



# Climate resilience of irrigated quinoa in semi-arid West Africa

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**ABSTRACT:** Quinoa (*Chenopodium quinoa* Willd.) is a herbaceous C<sub>3</sub> crop that has demonstrated resilience in regions concurrently affected by climate change and food insecurity, such as sub-Saharan Africa (SSA). The photosynthetic rate and productivity of C<sub>3</sub> crops are enhanced under increasing CO<sub>2</sub> concentrations. We looked at future climate trends in SSA to estimate their impacts on quinoa yields in Burkina Faso. Climate projections show a temperature increase of 1.67–4.90°C under Representative Concentration Pathways (RCP) 4.5 and 8.5, respectively by the end of the century. We demonstrate that any further climate disturbances can either be beneficial or harmful for quinoa, and modulating climate risks will depend on the decisions made at the farm level (e.g. planting date and crop choice). Crop modelling supports the identification of the most suitable transplanting dates based on future climate conditions (RCP 4.5 and 8.5), agroclimatic zones (Sahel, Soudano-Sahelian and Soudanian) and time-horizons (2020, 2025, 2050 and 2075). We show that quinoa yields can improve—when grown under irrigated conditions and transplanted in November—by about 14–20% under RCP 4.5 and by 24–33% under RCP 8.5 by 2075 across the Sahel and Soudanian agroclimatic zones, respectively. For the Soudano-Sahelian zone, the highest yield improvements (19%) are obtained when transplanting is assumed in December under RCP 8.5 by 2075. Overall, the findings of this work encourage policymakers and agricultural extension officers to further promote climate-resilient and highly nutritious crops. Such possibilities are of much interest in SSA, thought to be highly vulnerable to climate change impacts where millions of people are already experiencing food insecurity.

**KEY WORDS:** C<sub>3</sub> crops · AquaCrop · Food security · Climate projections · Crop modelling · Irrigation

## 1. INTRODUCTION

During the upcoming decades, the Sahel and West Africa regions are likely to encounter faster warming than the rest of the globe (Sanderson et al. 2011, Diffenbaugh & Giorgi 2012, James & Washington 2013, Mora et al. 2013). The projected timing of climate departure in Sub Saharan Africa (SSA), when the coldest year in the future is likely to be warmer than the hottest year in the past, is expected between 2030

and 2040 using 1860–2005 as a reference period (Mora et al. 2013). The lack of climate change knowledge within this region is often attributed to the difficulties related to poor signal-to-noise ratios. There is also a sparse observational network and an absence of relevant information to downscale climate models such as land cover changes, shifts in wind patterns and interannual changes in sea surface temperatures (Niang et al. 2014). In Africa, temperatures are projected to increase by 2–4°C under Representative

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Concentration Pathway (RCP) 4.5 using an ensemble of climate projections from the Coordinated Regional Climate Downscaling Experiment (CORDEX) (Laprise et al. 2013, Stanzel et al. 2018). With regards to RCP 8.5, global climate models (GCMs) predict temperature increases in Africa of 1.7°C by 2030, 2.7°C by 2050 and 4.5°C by 2080 (Luhunga et al. 2018).

Since the publication of IPCC's Fourth Assessment Report (AR4-IPCC), many studies have looked at the impacts of environmental changes on crop yields (Challinor et al. 2014), with most analysing crop temperature sensitivity, irrigation and cultivar selection across the globe (Zabel et al. 2014, Zhao et al. 2017, Ray et al. 2019). However, little scientific attention has been given to crop switch, also known as the geographical redistribution of crops (Sloat et al. 2020). Additional crop modelling studies are often focussed on major crops, whereas indigenous African crops are not drawing as much scientific attention (Challinor et al. 2007, Belem et al. 2018). In Burkina Faso, Salack (2006) has applied the Decision Support System for Agrotechnology Transfer (DSSAT), and projected yield losses for millet of 12, 17 and 30% in the Sahel and 15, 23 and 42% in the Soudano-Sahelian zone by 2020 (with temperature changes [ $\Delta T$ ] of 1.0°C), 2050 ( $\Delta T$ : 1.5°C) and 2080 ( $\Delta T$ : 3.0°C), respectively (Salack 2006). The same study estimates a sorghum yield reduction of 6, 10 and 15% in the Sahelian zone and of 5, 8 and 17% in the Soudano-Sahelian zone by 2020, 2050 and 2080, respectively (Salack 2006). Other research in SSA projects yield losses of 22% for maize and 17% for sorghum and millet by 2050, crops known for having a C<sub>4</sub> photosynthetic pathway (Schlenker & Lobell 2010). Some studies have used the Système d'Analyse Régionale des Risques Agroclimatologiques Version H (SARRA-H) model to assess the impacts of future climate scenarios (RCPs 4.5, 6.0 and 8.5) on sorghum and millet yields (Thornton et al. 2011, Sultan et al. 2013). The latter simulations estimate a 10% yield reduction (average of both crops) for at least 50 and 80% of the medium- (2031–2050) to long-term (2071–2090) climate projections relative to the 1961–1990 period. While yield declines are predicted along the Soudanian zone, due to crops' sensitivity to heat-stress conditions, crops along the Sahel region display a high sensitivity to precipitation changes over time (Sultan et al. 2013). Although less is known about projections on interannual rainfall variability along Western Africa, a warmer climate is likely to increase the pressure on water resources due to higher evapotranspiration rates. Additionally, heat-stress conditions are expected to adversely impact the flowering stage of

many crops due to pollen desiccation and low pollen viability (Hatfield et al. 2011, Hatfield & Prueger 2015).

Quinoa (*Chenopodium quinoa* Willd.) originates from the Andean Altiplano and is widely known for its high nutritional value (Repo-Carrasco et al. 2003, Shabala et al. 2012, Adolf et al. 2013, Hirich et al. 2014) as well as for having remarkable physiological responses and resistance to abiotic stresses necessary for coping with changing environmental conditions (Jacobsen et al. 2003, Razzaghi et al. 2011, Ruiz et al. 2014, Bazile et al. 2017, García-Parra et al. 2020). In fact, quinoa's photosynthetic activity is maintained after stomata closure, implying that CO<sub>2</sub> continues to be absorbed under severe drought stress conditions. Further studies have shown quinoa's ability to balance water uptake and water loss and its capacity to enhance water uptake in various ways: (1) by accumulating solutes with lower tissue water potential, (2) by modulating root architecture and (3) through tight stomata control, restricting shoot growth, accelerating leaf senescence and limiting water loss through evaporation (Zurita-Silva et al. 2015).

The main objective of this work is to assess the effect of future climate on quinoa yields and to identify the most suitable transplanting dates to cope with changing environmental conditions. We aim to evaluate the impacts of increasing temperatures and CO<sub>2</sub> concentrations on quinoa (cv. Titicaca), a recently promoted C<sub>3</sub> crop in SSA by the Food and Agriculture Organization (FAO) of the United Nations. We first simulate climate conditions into the future to then answer important questions on CO<sub>2</sub> enrichment in tropical environments (Schlenker & Lobell 2010), which, from our literature review, are topics that have not been extensively researched. Secondly, we support the crop modelling literature and provide a scientific baseline on the impacts of climate change on crop performance (Geerts et al. 2009). The latter is achieved by using a crop–water model (AquaCrop) for different climate scenarios and time-horizons and then assessing its impacts on crop productivity across the different agroclimatic zones of Burkina Faso. Finally, we investigate the effect of different planting dates on crop performance, mostly in terms of seed yields and above-ground biomass during the dry season, when food insecurity levels are highest.

## 2. MATERIALS AND METHODS

We initially processed climate projections from the Coupled Model Intercomparison Project (CMIP5)

until the end of the century using 1973–2017 as a reference period for each agroclimatic zone of Burkina Faso: Sahel (300–600 mm rain yr<sup>-1</sup>), Soudano-Sahe-  
lian (600–900 mm yr<sup>-1</sup>) and Soudanian (>900 mm yr<sup>-1</sup>). We then ran the AquaCrop model for 3 agrocli-  
matic zones, each with 3 dominant soil textures under 2 climate scenarios (RCP 4.5 and 8.5), for 4  
time-horizons (2020, 2025, 2050 and 2075) with 4 transplanting dates (October, November, December  
and January). We based the selection of transplanting upon (1) the avoidance of pests and diseases,  
heavy rainfall and associated strong winds occurring during the rainy season (May–October); (2) the dura-  
tion, intensity and frequency of heat-stress condi-  
tions, lower during the boreal winter; (3) the level of  
food insecurity, often higher at the end of the dry sea-  
son and (4) existing literature using the AquaCrop  
model with quinoa in SSA.

### 2.1. Generation of future climates

We retrieved daily historical temperatures for the 1973–2017 period from the National Oceanic and  
Atmospheric Administration (NOAA 2019). The se-  
lected weather stations, from north to south, were:  
Dori (Sahel; 14° 02' 00" N, 0° 02' 00" W; 277 m above  
sea level [a.s.l.]), Ouagadougou (Soudano-Sahelian;  
12° 21' 12" N, 1° 30' 45" W; 316 m a.s.l.) and Bobo Dio-  
ulasso (Soudanian; 11° 09' 38" N, 4° 19' 36" W; 460 m  
a.s.l.). The extra-terrestrial solar radiation ( $W m^{-2}$ )  
was calculated using a publicly accessible spread-  
sheet available for any latitude and time of the year  
(Dingman 2002). The evapotranspiration rates were  
calculated from extra-terrestrial solar radiation and  
from the maximum and minimum air temperatures  
and adjusted using Hargreaves' radiation formula  
(Hargreaves 1994).

Future climate trends were simulated using differ-  
ent RCPs, each with different range spans of CO<sub>2eq</sub>  
(CO<sub>2equivalent</sub>) atmospheric concentrations. The se-  
lected RCPs, both for climate projections and crop mod-  
elling, were RCP 4.5 (530–580 ppm CO<sub>2eq</sub>) and RCP  
8.5 (>1000 ppm CO<sub>2eq</sub>) (IPCC 2014a). All available  
GCMs within CMIP5 were used to project tempera-  
ture trends across the different agroclimatic zones of  
the country (Table 1). In particular, we examined  
temperature, which is a well-documented and con-  
sistently simulated climatic parameter by different  
GCMs (Diffenbaugh & Giorgi 2012). We performed  
simulations during the dry season assuming that pre-  
cipitation was null from October to March, which is  
often the case in the Sahel region (Nicholson 2009).

Table 1. List of global climate models from the Coupled  
Model Intercomparison Project (CMIP5) used for future  
climate projections for the 2018–2100 period

CMIP5 Model ID	Atmospheric resolution (°lat. & °lon.)	Ocean resolution (°lat. & °lon.)
ACCESS1.0	1.0 × 1.0	1.9 × 1.2
ACCESS1.3	1.0 × 1.0	1.9 × 1.2
BCC-CSM1.1	1.0 × 1.0	2.8 × 2.8
BCC-CSM1.1(m)	1.0 × 1.0	1.1 × 1.1
BNU-ESM	0.9 × 1.0	2.8 × 2.8
CanESM2	1.4 × 0.9	2.8 × 2.8
CESM4	1.1 × 0.6	1.2 × 0.9
CESM1(BGC)	1.1 × 0.6	1.2 × 0.9
CESM1(CAM5)	1.1 × 0.6	1.2 × 0.9
CMCC-CM	2.0 × 1.9	0.7 × 0.7
CMCC-CMS	2.0 × 2.0	1.9 × 1.9
CNRM-CM5	1.0 × 0.8	1.4 × 1.4
CSIRO-Mk3.6.0	1.9 × 0.9	1.9 × 1.9
EC-EARTH	1.0 × 0.8	1.1 × 1.1
FIO-ESM	1.1 × 0.6	2.8 × 2.8
FGOALS-g2	2.8 × 2.8	1.0 × 1.0
GFDL-CM3	1.0 × 1.0	2.5 × 2.0
GFDL-ESM2G	1.0 × 1.0	2.5 × 2.0
GFDL-ESM2M	1.0 × 1.0	2.5 × 2.0
GISS-E2-H <sup>a</sup>	2.5 × 2.0	2.5 × 2.0
GISS-E2-H-CC	1.0 × 1.0	1.0 × 1.0
GISS-E2-R <sup>a</sup>	2.5 × 2.5	2.5 × 2.0
GISS-E2-R-CC	1.0 × 1.0	1.0 × 1.0
HadGEM2-AO	1.0 × 1.0	1.9 × 1.2
HadGEM2-CC	1.0 × 1.0	1.9 × 1.2
HadGEM2-ES	1.0 × 1.0	1.9 × 1.2
INM-CM4	0.8 × 0.4	2.0 × 1.5
IPSL-CM5A-LR	2.0 × 1.9	3.7 × 1.9
IPSL-CM5A-MR	1.6 × 1.4	2.5 × 1.3
IPSL-CM5B-LR	2.0 × 1.9	3.7 × 1.9
MIROC-ESM	1.4 × 0.9	2.8 × 2.8
MIROC-ESM-CHEM	1.4 × 0.9	2.8 × 2.8
MIROC5	1.6 × 1.4	1.4 × 1.4
MPI-ESM-LR	1.5 × 1.5	1.9 × 1.9
MPI-ESM-MR	0.4 × 0.4	1.9 × 1.9
MRI-CGCM3	1.0 × 0.5	1.1 × 1.1
NorESM1-M	1.1 × 0.6	2.5 × 1.9
NorESM1-ME	1.1 × 0.6	2.5 × 1.9
<sup>a</sup> Ensemble of 3 models		

For the climate downscaling (Eq. 1), the delta method  
was used as a bias correction method to determine  
future daily maximum and minimum temperatures,  
using 2006–2017 as a reference period (Hawkins et  
al. 2013). The different time-horizons used in this ex-  
periment were: present (2020; average from 2006–  
2036), near-future (2025; average from 2010–2040),  
mid-future (2050; average from 2035–2065) and far-  
future (2075; average from 2060–2090).

$$T_{BC}(t) = T_{RAW}(t) + [\overline{O_{REF}} - \overline{T_{REF}}] \quad (1)$$

where  $t$  corresponds to temperature,  $T_{BC}$  corresponds  
to the bias-corrected temperatures,  $T_{RAW}$  to the raw

GCM-projected temperatures,  $\overline{O_{REF}}$  to the average observations during the reference period and  $\overline{T_{REF}}$  to the GCM average temperatures for the 2006–2017 reference period. This equation was then used for every GCM and RCP for the whole study period.

## 2.2. Soil mapping: ArcGIS

The soil data was obtained from the International Soil Reference and Information Centre (ISRIC 2019). The soil raster grid,  $0.25 \times 0.25$  km, for each type of soil texture (sand, loam and clay) at 0 cm was downloaded and processed in ArcMap v.10.2.1 (Fig. 1). We used the soil texture triangle and raster calculator in ArcMap to determine the 3 dominant soil textures (USDA 2019) across the different agroclimatic zones: Sahel (sand, sandy-clay-loam and sandy-loam), Soudano-Sahelean (sandy-clay-loam, sandy-loam and loam) and Soudanian zone (sandy-clay-loam, sandy-loam and loam). The most extended soil types across Burkina Faso were sandy-loam (72.5% of the total surface area), followed by sandy-clay-loam (15.8%), loam (9.3%) and sandy and clay-loam (1.2%) among others (Fig. 1). Soil inputs such as soil moisture at permanent wilting point, saturation point and field capacity were retrieved from a study examining the water holding capacity of different soil types across Burkina Faso and complemented with default values from AquaCrop (Leu et al. 2010, FAO 2019).

## 2.3. Crop modelling: AquaCrop

AquaCrop, a crop-water productivity model developed by the FAO, was used to evaluate the impacts of increasing temperatures and  $CO_2$  concentrations on quinoa growth and development (Raes et al. 2009, Steduto et al. 2009, FAO 2019). The model estimated the effect of atmospheric  $CO_2$  concentration on photosynthesis and of temperature on crop development, transpiration and pollination. Therefore, AquaCrop was considered a suitable model for simulating crop responses to abiotic stresses in terms of seed yields and biomass production (Gobin et al. 2017, Garofalo et al. 2019). In addition to climate and soil data, other

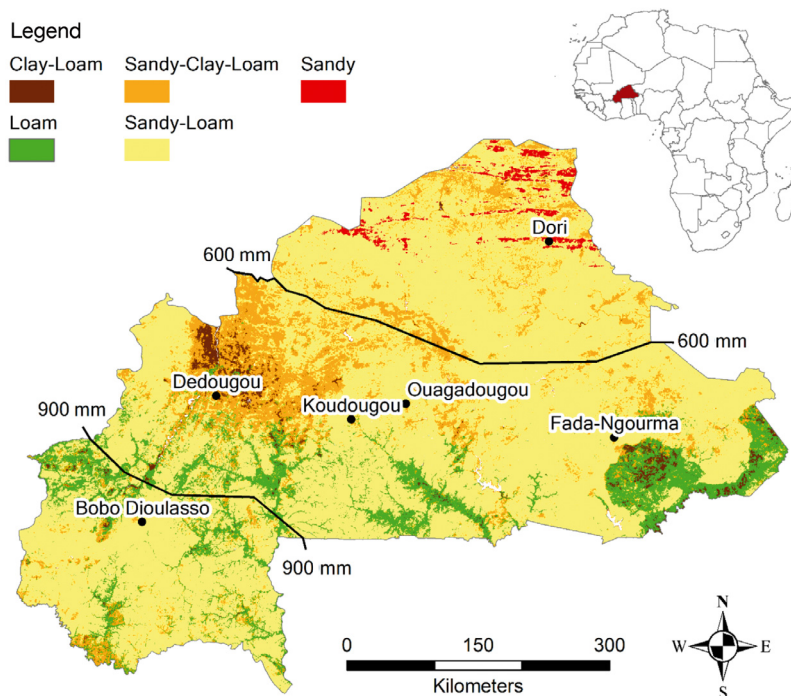


Fig. 1. Spatial variation of the soil texture (at 0 cm) across Burkina Faso including isohyets for each agroclimatic zone

input parameters for operating the AquaCrop model were obtained from a search of the literature and our own past work in the region (Table 2), including: (1) crop information (timing and duration of each phenological phase and canopy cover) from a 2 yr field experiment in Burkina Faso with quinoa under different irrigation schedules (Alvar-Beltrán et al. 2019a, 2021); (2) upper heat-stress thresholds ( $38^{\circ}C$ ) at which quinoa yields start to decline (Alvar-Beltrán et al. 2020a); (3) base temperature of quinoa, established at  $3^{\circ}C$  (Jacobsen & Bach 1998) and (4) seed yield and biomass production values calibrated and validated on AquaCrop (Alvar-Beltrán et al. 2020b, Dao et al. 2020).

The AquaCrop model was run under net irrigation requirements with 25 irrigation events on intervals of 3 d, from transplanting at 18 d after sowing (DAS) to physiological maturity at 73 d after transplanting (DAT). The process of transplantation was scheduled at the 4 leaf stage, allowing us to plant the seedlings at a space of 10 cm between plants and 50 cm between rows, equivalent to  $200\,000$  plants  $ha^{-1}$ . Such density level was shown to be the most suitable for optimising water resources, nutrients and sunlight to plants. In total, 465 mm of water was applied throughout the growing cycle (7 events of 15 mm followed by 17 events of 20 mm). This quantity (465 mm) remained constant for every time-horizon, agroclimatic zone and future climate scenario. The simulations

Table 2. Parameterisation of quinoa on AquaCrop. N/A: not applicable; S: sandy; SCL: sandy-clay-loam; SL: sandy-loam; L: loam; FI: full irrigation; PD: progressive drought; DI: deficit irrigation; EDI: extreme deficit irrigation; DAT: days after transplanting; GDD: growing degree days

Parameters (calibration)	Units	Value	Obtained from
<b>Climate (past/future)</b>			Present study (CMIP5)
Tmax	°C	Daily data (2006–2100)	
Tmin	°C	Daily data (2006–2100)	
Tmean	°C	Daily data (2006–2100)	
Precipitation	mm	Daily data (2006–2100)	
<b>Crop development</b>			
Plant density	plants ha <sup>-1</sup>	200000	Alvar-Beltrán et al. (2019a,b)
Planting method	N/A	Transplanting	
Transplanting	d	18	
Recovered	d	0	
Initial canopy cover	%	1.8	
Canopy size seedling	cm <sup>2</sup> plant <sup>-1</sup>	16	
Canopy expansion	% d <sup>-1</sup>	12.4	
Canopy decline	% d <sup>-1</sup>	10.7	
Max. canopy cover	DAT / GDD	40 / 790	
Senescence	DAT / GDD	48 / 950	
Maturity	DAT / GDD	73 / 1461	
Max. canopy cover	%	36	Jacobsen & Bach (1998)
Canopy decline	d	29	Alvar-Beltrán et al. (2020b)
Time to flowering	DAT / GDD	25 / 495	
Flowering duration	Days / GDD	12 / 234	
Temp. base	°C	3	
Air temperature stress (pollination)	°C	36	
<b>Management</b>			
<i>Irrigation</i>			
Method	N/A	Drip irrigation	Present study
Amount	mm	465	
<i>Soil</i>			
Texture	USDA	S / SCL / SL / L	Leu et al. (2010), FAO (2019)
Permanent wilting point	% v/v	6.0 / 20.0 / 14.8 / 15.0	
Field capacity	% v/v	13.0 / 32.0 / 25.9 / 31.0	
Saturation	% v/v	36.0 / 47.0 / 47.1 / 46.0	
Parameters (validation)	Units	Observed values	Obtained from
<b>Seed yield</b>			Alvar Beltrán et al. (2020b)
FI (T1,3)	kg ha <sup>-1</sup>	967 / 727	
PD (T5,6,8)	kg ha <sup>-1</sup>	871 / 1005 / 597	
DI (T4,7,9)	kg ha <sup>-1</sup>	612 / 943 / 748	
EDI (T2,10)	kg ha <sup>-1</sup>	348 / 303	
<b>Biomass production</b>			Alvar Beltrán et al. (2020b)
FI (T1,3)	kg ha <sup>-1</sup>	2655 / 2765	
PD (T5,6,8)	kg ha <sup>-1</sup>	2545 / 2420 / 1285	
DI (T4,7,9)	kg ha <sup>-1</sup>	1300 / 2540 / 2174	
EDI (T2,10)	kg ha <sup>-1</sup>	1338 / 1071	

with AquaCrop were conducted to (1) investigate the impact of 4 transplanting dates on crop performance (using the first day of each month, between October and January, as a transplanting date) and (2) quantify the changes in seed yields and biomass for different time-horizons (2020, 2025, 2050 and 2075) under future climate scenarios (RCP 4.5 and 8.5).

### 3. RESULTS

#### 3.1. Past and future climate trends

During the reference period (1973–2017), the average maximum temperatures between October and March increased twice as fast in the southern-

most and central parts of the country ( $0.30^{\circ}\text{C decade}^{-1}$ , equivalent to  $1.35^{\circ}\text{C}$  in total) compared to the northernmost parts ( $0.14^{\circ}\text{C decade}^{-1}$ ) (Fig. 2). Average maximum temperatures were projected to

increase by  $0.59^{\circ}\text{C decade}^{-1}$  under RCP 8.5, equivalent to a  $4.90^{\circ}\text{C}$  increase by 2100. Under RCP 4.5, the increase of average maximum temperature was considerably lower ( $0.20^{\circ}\text{C decade}^{-1}$ , equivalent to

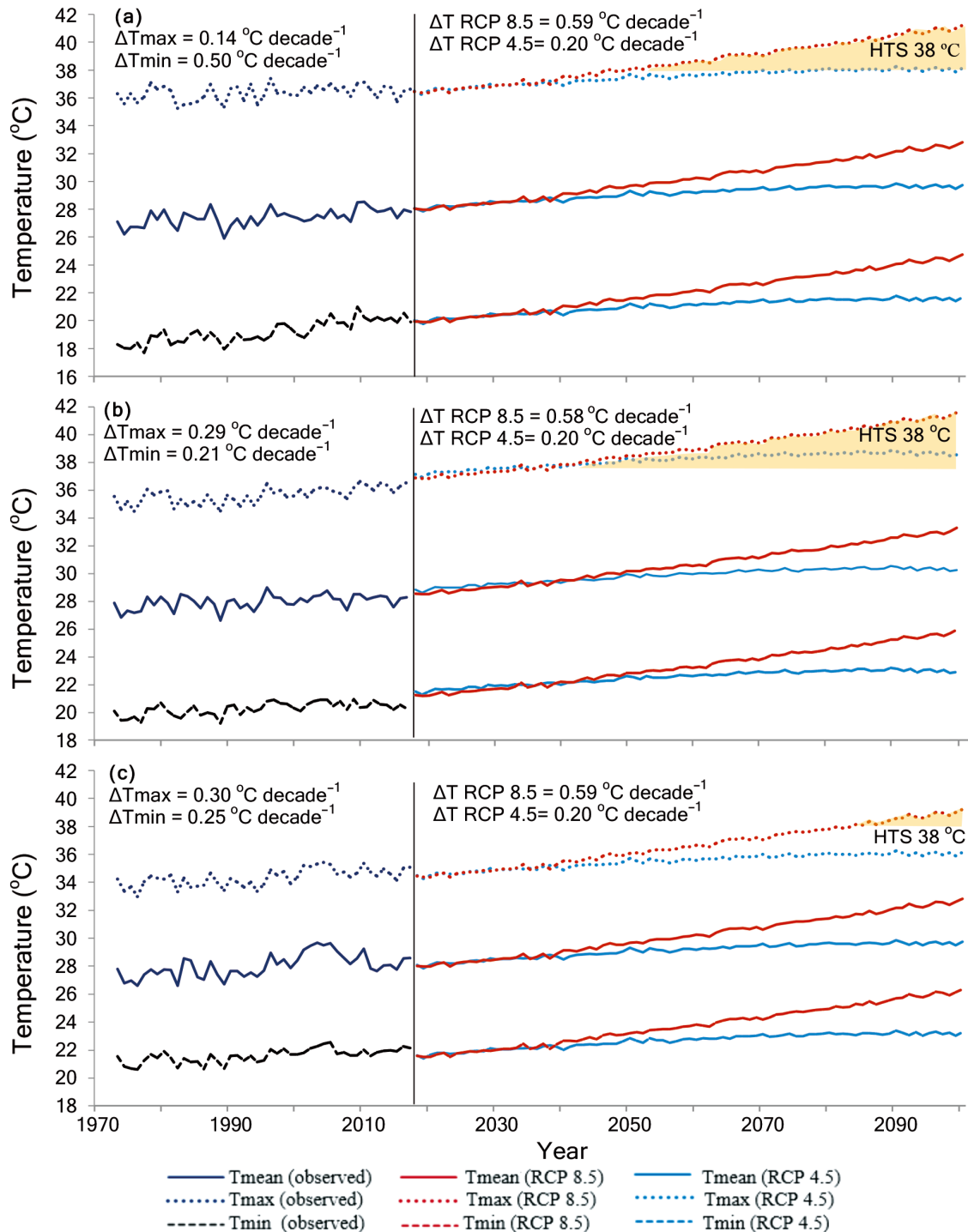


Fig. 2. Observed historical climate anomalies (average from October–March) for the 1973–2017 period across different agro-climatic zones: (a) Dori (Sahel), (b) Ouagadougou (Soudano-Sahelian) and (c) Bobo Dioulasso (Soudanian). Climate projections for the 2018–2100 period from CMIP5 GCMs for both RCPs (4.5 and 8.5). High temperature stress (HTS) threshold for quinoa is  $36^{\circ}\text{C}$ , and  $38^{\circ}\text{C}$  is the threshold at which yields start to decline (shaded in orange)

1.67°C under RCP 4.5 by 2100) compared to RCP 8.5. For the average minimum temperatures (1973–2017), the rate of increase was higher in the Sahel (0.50°C decade<sup>-1</sup>) and lower across the Soudanian and Soudano-Sahelian zones (0.21 and 0.25°C decade<sup>-1</sup>, respectively).

The effect of increasing temperatures on crop development, crop transpiration and pollination (described as the average temperature stress throughout the growing cycle) was determined using the air temperature coefficients (KsTr) and thresholds available on AquaCrop and adjusted as defined in Section 2.3. While 36°C (or lower temperatures) corresponded to the absence of heat-stress conditions (KsTr value of 1 in AquaCrop), 38°C was the threshold at which quinoa experienced some kind of heat stress and 41°C the threshold when plants were fully stressed and incurred crop failure (KsTr value of 0 in AquaCrop). During the 1973–2017 period, the high temperature stress (HTS) threshold of 38°C was attained on average during 3 months in the Sahel (October, November and March), 2 months in the Soudano-Sahelian (February and March) and 1 month in the Soudanian zone (March). The duration of HTS was projected to extend across space and time, particularly in the Soudano-Sahelian zone (from October to March) under RCP 8.5. In contrast, HTS in the Soudanian zone was expected to be limited to 2 months (October and March) under RCP 8.5.

### 3.2. Climate impacts on quinoa productivity

#### 3.2.1. Quinoa seed yield under RCP 4.5 and 8.5

We used the AquaCrop model to simulate the spatiotemporal variability of quinoa seed yields across Burkina Faso for different time-horizons under RCP 4.5 (Fig. 3, Table 3). For the transplanting in November and December, crop simulations projected a yield enhancement between 14 and 19% depending on the agroclimatic region and time-horizon, exceeding 1000 kg ha<sup>-1</sup> from 2050 onwards under RCP 4.5. Transplanting in January appeared suitable for all agroclimatic zones, with similar increasing yield trends to those simulated for November and December. However, when transplanting in October, a yield reduction was projected by 2050 in the Sahel, with an abrupt yield reduction of 61% by 2050 compared to 2020 (from 461–181 kg ha<sup>-1</sup>) under RCP 4.5. Under RCP 4.5, the Soudanian and Soudano-Sahelian agroclimatic zones showed the highest suitability for growing quinoa.

Quinoa yields were also simulated for the different agroclimatic zones and time-horizons under RCP 8.5 (Fig. 4, Table 3). Up until 2050, the seed yields were projected to increase by 10–18% across all agroclimatic zones when transplanting was performed between November and January. If transplanting was performed in December, yields were projected to exceed 1200 kg ha<sup>-1</sup> by 2075 in the Sahel and Soudanian zones, equivalent to a 30% yield increase when compared to 2020 under RCP 8.5. In contrast, October transplantations in the central and southernmost parts of the country were projected to be suitable until 2050, with seed yields exceeding 1000 kg ha<sup>-1</sup>. Thereafter, a marked yield decline was simulated, resulting in <300 kg ha<sup>-1</sup> by 2075. A similar pattern was projected for the Sahel region, where yields declined to 0 kg ha<sup>-1</sup> from 2050 onwards. Overall, simulated AquaCrop yields showed quinoa's suitability across all regions when transplanted between November and January under RCP 8.5. The different soil textures had a small impact on seed yields, with differences lower than 10% (owing to irrigation) under different types of soil texture. Despite the small differences, higher seed yields were projected under sandy-loam and loam soils compared to sandy-clay-loam soils.

The projected increases in temperature and HTS thresholds above 38°C were the principal factors determining seed yield losses for the 2 RCPs, different agroclimatic regions and time-horizons. The HTS conditions during flowering increased water vapour pressure deficits resulting in pollen desiccation. As a result, self-pollination and the subsequent production of seeds was constrained. Additionally, we observed a negative correlation between yields and average maximum temperatures above 38°C occurring 1 mo after transplanting, both matching the time for quinoa at flowering 25 DAT ( $r = -0.77$  and  $-0.85$  for RCP 4.5 and 8.5 in the Sahel;  $r = -0.90$  and  $-0.81$  for RCP 4.5 and 8.5 in the Soudano-Sahelian;  $r = -0.91$  and  $-0.71$  for RCP 4.5 and 8.5 in the Soudanian zone).

#### 3.2.2. Quinoa biomass production under RCP 4.5 and 8.5

Dry above-ground biomass simulations showed an increasing trend for both RCPs, with biomass production exceeding 3000 kg ha<sup>-1</sup> from 2050 onwards across the 3 agroclimatic zones (Table 4). The rate of biomass increase was projected to be higher under RCP 8.5 compared to RCP 4.5, with an average in-

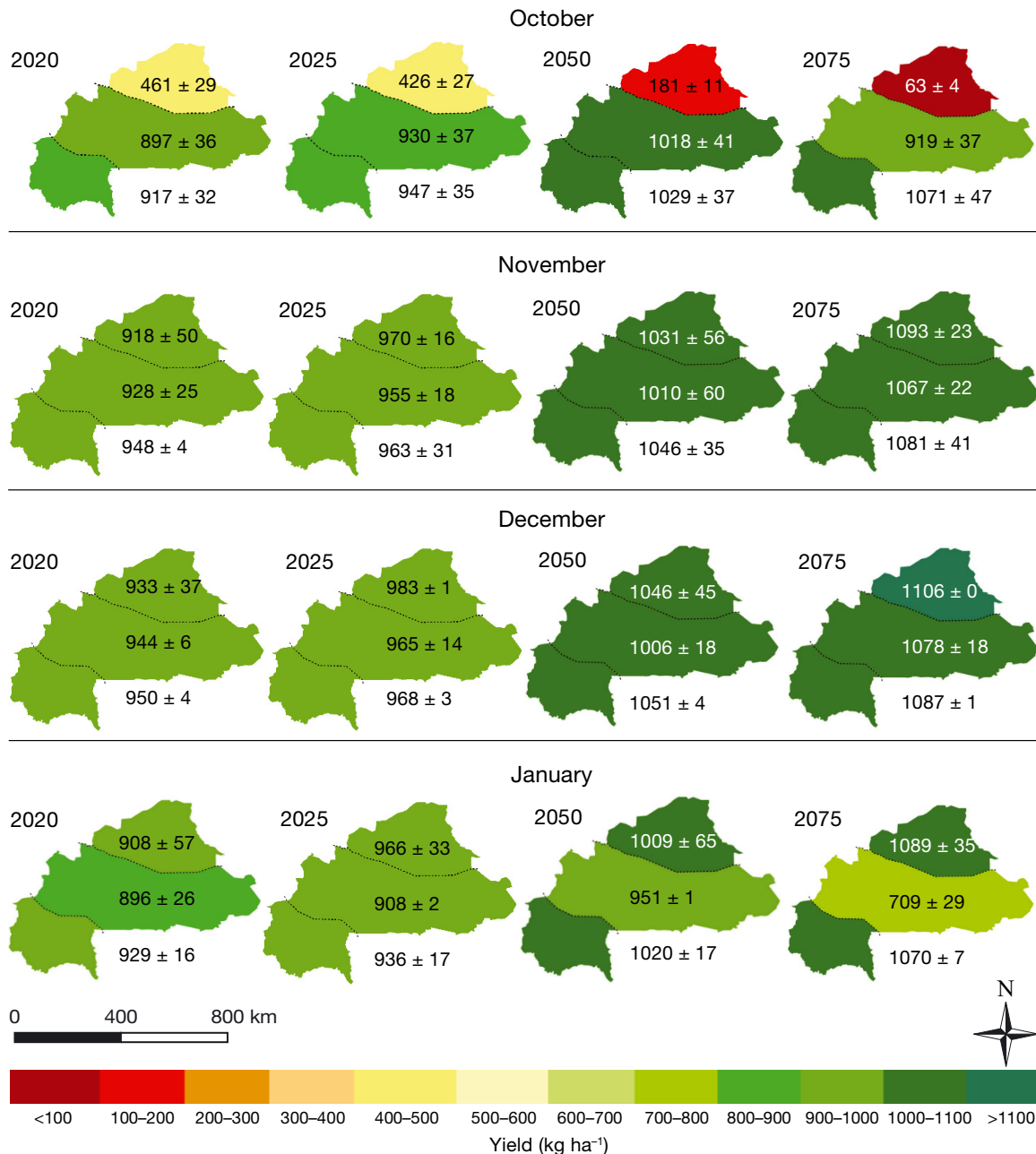


Fig. 3. Spatiotemporal distribution of quinoa seed yields ( $\text{kg ha}^{-1}$ ) across different agroclimatic zones (Sahel, Soudano-Sahelian and Soudanian), time-horizons (2020, 2025, 2050 and 2075) and transplanting dates (October, November, December and January) under RCP 4.5. All values within the maps correspond to the average simulated seed yield ( $\text{kg ha}^{-1}$ ), including its standard deviation (SD)

crease in biomass production of 32 and 16% by 2075, respectively, compared to 2020. Additionally, the rate of biomass increase with irrigation was estimated to be higher between 2025 and 2050 under RCP 4.5, and between 2050 and 2075 under RCP 8.5. No significant differences were depicted between biomass production when irrigated under different types of soil texture. Nonetheless, higher biomass values were esti-

mated for quinoa cultivated in sandy-loam and loam soils compared to sandy-clay-loam soils, owing to their more favourable water retention capacities. Increasing  $\text{CO}_2$  levels and temperatures were likely benefiting the production of biomass during the vegetative stage. Overall, the weight of the harvested product (seed yield), as a percentage of the total plant weight (total biomass), also referred to as the harvest



Table 3. Average seed yield changes (%) and standard deviation (SD) compared to 2020 under RCP 4.5 and RCP 8.5 for different agroclimatic zones (Sahel, Soudano-Sahelian and Soudanian), time-horizons (2025, 2050 and 2075) and transplanting dates (October, November, December and January)

	— 2025 —		RCP 4.5				— 2025 —		RCP 8.5			
	(%)	SD	(%)	SD	(%)	SD	(%)	SD	(%)	SD	(%)	SD
<b>Sahel</b>												
October	-7.6	0.2	-60.7	0.1	-86.4	0.1	-23.3	0.1	-97.3	0.1	-100.0	0.0
November	5.9	4.3	12.3	0.1	19.2	4.2	4.3	0.2	16.4	0.0	31.2	0.3
December	5.4	3.6	12.0	0.4	18.6	4.0	4.3	0.1	16.5	0.1	32.2	0.1
January	6.5	3.9	11.1	0.6	20.0	4.8	4.5	0.2	16.0	0.1	32.5	0.3
<b>Soudano-Sahelian</b>												
October	3.7	0.1	13.4	0.1	2.4	0.0	4.6	0.1	18.1	0.3	-68.8	0.1
November	2.9	1.5	8.7	3.8	15.0	1.5	4.1	0.1	17.0	0.8	-53.3	1.8
December	2.2	1.7	6.6	5.8	14.2	2.0	3.5	0.4	15.4	1.6	18.9	6.2
January	1.4	2.6	6.0	4.1	-20.9	3.9	0.9	5.5	10.0	8.2	-72.8	2.4
<b>Soudanian</b>												
October	3.3	0.2	12.3	0.2	16.8	1.7	4.8	0.1	16.8	0.6	-100.0	0.0
November	1.6	2.9	10.3	3.3	14.0	3.9	4.1	0.7	17.0	0.3	27.4	4.5
December	1.9	2.5	10.6	2.8	14.5	3.5	4.8	0.2	17.1	0.1	31.0	1.9
January	0.8	4.6	9.8	4.8	15.2	6.2	5.1	0.4	17.3	0.8	24.4	6.0

index, was projected to decrease in a warming climate, due to a faster rate of biomass production increase with respects to seed yield increase.

## 4. DISCUSSION

### 4.1. Past and future climate trends

Future temperature projections across Burkina Faso showed an average temperature increase of 0.66 and 1.95°C by 2050 and of 1.67 and 4.90°C by 2100 under RCP 4.5 and 8.5, respectively, compared to the 1973–2017 baseline period. These findings are in agreement with the literature, with a global mean surface temperature increase of 1.1–2.6°C projected by the end of the century under RCP 4.5 (IPCC 2014b). However, temperature projections are higher (4.90°C) than those reported globally (4.80°C) by the end of the century under RCP 8.5 (IPCC 2014b). The latter result suggests that temperature projections reported or simulated in this study, using the ensemble of 43 GCMs from CMIP5, are in harmony with other works conducted along the Soudano-Sahelian and Sahel agroclimatic zones of Burkina Faso (Salack 2006, Niang et al. 2014). The latter studies have projected a temperature increase of 1.5°C by 2050 under RCP 4.5. Moreover, a 2–4°C temperature increase is projected under RCP 8.5 by 2050 and 2100, respectively, across Western Africa (Luhunga et al. 2018, Stanzel et al. 2018). This study's climate projections showed

similar rates of temperature increase across the different agroclimatic zones and over time (0.20 and 0.59°C decade<sup>-1</sup> under RCP 4.5 and 8.5, respectively). However, these values differed from other studies, reporting faster warming towards the Sahel compared to the Guinean agroclimatic zone, located to the south of the Soudanian zone (Roudier et al. 2011). Our historical trends (1973–2017) displayed faster warming in the Soudanian zone (0.36°C decade<sup>-1</sup>) compared to the Soudano-Sahelian and Sahelian zones (0.17 and 0.24°C decade<sup>-1</sup>, respectively).

### 4.2. Crop switching under climate change

Many cereal crops are likely to be negatively affected by increasing duration, intensity and frequency of heat-stress conditions during sensitive phenological phases, particularly rainfed crops (maize, sorghum, rice and millet), which in many African countries provide the necessary calorie intake for human growth (Challinor et al. 2007, FAO 2008). Under IPCC's A1FI scenario (900 ppm of CO<sub>2</sub> by 2100), cereal yields are likely to decrease by 20% on average by 2080. For maize, this decrease is expected to be as much as 23% for a 5°C temperature increase in Western Africa by 2090 (Parry et al. 2004, Thornton et al. 2011). For Burkina Faso, yield declines are estimated at 17% for maize, 17–23% for millet and 8–10% for sorghum by 2050 (Jones & Thornton 2003, Salack 2006). For quinoa, we esti-

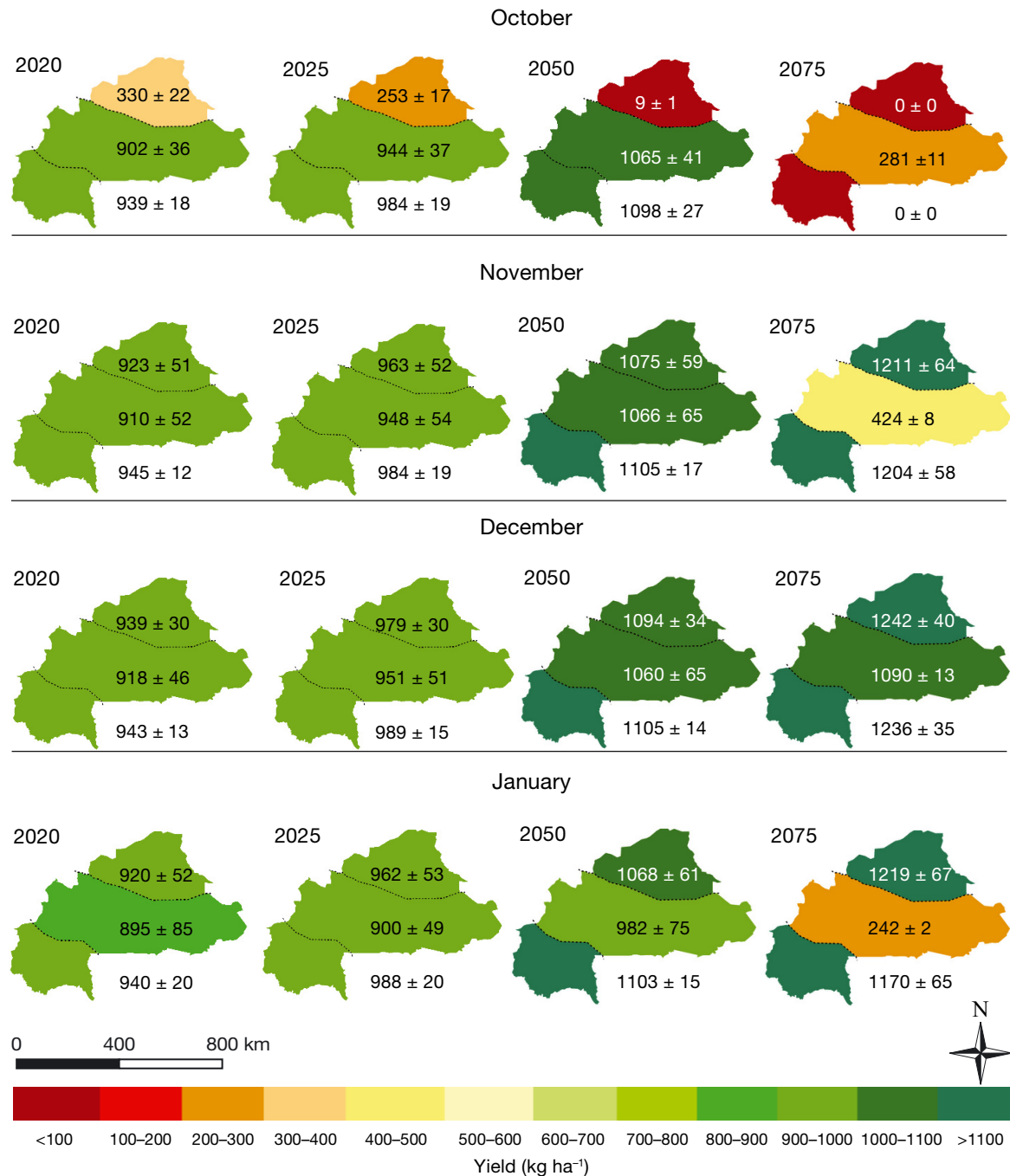


Fig. 4. Spatiotemporal distribution of quinoa seed yields ( $\text{kg ha}^{-1}$ ) across different agroclimatic zones (Sahel, Soudano-Sahelian and Soudanian), time-horizons (2020, 2025, 2050 and 2075) and transplanting dates (October, November, December and January) under RCP 8.5. All values within maps correspond to the average simulated seed yield ( $\text{kg ha}^{-1}$ ), including its standard deviation (SD)

mate (when averaging all the transplanting dates) a yield change of  $-7$  to  $-1\%$  for the Sahel,  $+3$  to  $-44\%$  for the Soudano-Sahelian zone and  $+15$  to  $-4\%$  for the Soudanian zone under RCP 4.5 and 8.5, respectively by 2075 compared to 2020. However, the selection of the most suitable transplanting dates between

November and January, both in the Sahelian and Soudanian zones, was shown to be critical for obtaining even higher yields, with yield enhancements of up to  $30\%$  by 2075 under RCP 8.5. Regarding biomass, our findings were aligned with field observations made in the Soudanian zone of Burkina Faso

Table 4. Average biomass production changes (%) and standard deviation (SD) compared to 2020 under RCP 4.5 and 8.5 for different agroclimatic zones (Sahel, Soudano-Sahelian and Soudanian) and time-horizons (2025, 2050 and 2075)

	RCP 4.5						RCP 8.5					
	2025		2050		2075		2025		2050		2075	
	(%)	SD	(%)	SD	(%)	SD	(%)	SD	(%)	SD	(%)	SD
<b>Sahel</b>												
October	3.6	0.2	12.7	0.2	16.8	0.4	4.4	0.2	16.7	0.1	33.5	0.8
November	5.8	4.3	12.3	0.0	19.1	4.2	4.3	0.2	16.4	0.0	32.6	0.3
December	5.3	3.5	12.1	0.3	18.5	3.9	4.2	0.0	16.5	0.1	32.2	0.1
January	6.4	3.8	11.2	0.5	19.8	4.7	4.5	0.2	16.0	0.1	32.4	0.2
<b>Soudano-Sahelian</b>												
October	3.7	0.1	13.3	0.1	16.8	0.0	4.6	0.1	18.0	0.2	34.6	0.4
November	2.8	1.4	8.7	3.7	15.0	1.4	4.2	0.0	17.0	0.8	36.2	5.3
December	2.3	1.6	6.8	5.7	14.3	2.0	3.6	0.4	15.4	1.6	35.3	7.0
January	1.5	2.4	6.4	4.0	15.5	5.3	4.0	0.0	17.7	3.6	36.0	6.3
<b>Soudanian</b>												
October	3.3	0.3	12.2	0.2	16.7	1.5	4.7	0.0	16.8	0.6	26.1	3.5
November	1.6	2.9	10.3	3.3	14.0	3.9	4.6	0.3	16.9	0.3	28.9	4.5
December	1.9	2.5	10.7	2.8	14.5	3.5	4.8	0.1	17.1	0.1	31.1	1.9
January	0.8	4.4	9.8	4.7	15.1	6.0	5.1	0.3	17.3	0.7	28.2	3.0

(Alvar-Beltrán et al. 2019a,b). The previous experiments, under full and deficit irrigation, resulted in seed yields of 900–1100 kg ha<sup>-1</sup> when sowing occurred in late October or early November. In the present research, under net irrigation requirements totalling 465 mm, 900 kg ha<sup>-1</sup> yields were simulated when transplanting was carried out in November. Similar results were observed when comparing biomass values from field experiments in Burkina Faso (2230 kg ha<sup>-1</sup>) to those simulated (2626 kg ha<sup>-1</sup>) on AquaCrop (Alvar-Beltrán et al. 2019b). Overall, the AquaCrop model showed a high performance when simulating quinoa seed yields and biomass, displaying a concordance between predicted values and field observations and implying that the results presented here are reliable. To conclude, the net irrigation requirements for quinoa in AquaCrop during the dry season (465 mm) were notably lower than those simulated using the CROPWAT model for the main rainfed crops grown in Burkina Faso: sorghum (406–558 mm), maize (494–622 mm), groundnut (515–548 mm), millet (593 mm) and cotton (747–822 mm) (Some et al. 2006).

### 4.3. Quinoa's resilience to abiotic stresses

In the long term, the resilience to abiotic stresses and the capacity of quinoa to take advantage of increasing temperatures (1.67–4.90°C under RCP 4.5 and 8.5), heat-stress conditions (38°C), CO<sub>2</sub> concentrations (≈550 and >1000 ppm CO<sub>2eq</sub> under RCP 4.5

and 8.5) with lower water requirements (465 mm) compared to main crops is remarkable. Overall, quinoa differs from many other C<sub>3</sub> crops grown in temperate environments. Quinoa appears to behave similar to C<sub>4</sub> crops grown in tropical environments, as it is capable of withstanding high light intensities, heat and drought stress conditions. Increasing CO<sub>2</sub> concentrations can enhance the rate at which carbon is incorporated into carbohydrates in the so-called light reaction. Therefore, the crop is able to continue incorporating carbon until there is another limiting factor (Poorter 1993). In addition, increasing temperatures accelerate the reactions catalysed by enzymes, thus increasing the photosynthetic rate (Long 1991). Nonetheless, enzymes are expected to denature if optimum temperatures for the ideal photosynthetic rate are exceeded. Therefore, the photosynthetic rate is likely to decrease until it stops, leading to crop failure (Bowes 1991). Some studies affirm that doubling CO<sub>2</sub> concentrations can increase the yield of many crops by one-third, particularly those having a C<sub>3</sub> photosynthetic pathway (Kimball 1983, Bowes 1991, Poorter 1993). Additionally, with current CO<sub>2</sub> concentrations, rubisco enzymes are not yet denatured and, consequently, have not yet reached the optimal atmospheric concentration at which maximum photosynthetic activity is attained. Therefore, under changing climatic conditions, some crops, including quinoa, have the potential of enhancing their photosynthetic activity and thus attaining higher seed yields and biomass production than currently observed (Kimball 1983, Ceccarelli et al. 2010).

In this study, we show that HTS thresholds (average  $T_{max} > 38^{\circ}\text{C}$ ) at flowering can result in crop failure. This is projected in the Sahel region, when transplantation of quinoa occurs in October under both RCPs across different time-horizons. A similar situation occurs in the Soudano-Sahelian when transplanting in October, November and January under RCP 8.5 by 2075. The heat-stress effect at flowering is widely understood, with increasing water vapour pressure deficits under increasing heat-stress conditions (Sato et al. 2000, Young et al. 2004, Prasad & Djanaguiraman 2011, Hatfield & Prueger 2015). There is a strong negative relationship between pollen production and pollen viability at higher temperatures. In the present study, the heat-stress coefficient for pollination of quinoa is between  $36$  and  $41^{\circ}\text{C}$ . Although these values are similar to those reported under controlled climatic conditions and field experiments in Burkina Faso and Mali (Alvar-Beltrán et al. 2019b, 2020b, Coulibaly et al. 2015), they differ from those given by default ( $38.5$ – $42.5^{\circ}\text{C}$ ) in AquaCrop (Geerts et al. 2009). Therefore, if critical temperature thresholds for quinoa ( $36$ – $41^{\circ}\text{C}$ ) continue to be exceeded, yields will decline due to the compounded impact of temperature on crop development, crop transpiration, pollen desiccation and pollen viability. Under warmer air conditions, gametophytes are expected to dry out, and its delivery to the embryo sac is expected to be constrained (Hatfield & Prueger 2015). As shown in this study, HTS thresholds ( $36$ – $41^{\circ}\text{C}$ ) are already being exceeded, particularly in October, November and March in the Sahel and in February and March in the Soudano-Sahelian zone. Hence, HTS conditions are likely to become more recurrent both over time and space for both RCPs during the 21<sup>st</sup> century. Interestingly, the observed temperature tolerance of quinoa ( $36$ – $41^{\circ}\text{C}$ ) at which pollen viability is reduced is higher than other West African crops, e.g. rice ( $36$ – $40^{\circ}\text{C}$ ), soybeans ( $38^{\circ}\text{C}$ ), groundnuts ( $37^{\circ}\text{C}$ ), maize and sorghum ( $34^{\circ}\text{C}$ ) and cotton and tomato ( $32^{\circ}\text{C}$ ) (Yoshida 1981, Jones et al. 1984, Peet et al. 1998, Prasad et al. 1999, Kakani et al. 2005, Salem et al. 2007). Therefore, the agroclimatic suitability and resilience of quinoa to forthcoming environmental changes is higher than that of main rainfed and irrigated crops grown in SSA.

Although slightly higher seed yields are reported on sandy-loam soils compared to sandy-clay-loam soils, these results are not significantly different. These observations are aligned with other studies showing a higher performance in terms of seed yield and biomass under sandy-loam and sandy-clay-loam soils (Razzaghi et al. 2012). The latter is

explained by a higher soil moisture retention capacity, and subsequent higher nitrogen uptake by sandy-loam soils compared to sandy soils. As a result, the interception of photosynthetically active radiation under sandy-loam and sandy-clay-loam soils is likely enhanced, as is the overall performance of the crop.

## 5. CONCLUSIONS

This study addressed the climate resilience of irrigated quinoa across the 3 agroclimatic zones of Burkina Faso, which extend over large parts of West Africa. We explored temperature as a critical variable for crop growth and development. The projected temperature increase, in an already warm environment, will continue to adversely impact West African crops. However, the extent of yield losses will depend on how rapidly farmers adapt to changing climatic conditions through measures including crop and/or cultivar selection, optimal growing calendars and measures to optimize water resources. Based on crop models and future climate simulations, we suggest focussing on the first months of the dry season and transplanting quinoa in November across the Soudanian and Sahelian zones and in December along the Soudano-Sahelian zone, particularly under the worst-case scenario (RCP 8.5). Depending on the rate of temperature increase, crop switching to  $C_3$  crops, which have a higher tolerance to abiotic stresses, is seen as the most effective agricultural adaptation measure. Unlike other West African cereal crops (e.g. maize and rice) vulnerable to abiotic stresses, quinoa (a  $C_3$  crop) responds positively to  $\text{CO}_2$  enrichment and adjusts better to heat-stress conditions at flowering.

Crop modelling supports the selection of the most suitable sowing dates, as it considers the crop's exposure to high temperatures, which are expected to increase in duration, frequency and intensity in a changing climate. Crop resilience to abiotic stresses and crop switching are outlined as major priorities for further research in support of decision-making in the agricultural sector. Strong evidence from the recent introduction of climate-resilient and highly nutritional crops has pointed to solutions for agricultural adaptation to climate change in West Africa. Overall, quinoa offers a window of opportunity for agricultural adaptation in SSA, and therefore we recommend further promotion of this crop, particularly during the dry season when food insecurity levels are highest.

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