 1.13 m^3 total volume. It is 2.25 m long and its external diameter is 779 mm. It was radially mixed using a mechanical stirrer. The reactor was fed via a pneumatic pump, conveying the substrate previously introduced into a 250-kg-capacity feeding hopper. The reactor was tested by filling it with 960 L of digestate (corresponding to about 85% of the total volume).

The digestate produced during the process was discharged into a 200-kg-capacity tank, by using a pneumatic pump. The reactor was heated by three electrical resistances located in its center, loading, and discharging sides.

Sampling operations for the reactor sludge were performed using two valves located in the loading and discharging sides of the reactor.

Operations and parameters settings were managed and controlled by a programmable logic controller (PLC).

The feedstock pre-treatment consisted in mechanical milling, by shredding hemp straw residues using a 20-L-capacity cutter (dry cut). Then, coarse particles (maximum size: 1 cm) were mixed with the recirculated digestate in a 40-L-capacity cutter. When necessary, different amounts of water were added.

The operative settings were changed during the experimental period to investigate different process conditions (see Section 2.2).

2.2. Feeding Phases

The reactor was filled with digestate coming from an anaerobic digestion industrial plant treating corn silage and triticale. The digestate was used as received from the industrial plant. Then, a start-up phase was performed. During this phase, the temperature was increased by 2 °C daily until a constant value of 39 °C (mesophilic conditions) was reached.

Subsequently, the daily feeding rate of admixtures (Q, $[m^3_{substrate} \cdot d^{-1}]$) was increased during the first phase to reach an adaptation of the bacterial consortium to the specific substrate. After the start-up phase, the hemp to digestate proportion (hereinafter: percentage of new hemp straw in the admixture C, [% wt/wt]), Q, and digestate recirculation ratio (R, adimensional) were changed during the experimental period.

C and R values were chosen keeping in account the fluid-dynamics behavior of the admixtures. An increase of the hemp straw amount, indeed, could make the pumping of the admixtures itself difficult.

Two reference values of C (C1: 3% wt/wt; C2: 5% wt/wt) were set to evaluate the process. These conditions were tested by considering the presence/absence of specific bioenhancers. Treatments were randomly applied during the entire experiment.

Concerning the ranges of the organic loading rate (OLR, $[kg_{VS} \cdot (m^3_{reactor} \cdot d)^{-1}]$), hydraulic retention time (HRT, [d], dependent on Q), R, and C, different regimes were defined.

The abovementioned variables were analyzed along with the specific gas production (SGP, $[m^3_{biogas\ or\ methane} \cdot kg_{VS}^{-1}]$) and the gas production rate (GPR, $[m^3_{biogas\ or\ methane} \cdot (m^3_{reactor} \cdot d)^{-1}]$).

A commercial enzymatic preparation (Micropan Biogas ®from Eurovix, IT) was applied to reduce the current supply of hemp straw residues and to maximize biogas production at the same time. It is made of microbial enzymes containing cellulase, lipase, xylanase, active principles of *Fucus Laminariae*, algae *Lithothamnium calcareum*, natural nutrients/grow factors, selected yeast, mineral biological catalysts rich in oligo elements, and selected microorganisms (facultative anaerobic bacteria, such as: *Bacillus subtilis*, *Bacillus macerans*; strictly anaerobic bacteria genus *Methanobacterium*). The specific gravity was 0.8 t/m^3.

The daily intake was introduced into the reactor by dissolving the powder into water (1:4 wt/v).

The dosage was divided into two parts, depending on the fiber composition of lignocellulosic feedstock (Table 4), C, and Q. The daily intake was defined by multiplying the percentage of cellulose and hemicellulose of hemp residues (see Table 4) with the hemp mass in Q and a coefficient of 0.05, as suggested by the producers. Thus, 20 g per day were obtained.

The first enzymatic inoculum of the reactor sludge was calculated by dividing the working volume of the reactor by Q, and by multiplying this value with the daily intake (500 g of bioenhancers were introduced into the reactor).

2.3. Management of the Reactor and Process Stability

Both the process stability and reactor features were controlled and managed by using a set of parameters.

Management of the reactor: As regards the reactor, the following were considered:

- TS (total solids), $VS_{d.b.}$, determined via proximate analysis on a weekly/sub-weekly basis for the new admixture introduced into the feeding hopper, the material in the hopper/in the digestate tank, and the sludge inside the reactor;
- HRT [d], calculated as:

$$HRT = \frac{V}{Q}, \tag{1}$$

where V is the total digester volume [$m^3_{reactor}$] and Q is the daily feeding rate [$m^3_{substrate} \cdot d^{-1}$];
- OLR ([$kg_{VS} \cdot (m^3_{reactor} \cdot d)^{-1}$]), calculated as:

$$OLR = \frac{V \cdot S}{Q}, \tag{2}$$

where S is the VS concentration on a wet basis in the feeding admixtures [$\%wt_{w.b.}$].

Management of process stability: The process stability was monitored by considering the below listed parameters:

- pH and FOS/TAC ratio (volatile fatty acids content/buffer capacity) of the reactor sludge (daily measures by means of, respectively, a multi-parametric analyzer Orion Versa Star (ThermoScientific Inc., Waltham, MA, USA) and an automatic titrator T70 (Mettler Toledo International Inc., Columbus, OH, USA));
- Biogas production [$m^3\ _{biogas} \cdot d^{-1}$] (daily values provided by a biogas flow meter);
- Biogas composition daily (CH_4, CO_2, O_2 [%wt]; NH_3, and H_2S [ppm]), determined using a portable gas analyzer GA2000 (Geotechnical Instruments UK Ltd., Coventry, UK). Biogas composition is strictly related to SGP and GPR;
- Temperature of the reactor sludge, measured through three temperature probes located in the center, the loading, and discharging sides of the reactor, and monitored through the PLC.

Performance parameters: The two main performance parameters considered in the anaerobic digestion trials carried out on hemp straw residues are:

- SGP [$Nm^3_{biogas\ or\ methane} \cdot kg_{VS}^{-1}$], calculated as:

$$SGP = \frac{G}{Q \cdot S}, \tag{3}$$

where Q and S were already described, G is the daily production of biogas/methane [$m^3_{biogas\ or\ methane} \cdot d^{-1}$];
- GPR ([$Nm^3_{biogas\ or\ methane} \cdot (m^3_{reactor} \cdot d)^{-1}$]), calculated as the daily production of biogas/methane per m^3 of sludge accumulated in the reactor.

The abovementioned parameters are related to:

- C (percentage of new hemp in the admixture, [% wt/wt]), calculated as:

$$C = \frac{Mass_{hemp}}{Mass_{hemp} + Mass_{digestate} + Mass_{water}} \cdot 100, \tag{4}$$

where: $Mass_{hemp}$, $Mass_{digestate}$, and $Mass_{water}$ are the mass of the hemp, digestate, and water composing the admixtures;

- R (digestate recirculation ratio, adimentional), following Equation (5):

$$R = \frac{\sum_i Mass_{digestate}}{\sum_i Mass_{hemp}}, \quad (5)$$

where $\Sigma_i Mass_{hemp}$ and $\Sigma_i Mass_{digestate}$ [$g \cdot 10^3$] are the cumulative amounts of new hemp or digestate composing hemp-digestate admixtures in a specific time window.

2.4. Statistical Analyses

Statistical analyses were performed on biogas composition, SGP, and GPR using Statgraphic Centurion XVI [49]. The mean, standard deviation, maximum and minimum values, and median were calculated for each feeding phase composing the experimental period. Also, the skewness and kurtosis were calculated to determine which kind of statistical analysis should be performed.

Depending on this first data analysis and with a specific focus on the skewness and kurtosis, any evenness emerged among variances. Consequently, non-parametric tests were applied.

Two non-parametric tests were considered: Mann–Whitney [50,51] and Kruskal–Wallis [52]. The former was used to determine if two ordinal and independent random samples (feeding phases) were part of the same population. The latter was useful to compare median values of the different groups to identify whether they belonged to a population characterized by the same median.

Statistical analyses were developed by considering $p < 0.05$. Graphical representations were provided by using box-and-whisker diagrams.

3. Results and Discussion

3.1. Feeding Phases

Based on the outcomes of the experiment, it was divided into phases. The main characteristics of the feeding phases, except for the start-up phase, are reported in Table 5. Indeed, the start-up phase was characterized by high instability of the main process parameters as well as by a rapid variation of admixture feeding rates over time. Thus, the remaining feeding phases were labeled from 1 to 7.

Table 5. Main parameters (with their standard deviations) of anaerobic digestion trials on hemp residues.

Phase [-]	Description [-]	Duration [d]	OLR [1] [$kg_{VS} \cdot m^{-3} \cdot d^{-1}$]	HRT [2] [d]	C [3] [% wt/wt]	R [4] [-]
1	No enzymatic treatment	45 (day 98–day 143)	2.8 ± 0.6	29 ± 2	2.3 ± 0.0	16.3 ± 1.1
2	No enzymatic treatment	27 (day 144–day 171)	1.3 ± 0.2	34 ± 4	3.0 ± 0.9	18.9 ± 0.4
3	No enzymatic treatment	55 (day 172–day 227)	2.9 ± 0.8	34 ± 7	2.9 ± 1.8	20.7 ± 0.8
4	Enzymatic treatment	34 (day 228–day 262)	3.8 ± 0.8	31 ± 7	2.5 ± 1.7	22.0 ± 0.3
5	Enzymatic treatment	35 (day 263–day 298)	3.2 ± 0.8	30 ± 6	5.1 ± 0.2	22.0 ± 0.4
6	No enzymatic treatment	36 (day 299–day 335)	3.1 ± 0.9	33 ± 9	5.2 ± 1.0	20.9 ± 0.3
7	Enzymatic treatment	87 (day 336–day 423)	3.1 ± 1.0	29 ± 3	4.4 ± 2.0	20.3 ± 0.2

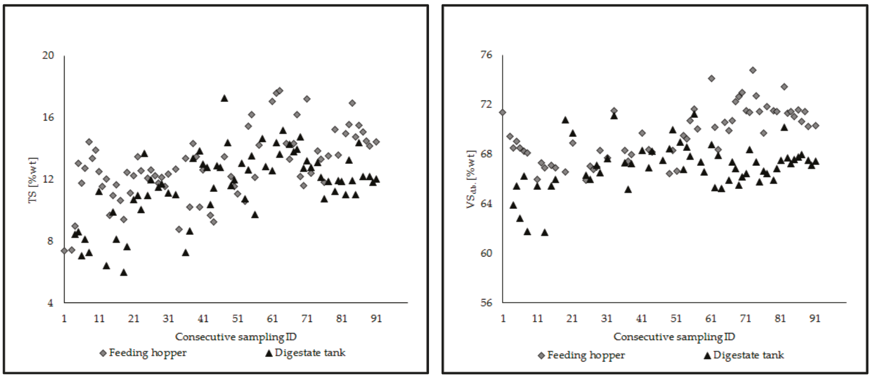
[1] OLR means "organic loading rate"; [2] HRT means "hydraulic retention time"; [3] C means "percentage of new hemp in the admixture"; [4] R means "digestate recirculation ratio".

Feeding phases were classified according to enzymatic treatment, OLR, HRT, C, and R (Table 5).

The two C reference values applied in this study are close to the organic loadings used in the industrial plants of anaerobic digestion.

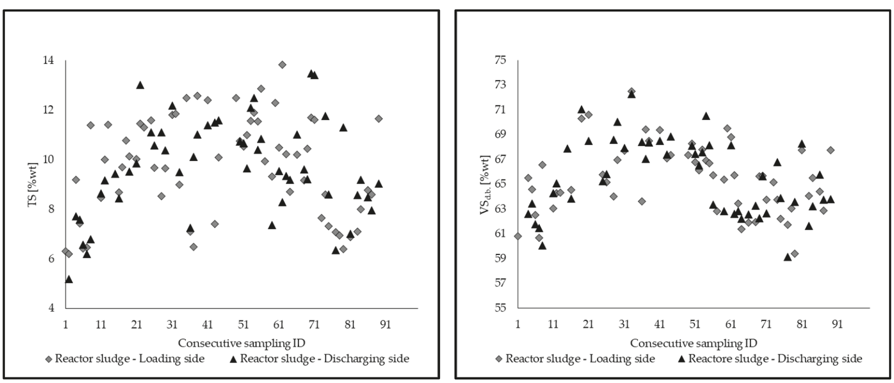
3.2. Management of the Reactor and Process Stability

Management of the reactor -TS and $VS_{d.b.}$ trends of the material in the feeding hopper, in the reactor sludge, and the digestate tank are reported in Figures 2 and 3.



a) b)

Figure 2. TS (total solids) (**a**) and $VS_{d.b.}$ (volatile solids on a dry basis); (**b**) trends of the material in the feeding hopper and the digestate tank, concerning consecutive sampling.



a) b)

Figure 3. TS (total solids) (**a**) and $VS_{d.b.}$ (volatile solids on a dry basis); (**b**) trends of the reactor sludge, concerning consecutive sampling.

By comparing the TS and $VS_{d.b.}$ trends in the feeding hopper and digestate, it can be seen that from the 70th sampling, these parameters were notably lower in the discharged sludge than in the corresponding feeding mixtures. The 70th sampling corresponds to the beginning of the 5th feeding phase and this occurrence emerged from the observations related to the 6th and 7th phases as well. In the previous feeding phases, a distinction between the TS and $VS_{d.b.}$ evolution in the fed slurry and the corresponding digestate cannot be seen. This result is related to the higher reference value of C (C2), which was better than the other one (C1).

With regard to Figure 3, the reactor sludge did not show relevant differences in terms of TS and $VS_{d.b.}$ by comparing the loading side to the discharging side, mainly due to a certain mixing of the sludge along the longitudinal section of the reactor. TS and $VS_{d.b.}$ seemed to increase from phase "1" to phase "4" and to decrease in the subsequent phases (characterized by the reference value, C2).

Management of process stability: Concerning the main design and operation process parameters of the reactor, the trends of HRT and OLR are shown in Figures 4 and 5.

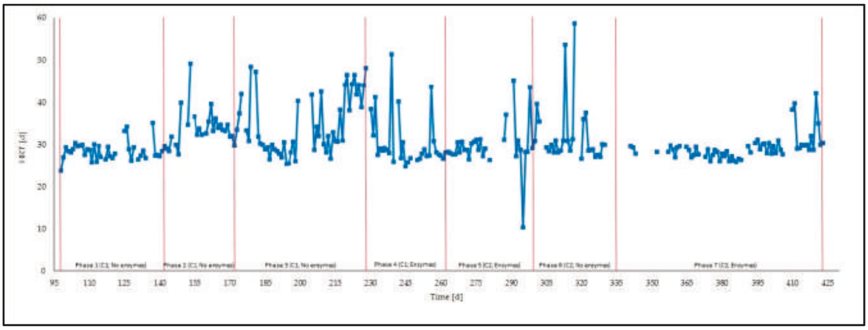


Figure 4. Hydraulic retention time (HRT) trend.

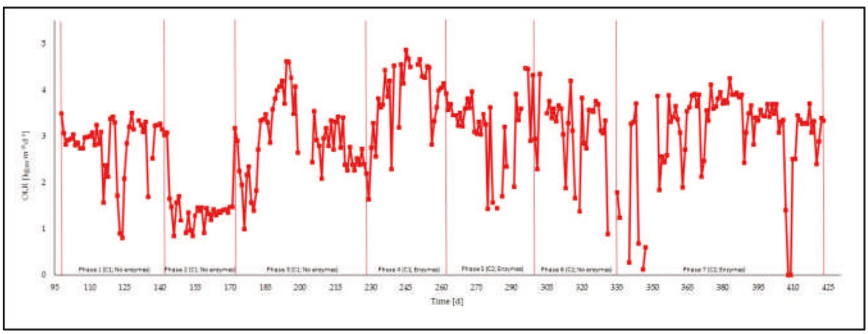


Figure 5. Organic loading rate (OLR) trend.

HRT did not show significant variations during the entire experiment (Figure 4) and it was excluded from the statistical analysis.

OLR (Figure 5) was monitored through the daily determination of TS and $VS_{d.b.}$ in the feeding admixture and adjusted by setting the hemp share in the feeding admixture and the loading flow rate (Figure 2).

Regarding the process stability parameters, the trends of FOS/TAC and pH, biogas production, and biogas composition (CH_4, CO_2, NH_3, H_2S) are reported in Figures 6–9.

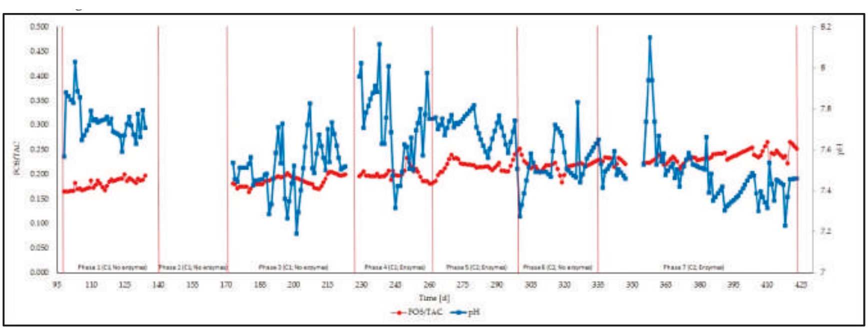


Figure 6. FOS/TAC (volatile fatty acids/buffer capacity) and pH trends.

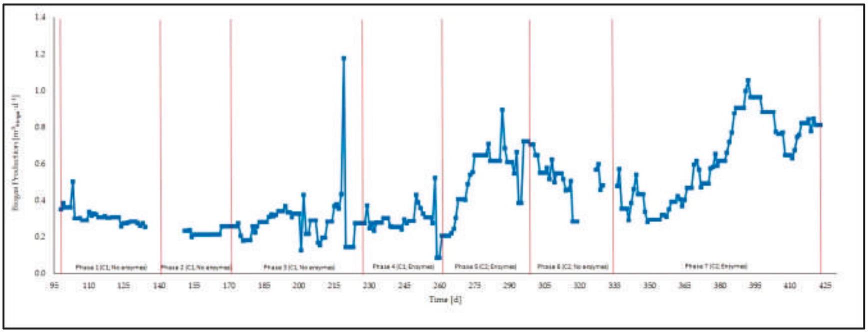


Figure 7. Biogas production trends (GPR) (via biogas metering).

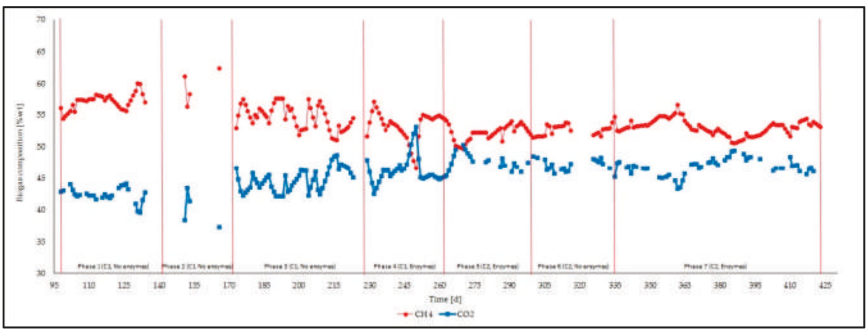


Figure 8. Biogas composition (CH_4 and CO_2, [%wt]) detected by the portable gas analyzer during the experimental period.

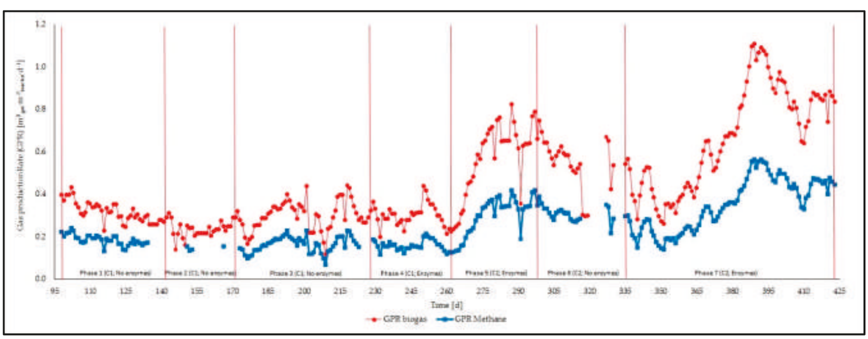


Figure 9. Gas production rate (GPR) trends of biogas and methane.

By considering the entire experimental campaign, pH varied between 7.2 and 8.0, accompanied by higher values during the first phase.

The FOS/TAC ratio increased over time, from about 0.170 to values close to 0.270. These values are very similar to the typical ones of the industrial plants treating lignocellulosic biomass, such as corn silage.

Overall, the FOS/TAC trend is consistent with the increase in the percentage of new hemp in the feeding admixtures (C2 treatment) (see Table 5) from the fifth feeding phase to the seventh one. It can be supposed that the introduction of higher amounts of hemp provoked a shift of the anaerobic digestion microbial dynamics towards the predominance of acidogenic reactions.

Daily biogas production (Figure 7) was characterized by high variability during the experimental campaign. It showed a significant increase of the biogas produced during the experimental phases from "5" to "7" (C2), accompanied by a rapid increase during the fifth phase and a decrease over the sixth one (without enzymes). The last feeding phase showed rising values for most of the days (to reach about 1.1 m^3 biogas per day), corresponding to the coupling of higher C and enzymatic treatment. It can be considered as the most suitable among all the treatments applied. On average, the CH_4 content [%wt] in the biogas produced during the entire experimental campaign was 53.8 ± 2.2. CO_2 content [%wt] was 45.6 ± 2.4. CH_4 concentration showed a slow reduction from the phase "1" to the phase "4". From the phase "5", a gradual increase of its concentration was detected. CH_4 and CO_2 trends (Figure 8) did not show any peak attributed to organic overload.

Performance parameters: The performance parameters, SGP and GPR, of the anaerobic digestion trials are shown in Figures 9 and 10.

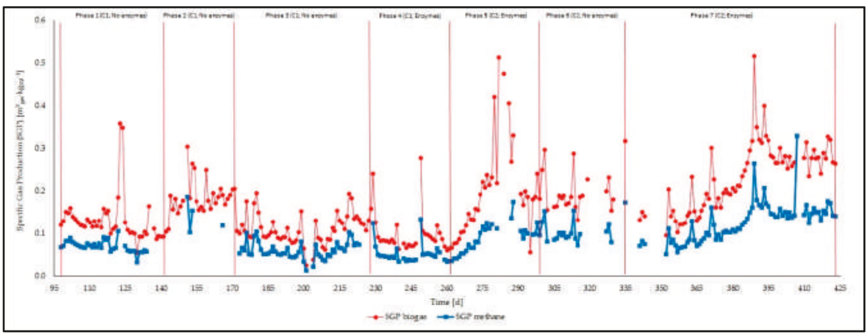


Figure 10. Specific gas production (SGP) trends of biogas and methane.

SGP of biogas/methane is the energy yield of an anaerobic digestion system regardless of OLR, thus it plays an important role when assessing the energy yield of the considered process.

Both trends showed an increase starting in the fifth feeding phase. It was more evident during the seventh period.

By comparing these outcomes with those obtained on a laboratory scale [30,32], it can be pointed out that the present work provided higher SGP values both for biogas and methane than the previous literature on anaerobic digestion trials of hemp straw. Overall, the management of the reactor and the process stability was enhanced with respect to biogas production, especially in the last part of the experiment, characterized by the combination of higher values of C and the application of enzymes.

SGPs of the present work are lower compared to those obtained in the same pilot plant, using vegetable feedstock characterized by high degradability (lower lignin contents and higher starch content). Due to the lignocellulosic nature of this crop, the specific biogas/methane production of hemp straw was lower than those related to raw potatoes (0.68 Nm^3 of biogas $\cdot kgVS^{-1}$ and 0.37 Nm^3 of methane $\cdot kgVS^{-1}$) [53], potato chips (0.81 Nm^3 of biogas $\cdot kgVS^{-1}$ and 0.47 Nm^3 of methane $\cdot kgVS^{-1}$) [54], and fruit and vegetable wastes (0.78 Nm^3 of biogas $\cdot kgVS^{-1}$ and 0.43 Nm^3 of methane $\cdot kgVS^{-1}$) [55].

Experiments carried out on the same pilot digester using admixtures made of different kinds of feedstock (admixture composition: 30%wt of shredded corn, the remaining part consisting in whey, vegetable water, pomace pitted, and manure to maintain the OLR between 2.5 and 3.5 $kgVS{\cdot}m^3{}_{reactor}{\cdot}d^{-1}$) reported SGP_{biogas} from 0.623 ± 0.212 $Nm^3{\cdot}kgVS^{-1}$ to 0.768 ± 0.227 $Nm^3{\cdot}kgVS^{-1}$ and $SGP_{methane}$ from 0.281 ± 0.160 $Nm^3{\cdot}kgVS^{-1}$ to 0.438 ± 0.096 $Nm^3{\cdot}kgVS^{-1}$ [56]. Also, hemp straw residues' performance in anaerobic digestion was found to be similar to other lignocellulosic crops [57], the specific methane production of which is between 0.17 and 0.39 $Nm^3{\cdot}kgVS^{-1}$. Results are comparable to those reported by [58] for other agricultural crops, such as oats, flax, and sorghum, but lower than the hemp energy yields considered there.

Thus, hemp straw residues used in the same pilot plant showed lower SGP of biogas and methane probably because of the lignocellulosic composition. The results obtained by the residues considered in this work could be affected by the harvesting time, which is the reproductive stage when the lignin content is higher than in the vegetative stage. By considering that the reproductive stage is the core of the supply chain scenario assumed in this study, related to the extraction of oil from seeds, the results already discussed about the potential of biogas production from straw residues suggest the recovery of this low-value by-product to energy conversion. By considering the ultimate analysis, the carbon:nitrogen ratio is useful to define the biomass suitability for biochemical (ratio <30) or thermochemical processes (ratio >30). The ratio of hemp straw residues is 28.9 (Table 3), thus it can be considered for both, but with slightly higher suitability for biochemical conversion.

3.3. Statistical Analysis

Results of the data analysis (mean, standard deviation, maximum and minimum, skewness, kurtosis, and median values) carried out on the most significant process parameters and outcomes are reported in Tables 6 and 7.

Table 6. Main statistical variables of the biogas composition and biogas and methane gas production rate (GPR) and specific gas production (SGP).

Process Parameter	Variable	Unit	Feeding Phase	No. of Values	Mean ± Std.dev.	Minimum	Maximum
Biogas composition	CH_4	[%wt]	1	37	57.1 ± 1.2	54.4	60.0
			2	4	59.5 ± 2.8	56.3	62.4
			3	51	54.7 ± 1.9	51.0	57.6
			4	34	53.3 ± 2.3	46.6	57.1
			5	36	52.1 ± 1.2	49.7	54.1
			6	28	52.6 ± 0.9	51.4	54.7
			7	88	53.0 ± 1.2	50.5	56.6
	CO_2	[%wt]	1	27	42.4 ± 1.1	39.6	44.2
			2	3	41.1 ± 2.6	38.4	43.5
			3	51	44.7 ± 1.8	42.2	48.7
			4	34	46.2 ± 2.2	42.6	53.1
			5	20	47.7 ± 1.3	45.4	50.3
			6	19	47.0 ± 1.0	45.2	48.5
			7	52	46.8 ± 1.3	43.4	49.4
GPR	GPR Biogas	[$Nm^3 \cdot d^{-1}$]	1	46	0.317 ± 0.047	0.228	0.433
			2	28	0.232 ± 0.035	0.140	0.291
			3	56	0.299 ± 0.070	0.119	0.441
			4	35	0.301 ± 0.052	0.199	0.438
			5	36	0.581 ± 0.162	0.238	0.238
			6	26	0.552 ± 0.115	0.297	0.297
			7	88	0.668 ± 0.036	0.262	1.109
	GPR CH_4	[$Nm^3 \cdot d^{-1}$]	1	37	0.186 ± 0.025	0.132	0.241
			2	4	0.147 ± 0.010	0.135	0.155
			3	51	0.164 ± 0.038	0.068	0.231
			4	34	0.160 ± 0.025	0.114	0.215
			5	36	0.303 ± 0.086	0.129	0.418
			6	23	0.307 ± 0.036	0.218	0.388
			7	88	0.353 ± 0.123	0.141	0.424
SGP	SGP Biogas	[$Nm^3 \cdot kgVS^{-1}$]	1	45	0.129 ± 0.054	0.054	0.358
			2	27	0.191 ± 0.037	0.148	0.304
			3	54	0.110 ± 0.035	0.025	0.194
			4	33	0.097 ± 0.047	0.059	0.277
			5	32	0.207 ± 0.113	0.055	0.514
			6	23	0.198 ± 0.048	0.132	0.316
			7	75	0.250 ± 0.119	0.095	0.825
	SGP CH_4	[$Nm^3 \cdot kgVS^{-1}$]	1	35	0.069 ± 0.013	0.032	0.105
			2	4	0.140 ± 0.037	0.103	0.186
			3	49	0.060 ± 0.019	0.013	0.104
			4	31	0.050 ± 0.023	0.033	0.133
			5	27	0.092 ± 0.033	0.041	0.174
			6	20	0.104 ± 0.027	0.071	0.173
			7	75	0.132 ± 0.062	0.052	0.439

Table 7. Skewness, kurtosis, and median values of the biogas composition, and biogas and methane gas production rate (GPR) and specific gas production (SGP).

Process Parameter	Variable	Unit	Feeding Phase	No. of Values	Skewness	Kurtosis	Median
Biogas composition	CH_4	[%wt]	1	37	0.041	0.571	57.3
			2	4	−0.167	−1.191	–
			3	51	−0.297	−1.401	44.7
			4	34	−3.061	2.19	53.8
			5	36	−1.043	−0.722	52.2
			6	28	0.773	−0.717	52.5
			7	88	0.543	0.326	53.1
	CO_2	[%wt]	1	27	−1.652	1.25	42.3
			2	3	−0.383	–	–
			3	51	0.934	−1.069	43.6
			4	34	3.808	3.712	45.7
			5	20	0.478	−0.446	48.2
			6	19	−0.257	−0.962	46.6
			7	52	−1.431	0.653	46.8
GPR	GPR Biogas	[$Nm^3 \cdot d^{-1}$]	1	46	1.231	−0.350	0.311
			2	28	−1.027	1.151	0.232
			3	56	−0.473	−0.079	0.295
			4	35	1.028	0.835	0.303
			5	36	−2.012	−0.395	0.639
			6	26	−2.098	0.995	0.582
			7	88	0.161	−2.276	0.674
	GPR CH_4	[$Nm^3 \cdot d^{-1}$]	1	37	−0.197	0.073	0.188
			2	4	−0.444	−1.202	–
			3	51	−0.761	−0.559	0.168
			4	34	0.588	−0.33	0.157
			5	36	−1.944	−0.643	0.339
			6	23	−0.172	1.138	0.310
			7	88	0.000	−2.399	0.351
SGP	SGP Biogas	[$Nm^3 \cdot kgVS^{-1}$]	1	45	8.717	16.069	0.118
			2	27	3.400	2.619	0.182
			3	54	1.225	0.748	0.104
			4	33	6.655	9.930	0.084
			5	32	2.940	1.566	0.193
			6	23	2.462	0.869	0.185
			7	75	8.592	16.019	0.248
	SGP CH_4	[$Nm^3 \cdot kgVS^{-1}$]	1	35	0.240	1.828	0.069
			2	4	0.375	−0.860	–
			3	49	1.195	0.743	0.054
			4	31	6.431	9.402	0.046
			5	27	0.570	0.032	0.080
			6	20	2.450	0.980	0.095
			7	75	9.078	17.583	0.130

As already mentioned in Section 2.4, skewness and kurtosis indices show that, except for SGP of biogas, the considered parameters can be attributed to a normal distribution, but variances of the two groups differ. Thus, comparisons were made on medians instead of mean values.

The outcomes of the Kruskal–Wallis test performed on the feeding phases "3", "4", "5", and "6", which are the most representative phases with respect to the treatments applied in this work (C1 and C2; presence/absence of enzymes), are shown in Figure 11.

The main outcomes of the two comparisons, "3" and "6", and "4" and "5", are described below.

Methane content [%wt] showed a tendency to lower median values when C is higher (C2) and higher values for the lower C regime (C1). This is confirmed by the Kruskal–Wallis test. Conversely, the behavior of the median value of the CO_2 content in biogas is opposite to the methane content, and it was higher for the higher C regime (C2). This is due to the addition of new raw material that modifies the reactions towards acidogenic conditions and promotes an increase of the CO_2 content in biogas with respect to the effect of the digestate recirculated, containing an amount of undigested substrate that is less reactive.

An increase of C led to an increase of GPR (median values: Phase "3": 0.295 $Nm^3 \cdot d^{-1}$; phase "4": 0.303 $Nm^3 \cdot d^{-1}$; phase "5": 0.639 $Nm^3 \cdot d^{-1}$; phase "6": 0.582 $Nm^3 \cdot d^{-1}$). When the enzymatic treatment was not applied (phase "3" and phase "6"), the higher C regime (C2) corresponded to an increase of the GPR_{biogas} median values of 92.1%. This was about 116.6% when bioenhancers were applied.

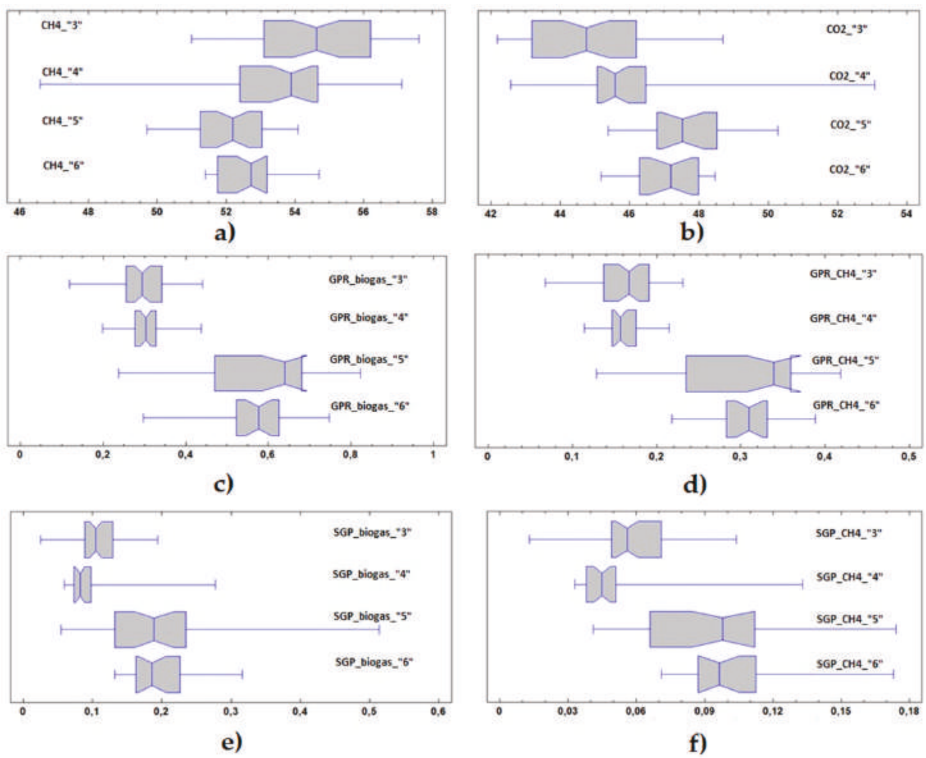


Figure 11. Box-and-whisker plots of the feeding-phases "3"–"6" and "4"–"5". Kruskal–Wallis test on the statistic variables: CH_4 content in biogas (**a**), CO_2 content in biogas (**b**), gas production rate (GPR) biogas (**c**), GPR methane (**d**), specific gas production (SGP) biogas (**e**) and SGP methane (**f**).

$GPR_{methane}$ showed similar trends observed for GPR_{biogas}: Higher values in the phases characterized by the C2 regime (median values: Phase "5": 0.339 $Nm^3 \cdot d^{-1}$; phase "6": 0.310 $Nm^3 \cdot d^{-1}$) than in those related to the C1 treatment (median values: Phase "3": 0.168 $Nm^3 \cdot d^{-1}$; phase "4": 0.157 $Nm^3 \cdot d^{-1}$). Hence, the increase due to the higher C regime was, respectively, +115.9% and +84.5% with and without enzymes.

With regard to the SGP of biogas/methane, an increase of C values led to higher energy yields.

The increase of SGP_{biogas} due to the increment of C was +77.9% without enzymatic treatment and +129.8% with enzymatic treatment. Thus, the coupling of a higher C regime with the addition of enzymes allowed the best management of the pilot plant to be obtained.

Essentially, similar behavior was observed for $SGP_{methane}$: The increasing of C promoted $SGP_{methane}$ (+165.9%) when enzymes were not applied. The increase associated with the enzymatic treatment was +73.9.

Statistically significant differences were found between phases "5" and "6" and phases "3" and "4", for all the parameters considered in the statistical analysis. Thus, it is reasonable to assert that variations of C influence all the parameters contributing to energy yields (SGP, GPR). The enzymatic treatment, instead, showed statistically significant differences in SGP in phases characterized by lower C values ("3" and "4").

The results of the Mann–Whitney test on the feeding phases "6" and "7", performed in order to assess the effect of the enzymatic treatment when the biodigester is managed by applying higher values of C, are reported in the box-and-whisker plot of Figure 12.

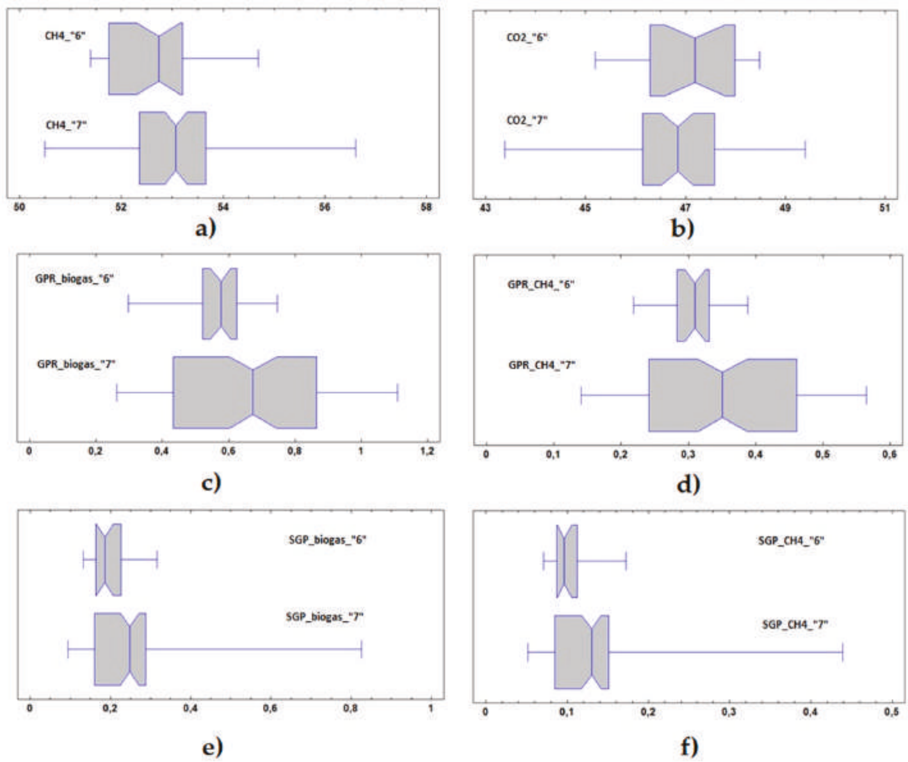


Figure 12. Box-and-whisker plots of the feeding-phases "6" and "7". Mann–Whitney test on the statistic variables: CH_4 content in biogas (**a**), CO_2 content in biogas (**b**), Gas Production Rate (GPR) biogas (**c**), GPR methane (**d**), Specific Gas Production (SGP) biogas (**e**) and SGP methane (**f**).

Skewness and kurtosis (Table 7) showed normal distributions of CH_4 and CO_2 contents in biogas, but SGP and GPR deviated from normality.

The Mann–Whitney test did not show any statistically significant difference in CH_4 content. Similar results were obtained for the CO_2 content in biogas (median of phase "6": 47.2% wt, median of phase "7": 46.8% wt).

SGP and GPR of biogas and methane were higher in the last phase of the experiment (with enzymatic treatment) than the second-last phase (without enzymes). More specifically, GPR and SGP of biogas and methane in the seventh phase reached the maximum values of the entire experimental campaign.

Concerning $GPR_{methane}$, any statistically significant difference was found between the two feeding phases (median value of phase "6": 0.310 $Nm^3{\cdot}d^{-1}$, median value of phase "7": 0.351 $Nm^3{\cdot}d^{-1}$).

More generally, in the last feeding phase, characterized by the enzymes, SGP and GPR of biogas and methane were higher than in the previous periods. Thus, the best management of the biodigester was characterized by this combination: A higher percentage of new hemp straw in the admixtures (C2) coupled with enzymatic addition.

4. Conclusions

The experimental campaign carried out on the cultivar "Futura 75" grown on the pilot site "San Giovanni Suergiu" (Sardinia, Italy) allowed an assessment of the effectiveness of using *Cannabis sativa* L. straw residues as a substrate for anaerobic digestion at an industrial scale and to enhance the management of the biodigester fed with hemp straw residues.

In this work, the feasibility of using this substrate in anaerobic digestion (which is currently often underutilized) was evaluated.

Results in terms of GPR and SGP of biogas/methane are promising, especially if compared to other vegetable feedstocks commonly used in anaerobic digestion and by considering that industrial hemp is characterized by higher values of lignin, which leads to high recalcitrance [59,60]. However, the SGP of biogas/methane is lower compared to corn silage, commonly used in industrial plants of anaerobic digestion (common values of about 0.7 to 0.85 $Nm^3 \cdot kg_{VS}^{-1}$), but the low cost of hemp straw residues and their behavior in the anaerobic digestion contribute to the definition of this by-product as a good process moderator when using other types of biomass leading easily to process instability.

The comparison between the findings of this work and the literature related to previous experiments carried out on a laboratory scale led to the assertion that biogas and methane yields provided by the trials carried out on hemp straw residues in the Sardinian pilot digester are similar or higher than those provided by the previous studies based on few liters-capacity reactors. It should be considered that differences in the energy yields reported may depend on environmental conditions (climate, soil type, crop management, etc.), the different cultivars used, hemp stage (vegetative versus reproductive stage), and hence, chemical and physical characteristics (such as TS, $VS_{d.b.}$, carbon:nitrogen ratio, etc.).

Results of SGP are close to those of other lignocellulosic crops but lower than those produced by highly degradable vegetable feedstocks studied through the same pilot plant. It suggests conducting additional experimental studies on hemp straws residues as a co-substrate in anaerobic digestion involving one or more easily digestible types of biomass.

Energy yields of anaerobic digestion carried out on hemp straw residues are influenced by different operating conditions: Increased feeding admixture composition (depending on C and R) produced a statistically significant increase in terms of methane content in biogas and of the parameters influencing GPR and SGP. Enzymatic treatments tended to enhance the SGP of biogas/methane.

The fluid dynamics of hemp-digestate admixtures play an important role in digestion kinetics, affected by solid–liquid separation and solid particles' tendency to sedimentation. Thus, further research should pay attention to this topic, to define relationships between the reactor and specific characteristics of admixtures.

These prodromal studies based on pilot-scale experiments on *Cannabis sativa* L. residues should be continued by analyzing more extensive conditions for factors inhibiting anaerobic digestion of hemp (e.g., heavy metals absorbed by roots, straw, leaves, and seeds during plant growth), and to different daily intakes of enzymatic preparations. Further investigations should pay attention to the enzymatic or other chemical additives' effects on energy yields (GPR, SGP, etc.).

The sustainability of hemp straw residues' biogas conversion should be evaluated as well, to define achievable costs and economic benefits. This hypothetical chain based on this emerging crop must be compared to the most commonly used energy feedstock. The main advantage in the energy conversion of hemp straws residues is to use a by-product of a cultivation carried out to obtain seeds as the main product: The consumption of water and fertilizers, however limited, is necessary to obtain seeds and no other input is spent, except for harvest and transport operations from the field to the plant.

In addition, with respect to the hemp-related supply chain, it has to be considered that relevant constraints to industrial hemp market development are fewer innovations in harvesting technologies and processes or processing facilities, as well as transportation/distribution issues (mainly due to the high low bulk density of this type of biomass) [61]. New research should overcome these current limits of industrial hemp exploitation and valorization to ensure more effective development of sustainable supply chains.

The results of this study produce a baseline to stimulate new perspectives of using hemp straw residues in the biogas sector and to inspire its consideration in the biorefinery thinking.

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

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Impact of Climate Change on Twenty-First Century Crop Yields in the U.S.

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Abstract: Crop yields are strongly dependent on the average climate, extreme temperatures, and carbon dioxide concentrations, all of which are projected to increase in the coming century. In this study, a statistical model was created to predict US yields to 2100 for three crops using low and high-emissions future scenarios (RCP 4.5 and 8.5). The model is based on linear regressions between historical crop yields and daily weather observations since 1970 for every county in the US. Yields were found to be most strongly dependent on heat waves, summer average temperatures, and killing degree days; these relationships were hence used to predict future yields. The model shows that warming temperatures will significantly decrease corn and soybean yields, but will not have as strong of an influence on rice. Before accounting for CO_2 fertilization, crops in the high-emissions scenario are predicted to produce 77%, 85%, and 96% of their expected yield without climate change for corn, soybeans, and rice, respectively. When a simple CO_2 fertilization factor is included, corn, a C4 plant, increases slightly, while the yields of the C3 plants (soybeans and rice) are actually predicted to increase compared to today's yields. This study exhibits the wide range of possible impacts of climate change on crop yields in the coming century, and emphasizes the need for field research on the combined effects of CO_2 fertilization and heat extremes.

Keywords: future crop yields; climate change impacts; CO_2 fertilization; corn; rice; soybeans

1. Introduction

1.1. Impacts of Climate Change and the Social Cost of Carbon

On 8 October 2018, the Intergovernmental Panel on Climate Change (IPCC) released a new report titled *Global Warming of 1.5 °C*, which concludes that drastic action must be taken to limit global temperature rise and avoid serious negative impacts. It finds that natural, managed and human systems have a high risk of permanent damage as the climate warms. Extreme weather events will occur more often, including droughts, floods, coastal storms, and heat waves, increasing mortality and property damage. As warmer temperatures combine with more extreme weather events, cereal yields will decrease [1,2]. If we fail to limit fossil fuel combustion, all of the effects will increase [3].

Also on 8 October, the Nobel Prize in Economic Science was awarded to Paul Romer and William Nordhaus for their research on using economics as a driving factor to reduce greenhouse gas emissions [4]. Nordhaus, recognized as the founder of climate change economics, developed economic models to weigh the cost of reducing carbon footprints today against future costs of current emissions [5]. Romer focused on how market factors influence technological growth. Both advocate carbon taxes to employ market forces to reduce emissions and spur innovation in energy efficiency.

The correct amount to tax carbon may be found through the social cost of carbon, or the external cost of carbon emissions. The social cost of carbon is calculated by integrating all future economic losses due to climate change discussed in the IPCC. In total, warming temperatures cause a loss of annual national average gross domestic product (GDP) of 1.0% to 3.0% at the end of the century [6]. Agriculture is a substantial portion of the economy, and crop yields are highly dependent on temperature. Other impacts are more difficult to put a price on, such as biodiversity and ecosystem loss. The currently accepted cost of carbon dioxide when considering these externalities varies between $37 and $220 per ton emitted [7].

1.2. Warming Temperatures Impact Agriculture

The United States produces 41% of the world's corn and 38% of the world's soybeans, two of the four largest crop sources of caloric energy [8]. These crops are thus crucial to food security, and understanding how their yields will change in the next century could help drive more informed policy decisions.

The growing world population requires a larger food supply. Historical improvements in crop yields from agricultural technology (e.g., pesticides, fertilizers, farm machinery, gene modification, and shifting of production to large corporations [9]) have kept up with increasing demand for several decades, but it is doubtful that yields will continue to grow at the same rate as they have since 1970. Population is unlikely to stop growing this century, and by 2100 there will be between 9.6 and 12.3 billion people on earth [10]. Research has shown that yields are projected to drop in coming decades due to warming temperatures and the potential emergence of virulent crop diseases [11,12].

Crop yields are strongly dependent on the weather and may be predicted from observed weather events during the growing season [13–16]. Over 60% of yield variability in global breadbaskets can be explained by climate variation [17], particularly temperature extremes during crucial phases of the growing season, such as the grain fill stages [18]. Some research suggests that yields decrease exponentially as temperatures warm [8]. Therefore, a warming climate could harm crop yields and global food security. In fact, corn and wheat yields have already decreased by 1–2% per decade since 1980 relative to the expected harvest without warming [19].

There are many different approaches to identifying the the impacts of climate change on crop yields. Statistical models, including this study, use historical correlations from observations to develop empirical relationships between yields and weather. These relationships are then applied to climate model output to predict future crop yields. Process models are based on the mechanisms of an individual plant's physiology and then are scaled up to large domains. Each type of model has its own advantages and disadvantages. Statistical models are accurate for the specific locations and conditions of their training data sets, and are a direct way to model yields within those constraints [20,21]. Process models offer a deeper understanding of the cause and effect of the environmental impacts on yields, and they can potentially model future yields outside of historical observations. Process models have become more sophisticated in recent years [22], but still have difficulty reproducing historical yields in certain circumstances [23].

Many previous studies have analyzed the relationships between crop yields and emperature [13,24,25], precipitation [14,26,27], or radiation measurements [28,29], and have predicted future yields based on these relationships [13,26,30]. These models may be statistical [17,31], process-based [30,32], or both [33], and have focused on US [14,24,33], China [23,25,29,31,32], Europe [28,30], or global bread baskets [15,17,27]. All of these studies conclude that climate change will have a negative impact on future crop yields, and bread basket failures could pose a threat to food security.

The purpose of this study is to evaluate the future economic losses or gains of three crops through 2100 for different climate scenarios. It examines the historical relationship between crop yields and extreme weather to better understand which factors affect yields, and then projects crop yields into the future for every county in the United States. This study also incorporates CO_2 fertilization to show the range of possible future impacts from these processes. Finally, a monetary value of changing crop yields is calculated, an integral part to the social cost of carbon.

2. Methods

A statistical model was created to evaluate historical weather and crop data, compute correlations and linear regressions for each county, and project crop yields to 2100 based on two future climate model scenarios. Annual crop yield data of corn, soybeans, and rice was obtained for every US county for 1970 through 2015 from the United States Department of Agriculture (USDA, [34]). In addition, 1970 was chosen as a start date because yields were more variable and the farming practices were not as standardized before then (e.g., irrigation, pesticides, fertilizers). Daily weather station observations, provided by the Daily Global Historical Climatology Network [35], were downloaded for all weather stations in the US with data since 1970. Daily minimum and maximum air temperature and precipitation were computed for each county from the average of the two weather stations closest to the center of that county. This provided redundancy—if one station was missing data, the other station's data was used.

Next, various means and extremes were computed for each county and year. Most of these are standard measures reported by the Intergovernmental Panel on Climate Change (IPCC, [36], Box 2.4 p. 221). Table 1 lists all extremes computed from the daily temperature. Values of the 10th and 90th percentile for each variable and county were computed from the daily data from the years 1970 to 1990. The extreme measures were computed over the growing season, which varies for each crop and state, and were obtained from the USDA [37].

Table 1. Temperature measures computed to find correlations to crop yields. Summer average temperature, heat waves, and killing degree days had the highest correlation, and thus were used as predictors of crop yields. All statistics after the first four are summed over the growing season for each crop and location. Here, highs and lows refer to the recorded daily high and low temperature at each site.

Measurement	**Definition**	**Units**
Average Yearly high	Average of all daily highs in a year	°C
Average Yearly low	Average of all daily lows in a year	°C
Summer Average	Average of all daily max temps over months June, July, and August	°C
Warmest Day	The warmest high in the growing season	°C
Coldest Day	The coldest high in the growing season	°C
Warmest Night	The warmest low in the growing season	°C
Coldest Night	The coldest low in the growing season	°C
Heat Waves of highs	Frequency of 3 daily highs in a row >90th percentile	#/year
Heat Waves of lows	Frequency of 3 daily lows in a row >90th percentile	#/year
Cold Spells of lows	Frequency of 3 daily lows in a row <10th percentile	#/year
Cold Spells of highs	Frequency of 3 daily highs in a row <10th percentile	#/year
Warm Days	Days when daily high >90th percentile	days/year
Cold Days	Days when daily high <10th percentile	days/year
Warm Nights	Days when daily low >90th percentile	days/year
Cold Nights	Days when daily low <10th percentile	days/year
Tropical Nights	Frequency of daily lows >20 °C (68 °F)	days/year
Frost Nights	Frequency of daily lows <0 °C (32 °F)	days/year
Growing Degree Days	Summation of daily highs above 10 °C (50 °F)	°C*days
Killing Degree Days	Summation of daily highs above 29 °C (68 °F) [13]	°C
Precipitation	Total precipitation	mm/year

Correlations between the detrended crop yield and each of the weather statistics were then computed for each county and crop. In order to account for increasing crop yields due to improvements in agricultural technology, the yields were first detrended for each county. Figure 1a shows the increase in corn yields since 1970 in an example county of Champaign, Illinois, and Figure 1b shows the correlation between the detrended corn yield and summer average temperature for that same county. Correlations with a p-value less than 0.05 are considered significant and ones under 0.01 are highly significant [38]. The three with the highest correlations were summer average temperature, heat waves, and killing degree days. Thus, these three statistics were used to predict future yields. Although regressions were also computed with precipitation, it was found to have little to no correlations with yields.

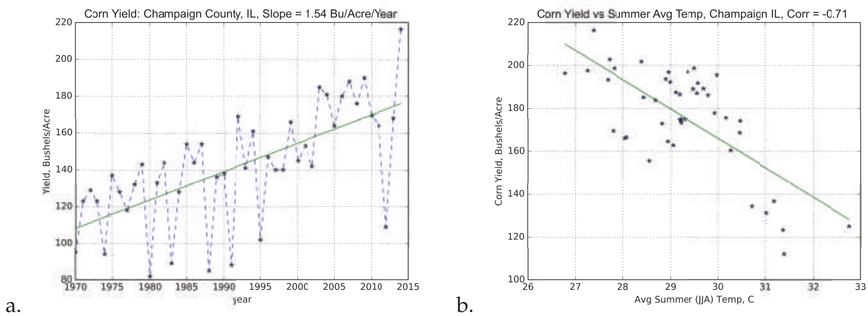

Figure 1. The corn yield over time for an example county (**a**) and detrended corn yield plotted against summer average temperature (**b**). The correlation of −0.71 is highly significant. Data is from the USDA [34].

Future climate model data was obtained from the Coupled Model Intercomparison Project Version 5 (CMIP5), using the Community Climate System Model (CCSM4) [39], and was obtained from the MACA data portal. I downloaded datasets for two IPCC scenarios: a high emission future with a Representative Concentration Pathway (RCP) that induces an extra 8.5 W/m^2 of radiative forcing (RCP 8.5) and a low emissions scenario with an RCP of 4.5 W/m^2 (RCP 4.5). Climate forcings in the MACAv2-METDATA were drawn from a statistical downscaling of global climate model data from CMIP5 [40] utilizing a modification of the Multivariate Adaptive Constructed Analogs (MACA) [41] method with the METDATA [42] observational dataset as training data. The climate data had high resolution in space (one-tenth of a degree) and time (daily). Summer average temperature, heat waves, and killing degree days were computed for each county for every year until 2100, using data from the closest model grid-cell to the center of each county. The histograms displaying these future heat measurements (Figure 2) were computed using a latitude/longitude rectangle around the dominant corn-growing region, with corners at (40N, 100W), (44N, 85W).

Crop yields were then predicted by applying the historical linear regressions to the future projections of summer average temperature, heat waves, and killing degree days. For each county, the crop predictions from the three statistics were averaged, as each measure predicted the yields slightly differently. National averages of crop yields were computed by averaging all counties that either consistently grew their crop over the past 10 years or grew at least 10% as much as the highest-producing county for that crop.

After future crop yields were predicted from temperature projections, the yield was multiplied by the expected yield factor from CO_2 fertilization. Future carbon dioxide concentrations to 2100 for RCP8.5 and RCP4.5 scenarios were obtained from [43]. The yield factor is the change in yield due to carbon dioxide fertilization, where 0.8 is a 20% reduction and 1.2 is a 20% increase in yield. The yield factor for C3 and C4 crops under different CO_2 concentrations (Figure 3) was acquired from [44], in which results from the DSSAT4 models [45] were interpolated based on CO_2 enrichment experiments, and were then normalized at 2015 CO_2 concentrations. Figure 4 displays the yield factor due to carbon dioxide fertilization to year 2100 for C3 and C4 crops under low and high-emissions scenarios.

Crop yields in the US have improved in recent decades due to better technologies. In fact, corn yields have doubled since 1970. It is not known whether these trends will continue to hold in the future or if biological constraints will impose maximum achievable crop yields. In this study, best and worst case scenarios were computed as a proxy for all possible futures. For the best case scenario of continuous technology improvement, the historical trend was added to the future yield predictions. For the worst case scenario of no future technology improvement, no trend was added to the yield predictions.

Ultimately, future yield forecasts were computed based on three sets of indicators: (1) only temperature changes, (2) only CO_2 fertilization, and (3) both combined. Each of these predictions were then split into two technology scenarios: (1) no technology improvement and (2) continuous technology improvement, resulting in six forecasts for each crop.

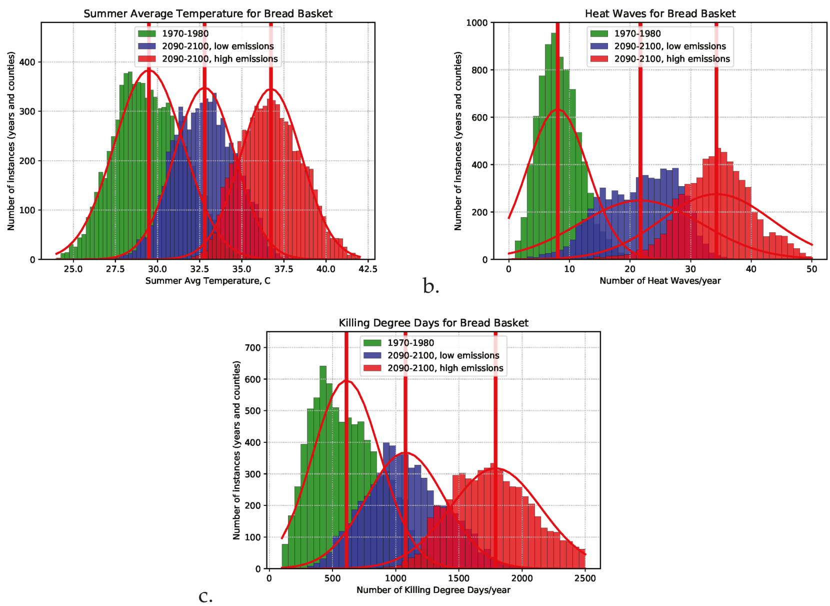

Figure 2. Distributions of summer average temperature (**a**), heat waves (**b**), and killing degree days (**c**) for historical (green), future low-emissions RCP 4.5 scenario (blue) and future high-emissions RCP 8.5 scenario (red). Results are for the US corn growing region. Historical data from [35] and future projections from [41].

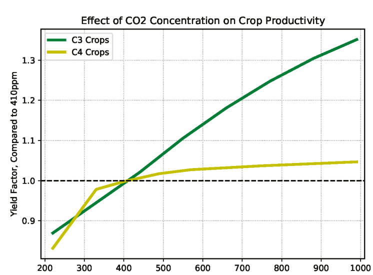

Figure 3. Yield factor for C3 (green) and C4 (yellow) crops versus CO_2 concentration. Crop productivity was acquired from [44], in which results from the DSSAT4 models [45] were interpolated based on CO_2 enrichment experiments.

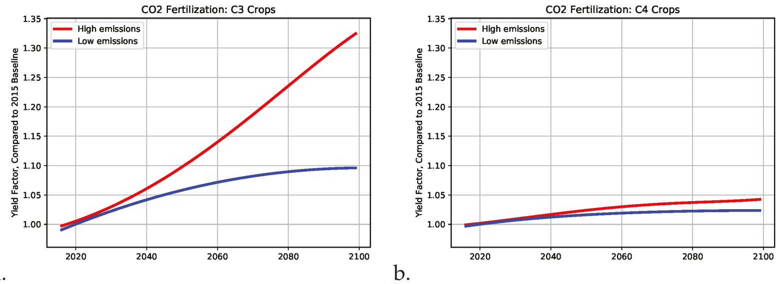

Figure 4. Yield factor for C3 (**a**) and C4 (**b**) crops through 2100 for a low (blue) and high (red) emissions scenario. Crop productivity under CO_2 concentrations was obtained from [44], and CO_2 concentrations for RCP4.5 and RCP8.5 are from [43].

3. Results

3.1. Historical Correlations and Regressions

The slopes of the linear regressions computed between crop yields and weather statistics for every county in the US can be seen in Figure 5. Almost all of the slopes are negative, meaning that higher temperatures result in lower crop yields. Corn has average correlations of −0.44, −0.46, and −0.41 to summer average temperature, heat waves, and killing degree days, respectively (Figure 6), and three in every five counties have a significant correlation. All temperature indices have similar correlations, indicating that all three have similar predictive power. Corn and soybeans observe large geographical distributions in the eastern and central US, while rice is mostly grown along the Mississippi River. Spatial variations of slopes and correlations can be examined for corn and soybeans. In southern growing regions (Missouri, southern Illinois, and Indiana), slopes are very negative with highly significant correlations (Figures 5 and 6). Crops here are thus extremely sensitive to heat extremes. In contrast, slopes and correlations farther north (Minnesota and South Dakota) are about zero, indicating that the yields are not affected by temperatures classified as extreme events in these states. The correlations with heat waves, summer average temperature, and killing degree days all follow similar geographic distributions. These results indicate that the places where crops are grown will likely shift north over time, where average temperatures are cooler.

Heat waves have the highest impact on all three crops. Corn has the strongest correlation to heat measurements, soybeans have a slighly weaker correlation, and rice has little to no correlation to temperatures. When averaged across crop-growing counties, soybeans have a correlation of −0.37 with heat waves, and about half of the counties have significant correlations. Rice has an average correlation −0.22 with heat waves and no counties have significant correlations (Figure 6).

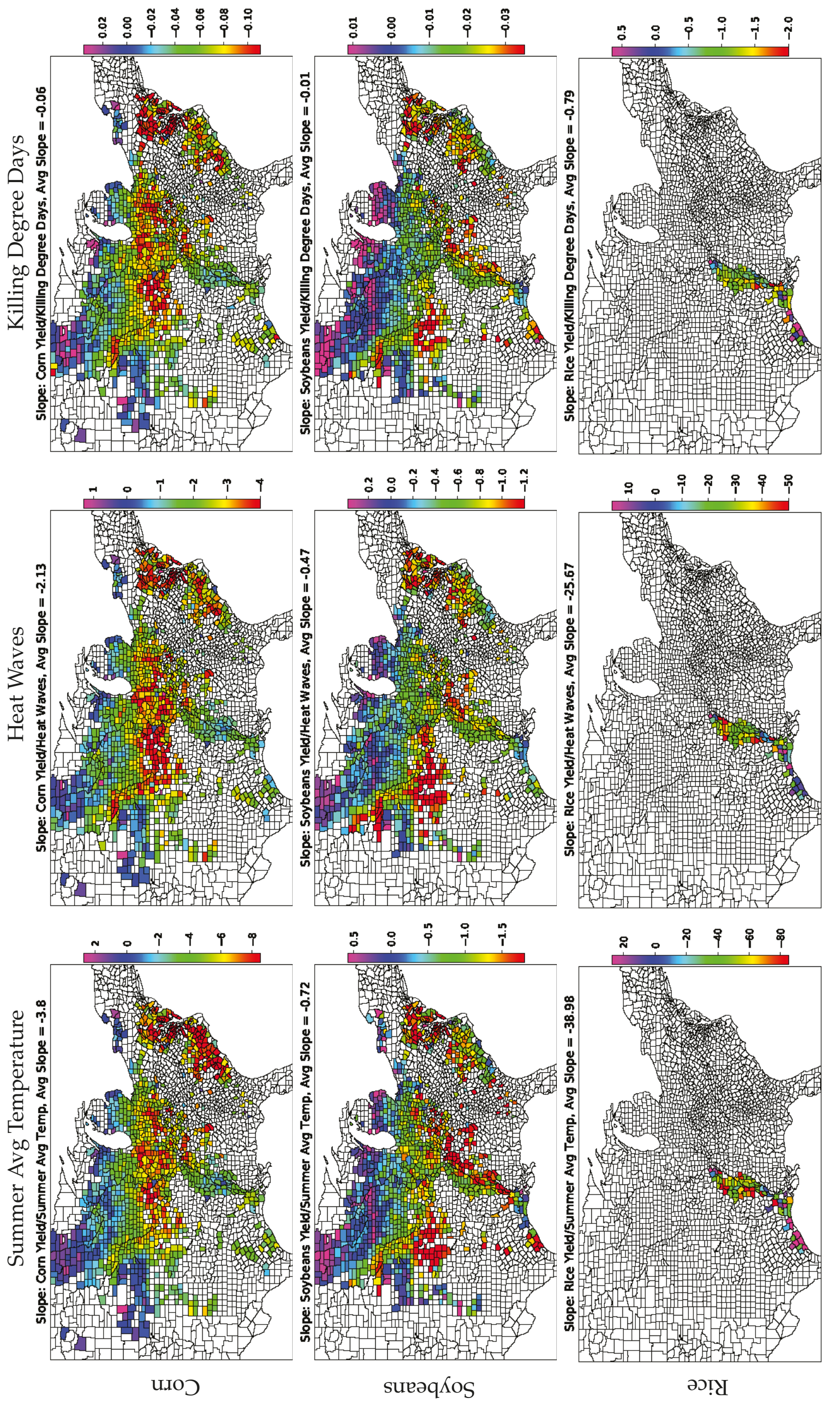

Figure 5. The slopes of the linear regressions between corn (top), soybean (middle), and rice (bottom) yields and summer average temperature (left), heat waves (center), and killing degree days (right), in each US county with reported crop yields.

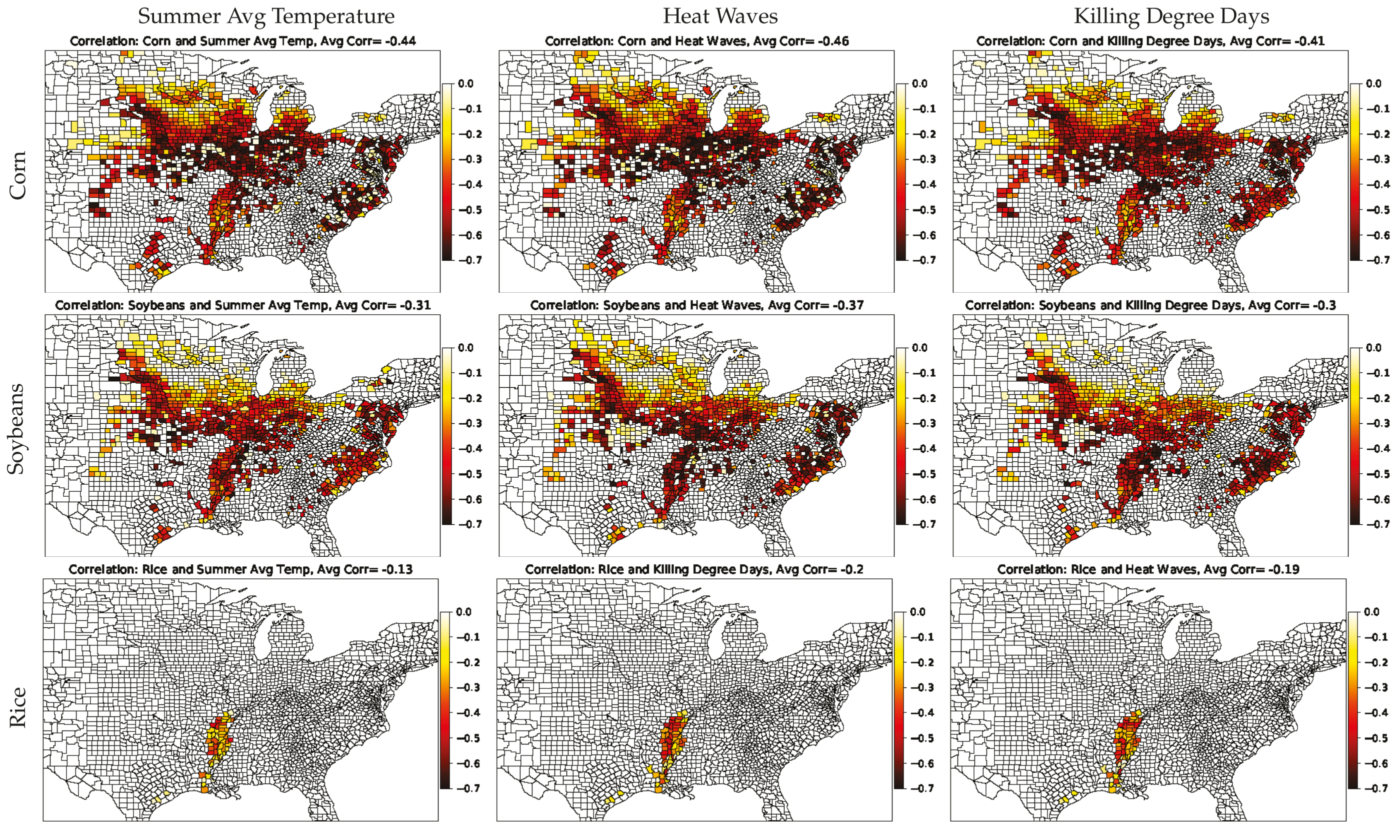

Figure 6. The same as Figure 5, but for correlations between the crop yield and the temperature metric. Correlations below −0.49 are significant ($p < 0.05$) and below −0.59 are highly significant ($p < 0.01$).

3.2. Prediction of Future Crop Yield

Heat extremes are expected to increase in the coming century. Histograms of the three heat measurements are shown for three different times and scenarios: 1970–1980 observed, 2090–2100 low emissions, and 2090–2100 high emissions, over the corn growing counties (Figure 2). Both mean and extreme temperatures dramatically increase in the future, with high emission scenarios increasing more than low emission. For example, the average summer daily high temperature was 29 °C (85 °F) in 1970 to 1980. In 2090 to 2100, the summer average temperature is projected to be 33 °C (91 °F) for RCP 4.5 and 36 °C (97 °F) for RCP 8.5. Heat waves and killing degree days are also expected to increase dramatically (Figure 2b,c). Interestingly, the tails of histograms in the future are much wider, indicating higher probabilities of extreme weather events.

Historical regressions and future climate extremes were used to predict future yields to 2100 for each county, year, and crop. First, results without CO_2 fertilization will be presented, followed by those including CO_2 fertilization.

Before accounting for CO_2 fertilization, crop yields are projected to dramatically drop in the coming century. Forecasted crop yields, with and without future technology improvements, can be seen in Figure 7. In addition to having the highest correlations, corn is also affected the most by the warming climate. Average US corn yields doubled from 80 bushels/acre in 1970 to 170 bushels/acre in 2015. Predicted yields in 2096 through 2100 drop to 76% (86%) of expected yields without warming for a high (low) emissions scenario. This translates to a 3.8% decrease in corn yields per decade for a high emissions scenario and a 1.8% decrease per decade for a low emissions scenario, compared to a historical 24% increase in corn yields per decade due to agricultural technology improvements. For more details, refer to Table 2.

Table 2. Statistics on future yield predictions, for forecasts without and with CO_2 fertilization. Future yield change per decade are in comparison to expected yields without climate change. Monetary losses are calculated from the acres harvested and the crop prices in 2016 [46,47].

	Corn		**Soybeans**		**Rice**	
Historical yield change/decade (%)	23.7		17.7		17.4	
Future: low emissions	no CO_2	with CO_2	no CO_2	with CO_2	no CO_2	with CO_2
Yield change/decade (%)	−1.77	−1.50	−1.20	+0.002	−0.367	0.860
Projected yield diff to steady climate (%)	87.9	90.0	92.3	101	98.6	108
Monetary loss or gain (billion 2019 US$)	−12.7	−10.5	−5.00	+0.717	−0.343	+1.99
Future: high emissions	no CO_2	with CO_2	no CO_2	with CO_2	no CO_2	with CO_2
Yield change/decade (%)	−3.78	−3.41	−2.40	0.96	−0.830	3.09
Projected yield diff to steady climate (%)	76.8	80.0	84.6	111	95.7	126
Monetary loss or gain (billion 2019 US$)	−24.3	−21.0	−10.0	+7.29	−1.06	+6.42

Even with the optimistic conditions of continuous technology improvement, there is a huge loss in yields below expected yields with a steady climate. In 2100, there is a loss of $24 billion per year for high emissions and $13 billion per year for a low emissions scenario. This estimate assumes the acres harvested and the cost of corn in 2016, and does not account for inflation [46,47]. Soybeans are affected by temperature extremes slightly less than corn, with losses of $5 and $10 billion per year in 2100 for high and low emission scenarios. Rice, being least sensitive to climate change, only has losses of $0.34 and $1.06 billion per year (Table 2). Rice is the least affected by heat, likely because it is grown in flooded conditions. These computations assume the current market prices of crops and do not include CO_2 fertilization.

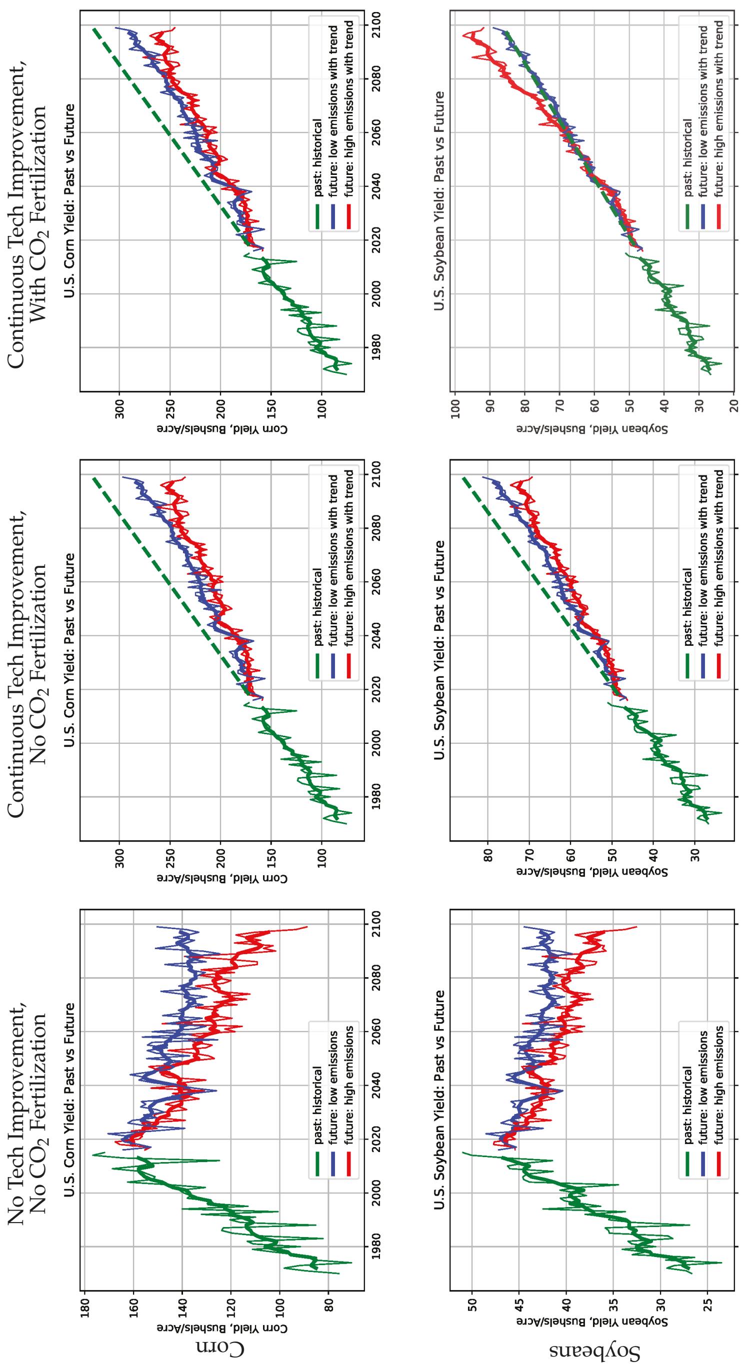

Figure 7. *Cont.*

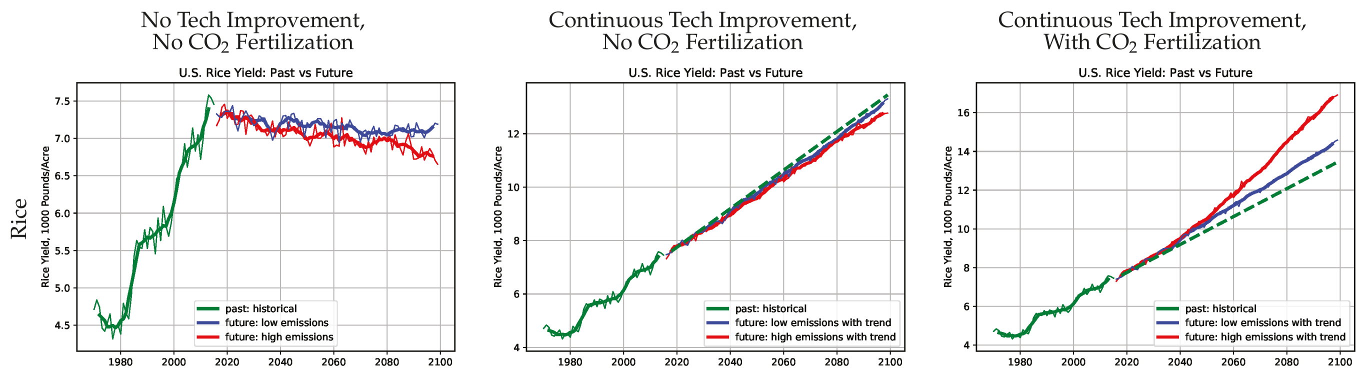

Figure 7. Projected US corn (top), soybean (middle), and rice (bottom) yields to 2100. The prediction scenarios include: (left) no technology improvement and no CO_2 fertilization; (center) continuous technology improvement and no CO_2 fertilization; and (right) continuous technology improvement with CO_2 fertilization. The green dashed line is a linear extension of the 1970–2015 trend. Thin lines are yearly data, solid is the five-year running average.

Although these results display a dismal future, the story changes when we account for CO_2 fertilization. In RCP 8.5, carbon dioxide concentrations break 900 ppm by 2100. That translates to almost 135% productivity for C3 crops (here: soybeans and rice) compared to productivity in 2015. Even for a low emissions scenario, C3 crops gain 10% productivity by the end of the century. CO_2 concentrations have a much smaller effect on C4 crops (here: corn), which reach 104% and 102% productivity in 2100 for a high and low-emissions scenario.

The projections of corn, a C4 crop, are very similar before and after accounting for CO_2 fertilization (Figure 7). Projections of soybeans and rice with CO_2 fertilization, however, are considerably higher. In fact, rice reaches 126% expected productivity by 2100 with a high emissions scenario. A summary of future crop yield estimates is shown in Figure 8.

The spatial distributions of projected crop yields may be examined (Figure 9). In 2005 through 2015, corn and soybean yields are relatively uniform across the US. In contrast, their yields are spatially disparate in 2100, with very low yields in the south and much higher yields in the northern Midwest. This distribution likely is a product of cooler climates farther north, and holds true with and without CO_2 fertilization. Few spatial differences are predicted in rice yields, as rice is grown in a relatively small geographic range and has weaker correlations to temperature.

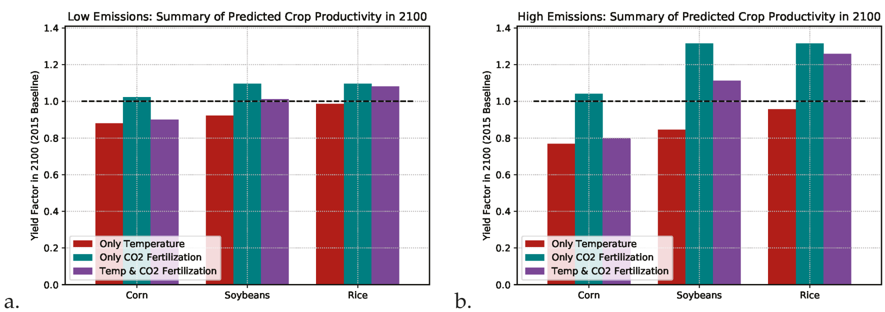

Figure 8. Crop productivity averaged over 2096–2100, compared to a 2011 through 2015 baseline for a low (**a**) and high (**b**) emissions scenario. Estimates are based on only temperatures (red), only CO_2 fertilization (teal), and both assuming compounding effects (purple).

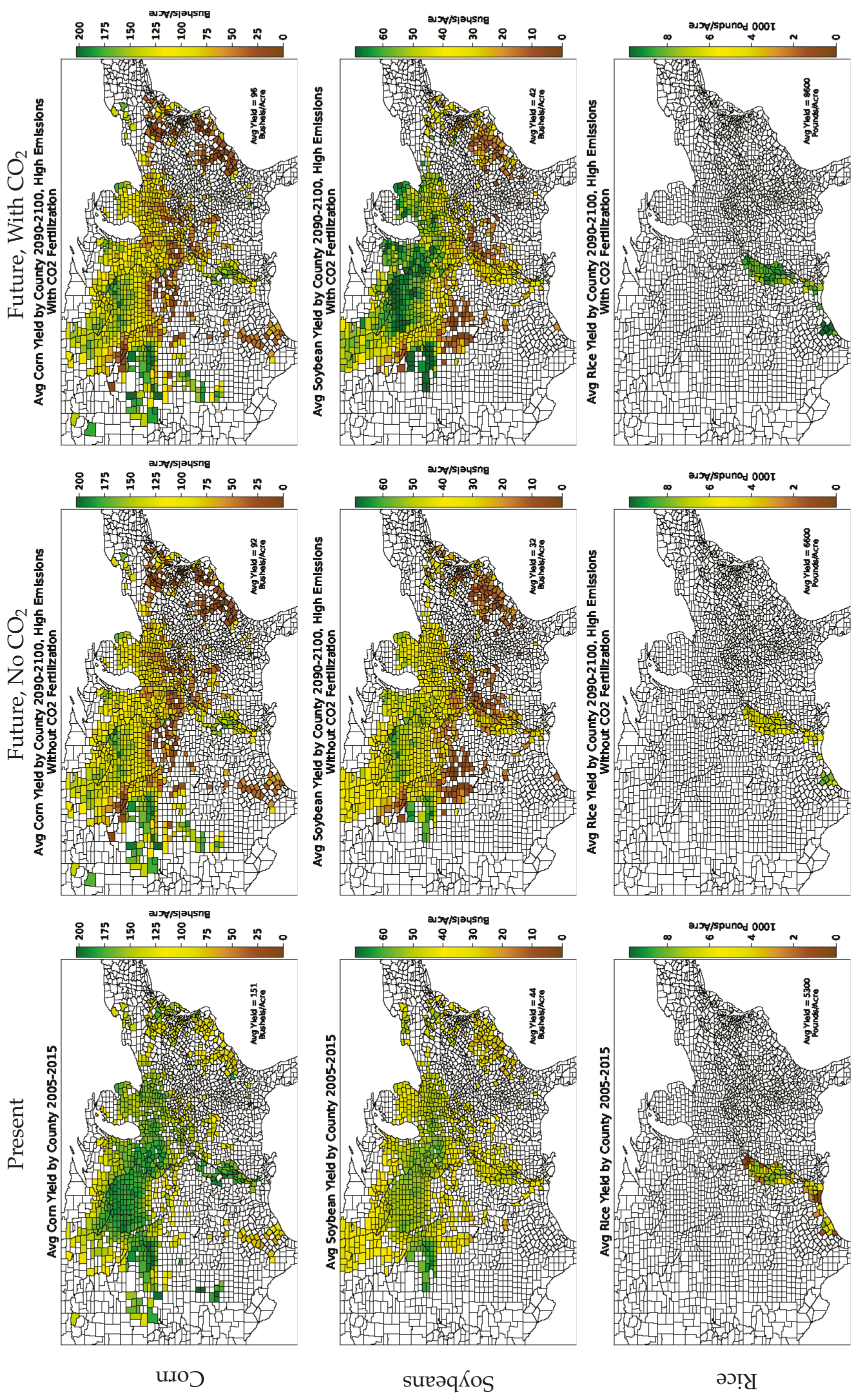

Figure 9. Crop yield of corn (top), soybeans (middle), and rice (bottom) for 2005–2015 (left), 2090–2100 without CO_2 fertilization (center), and 2090–2100 with CO_2 fertilization (right). Crop predictions are for a high-emissions scenario without future technology improvements.

4. Discussion

The purpose of this study was to analyze the potential economic losses or gains of US crop yields due to climate change by applying historical relationships between yields and heat extremes to multiple future climate scenarios, while accounting for CO_2 fertilization. Historical records give insights into factors that affect yields. The most dominant influence on crop yields since 1970 is the secular trend due to improving farming practices and technologies, where yields nearly double over that period. On top of this trend, there is year-to-year variability that can be explained by local weather. Corn, soybean, and rice yields were correlated to several measures of mean and extreme weather, and all were most strongly dependent on heat waves, summer average temperature, and killing degree days. This indicates that hot temperatures have the strongest effect on crop growth, while moderate or cold temperatures have little effect. Interestingly, precipitation had insignificant correlations with crop yields, possibly because of the prevalence of drought-resistant breeds in the US or the confounding influence of irrigation.

This study evaluates future crop yields with and without CO_2 fertilization. Without CO_2 fertilization, increasing temperatures significantly decrease crop production, with yields reaching as low as 77% of their expected productivity without climate change. In all cases, corn is most sensitive to heat, soybeans slightly less so, and rice the least, likely because rice is grown in flooded conditions. When carbon dioxide fertilization is added into the future projections, crop yields increase dramatically. Carbon dioxide concentrations alone are expected to increase C3 crop yields by 35% by the end of the century for a high emissions scenario. When the effects of CO_2 and temperatures are combined in a simple way, rice and soybean yields are actually shown to increase over the next century.

In this study, the effects of temperature extremes on crop yields were measured during historical CO_2 concentrations, while the effects of increased CO_2 concentrations were measured under laboratory conditions, independently of heat extremes. To project the effects of both together, the two factors were multiplied, but this may in fact not be how plants respond. It is unknown whether CO_2 fertilization and temperatures will have compounding physiological effects: the positive influence of CO_2 fertilization may be severely curbed at sufficient heat. Thus, more data on the effects of these combined influences is required for more accurate yield forecasts.

Projected yield losses due to climate change may be compared to past studies, shown in Table 7-2 of the IPCC Working Group II [36]. Numbers in this study compare well with the past corn and rice studies (10 and 13 studies, respectively). The soybean losses here are much greater than the 10 past publications when only accounting for temperatures, but are comparative when including CO_2 fertilization. These comparisons are complicated by the mixture of scenarios and model types in the IPCC summary, and most previous studies do not include CO_2 fertilization.

This study is very similar to [44], which predicts global crop yields for different low-emission climate scenarios, with and without CO_2 fertilization. They find that accounting for CO_2 fertilization mitigates the effect of warming temperatures. The results of this study are comparable to those of [44], since both studies find that C3 crops benefit strongly from higher carbon dioxide concentrations. The results of this study are also similar to those of [15], who use temperature, precipitation, and CO_2 fertilization to predict global corn and wheat yields. They also find clear benefits of reducing greenhouse gas emissions for corn yields, but fewer for wheat yields, as wheat is a C3 crop and benefits from CO_2 fertilization [48].

The statistical model developed here includes several assumptions. The three seasonal climate statistics only involve temperature, but crop yields may also be correlated with other conditions, such as precipitation, soil moisture, and radiation. Some other statistical models include these, but this study found much higher correlations with temperature than precipitation. Soil moisture and radiation were not available from weather station data. In order to project into the future, the model assumes that temperature continues to influence crop yields as they have historically, despite potential changes in other factors such as precipitation, soil conditions, or more advanced technologies. Another assumption is that linear regressions may be used as a predictive model for temperatures much hotter than those recorded historically, even though previous papers have found crop growth to respond nonlinearly to climate [8,49]. Despite these shortcomings, the high correlations in Figure 6 show that the climate statistics used for prediction are reasonable predictors of crop yields.

This study indicates that land in the northern United States may be more suitable for crop production as temperatures rise. Crops in the northern counties are less susceptible to events classified as extreme temperatures in those counties (Figure 6), and are forecasted to have much higher yields in 2100 (Figure 9). A limitation of a statistical model is that it can only predict crop yields in areas with sufficient crop data. Thus, this model cannot judge whether crops will have high yields in counties further north where crops have not been historically grown. A process model would be required to predict crop performance in these counties. A large unknown in this study is whether agricultural technology will continue to improve or whether crop yields will hit a fundamental biological limit. Given the difficulties of predicting future technologies, this study has instead projected a best case and a worst case scenario. Most likely, technology will have decreasing effects on crop yields due to biological constraints on production, and crop yields will increase at slower rates than have been in the last 50 years. In order to prepare for climate change, we should develop farming practices and crop breeds that are resistant to stronger and more frequent heat extremes.

This study highlights the trade-offs of climate change, where CO_2 fertilization is a potential benefit even while average temperatures and heat waves are increasing. Research to date has shown that the positive influences of CO_2 fertilization will increase yields for much of the 21st century, but will be countered by increasingly hot and dry conditions [50–52]. The results in this study exhibit the wide range of possible future impacts of climate change in the next century, and emphasize the need for continued research on the compounding effects of carbon dioxide fertilization and heat extremes.

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climate

MDPI

Perspective

Climate-Smart Agriculture and Non-Agricultural Livelihood Transformation

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Abstract: Agricultural researchers have developed a number of agricultural technologies and practices, known collectively as climate-smart agriculture (CSA), as part of climate change adaptation and mitigation efforts. Development practitioners invest in scaling these to have a wider impact. We use the example of the Western Highlands in Guatemala to illustrate how a focus on the number of farmers adopting CSA can foster a tendency to homogenize farmers, instead of recognizing differentiation within farming populations. Poverty is endemic in the Western Highlands, and inequitable land distribution means that farmers have, on average, access to 0.06 ha per person. For many farmers, agriculture per se does not represent a pathway out of poverty, and they are increasingly reliant on non-agricultural income sources. Ineffective targeting of CSA, hence, ignores small-scale farming households' different capacities for livelihood transformation, which are linked to the opportunities and constraints afforded by different livelihood pathways, agricultural and non-agricultural. Climate-smart interventions will often require a broader and more radical agenda that includes supporting farm households' ability to build non-agricultural-based livelihoods. Climate risk management options that include livelihood transformation of both agricultural and non-agricultural livelihoods will require concerted cross-disciplinary research and development that encompasses a broader set of disciplines than has tended to be the case to date within the context of CSA.

Keywords: climate-smart agriculture; livelihood transformation; Guatemala; climate change

1. Introduction

Climate change will have a detrimental impact on agricultural productivity in many parts of the developing world [1]. Farmers have long adapted to climate variability, but the severity of the predicted changes may be beyond many farmers' current ability to adapt and improve their livelihoods [2,3]. There is an urgent need to work with farmers to develop climate change adaptation, mitigation and transformation strategies. Sustainable development goal (SDG) 13 is on *Climate Action* and, hence, there is much interest in the promotion of climate-smart agricultural practices (CSA). These are practices that contribute to an increase in global food security (and other development goals), an enhancement of farmers' ability to adapt to a changing climate and the mitigation of emissions of greenhouse gases [3,4]. CSA, hence, not only contributes to the realization of SDG 13, but is also intrinsically linked to several other SDGs, for example, SDG 1: *No Poverty* and SDG 2: *Zero Hunger*.

Transformative approaches have gained traction in contemporary policy debates on climate impacts, stimulated, amongst other factors, by the United Nations Sustainable Development Goals (SDGs) and the Intergovernmental Panel on Climate Change (IPCC). CSA can be transformative in terms of its aims to ensure food security via a reorientation of agricultural development in the context of the realities of climate change. For example, recent research on the climate-smart village (CSV) approach [4] highlights the potential of scaling out so as to benefit larger number of farmers. However, there has been limited scaling of the CSV approach. One of the challenges is that the scaling of the CSV approach is premised largely on identifying a portfolio of CSA options and the financial or institutional mechanisms that enhance adoption by farmers, and targeting these at regions with similar agro-ecological conditions [4], with less attention being given to the local context [5,6]. The danger is the a priori belief that CSA is a pathway out of poverty. For many farmers, adaptation to climate change in ways that lead to an escape from poverty, and greater prosperity may not be via CSA [7].

Lipper et al. [3] stress that CSA results in higher resilience and lower risks to food security. While this may be the case, there are farmers for whom agricultural-based livelihoods are so precarious that even "climate-proofing" their agricultural systems represents a higher risk to food security and prosperity than non-agricultural livelihood options. The challenge, therefore, is that at the same time that international calls for transformative approaches are made, current and future rural livelihood conditions are so adverse that, for some, this is a matter of changing to grasp any livelihood opportunity, including adverse coping strategies, without any ability to improve agricultural practices in ways that could be considered synonymous with transformative change in a positive sense. Hence, "climate-smart" may actually mean the need for actions that focus on supporting people in building non-agricultural-based livelihoods [3,4]. If this livelihood transformation is to be positive, it will require concomitant policy and development support to provide enabling conditions for non-agricultural livelihoods to be built. Moreover, this needs to be performed in ways that improve household income and security, i.e. are prosperity-enhancing, thus avoiding recourse to adverse coping strategies. The Western Highlands of Guatemala illustrates this challenging development scenario.

2. Climate-Smart Agriculture in the Western Highlands, Guatemala

Scientific evidence points to negative impacts on agriculture in Guatemala, and other parts of Central America, due to changing temperature and rainfall patterns, e.g., [8]. Inequalities in land distribution have forced many resource-poor farmers to farm steep hillsides, areas that are very susceptible to soil and land degradation. The response has often been the promotion of CSA. Development practitioners are rediscovering technologies and practices that were promoted in the region in the 1980s and 1990s under the guise of soil and water conservation [9]. These included live barriers, stone terraces, cover crops, green manures and agro-forestry. Farmers' uptake of these technologies and practices was disappointing 20–30 years ago [10], largely because, as is the case worldwide, a technology-led approach tends to ignore the needs for institutional enabling factors, which are very important when it comes to farmers' uptake of agricultural technologies [6,11,12].

The promotion of CSA in Guatemala is particularly challenging. The country suffers from extreme rural poverty and food insecurity [13]. Guatemala is ethnically very diverse, and indigenous groups (who make up almost 40% of the total population) live mainly in the Western Highlands. The underpinnings of present-day poverty are rooted in conflict, linked to Guatemala's 36-year civil war, which ended in the mid-1990s, and during which tens of thousands of indigenous people died [14]. This has left a legacy of inequality and continued social tension.

Small-scale farmers practice largely subsistence and some market-oriented agriculture. The most important cultivated food crop is maize, which is intercropped with beans, chilies and squash [15]. Recent research has shown that land availability in the Western Highlands is 0.06 ha per person [13]. This contributes to considerable food insecurity: farm households produce enough maize (the main staple crop) for fewer than seven months of consumption per year, and for household consumption have to purchase maize to make up the deficit. As a consequence, the majority of farmers seek off-farm employment on a temporary basis, while a minority have managed to branch into the production of higher-value vegetable crops for the export market [16].

Donors have invested much in rural development projects [17,18]. One such rural development project in the Western Highlands was implemented from 2013–2018. The Buena Milpa project was supported by the United States Agency for International Development (USAID), through its Global Hunger and Food Security Initiative "Feed the Future". Its main objectives were to reduce poverty, food insecurity and malnutrition, while increasing the sustainability and resilience of maize-based farming systems (The ideas reported here stem from Hellin's involvement as a socio-economist in this project in the Western Highlands of Guatemala). More details are provided in [13,19]. A strong emphasis of the project was the promotion of CSA, and the project worked through a number of non-governmental organizations. During the course of the work, it became clear that more attention needed to be focused on farmers' different capacities to engage in climate risk management. The danger was that poor targeting of CSA would lead to weak farmer uptake, by implication excluding many poor farmers and/or including those farmers for whom farming (and improvements in farm productivity via the use of CSA) would do little to enable them to escape poverty.

That project brought to the fore the need to recognize more explicitly the heterogeneity of farm households and the need to broaden the portfolio of livelihood options available to them. A further challenge was to accommodate the understandable desires of the donor to see an impact on the ground. There was pressure to scale CSA, in terms of enhanced farmer uptake of technologies and practices. Implicitly, this served to dismiss emerging evidence that the role of non-agriculture-based livelihoods needed to be taken into account in decision-making regarding appropriate interventions; the promotion of livelihood improvement through CSA was inappropriate for some categories of farmer. There was a danger that the focus on numbers would distract from whether farmer uptake of CSA, while contributing to an improvement in food security, would still leave farmers trapped in poverty, not to mention the potential for other unanticipated impacts, such as when wealthier farmers are able to capture the benefits of CSA, with the consequence that their wealth grows at the expense of poorer farmers, leading, ultimately, to greater social inequality.

The project in Guatemala clearly demonstrates the importance of priority-setting and factoring in the varied possibilities and local conditions that farmers face when it comes to targeting project interventions. Thornton et al. [5] provide a useful framework for CSA priority-setting that is based on six elements, and is designed to help guide best-bet CSA intervention. There is widespread recognition of the trade-offs when implementing CSA among the three pillars of food security, adaptation and mitigation [5,6]. The example of the Western Highlands illustrates "higher-level" trade-offs between some of the SDGs. These include trade-offs between SDG 13: *Climate Action* and SDG 5: *Gender Equality* together with SDG 10: *Reduced Inequality*.

In short, the Guatemalan project illustrates that a focus on the number of farmers adopting CSA can divert attention from the far more important issue, which is to support farmers' adaptation to climate change, either through making their agriculture-based systems more climate-resilient and/or by expanding their envelope of prosperity-enhancing non-agricultural livelihoods. The latter has been less prevalent in CSA interventions, and this has been at the expense of potentially ensnaring poorer categories of small-scale farmers in an agricultural-based poverty trap.

3. Climate-Smart Agriculture and Poverty Reduction

Farm households can be distinguished based on their asset endowment, e.g., their amount of land, access to key agricultural inputs etc., coupled with characteristics that determine the livelihood strategies available to them. These livelihood strategies, in turn, influence the livelihood incomes that hopefully enable a household to maintain and strengthen its livelihood security. The livelihood pathways available to a farm household are determined by the household's characteristics (e.g., dependency ratio, availability of labour, etc.), along with the interaction between the available assets (financial, natural, social, human) and the enabling or disabling economic, institutional and policy environment. An understanding of these livelihood pathways informs decisions as to where to target CSA and where to develop enabling approaches that facilitate livelihood changes.

There is no doubt that CSA and agricultural interventions can contribute to poverty reduction and enhanced prosperity. Numerous examples abound, e.g., [20–22]. However, the agricultural future is bleak for some farmers struggling with few resources and the additional challenge of climate change. Harris and Orr [23] argue that for rain-fed agriculture, crop production could be a pathway from poverty where smallholders are able to increase farm size or where markets stimulate crop diversification, commercialization and increased farm profitability. The potential to improve productivity is also, of course, important. Nevertheless, as Cavanagh et al. [24] comment, "*the poor and less poor are [...] more capable of diversifying into off-farm and non-farm activities compared to the very poor, whose small land holdings and poor access to capital constrain their ability to diversify away from on-farm income and seasonal off-farm wage labour*". We certainly found this to be the case in the Western Highlands of Guatemala [13].

Agriculture is not a pathway out of poverty for all farm households. Hence, for certain categories of household, poverty reduction will come from farmers moving out of agriculture and into the non-farm economy. For poor households, non-agricultural livelihood transformation can, of course, represent nothing more than a negative coping strategy. The challenge is to ensure that non-agricultural livelihood options are positive, i.e., prosperity-enhancing. It is a challenge in all parts of the world due to profound rural changes. In many parts of the world, agricultural production will have to increase hugely, along with labour productivity; the latter will lead to fewer people engaging in agriculture [25]. This has already led, in parts of Asia, to what Li [26] refers to as a rural population that is "surplus" to the needs of capital, as many of those dispossessed from their land are also unable to find meaningful employment off-farm. It is also increasingly common in Latin America.

The idea of a "surplus" population mirrors the earlier thesis of "functional dualism", proposed by de Janvry et al. [27] and expanded on by Blaikie [28]. The authors suggest that farmers rely upon returns from market activities to complement their agricultural returns from farming plots of land that are too small to allow for self-sufficiency. Farmers are often obliged to work as part-time wage laborers due to their resulting food insecurity, thus needing to make up shortfalls of staples and cash requirements for household goods, as well as to pay for inputs for the production process itself on their farms. They are increasingly dependent on non-farm sources of income but are unable to find sufficient employment opportunities or capital to migrate (and abandon the agricultural sector) or to depend fully on wage earnings for their subsistence. Returns from subsistence-oriented agricultural activities provide a necessary complement to the low wages that farmers receive in the labour market. In addition, where opportunities for wage labour are primarily in the agricultural sector, poor returns from own-farm agricultural production are reinforced, given that peak demand for agricultural labour may coincide with labour demands on farmers' own land.

The situation in the Western Highlands of Guatemala, as described in the section above, is in keeping with the functional dualism thesis, and has major implications for identifying and targeting appropriate pathways leading to rural poverty reduction. As suggested, for many farmers in the Western Highlands, CSA may not be an attractive option because of labour and land shortages. In the case of many farmers in the Western Highlands of Guatemala, temporary migration in search of non-farm employment has been a traditional coping strategy, with farmers investing the earned off-farm income in their villages and/or diversifying into non-farm agricultural activities, such as setting up a local shop. For many farmers, labour, essential for investment in soil improvement or maintenance of conservation structures, is not available, because they are working off-farm (and households may also have high dependency ratios) [23]. Similarly, another refrain, when CSA practices such as conservation agriculture are promoted, is that farmers should not burn their fields to clear the vegetation prior to planting because of the adverse impact on soil quality, especially biological health. For farmers who have been working off-farm, and for whom labour is scarce, this can be an unattractive recommendation.

CSA is also very problematic when it comes to small-scale farmers with very small landholdings, as is the case in the Western Highlands. Firstly, in the case of cross-slope soil conservation technologies, such as live-vegetation barriers and stone walls, land is taken out of production. In the case of live barriers, however, this can be partly compensated for by using species that make a contribution to the farm household, e.g., edible products for humans and/or animals. Secondly, even if CSA were to lead to significant improvements in agricultural productivity, the increase (while a contribution to food security) would be unlikely to help the farmer escape poverty. "*For most smallholders, however, small farm size and limited access to markets mean that returns from improved technology are too small for crop production alone to lift them above the poverty line*" [23].

This raises the question of how best to support categories of farmers who are being targeted but whose small holdings, household structure and asset endowment may be inappropriate for the measures advocated under the guise of CSA. It may be the case that the CSV approach would be more successful, but in the absence of effective scaling of this approach and comprehensive impact studies, this remains an under-researched area.

4. Non-Agricultural Livelihood Transformation

In rural contexts where small-holder farmers are based, development involves decreasing livelihood vulnerability and increasing incomes, typically through changes in livelihood activities [29]. Ideally, CSA should enable farmers to pursue livelihood pathways that lead to greater prosperity, while also building resilience. Recent thinking has advocated addressing the need to support changes that can be transformative, in the face of climate-related impacts that imply dramatic changes to environmental conditions. There is much research on developing a framework for assessing and comparing different types of interventions that address the key elements of CSA [5,10]. This research is necessary and important; however, in the context of agricultural transformation, the focus needs to broaden to systematically factor in livelihood trajectories outside of agriculture. CSA, to enhance food security and meet the SDGs, will require a longer-term perspective and bolder action that comprehensively targets farmer livelihoods [5].

The reality is that positive, sustainable livelihood pathways within the agricultural sector may not be an option for all types of farmers, i.e., not all households face the agro-ecological and socio-economic conditions necessary to move from one asset threshold and livelihood pathway to another, enabling them to escape poverty, while still remaining in agriculture. Guatemala epitomizes this reality. A report produced for the United States Agency for International Development (USAID) noted that "*given the agricultural foundation and 'capital' that many Western Highland communities continue to hold, [there is a need to] re-assess the productive options available in agriculture or agriculture-based livelihoods; and engage youth (many of whom have written agriculture off as an option) in development of potential integrated economic/environmental/social development initiatives*" [18].

Incorporating non-agricultural livelihood transformation within CSA requires innovative and open thinking on the way forward for CSA. This has been acknowledged by proponents of CSA, e.g., [3,4], but it poses disciplinary challenges and has not led to the type of holistic and transformative changes are that needed. What is required is a broader and more comprehensive understanding of the realities faced by farmers and the changes needed to foster large-scale transformation in their livelihood trajectories [30]. This means that CSA thinking has to involve those from a plethora of disciplines from the natural and social sciences [31]. In the context of CSA, we have a practical example of how transformation also becomes a political issue [32]. The debate around adaptation to environmental change often avoids questioning the socio-economic and political reasons why farmers' livelihoods are so vulnerable [33].

In the context of Guatemala, serious discussion around climate change adaptation, mitigation and transformation will have to contend with politically divisive issues. In a small way, within a project, "politics" can mean challenging the premises that drive inappropriate scaling. Within the bigger picture, it also means taking into account the political economies within which CSA is advocated for small-scale farmers. In the Guatemalan context, this political economy relates to several decades of conflict and on-going socio-economic inequality that structurally disadvantage small-scale farmers in the Western Highlands. While there are, of course, specificities to the political economy of Guatemala, which have shaped its uptake of CSA, in any given context there will be political economy issues underpinning the implementation of CSA that cannot and should not be ignored. The climate change discourse has tended to focus on the adaptation and mitigation of greenhouse gas emissions, rather than "*problems of unevenly distributed power relations, networks of control and influence, and rampant injustices of the 'system"* [34].

Clearly, a disregard for issues of power and inequality is not tenable if CSA is to provide a viable mechanism for livelihood transformation and a contribution to the SDGs. Indeed, there is growing evidence of CSA proponents adopting a more "radical" agenda, factoring in more readily political and institutional issues and ensuring that CSA debate and implementation does not remain largely a discourse among "elite development and research agencies" [35]. Such recognition of the political realities of small-holder agricultural development are important if CSA is to have continued longevity and relevance within international agendas on climate change action and the SDGs.

5. Conclusions

Climate adaptation requires transformative change. The CSA approach needs to move even more squarely beyond a focus on resilience of food systems to encompass systematic thinking and action with respect to the resilience of farm households. This poses a real challenge, because CSA has tended to overlook targeting issues related to socio-economic differentiation within small-scale farming populations, although recent CSA initiatives have more readily included analyses of the institutional dimensions of CSA. Greater acknowledgement of institutional issues, and indeed the politics, of CSA interventions within rural planning are to be welcomed. CSA has nevertheless, in practice, tended to exclude systematic consideration of support for non-agricultural livelihood transformation that is positive for farm households in marginal contexts, such as the Western Highlands of Guatemala.

In some cases, CSA can lead to the triple win of increased productivity, adaptation and mitigation, but this is not the case for all types of farmers. We argue that more systematic attention be directed at climate risk management that moves beyond the more conventional adaptation and mitigation discourse, towards an approach that includes livelihood transformation from a broader perspective, i.e., one that does not just focus on rural–agricultural transformation, but also identifies (and embraces) where agriculture per se is not a pathway out of poverty and where support for positive non-agricultural livelihood trajectories are needed for small-scale farmers. This requires more disciplines working together, and, perhaps, meeting the challenge of addressing entrenched power balances, both within communities of scientists and in the small-scale farming populations that are the subject of CSA interventions.

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Article

Climate Change-Induced Impacts on Smallholder Farmers in Selected Districts of Sidama, Southern Ethiopia

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Abstract: Different factors control the types of adaptive strategies and likelihoods of experiencing climate change-induced impacts by smallholder farmers. By using a mixed research method, this study examines the types and determinants of climate change-induced impacts on smallholder rural farmers in drought-prone low lands of Sidama, Southern Ethiopia. Randomly selected (401) households were surveyed on climate change-induced impacts. Longitudinal climatic data were also collected from the Ethiopian National Meteorological Agency to assess the trend of rainfall (RF), temperature and drought incidents. The analyses of the data revealed that RF and temperature had shown decreasing and increasing trends, respectively, during the three decades under consideration (1983–2014). These changes in RF and temperature exposed farmers to climate-related epidemics, drought, harvest loss, and hunger. The logit model results revealed that different factors control the likelihood of exposure to climate change-induced impacts. The findings revealed that literacy level, involving women in family decisions and farmers' involvement in adaptation planning, reduces the likelihood of exposure to climate change-induced hunger. Therefore, there is a need to work on human capital of the farmers through expanding education, strengthening women's participation in family decision-making, and by improving public participation in climate change adaptation undertakings to minimize climate change-induced impacts.

Keywords: climate change-induced impacts; smallholder farmers; drought-prone low lands; rural Sidama; southern Ethiopia

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1. Introduction

Climate change has emerged as one of the development challenges of the 21st century [1,2]. There is high confidence and agreement among the global scientific community that climate change poses a serious threat to current and future sustainable development. According to the forecasts, climate change-induced impacts will continue to affect people, even if anthropogenic greenhouse gasses emissions stop today [3]. Sub-Saharan Africa (SSA), where smallholder farmers dominate agriculture [4], is one of the global hotspots for climate change-induced impacts [5]. In SSA, agriculture directly employs about 175 million people who cultivate degraded lands where there is no reliable supply of water for irrigation [6]. These smallholder farmers in SSA are among the most vulnerable groups to climate change and variability-induced impacts due to dependency on RF, limited use of irrigation, and weak adaptive capacity. Furthermore, limited human and material capacity, poor infrastructure, fragile environments, political instability, and marginalization contributed to the vulnerability in this region [7–10]. The case is not different in Ethiopia where smallholder farmers, who produce 90% of the total agricultural yield and own 95% of the total cultivated land [11], suffer from different climate change induced-impacts. Most of these subsistent farmers practice rain-fed traditional farming, use little modern agricultural inputs, and have little surplus to sell in local markets. They are not resilient enough to cope with climate change-induced recurrent shocks and long-term impacts [12–14]. Although climate change-induced impacts have been recurrent in Ethiopia and in the study area, little is known about the factors that affect the likelihood of exposure to such impacts in Ethiopia and SSA. Thus, by using mixed research strategy, this study presents the types and determinants of climate change induced-impacts on smallholder rural farmers in drought-prone lowland context.

Climate change induced-impacts refers to effects on natural and human systems due to gradual changes in climate, variations in weather and climatic elements from the average, and that of the impacts of climatic extremes. As IPCC report, climate change-induced impacts refer to impacts on human lives, livelihoods, culture, economies, ecosystems, and material resources due to hazardous climatic events over a period of time [3]. Climate change-induced impacts also include consequences and outcomes of the direct impacts including droughts, hunger, famine, loss of life and property, and sea level rise which can be potential or residual (ibid). The former includes impacts that occur due to a projected change in climate without adaptation. The latter refers to the impacts with adaptation [15]. Therefore, in this research, climate change-induced impacts include the immediate effects as well as outcomes and consequences of the immediate effects on human and natural systems. As global warming increases the likelihood of experiencing severe, persistent, and irreversible impacts on natural and human systems will be stronger [3,16]. Greenhouse gas emissions have adverse effects on biodiversity, ecosystem services, and economic development, which are causing risks for livelihoods and human security [17,18]. The 4th IPCC report argues that … *by 2020, between 75 million and 250 million people are projected to be exposed to increased water stress due to climate change*[15] (p13). Agricultural crop yield in some African countries could be reduced by 50% by 2020 and this can endanger the existence of many smallholder rural farmers.

Climate change-induced impacts have hampered poverty reduction and sustainable development in the Global South [5,19,20]. This is because most climate-related impacts affect the poor, who are struggling to come out of poverty [21]. Furthermore, livelihood strategies and housing conditions of the poor are more vulnerable to climate change and variability-induced impacts [22,23]. The poor usually have houses made of mud, bamboo, straw, and other inexpensive materials that are the most vulnerable to extreme weather events. The poor also cannot buy climate insurance against climate-related risks. Besides the direct impacts on agriculture-related livelihoods, climate change is also indirectly affecting the health and well-being of the poor through its effect on human and livestock health [24,25]. For example, because of increasing surface temperature, malaria is expected to migrate to higher altitudes and cause further health problems, which affect the poor's income and productivity. According to the World Health Organization (WHO) estimates, global warming causes about 150,000 deaths per year [26]. RF and temperature variability also result in pests and diseases incidents that affect the quantity and the quality of the crop yield [27]. Besides impacts, social strains caused by increased resource scarcity may lead to greater conflict [5,28], with the poor again being the most likely victims.

Erratic RF and higher temperatures characterize the drought-prone lowlands of Sidama. The area is part of the Great East African Rift Valley (GEARV). Climate change-induced impacts such as drought, crop failure, livestock loss, flooding, and water-borne and related diseases (such as diarrhea and malaria) have been recurrent in this area. The problem worsened in 2016 despite various adaptive strategies of the households, communities, and other actors, including the government. This needed a large-scale emergency relief for about 100,000 people, which is highest in recent documented drought history of the area. Despite a few research works on climate change-induced impacts on smallholder farmers, there is a gap in the literature about factors that control the likelihood of exposure to the impacts. Therefore, the main goal of this study is to identify factors that determine the likelihood of exposure to climate-induced impacts on smallholder rural farmers. Identifying such determinants is important for policy-makers, practitioners, and smallholder farmers to identify leverage points to manage the imminent impacts of climate change in the country and beyond.

2. Climate Change-Induced Impacts in Ethiopia

While agriculture is the backbone of Ethiopia's economy, it is RF dependent and dominated by smallholder subsistent farmers. About 80% of the Ethiopian population lives in rural areas making drought-prone agriculture as the primary means of livelihood. This figure is much higher than the SSA average, which stood at 63% in the year 2014 [11,29]. Furthermore, agriculture constitutes 40% of the GDP, supports 80% of the total employment, and is a source of 90% of the export in Ethiopia [11,30,31]. Nonetheless, climate change-induced impacts are challenging the roles of agriculture for the overall growth of the country [12]. In the 20th century alone, twelve extreme droughts happened in Ethiopia that hampered the economic development of the country. The drought incidents claimed the lives of hundreds of thousands and affected the livelihoods of over 50 million people [32]. Drought incidents have been increasing in recent decades in the country. Eight major droughts had occurred in the last three decades in Ethiopia: 1984/85 1987/88 1991 1994 1997 2002/03 2010/11, and in 2015/16 [32,33].

Previous studies revealed that climate change and variability had exerted significant impacts on agriculture and the overall economic growth in Ethiopia [32,34,35]. Specifically, climate change-induced impacts have hampered the country's economic growth and effort to move out of poverty. For instance, it was reported that from 1991–2010, the growth estimates were reduced by 2–9% because of climate change-induced impacts [30]. Under the worst-case scenarios, the economic impacts of climate change may reduce Ethiopia's GDP by up to 8% [36]. On the other hand, another study on climate change impact on agriculture and related sectors revealed a 10% GDP drop from the target [37]. The same study revealed a widening income inequality that could reach up to 20% due to the effect of climate change. In general, with higher vulnerability, and lesser resilience to climate change-induced impacts, the country is projected to experience a 6% decline in total agricultural output in the coming years [38].

Besides the impacts on the national economy, climate change-induced impacts have been affecting health and livelihood status of smallholder farmers in Ethiopia. Some of these impacts include climate-related epidemics, crop failure, flooding, livestock mortality, shortage of water and pasture, migration, and food aid dependency [2,39,40]. Unsustainable adaptation strategies of the farmers, such as selling assets and charcoal production, have resulted in the degradation of assets, environment degradation, and biodiversity losses. Climate change-induced food and water shortages affect the health, educational, and economic status of the households [8]. For instance, during drought events, children are forced to drop out of the school to participate in such household activities as collecting water and fuel-wood from long distances. Malaria affects labor availability at the household level and increases the health expenses of the family.

3. Data and Methods

3.1. Study Area

Located in the Horn of Africa, Ethiopia had a population of 94.35 million in 2017, according to the Ethiopian Central Statistical agency. The country has nine regional states and two city administrations. The Southern Nations Nationalities and Peoples' Regional State (SNNPRS) is one of the nine administrative regions comprising about 20% of the country's total population and 10% of the land area. The Sidama Administration Zone is one of the 14 administrative zones in the SNNPRS. With a population of 3,677,370 in 2014 [41], it is the most populous zone in the region. The zone is located in the central-eastern part of the region bordered by Oromiya in the North, East, and Southeast, Gedeo Zone in the South, and Wolayita Zone in the west. The zone lies between 6°10′ to 7°05′ North latitude and 38°21′ to 39°11′ East longitude. The total area of the zone is 6981.9 km^2 [42].

Three drought-prone districts (Hawassa Zuria, Boricha, and Loka Abaya) were selected for this study (Figure 1). The districts are located in the heart of the East African Rift Valley and they were chosen based on their higher potential risk of exposure to adverse climate change and variability. Variable RF and higher temperatures characterize the districts compared to other districts of the zone. The population of the districts is 576,865 from 113,285 households. About 97% of the population in these districts lives in rural areas where drought-prone agriculture is their source of livelihood. Agro-pastoral communities dominate the southwestern parts of the study area, where climate-related animal diseases are prevalent.

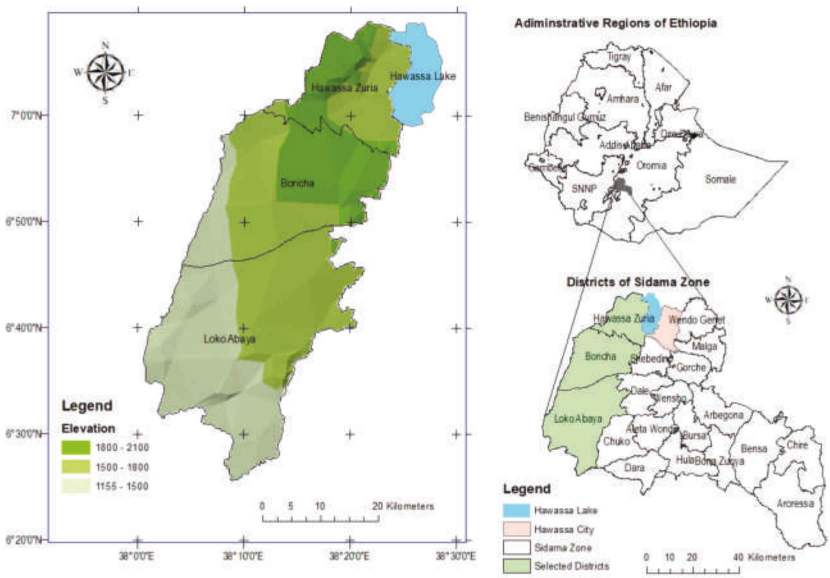


Figure 1. The geographic location of the study area.

Diverse climate characterizes the drought-prone districts of Sidama Zone. Altitude ranges from 560–2300 meters above sea level and the average annual RF ranges between 700 and 1200 mm. The RF pattern in the area is bimodal, which occurs in the summer and spring seasons. The summer (*kiremt*) rains last from June to September while the spring (*belg*) rains usually begin in February and end in late May. Both the *kiremt* and *belg* rains are irregular and unpredictable, resulting in frequent losses of harvest and cattle. The region has a bimodal precipitation distribution and high RF variability due to the seasonal progression of the inter-tropical convergence zone (ITCZ), an atmospheric circulation feature often modified by the El Niño–Southern Oscillation (ENSO). Also, there is severe livestock and human diseases (for example, malaria, cholera, and trypanosomiasis) in the area largely due to the inhospitable climate. The perennial Bilate River, which dissects the Wolayita and Sidama Zones, drains the western part of the area. The eastern part lacks perennial rivers, and households largely depend on artificial ponds and hand-dug shallow wells for water for domestic uses and watering livestock. The area experiences severe water shortages when the ponds run out of water during the December–February dry period.

3.2. Data

This study employed a cross-sectional household survey method. Randomly selected 401 rural household heads took part as respondents for the study. The following sampling procedure was applied. Based on their climatic conditions, accessibility, population size, and population density three kebeles from Boricha, two kebeles from Hawassa Zuria, and two kebeles from Loka Abaya districts (a total of seven kebeles) were selected. Accordingly, Hanja Cafa, Haldada Dela, and Korangoge from

Boricha district, Muticha Gorbe, and Sala Kore kebeles from Loka Abaya district, and Doyo Cala and Doyo Otilicha kebeles from Hawassa Zuria districts were selected for the study. The ideal sample size was calculated based on the Krejcie and Morgan formula; the maximum sample size at a 95% confidence interval and 5% margin of error for 750,000 people is 382 [43]. Considering attritions of the responses, a 5% contingency (19 HHs) gives 401 households, which were selected from the three districts. The 401 sample size was proportionally distributed based on the number of households in each district. So, 189 HHs from Boricha, 93 HHs from Loka Abaya, and 119 HHs from Hawassa Zuria districts were included for this study. The respondents were household heads who were selected by using systematic random sampling. Female-headed households were also included proportionately in all the districts (Table 1).

Table 1. Distribution of rural population and sampled households (HHs) in selected districts.

District Name	Total Rural Population	Total HHs	Kebele Name	Sampled HHs	Total
Boricha	299,175	58,823	Hanja Cafa	66	189
			Haldada Dela	66	
			Korangoge	57	
Loka Abaya	122,445	25,278	Muticha Gorbe	36	93
			Sala Kore	58	
Hawassa Zuriya	155,245	29,184	Doyo Chala	53	119
			Doyo Otilicho	66	
TOTAL	576,865	113,285		401(143)	401

( ) female headed HHs. Source: Own compilation from SNNPRS, BoFED 2015.

The field data collection process took place from April to May 2017 with trained data collectors supervised by the researcher. More data were gathered through focus group discussions, interviews with key informants, and field observation. The study also used RF data collected from the National Meteorological Agency of Ethiopia for the period 1983–2014 to support other data.

The RF data was analyzed by using trend analysis, Mann–Kendall's rank test, and standard RF anomalies (SRA). The SRA refers to standard RF anomaly and Pi and $P\mu$ represent RF of a given year and the mean RF, respectively. Accordingly, the result helps to classify temperature RF condition into different categories (Table 2).

$$\text{SRA} = \frac{P_i - P\mu}{\delta} \quad (1)$$

The collected quantitative data were encoded into STATA software (Version 14.2), and various descriptive and inferential techniques (mean, percent, standard deviation, and logit model) were used to analyze and interpret the results. The logit model analysis was carried out by using the STATA software to identify the determinants of climate change-induced effects on smallholder farmers. The qualitative data were analyzed via systematic thematization to augment the quantitative results.

3.3. Model Specifications

A logit model is a statistical approach used when the dependent variable (DV) is nominal with two or more categories commonly grouped as dummy variables (Table 3). On the other hand, the independent (predictor) variables (IVs) in a logit model can be qualitative (nominal or ordinal level) and interval/ratio level variables. This study used a logit model to identify factors that control the likelihood of households' exposure to climate change-induced impacts. Climate change-induced impacts considered in this study include the likelihoods to exposure to drought, harvest loss, flooding, and hunger. The exposure to hunger is examined vis-à-vis eighteen socio-economic and institutional s (Table 2). The eighteen dependent variables were selected among other socioeconomic and institutional variables after all the variables were tested to have a relationship with the four dependent variables considered for this study. The logit model showed that the selected eighteen variables have some explanatory power on the dependent variables considered.

Table 2. Variables description.

S.N	Variables	Variable Type	Description	Code
1	Sex	Explanatory	Sex of the HHs head	continuous
2	Family size	Explanatory	Number of HH members	continuous
3	Educational status	Explanatory	HHs head no. of years in school)	continuous
4	Total land size	Explanatory	Size of land in hectare	continuous
5	Land use certificate	Explanatory	I have land use right certificate	1) yes 0) no
6	PSNP beneficiary	Explanatory	Beneficiary of PSNP support	1) yes 0) no
7	Produce *enset*	Explanatory	Produce *enset* crop	1) yes 0) no
8	Membership in 1 to 5	Explanatory	Membership in 1 to 5	1) yes 0) no
9	Head of 1 to 5	Explanatory	Head of 1 to 5	1) yes 0) no
10	Communal grazing land	Explanatory	Communal grazing land	1) yes 0) no
11	Communal water pond	Explanatory	Communal water ponds	1) yes 0) no
12	Drought resistant variety	Explanatory	Drought resistant crop variety	1) yes 0) no
13	Fertilizer/urea/NPS	Explanatory	Fertilizer/urea/NPS	1) yes 0) no
14	Training on climate change	Explanatory	Get trained on climate change adaptation	1) yes 0) no
15	Early warning information	Explanatory	Get early climate change induced information	1) yes 0) no
16	Improved animal fodder	Explanatory	Use improved animal fodder	1) yes 0) no
17	HHs participation in adaptive decision	Explanatory	HHs participation in climate decision making	1) yes 0) no
18	Women participation in HHs decision	Explanatory	Women participation in HHs decision making	1) yes 0) no
19	Drought	Dependent	Exposure to the effects of drought	1) yes 0) no
20	Harvest loss	Dependent	Experienced harvest loss	1) yes 0) no
21	Flooding	Dependent	Affected by flooding	1) yes 0) no
22	Famine	Dependent	Experienced hunger	1) yes 0) no

1. Productive Safety Net Program is a government program being implemented in the study area to support poor and vulnerable people. 2. Are groups of 5 people organized by government and used for political, economic, and social purposes. 3. Drought resistant varieties are plant seeds that are supplied by the government and can grow in moisture stress conditions. 4. Urea and NPS are the two types of chemical fertilizers supplied to farmers by the government (usually in loan) NPS refers to Nitrogen-Phosphoric fertilizer containing Sulphur. 5. Improved animal fodder is a plant species (supplied by the government) that is used as a forage to feed animals during a shortage of pasture. 6. HHS are members of a family living in a house.

Table 3. Mann–Kendall's rank test result for inter-annual rainfall (RF).

Coefficicnt	n	Winter RF	Spring RF	Summer RF	Annual RF
Correlation Coefficient	1.000	0.117	0270 *	−0.020	−0.161
Sig. (2-tailed)		0.347	0.030	0.871	0.195
N	32	32	32	32	32

* Correlation is significant at the 0.05 level (2-tailed).

Logistic regression involves a linear function:

$$Z = b_0 + b_1X_1 + b_2X_2 + \ldots + b_nX_n \quad (2)$$

where Z is a dependent variable and $X_i \ldots X_n$ are explanatory variables.

The logistic regression function is thus, given by:

$$p = \frac{e^z}{1+e^z} \quad (3)$$

where p is the probability that an event occurs; and the odds in favor of the occurrence are related according to $p = \frac{\text{Odds}}{1-\text{odds}} = \frac{p}{1-p}$.

$$\log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1X \quad (4)$$

Thus, odds is defined for an event with probability p and the logit is the log of the odds, i.e.;

Model - $p(x)$ = probability of the event occurring at (Y=(x))

$$p(y/x) = \frac{e^{\beta_0+\beta_1 X_1+\beta_2 X_2+\ldots+\beta_k X_k}}{1+e^{\beta_0+\beta_1 X_1+\beta_2 X_2+\ldots+\beta_k X_k}} \quad (5)$$

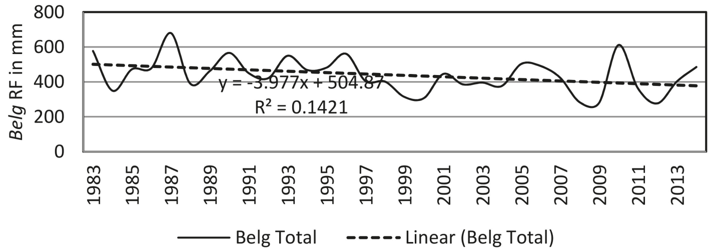
A smaller sample size with a large number of predictors creates problems with the analysis, specifically when there are categorical predictors with limited cases in each category. Descriptive statistics were run for each of the predictors to solve the problem. The result showed that all categorical variables have a required number of cases set as a minimum standard [44]. A multicollinearity test was done to check for high intercorrelations among predictor (independent) variables. The test result suggested that the maximum r-value of the independent variables is 0.7, which is within an acceptable limit [44]. The presence of outliers or cases that would not well be explained by the model was also checked to make sure the model fits the data well. The model tried to find out factors that control the HHs likelihood of exposure to climate-induced impacts such as the exposure to the effects of drought, harvest loss, flooding, and hunger in the study area. R^2 and adjusted R^2 were also used to discuss the amount of variation explained by the independent variables. The former supposes that every independent variable in the model explains the variation in the dependent variable by explaining the variation in percent as if all independent variables in the model affect the dependent variable. On the other hand, the adjusted R^2 gives the percentage of variation explained by independent variables that in reality, affect the dependent variable. In this context, it is also called marginal effect after logit.

4. Results and Discussion

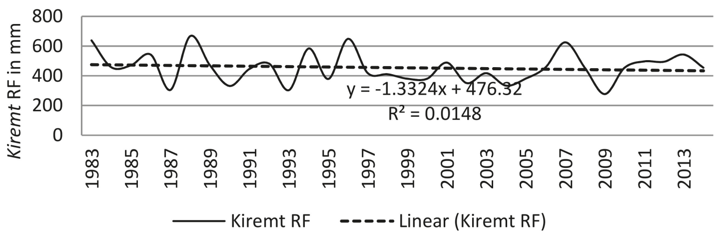
4.1. RF Condition and Drought Incidents

Studies on RF over Ethiopia revealed high variability and drought incidents [32,35,45]. Similarly, the analyses of RF data have shown declining RF trends and incidents of drought during the years under consideration (1983–2014). Annual and growing season (*belg* and *kiremt*) RF amounts had shown declining trends in the study area. The *belg* season (February, March, April, and May) RF accounts for 40% of the annual RF in the study area. It is an important season not only to grow short-growing season crops, but also it provides water for livestock and helps the growth of pasture. Though the current study does not check daily RF data of the growing seasons, the experts and focus group discussion participants reported that problems related to its onset, duration, and offset have serious consequence on food security in the study area. However, despite its huge role for livelihood security, it has shown a significant ($p \leq 0.05$) declining trend in the last three decades (Figure 2a, Table 3). The *kiremt* season (June, July, August, and September) is the main rain growing season in the study area which accounts for 41% of the total annual RF. *Kiremt* RF has also shown a declining trend over the years under consideration (Figure 2b), though the trend is not statistically significant (Table 3). The trend analysis of annual RF data has also revealed a declining trend, though the result is statistically insignificant (Table 3). The annual RF had varied from its average amount, which amounts to 1100 mm. The year 2009 was the driest year among the years under consideration with the annual amount of 796.37 mm. The years 1984, 1999, 2000, 2002, 2003, 2004, and 2009 were the drier with annual RF of 950.44 mm, 870.1 mm, 934.02 mm, 960.09 mm, 994.71 mm, and 925.08 mm, respectively.

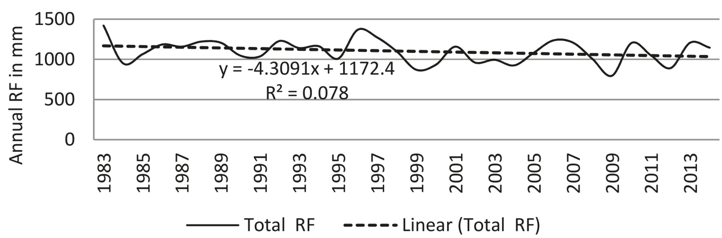
The years 1983 and 1996 were the wettest years with annual RF amounts of 1420.42 mm and 1368.41 mm, respectively (Figure 3). On the other hand, the analysis of minimum, maximum, and mean monthly temperature had shown increasing trends, all of which are statistically significant



(a)

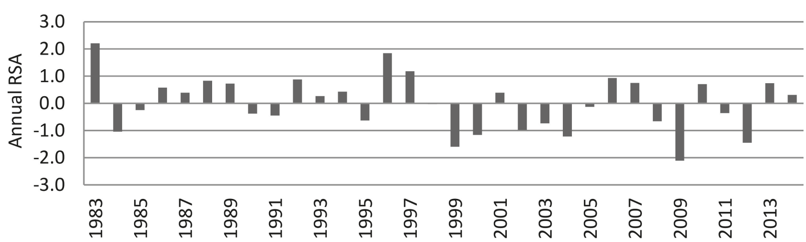


(b)



(**c**)

Figure 2. Rainfall trend in the study area (1983–2014). Source: Own computation from Ethiopian National Meteorological Agency data.



Source: Own computation from Ethiopian National Meteorological Agency data.

Figure 3. Annual RF standard anomalies in the study area (1983–2014).

The RF Standard Anomalies (RSA) helps to estimate the extent of drought based on the RF data [46] (Table 4).

Table 4. Drought severity index based on standard rainfall anomalies (SRA).

Anomaly	Temperature	RF
<−1.65	Extremely hot	Extreme drought
−1.65 to −1.28	Severe hot	Severe drought
−1.28 to −0.84	Moderate hot	Moderate drought
>−0.84	Cool	No drought

Source: Janowiak et al. 1986.

The analysis of annual RSA pointed out seven droughts incidents of different extent during the three decades under consideration. The year 2009 with annual SRA value of −2.11 was the driest year in the last three decades, which coincides with the 2009/10 extreme drought all over the country. The years 1999 and 2012 were also years of severe drought in the study area with SRA vales of −1.6 and −1.45, respectively. The other four moderate drought years were in 1984 (SRA = −1.04) 2000 (SRA = −1.16) 2002 (SRA = −0.98), and 2004 (SRA = −1.22) (Figure 3).

4.2. Types of Climate Change-Induced Impacts

Drought and flooding are the most common climate change variability-induced risks in Ethiopia [2,39,47]. The findings of this study nevertheless revealed other climate change-induced impacts that are recurrent in the study area. The common ones include climate-induced seasonal epidemics, drought, harvest loss, flooding, hunger, migration, and school dropout [48].

4.2.1. Climate Change and Variability Related Epidemics

Climate change-related epidemics globally claim over 150,000 lives per year [26]. Studies on the health impact of anthropogenic climate change show that climate change is affecting human health. Diseases such as cardiovascular mortality, respiratory illnesses, water-related contagious diseases, and malnutrition are directly or indirectly associated with climate change [24,26–50]. Malaria, cholera, and animal diseases were the major climate change and variability induced epidemics reported by the HHs in the study area. Of the total respondents asked about the incidence of malaria in their locality, 46% (n = 183) said that they had suffered from a malaria epidemic in their family. Malaria has been the most prevalent disease in the study area and its prevalence increases in the wet season from May to November. During wet seasons, the availability of moisture creates a conducive environment for mosquitos to breed and spread, such as those places left open to harvest rainwater.

On the other hand, thirty-five percent (n = 138) of the households reported cholera incidences. Water supply coverage in the study area has been marginal because of poor hydro-geological conditions and limited resources to improve water supply coverage. Water scarcity forces people to use untreated water for domestic consumptions. Key informants in Boricha district said that such incidences usually happen during water-scarce seasons where families resort to using unsafe water for domestic consumptions. Diarrheal diseases incidents are very common during the dry season (from December to March) affecting health and household labor availability in the area. Twenty-one percent (n = 85) of the study participants also reported the prevalence of animal diseases. The problem is more acute for agro-pastoral communities living in the western parts of the study area, especially in Loka Abaya district. Some HHS also reported the prevalence of animal diseases, such as trypanosomiasis. It affects animal farming in the study area. About 21% (n = 81) of respondents reported that they had experienced climate change-related livestock diseases. Trypanosomiasis is one of the tropical livestock diseases, which has widely spread all over the SSA [51,52]. The World Health Organization (WHO) has also pointed out that climate change induced animal diseases are affecting cattle header Maasai pastoralist communities living in Tanzania and Kenya [53].

4.2.2. Drought

Drought is a climatic condition, which occurs when there is a RF below its normal pattern for a long period of time [54]. Drought has happened in the study area every year since 2000, compelling large-scale relief intervention by government and international donors. A prolonged delay or a total absence of the rains during the two growing seasons (*belg* and *kiremt*) adversely affects crop and livestock productivity. About 84% (n = 336) of the households interviewed reported to have suffered from drought-related effects in the last ten years. During the dry season, pastoral household members travel eight to ten hours every other day to water their livestock at the Hawassa Lake or Bilate River. Such long-distance trekking undoubtedly hinders household heads or other family members from devoting enough time to other livelihoods and, therefore, incurring further economic losses. To support the farmers' drought incident experience with the RF data, the researchers carried out RSA analysis. The result pointed out decreasing annual, summer, and spring RF amounts for the years under consideration. The SRA results pointed out that seven drought events of different extent occurred in the study area of which one was extreme, two were severe, and four were moderate (Figure 3). The incidence of drought had increased in the study area because 88% of the drought happened in the last fifteen years of the three decades.

4.2.3. Harvest Loss

Climate change-induced harvest loss due to rainfall shortages in the growing season is one reason for food insecurity in developing countries [55]. There had been harvest losses because of climate change in the study area. This happened due to the shortage of RF during the growing season. Out of 401 HHs interviewed, eighty-two percent (n = 329) said that they have experienced harvest losses in the last ten years. The farmers in the study area practice a mixed livelihood: crop cultivation and animal husbandry. When drought occurs, the productivity of both suffers. The exception is for *enset* crop. Because of its biological characteristics, *enset* has strong drought resistance capacity and has a strong link with animal husbandry. The mixed livelihoods are dependent on RF since there are no small-scale irrigation projects in the study area. During the drought years when animal pasture/grass is scarce, farmers fed their cattle *enset* (false banana). This alternative is less feasible nowadays because of the scarcity of animal dung, which is a critical fertilizer to grow *enset*. As a result, as the number of cattle owned by households dwindles, *enset* production also declines. Thus, climate change is affecting the mixed (crop cultivation and animal husbandry) rural livelihood by degrading its natural connection.

4.2.4. Flooding

Climate change-induced flooding is one of the impacts of climate change, which has vast economic and social consequences. It has been occurring in Ethiopia for years inflicting heavy social and economic costs [56]. Flooding during rainy seasons is one of the primary climate-induced effects in the study area. Of the 402 households asked about their exposure to flooding, 74% (n = 297) said that flooding had affected them in the last ten years. Most parts of the study area, especially the western part, have suffered from devastating flooding due to the seasonal overflow of the Bilat River. On the other hand, since the area is located in lower elevations, there are run-offs from the surrounding highlands that destroy terraces built to control soil erosion. Also, several gullies occurred because of heavy rain that has affected the landscape as noted by the researcher during field visits. Flooding during rainy seasons causes property and harvest loss incurring a significant economic cost to the farmers. The social and economic effects mentioned by households include loss of human lives and livestock, property damages, destruction of crops, water-borne diseases, and soil erosion.

4.2.5. Climate Change-Induced Hunger

Famine is a condition where people lack food for a longer period whereas hunger is a seasonal lack of food because of natural or human-made causes. Hunger becomes famine when it persists and affects many people [57]. RF shortage is one of the main reasons for famine and hunger in SSA [4,5]. Of the 401 respondents included in this study, 77% (n = 309) did experience hunger in the last ten years. Data collected from the Sidama Zone Agriculture and Natural Resources Management Department show that climate change-induced hunger did happen in the three districts in the previous fifteen years. Many people received emergency food aid in 2000, 2004, 2009, and 2016. These years coincide with the years of lower SRA discussed in part 4.1. According to key informants, signs of hunger include a delayed start of rain during rainy seasons (*belg* or *kiremt*) or its absence during critical sowing seasons. Both affect crop and livestock productivity and food security.

4.3. Determinants of Climate Change-Induced Impacts on Smallholder Farmers

4.3.1. Determinants of Exposure to the Effects of Drought

The result of the logit model shows that several reasons decide the likelihood of exposure to the effects of drought in the study area. The model is statistically significant for the determinants of drought (N = 357, Chi^2 = 59.99, p = 0.0000). The pseudo R^2 and adjusted R^2 (after marginal effect) values for this category of explanatory variables are 18.56% and 88.83%, respectively (Table 5). Out of the explanatory variables considered in the model, educational status, growing enset, membership in 1 to 5 groups, and being head in 1 to 5 groups affect the exposure to the effects of drought. Besides, the use of chemical fertilizer and the participation of women in family decision-making are found to be the main determinants of exposure to the effects of climate change-induced drought. Specifically, the findings show that a one year increase in schooling decreases the likelihood of being affected by drought by 10% (at $p < 0.05$ level).

Growing enset is another determinant of climate change-induced drought. Households who grow enset are 111.3% less likely to experience the effects of drought than those without *enset* at $p < 0.05$ level (Table 5). *Enset* (false banana) is a perennial crop known for its drought-resistant nature and is wildly used as a staple food in the most southern part of Ethiopia [58,59]). *Enset* is important for the local economy because its products, locally called *waasa* and *bu'la*, are sold in markets and are a source of income. Its roots, leaves, and stem are also used to feed animals during drought years. The Peasant Association (Kebele Administration) is the lowest administrative unit in Ethiopia that is accountable to the district (district) administration. Locally, households are organized in small groups of five households known as the 1 to 5 group. The government designed it without having local farmers say in its formation. The government widely uses this group for economic, political, and social purposes. Of the total 402 households involved in this study, 60% (n = 242) were members in the 1 to 5 group organization and the remaining 40% (n = 160) were not. On the other hand, 11% (n = 42) were serving as group leaders. There is widespread debate and controversies on the merits and demerits of such grouping. However, the purpose here is as a social organization, to what extent being a member or a leader in 1 to 5 groups is related to the likelihood of facing climate change-induced impacts?

The model revealed that being a member or having a position in the 1 to 5 groups affects the likelihood of exposure to climate change-induced drought. Being a member of the group increases the likelihood of exposure to drought effects by 120.2% (at $p < 0.01$ level). On the other hand, having a position of leadership of a group decreases the exposure to climate change-induced drought by 149.7% at $p < 0.01$ level (Table 5). A further investigation on the socio-economic status of the 1 to 5 group heads pointed out that they are were individuals with a better resource base. Furthermore, the group heads have more decision making power on resources owned by the community. On the other hand, the members of these groups were poor farmers who joined the group to get government support. Despite the claims of the government to support the poor organized in the groups, the members were most vulnerable compared with others. Also, the model examined agricultural technology use and the likelihood of exposure to climate change-induced impacts. The results of the model show that except for improved animal fodder, other agricultural technologies did not decrease the likelihood of exposure to climate change-induced impacts. Using chemical fertilizers (Urea and NPS) increases the possibility of experiencing the effects of drought and harvest losses. It increases the likelihood of experiencing drought effects by 150.4% (at $p < 0.01$ level). This is contrary to the claims of government officials who argue using chemical fertilizers as rewarding for farmers. Interviews with farmers revealed that when RF onset is late, the application of chemical fertilizers is calamitous to farmers because the fertilizers wilt the crops in their early stages. Thus, applying chemical fertilizers during drought seasons increases their likelihood of exposure to the effects of drought. Moreover, those farmers who use chemical fertilizers are more likely to experience bankruptcy during drought years for they have to pay back the fertilizer loan, which is expensive according to key informants. Thus, the debt and risks associated with borrowing in precarious situations are found to be factors for the higher vulnerability of farmers.

Table 5. Marginal effects due to independent variables (the coefficients table).

Variables	Drought	Lost Harvest	Flooding	Hunger
Sex	−0.244	−0.370	−0.179	−0.559
	(0.360)	(0.355)	(0.278)	(0.327) *
Land certificate	0.468	0.100	−0.645	−0.273
	(0.424)	(0.448)	(0.379) *	(0.417)
Family size	0.026	0.063	0.009	0.021
	(0.080)	(0.087)	(0.063)	(0.073)
Educational status	−0.100	−0.030	0.069	−0.116
	(0.048) **	(0.051)	(0.042)	(0.045) ***
Total land size	−0.095	−0.202	−0.439	−0.571
	(0.160)	(0.172)	(0.181) **	(0.209) ***
PSNP beneficiary	0.003	−0.919	−0.923	−0.004
	(0.393)	(0.354) ***	(0.308) ***	(0.358)
Do you produce enset?	−1.113	−0.636	−0.209	0.094
	(0.497) **	(0.455)	(0.338)	(0.365)
Weather early warning information	0.176	0.436	−0.155	0.108
	(0.327)	(0.326)	(0.268)	(0.295)
Climate change adaptation training	0.202	0.127	−0.262	0.232
	(0.355)	(0.350)	(0.283)	(0.318)
Membership in 1 to 5	1.202	1.598	−0.852	1.475
	(0.380) ***	(0.387) ***	(0.301) ***	(0.343) ***
Head of 1 to 5	−1.497	−2.000	0.719	−1.427
	(0.510) ***	(0.515) ***	(0.486)	(0.482) ***
Grazing land	0.857	0.406	0.134	0.958
	(0.648)	(0.604)	(0.477)	(0.599)
Water pond	1.022	1.434	0.289	1.070
	(0.865)	(0.869) *	(0.542)	(0.870)
Improved animal fodder	−0.761	−0.816	−0.597	−0.887
	(0.521)	(0.480) *	(0.409)	(0.488) *
Fertilizer/urea/NPS	1.504	1.041	0.075	1.429
	(0.534) ***	(0.531) **	(0.506)	(0.506) ***
Drought resistant crop variety	0.437	−0.151	0.268	0.687
	(0.420)	(0.396)	(0.327)	(0.392) *
Women participation in family decision making	−1.089	−0.350	−0.020	−1.015
	(0.419) ***	(0.370)	(0.295)	(0.360) ***
Participation in adaptation decision	−0.135	−0.007	−0.529	−0.043
	(0.408)	(0.396)	(0.305) *	(0.360)
N	357	358	357	357
Chi^2	59.99	85.78	39.62	82.49
P	0.0000	0.0000	0.0024	0.0000
Pseudo R^2	0.1856	0.2444	0.0958	0.2118
Adjusted R^2 (Marginal effect after logit)	0.8883	0.8775	0.7570	0.8325

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; (SE) = standard error.

4.3.2. Determinants of Facing Harvest Loss

The logit model results show that several factors affect the possibility of exposure to harvest loss in the study area. The model is statistically significant for the determinants of harvest loss (N = 358, $Chi^2 = 85.78$, $p = 0.0000$). The pseudo R^2 and adjusted R^2 values are 24.44% and 87.75%, respectively (Table 5). Among the explanatory variables, membership and headship in 1 to 5 groups, PSNP, and animal fodder control the likelihood of experiencing harvest loss. Also, the use of chemical fertilizer controls the likelihood of harvest loss. The PSNP is a social protection program that government instruments in drought-prone and food insecure areas of Ethiopia. Because of the widespread food insecurity, the government has been carrying out the PSNP in the study area. It aids vulnerable farmers in cash and kind in the study area. Of the sampled households, 29% (n = 114) were PSNP beneficiaries, whereas the remaining were not. The results of the model revealed that HHs supported by the program are less likely to experience the effects of harvest loss by 91.9% (at $p < 0.01$ level) than the non-users of the program. Like the case of drought exposure, membership in the 1 to 5 group increases the possibility of facing a harvest loss by 159.8% (at $p < 0.01$ level). On the contrary, bearing the leadership position in the 1 to 5 group reduces the likelihood of exposure to harvest loss by 200% (at $p < 0.01$ level). One of the challenges for farmers during the drought season is the lack of pasture and water for their livestock. To solve the problem, the government has introduced a plant species that farmers grow to feed their livestock. Farmers call it animal fodder in the study area. The logit model analysis shows that the use of this improved animal fodder reduces the likelihood of facing harvest loss. Farmers who use improved animal fodder are 81.6% less likely to experience harvest loss than the non-users (at $p < 0.1$ level). This is because, without the fodder, farmers use crops to feed livestock. Using chemical fertilizers in crop fields increases the chance of experiencing harvest loss. Farmers who apply chemical fertilizers in their crop field are 37% more likely to experience harvest loss during a drought season because crops wilt under inadequate rain conditions (Table 5).

4.3.3. Determinants of Exposure to the Effects of Flooding

Flooding is one of the climate change-induced impacts experienced by the HHs in the study area. The model is statistically significant for the determinants of experiencing flooding (N = 357, $Chi^2 = 39.62.78$, $p = 0.0958$). The pseudo R^2 and adjusted R^2 values of the model are 9.58% and 75.7%, respectively (Table 5). Among the variables considered, land use right certificate, being a beneficiary of PSNP, and membership in the 1 to 5 groups are the determinants of exposure to flooding. Also, taking part in climate change adaptation decisions affects exposure to climate change-induced flooding (Table 5). Land use right certificate affects the likelihood of experiencing climate change-induced impacts. The likelihood of facing flooding decreases by 64.5% for farmers who have land ownership certificate. This result is statistically significant (at $p < 0.1$ level). This is because farmers with a land use right certificate have a stronger landownership feeling than those without and this encourages farmers to carry out different soil and water conservation practices. Households with larger landholding size are less likely to experience flooding than HHs with a smaller landholding size. A unit increase in landholding size decreases the likelihood of experiencing flooding by 43.9% (at $p < 0.05$). Being a PSNP beneficiary also decreases the likelihood of facing climate change-induced flooding by 92.3% (at $p < 0.01$ level). On the other hand, membership in the 1 to 5 groups controls the likelihood of exposure to flooding impacts. Being a member in 1 to 5 group decreases the chance of experiencing flooding impacts by 85.2% (at $p < 0.01$ level). Participation in climate change adaptation decisions at the local level is also relevant. Farmers who take part in local level decision-making are 52% less likely to experience climate change induced flooding impacts than the non-participants (Table 5). The incident of flooding is common for low-lying areas, but the model did not consider topography and is a limitation of the model.

4.3.4. Determinants of Facing Hunger

Climate change and variability-induced hunger are one of the impacts experienced by the HHs in the study area, especially during drought periods. The model is statistically significant for the determinants of experiencing hunger by the HHs (N = 357, $Chi^2 = 82.49$, $p = 0.0000$). The pseudo R^2 and adjusted R^2 values are 21.18% % and 83.25%, respectively (Table 5). The logit model result identified sex, educational status, farmland size, membership, and headship in the 1 to 5 groups as determinants of exposure to hunger. Besides, the use of improved animal fodder, chemical fertilizer, and improved seed variety also control the chance of exposure to hunger. Furthermore, female participation in family decision making also decides the likelihood of exposure to change-induced hunger. The sex of the household head is associated with the likelihood of facing climate-induced impacts; being a male household head decreases the chance of exposure to hunger by 55.9% (at $p < 0.1$ level). This means female-headed HHs are more vulnerable to the exposure of hunger than the male counterpart. This is due to issues related to access to and control over resources owned by the family and the community.

On the other hand, a unit increase in education decreases the likelihood of facing hunger by 11.6% (at $p < 0.01$ level). This suggests the role of education in minimizing the impacts of climate change induced hunger. Household's total farm size also lowers the chance of facing hunger. A unit increase in farm size reduces the likelihood of facing hunger by 57.1% (at $p < 0.01$ level). This means as land holding size decreases, farmers become more vulnerable to climate change-induced hunger. Like the case of exposure to drought, membership in the 1 to 5 groups increases the likelihood of exposure to hunger. The likelihood of facing hunger increases by 147.5% for members in 1 to 5 group and decreases by 142.7% for the heads of the group (at $p < 0.01$ levels). Using improved animal fodder decreases the likelihood of experiencing hunger. Users of improved animal fodder are 88.7% less likely to face climate change-induced hunger than non-users (at $p < 0.1$ level). Women's involvement in family decision-making such as selling assets and renting out lands affects the likelihood of exposure to hunger. It reduces the chance of experiencing climate change-induced hunger by 101.5% (at $p < 0.01$ level). The use of chemical fertilizers and drought-resistant varieties also affects the possibility of experiencing climate change-induced hunger. Using these inputs increases the chance of experiencing hunger by 142.9% and 69.7%, respectively (Table 5). Key informants' interviews to justify the reasons behind these findings suggested the use of chemical fertilizer and improved seed varieties is disadvantageous for farmers. This is because farmers who use agricultural inputs usually get them in the form of a loan. The farmers have to sell their assets to pay back the debt since there is no surplus produce to sell in the market during drought years. This further degrades their asset base, exposing them to food security.

5. Conclusions

The analyses of data collected from different sources have shown that RF had been scarce, erratic and declining from time to time, exposing rained smallholder farmers to various climate change-induced impacts. Annual and growing season (*belg* and *kiremt*) RF had shown a declining trend in the study area. The analysis annual RSA has shown that the study area had experienced seven droughts of different extent during the three decades (1983–2014) under consideration. The monthly minimum, maximum, and average temperature had increased over the years under consideration, all of which are statistically significant. These changes in climatic variables resulted in climate change-induced epidemics, drought, harvest losses, flooding, and hunger.

The logit model results have shown that different several socio-economic and institutional factors control the likelihood of exposure to the impacts. The likelihood of exposure to the effects of drought is controlled by the educational status of the HH head, growing enset, and membership in the 1 to 5 groups. Furthermore, leadership in 1 to 5 groups, use of chemical fertilizers, and female involvement in family decision-making are other determinants. Furthermore, membership and headship in the 1 to 5 groups, being the beneficiary of the PSNP, the use of improved animal fodder, and the use of chemical fertilizer affect the likelihood of exposure to harvest loss. On the other hand, land use right certificate, participation in the PSNP, membership in the 1 to 5 groups, and participation in climate change adaptation decisions are determinants of climate change-induced flooding. Moreover, the logit model has identified that sex, educational status, farmland size, and membership and headship in the 1 to 5 groups affect the likelihood of experiencing climate change-induced hunger. Besides, the use of improved animal fodder, chemical fertilizers, and improved seed variety also control the likelihood of exposure to climate change-induced hunger. Participation of women in family decision-making also reduces climate change-induced hunger.

Climate change and variability-induced impacts are widely available in the study area despite various adaptive strategies of the government and the households. Government policies on education, female empowerment, land use right certification, and participation of the households in adaptation decisions can help to minimize climate change-induced impacts. The empirical literature also suggests that working on human capital is key to successful livelihood diversification [60–62]. In this regard, education (both formal and informal) and skills training need to be emphasized. On the contrary, organizing farmers into 1 to 5 groups contributed positively only in minimizing the incidence of flooding. Memberships in such organization did not help to reduce the possibility of facing the effects of drought, harvest loss, and hunger. Thus, the government needs to reform such organizations in a manner that they can contribute to lessening climate change impelled impacts. Besides, the supplies of agricultural inputs (improved seed varieties and chemical fertilizers) specifically during drought years increased the likelihood of exposure to climate change-induced impacts. Therefore, there is a need to build human capital through expanding education, strengthening female participation in family decision-making, and improve public participation in climate change adaptation undertakings to manage climate change-induced impacts sustainably.

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Article

Warming Winters Reduce Chill Accumulation for Peach Production in the Southeastern United States

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Abstract: Insufficient winter chill accumulation can detrimentally impact agriculture. Understanding the changing risk of insufficient chill accumulation can guide orchard management and cultivar selection for long-lived perennial crops including peaches. This study quantifies the influence of modeled anthropogenic climate change on observed chill accumulation since 1981 and projected chill accumulation through the mid-21st century, with a focus on principal peach-growing regions in the southeastern United States, and commonly grown peach cultivars with low, moderate, and high chill accumulation requirements. Anthropogenic climate change has reduced winter chill accumulation, increased the probability of winters with low chill accumulation, and increased the likelihood of winters with insufficient chill for commonly grown peach cultivars in the southeastern United States. Climate projections show a continuation of reduced chill accumulation and increased probability of winters with insufficient chill accumulation for cultivars with high chill requirements, with approximately 40% of years by mid-century having insufficient chill in Georgia. The results highlight the importance of inter-annual variability in agro-climate risk assessments and suggest that adaptive measures may be necessary in order to maintain current peach production practices in the region in the coming decades.

Keywords: chill accumulation; climate change; peaches; perennial crops; Georgia; South Carolina

1. Introduction

The peach industry in the southeastern United States (SEUS) has been a part of the regional iconography since at least the mid-1920s, and was historically an important part of the agricultural economy [1]. While California's current peach production dwarfs that of Georgia and South Carolina [2], the industry in the SEUS continues to contribute millions to regional, state, and local economies [3], and peaches remain important to regional identity [1]. In 2017, approximately 80% of Georgia's peach crop and 90% of South Carolina's peach crop were damaged due to warm winter temperatures. The warm conditions resulted in insufficient winter chill accumulation in some areas, while other parts of the SEUS were impacted when an early bloom, due to unseasonably warm temperatures, was followed by a mid-March freeze. In Georgia, an estimated 70% of the total 2017 peach losses were attributed to inadequate chill and 10–15% of the losses, the result of a spring freeze [4]. The combined impacts of anomalously low chill accumulation and spring freeze yielded substantial economic damage across the region [5]. Given the role of the peach industry in both the economy and culture of the SEUS, the 2017 crop failure garnered much public interest including whether such warm winters and impacts to perennial agriculture may become more commonplace in the coming decades.

Like other fruit trees, peaches undergo a series of physiological changes during the fall that allow for the onset of dormancy, when growth and development are slowed or stopped and the plant is better able to tolerate cold temperatures. Many perennial crops must be exposed to a certain amount of cold temperatures, or chill, during this period of dormancy to continue their development in the spring [6]. Peach cultivation is governed by a number of climatic factors such as cold hardiness, frost tolerance, and sufficient heat accumulation. Peach cultivars are frequently selected based on climatological chill accumulation [7] as insufficient chill accumulation can reduce flower quality, inhibit pollination and fruit development, and lower fruit quality and yield [6,8,9], with subsequent economic impacts to both growers and consumers [10].

Observational studies have shown warming in both the mean and extreme cold winter temperatures over the past half century across the US [11–13], much of which is consistent with anthropogenic forcing [14] and is expected to continue under climate change [15,16]. The exceptions of observed warming trends are primarily found in the warming hole across parts of the SEUS where winter temperatures cooled and spring onset trended later over the latter half of the 20th century [17,18]. The warming hole is likely a consequence of internal variability of the climate system that has buffered the influence of anthropogenic forcing to date, but is not expected to persist into the coming decades [17]. While it is acknowledged that chill accumulation is only one of many thermal-metrics that might directly impact crop suitability in a changing climate [19], declines in chill accumulation have been observed in some regions [20] and are projected to decline further [21]. Likewise, increases in winter temperatures are projected to reduce chill accumulation below the thresholds needed for peach cultivars in many peach-growing portions of the US [20,22].

In view of recent crop impacts due to warm winters, we examine chill accumulation across the SEUS in the context of ongoing climate change with a focus on implications for peach cultivation. First, a first-order estimate is provided of the contribution of anthropogenic climate change to observed low chill accumulation winters in the SEUS and years with insufficient chill in prime peach-growing areas in Georgia and South Carolina during 1981-2017. Secondly, using a suite of downscaled climate projections, changes in chill accumulation, the frequency of low-chill winters, and changes in the risk of winters with insufficient chill for common peach cultivars in the coming decades were investigated. Comprehensively, this study presents methodologies that may be applied to agro-climate metrics for conducting climate change risk and impact analyses for perennial crop systems globally, and provides a risk assessment of insufficient chill for peaches—and general chill accumulation for other perennials—in the SEUS, presenting information useful for climate-informed decision making.

2. Materials and Methods

Two primary datasets were used in this study (available at https://data.nkn.uidaho.edu/). First, the observed daily maximum and minimum temperature (T_{max}, T_{min}) at a ~4-km spatial resolution for the period 1981–2017 for the SEUS [25°–35.2° N, 78.5°–88.5° W (see Figure 1a)] were acquired from the gridded surface meteorological dataset (gridMET) of [23]. Previous validation of gridMET showed high correlation and low bias of temperature when compared to meteorological station observations across the US [23], and comparisons in chill accumulation between gridMET and data from 50 SEUS meteorological stations from 1980–2017 showed strong spatial correlation (r = 0.99), with a mean absolute error of 50 chill hours and a median bias of -17 chill hours (analysis not shown). Second, the projections of daily T_{max} and T_{min} from 20 global climate models (GCMs) that participated in the fifth phase of the Climate Model Intercomparison Project (CMIP5) were statistically downscaled using the multivariate adaptive constructed analogs (MACA) method [24]. The MACA used gridMET as training data, thereby ensuring compatibility in contemporary climate statistics between the downscaled GCM experiments and gridded observations. The analysis of climate projections was constrained to simulations for the early (2010–2039) and mid- (2040–2069) 21st century periods given the limited ability for developing meaningful management strategies relevant to the end-of-century projections. Further, we focused on future experiments run under the Representative Concentration Pathway 4.5 (RCP 4.5) to provide a conservative estimate of projected changes in chill accumulation. The projections using RCP 8.5 would likely show similar qualitative changes, but with larger magnitudes, particularly for the mid-21st century where multi-model mean changes in winter mean temperatures show an additional

0.6 °C warming above RCP 4.5, although the variability among models exceeds the difference between RCP 4.5 and RCP 8.5 for the time horizons highlighted herein.

A first-order estimate is provided on the influence of anthropogenic climate change on observed 1981–2017 chill accumulation using a large ensemble of CMIP5 simulations and a pattern scaling approach that allows for comparisons between rates of local and global change [25]. The differences in monthly T_{max} and T_{min} as simulated by 23 different GCMs at their native spatial resolution were taken between two 30-year periods, 1850–1879 and 2070–2099. The pattern scaling approach allows the expression of modeled rates of regional change for an individual variable and month to modeled rates of change in the global mean annual temperature. This approach assumes a linear relationship between the variables, which is reasonable for climate change timescales [25]. The pattern scaling was calculated separately for each model, as well as for the 23-model median. For each model, the anthropogenic climate change signal was defined for monthly T_{max} and T_{min} by multiplying the monthly varying pattern scaling function by an 11-year moving average of the change in the modeled global mean annual temperature relative to each model's 1850–1879 baseline. It is acknowledged that this is one of several first-order approaches for approximating the modeled influence of anthropogenic climate change over the historical record [26,27].

Following [26], a time series of daily T_{max} and T_{min} for 1981–2017 for the SEUS was created that preserves the observed interannual climate variability, but removes the influence of modeled anthropogenic climate change by subtracting the estimated difference in modeled monthly temperature anomalies (relative to the 1850–1879 baseline) using pattern scaling from the observed temperatures. These counterfactual scenarios do not make an effort to discern the sources of change in the observed data. Rather, they provide an approach for estimating the proximal effects of modeled anthropogenic climate change in the context of real-world observations.

The peach location data were obtained from the 2016 United States Department of Agriculture—National Agricultural Statistics Service Cropland Data Layer (CDL, available at https://www.nass.usda.gov/Research_and_Science/Cropland/Release/index.php) for the SEUS states of Alabama, Georgia, South Carolina, and Florida [28]. Approximately 94-km^2 were classified as peach in the 2016 Southern CDL with nearly all of the orchards located in Georgia (~34.5-km^2) and South Carolina (~58-km^2) (Figure 1a). The 30-m resolution CDL data was aggregated to the common 4-km resolution of the climate data for analyzing chill accumulation over peach-growing locations, summing the number of 30-m peach cells within each 4-km grid cell. The peach-growing locations were classified as those 4-km grid cells with >0.01% peach density. Finally, in order to provide locally-relevant results in addition to the regional analysis, our peach cultivar-specific analysis focused on peach locations within a 4-county area of central Georgia and a 3-county area in the Piedmont region of South Carolina that are responsible for ~75% and ~50% of each state's peach production, respectively.

Estimates of chill accumulation derived from chilling models are used for selecting appropriate crop species and cultivars, and to track plant phenology for farm management practices [29,30]. While there are multiple modeling approaches for calculating chill, the Weinberger Chilling Hours Model [31] was utilized as chill requirements for SEUS peaches are most commonly reported in chilling hours. The chill thresholds for peach cultivars examined in this study were quantified using the Weinberger model in central Georgia. Further, this model is commonly used to track winter chill accumulation across the SEUS as part of the online tools available through regional university consortiums and university extension programs (e.g., http://agroclimate.org/; http://weather.uga.edu/), and as such, using this chill model allows for the most direct translation of this work to end users.

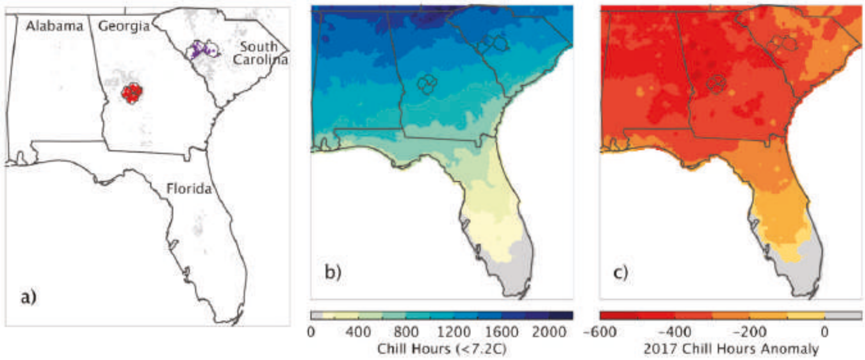

Figure 1. (**a**) The southeastern US study area. 4-km cells with >0.01% peach density are highlighted in grey. Georgia and South Carolina peach-growing counties examined explicitly in this study are outlined in grey and those cells with >0.01% peach density within these counties are highlighted in red (Georgia) and purple (South Carolina). (**b**) The average annual number of chill hours for the 1981–2017 observed period. Areas with <100 chill hours are masked in grey. (**c**) The winter chill accumulation anomaly in 2017 compared to the 1981–2017 average. Areas masked in grey as in (**b**).

The Chilling Hours Model sums the number of hours per day with temperatures <7.2 °C; hourly data were temporally disaggregated from daily T_{max} and T_{min} using a modified sine curve model [32]. Annual chill accumulation was considered from 1 October to 15 February, as is standard in the SEUS peach industry [33]. Peach chill requirements were obtained from the University of Georgia [34] for three cultivars grown in the SEUS. Gulfprince and Juneprince peaches require 400 and 650 chill hours, respectively, and are hereafter referred to as low- and moderate-chill cultivars. The Elberta peach cultivar (hereafter referred to as high-chill) requires 850 chill hours and is a cultivar standard to which the phenology of other peach cultivars is compared [34]. It is noted that not all of these cultivars are grown across all peach-growing locations of Georgia and South Carolina. Gulfprince is a cultivar grown primarily in southern Georgia, while central Georgia principally grows peaches with chill requirements ≥600 chill hours (Dario Chavez, University of Georgia Extension Specialist, personal communication). However, these three cultivars have been included as exemplary of the range of chill requirements across SEUS-grown peaches. By including the low-chill cultivar in our analyses of selected South Carolina and Georgia peach-growing counties, we show the capacity for these counties to continue to produce peaches under future climate conditions should future chill accumulation limit the productivity of the currently-grown moderate- and high-chill cultivars.

Chill accumulation was calculated over the 1981–2017 period with the observational data, and for the counterfactual scenarios using the observed data from 1981–2017 after removing the influence of anthropogenic climate change. The 1981–2017 data were further used to quantify changes in the frequency of low-chill winters, defined as the bottom decile (10th percentile). This provides both additional context for the peach-focused analysis herein and may be of broader interest to the SEUS fruit and nut industry reliant on understanding exposure of low-chill winters as it pertains to the economics of orchard operations [29]. The observed and counterfactual scenarios for 1981–2017 were used to quantify the degree to which modeled climate change influenced the average chill accumulation, the probability of experiencing a low-chill winter, and the risk of insufficient chill accumulation for the three peach cultivars across the key Georgia and South Carolina peach-growing regions. Chill accumulation was also calculated for the 2010–2069 period for each of the 20 downscaled climate datasets. A similar set of tests were applied to projections including changes in average chill accumulation and the probability of experiencing a low-chill winter across the SEUS. Finally, the probability of insufficient chill was estimated for the early and mid-21st century conditions for the key peach cultivars and regions in order to highlight the potential risk to peach cultivation. Given our focus on the changes to chill accumulation with respect to perennial fruit cultivation, areas with <100 chill hours over the 1981–2017 observed period were masked out.

3. Results

The average chill accumulation for the observed period 1981–2017 across the SEUS ranged from less than 100 h in southern Florida, to more than 2000 h in the Blue Ridge mountains of northeastern Georgia (Figure 1b). The majority (>65%) of the region—from northern Florida to northern Alabama, Georgia, and South Carolina—averaged 500–1500 chill hours, including approximately 1100 h in the central Georgia peach-growing region and 1350 h in the Piedmont peach-growing region of South Carolina. With the exception of southern Florida, the 2017 chill accumulation was substantially lower than the 1981–2010 normal. The accumulated chill in 2017 showed an SEUS average anomaly of approximately 330 h below normal. The Georgia peach regions showed an anomaly of ~430 h below normal, and South Carolina peach regions showed an anomaly of ~360 h below normal (Figure 1c).

The observed average chill accumulation over 1981–2017 was less than that modeled in the absence of anthropogenic climate change, consistent with the expectations from modeled warming (Figure 2a). A distinct geographic pattern of the reduced chill hours due to climate change was evident across the SEUS, with nominal differences in southern Florida and reductions of more than 120 h in northern Alabama, Georgia and South Carolina. The peach-growing regions showed average reductions of ~115–120 chill hours in Georgia and South Carolina. Notably, these reductions are averages over the 37-year period as the modeled estimate was larger in more recent years. Complementary to average reductions in chill hours, the percent of years experiencing low winter chill was substantially higher across the SEUS over the 1981–2017 period than it would have been in the absence of climate change (Figure 2b). These trends were found across models. The 23-model range for declines in chill was ~68–140 h, while the range for the probability of low-chill winters was 1.6–4.6% of years (from a reference of 10% of years).

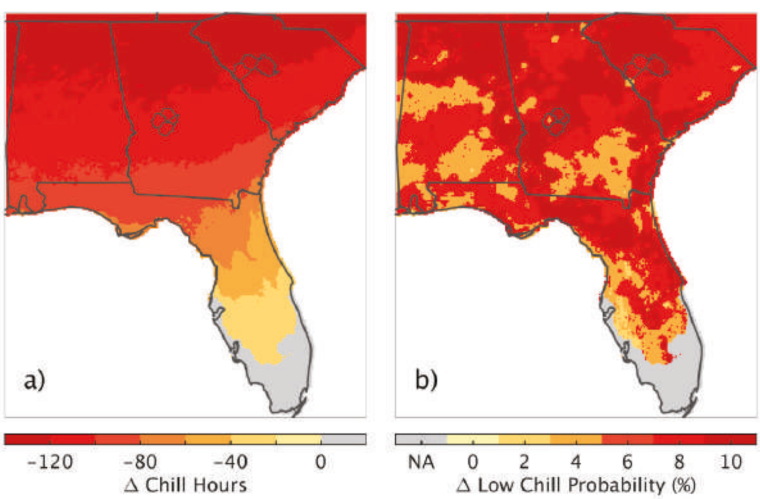

Figure 2. (**a**) The average change in 1981–2017 observed winter chill hours due to the influence of anthropogenic climate change (23-model median). (**b**) The change in the probability of a low-chill winter as a result of climate change, shown as 1981–2017 observed minus 1981–2017 counterfactual (23-model median). For both panels, the areas with <100 chill hours for the 1981–2017 observed climatology are masked in grey.

The reductions in chill accumulation and increases in the occurrence of low-chill winters may be inconsequential for agriculture unless there are direct impacts to plant physiology or indirect crop impacts (e.g., pathogens, pests). For the three peach cultivars, we show that the Georgia peach-growing region had five winters from 1981–2017 that did not accumulate sufficient chill for the high-chill cultivar (Figure 3a). No winters in the South Carolina peach-growing regions had insufficient chill for the cultivars considered from 1981–2017 (Figure 3b). By contrast, the counterfactual scenarios all showed greater chill accumulation and reduced occurrence of winters with insufficient chill for high-chill cultivars in Georgia. Notably, we show that the chill accumulation in 2017 would have been the lowest in the 37 year period in Georgia without climate change, suggesting that it was primarily driven by natural variability. However, the estimated 2017 chill accumulation excluding the modeled first-order influence of climate change for the peach-growing area of Georgia ranged from ~760 to ~920 chill hours across 23 models, with a median of ~825 h, well above the threshold of 650 chill hours required for moderate-chill cultivar and the ~660 chill hours observed that winter.

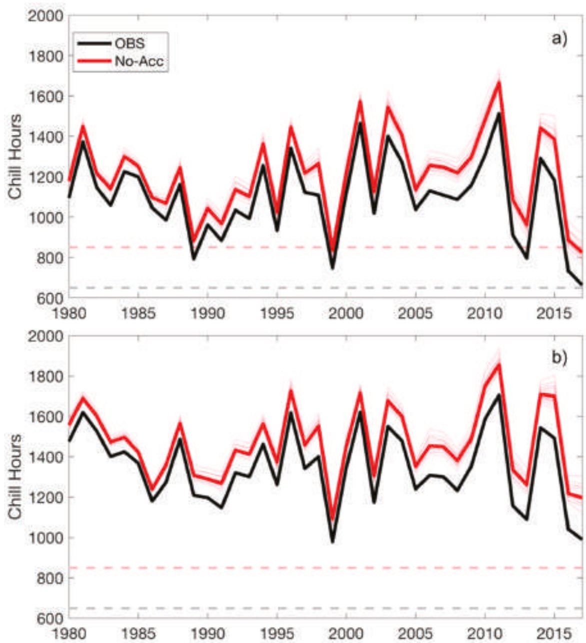

Figure 3. Time series of 1981–2017 chill accumulation for (**a**) the Georgia peach-growing region, and (**b**) the South Carolina peach-growing region. The observed data (OBS) are shown in black, while modeled chill accumulation estimates excluding the influence of anthropogenic climate change (No-Acc) are shown in red, with lighter red lines indicating individual models and the heavy red line indicating the 23-model median. The light pink dashed line indicates the chill requirement for a high-chill peach cultivar and the dashed grey line indicates the chill requirement for a moderate-chill peach cultivar.

The reduced chill accumulation across the SEUS was modeled relative to contemporary 1981–2017 averages for the early and mid-21st centuries, with multi-model mean SEUS declines of ~100 h, and ~185 h, respectively (Figure 4a,b). The geographic patterns of reductions in chill hours were similar to those shown for the influence of modeled climate change for the 1981–2017 period. Over Georgia (South Carolina) peach-growing regions, the average declines in chill were calculated as ~110 (~135) hours by the early 21st century and ~210 (~250) hours by the mid-21st century. In addition to declines in the average chill accumulation, the probability of experiencing a year with low winter chill accumulation increased. Averaged across the SEUS and across all models, approximately 20% of years by the early 21st century and 40% of years by the mid-21st century experienced low winter chill, with the greatest increases across western and northern Alabama, northern and central Georgia, and northern and central South Carolina (Figure 4c,d). By the early and mid- 21st century, Georgia (South Carolina) peach regions saw ~15% (30%) and 32% (52%) of years having low winter chill, respectively.

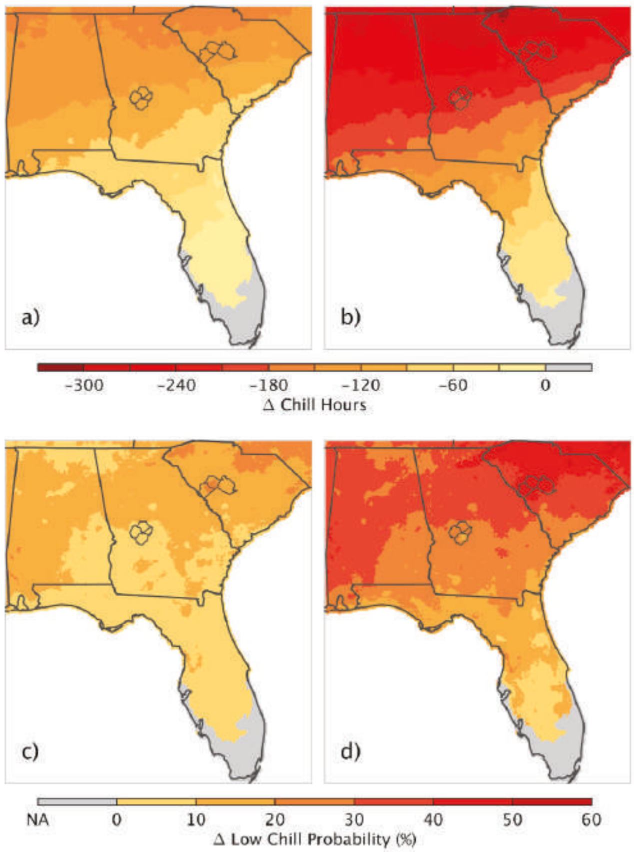

Figure 4. The difference in climatological chill hours for **(a)** the early 21st century (2010–2039) and (**b**) mid-21st century (2040–2069), relative to the observed 1981–2017 period. Panels (**c**) and (**d**) show differences in the probability of a low-chill winter for 2010–2039, and 2040–2069, respectively, relative to the observed 1981–2017 period. For all panels, the areas with <100 chill hours for the 1981–2017 observed climatology are masked in grey.

With respect to peach cultivar-specific chill requirements, 23% (4%) percent of years showed insufficient chill for the high- (moderate-) chill cultivar in prime peach-growing counties in Georgia by the early 21st century, rising to 43% (11%) percent of years by the mid-21st century (Figure 5a). The peach-growing regions in South Carolina, which did not see chill accumulations below established thresholds from 1980–2017, had 5% (0.25%) percent of years with insufficient chill for the high-chill (moderate-chill) cultivar by the early 21st century, and 12% (1.5%) percent of years by the mid-21st century (Figure 5b). Notably, there was substantial inter-model variability in the risk of winters with insufficient chill. For example, the percent of winters with insufficient chill for the moderate-chill cultivar in Georgia ranged from 0–16% for the early 21st century, and 0–30% for the mid-21st century.

By contrast, chill accumulation was sufficient for the low-chill peach cultivar under both future time periods in both states' peach-growing regions.

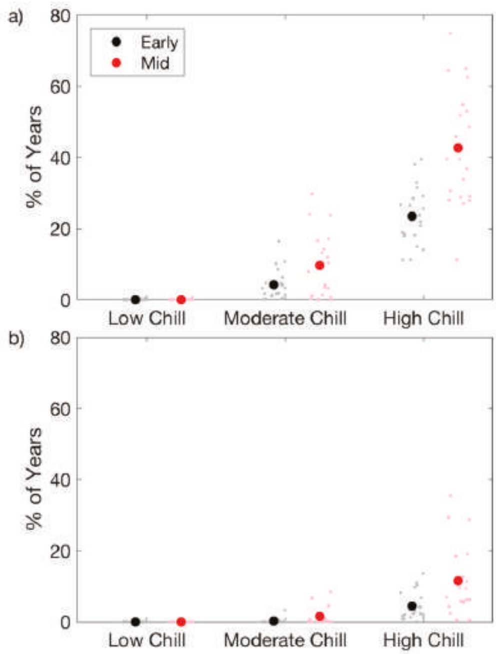

Figure 5. (**a**) For the Georgia peach-growing region, the percent of years with insufficient chill for a low-, moderate-, and high-chill peach cultivar under early 21st (black/grey) and mid-21st (red/pink) century conditions. Small grey and pink dots indicate the percent years for individual models, while the larger black and red dots indicate the 20-model average (**b**) As in (**a**) but for the South Carolina peach-growing region.

4. Discussion

Recent studies have shown that extreme events around the globe would not have been possible without the influence of human-induced warming [35–37]. Temperatures in the SEUS during the October-February chill accumulation periods of 2015–2016 and 2016–2017 were the 2nd and 3rd warmest since 1895, with the 1931–1932 winter being the warmest [38], suggesting that such warm winters are possible within the bounds of natural variability and can occur without significant contributions from anthropogenic climate change. While we do not undertake a detailed attribution analysis, our modeling exercise provides support that recent insufficient chill accumulation in the SEUS peach regions, such as in 2017, would not likely occur under the same synoptic conditions in the absence of climate change. Further, our results showing an increased probability of low-chill winters due to climate change add to the growing body of literature defining the contribution of anthropogenic climate change to observed adverse climate impacts [27,39,40].

Although insufficient chill accumulation is not a principle cause of loss for federally-insured crops in the SEUS [41,42], previous work has postulated that projected declines in chill may reduce suitability for perennial crop production [19,43]. Similarly, the projected future declines in chill accumulation across the SEUS complement previous work showing increases in the average and coldest winter minimum temperatures [16], and declines in chill accumulation in regions around the globe [21]. While this warming may offer range expansion for cold-intolerant crops, the related reduction in the winter chill accumulation in subtropical climates like the SEUS is projected to have negative impacts on warm-region fruit and nut crops, particularly those with moderate and high chill requirements [20,21]. However, the degree to which these declines may impact crop yield is unclear as uncertainties remain regarding the chill requirements that are physiologically needed for production, and the overall effect of marginal chill accumulation on crop yield and quality [44,45]. For example, while a common commercial peach cultivar grown in central Georgia has a stated chill requirement of 850 h, Georgia peach specialists have suggested that only 800 h are needed for a suitable crop [4]. Consequently, we underscore that this work is not predictive of yield impacts related to reduced chill accumulation.

Compounding the problem of crop chill requirements is the questionable accuracy of the chilling model. While this model has been widely used for quantifying crop chill requirements, it may be overly sensitive to warming, potentially overestimating the impact of climate change [43]. However, while it is acknowledged that previous studies have shown that the Dynamic Model may provide a more accurate representation of chill accumulation [21], the 20-model mean changes in the average chill accumulation show an agreement of declines across the SEUS and other warm-winter regions, regardless of the chilling model (Figure 6). Further, we recognize that familiarity with chill portions (the units of the Dynamic Model) may be lacking among extension agents and fruit industry professionals (Pamela Knox, University of Georgia Agricultural Climatologist, personal communication), and that regionally-defined chill portion thresholds do not yet exist for SEUS peach cultivars (Dario Chavez, personal communication). Finally, we acknowledge the limitations of using temporally disaggregated daily data [46], and that the microclimates of orchard sites and orchard management practices may augment or abate the projected changes and impacts.

Despite research suggesting that declines in crop suitability due to climate change may not be as severe as shown in our results [45], it is worth noting that we examined changes in chill accumulation under a conservative, moderate warming scenario. Provided that some degree of reductions in suitability are anticipated for peach crops across the SEUS—as well as for other crops with similar chill requirements—adaptive measures may be warranted to maintain production. These measures may include altering orchard management practices and selective planting. For existing orchards, the application of chemicals such as hydrogen cyanamide may effectively break dormancy in insufficiently-chilled peach crops [47], overhead irrigation to encourage evaporative cooling may aid chill accumulation, and orchard management practices such as controlling tree vigor may help to lower the chill needed for successful bud break [48]. For future orchards, site selection with preferential planting in sites with cooler microclimates, such as low-lying cool-air sinks, may provide an opportunity to increase exposure to chilling temperatures. Orchard managers may also consider specific scion and rootstock combinations that may help mitigate the negative impacts of low chill [49]. Moreover, a transition to crop cultivars with lower chill requirements (e.g., Gulfcrest or other varieties developed for warmer climates) may reduce or eliminate the negative impacts of declining chill accumulation under climate change, as evidenced by the minimal impact of future warming to the low-chill cultivar examined in this study. However, it is noted that orchards planted in cool-air microclimates may be at increased risk of frost damage, and lower-chill cultivars may be more susceptible to early bloom and subsequent frost damage. While quantifying the complex relationships between chill accumulation, bloom, and the relative risks of insufficient chill and spring frost damage are beyond the scope of this work, the interactions between these physiological and climatic conditions highlight the need to consider a broader suite of environmental and economic considerations in planning for future orchard management.

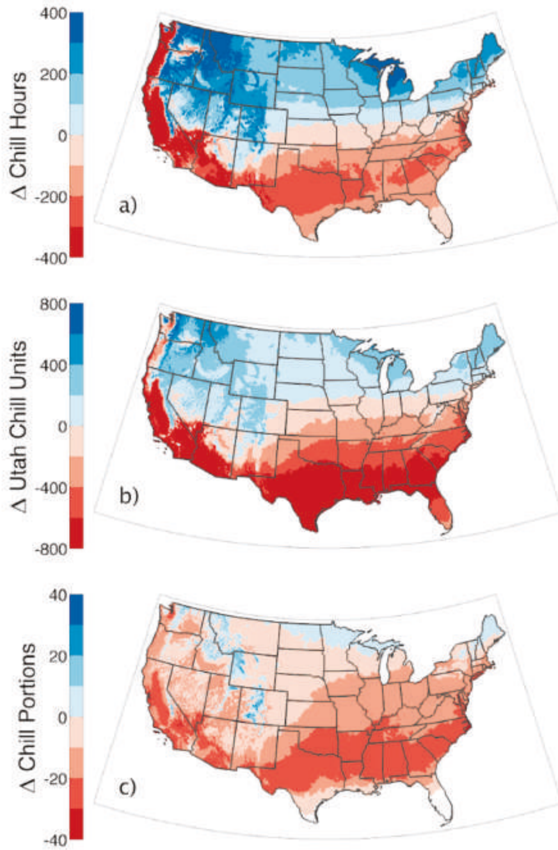

Figure 6. The 20-model average difference in annual accumulated chill between the modeled historical period (1971–2000) and the mid-century (2040–2069) period under RCP 4.5, where chill was accumulation was calculated over the October 1—April 30 cool season using (**a**) the Modified Chill Hour Model as chill hours 32–45 °C, (**b**) the Utah Model as chill units, and (**c**) the Dynamic Model as chill portions. The red shades indicate a reduction in chill accumulation under RCP 4.5, while the blue shades indicate an increase in chill accumulation. The white regions in (**c**) indicate areas with no chill accumulation under historical conditions. These data can be viewed and downloaded from the Climate Toolbox (https://climatetoolbox.org/) at (**a**) https://bit.ly/2QjbT2l (**b**) https://bit.ly/2AtEpZI and (**c**) https://bit.ly/2SBDcqm.

As has been suggested for perennial crop adaptation in other regions [19,50], the translocation of crops to cooler climates may also provide an adaptive measure for maintaining peach cultivation in the SEUS, particularly for those cultivars with higher chilling requirements. Historically, peach cultivation in Georgia extended into the northern portion of the state, but the favorability of that region declined over time due to frequent freeze damage [51]. If climate change reduces the freeze risk in northern Georgia, the area may provide a refuge within the state for continued cultivation of high-chill peach cultivars and other similarly at-risk perennials. However, any future translocation would require significant capital and be contingent upon economic viability, which is likely to be predicated on factors such as topography and soils, the costs associated with the purchase of farmland and the packing or processing facilities, competing land use, and market forces.

5. Conclusions

Quantifying the potential consequences of warming winters on chill accumulation may have implications for long-term orchard management and land use planning and may provide insights useful for climate-informed decision making for a variety of perennial crops that require winter chill. Our results show that anthropogenic climate change has negatively affected chill accumulation in the SEUS over the observed 1981–2017 period, and that ongoing climate change is likely to continue to reduce chill accumulation, with notable impacts on high- and moderate-chill peach cultivars in Georgia. We also highlight the importance of examining interannual variability when assessing climate change risks to agriculture, be that impacts to crop climatic niche or crop yield [19,52]. The adaptation measures (e.g., investments in lower-chill varieties) may be necessary in order for the SEUS, particularly Georgia, to continue to cultivate the crop that has historically been central to its cultural identity. Further, given the relationship between mild winter temperatures, early bloom, and damages due to a false spring—as also seen in 2017—we recommend future work consider the interaction between multiple agro-climatic variables to provide a more complete assessment of future crop suitability and identify the most appropriate adaptive efforts. Finally, as our study employs a methodology that is applicable across other geographic locations, perennial crop cultivars, and agro-climatic metrics, we recommend that similar work be undertaken across agricultural systems and regions to help identify potential crop-specific risks and adaptation opportunities.

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Article

Defining Crop–Climate Departure in West Africa: Improved Understanding of the Timing of Future Changes in Crop Suitability

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Abstract: The future climate is projected to change rapidly with potentially severe consequences for global food security. This study aims to improve the understanding of future changes in the suitability of crop growth conditions. It proposes a definition of crop realization, of the climate departure from recent historical variability, or crop–climate departure. Four statistically downscaled and bias-corrected Global Climate Models (GCMs): CCCMA, CNRM5, NOAA-GFDL, and MIROC5 performed simulations for the period 1960–2100 under the Representative Concentration Pathway RCP8.5 scenario to compute 20 year moving averages at 5-year increments. These were used to drive a crop suitability model, Ecocrop, for eight different crops across the three Food and Agriculture Organizations (FAO) AgroEcological Zones (AEZs) of West Africa (Guinea, Sahel, and Savanna). Simulations using historical climate data found that all crops except maize had a suitability index value (SIV) ≥0.50 outside the Sahel region, equivalent to conditions being suitable or strongly suitable. Simulations of future climate reveal that warming is projected to constrain crop growth suitability for cassava and pineapple in the Guinea zone. A potential for the northward expansion of maize is projected by the end of the century, suggesting a future opportunity for its growth in the southern Sahel zone. Crop growth conditions for mango and pearl millet remain suitable across all three AEZs. In general, crops in the Savanna AEZ are the most sensitive to the projected changes in climate. The changes in the crop–climate relationship suggests a future constraint in crop suitability, which could be detrimental to future food security in West Africa. Further studies to explore associated short- and long-term adaptation options are recommended.

Keywords: climate-departure; crop–climate departure; crop suitability; Ecocrop; food security; West Africa

1. Introduction

The livelihood and economies of most Sub Saharan African (SSA) countries are driven by rainfed agriculture [1–3]. About 96% of agricultural lands in SSA are rainfed [1,4]. Agriculture employs over 65% of the active labour force of the region, the majority of whom are practicing subsistence rainfed farming [5]. The agricultural sector is also responsible for 75% of SSA domestic trade [6,7]. It adds significantly to the economy of the region by contributing up to 15–20% to the Gross Domestic Product (GDP) [1,4,8,9]. In 2000, about 80% of the cereals consumed in SSA were domestically produced locally [4]. However, West Africa has been identified as one of the most vulnerable regions of the world owing to its low adaptive capacity and a fast-growing population, with many citizens whom are faced with malnourishment [1,10–12]. An adverse change in the climate over West Africa, both spatially and temporally, coupled with inadequate institutional and economic capacity to cope or adapt to its impact could become a determinant threat to agricultural production. Thus, food security and socio-economic activities across the region may be affected [13–17].

Climate strongly affects rainfed agriculture with direct consequences on food security [18–20]. This has resulted in different studies focusing on the response of crops and agriculture to the impact of increased greenhouse gas emissions across different regions of SSA owing to malnutrition and the need to improve food security [1,11,20–22]. Extreme changes in climate are projected to increase [23], translating into increased occurrence of both droughts and floods, which already account for 70% of economic losses through soil erosion and drought in West Africa [24,25]. The fifth Intergovernmental Panel on Climate Change (IPCC) assessment reported a projected warming across the different seasons over SSA to be larger than the global annual mean temperature increase [23]. The projected warming (1.5–4 °C by 2100) is likely to affect the agricultural sector by a reduction of up to 50% in crop yield and 90% in revenue across the region by the end of the century [7,23]. However, this may be further aggravated in regions like West Africa where the climate is warming faster and may lead to a radical departure from the regions' historical variability [26].

The definition of departure varies across disciplines. Broadly, a departure refers to a deviation or variation from a norm, standard rule, or behaviour. It can also mean starting out on a new course of action. In climate science, climate departure can be defined as a shift in the climate pattern of a region outside the range of historical variability and may be described in terms of mean local temperature exceeding historical highs [27–29]. Mora et al. [29] described climate departure as the year in which the average temperature of the coldest year after 2005 was warmer than the historic hottest year at a given location. Here we have defined climate departure as a deviation from the historical mean and/or variance of the local climate of an area or region induced by global warming [30].

The projected global warming level and the timing over the continent may intensify the impact of climate change on crop suitability. Severe temperature fluctuations and other extreme weather conditions such as droughts and floods may also threaten crop suitability thresholds. They vary spatially, resulting in potential yield declines where crop growth conditions are currently suitable and possible yield increases in other areas [31,32]. Challinor et al. [33], for instance, projected a future decline in crop yield of up to 5% for every degree of warming above the historical level in Africa.

Given the current state of climate departure research and the direct impact of climate on crop production systems (particularly rainfed), we are interested in the climate change induced crop realizations when climate departs from historical variability, which we term crop–climate departure. This study explores and proposes the information value of a comprehensive definition of crop–climate departure as "a departure from historical crop suitability threshold, whether in terms of variability, mean or both, due to warming of the climate over a location both in space and time resulting from climate change whether of radical climatic nature or not". This is in the context of recent climate historical variability and future climate projections using three West African weather stations, within three Food and Agriculture Organizations (FAO) Agro-Ecological Zones (AEZs). Mora et al. [29] suggests that West Africa will experience a climate departure with a mean temperature about two decades (2029) earlier than the global mean temperature (2047). Thus, we use the region as our proof of concept and to examine any likely large-scale crop suitability consequent changes the region may already be experiencing. Section 2 describes the data and methods used. Results from the study are outlined in Section 3. The discussion of the results and concluding remarks and recommendations for future are in Sections 4 and 5, respectively.

2. Data and Methods

2.1. Study Area

The demonstration area for this work is West Africa (Figure 1), which has rainfed agriculture as its mainstay economy. It is located at latitude 4–20° N and 16° W–20° E. The region comprises of 15 countries namely Benin, Burkina Faso, Gambia, Ghana, Guinea Bissau, Guinea, Ivory Coast, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, and Togo. It is divided into three FAO AEZs: Guinea (4–8° N), Savanna (8–12° N), and the Sahel (12–20° N) [25,34]. The temperature increases to the north of the region, while precipitation increases towards the south [25,34,35]. The Sahel zone is the warmest and driest, while the Guinea zone is the coolest and wettest of the three AEZs in West Africa. The climate of the region is mainly controlled by the West African Monsoon (WAM) which accounts for about 70% of the annual rainfall [20,34]. The WAM is an important and dynamic characteristic of the West African climate during the summer period [36]. It is produced from the reversal of the land and ocean differential heating and dictates the seasonal pattern of rainfall over West Africa between latitudes 9° and 20° N. The WAM is characterized by winds that blow south–westerly during the warmer months (June–September) and north-easterly during the cooler months (January–March) of the year [25,36]. It is the major system that influences the onset, variability, and pattern of rainfall over West Africa [3,37]. This affects rainfall producing systems with an impact on rainfed agriculture, which influences crop growth suitability and consequently food production in the region.

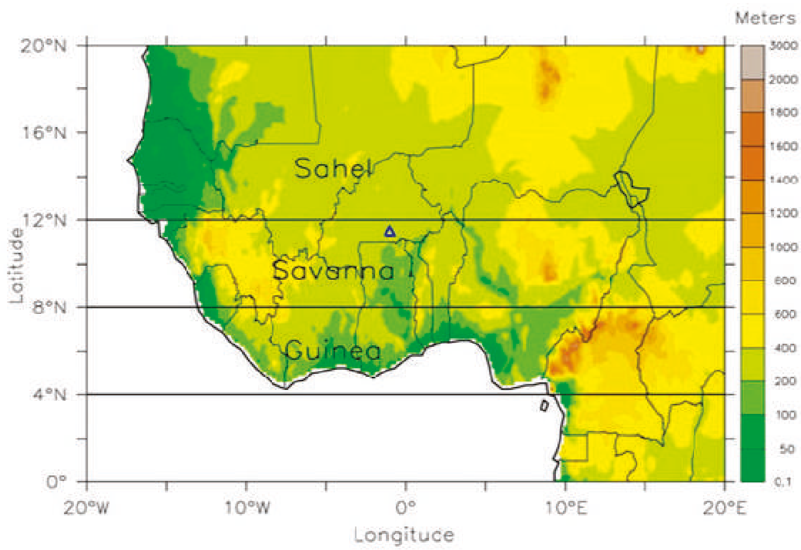

Figure 1. West African topography and the three Food and Agriculture Organizations (FAO)-Agro-ecological zones (AEZs): the Guinea, Savanna, and Sahel zones [25,34].

Different crops are grown in various parts of West Africa. Some of the major crops grown in the region are cassava, groundnut, millet, maize, sorghum, yam, plantain, cocoa, rice, and cowpea [20,38–40]. Millet and sorghum accounted for 64% of cereal production within the region in the year 2000, making them among the more important staple crops in West Africa [20,41]. Cassava is also an important staple food crop in terms of production in West Africa owing to its high resilience to drought [20,40,42]. This also applies to yam production, which accounts for about 91% of the world's production [20,41,43]. Maize provides about 20% of the calorie intake in West Africa and is adjudged the most important staple food overall in SSA [20,41]. Other crops such as cocoa and plantain, to mention a few, contribute significantly to the economy of the region.

2.2. Data

This study used three dataset types: observational weather station data, climate modelled data (statistically downscaled at the weather station level), and crop suitability data. The observed weather station data validated the mean monthly temperature and total monthly rainfall across the three AEZs. The crop suitability time series were simulated based on output from the Ecocrop suitability model [43] and the modelled climate data.

2.2.1. Climatic Variables

Temperatures (minimum and mean) and rainfall are important climate variables used in determining the impacts of climate change at subcontinental to global scales [44,45]. These two climate variables also have a significant effect on crop yield [46]. While rainfall affects the crop production in relation to its photosynthesis activities and leaf area, temperature affects the length of the crop growing season [47,48]. For this study, we used mean monthly minimum temperature (t-min) and mean monthly temperature (t-mean) and total monthly precipitation (prec.) of weather station data from Tabou, Ivory Coast; Sokode, Togo; Magaria, Niger. These weather stations each lie in three AEZs, Guinea, Savanna, and Sahel, respectively over West Africa. For the study, we used four statistically downscaled and bias corrected Global Climate Models (GCMs) in our analysis (CCCMA, CNRM5, GFDL, and MIROC) under a high-end climate change emission scenario (no adaptation), RCP8.5 (See Table 1 below for a description of the model). The GCMs were statistically downscaled using the Conditional Interpolation method as described in Hewitson and Crane [49]. The Conditional Interpolation downscaling method calculates the local phase relationships (PMI) for each weather station and each synoptic state combination. The bias relationship (BSI) between the weather station and its surroundings is then calculated. The method estimates the spatial extent of precipitation accurately and derives spatially referenced values representative of the area average. Overall, the interpolation conditioned by the synoptic state appears to better estimate realistic gridded values appropriate for use with model simulation output. For the temperature variable, the conditional interpolation employs the information content of the source data coupled with additional assumptions that may be physically justified (such as lapse-rate effects). The climate data were sourced from the Climate Information Portal (CIP) of the Climate System Analysis Group (CSAG), University of Cape Town (http://www.csag.uct.ac.za/climate-services/cip/). Data from this portal are at the station scale and weather stations in each AEZ are representative of that area.

Table 1. List of statistically downscaled and bias-corrected GCMs used in the study.

Modelling Institution	Institute ID	Model Name	Resolution
Canadian centre for climate modelling and analysis	CCCMA	CanESM2	2.8° × 2.8°
Centre National de Recherches Meteorolo-Giques/Centre Europeen de Recherche et Formation Avanceesencalcul scientifique	CNRMCERFACS	CNRM-CM5	1.4° × 1.4°
National Oceanic and Atmospheric Administration Geophysical Fluid Dynamic Laboratory	NOAAGDFL	GFDL_ESM2M	2.5° × 2.0°
Japan agency for Marine-Earth Science and Technology	MIROC	MIROC5	1.4° × 1.4°

2.2.2. Crop Thresholds to Suitability

The results of field experiments apply globally. A database of crop thresholds that translate into climate suitability has been collected and used in many locations to describe the suitability range of many plant and crop species using prec., t-min, t-mean, and the length of the growing season [43,50]. The climate threshold hosted by FAO dataset was obtained from the "dismo" package of the cran R software [51] (https://cran.r-project.org/web/packages/dismo/index.html). It was used in computing the climate suitability of each crop evaluated. It is acknowledged that thresholds will vary depending on finer resolution of the species (e.g., different varieties) or location (e.g., different soil, different rain distribution). However, the concept of crop suitability and the general validation of the thresholds makes this a useful tool to assess the impact of climate change and the emergence of novel regional climates on crop suitability over large areas examining the concept of crop–climate departure. The Ecocrop suitability model assessed four broad crop types and eight crops in total: cereals (pearl millet and maize); horticultural crops (tomato and pineapple); root and tuber crops (plantain and cassava) and fruit crops (mango and orange), using Ecocrop. The crop thresholds are listed in Table 2.

Table 2. Crop growth thresholds for eight crops as generated by the Ecocrop model.

Crop Name	Growing Duration (Days)	Temperature (°C)				Rainfall (mm)			
		Tmin	Topmin	Topmax	Tmax	Rmin	Ropmin	Ropmax	Rmax
Pearl millet	60–120	12	25	35	40	200	400	900	1700
Maize	65–365	10	18	33	47	400	600	1200	1800
Cassava	180–365	10	20	29	35	500	1000	1500	5000
Plantain	365	16	23	28	38	1000	1300	2000	5000
Pineapple	330–365	10	21	30	36	550	800	2500	3500
Tomato	70–150	7	20	27	35	400	600	1300	1800
Orange	180–365	13	20	38	38	450	1200	2000	2700
Mango	150–365	8	24	30	48	300	600	1500	2600

Where Tmin, Topmin, Topmax, and Tmax represents monthly minimum temperature, minimum optimum temperature, maximum optimum temperature, and maximum temperature, respectively; Rmin, Ropmin, Ropmax, and Rmax represents total monthly minimum rainfall, minimum optimum total monthly rainfall, maximum optimum total monthly rainfall, and maximum total monthly rainfall, respectively; optimum values represent the most suitable period for crop planting.

2.2.3. Model Description

The Ecocrop model is a crop suitability model. It uses a crop growth suitability threshold dataset hosted by the FAO [43]. It is an empirical model originally developed by Hijmans et al. [43] and based on the FAO-Ecocrop database [50] (Figure 2). The computation of optimal, suboptimal, and non-optimal conditions based on these datasets allows for the simulation of the suitability of crops in response to 12-month climate via t-min, t-mean, and prec. [43] (Figure 2). The Ecocrop model evaluates the relative suitability of crops in response to a range of climates including rainfall, temperature, and the growing season for optimal crop growth. A suitability index is generated as follows: 0 < 0.25 (not suitable), 0.25 < 0.5 (marginally suitable), 0.5 < 0.75 (suitable), and 0.75 < (highly suitable) [50,52]. The default Ecocrop parameters were assumed. Although those thresholds may vary with different geographical and/or climatic conditions, previous studies report a close correlation between the Ecocrop model and the climate change impact projections from other crop models [16,27,33,50]. A paucity of data over regions of interest like SSA limits the validation of these processes [53]. Nevertheless, the method contributes to the demand for regional scale assessment of crop response to future climate projections. The 12 coloured lines observed for the Ecocrop climate suitability simulations in Figure 2a,b below represents 12 months. Each describes the most suitable conditions for the crop under consideration in any given month. A highly seasonal crop (e.g., maize) has suitable growth conditions for a limited number of months. The conditions for non-seasonal crops are suitable throughout the year. Crops with a growing cycle longer than a year (e.g., pineapple and plantain) are represented by a single 12-month period.

2.3. Method

Four GCMs for the period 1960–2100 under the RCP8.5 scenario computed a 20-year moving average at 5 year time increments. It generated one mean 12-month value per 20-year window period for t-min, tmean, and prec. The mean 12-month climate value informed the crop suitability model, Ecocrop, for each GCM based on the methodologies described in Ramirez-Villegas, Jarvis, and Läderbach [50] for eight crops across the three AEZs of West Africa. The Ecocrop model simulated crop suitability indices characterized the crop–climate relationship and the impact global warming has on this relationship for each AEZ both spatially and temporally for each climate window. The suitability index scores were calculated for a range of climate variables for the period 1980–2000 using observed weather station data. This was used as a baseline to evaluate the downscaled GCM results spanning 1960–2100 at the three West African weather stations. It assessed the crop growth suitability in the zone for past climate conditions in reference to the published literature. Present day climate data was used as the preference for this zone owing to the constraint and paucity of weather station data and this data being the best available data to overlap with the Ecocrop model for the zone in the given study period.

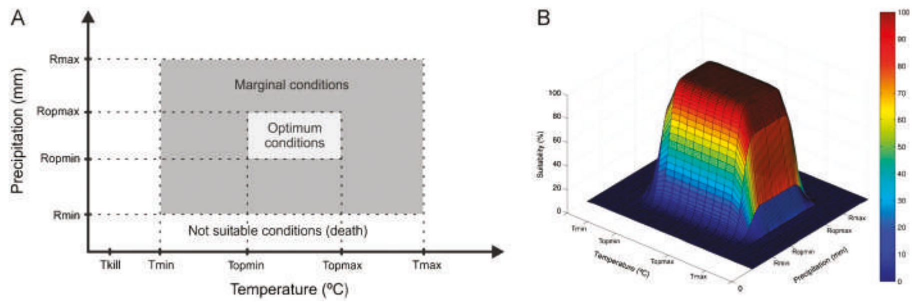

Figure 2. (**a**) two dimensional and (**b**) three dimensional diagram describing climate thresholds and its translation into crop suitability (Adapted from [50]).

3. Results

3.1. Evaluation of the GCMs in Simulating Rainfall and Temperature over West Africa

The downscaled climate data was firstly validated with the observed weather station data. Where missing records occurred, the corresponding month in the model's data were removed before computing the relationship between the datasets. Each GCM was correlated with the observed data for prec. and t-mean over the three weather stations, despite some discrepancy in precipitation over the Guinea zone (Figures 3 and 4). For temperature, the four models were correlated ($r \geq 0.6$) with the observed t-mean across the three AEZs of West Africa with the highest correlation ($r = 0.9$) over Magaria. The models were also correlated ($r \geq 0.6$) with the observed prec. in the Savanna and Sahel AEZs. A moderate correlation ($r \geq 0.3$) with observed weather station data was evident in the Guinea AEZ. This weak correlation may be due to the low resolution of the GCMs in capturing the total monthly rainfall in the Guinea zone. The validated GCM data was then input into the Ecocrop model.

3.2. GCMs Representation of AEZs, Seasons, and Suitability over West Africa AEZs

A correlation exists between the Ecocrop suitability model simulated with climate inputs from four GCMs, CCMA, CNRM, GFDL, and MIROC (hereafter Eco-GCMs), although with minor variations in amplitude and time. However, it is worth stating that the variation in simulated suitability by the four GCMs may be attributed to the inter-annual variability of the GCMs or the GCMs parametrization scheme. Nevertheless, Eco-GCMs simulated crop suitability is similar across the three AEZs over West Africa for the eight crops considered in the study. For example, cassava shows a similar suitability pattern across the AEZs (Figure 5). It is unsuitable (Eco-CCMA and CNRM) to marginally suitable (Eco-GFDL and MIROC) for cassava crop growth in the Sahel AEZ. In the Savanna AEZ, it is currently highly suitable for cassava, but this is predicted to decline in the future to become marginally unsuitable. The Guinea AEZ suitability for cassava does not change. The variability in crop growth suitability curves may be attributed to the variation in yield and production of cassava across the region due to the impact of climate change, corroborating previous studies [8,38].

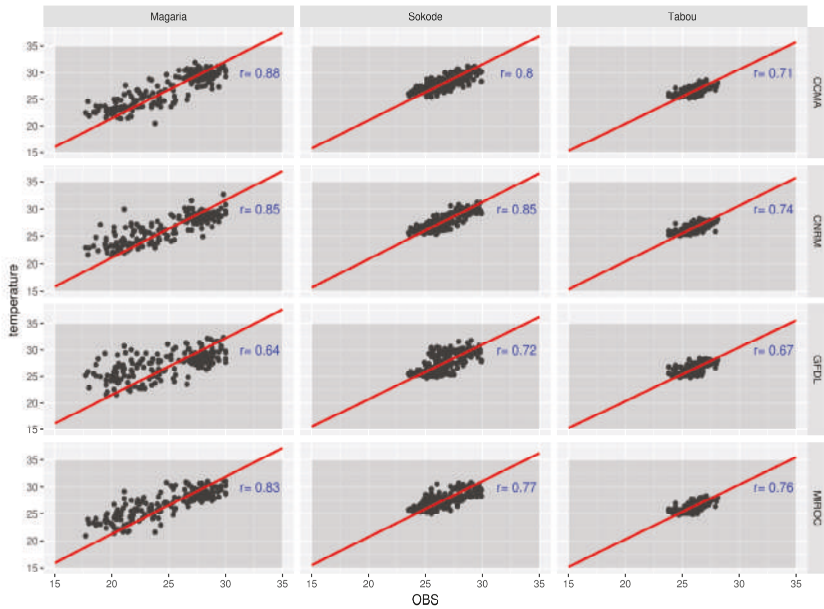

Figure 3. Mean monthly temperature (°C) as depicted by station observations and statistically downscaled CMIP5 GCMs (CCMA, CNRM5, GFDL, and MIROC) across the three agro ecological zones, Tabou, Sokode, and Magaria, of West Africa for the period 1980–2000. The top right corner r-values in each panel represent the correlations between the simulated and observed mean monthly temperature.

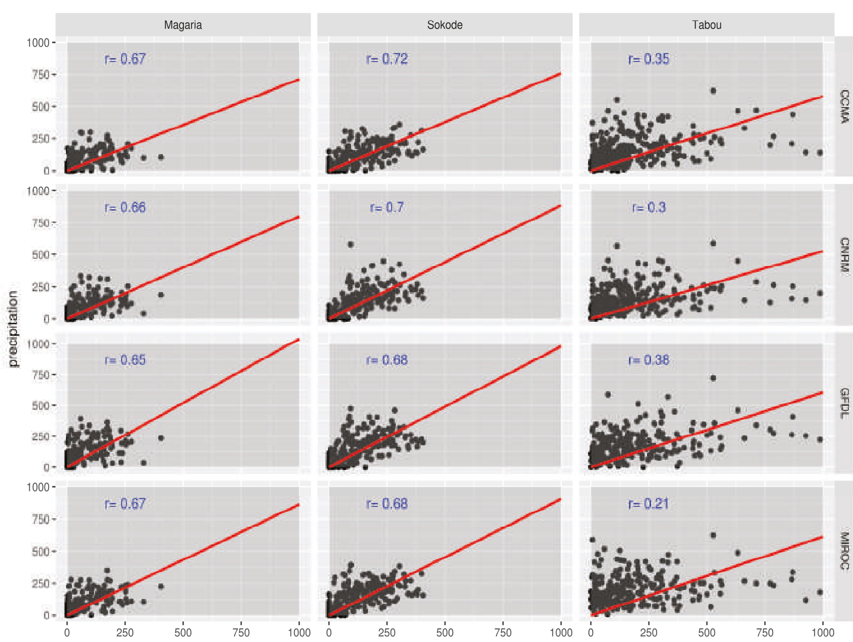

Figure 4. Total monthly rainfall (mm/month) as depicted by station observations and statistically downscaled CMIP5 GCMs (CCMA, CNRM5, GFDL, and MIROC) across the three agro ecological

zones, Tabou, Sokode, and Magaria, of West Africa for the period 1980–2000. The top right corner r-values in each panel represent the correlations between the simulated and observed mean monthly temperature.

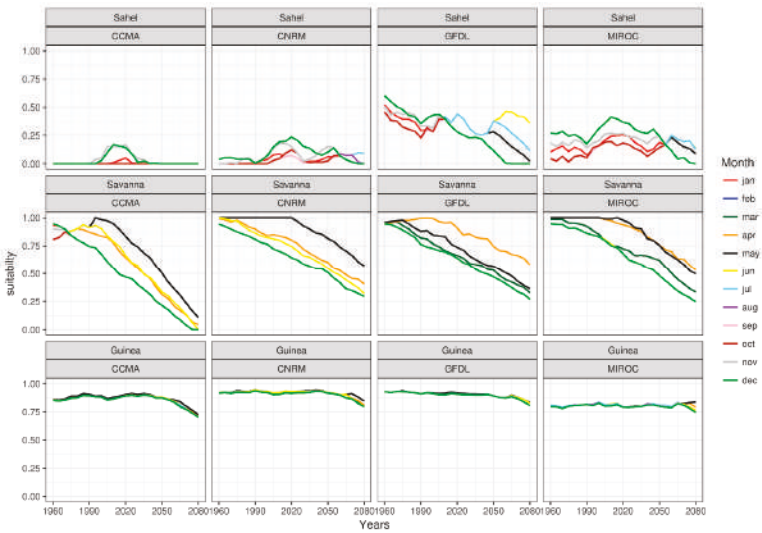

Figure 5. Cassava planting month suitability plots in the Guinea, Sahel, and Savanna as simulated by the four GCMs (CCMA, CNRM, GFDL, and MIROC) used as climate inputs into the Ecocrop suitability model.

Variability in the suitability of the month of planting for cassava crops in response to both AEZ and time increment is observed across the GCMs (Figure 5). The Guinea AEZ is currently the most suitable AEZ in which to grow cassava and is predicted to remain so. Suitable planting months in the Savanna AEZ as identified by all four models includes April–June and December, however a notable decline is observed, consistent for all four GCMs. Suitability declines from just below 1.0 to below 0.5 by 2050 in most cases. Conditions in the Sahel are presently and remain of low suitability. The simulation of the cassava crop growing season and period of planting across the three AEZs: Guinea (January–July and September–December), Savanna (April–November), and the Sahel (May/June–November) corroborates with previous findings with respect to the planting period and growing season in West Africa [54–56].

The concept of crop–climate departure allows for a consolidation of climate outputs from an ensemble of four GCMs into simulated crop suitability indices. Despite the marginal scale differences, the four GCMs consistently represent the unsuitability of cassava in the Sahel AEZ, its fast-declining suitability in the Savanna AEZ, as well as the high suitability of the Guinea AEZ. The cassava growing season is 12 months. Due to the predicted decline in the suitability of growth conditions, it is expected that it will become seasonal i.e., the suitability remains subject to appropriate seasonal planting, but conditions will then become unsuitable in the Savanna AEZ. Farmers will be required to adapt their practices in this AEZ. There is no reason at this stage to prefer one over the other GCMs, thus we use GCMs ensemble data as future climate scenario to simulate crop suitability in the subsequent sections of the paper plots of crop suitability from the Eco-GCMs. As seen from Figure 5, the ensemble suitability plots give a good representation of the Eco-GCMs model simulated suitability across the AEZs over West Africa. It shows the non-suitability of cassava in the Sahel, the fast-declining suitability and the observed seasonality in the Savanna AEZ, and high suitability in the Guinea zone. Thus, the crops ensemble suitability simulations are used in the results and discussion in the subsequent sections of this paper. A summary of crop suitability index values are given in Table 3.

Table 3. Ecocrop simulated crop Suitability Index Value (SIV) for the eight (8) different crops across the three Agro-ecological zones (AEZs) of West Africa.

Years	**1960**			**1990**			**2020**			**2050**			**2080**		
Crops/AEZs	GUI	SAV	SAH	GUI	SAV	SAH	GUI	SAV	SAH	GUI	SAV	SAH	GUI	SAV	SAH
Cassava	>0.75	>0.75	<0.25	>0.75	>0.75	<0.25	>0.75	>0.50	<0.25	>0.75	≤0.50	<0.25	>0.75	<0.50	<0.25
Maize	≤0.50	≥0.50	<0.75	≤0.50	≥0.50	0.50–0.75	<0.50	>0.50	>0.50	<0.50	>0.50	>0.50	<0.50	>0.75	>0.75
Mango	0.50–0.75	1.00	≤0.75	0.50–0.75	1.00	≤0.75	0.50–0.75	>0.75	>0.75	0.50–0.75	>0.75	0.75	0.50–0.75	>0.75	0.75
Orange	>0.75	>0.75	<0.25	>0.75	>0.75	<0.25	>0.75	>0.75	>0.25	>0.75	0.50–0.75	<0.25	>0.75	0.50–0.75	<0.25
Pearl millet	>0.75	>0.50	>0.50	>0.75	>0.50	>0.50	>0.75	>0.50	>0.50	>0.75	>0.50	>0.50	>0.75	>0.50	>0.50
Pineapple	>0.75	>0.75	<0.5	>0.75	<0.50	<0.50	>0.75	>0.75	0.50	>0.75	0.50–0.75	<0.50	>0.75	<0.50	<0.50
Plantain	1.00	>0.75	0.00	1.00	>0.75	0.00	>0.75	<0.75	0.00	>0.75	<0.75	0.00	>0.75	<0.50	0.00
Tomato	>0.75	>0.25	<0.5	>0.75	>0.50	<0.5	>0.75	>0.50	<0.5	<0.75	<0.50	<0.25	<0.75	<0.50	<0.25

GUI—Guinea AEZ, SAV—Savanna AEZ, SAH—Sahel AEZ. Ecocrop suitability Index: 0.0–0.25—Unsuitable/No suitability, 0.25–0.50—Marginally suitable, 0.50–0.75—Suitable, 0.75–1.00—Highly suitable.

3.3. Crop Suitability Response with Past Climate

Past climatic conditions (1960–2010) indicate that a crop growth suitability gradient existed from south to north across the three AEZs for each crop type considered. A Suitability Index Value (SIV) (0.75–1.00) is observed for each crop type in the Guinea and Savanna zones throughout the year (Figures 6 and 7). An exception is the cereal crop maize. Maize is marginally suitable (0.25–0.50) in the Guinea AEZ, suitable (0.50–0.75) for planting in May, September, and December in the Savanna AEZ, and January–February in the Sahel AEZ. The suitability increases (0.75–1.00) in 2050 (Figure 6). In the Sahel AEZ, other cereals and mango are suitable (above 0.50). Crop growth suitability increased for pineapple crops in this AEZ.

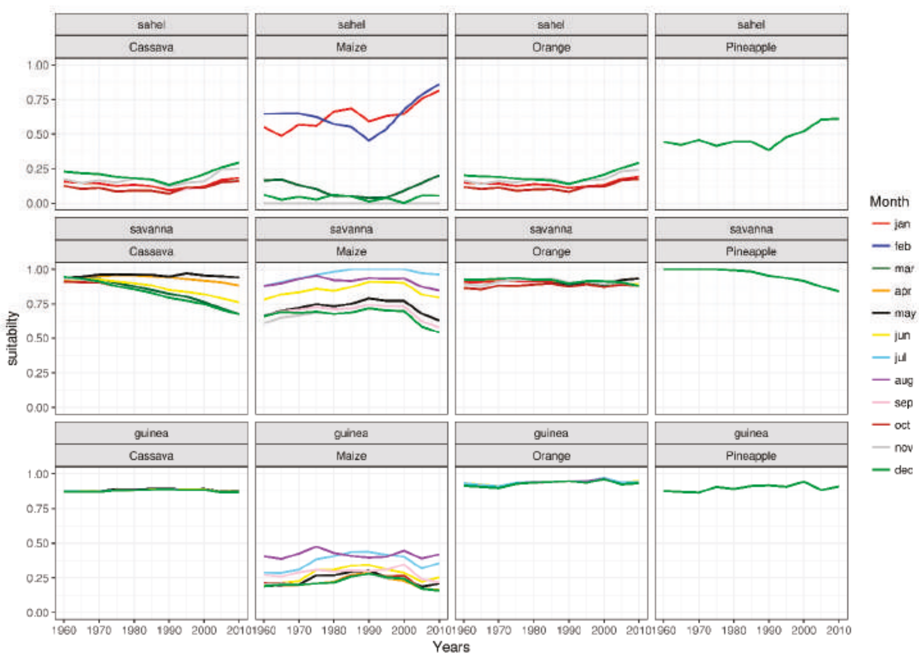

Figure 6. Ensemble crop suitability plots in the past climate (1960–2010) for cassava, maize, orange, and pineapple.

The Ecocrop simulations of crop growth suitability for the period 1960–2010 and the crop types evaluated corroborate previous findings with respect to the type of crops actually grown in the region. Cereals and root and tuber crops were the principal agricultural commodities in the region during this period [57,58]. Cassava and maize crops demonstrated modest yield increases of 6.3 to 10.3 and 1.1 to 1.8 tons ha^{-1}, respectively in the last 40 years [58,59]. The historical suitability of growth conditions for maize across the region (although marginal in the Guinea zone) highlights its importance as a staple crop here, accounting for almost 20% of the calorie intake for the population of West Africa [20,41]. The large area grown and high yield of pearl millet between 1960 and 2010 can be linked to the high suitability indices across the AEZs of West Africa over this period, contributing considerably to the livelihoods and economies of the countries in this region [60,61]. Increased productivity has also been witnessed in crops such as orange, mango, pineapple, and tomatoes in the last 40 years, again correlating with the high crop growth suitability indices identified for these crops [62,63]. Given the importance of these crops in the regional economy, a key question is, how is the projected change in climate predicted to impact on the crop growth suitability of these key crops in West Africa?

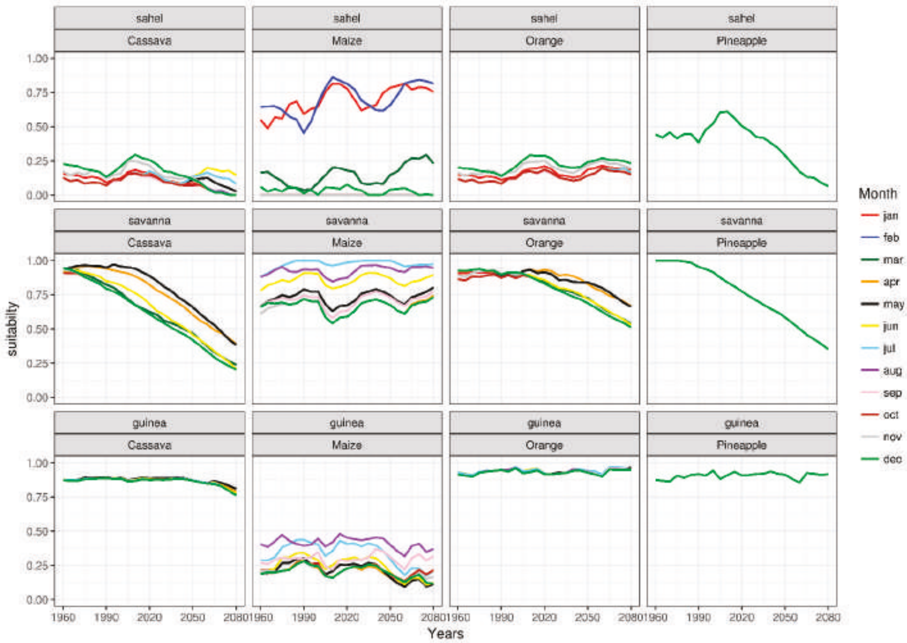

Figure 7. Projected model ensemble suitability over West Africa between 1960–2100 for cassava, maize, orange, and pineapple.

3.4. Projected Changes in Crop Suitability and Time of Planting over West Africa

The projected increase in global temperature is predicted to have a varied impact on crop growth suitability in West Africa (Figures 8 and 9). The Guinea AEZ remains largely unchanged with respect to crop growth suitability, evidently a more resilient area. Drastic declines are predicted for multiple crops in the Savanna AEZ including for cassava, orange, and pineapple. The main staple crop, maize, remains stable with an SIV of 0.5–1.0. It is interesting to note that the SIV for maize in the Sahel AEZ is projected to increase, shifting from suitable in 2020 to highly suitable by 2050 (Figure 7). Conditions for pearl millet will remain highly suitable (Figure 9), although the SIV for mango will decline post 2020.

The impact of future warming will affect crop seasonality, i.e the suitability of the time of planting. For root and tuber crops and cassava, in the months of April and May, they will become marginally suitable for cultivation by mid-century in the Savanna AEZ. Conditions will be unsuitable if planted in March, June, or December, which are currently optimal seasons. No change is predicted for cereal crops mango or orange.

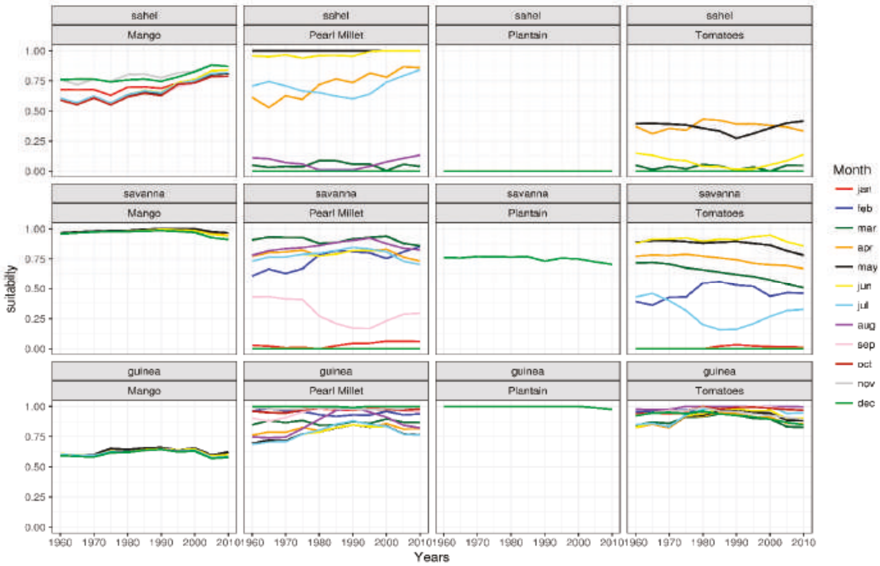

Figure 8. Ensemble crop suitability plots in the past climate (1960–2010) for mango, pearl millet, plantain, and tomatoes.

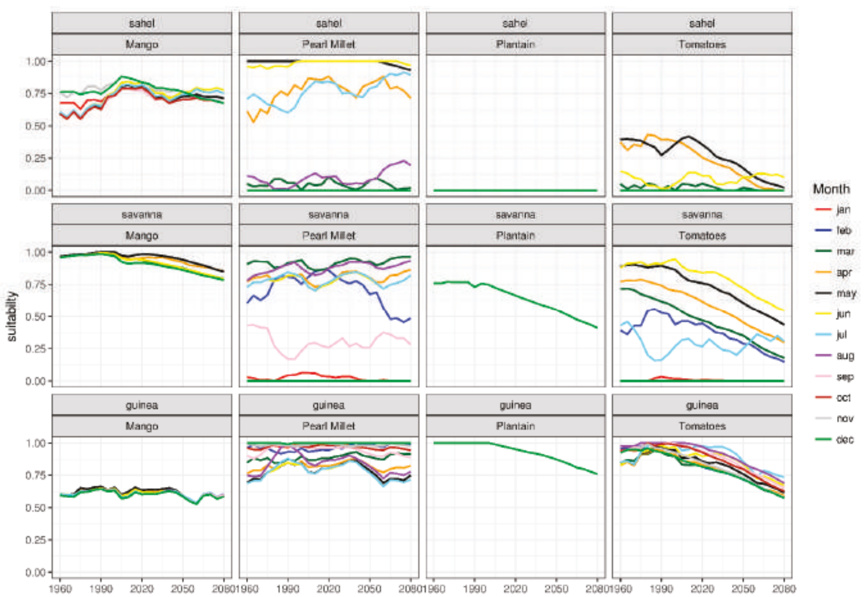

Figure 9. Projected model ensemble suitability over West Africa between 1960–2100 for mango, pearl millet, plantain, and tomatoes.

4. Discussion

4.1. From Climate Departure to Crop–climate Departure

The impact of global warming on the crop–climate relationship in the three AEZs of West Africa varies depending on the crop grown. The combination of a changing climate and crop growth suitability thresholds results in a projected deviation for the SIV from historical data. This may be a predicted increase in SIV, as observed for maize, or a decline as noted for crops such as cassava. A further variable is the AEZ itself. The predicted increase in SIV for maize in the Sahel zone by 2100 results from the projected increase in temperature and precipitation in this location. The decline in SIV forecast for cassava and pineapple in the Savanna AEZ decreases the suitability of the SSA region for these crops, spatially constraining suitable areas to the Guinea AEZ by 2100. The warming climate also influences the suitability of the month of planting of many crops. A potential cause for concern is the timing of crop–climate departure in the Savanna AEZ, which is already evident in root and tuber, cassava, and pineapple crops, and projected for orange crops by 2100. The diversity of crops grown in this AEZ may be diminished in the future.

The projected shifts in suitability and the variation of suitability between different crops and AEZ due to global warming highlights the importance of local climatic conditions in determining the extent of crop growth, development, and yield in response to climate suitability thresholds [31,64]. The above characteristics observed from the crop–climate relationship of different crops in the three AEZs of West Africa supports our proposed crop–climate departure definition of "a departure/shift from a historical crop suitability threshold, whether in terms of variability, mean or both, resulting from climate change whether of radical climatic nature or not due to warming of the climate over a location both in space and time". This definition can be used to inform adaptation responses to impacts resulting from climate change that will influence crop suitability, especially in a vulnerable region with low adaptive capacity like West Africa. Cultivating crops with high suitability as projected by the models such as cassava in the Guinea and maize in the southern Sahel may be the best solution. However, with improved/hybrid seedlings of the crop projected to decline that can withstand the variability in climate, this improved suitability may be considered another option.

4.2. Crop–Climate Departure and the Spatio-Temporal Variability of Crop-Suitability in West Africa

The temporal and spatial targeting of adaptation measures under an increasing global temperature will be crucial in maintaining and improving food security in the future. Identifying the timing and location of changes in crop growth suitability due to climate change can play a potentially key role in addressing the challenge of food production [16,33]. This is particularly relevant for the crops of vital importance in the West African region assessed here. The projected decrease in growth suitability conditions for cassava crops in the Savanna AEZ between 2020 and 2050, for example, depends on the time of planting or season. This projected departure is critical for the Savanna region as it may impact negatively on both the economy and livelihoods within the region. The improved understanding of crop–climate departure timing may permit timely adaptation plans such as modification to crop management regimes that account for this change in crop seasonality. If this were to be included in combination with increased use of key varietal traits, e.g., drought resistance, it will greatly assist in improving the adaptive capacity of such crops and mitigating the future impacts of a warmer climate to increase the resilience of current cropping systems within the region [16,65]. Improvements to the underlying knowledge base can therefore potentially improve both crop yield and crop quality.

In AEZs where the continued growing of given crop types is no longer possible, a further adaptation strategy is a shift to other more resilient crop species [66], or the substitution of existing crops with crops not previously grown within a given AEZ. Maize, for example, is projected to increase in yield by up to 7% in comparison to non-adapted crops under future climate change scenarios in SSA [33]. An increase in the planting area of crops such as maize further northwards into the southern Sahel AEZ due to the projected rainfall increase in this AEZ [31], or a shift of cassava or pineapple cropping into the Guinea AEZ due to reduced rainfall and the crops ability to withstand drought [16,31,65,67] represent further opportunities. A spatio-temporal projection of potential crop growth suitability can help provide information on future opportunities and constraints that will arise from shifts in the location of suitable crop lands within each AEZ [65]. Adaptation measures may then be prioritized for individual countries in response to the predicted changes [31,32], resulting in the maximum utilization of suitable areas for specific crop types, which will greatly assist in mitigating the future impacts from a warmer climate.

5. Summary and Conclusion

In order to improve the understanding of climatic impacts on agriculture, we conceptualized and explored the notion of crop–climate departure from historical variability in West Africa. We used four downscaled CMIP5 GCMs (CCMA CNRM5, GFDL, and MIROC) for the period 1960–2100 under RCP8.5 emission scenario and a crop suitability model, Ecocrop, across three weather stations representative of the Guinea, Savanna, and Sahel AEZs. In summary, all four GCMs correlate with observed weather station data in their simulation of monthly mean temperature and total monthly rainfall in the Savanna and Sahel zones, but moderately over the Guinea zone. It is recommended that future simulations acquire data from additional weather stations and utilize additional CMIP5 GCMs such as CSIRO, ICHEC, HADGEM, IPSL, MPI etc. In terms of crop rotations, the current climate is suitable for maize in the Savanna and Sahel AEZs, while future projections predict a potential for the expansion of maize further into the Sahel zone. The Guinea zone remains less suitable for maize but provides the correct climate both currently and in the future for crops such as cassava and pineapple. The predicted range for pearl millet and mango will remain stable in all three AEZs. Importantly, the Savanna AEZ, given its current cropping regime, is the most sensitive to climate change and shows the least resilience of the three AEZs considered. Climate change adaptation strategies will require prioritization in this zone. The climate-departure concept has been used to characterize crop–climate relationships i.e., crop–climate departure with increased warming and how it can, with appropriately planned adaptation and mitigation strategies, increase food security in the future.

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Abbreviations

ACCESS	Alliance for Collaboration for Climate and Earth System Sciences
AEZs	AgroEcological Zones
CCCMA	Canadian Centre for Climate Modelling and Analysis
CIP	Climate Information Portal
CMIP5	Coupled Model Intercomparison Project (Phase 5)
CNRM5	Centre National de Recherches Meteorolo-Giques
CSAG	Climate System Analysis Group
FAO	Food and Agriculture Organisation

GCMs	Global Climate Models
GFDL	Geophysical Fluid Dynamic Laboratory
MIROC	Japan agency for Marine-Earth Science and Technology Model
NRF	National Research Foundation
SSA	sub Saharan Africa
Declarations	
Ethics approval and consent to participate	Not applicable
Consent for publication	Not applicable
Availability of data and materials	Not applicable

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Assessing Future Spatio-Temporal Changes in Crop Suitability and Planting Season over West Africa: Using the Concept of Crop-Climate Departure

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Abstract: The changing climate is posing significant threats to agriculture, the most vulnerable sector, and the main source of livelihood in West Africa. This study assesses the impact of the climate-departure on the crop suitability and planting month over West Africa. We used 10 CMIP5 Global climate models bias-corrected simulations downscaled by the CORDEX regional climate model, RCA4 to drive the crop suitability model, Ecocrop. We applied the concept of the crop-climate departure (CCD) to evaluate future changes in the crop suitability and planting month for five crop types, cereals, legumes, fruits, root and tuber and horticulture over the historical and future months. Our result shows a reduction (negative linear correlation) and an expansion (positive linear correlation) in the suitable area and crop suitability index value in the Guinea-Savanna and Sahel (southern Sahel) zone, respectively. The horticulture crop was the most negatively affected with a decrease in the suitable area while cereals and legumes benefited from the expansion in suitable areas into the Sahel zone. In general, CCD would likely lead to a delay in the planting season by 2–4 months except for the orange and early planting dates by about 2–3 months for cassava. No projected changes in the planting month are observed for the plantain and pineapple which are annual crops. The study is relevant for a short and long-term adaptation option and planning for future changes in the crop suitability and planting month to improve food security in the region.

Keywords: crop-climate departure; Ecocrop; crop suitability; planting month; CORDEX; West Africa

1. Introduction

The West African region has been identified as one of the hotspots with high susceptibility and vulnerability to the impact of climate change and global warming [1]. For example, the global climate is projected to be above 1.5 °C above the pre-industrial level in the next decade [2]. An increase in temperature between 3 °C and 6 °C coupled with a rise in the rainfall variability is projected into the future over West Africa from the AR5 report [3]. Most countries in West Africa heavily rely on agriculture, which is predominantly rainfed, as an important and significant contributor to their economies. It accounts for over 16% of the Gross Domestic Product (GDP) of the region's economy and employs over 60% of the labour force [4–6]. Additionally, West Africa has accounted for about 60% of the total value of the agricultural production in the continent for about 24 years [7]. However, the region has been identified as a hotspot to climate change impacts in the recent time owing to its reducing yields in the total agricultural production since 2007 in comparison to other sub-regions on the continent [7]. Current trends show that there may be further decreases in yields especially in the face of increasing warming and droughts which may lead to food insecurity over the region [8–10].

Findings from the Intergovernmental Panel on Climate Change (IPCC) fifth Assessment Report (AR5) shows widespread impacts from the changing climate to the historical month across all continents [11]. The report reveals a high exposure to climatic events and a low adaptive capacity of the African continent makes it one of the most vulnerable regions of the world. Agriculture is the most and major economic sector of Africa and has been described as the most vulnerable sector to the climate change impact with a great threat to the farming systems, crop production and food security at any level [7,12–14]. For example, past studies e.g., [15–19] have shown the impact of climate change on crop production and yield in Africa and West Africa in particular using different crop models. Sultan et al. [15] showed the decrease in the mean yield of sorghum cultivars due to the impact of climate change resulting from variation in the rainfall pattern and increasing temperature. Jalloh et al. [17] revealed that the impact of climate change will badly affect the production of major staple crops in West Africa particularly sorghum and groundnut in the Sahel. Moreover, Roudier et al. [6] combining the result of 16 published studies, showed that the projected impact of climate change on the crop yield over most African countries is negative (about 11%) with variations among crops, regions and modelling uncertainties posing the challenge for robust assessment of future yields at the regional scale. Further changes in the climate are expected in Africa over the next decades [1], as projections suggest a threat to food security due to the likely increase in climate variability over the next decades in Sub-Saharan Africa (SSA) [7]. As a result, impacts from the changing climate varies from subsectors among regions and different countries in SSA including West Africa but may be more detrimental to the West African region owing to its high susceptibility and low adaptive capacity with further warming [14,20].

The increase in global warming will lead to a new climate regime with a deviation from historical variability with a variation in the timing of emergence for different regions of the world called the climate departure [21,22]. For instance, [21] found that the mean temperature over West Africa will move outside the bounds of historical variability about two decades earlier before the global mean temperature thus making the region a hotspot of climate departure due to the impact of the global warming. On this premise and its direct consequence on rainfed crop production in West Africa, Egbebiyi et al. [23] explored the climate change induced crop realizations of the climate departing from historical variability, developed and proposed the concept called the crop-climate departure (CCD) in the context of recent climate historical variability and future climate projections. The study defines CCD "as a departure from historical crop suitability threshold, whether in terms of variability, mean or both, over a location both in space and in time resulting from climate change (whether radical climatic change or not)" This concept was used to characterize crop suitability across the three agro-ecological zones (AEZs) of West Africa. However, the CCD concept was only tested and applied using three weather stations, within the three AEZs of West Africa. Although these stations are a representation of the three AEZs, nevertheless these cannot be generalized for the entire region, hence there is a need to examine how CCD at different climate windows, near the future (2031–2050) till end of the century (2081–2100) will affect crop suitability over the region using the concept of CCD.

Based on our definition and understanding on CCD, the aim of this present study is to examine the impact of CCD from the historical variability on future changes in crop suitability and month of planting over the entire West African region. Section 2 describes the data and methods used. Results from the study are outlined in Section 3. The discussion of the results and concluding remarks and recommendations for the future are in Sections 4 and 5, respectively.

2. Data and Methodology

2.1. Study Area

The West African (shown in Figure 1) region comprises of 15 countries namely Benin, Burkina Faso, Gambia, Ghana, Guinea Bissau, Guinea, Ivory Coast, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone and Togo. It is geographically located at latitude 4–20 °N and 16 °W–20 °E and has rainfed agriculture as its mainstay economy. The region can be divided into three Food and Agriculture Organization (FAO) agro ecological zones (AEZs) namely, Guinea (4–8 °N), Savanna (8–12 °N) and the Sahel (12–20 °N) [24,25]. The region also has some localized highlands (Cameroon Mountains, Jos Plateau, and Guinea Highlands) which influence its climate. The climate of the region is mainly controlled by the West African Monsoon (WAM) which accounts for about 70% of the annual rainfall [24,26]. WAM is an important and dynamic characteristic of the West African climate during the summer month [27].WAM is produced from the reversal of the land and ocean differential heating and dictates the seasonal pattern of rainfall over West Africa between latitudes 9° and 20 °N. It is characterized by winds that blow south-westerly during warmer months (June–September) and north-easterly during cooler months (January–March) of the year [25,27]. It is the major system that influences the onset, variability and pattern of rainfall over West Africa [28], [29]. It alternates between wet (April–October) and dry seasons (November–March) as the rainfall belt follows the migration of Inter-Tropical Discontinuity (ITD) [30] and thus affects the rainfall producing systems with an impact on the rainfed agriculture and influences crops suitability and food production in the region.

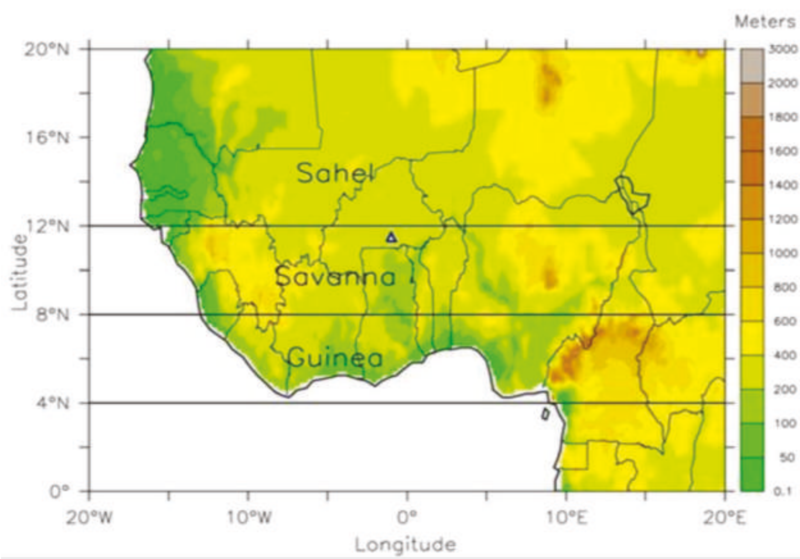

Figure 1. The study area, showing the West African topography and the three Food and Agriculture Organization (FAO) agro-ecological zones, designated as Guinea, Savannah and Sahel, respectively [24,25].

Different crops are grown in various parts of West Africa. Some of the major crops grown in the region are cassava, groundnut, millet, maize, sorghum, yam, plantain, cocoa, rice, wheat [8,26,31,32]. Millet and sorghum account for 64% of the cereal production over the regions in the year 2000 thus making them among the important staple crops in West Africa [26,33]. Cassava is one of the most important staple food crops in terms of production in sub-Saharan West Africa owing to high resilience to drought in the region [26,32,34] This also applies to the Yam production, which account for about

91% of the world's production [26,34,35]. Cereal, maize provides about 20% of the calorie intake in West Africa and is adjudged the most important staple food in the sub-Saharan Africa [26,33]. Other crops such as cocoa and plantain to mention a few contribute significantly to the economy of the region.

2.2. Data

2.2.1. Historical and Future Climate Datasets

For this study, three datasets were used as observations of the present-day climate and the locations where crops are grown as observed from the crop suitability model, Ecocrop output, and modelled simulations of the present and projected crop suitability driven by the observed and projected climate data. The observation dataset was the 0.5° × 0.5° resolution monthly precipitation and minimum and mean temperature gridded dataset for the month of 1901 to 2016 obtained from the Climate Research Unit (CRU TS4.01 version, land only) University of East Anglia [36]. This was used to evaluate the available bias corrected RCMs forced by the 10 CMIP5 global climate models. The bias-corrected climate data were obtained from the Swedish Meteorological and Hydrological Institute, Linköping, Sweden. The modelled climate data were used as inputs into the crop suitability model, Ecocrop [37]. For this study, five different crop types namely; cereals (maize, pearl millet and sorghum), root and tuber (cassava, plantain and yam), legumes (cowpea and groundnut), horticulture (pineapple and tomato) and fruit (mango and orange) were selected based on the FAO 2016 statistics and their economic importance in the region. These different datasets are defined in the sub-sections below.

Temperatures and rainfall are important climate variables used in determining the impacts of climate change at different scales [38,39]. These two climate variables have a significant effect on crop yield [40,41]. While rainfall affects crop production in relation to the photosynthesis and leaf area, the temperature affects the length of the growing season [42,43]. For this study, we used the bias-corrected mean monthly minimum temperature (tmin), mean monthly temperature (tmean) and total monthly precipitation (prec). Data from 10 CMIP5 GCMs downscaled by SMHI-RCA4 are used as input into the crop suitability model (Table 1). We used the RCP8.5 emission scenario for the analysis to investigate the impact of CCD from the historical variability on the crop growth suitability and month of planting over West Africa. We used RCP8.5 because it seems the most realistic emission scenario as seen from the greenhouse gas emission trajectories in comparison to other scenarios and also has the largest simulation ensemble members [44].

Table 1. List of dynamically downscaled Global Climate Models (GCMs) used in the study.

Modelling Institution	Institute ID	Model Name	Resolution
Canadian centre for climate modelling and analysis	CCCMA	CanESM2	2.8° × 2.8°
Centre National de Recherches Meteorolo-Giques/Centre Europeen de Recherche et Formation Avanceesencalcul scientifiqu	CNRMCERFACS	CNRM-CM5	1.4° × 1.4°
Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3.6.0	1.875° × 1.875°
NOAA geophysical fluid dynamic laboratory	NOAAGDFL	GFDL_ESM2M	2.5° × 2.0°
UK Met Office Hadley centre	MOHC	HadGEM2-ES	1.9° × 1.3°
EC-EARTH consortium	EC-EARTH	ICHEC	1.25° × 1.25°
Institute Pierre-Simon Laplace	IPSL	IPSL-CM5A-MR	1.25° × 1.25°
Japan agency for Marine-Earth Science and Technology	MIROC	MIROC5	1.4° × 1.4°
Max Planck institute for meteorology	MPI	MPI-ESM-LR	1.9° × 1.9°
Norwegian climate centre	NCC	NorESM1-R	2.5° × 1.9°

2.2.2. Ecocrop—A Crop Suitability Model

The Ecocrop model is a crop suitability model. It uses a crop growth suitability threshold dataset hosted by the FAO [37]. It is a simple mechanistic and empirical model originally developed by Hijmans et al. [37] and based on the FAO-Ecocrop database [45]. It is designed at a monthly scale with the ability to analyse the crop suitability in relation to the climate conditions over a geographical location [37,45]. Ecocrop employs environmental ranges of a crop coupled with numerical assessment of the environmental condition to determine the potential suitable climatic condition for a crop. The suitability rating can be linked to the agricultural yield which is partly dependent on the strength of the climate signal in the agricultural yield [46] The computation of optimal, suboptimal and non-optimal conditions based on these datasets allows for the simulation of the suitability of crops in response to the 12-month climate via t-min, t-mean and prec. [37]. The Ecocrop model evaluates the relative suitability of crops in response to a range of climates including rainfall, temperature and the growing season for optimal crop growth. A suitability index is generated as follows: 0 < 0.20 (not suitable), 0.20 < 0.4 (very marginally suitable), 0.4 < 0.6 (marginally suitable), 0.6 < 0.8 (suitable), and 0.8 < 1.0 (highly suitable) [45,47]. The default Ecocrop parameters were assumed. Although those thresholds may vary with different geographical and/or climatic conditions, previous studies have reported a close correlation between the Ecocrop model and the climate change impact projections from other crop models [45,48–50]. A paucity of data over regions of interest like SSA limits the validation of these processes [51]. Nevertheless, the method contributes to the demand for the regional scale assessment of the crop response to future climate projections.

2.3. Methods

We analyzed 10 CMIP 5 GCMs datasets downscaled by CORDEX RCM, RCA4 to assess the impacts of CCD from the historical variability on crop suitability and planting season over West Africa for five different crop types, cereal (maize, pearl millet and sorghum), fruit (mango and orange), horticulture (pineapple and tomato), legume (cowpea and groundnut) and root and tuber (cassava, plantain and yam). We used the RCA4 simulation output for the monthly minimum and mean temperature and total monthly precipitation as input into Ecocrop, a crop suitability model. Using a 20-year moving average at five year time steps, we computed the Suitability Index Value (SIV) for each crop across the 10 downscaled GCMs over West Africa. The Ecocrop suitability output were then used to assess the impact of global warming through CCD from the historical variability on the crop suitability and planting season over a month 1951–2100. Across the agro-ecological zones (AEZs) of West Africa. After the simulation, we computed the mean of the best three consecutive suitability index and best three months of planting window within the growing season across each grid point over the region for the historical and future month. Before examining the RCM-projected changes in the future crop suitability and planting season, we evaluated the capability of the models in simulating the crop suitability spatial distribution and planting date/season during the reference month (1981–2000).

We also used the statistical tool to calculate the trend of change across the three windows compared to the historical month. We assessed the trend of change in the crop suitability and month of planting at each global warming levels for each crop using the Theil-Sen estimator or Sen's slope [52,53]. The Theil-Sen slope estimator is an estimation of the average trend rate only and magnitude of the trend. It is a linear slope that is compatible with the Mann-Kendall test and more robust such that it is less sensitive to outliers in the time series as compared to the standard linear regression trend [54]. The Theil-Sen slope method can detect significant trends with the changing rate than the linear trend [55]. Previous studies [56,57] have used this method in calculating trends.

2.3.1. Simulation Approach and Analysis of suitability

Past studies (e.g., [25,58–60] have evaluated the performance of the RCA4 historical data against the CRU dataset in the past climate. Their results showed that there is a good agreement with a strong correlation ($r \geq 0.6$) between the CRU dataset and RCA4 monthly simulated past climate data for both the temperature and precipitation over West Africa. For example, the model replicates the CRU north-south temperature gradient that concurs with previous findings by [58]. Additionally, the RCA4 simulated total monthly rainfall realistically captures the essential features namely, both the zonal pattern and meridional gradient and the rainfall maxima over high topography (i.e., Cameroon Mountains and Guinean Highlands) as observed in CRU which agrees with previous findings by [25,59,60]. The performance of RCA4 in simulating the essential features of West African climate variables, temperature and rainfall, and doubles as the needed input variables for the crop suitability model, Ecocrop makes it suitable and gives confidence in the use of the RCA4 for the crop suitability simulation over the region.

In addition, we compare the Ecocrop simulation over the region with the MIRCA2000 annual harvested area around year 2000 from the global monthly gridded data as described by [61] for six crops, cassava, maize, groundnut, sorghum, millet and plantain available in the MIRCA2000 dataset. The MIRCA2000 dataset provides monthly irrigated and rainfed crops area for 26 crop classes for each month of the year around year 2000 with a spatial resolution about 9.2 km. We compare the spatial agreement between the Ecocrop simulation and MIRCA2000 by using an overlap in the spatial agreement between the two datasets. Although, we admit the short time length of the MIRCA dataset however, it is a useful gridded dataset that has been used to provide information on the crop harvested area across different regions of the world [61] and will be useful to evaluate the simulated Ecocrop spatial suitability distribution at present due to the paucity of the suitability dataset across the globe. To see the overlap and area of agreement in the spatial suitability output of the two datasets, we set the MIRCA2000 annual harvested area dataset as one (1) and the Ecocrop simulated suitable area suitability index value from 0.2 ($SIV \geq 0.2$) as two(2). Where the two datasets agree as three(3). The output shows a good agreement between the Ecocrop and MIRCA2000 data for the examined crops with a strong spatial correlation ($r > 0.7$) (Figure 2). This gives some level of confidence in the use and performance of the Ecocrop simulation over the region.

To assess the impact of CCD from the historical variability on the crop suitability over West Africa, we computed the monthly climatological mean for a 20-year running month, at every five-year timestep for the t-min, t-mean and prec. from 1951–2100. For example, the first 20-year mean computed was 1951–1970, the second 20-year mean was 1956–1975, etc., until the last month 2081–2100. The resulting 12-month values per the 20-year month window was used as an input climatology into the Ecocrop suitability model as developed by the Food and Agriculture Organization, FAO [37] to simulate crop suitability for each downscaled GCM based on the methodologies described in [45]. Ecocrop calculates the crop suitability values in the response climate variables such as a monthly rainfall and temperature datasets and generates an output with a suitability index score from zero (unsuitable) to one (optimal/excellent suitability). It should be noted that this study did not undertake any additional ground-truthing or calibration of the range of climate parameters preferred for either crop and therefore the default EcoCrop parameters were assumed. Suitability index scores were calculated for the range of climate variables reported for the historical baseline (1981–2000) future months, near future (2031–2050), mid-century (2051–2070) and end of century (2081–2100) for the downscaled 10 CMIP5 GCMs that participated in the CORDEX experiment.

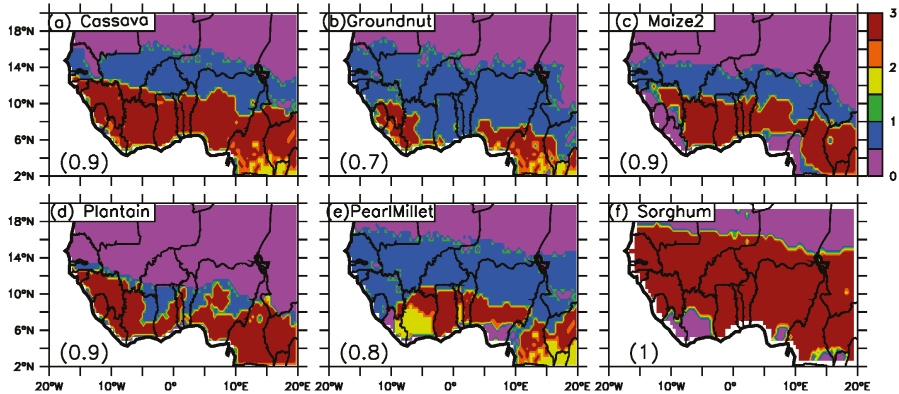

Figure 2. A simulated spatial distribution of the crop harvested area and suitability over West Africa for the year 2000 as simulated by the MIRCA2000 dataset and Ecocrop, respectively. The blue area (represented by 1) are the crop harvested area around the year 2000 as simulated by the MIRCA2000 dataset while the yellow colour represents the suitability index value above0.2 (SIV ≥ 0.2) which is represented by two. The red colour represents the area where the two datasets agree as denoted by three. The number at the left-hand corner represents the spatial correlation (r ≥ 0.7) value between the two datasets. The red colour depicts in Fig. 2a-2f depicts harvested and suitable areas as simulated by MIRCA2000 and Ecocrop from cassava to sorghum respectively. The blue colour depicts MIRCA2000 simulated harvested area only for each crop while yellow means Ecocrop simulated suitable areas for cultivation of each crop in year 2000. The purple colour, 0 depicts non harvested and unsuitable areas as simulated by both MIRCA2000 and Ecocrop for each of the crops around the year 2000.

2.3.2. Assessing the Robustness of Climate Change

We use two conditions (model agreement and statistical significance) to evaluate the robustness of the projected climate change for the three future months. For the model agreement, at least 80% of the simulation must agree on the sign of change. For the statistical significance, at least 80% of the simulations must indicate that the influence of the climate change is statistically significant, at 95% confidence level using a *t* test with regards to the baseline month, 1981–2000. When these two conditions are met then we consider the climate change signal to be significant. [30,44,62,63] have all used the methods to test and indicate the robustness of the climate change signals.

3. Result

3.1. Crop Suitability in the Historical Climate over West Africa

The RCA4 simulated crop suitability from the observed climatology inputs (RCA4-Ecocrop) shows a decreasing mean suitability from south to north over West Africa (north-south suitability gradient). The spatial suitability representation reveals unsuitable or very marginal suitability to the north in the Sahel from lat. 14 °N with a low Suitability Index Value (SIV) value between 0.0–0.4 and a higher suitability to the south in the Guinea-Savanna AEZ with a high SIV (0.6–1.0) sandwiched by an ash/silver suitability line called the Marginal Suitability Line (MSL) with an SIV between 0.41–0.59. In general, the MSL are observed around lat.14 °N in the Sahel AEZ (northern Sahel) for the simulation across the region except for the one observed around lat. 12 °N, the boundary between the Sahel and Savanna AEZ. The RCA4 simulation of all crop types examined, legumes (cowpea and groundnut), root and tuber (cassava, plantain, Yam, white yam), cereals (maize, pearl millet and sorghum) and fruit and horticultural crops (mango, orange, pineapple and tomato) shows that all the crops are very suitable to the south of the MSL but with no or low suitability to the north (Figures 3–6, column 1).

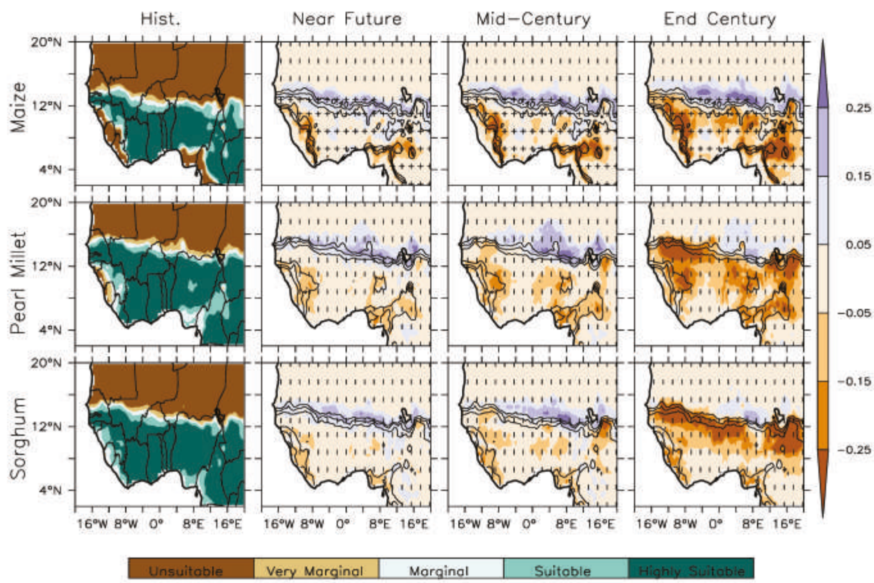

Figure 3. Simulated spatial suitability distribution for the cereal crops, maize pearl millet and sorghum over West Africa for the historical month (1981–2000) (column 1) and the projected change in the crop suitability for the near future month (2031–2050), mid-century (2051–2070) and end of century (2081–2100) (column 2–4, respectively). The vertical strip (|) indicates where at least 80% of the model simulations agrees on the projected sign of change while the horizontal strip (−) indicates where at least 80% of the model simulations agree that the projected change is statistically significant at 99% confidence level. The cross (+) indicates where the two conditions are met, meaning that the change is robust.

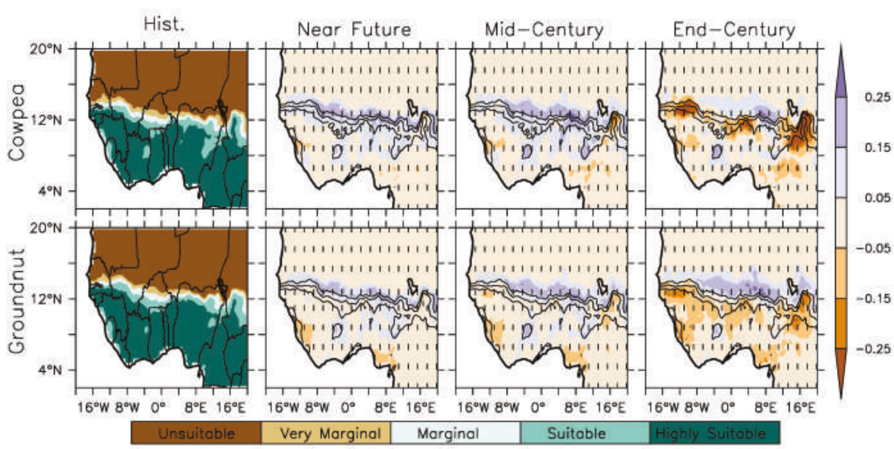

Figure 4. Same as Figure 3 but for the legume crops, cowpea and groundnut.

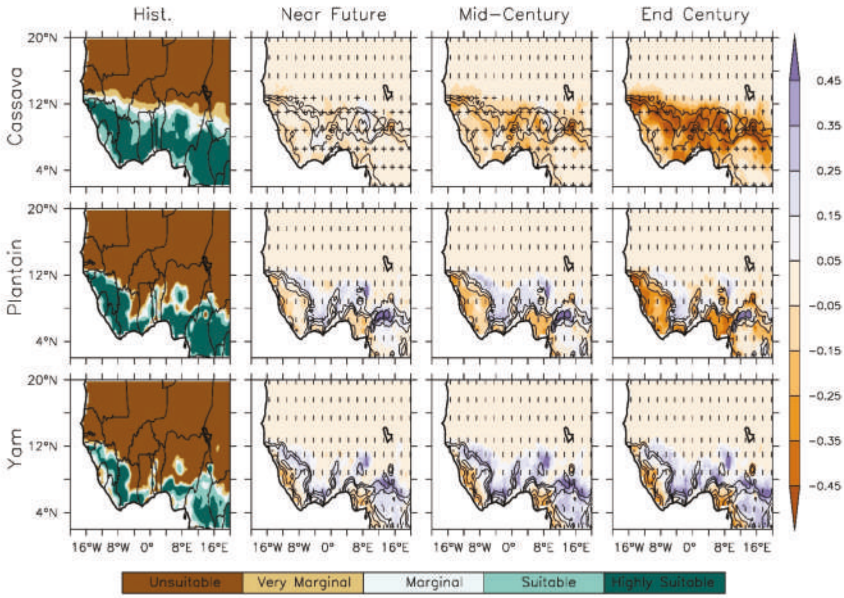

Figure 5. Same as Figure 3 but for the root and tuber crops, cassava, plantain and yam.

Along the coastal areas, legumes and root and tuber crops are suitable along the south-west coast of Senegal to the south-west coast of Cameroon. High SIV are observed for the root and tuber crops, plantain and Yam in the north central part of Nigeria in the Savanna. It is worth mentioning because the surrounding areas are observed to be unsuitable for the cultivation of both crops. For cereals, pearl millet is suitable along the west coast of Senegal and from the south coast Ivory Coast to the south-west coast of Cameroon. Maize is suitable from the south coast of Ivory Coast to the south-west coast of Nigeria. Fruit and horticultural crops are all suitable along the south coast of the Ivory Coast to the south-west coast of Nigeria. Mango and pineapple are suitable along the west coast of Senegal to Gambia while orange and tomato are only suitable along the west coast of Gambia.

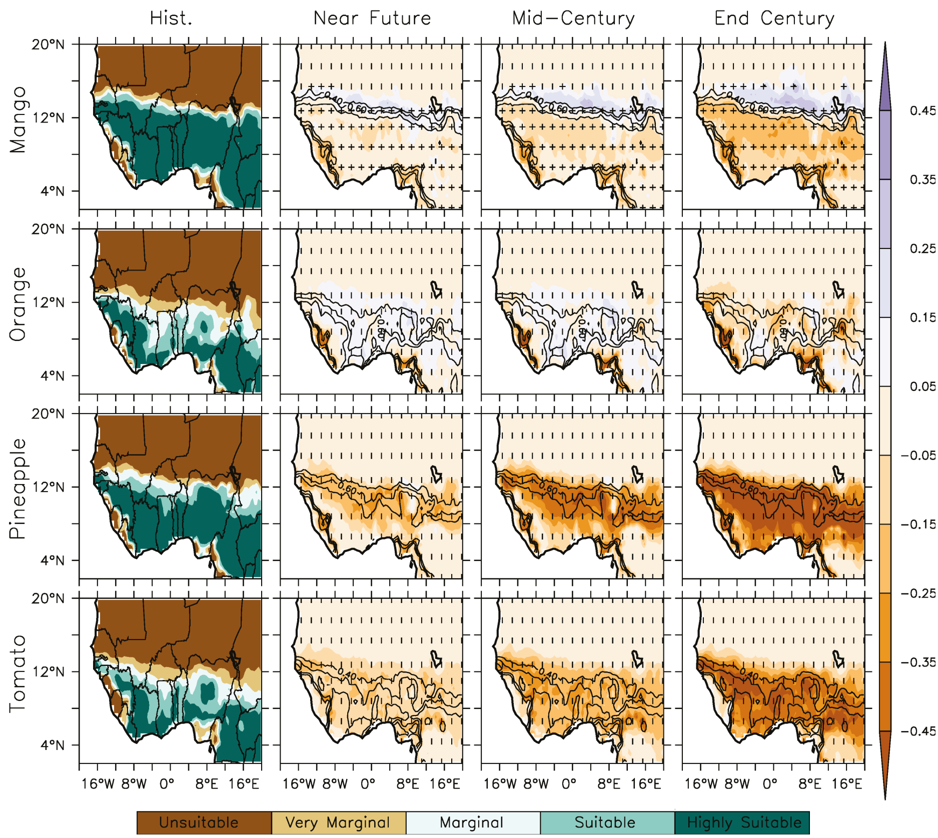

Figure 6. Same as Figure 3 but for the fruit crops, mango and orange and horticultural crops, pineapple and tomato.

RCA4 was also used in simulating the best planting months (PM) from the range of month in a planting window within the Length of Growing Season (LGS) over West Africa for the historical climate (Figures 7–10, column 1). LGS provides information on the start and end of the growing season and can also assist in the simulation process of identifying the best PM within a possible planting window in a growing season over a given location. The simulated planting month represents the first month of the best three months of the planting window. For example, a simulation of April means April–June is the three best PM and varies with crop types across the three AEZs of the region. For the legumes, our simulation shows January–July as the planting windows for cowpea and groundnut over the region (Figure 7, column 1). Jan (January–March) and Feb (February–April) as the best PM for cowpea and groundnut, respectively in the central Guinea and Savanna AEZs except over Sierra Leone, Liberia and the south coast of Nigeria. The month of Feb (Feb-April) was simulated as the best three planting months in the western and eastern Savanna-Sahel AEZs for cowpea, while it was Mar (March–May) over the same area and month for the groundnut. Along the coastal areas, July is simulated as the PM along the southwest coast from southern Sierra Leone to Liberia and the south coast of Nigeria and April along the southwest coast of northern Sierra Leone. For the groundnut, April is the PM along the west coast of Guinea, while May is the PM along the west coast of Sierra Leone and northern Liberia. August and March are the PM at the south coast of Liberia and Nigeria, respectively. The months of December and January are the PMs along the south coast of Ivory Coast to Ghana for the cowpea and groundnut, respectively.

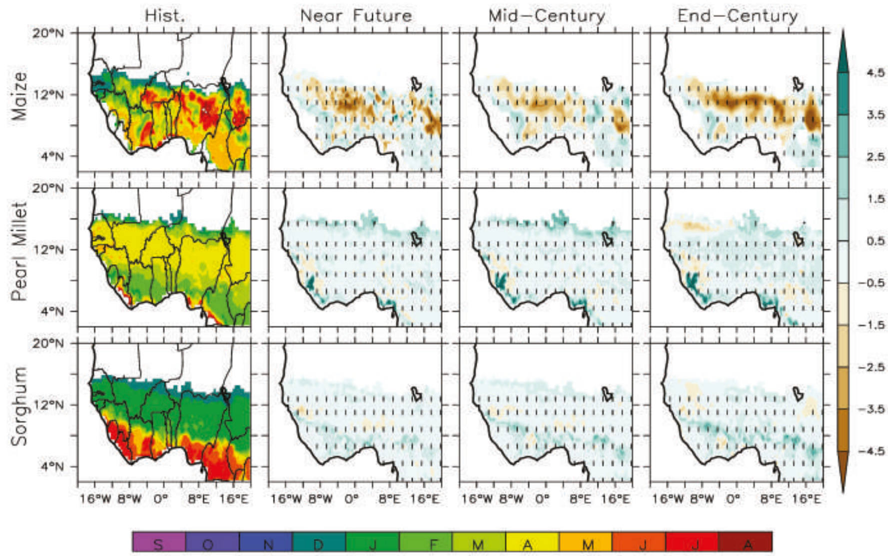

Figure 7. Simulated month of planting for cereals, maize, pearl millet and sorghum over West Africa for the historical month (1981–2000) (column 1) and the projected change in the crop planting month for the near future month (2031–2050), mid-century (2051–2070) and end of century (2081–2100) (column 2–4 respectively). The planting is simulated from September to August. The vertical strip (|) indicates where at least 80% of the model simulations agrees on the projected sign of change while the horizontal strip (−) indicates where at least 80% of the model simulations agree that the projected change is statistically significant at 99% confidence level. The cross (+) indicates where the two conditions are met, meaning that the change is robust.

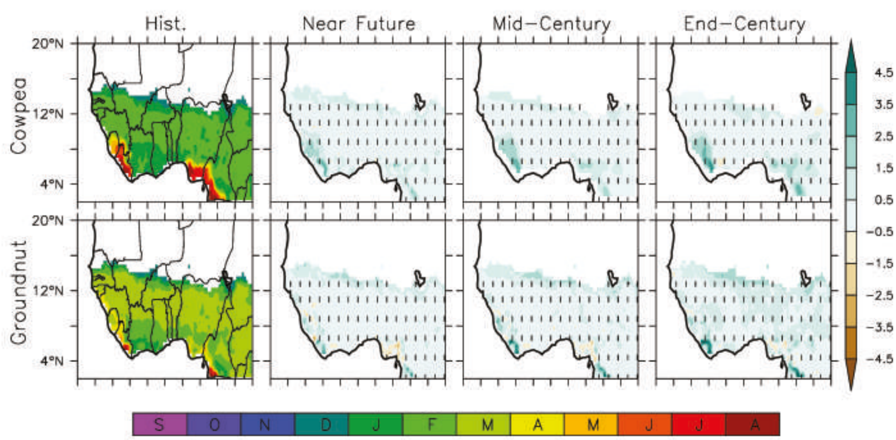

Figure 8. Same as Figure 7 but for the legumes, cowpea and groundnut.

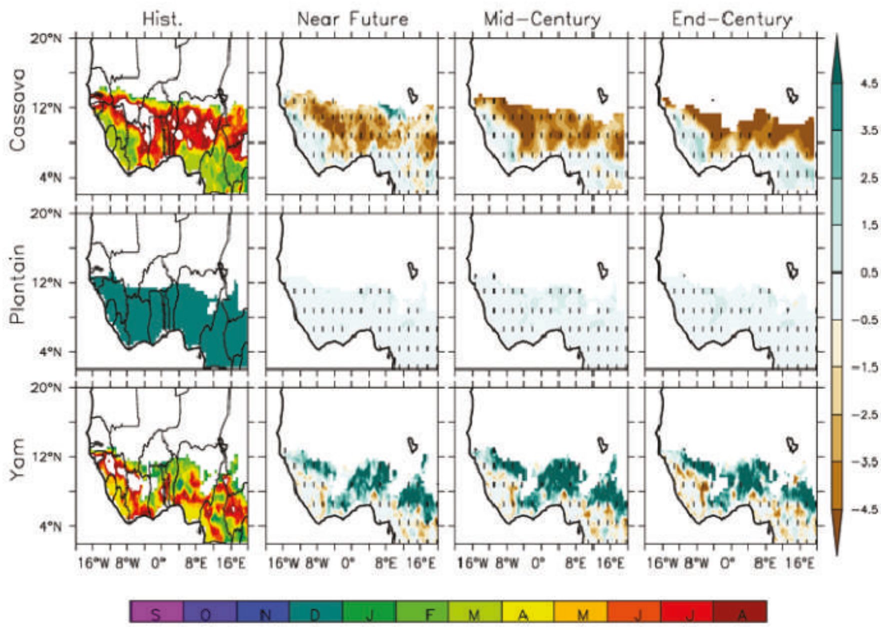

Figure 9. Same as Figure 7 but for the root and tubers, cassava, plantain and yam.

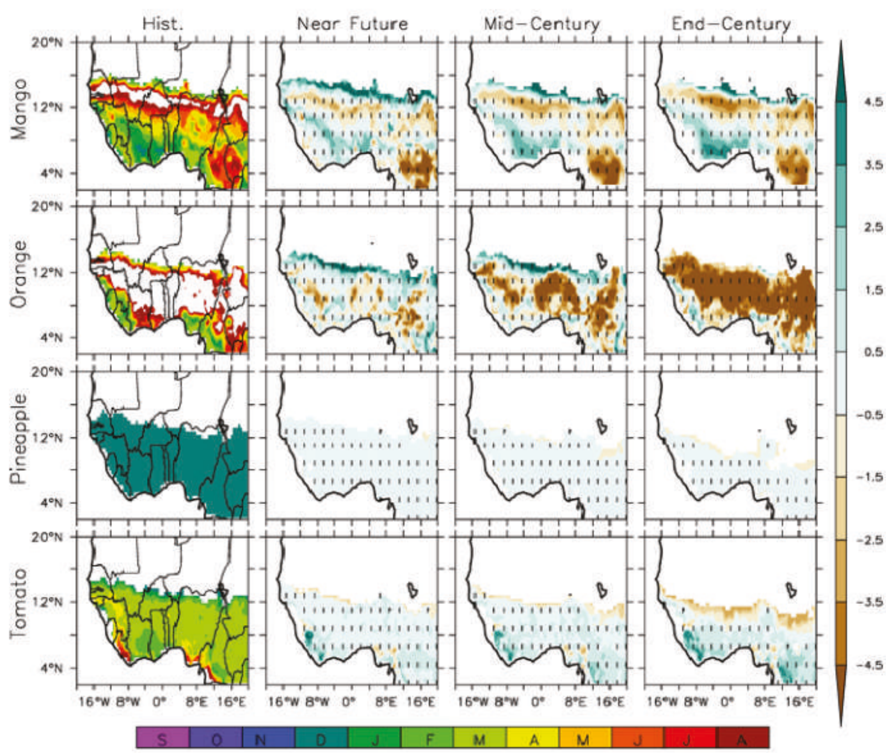

Figure 10. Same as Figure 7 but for the fruit and horticultural crops.

The root and tuber plantain is an annual crop that can be planted at any month of the year (Figure 9). The simulated PM is an overlay of the simulation of other months in the year as the crop may be planted in the suitable zones, Guinea and Savanna at any month/month of the year. For cassava, our simulation shows March (March–May) as the best PM generally over the region (Guinea-Savanna AEZs) except along the south-east coast of Ivory Coast to Ghana with PM in July, northern Guinea to Gambia and south east Senegal and from the boundary of Benin Republic to north west Nigeria in April. The Ecocrop simulation for Yam shows June as the best PM in the central Guinea zone from the south-east Ghana to the south-east of Nigeria and in the north central part of Nigeria as well as Togo in the central Savanna zone. The month of February is observed as the best PM from the south-east Mali to the north-western part of Nigeria in the Savanna. Over the coastal area, April is observed as the PM along the south west coast from Sierra Leone to Liberia and the south coast of Nigeria and June along the west coast of Guinea and from the south coast of Ivory Coast to the south-west coast of Ghana in the past climate.

Our simulation for cereal crops shows February as the PM for pearl millet in Guinea, March and April are the best PMs in the south Savanna and northern savanna and Sahel AEZs, respectively although with exception. For example, in central savanna, from the northern Benin Republic to the north-western Nigeria for millet, the PM is April while in the north-eastern Nigeria in the Sahel it is March compared to April in the Sahel zone. However, for the pearl millet, the PM is April in the western Sahel along the south-west coast of Senegal, June along the west coast of Guinea and January along the south coast of Ivory Coast to the south-west coast of Nigeria. For maize, the PM is simulated to be in May (May–July) in the Guinea and southern Savanna zone of West Africa while it is in December (December–February) in the northern Savanna into the Sahel zone. For sorghum, June is simulated as the PM over Sierra Leone to Liberia and its coastal areas as well as the south coast of Ivory coast and Nigeria while it is May in the central south of Ivory coast and southern Ghana. The crop is simulated to be best cultivated in January in the Savanna-Sahel zones and best in December in the northern Sahel.

The Ecocrop simulation of the best PM for the horticultural crops (Figure 10) in the past climate shows tomato is mainly planted in March over the regions except from the south-east Ivory coast to south-west Ghana and around 14 °N in the Sahel where the best PM in February, along the west and south coast of Liberia and Nigeria, respectively where the best PM is July. Pineapple is an annual crop and it shows similar characteristics as plantain as mentioned above, which can be planted at any month of the year. For the fruit crop, orange shows February as the best PM over Sierra Leone to Liberia and along the west coast from Guinea to Liberia and the south coast of Nigeria. June is observed as the best PM in the south of Ivory coast to Ghana and Nigeria as well as the south coast of the Ivory and Ghana. June is also simulated as the best PM from Guinea Bissau to north-east Nigeria around lat 14 °N in the Sahel. The Ecocrop simulation for mango in the past climate shows February as the PM from the Guinea to southern savanna AEZ, April, May in the northern savanna AEZ and June as the best PM in the southern Sahel AEZ. Along the coastal areas, March is simulated and observed as the best PM from the west coast of Guinea to Liberia and south coast of Nigeria but February over the south coast of Ivory coast and Ghana.

Nevertheless, the evaluation simulations demonstrate that (RCA4-Ecocrop) captures the spatial variation in the suitability with different crops across the three AEZs of West Africa in the present-day climate and can serve as a baseline for evaluating the changes in crop suitability under global warming at different time windows over the region. The model also captures the spatial distribution of the best planting month within a growing season for crops over the region which varies with different months of the year.

3.2. Projected Changes in Tmin, Tmean and Precip over West Africa

An increasing clear trend of warming is projected across West Africa in the future, with predictions of increases of the t-min and t-mean of approximately 1–4.5 °C (Figure 11, Row 2 and 3 respectively). The mean and minimum monthly temperature (t-mean and t-min) is predicted to increase by 1.5–2 °C in the Guinea-Savanna of the regions, about 2–2.5 °C in the Sahel and increases of about 1 °C predicted for the south-west coastal area in the near future month (2031–2050). By mid- century, the t-mean is projected to increase by 2.5 °C and 3.0 °C over the Guinea-Savanna and Sahel, respectively and 3.0 °C increase over the Guinea and 3.5 °C over the Savanna-Sahel for t-min. At the end of the century, a 4.0 °C temperature increase is projected over the Guinea-Savanna zone except the western area and 3.5 increase over the Sahel for t-mean. The projected change in the minimum temperature by the end of the century showed a different pattern over the region as the Guinea zone, southern Guinea-coastal area, is warmer than the Sahel. The projection shows an increase up to 4.5 °C in the southern Guinea (coastal area) and 4 °C inland. A similar characteristic is also observed over the Sahel as the southern Sahel (12–14 °N) is projected as warmer (4.0 °C) than north of 14 °N (3.5 °C) in the Sahel zone. The savanna zone is however different to the Guinea and Sahel as the temperature increases northward over the zone, i.e., southern Savanna (3.5 °C) is lower to the northern Savanna (4.0 °C) except for the western part of the Savanna zone, which is much cooler than the rest with an increase of 2.5 °C. Our findings are consistent with the findings by [30].

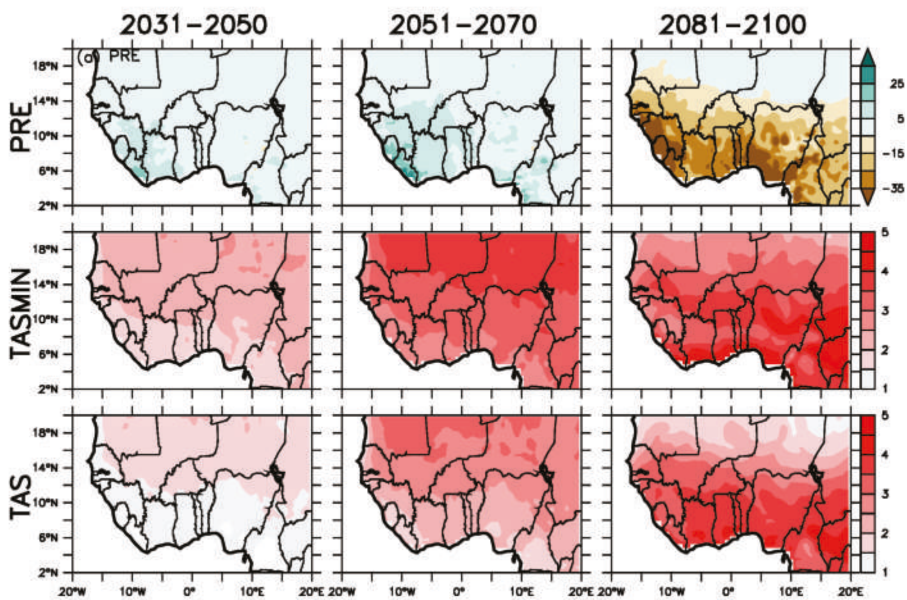

Figure 11. Projected changes in the total monthly rainfall (PRE), minimum (TASMIN) and mean (TAS) monthly temperature over West Africa as simulated by RCA4 for the near future month (2031–2050), mid-century (2051–2070) and the end of the century (2081–2100).

With respect to the predicted effects of climate change on rainfall, it is not a major change in the mean monthly precipitation that is projected over the region except in the south-west Guinea zone extending to the southern Guinea in the Savanna and the south coast of Nigeria (Figure 11, Row 1). The projected increase of about 10 mm extends from the south-west coastal area of Sierra-Leone to Liberia to the south-west coast of Ghana and south coast Nigeria in the near future (2031–2050) compared to the historical climate. By mid-century (2051–2070), the projected change of about 10 mm is expected in the western part of the region from the Guinea zone to the southern Sahel zone and the north-central part of Nigeria. Over the coastal area, an increase up to 25 mm is projected along the south-west coast of Sierra-Leone to Liberia and 10 mm over the south coast of Nigeria. The projection shows that no change is expected in the eastern part of the region by the mid-century. In contrast, by the end of the century, the projected change in the rainfall will be characterized by a decrease in the monthly precipitation across the entire region compared to the baseline. A gradient decrease in the rainfall is projected from south to north with a reduction up to 35 mm over the Guinea-Savanna and about 25 mm over the Sahel. Over the coastal area, a decrease above 35 mm is projected along the west coast of Gambia to northern Liberia and south coast of Nigeria. Our findings are in agreement with [30].

3.3. Impact of CCD on Future Crop Suitability over West Africa

Projected changes in the future crop suitability for all crop types varies across the three future climate windows, from the near future period (2031–2051) to the end of the century (2081–2100) (Figures 3–6, column 2–4). The variation in the impact for the crops can may be linked to the difference in crops response to the different climate window as described in Table 2 below for the three-climate window/period. For the near future, our simulation projects a general no change in the suitability for cereals south of 12 °N except the south coast of Nigeria (Figure 3, column 1). However, a project decreases of about 0.1 SIV is expected in the south coast of Nigeria for all the cereal crop, over Guinea for pearl millet, from Sierra Leone to Liberia for sorghum and from eastern Guinea to Liberia in the western Guinea-Savanna zone. In contrast, an increase in SIV up to 0.2 is expected in the southern Sahel zone for cereals. No suitability change is projected for legumes (Figure 4, column 2) except an increase in SIV of about 0.1 in the southern Sahel (12–14 °N) and up to 0.2 in the central savanna zone, (Figure 6). On the other hand, a projected decrease of 0.1 in SIV is expected along the west coast of Sierra Leone and the south coast of Nigeria for groundnut. The projected increase in SIV provides an increase in the suitable area for the cultivation of both crops. This is so because a 0.2 increase in SIV for the marginally suitable (SIV, 0.4–0.6) areas in the southern Sahel results in the area becoming suitable (SIV, 0.6–0.8) for both crops. The projected decrease in the SIV values along the coastal areas and over Sierra Leone also does not affect the area negatively as the area remains suitable for these crops. For the root and tuber crop (Figure 5, column 2), a projected decrease of about 0.1 SIV is expected for cassava and up to 0.2 in southern Nigeria and along the west coast of Guinea to Liberia for plantain and yam extending to south of Ivory Coast for plantain. A similar magnitude decrease is also expected in the western Guinea-Savanna zone from Guinea to the western Ivory Coast. For the horticulture and fruit crops (Figure 5, column 1), a 0.1 projected decrease in SIV is expected south of 12 °N and the savanna zone for tomato and pineapple, respectively while up to 0.2 SIV decrease is expected in the south coast of Nigeria for mango and orange. However, a projected increase up to 0.2 SIV is expected in the southern Sahel for mango. The projected suitability changes are robust (i.e., at least 80% of the simulation that the climate change is statistically significant at 95% confidence level) for cassava, maize and mango in the near future month (2031–2050) while the changes are consistent for the other nine crops (i.e., at least 80% of the model agree to the sign of change).

Table 2. Projected changes in crop suitability over West African AEZs at different future window periods.

Crops	Near Future (2031–2050)			Mid-Century (2051–2070)			End-Century (2081–2100)		
	Guinea	**Savanna**	**Sahel**	**Guinea**	**Savanna**	**Sahel**	**Guinea**	**Savanna**	**Sahel**
Cassava	No change remains suitable	No change remains suitable	No change remains unsuitable	A 0.2 SIV decrease but still suitable	A 0.2 SIV decrease but still suitable	Same as GWL1.5	About 0.4 SIV decrease still suitable	About 0.4 SIV decrease but still suitable	Same as GWL1.5
Plantain	About 0.1 SIV decrease but still suitable	A 0.1 & 0.2 SIV decrease and increase in west and central respectively	No change unsuitable	About 0.2 decrease in SIV but still suitable	A 0.2 SIV decrease and increase in west and central respectively	No change remains unsuitable	About 0.4 SIV decrease may become marginally suitable	About 0.4 and 0.2 SIV decrease to the west and central respectively	No change unsuitable
Yam	Suitable, but not along the coastal area	Only suitable in the west & central Savana	No change, unsuitable	Same as in GWL1.5	Same as GWL1.5	Same as GWL1.5	Same as in GWL1.5	Same as GWL1.5	Same as GWL1.5
Maize	No change but 0.1 decrease SIV northern Cameroon	Suitable, but not along the west coast of Guinea to Sierra Leone	About 0.2 SIV increase, now suitable over the southern Sahel	No change in suitability	About 0.1 SIV decrease but still suitable	Same as GWL1.5	No change in suitability	About 0.2 decrease in SIV but still suitable	Same as GWL1.5 but SIV increase up to 0.3
Pearl millet	No change but very marginal suitability in the south coast Nigeria and north Liberia	No change but about 0.1 SIV decrease in eastern Guinea	About 0.2 SIV increase make northern Sahel suitable	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5	About 0.3 decrease in SIV but still suitable	A 0.4 SIV decrease in west Sahel but still suitable
Sorghum	No change in suitability	No change in suitability	About 0.2 SIV increase make northern Sahel suitable	No change in suitability	About 0.1 decrease in SIV but still suitable	About 0.1 SIV increase makes Sahel suitable	About 0.1 decrease in SIV but still suitable	About 0.2 SIV decrease west respectively	Above 0.2 SIV decrease but still suitable

Table 2. *Cont.*

Crops	Near Future (2031–2050)			Mid-Century (2051–2070)			End-Century (2081–2100)		
	Guinea	Savanna	Sahel	Guinea	Savanna	Sahel	Guinea	Savanna	Sahel
Mango	No change in suitability	No change in suitability	No change in suitability	About 0.1 decrease in SIV but still suitable	About 0.1 decrease in SIV but still suitable	About 0.1 increase in SIV but still unsuitable	About 0.2 SIV decrease but still suitable	About 0.2 SIV increase but still unsuitable	About 0.2 SIV increase but still unsuitable
Orange	About 0.1 SIV increase	About 0.1 SIV increase	No change in suitability	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5	About 0.2 SIV decrease but still suitable	About 0.2 SIV decrease but still suitable	Same as in GWL1.5
Pineapple	No change in suitability	About 0.2 SIV decrease but still suitable	No change in suitability	About 0.1 decrease but still suitable	About 0.3 decrease but still suitable	Same as GWL1.5	About 0.4 decrease but still suitable	About 0.4 SIV decrease but still suitable	Same as GWL1.5
Tomato	About 0.1 decrease but still suitable	About 0.1 decrease but still suitable	No change in suitability	About 0.3 decrease but still suitable	About 0.3 SIV decrease but still suitable	Same as GWL1.5	About 0.4 decrease but still suitable	About 0.4 SIV decrease but still suitable	Same as GWL1.5
Cowpea	No change in suitability	No change in suitability	About 0.2 SIV increase make southern Sahel suitable	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5	About 0.1 decrease in SIV but still suitable	Same as GWL1.5
Groundnut	No change in suitability	No change in suitability	About 0.2 SIV increase makes southern Sahel suitable	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5	About 0.1 decrease in SIV but still suitable	Same as GWL1.5

The Ecocrop suitability simulation by mid-century (2051–2070) shows a projected increase in the magnitude of change of SIV and spatial suitability distribution of suitable areas compared to the past climate for the different crop types. The projected spatial suitability distribution for mid-century shows a similar spatial pattern as the near future period (2031–2050) with an increase in the suitability spatial extent and the magnitude of change in SIV. For cereals (Figure 3, column 3), the projected change is like the spatial suitability pattern as the near future period except for the spatial extension in the suitable area further north in the central Sahel zone for pearl millet. In contrast, a decrease in the suitable area in the western Nigeria for pearl millet and north-west Nigeria for maize and sorghum. The legume (Figure 4, column 3) crops show a similar projected suitability spatial pattern as the near future period except a projected decrease in SIV of about 0.1 and 0.2 of the suitable area is expected in the south-west Chad Republic in the eastern Sahel zone for the groundnut and cowpea, respectively. For the root and tubers (Figure 5 column 3), a decrease of about 0.2 SIV is projected for both the plantain and yam but with a similar spatial suitability pattern as shown for the near future period. However, for cassava about 0.2 decrease SIV is projected over the guinea-Savanna zone but the area remains suitable. For the fruit and horticulture crops (Figure 6, column 3), there are no changes in the projected spatial suitability pattern as observed in the near future period by mid-century. However, there is an increase in the magnitude of change of SIV from 0.1 to 0.2 and 0.2 to 0.3 for the tomato and pineapple, respectively. All the projected suitability changes are statistically significant at 95% confidence level for cassava, maize and mango and are consistent for the other nine crops (i.e., at least 80% of the model agree to the sign of change) by mid-century (2051–2070).

The projected increase in global warming will lead to increasing the magnitude in the projected change for the crop SIV and spatial suitability distribution across different crop types by the end of the century (2081–2100). Cereal (Figure 3, column 4) as projected will be severely affected as more areas becomes less suitable by the end of the century. For legume (Figure 4, column 4), the Savanna zone will be less suitable with a decrease of about 0.1 in SIV while a decrease of about 0.2 SIV is expected along the eastern Sahel zone for groundnut as well as the south coast of Nigeria. Cowpea as projected will be more affected with a decrease of about 0.2 SIV in the northern savanna in the southern Chad Republic and Nigeria with its boundary with south-east Niger Republic in the Sahel and south-west Mali in the western Sahel zones. A decrease up to 0.2 in SIV is expected in the southern Sahel for cereal except maize with an increase of about 0.2 in the central southern Sahel zone. The root and tubers (Figure 5, column 4), show a similar spatial pattern for the decrease in the suitable area as the near future period and mid-century but with an increase in the SIV magnitude of about 0.2, 0.3 and 0.4 for yam, plantain and cassava, respectively. The fruit and horticulture crops (Figure 6, column 4) shows further reduction in the suitable area compared to the near future period with an increase up to 0.4 SIV for the horticulture crop. The Guinea-Savanna will become less suitable with a decrease of 0.1 and 0.2 SIV for orange and mango, respectively. All the projected suitability changes are statistically significant at 95% confidence level for cassava, maize and mango and are consistent for the other nine crops (i.e., at least 80% of the model agree to the sign of change) by the end of the century (2081–2100).

3.4. Impact of CCD on Crop Planting Month over West Africa

At all the three future climate windows, the Ecocrop projected change on the planting month varies for different crop types across the different AEZs of West Africa (Figures 7–10). The impact of CCD resulted in an early or late/delay in the PM for different crops and increases in magnitude across the three zones as described in Table 3 below. It is worth stating that the change in PM describes a change in the best three planting months under the three future windows.

Table 3. Projected changes in time of planting (crop planting months) over West African AEZs at different global warming levels.

Crops	Near Future (2031–2050)			Mid-Century (2051–2070)			End-Century (2081–2100)		
	Guinea	Savanna	Sahel	Guinea	Savanna	Sahel	Guinea	Savanna	Sahel
Cassava	Delayed planting for one month	Early planting by four months	Not applicable	Same as GWL1.5	Same as GWL1.5 but for more area	No planting date	Same as GWL1.5	Same as GWL1.5	No planting date
Plantain	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date
Yam	On month delayed planting	No change in planting date	No change in planting date	Same as GWL1.5	Same as GWL1.5	No change in planting date	Same as GWL1.5	Same as GWL1.5	No change in planting date
Maize	Three months delayed planting	Four months early and delay planting in east and west respectively	No change in planting date	Same as GWL1.5	Same as GWL1.5	No change in planting date	Same as GWL1.5	Same as GWL1.5	No change in planting date
Pearl millet	One-month delayed planting	Two months delayed planting	Two months delayed planting	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5
Sorghum	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date
Mango	Delayed planting for two months	Early planting by four months	One-month delay in southern Sahel zone	Same as GWL1.5	Same as GWL1.5 but for more area	No planting, date	Same as GWL1.5	Same as GWL1.5	No planting date

Table 3. *Cont.*

Crops	Near Future (2031–2050)			Mid-Century (2051–2070)			End-Century (2081–2100)		
	Guinea	**Savanna**	**Sahel**	**Guinea**	**Savanna**	**Sahel**	**Guinea**	**Savanna**	**Sahel**
Orange	One-month delayed planting	No change in planting date	No change in planting date	Same as GWL1.5	Same as GWL1.5	No change in planting date	Same as GWL1.5	Same as GWL1.5	No change in planting date
Pineapple	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date
Tomato	One-month delayed planting	No change in planting date	No change in planting date	Same as GWL1.5	Same as GWL1.5	No change in planting date	Two months delayed planting	One-month early planting	No change in planting date
Cowpea	One-month delayed planting	Two months delayed planting	Two months delayed planting	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5	Same as GWL1.5
Groundnut	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date	No change in planting date

In the near future, cereals crops, pearl millet and sorghum are projected to experience a one-month delay over the region and up to 0.2 along the west coast of Sierra Leone to Liberia and the south coast of Nigeria (Figure 7, column 2). In contrast, the two-month delayed planting is expected over the Savanna-Sahel zone for maize. For the legumes crops, cowpea and groundnut (Figure 8 column 2, see Table 4) no projected change in the PM compared to the past climate is expected over the regions except about one-month delay (i.e., from June to July) in planting over Sierra-Leone and Liberia in the Guinea zone and the southern Sahel zone from Senegal to Chad Republic compared to the planting month (June) over the area. For the root and tuber (Figure 9 column 2), about three to four months early (February/March) the planting is projected for cassava in the near future as compared to June/July, the PM from the historical climate across the region except the north-east Nigeria and the coastal areas (Figure 9, Table 3). No change in the PM is expected in the near future over the coastal areas but about three months delay in planting is projected in the north-eastern part of Nigeria. No change in the PM is projected for plantain, an annual crop which can be planted anytime of the year while a 3–4 months delay is expected for yam except in western Guinea-Savanna and the south coast of Nigeria. For fruits and horticulture (Figure 10, column 2), no projected change in the planting month is expected for tomato and pineapple except a two-month delay over Liberia. Early planting between one to two months is expected in the Guinea-Savanna zone and about three-months delay in the planting of orange in the southern Sahel zone. About two-months and up to four-months delay in planting is projected for mango in the Guinea-Savanna zone and the northern Sahel zone, respectively while a two-month early planting of the crop is expected in the southern Sahel zone. The projected change is consistent for all crops as 80% of the simulation agree to the sign of change.

Table 4. Trends in the projected change in suitability over West Africa for the near future, mid and end of the century periods for different crops.

Crops/Period	2031–2050	2051–2070	2081–2100
Cassava	1.053	1.141	1.497
Cowpea	1.000	1.000	1.002
Groundnut	1.000	1.001	1.030
Maize	1.007	1.021	1.082
Mango	1.013	1.046	1.137
Orange	0.981	0.974	1.089
Pearl millet	1.007	1.022	1.057
Pineapple	1.061	1.216	1.580
Plantain	1.017	1.025	1.215
Sorghum	1.007	1.018	1.032
Tomato	1.219	1.421	1.997
Yam	0.873	0.784	0.779

By mid (2051–2070) and end of the century (2081–2100), most crop types show a similar spatial pattern in the planting month as observed in the near future but with an increase in the magnitude of the delay or early planting period (Figures 7–10, column 3–4). For example, cereal crops show a similar spatial pattern as projected for the near future for sorghum and pearl millet by mid-century (Figure 7, column 3) and the end of the century (Figure 7, column 4) except over Liberia and south coast of Nigeria for pearl millet. These areas are expected to experience a 2–3-month delay in planting. Legume crops, cowpea and groundnut show similar characteristics of no projected change in the PM as the near future period but for an increase in the magnitude a delay period in the south coast of Nigeria and southern Liberia. A delay in planting from one to two months is expected from Sierra-Leone to Liberia and over the south coast of Nigeria for cowpea by mid-century (Figure 8, column 3) and up to three months by the end of century (Figure 8, column 4). A two-month delay in the PM is projected over southern Liberia and a one-month delay in the southern Sahel zone by mid and end of the century (Figure 8, column 3–4). For the root and tuber crops (Figure 9, column 3–4), about a four-month delay in planting is projected over the Savanna zone except the western area of the zone and in the central Guinea zone by mid-century for yam (Figure 9, column 3). A similar pattern is projected by the end of the century for crop (Figure 9, column 4). No change in the planting period is projected for plantain because it is annual crop over these two periods. For cassava a month delay planting by mid-century and up to two-months by the end of the century is projected in the western Guinea-Savanna zone while an early planting is expected in other parts of the Savanna zone and north of the Guinea zone over the two-climate change period. For the fruit and horticulture crops, there is no change in the PM for pineapple being an annual crop. A one-month PM delay is projected for tomato over the region and up to two-months over Liberia by mid and end of the century. However, a projected two-month early planting is expected by the end of the century in the southern Sahel zone. For fruit crops, a four-month early planting compared to the historical climate is projected in the Guinea-Savanna zone with a delay of about three-months in the south Sahel by mid-century. By the end of the century, an early planting of about four-month early compared to the historical climate is projected over the region for orange. Similarly, a two-month early planting is projected for mango in the southern Sahel zone for mid and up to three-months by the end of the century. In contrast, a delay in planting of about two-three months is expected over the Guinea-Savanna zone and up to four-months in the northern Sahel zone. All the projected changes are consistent for all crops as 80% of the simulation agree to the sign of change over the two climate periods.

3.5. Trends in Projected Crop Suitability and Crop Planting over West Africa

We used the Theil-Sen slope to evaluate the trend in the projected suitability and month of planting for the crop types for the near future, mid and end of the century over West Africa (Tables 4 and 5). The trend describes the rate of increase and decrease of the suitable area and SIV with increasing warming over the three-window month. In general, all the crop types show an increasing trend in the projected change in the crop suitability compared to the past climate from the near future to the end of the century when compared to the past climate except for yam (Table 4). The projected change in the suitability index value of suitable areas for tomato showed the highest trend value from 1.219 in the near future month to 1.997 by the end of the century. Compared to other crops, our analysis showed that there was a decreasing trend (from 0.873, the near future to 0.779, end of the century) for yam in the projected suitability change with increasing warming across each time of month from the near future to the end of century over West Africa. Additionally,, there was decrease in the trend between the near future month and mid-century month in the projected change for orange but later increased at end of the century. Moreover, there was no trend in the projected change in the suitability for cowpea over the near future month and mid-century but there was increase in the trend of the projected change for the crop by the end of the century.

Table 5. Trends in the projected change in the month of planting over West Africa for the near future, mid and end of the century periods for the different crops.

Crops/Period	2031–2050	2051–2070	2081–2100
Cassava	1.125	1.171	0.974
Cowpea	0.972	0.957	0.887
Groundnut	0.969	0.952	0.857
Maize	1.000	0.990	0.950
Mango	1.000	0.976	0.909
Orange	1.000	1.111	1.930
Pearl millet	0.980	0.959	0.912
Pineapple	1.000	1.000	1.000
Plantain	1.000	1.000	1.000
Sorghum	1.000	1.000	0.944
Tomato	0.938	0.900	0.851
Yam	1.000	0.924	0.909

Our Theil-Sen slope trend analysis shows a general decreasing trend in the projected change in the planting month compared to the past climate for the different crop types except for orange which gives an increasing trend pattern of the projected planting for all the crop (Table 5). Our trend analysis test show there was no change in the projected change in planting for plantain, pineapple (1.000) and for sorghum for the near future and mid-century month (1.000).

4. Discussion

4.1. Crop Type Sensitivity to CCD and Impact on Food Security

Horticulture, cereals, root and tubers (hereafter HCRT) crops, respectively will be the most impacted by the climate change/departure impact from the historical variability in West Africa. All the five different crop types show a different response to the impact of the global warming induced CCD across the examined three-window month, near the future to the end of the century in West Africa. The variability in the response of the different crop types to CCD is very cardinal to the agricultural production and food security in the region. HCRT are the most negatively affected with decreasing suitability across the three AEZs of West Africa due to the impact of the climate change compared to the legumes and fruit crops. In terms of sensitivity, the HCRT crop suitability show a negative linear relationship with increasing global warming over the region except for cereals with a positive linear relationship in the southern Sahel zone. The negative linear relationship is observed notably over the Guinea-Savanna zone for the HCRT resulting in a decrease in the crop suitable area with increasing warming across the three months examined. The projected negative linear relationship due to an increase in global warming may result in a decrease in the yield of these crop types over West Africa due to a decrease in the crop suitable land [6,64]. For example, previous studies (e.g., Lobell et al. [65], Sultan et al. [15]) have revealed that the impact of climate change will result in a decrease in the yield of cereals by 20% in the near future month over West Africa. Additionally, the result is in line with the findings of [32] that there will be a decline in the suitability and suitable cultivated areas for cassava due to a result of the temperature increases but the crop will remain suitable over the region. In addition, our result also agrees with [66] findings that increasing warming will lead to a decrease in the availability of the suitable land for the cultivation of horticulture with a direct implication on the horticultural production. This agrees with [14] that the variability in the climate will lead to a reduction in the yield quantity of pineapple in Ghana which is one of the key producers of pineapple, which may be linked to the decrease in the suitable areas and SIV as projected in this study.

The projected impacts of CCD on crop suitability will further compound the challenge of food security in West Africa. This is in line with past findings that climate variability and change in the coming decades will further threaten food security in sub-Saharan Africa notably West Africa, a region that plays a major role in the agricultural production [1,7]. West Africa for about 24 years mainly accounts for about 60% of the total value of agricultural outputs within Africa [7]. However, the story has not been the same since 2007 due to instability in the agricultural production over the region and this has been a source of concern [7]. As a result, the projected decrease in crop suitability due to a reduction in the suitable area for crop cultivation coupled with the projected delay in the month of planting will both strongly have a negative impact on the crop yield and agricultural production. This may further plunge the plan for food security in the region into a mirage.

4.2. Impact of CCD on Spatial Suitability Distribution

The impact of CCD will lead to a projected variability in the spatial suitability distribution across the three AEZs for the three future months and different crop types. The magnitude of deviation due to the increase in warming may influence the suitability over the zones as well as crop sensitivity to the projected change in the climate. The crop growth and yield are directly proportional to the climate-crop threshold i.e., climate suitability/threshold [67]. It is important to note that each crop has their climatic or suitability threshold for healthy growth, development and optimal yield and that future changes/departure in the climate generally has a reaching impact on the yield of the crop. This is further buttressed by our finding that CCD may lead to future constraint in the available cultivated area in the Guinea and southern Savanna zones of West Africa. On the other hand, it tends to provide an opportunity in the northern Savanna extending to the southern Sahel. The projected spatial constraint in the suitability and cultivated area will strongly affect the crop production and yield over West Africa. The Guinea-Savanna zone provides and significantly contributes to the agricultural production over the region and a large proportion in the continent [7]. For example, about four of the five different crop types (except the legumes) examined in the study is and will be significantly affected with the projected decrease in SIV and reduction in the cultivated area of the crops. This projected decrease in SIV and the reduction in the spatial distribution of suitable areas for cultivation of major crops such as cassava and the horticulture crops such as pineapple pose a great challenge to the economy of most countries and further raises the challenge of food security in the region. The challenge of food security arising from the projected decrease in the crop suitable area may compound the climatic stress over the region due to the increase in food production to meet the present food demand but with the projected and limited available land for cultivation are not realistic and may become a mirage with the projected increase in the population over the region by mid-century, 2050 [68,69].

On the other hand, crop suitability due to CCD from the historical variability is projected and will lead to an increase in SIV and more suitable area notably in the Southern Sahel. The increase in suitable areas provides an opportunity for more suitable areas in the region for the cultivation of cereals, legumes and mango in the southern Sahel zone (12–14 °N), plantain and yam in the Savanna zone as well as the legume crops in the central savanna zone of West Africa. The projected increase into the Sahel agrees with the previous finding for maize in the Sahel zone with CCD. This shows that the crop spatial suitability distribution and productivity are highly sensitive to variations in the climate such that a departure of the future African climate from the recent range of historical variability will have the most devastating effect on agriculture over the continent [70–72].

4.3. Implication for Socio-Economic Development and Strategy Policy

The above result provides a basis for developing the policy and strategy to reduce future crop loss due to a lack of suitable land and risks of food security over West Africa. At the same time, it advocates for a more proactive response to increase resilience and adaptive options via the urgency and timing of adaptation. For instance, the analysis of crop suitability indicates that a greater proportion of suitable land areas in the West African region may become less suitable or unsuitable in the future from CCD due to global warming, which may enhance a decrease in the crop yield and agricultural production of some crop. On the other hand, the analysis showed an expansion of the suitable area into the Sahel for the cereal and legume crops with CCD, which provide future opportunities for more suitable areas for the cultivation of one of the most staple crops, maize. This will have both positive and negative impacts on regional development and economic activities (e.g., regional trade and international relation in terms of exports and importing goods). The increasing population also implies that the demand for food will be on the increase. However, the projected change in suitability also suggests that a well-planned land use change (through the urgency of adaptation to the CCD) could help reduce the impacts of CCD on the crop yield and food security in the region. Hence, there is a need for the formulation of a strategic policy that can accommodate or encourage such a land-use change. A strategic policy is also required more importantly for the new opportunities such as an expansion into the Sahel for maize and the other crops that may arise out of the impact of CCD over the region. Hence, the results can guide policymakers on how to prioritize their adaptation plan in terms of the urgency of response and redefine mitigation measures to the future impact of CCD on the crop suitability and planting season over West Africa.

5. Conclusions

Summary and Conclusions

In investigating the impact of CCD on the crop suitability and planting month over the entire West African region, we analyzed 10 CMIP 5 GCM datasets downscaled by CORDEX RCM, RCA4 for five different crop types, cereal (maize, pearl millet and sorghum), fruit (mango and orange), horticulture (pineapple and tomato), legume (cowpea and groundnut) and root and tuber (cassava, plantain and yam). The summary from our study are as follows:

We suggest that projected changes in the temperature may lead to an increase between 1–4.5 °C for the minimum and mean temperature over West Africa from the near future to the end of the century. A change of about 10 mm is projected over the western Guinea-Savanna zone and no major changes in other parts of the region and up to 25 mm along the coastal areas (west coast of Sierra-Leone to south-west Ghana and the south coast of Nigeria) for the near future and mid-century. A projected decrease up to 25 mm is expected over the region and up to 35 mm over the coastal area (from the west coast of Gambia to north Liberia) by the end of the century.

Addressing our main objective, the Ecocrop simulated spatial suitability distribution of the crops shows higher suitability are to the south of 14 °N while a lower suitability is to the north. The marginal suitability line (around 12–14 °N) shows the transition between the higher and lower suitability of the crop. Results show that the horticulture crops, pineapple and tomato, respectively are the most negatively affected by the impact of CCD from the historical variability over the region. There is a projected constraint showing a negative linear correlation with increasing warming in the cultivation of most different crop types except for cowpea in the Guinea-Savanna AEZs (south of 14 °N) by the end of the century due to an increasing reduction in the suitable area and crops suitability index value due to the climate departure although most of the crop remains suitable. The impact of CCD will provide opportunities for more suitable areas in the southern Sahel zone for cereals, mango and legumes crops showing a positive linear correlation with increasing warming thus creating more land for cultivation, which can in turn increase the yield and production of the crops. Generally, a projected delay of 1–4 months is expected for most of the crop types with CCD except for orange and cassava as well as maize in the Savanna zone. No projected changes are observed for plantain and pineapple, mainly because they are annual crops.

Statistically, we demonstrated that over 80% of the simulations agree with the sign of the projected change for all the crop types due to the CCD and the changes are statistically significant at 95% confidence interval for maize, cassava and mango. Additionally, we showed there is an increasing trend in the projected crop suitability for all crops except yam with a decreasing trend due to CCD from the historical variability while a decreasing trend is projected for the future change in the month of planting of the crops.

Despite our analysis, the results of this study can be improved and applied to reduce the future impact of crop suitability and risks of food security over West Africa in many ways. For instance, future studies may investigate the impact of CCD on the crop suitability and planting season over the region using more RCMs with different forcing GCMs other than only RCA4. This may help resolve the challenge of uncertainty in the future simulation of the crop suitability and planting season. In addition, the results of the study will be more robust and improve our knowledge on the impact of CCD and its influence on the crop suitability and planting season over West Africa. Further studies on how to reduce the uncertainty will improve the credibility and application of the results. Nevertheless, the present work shows the impact of CCD on the crop suitability and planting season using GCMs downscaled with RCMs. This establishes a premise for future work in advancing our knowledge into how CCD influences the crop suitability and planting season in West Africa.

In conclusion, the application of the concept of CCD in this study has demonstrated future changes in how the crop suitability and planting season can be analyzed. The application of CCD established the impact of climate change on crop suitability over West Africa and further identified spatial variability in the future suitability showing that horticulture, cereal, root and tubers crops will be most negatively affected by the impact of CCD in West Africa. It also identifies the three best planting months in a growing season and the changes in the planting time is about four month delay in the planting season for most crops but early planting for cassava, orange and maize but only in the savanna zone. The application of CCD aims to underpin future works to advance the study of future changes in crop suitability and planting in any region of the world. This type of analysis is important for adaptation options and planning for future changes in the crop suitability and planting period to improve food security.

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Managing New Risks of and Opportunities for the Agricultural Development of West-African Floodplains: Hydroclimatic Conditions and Implications for Rice Production

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Abstract: High rainfall events and flash flooding are becoming more frequent, leading to severe damage to crop production and water infrastructure in Burkina Faso, Western Africa. Special attention must therefore be given to the design of water control structures to ensure their flexibility and sustainability in discharging floods, while avoiding overdrainage during dry spells. This study assesses the hydroclimatic risks and implications of floodplain climate-smart rice production in southwestern Burkina Faso in order to make informed decisions regarding floodplain development. Statistical methods (Mann-Kendall test, Sen's slope estimator, and frequency analysis) combined with rainfall—runoff modeling (HBV model) were used to analyze the hydroclimatic conditions of the study area. Moreover, the spatial and temporal water availability for crop growth was assessed for an innovative and participatory water management technique. From 1970 to 2013, an increasing delay in the onset of the rainy season (with a decreasing pre-humid season duration) occurred, causing difficulties in predicting the onset due to the high temporal variability of rainfall in the studied region. As a result, a warming trend was observed for the past 40 years, raising questions about its negative impact on very intensive rice cultivation packages. Farmers have both positive and negative consensual perceptions of climatic hazards. The analysis of the hydrological condition of the basin through the successfully calibrated and validated hydrological HBV model indicated no significant increase in water discharge. The sowing of rice from the 10th to 30th June has been identified as optimal in order to benefit from higher surface water flows, which can be used to irrigate and meet crop water requirements during the critical flowering and grain filling phases of rice growth. Furthermore, the installation of cofferdams to increase water levels would be potentially beneficial, subject to them not hindering channel drainage during peak flow.

Keywords: inland valley development; hydroclimatic hazard; water control structure; sustainable rice production

1. Introduction

The future of West Africa, and its economic, political, and social balance, depend on the ability of the agricultural sector to adapt and ensure food security under multiple pressures, such as climate change and demographic growth. In Africa, only 12.5 million hectares are irrigated out of a total of 202 million hectares of cultivated land, or 6.2%. The proportion of irrigated land in the south of Saharan Africa is even smaller, with only 5.2 million hectares, or 3.3%, of cultivated land being irrigated [1]. The increase in population will have serious implications in terms of agricultural production and the availability of natural resources. Adaptive strategies to help cope with the potential decrease in crop yields include promoting the extensive development of inland valleys in West Africa. This is because of their great potential as rice-based production systems due to the high and secure water availability and soil fertility [2]. As such, the West African floodplains are privileged places for agricultural intensification, but play a diminishing role in the face of droughts that affect rainfed crops. Key factors of concern for the agricultural development of floodplains include flood hazards, surface flow deficits due to dry spells, and early flood recession. The valorization of floodplains faces numerous technical, social, and economic constraints that involve an intensification of crops and hence new risks linked to climate change. These are characterized by increased irregularities in rainfall, onsets of extreme floods, and long-lasting droughts.

As a landlocked country, Burkina Faso is vulnerable to climate variability [3]. This variability not only occurs at a daily, seasonal, and interannual scale, but can also be multidecadal. A break in annual rainfall was observed during the 1970s, irrespective of latitude or longitude, in West Africa [4]. It was especially prominent in the savanna, which includes the study area of Dano. The causes of this prolonged drought, subcontinental in scale, remain controversial and undoubtedly multifactorial and multiscalar. Many authors have shown, in addition to the global natural variations (i.e., astronomical, oceanic, and volcanic), the anthropogenic effects at different scales. These are observed at a regional (increase in the albedo effect because of the rapid urbanization of the Sahel, and deforestation of the lower coast reducing real evapotranspiration (ETR) and increasing flow), intercontinental (European air pollution of the 1970s, favoring regional cooling, i.e., anticyclonic conditions in regulatory pathways), and global (greenhouse gas-related climate change and its effects on heat and excessive events) level [5]. A change in hydroclimatic conditions can substantially modify the hydrological regime of an inland valley and its drainage area [6]. This modification can result in flooding or drying conditions in the lowlands, implying a possible reduction in its productivity. Furthermore, land cover and land use change can alter the floodplain and impact its ecosystem [7], but investigating this is beyond the scope of this study. Given the uncertainties in climate model predictions (especially for precipitation), analyzing the current climate hazards using observed data and their possible implications for the future is required.

Burkina Faso's agricultural sector continues to generate approximately one-third of the country's GDP and employs 80% of the population [8], despite the harsh climatic condition. Notwithstanding the importance of agriculture in the economy of Burkina Faso, the sector is facing many challenges, including threats from many natural disasters, such as floods, droughts, and violent winds, which lead to low crop and livestock productivity [9]. Since 1970, investment has been made by the government of Burkina Faso to address the issue posed by hydroclimatic risks. This includes developing rice production intensification policies in inland valleys that encompass physical development, the social organization of production, material support, organization of the rice sector, subsidies, and legal connotations. Subsequently, 10% of the inland valleys suitable for agriculture have been developed in southwestern Burkina Faso. However, as reported by the regional agriculture extension service, up to 30% of the developed inland valleys have been abandoned due to increasing hydroclimatic hazards.

There is therefore a need to describe the seasonal, average, and frequency characteristics of the climate that can impact rice production in the region.

The objective of this work is to analyze the hydroclimatic hazards by considering the period of 1922–2017 and their implications for rice production in southwest Burkina Faso to support agricultural policies for adequate water infrastructural development. Two research questions are considered: (i) What are the current trends in climatic and hydrological hazards and what are their implications for food production in inland valleys? (ii) What are farmers' perceptions of the hydroclimatic risks in the region, and what strategies have consequently been developed to face the challenges encountered?

2. Materials and Methods

This section is divided into five sub-sections, which are the study area and data used, the various modalities of lowland development (traditional vs. modern development), climate-related local knowledge and hydroclimatic variables' analysis, rainfall–runoff modeling and frequency analysis, and water availability evaluation during the critical phase of rice development.

2.1. Study Area and Data Used

The case study areas are the Lofin catchment and Lofin inland valley, located in the municipality of Dano in the southwest region (région du Sud-Ouest) of Burkina Faso, West Africa (Figure 1). Dano is situated in a tropical climate region with a unimodal rainfall regime (Figure 2). The mean annual rainfall is approximately 921 mm, with a standard deviation of 106 mm for the period 1980–2018. The annual rainfall regime is characterized by the alternation of two contrasting seasons: a dry season from November to March, in which rainfall is almost absent (58 mm in October, the driest month), and a rainy season from April to October (average 238 mm in August, the wettest month) [10]. The climatic water demand (ET0) is more stable during the year, but it varies, on average, from 123 mm in August to 175 mm in April [10]. Long-cycle crops (120 days), such as rice sown after the 10th of July, are at risk of water stress in the middle and end of the growing cycle. The average annual temperatures between 1970 and 2013 ranged from 25 to 33 °C and from 25 to 31 °C at the Boromo and Gaoua stations, respectively (Figure 2). The annual insolation varies between 6 and 8 h/day, and the air humidity ranges from 35% to 80%. The dominant vegetation comprises shrubs and/or the tree savanna type, and resulting successional vegetation from the degradation of cleared forests [11]. This is due to both human activities and the dry period since 1970.

In this region, wetlands have historically been used as pasture in the dry season. Rice was one of the first crops cultivated in these areas (Figure 3). From the 20th century onwards, the agricultural use of the inland valleys, referred to locally as 'bas-fonds', was fostered because of population growth and migratory flows. Currently, in addition to rice, wetland use has been diversified with other crop types, such as vegetables, fruits, and cereals [12]. Rice products are mainly intended for consumption, with an increasing share of rice in the local food.

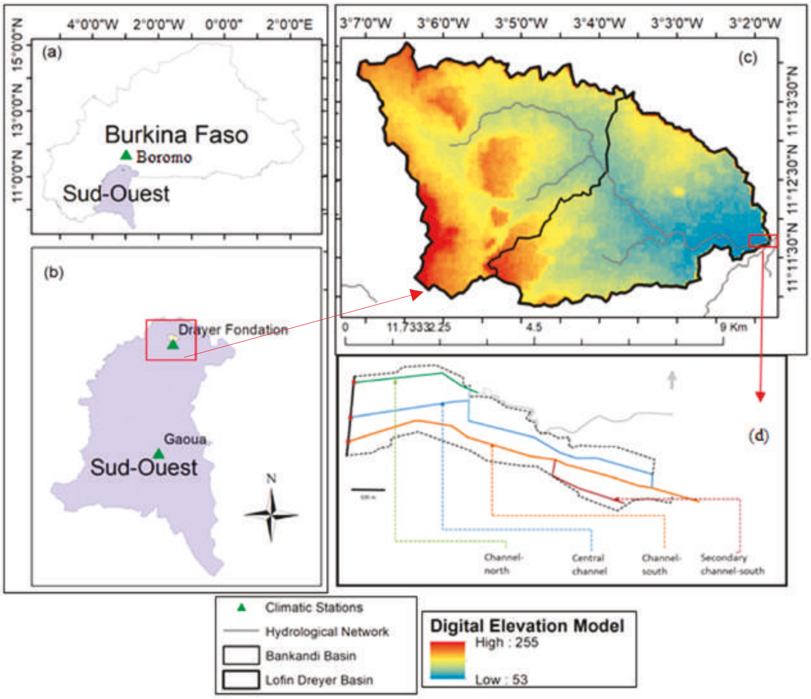

Figure 1. (**a**) Location of the study area in Burkina Faso. (**b**) The southwest region. (**c**) The Lofin catchment. (**d**) The Lofin inland-valley with irrigation/drainage channels.

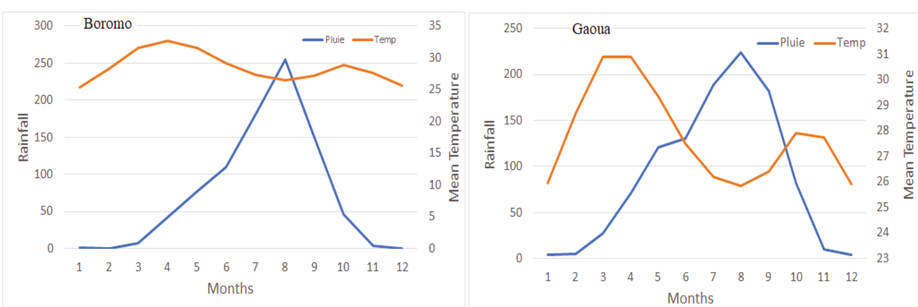

Figure 2. Rainfall and temperature at Boromo and Gaoua climatic stations.

The data used in this study are rainfall data of the Boromo and Gaoua stations from 1922 to 2016, and rainfall data of the Dreyer Foundation from 2017 to 2018. Discharge data of the Lofing-Radier station from 2017 to 2018 were measured by WASCAL (www.wascal.org) during project implementation. Other climate data, such as the minimum and maximum temperature, sunshine duration, wind speed, and minimum and maximum relative humidity from 1922 to 2016 of the Boromo and Gaoua stations were used and obtained from the Burkina Faso national meteorological directorate (including long-term rainfall data).

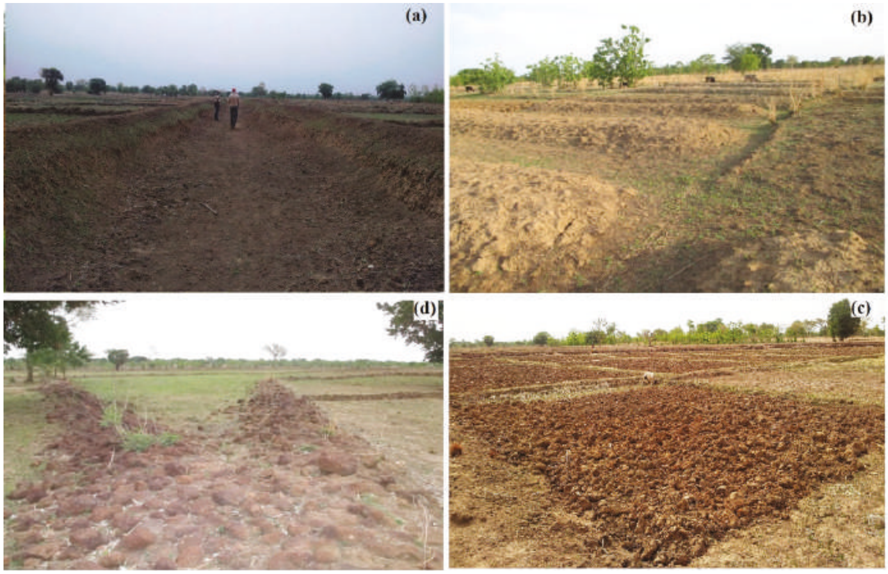

Figure 3. Different types of lowland development, including a rice field model with sprinkler drains (**a**,**b**), cyclopean concrete pouring dikes with a central cofferdam (**c**), and compacted clay bunds protected by geotextiles and rocks following the level curves with openings (**d**).

2.2. Various Modalities of Lowland Development: Traditional vs. Modern Development

Four types of lowland development have been observed and can be classified into two main groups: traditional and modern lowland designs. Traditional lowland development is a combination of the techniques developed by farmers for managing the agrarian space, the water, and the various types of production. The objective pursued by the farmers is to grow crops while minimizing the risks associated with drought and flooding. Schemes designed by farmers for the control and management of water in the lowlands include, firstly, large ridges arranged perpendicularly to the water flow direction, and secondly, large ridges in the shape of a contour dike with gaps.

Baffles are formed that not only slow the flow of water favoring infiltration, but that also enable the management of a water level in the grooves between the ridges. Upland crops (maize or tobacco) are placed on the ridges. Sorghum and taro are placed on the flank of the ridges. Rice, a water-demanding crop, is sown and transplanted into the furrows. This polyculture system is adapted to local conditions, has a low associated cost, and is more resilient to the risk of climatic disasters.

In contrast, modern lowland developments are those designed and implanted by external organisations, such as funded projects and programs, and NGOs. The principle objectives of such developments are multi-functional, aiming to

- Partially control water through the installation of hydraulic structures;
- Distribute the water at the landscaped site;
- Optimize the drainage of flood waters;
- Avoid and minimize the adverse effects of water shortages due to dry spells during the crop season; and
- Support non-seasonal crops, if possible.

To achieve these objectives, several types of development were designed, of which three (3) types of models are described. First is the rice field model with sprinkler drains (Figure 3). This model consists of channeling runoff by following preferential paths marked by the differentiation of surface elevation.

The canals are used for irrigation and drainage. The individual plots are partitioned by small bunds which the producers can open to irrigate their plants. This model is promoted in the area by the Dreyer Foundation. Second are compacted clay bunds protected by geotextiles and rocks that follow the level curves with openings. This model is a flood spreading arrangement, with the possibility of drainage being provided by the openings. The third model is the cyclopean concrete pouring dikes with a central cofferdam. This model is based on the threshold for slowing the flow of water on the course bed, which leads to a substantial change in the height of the water level, and is then managed using the cofferdam.

With these three models of landscape control, adding garden plants arranged with wells is necessary. The modern development models of lowlands strongly alter the hydrology of the valley bottom. Although this may be advantageous, it also adds new constraints that can become risks, depending on the physical and social environment.

2.3. Climate-Related Local Knowledge and Hydroclimatic Variables' Analysis

A survey of farmers' perceptions on climate and climatic changes was conducted in the Lofing lowland in 2017 using a questionnaire. A total of 17 farmers were randomly selected, and a questionnaire was administered individually. The hydroclimatic variables were statistically analyzed using the quantile method, Mann-Kendall test, and Sen's slope estimator. Different time steps were considered to aggregate the time series over 10-day, monthly, and annual time scales. Reference evapotranspiration was computed using the Food and Agriculture Organisation (FAO) ETo calculator software based on the Penman–Monteith formula [13]. The rainfall onset and cessation dates were defined using the Franquin (1969) [14] method. At the 10-day scale, the rainfall onset corresponds to the date from which rainfall is greater than half of the potential evapotranspiration (R > ET0/2). The methodological framework of the study is presented in Figure 4. It shows the different steps fulfilled to perform this study. The Mann-Kendall test [15,16] is a nonparametric trend detection method widely applied to hydroclimatic variables [17–19]. The null hypothesis H_0 for the test is that there is no trend in the time series, while for the alternative hypothesis H_1, there is a significant trend in the time series at the 0.05 significance level. This is a robust test in the sense that it does not make any assumptions about the distribution of variables. In addition, the Sen slope method [20] is considered for estimating the magnitude of the slope if a trend is detected in the time series.

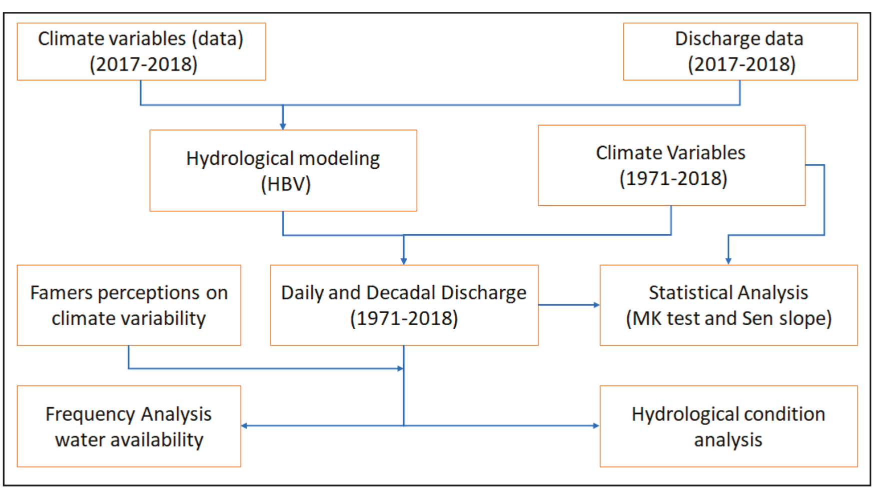

Figure 4. Methodological framework of the study.

2.4. Rainfall–Runoff Modeling and Frequency Analysis

To further access the hydrological aspect of the study area, an HBV model [21] was calibrated and validated for the Lofing basin at the outlet of Lofing Radier. HBV is a conceptual, lumped, and time-continuous hydrological model that simulates discharge using rainfall and potential evaporation as inputs. The HBV model has four main component routines: (1) snow (not used); (2) soil moisture (computes actual evapotranspiration, soil moisture, and groundwater recharge); (3) response function (calculates runoff and groundwater levels); and (4) routing (calculates the distribution of runoff for a given time series). Model calibration used 2018 data, and validation was performed with data from 2017. Performance criteria included the Nash–Sutcliffe efficiency (NSE) normalized statistic [22] combined with the coefficient of determination (R^2). The past hydrological condition of the basin was then simulated using climatic data from the Boromo and Dano stations (Figure 1) for the period 1971–2018 (Figure 4).

2.5. Water Availability Evaluation during the Critical Phase of Rice Development

The flowering and grain filling growth stages of rice are the most critical phases of its development. Water stress during these phases can be seriously detrimental to the rice yield [10]. In the Dano region, rice varieties with a growing period of 120 days are the most cultivated. By considering the following 10-day periods of rice sowing seed (21–30 June, 1–10 July, and 11–20 July), the critical periods for rice development ranged from 11–20 September to the 11–20 October. The total discharge of water during these 10-day periods was obtained. Trends in these data collection periods were evaluated using the Mann-Kendall and Sen slope tests. The availability of water in terms of discharge, level, and volume needed for effective rice development in the Lofing inland valley was then assessed.

3. Results and Discussion

3.1. Farmers' Perceptions of Changes in Climatic Hazards in the Lofing Inland Valley

Farmers have both positive and negative consensual perceptions of climatic hazards. According to them, no severe drought has been observed since 1974, except in 1984, when a famine was experienced. Since 1996, extreme rains able to destroy houses have not been observed, except in 2015, when a long-lasting and heavy rainfall event was recorded. Events perceived negatively were deemed to be of the greatest importance. Farmers consider that the heat waves initially experienced mainly in April have shifted to March and that they last almost the entire year. The weather is therefore perceived as becoming warmer. Furthermore, the farmers perceive there to be changes in annual rainfall patterns because, according to them, rainfall was previously well-distributed throughout the rainy season. Now, they believe that the dry season is longer, and the rainy season is shorter and irregular. Dry spells have become more frequent during crop growth and mainly occur during the rice grain formation stage. According to the interviewed farmers, there is currently a decrease in rainfall amount per event, with more thunderstorm winds, but limited rainfall, in comparison to past observations.

The events best-described by the farmers are the catastrophic years, the increasing heat, and the effect of wetland development over the last two years. The consensual perceptions of the degrading rainy season should be considered with caution, given the vagueness of the compared periods and the intensity of the variations. For example, it is virtually impossible to attribute a precise date to references such as "previously", "formerly", or "around 2000", when farmers stated that there have been more severe droughts in the past than at present. Was there a period of a small series of very regular years that was idealized and would now be "referenced"? Did the farmers identify recent problematic years to more comprehensively judge the past, thereby forgetting about the reality of the variability and the change in the process? An in-depth analysis of several timescales of the long climatological series, including a frequency analysis, is required to answer these questions.

Some perceptions are not consensual, namely, the rainfall onset date in 2017 and the effect of the dike and channel rehabilitation in 2017. In fact, 10 of the 17 people interviewed reported an early rainfall onset, 3/17 interviewees reported a normal onset, and 4/17 interviewees indicated a late rainfall onset in 2017. The least consensual perceptions are paradoxically related to the climate or the water regime of the year. These perceptions address, on the one hand, the location of the respondent's plot in relation to the newly constructed dike, and on the other hand, the expectations that are relative to a farmer's specific needs and workplan. The perceptions of climate risk also do not have the same levels of concern among individual respondents. Few have seen "no change" to the climate. In terms of the motivation for sowing rice rather than transplanting in 2017, respondents cited the climatic risk. However, the perception of climate risk varies, according to the respondents' gender and the level of development of the lowlands (Table 1). Indeed, excluding the developed lowlands, the climate risk was mentioned by 100% of women as the reason for rice transplanting. This result might be due a lack of knowledge about agricultural rainfall onset identification. Early sowing is adopted by farmers to free themselves from rainfall and hydrological hazards (i.e., uncertainty about the moisture conditions of the lowland region). Despite existing water control structures in the developed lowlands (which are designed to enable transplanting), up to 20% of farmers do not wait for good sowing conditions. Men are more restricted by their other farming operations. Rice is of a lower priority, and where there is a competition of labor against cotton, the lowlands are often abandoned. Indeed, the climate risk is less important to them, as it is shifted toward alternative activities. This local information is extremely valuable as it both identifies the concerns of local farmers and provides new information regarding their perceptions and likely responses as a result. It is nevertheless necessary to compare the local farmers' perceptions with measured data, which is independent of the farmers' gender, knowledge, and situation.

Table 1. Reasons for the choice of sowing (rather than transplanting) in 2017, according to gender and situation.

Reasons	Operational Constraints	Social Organization	Climate Risk	Lack of Know-How
Undeveloped lowland by men (%)	43	0	43	14
Undeveloped lowland by women (%)	0	0	100	0
Developed lowland by men (%)	63	13	25	0
Developed lowland by women (%)	80	0	20	0

3.2. Analysis of Rainfall over the Last 40 Years at the Regional Scale

The mean rainfall recorded at Dano during 2013–2017 by the Dreyer Foundation (951 mm) is similar to that of the period 1970–2013 at Boromo-Gaoua (962 mm). For that reason, the Boromo-Gaoua rainfall stations, which are the closest to Dano, have been used to provide a detailed understanding of the local climatic pattern. Increased water exceedance events (water available to recharge the reserve and water flows) have been observed in Boromo since 1984 (Figure 5a). There has been no increase in rainfall; however, an increase in water excess implies a change in rainfall regime and/or land use. More rainfall in a shorter time period results in an increase in flood risk and less actual evapotranspiration. In Gaoua, the change was small, but similar, to the change depicted in Boromo, except that the water excess did not increase. Figure 5b shows the climatic balance of the last five years in Dano. There was a high seasonal and interannual variability of rainfall during this period. In 2013, there was no pre-humid period, the water excess was limited, and an early cessation of the season occurred, while in 2014, the pre-humid period occurred in mid-July. In 2015 and 2016, there was no pre-humid period, and the risk of inundation was high. A pre-humid period was detected in early September 2017, with limited water excess.

The period of rainfall uncertainty is longest during the pre-humid season. The hazard zone corresponds to rainfall being less than half of the potential evapotranspiration between the 25 and 75 quantiles of ten days of rainfall. The season profile is asymmetric, meaning that the cessation of the season is more predictable than its onset and that the early rainy season provides more information on the rainy season duration. An ideal opportunity for an informed choice of season length, mainly if there is the potential to irrigate, is provided based on this data.

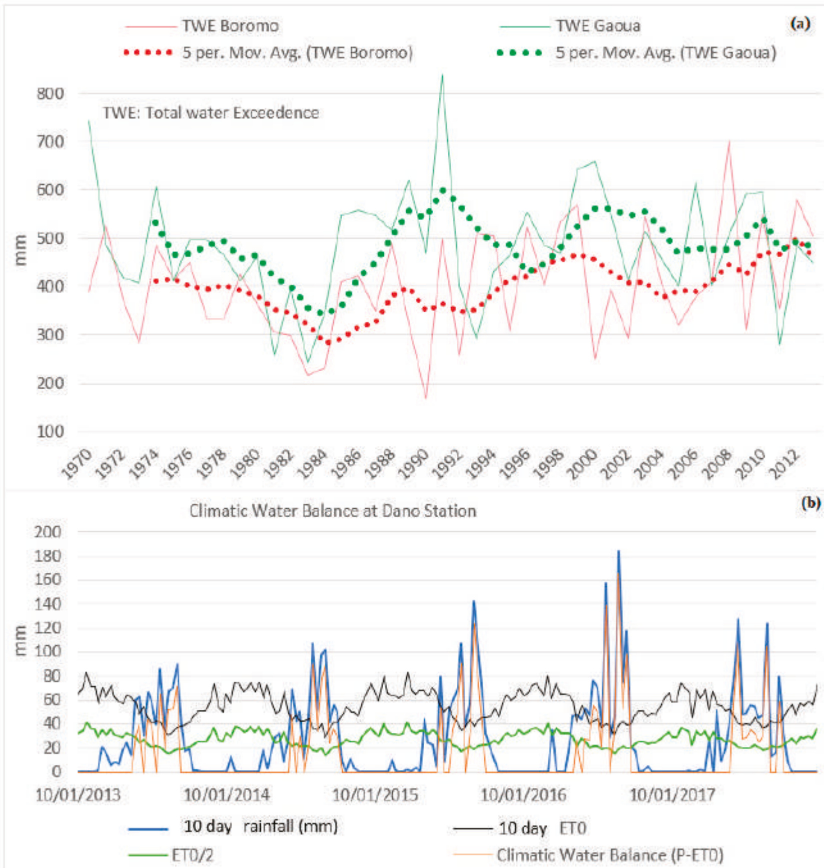

Figure 5. Water excess at Boromo and Gaoua rainfall stations from 1970 to 2012 (**a**) and the climatic water balance at Dano station (2013:2017) (**b**).

3.3. Temperature Analysis at the Regional Scale

The Sen slopes estimated for each month by considering the minimum and the maximum temperatures at Boromo and Gaoua from 1970 to 2013 indicate a tendency toward a warmer atmosphere. During the rainy season (August to October), the average minimum temperature and the average maximum temperature increased at a rate of 0.031–0.035 and 0.005–0.016 °C yr^{-1}, respectively, which is in line with the global observation [23,24]. The minimum temperature increased faster (around two times) than the maximum temperature during the rainy season. Climate change causes increasing air temperatures and evapotranspiration, increases the risk of intense rainstorms, and increases the risk of heat waves associated with drought [25]. An increase in temperature was also observed in the Beninese part of the Niger basin by Badou et al. (2017). An increase in temperature implies a higher level of evapotranspiration, a higher water demand for crops, and a lower level of water exceedance. An increasing temperature will exhibit a larger impact on the grain yield than on vegetative growth and will reduce the ability of the crop to efficiently fill the grain or fruit [26]. This output has the potential to inform famers and stakeholders in framing appropriate policies for rice intensification in the region. The minimum relative humidity (RH) increases from July to October at Boromo and from August to December at Gaoua. The maximum RH decreases from May to September at Boromo and from July to September at Gaoua.

3.4. Potential of Watering/Drainage of the Channels' System in the Lofing Inland Valley

High seasonal and interannual variabilities of discharge were observed at the Lofing-Radier outlet (Figure 6). Throughout the growing season, the river provides enough water to satisfy the requirements of rice (100 L s^{-1} is needed to irrigate 30 ha) (Figure A1). Irrigation should be possible whenever necessary, mainly during the dry spell period. Irrespective of the rice sowing date, the critical period (end of the rice cycle) requiring irrigation varies between the 10th of September and 20th of October. Channel dimensioning is challenging in rice cultivated in inland valleys. There must be a trade-off between the necessities of the discharge peak flow, while maintaining a water level in the channels required for direct irrigation (through, for instance, the use of cofferdams), but also maintaining the wetness of cultivated parcels. The drainage capacity of the channels is large enough for discharging the peak flows arriving from the Dano basin at the outlet of Lofing, while its irrigation potential is problematic. Although the inflow into the channel system was adequate, the water level in the channels is problematic. The minimum water level required in one of the main channels for irrigation is 35 cm. In 2017, the water level in the channels rarely exceeded 35 cm (Figure A2), suggesting that the installation of cofferdams to increase water levels would be beneficial. The implementation of cofferdams, however, may result in additional problems, such as hindering the channel drainage function during peak flow. Frequency analysis has shown that the likelihood of obtaining a high flow during the critical period is low, and mainly occurs after the 21st of September. To ensure that irrigation at the end of the rice cycle is sufficient, different mobile cofferdam types require testing to ensure their efficiency and acceptability in terms of cost and the capacity of farmers to implement the technology.

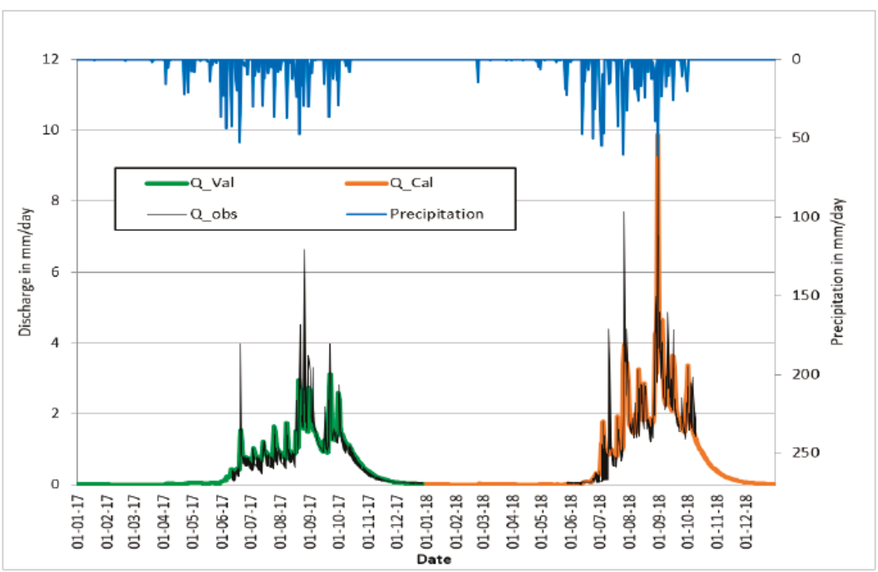

Figure 6. Observed and simulated discharges produced by the HBV model (Q_Val, Q_Cal, and Q_obs corresponding to the validation discharge, the calibration discharge, and the observed discharge, respectively).

3.5. Model Calibration and Validation

The HBV model was calibrated for the year 2018, and the simulated discharge was compared to the observed discharge using the numerical and visual criteria. The observed and simulated discharges are similar (Figure 6). NSE values for calibrated/validated data were 0.75/0.70, with a coefficient of determination of 0.75/0.73 and a logarithm of NSE of 0.74/0.85. The high values imply a strong performance of the HBV model for the two years of observed discharge. Both high discharge and recession discharge (lower discharge) series were accurately simulated, although it is acknowledged that a greater number of discharge observations are required to increase the accuracy in the future.

3.6. Hydrological Condition of the Lofing Upstream River

The calibrated and validated HBV model simulated discharge of the Lofing-Radier River for the period 1971–2018. The water balance components, precipitation, discharge, and actual evapotranspiration are shown in Figure 7. The results of the Mann-Kendall trend test applied to the discharge statistic are shown in Table 2. No statistically significant trend at the 5% level was found in the total annual discharge for the period 1971–2018, indicating that the hydrological regime of the catchment did not vary at the annual scale. Nevertheless, a small annual increasing rate of the discharge of 0.0074 mm per day (2.7 mm yr^{-1}) was evident, implying a constant availability of water at the annual scale. The flowering and grain filling of rice seeded between the 20th and 30th of June occurred between the 11th and 20th of September. This stage of rice growing is critical since water stress experienced in this period may drastically reduce the rice yield. No significant increase in the water stress level is found during this period. Between the 21st and 30th of September, the third quartile displays an increase in the risk of excess water levels. In October, there is an increase in water resource availability, which is mainly beneficial for rice production during this critical stage.

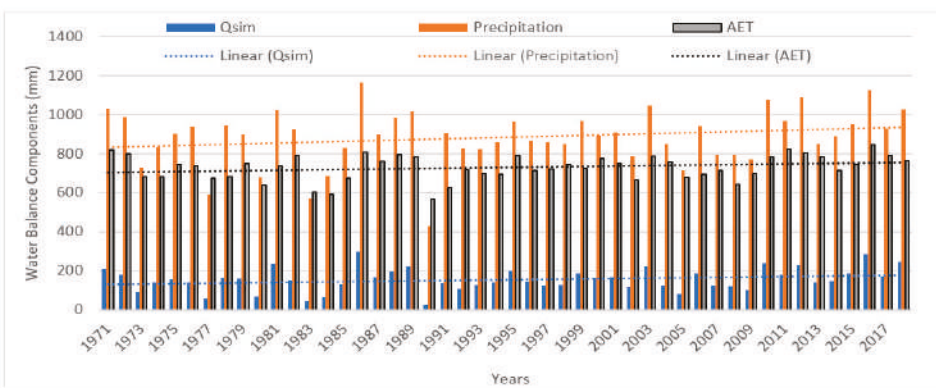

Figure 7. Water balance components: precipitation, simulated discharge (Qsim), and actual evapotranspiration (AET) for the period 1971–2018.

Table 2. Sen slope (SS) and total 10-day water discharges (see Section 3.3) in different conditions for 1971–2018. * indicates a significant trend obtained through the Mann-Kendall test.

	11–20 September		21–30 September		1–10 October		11–20 October	
Test implemented (1971–2018)	SS/MK *	10 day water (mm)	SS/MK *	10 day water (mm)	SS/MK *	10 day water (mm)	SS/MK *	10 day water (mm)
1st Quartile (Dry Condition)	0.006	<12.7	0.009	<11.7	0.009 *	<9.2	0.006 *	<6.4
Median (Normal Condition	0.009	19.5 [12.7, 24.1]	0.010	16.8 [11.7, 20.5]	0.010 *	12.6 [9.2, 5.7]	0.007 *	9.2 [6.4, 10.4]
3rd Quartile (Wet Condition)	0.014	>24.1	0.016 *	>20.5	0.013 *	>15.7	0.008 *	>10.4
Sum	0.120	-	0.125	-	0.127 *	-	0.070 *	-

The water level in the river at the gauging station decreased from the 10th of September to 10th of October (Table 2). Therefore, if there is enough rainfall, sowing the rice during 10–30 June will be optimal to take advantage of the higher surface water flows that can be mobilized to irrigate and meet the crops' water requirements during the critical phases of flowering and formation-filling of the grains. Lower flow rates can be utilized to irrigate the crop during the critical phases if sown between the1st and 20th of July.

4. Conclusions

Rainfall events exceeding 100 mm and flash flooding are becoming more frequent, leading to severe damage to crop production and water infrastructure. Special attention must therefore be given to the design of water control structures to ensure their flexibility and sustainability in discharging floods while avoiding overdrainage during dry spells. In this study, we analyzed the hydroclimatic conditions of the study area Dano, Burkina Faso, and the implication for rice production in the region. There was no significant increase in annual rainfall for the period of 1970–2013; however, an increasing delay in the onset of the rainy season (with a decreasing pre-humid season duration) was observed. This causes difficulties in predicting the onset due to the high temporal variability of rainfall in the studied region. As a result, a warming trend was observed for the past 40 years, raising questions about its negative impact on very intensive rice cultivation packages. During the rainy season (August to October), the average minimum and maximum temperatures increased by 0.031 and 0.016 °C yr^{-1}, respectively, comparable to global observations. The maximum relative humidity decreased due to this increase in temperature, while the sunshine duration also decreased. Farmers have both positive and negative consensual perceptions of climatic hazards. The HBV hydrological model indicated no significant increase in water discharge; however, the total 10-day water level observed between the 11th of September and 20th of October, corresponding to the critical flowering and grain filling phases of rice growth, showed an increasing trend for the period 1971–2018.

The sowing of rice during the 10–30 June has been identified as optimal in order to benefit from the higher surface water flows, which can be used to irrigate and meet the crop water requirements during the critical phase outlined. The installation of cofferdams to increase water levels would be beneficial, subject to them not hindering channel drainage during peak flow, although water flow after the 21st of September was generally insufficient to be deemed an issue. To ensure that irrigation at the end of the rice cycle is sufficient, different mobile cofferdam types require testing to ensure their efficiency and acceptability in terms of cost and the capacity of farmers to implement the technology. The results of this study will be useful to rural communities, as well as decision makers, in framing agricultural risk management in the study region and devising policy for rice intensification in lowland areas. Further data collection is required to improve the HBV model output and to account for climate and land change effects on rice production in Dano, Burkina Faso.

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Appendix A

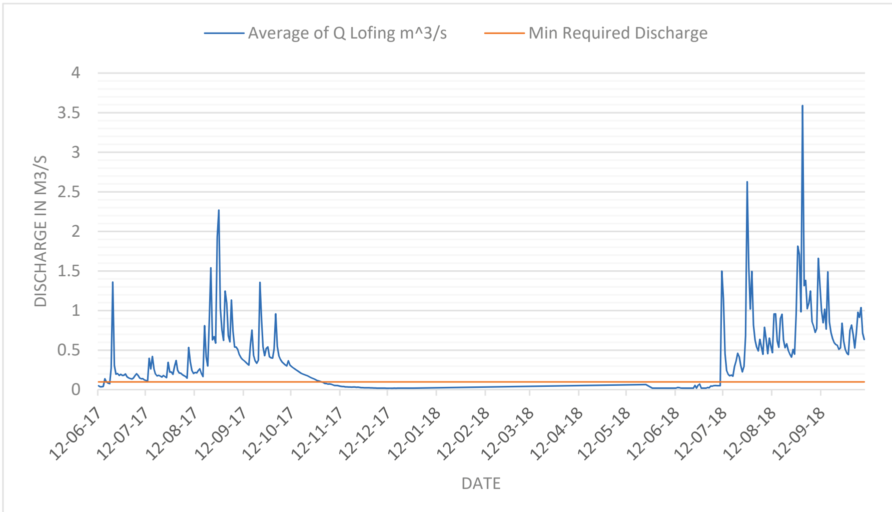

Figure A1. Comparison of the available discharge and irrigation water requirement for the 30 ha Lofing inland-valley.

Appendix B

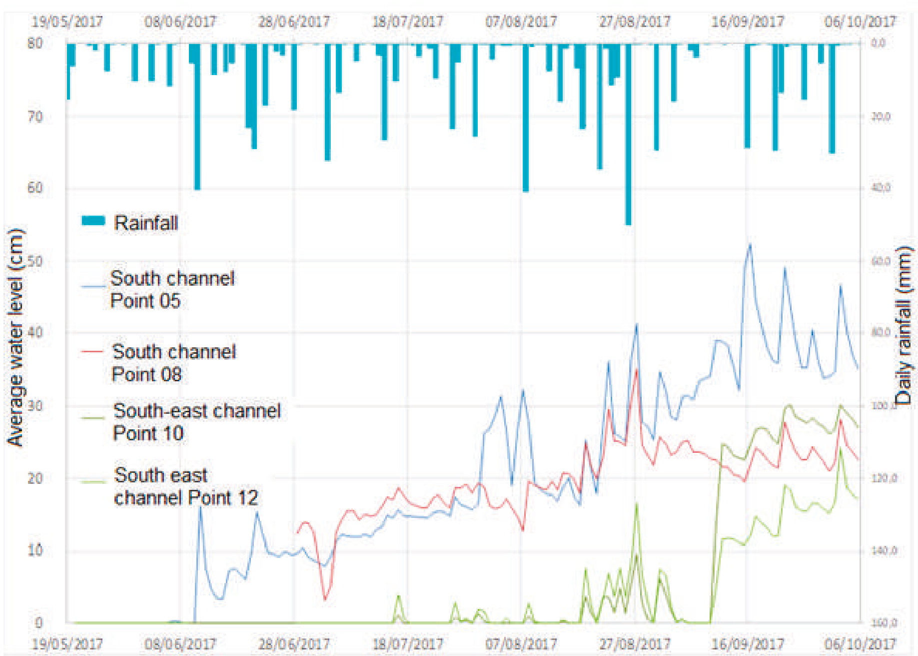

Figure A2. Comparison of the observed and required water height in the irrigation/drainage channels of Lofing inland-valley. Points represent the water level measurement locations.

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