



**HAL**  
open science

## **Potential for expanding sorghum production in Europe in the face of climate change**

Mohsen Davoudkhani, Nicolas Guilpart, David Makowski, Nicolas Viovy, Philippe Ciais, Ronny Lauerwald

### ► **To cite this version:**

Mohsen Davoudkhani, Nicolas Guilpart, David Makowski, Nicolas Viovy, Philippe Ciais, et al.. Potential for expanding sorghum production in Europe in the face of climate change. 2025. <hal-05059188>

**HAL Id: hal-05059188**

**<https://hal.science/hal-05059188v1>**

Preprint submitted on 24 Jun 2025

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License

# Potential for expanding sorghum production in Europe in the face of climate change

Mohsen Davoudkhani

[mohsen.davoudkhani@inrae.fr](mailto:mohsen.davoudkhani@inrae.fr)

Université Paris-Saclay, INRAE, AgroParisTech, UMR ECOSYS <https://orcid.org/0000-0001-5924-506X>

Nicolas Guilpart

AgroParisTech <https://orcid.org/0000-0003-3804-0211>

David Makowski

INRAE - University of Paris-Saclay <https://orcid.org/0000-0001-6385-3703>

Nicolas Viovy

CEA CNRS UVSQ

Philippe Ciais

Laboratoire des Sciences du Climat et de l'Environnement <https://orcid.org/0000-0001-8560-4943>

Ronny Lauerwald

Université Paris-Saclay <https://orcid.org/0000-0001-5554-0897>

---

## Article

**Keywords:** Sorghum yield, Climate change, Random Forest, Animal feed

**Posted Date:** January 28th, 2025

**DOI:** <https://doi.org/10.21203/rs.3.rs-5723731/v1>

**License:**  This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

**Additional Declarations:** There is **NO** Competing Interest.

---

# Abstract

Today, sorghum is a minor crop in Europe cultivated on only ~0.1% of the cropland area. Nonetheless, sorghum is of growing interest due to its high heat tolerance compared to other crops and better adaptation to future hot and dry summers. In this study, we investigated the feasibility of expanding sorghum cultivation in Europe under current and future climatic conditions. We also explored the possibility of replacing maize with locally-produced sorghum for feeding livestock. To this end, we developed a machine-learning model that predicts sorghum yields from high-resolution climate data. The model was trained on historical sorghum yield data collected at the county level in France, Italy, Spain, and the USA. Then, we used the model to predict sorghum yields for current and future climate conditions, following different climate change scenarios. In almost all scenarios, sorghum yields decreased by up to  $-1.5 \text{ t ha}^{-1}$  in the southern part of Europe but increased substantially by up to  $+3 \text{ t ha}^{-1}$  in the northern part of Europe by end-of-century. We found that at least 90% of maize currently used to feed livestock could be replaced by sorghum in Europe if grown in one out of three years. These results provide valuable information for improving feed security in Europe in the face of climate change.

## Introduction

Climate change is associated with shifts in precipitation patterns and temperature regimes, posing challenges to current and future crop production (Olesen et al., 2011). Moreover, projections predict an increasing frequency and intensity of extreme meteorological conditions, including heavy rainfall, droughts, and rising temperatures (IPCC, 2023). These meteorological risks concern in particular the summer months, which are of major importance for crop growth.

Consequently, there is a growing urgency for the agricultural sector to adapt to these changing conditions (Vautard et al., 2023). An essential strategy for adaptation involves the careful selection of crops that can withstand these challenging circumstances (Labeyrie et al., 2021; Sloat et al., 2021). This approach not only helps maintain agricultural productivity but also contributes to food security and economic stability in the face of climate change since the world population is expected to reach 10.4 billion by 2100, an increase of 30 percent from today (United Nations, 2022). Coupled with an improving standard of living in developing countries, the expected population growth and shift in diet will increase demand for food and animal feed (Gouel and Guimbard, 2019; Van Dijk et al., 2021) and raise concerns about food and feed security.

In this regard, sorghum has gained attention as an attractive crop for climate change adaptation due to its high heat tolerance and resilience to water stress compared to other crops (Farré and Faci, 2006; Hossain et al., 2022; Schaffasz et al., 2019; Schittenhelm and Schroetter, 2014; Prasad, Bheemanahalli, and Jagadish, 2017; Rezaei et al., 2023; Negri et al., 2024; Kunrath et al., 2020). Sorghum holds the fifth position worldwide in terms of both grain production and cultivation area (Hariprasanna and Rakshit 2016). Africa and the USA are the primary regions for sorghum production, accounting for 42% and 17% of global production over the period of 2000–2020, respectively (FAOSTAT, 2023). Sorghum is still a minor crop in Europe (here defined as all 44 countries in Europe except for Iceland and Russia but including Turkey) where it was cultivated on only ~0.1% of the cropland area between 2017 and 2021 (FAOSTAT, 2023). Nonetheless, its production is expanding in this region, with a 57% increase during the second decade compared to the first decade of the 21st century (FAOSTAT, 2023) (Figure S1).

A number of recent studies illustrate the growing interest in cultivating sorghum in Europe in the face of climate change (Didenko et al., 2023; Schaffasz et al., 2019; Tóth et al., 2023; Von Cossel et al., 2019). Sorghum is usually considered a good alternative to maize in environments with limited water availability because of its high water and nitrogen use efficiency, and ability to better withstand heat and water stress (Rooney et al. 2007; Shoemaker et al., 2010). The productivity of sorghum has been found to be less sensitive to water limitation than maize in some experimental studies from Germany (Schittenhelm and Schroetter, 2014) and Spain (Farré and Faci, 2006). However, despite this growing interest in sorghum, only a few studies assessed the effect of climate change on potential sorghum production in Europe

(Tubiello et al., 2000; Rinaldi and De Luca, 2012; Graß et al., 2015; Pohle et al. 2015). Yet, these studies focused on specific regions (primarily in Italy and Germany) and did not address the full diversity of European climates and agricultural landscapes.

Similar to maize, sorghum is mainly used for feeding livestock in Europe (80% of sorghum grown in Europe is used as livestock feed (Lidea Seeds, 2023)). Various studies have highlighted the interchangeable nutritional values of sorghum and maize grains in feeding livestock, provided that animals can be progressively acclimated to sorghum-based feed products (Ciurescu et al., 2023; Mengistu Urge, 2015; Onunkwo et al., 2015). Notably, sorghum grains have been demonstrated to offer comparable benefits to maize grains, with higher protein content and energy provision while being more cost-effective. Ronda et al. (2018) compared the nutritional values of sorghum and maize fed to dairy cattle. They showed that sorghum has 6% more protein content and provides more energy than maize, while being 30% less expensive. Consequently, some farmers have recently incorporated more sorghum into their feed: pork pig producers in Romania and Hungary replaced some of their maize with sorghum in the feed formulation (Lidea Seeds, 2023). They demonstrated that pigs fed with sorghum grains showed the same weight gain as those fed with maize grains. However, to date, the potential for sorghum-based feed production has not been evaluated across Europe in its entirety.

Therefore, there is a need for a comprehensive study that examines the impact of climate change on sorghum yields under different future climate scenarios across Europe, and the associated potential for sorghum-based feed production. Such a study would allow for better decision-making on adaptation strategies and sustainable agricultural practices in the face of climate change. In this context, the main goals of the present study are to investigate 1) the feasibility of expanding sorghum cultivation in Europe under current and future (middle and end of the 21st century) climatic conditions, and 2) the possibility of replacing maize with locally-produced sorghum for feeding livestock in Europe. To this end, we developed a machine learning model for predicting sorghum grain yield as a function of key climate inputs based on a random forest algorithm over the eight months of the sorghum growing season (April–November) (USDA IPAD, 2024). The model was trained on historical sorghum grain yield data collected at the county or department level in France, Italy, Spain, and the USA, covering the period from 2000 to 2020. Our historical sorghum yield dataset comprises 11,644 data points covering a large range of climate zones. Climate conditions were further expanded with the inclusion of yield data where yields can be reasonably assumed to be zero due to climatic conditions incompatible with crop growth (for instance Arctic and desert regions). Gridded monthly values of climate variables (solar radiation, minimum and maximum temperature, rainfall, and relative humidity) were used as predictors. For each climate parameter, we calculated monthly averages over an 8-month season (April–November) during which sorghum can be cultivated (i.e., a total of 40 predictors). For future projections, we covered a total of twenty climate change scenarios generated with five climate models, two Representative Concentration Pathways (SSP1-RCP2.6 and SSP5-RCP8.5) and targeting the two future periods of the mid and late 21st century. The SSP1-RCP2.6 scenario represents a high mitigation pathway with moderate warming, characterized by sustainable development, low-carbon energy sources, and significant global efforts to reduce greenhouse gas emissions. In contrast, the SSP5-RCP8.5 scenario represents a low mitigation pathway with strong warming, depicting a future with continued high fossil fuel emissions, limited climate change mitigation, and more pronounced global temperature increases. This is the first data-driven assessment of the probable sorghum performance across the continent of Europe, taking climate change into account.

## Results and discussion

### Evaluation of model performance

Evaluated based on a 5-fold cross-validation against observed yields, the random forest model shows a good performance with an  $R^2$  of 0.83, a root-mean-squared error (RMSE) of  $0.94 \text{ t ha}^{-1}$ , and a Nash–Sutcliffe model efficiency (NSE, unitless) of 0.82 (Figure S2). Two additional sets of cross-validation analyses were performed to assess the

random forest model's ability to predict yields in time and space. For transferability in time, we first excluded yield data for one year from the dataset. Then, the random forest model was trained on the remaining yield data to predict yields for the year excluded. The random forest model exhibited an average NSE of 0.71, an average NRMSE of 34%, and an average  $R^2$  of 73% across the different yearly datasets produced by the cross-validation (Table S1). This indicates that the model can reliably predict yields for new years, even when faced with new, previously unseen data in time.

To assess the transferability in space, we evaluated model performance using buffer zones ranging from 100 to 1,000 km around randomly selected departments in France, Italy, and Spain. Our findings revealed that as the distance between training and test datasets increases, the model's predictive ability diminishes. Specifically, we observed a notable decline in performance beyond a threshold of 800 km (Table S2). However, most of Europe is less than 800 km from three important European sorghum producers (France, Italy, and Spain) from which a substantial amount of yield data was collected and included in our training dataset. Most of the predicted yield values thus fall within the 800 km range of these three countries, especially the high yielding regions. This gives us reasonable confidence in yield projections from the model for areas where sorghum is not grown today, but caution is advised for projections in East Europe (Ukraine, Belarus) which are more uncertain.

The model shows a slight tendency to overestimate low yields and underestimate high yields, but residuals revealed a symmetrical and centered distribution, with most residuals falling between  $-1$  and  $+1 \text{ t ha}^{-1}$  (Figure S3). These results suggest a good performance of the model despite its conservative behavior, which is consistent with previous studies applying random forest models to predict crop yields for other crop species (Jeong et al., 2016; Iqbal et al., 2018; Guilpart et al., 2022).

Among the climate variables considered as predictors, relative humidity of the fourth (July) and fifth (August) months of the growing season were found to be the most influential variables, followed by solar radiation across 7 months of the growing season (Figure S4A). This is consistent with existing literature that emphasizes the importance of relative humidity in sorghum growth and development (Choudhary et al., 2013; Hoffman et al., 2020; Pettigrew et al., 1990; Shekoofa et al., 2014). Relative humidity affects stomatal conductance, transpiration rates, and water use efficiency in sorghum, thereby influencing overall crop productivity.

The importance of solar radiation across most of the growing season as an influential predictor of sorghum yields aligns with our understanding of sorghum physiology. Sorghum yield is known to be sensitive to crop growth rate during the critical period for yield formation, particularly through its effect on grain number. This critical period typically occurs around the fourth month of growth, slightly before anthesis. The crop growth rate during this crucial phase is significantly influenced by solar radiation (Van Oosterom & Hammer, 2008). Adequate solar radiation during this period promotes photosynthesis and assimilate production, which are essential for determining the number of grains and, consequently, the final yield.

We further found that the optimum growing temperature as well as critical minimum and maximum temperatures estimated by our model (Figure S5) are consistent with results reported in experimental studies (Emendack et al., 2021; Hoffman et al., 2020; Tack et al., 2017, Prasad et al., 2015). Specifically, these studies demonstrated that during the main growth phase, sorghum has an optimum range of daily maximum temperatures between  $27^\circ\text{C}$  to  $30^\circ\text{C}$ . They also showed that sorghum needs a minimum temperature of  $15^\circ\text{C}$  for growth, while its yields decrease rapidly when the daily maximum temperature exceeds  $32.5^\circ\text{C}$ . These findings suggest that our model simulations are consistent with the current understanding of sorghum physiology.

Sorghum yield projections under current climate

Yield projections for current climate conditions revealed three distinct regions in Europe with contrasted sorghum yields under current (2000–2020) climate conditions (Fig. 1A). The first region shows the highest yield levels and is located in central Europe, with predicted average yields above  $5 \text{ t ha}^{-1}$ . The second region is characterized by medium yield values, ranging from  $2.5 \text{ t ha}^{-1}$  to  $4 \text{ t ha}^{-1}$ , and covers the southern part of Europe (e.g., center of Spain, southern France, and Italy), the center of Germany and Poland, and the northern part of Ukraine. The third region shows lower productivity (less than  $2 \text{ t ha}^{-1}$ ) and covers the north of Europe, where climate conditions are less favorable to sorghum.

According to our projections, at least 88 Mha (45%) of European croplands could support sorghum yields higher than  $4 \text{ t ha}^{-1}$ , the current average sorghum yield in Europe in the last two decades (FAOSTAT, 2023). If we assume that sorghum would be planted in rotations in one out of three years, the annual sorghum production area in Europe could thus be 400 times larger (88 Mha) than what it is today ( $0.22 \text{ Mha}$  from FAOSTAT, 2023).

### Sorghum yield projections under future climate

Yield projections reveal that sorghum would maintain its productivity in Europe under future climate for the mid and late 21st Century. Figure 1 (B and C) shows the projected rainfed sorghum yields for high- (SSP1-RCP2.6) and low-mitigation (SSP5-RCP8.5) climate scenarios at two time horizons: the middle and the end of the 21st century. For both scenarios, we used the projections of five global circulation models from the CMIP6 ensemble (Eyring et al., 2016). The reported yield values represent the average of the five predictions based on these global climate models. In both climate scenarios, sorghum yields are projected to decrease by up to  $1.5 \text{ t ha}^{-1}$  in the southern part of Europe (e.g., center of Spain, south of France, and Italy), but to increase substantially by up to  $3 \text{ t ha}^{-1}$  in the northern part (e.g., north of Germany, Poland, and Lithuania) until the end of the 21st century (Fig. 2). This is consistent with previous local studies showing that sorghum yields will decrease in Italy (Tubiello et al., 2000; Rinaldi and De Luca 2012) while they increase in Germany (Graß et al., 2015; Pohle et al., 2015) under future climate.

At the European scale, our projections suggest that climate change will have a positive impact on sorghum yields. Over the whole European cropland area, the mean projected sorghum yield was indeed expected to increase from  $3 \text{ t ha}^{-1}$  under historical climate (1995–2014) to  $3.4 \text{ t ha}^{-1}$  (SSP1-RCP2.6) and  $3.5 \text{ t ha}^{-1}$  (SSP5-RCP8.5) by mid-century, and up to  $3.5 \text{ t ha}^{-1}$  (SSP1-RCP2.6) and  $3.8 \text{ t ha}^{-1}$  (SSP5-RCP8.5) by end of the century. This average yield gain resulted from an increase in sorghum yields in presently low-yielding and large cropland areas of e.g., Northern Germany, Poland, and Lithuania, which exceeded the projected yield decrease in currently high-yielding but small cropland areas in e.g., Central Spain, Southern France, and Italy. Projected increases in average yield across Europe were higher under SSP5-RCP8.5 than under SSP1-RCP2.6.

Analyses of the standard variation between sorghum yields projected from the five global climate models revealed that the variability of future yields between climate models was higher under SSP1-RCP2.6 scenarios than that under SSP5-RCP8.5 scenarios (Fig. 1D, 1E). Under both SSP1-RCP2.6 and SSP5-RCP8.5 scenarios, yield predictions obtained with the five global climate models led to similar yield projections, except for the low-yielding areas of Northern Europe (e.g., Norway, northern Germany, and Poland), where the inter-model standard variation reached up to  $1 \text{ t ha}^{-1}$ . While there may be increased uncertainty in the yield predictions towards the end of the century, it is important to note that only a small fraction (0.27%) of the grid-cells in future climate scenarios lies outside the range covered by the training data (Table S3), which indicates that our model is almost never applied outside its climate range.

Figure 3 shows the percentage of total European cropland area (based on the cropland area in the year 2000, Ramankutty et al., 2008) with different yield levels. In all scenarios, at least 88 Mha (45%) of European croplands are projected to support sorghum yields higher than  $4 \text{ t ha}^{-1}$  (the current average yield in Europe in the last two decades) (FAOSTAT, 2023). This percentage is expected to reach 54% in both scenarios (SSP1-RCP2.6 and SSP5-RCP8.5) by mid-century, and

54% (SSP1-RCP2.6) and 57% (SSP5-RCP8.5) by the end of the century. Climate change will thus lead to an increase in cropland areas able to produce high sorghum yields.

#### Suitable areas leading to resilient sorghum production

We assumed that, in the future, sorghum will be preferentially grown in areas with high and stable yields. To this end, we established two primary selection criteria: an average inter-annual yield higher than  $4 \text{ t ha}^{-1}$  (the average sorghum yield in Europe in the last 20 years, (FAOSTAT, 2023)) and an inter-annual yield standard variation less than  $0.5 \text{ t ha}^{-1}$  over each future time period in 5 climate model projections. While the standard variation criterion was consistently applied across all models, we retained only those grid cells that met the average yield threshold in at least 4 out of 5 models. The corresponding areas are further referred to as “suitable areas”. Suitable areas were identified separately for the historical period and the current climate condition and for the different climate change scenarios in each of the two future periods (2041–2060 and 2081–2100).

Results suggest that the suitable areas for sorghum increase more substantially under SSP5-RCP8.5 compared to SSP1-RCP2.6 across both mid and end-century periods, especially at the end of the century. Under SSP1-RCP2.6, the proportion of suitable areas rises from 22% in the historical period to 24% by mid-century (2041–2060) and 29% by the end of the century (2081–2100) (Fig. 4). In contrast, the suitable areas are larger under SSP5-RCP8.5 with 29% of the total European cropland by mid-century (2041–2060) and 34% of cropland by the end of the century (2081–2100) (Fig. 4). Although our results indicated that average yields might increase by up to  $3 \text{ t ha}^{-1}$  in the currently low-yielding cropland areas for sorghum, such as Northern Germany, Poland, and Lithuania, climate change would reduce yield stability in these areas, as indicated by the higher standard variation between annual yields. In contrast, currently high-yielding cropland areas, such as France, Italy, and Central Europe, might experience a reduction in average yields, but their yield stability over time will remain relatively high and their average yield will remain higher than the current European average.

#### Replacing maize with locally-produced sorghum for feeding livestock in Europe

During the last five years, Europe produced on average 114 Mt of grain (silage) maize per year for domestic supply (FAOSTAT, 2023), of which 75% were used for feeding livestock (Erenstein et al., 2022). Although the total EU cereal area, including maize, is projected to decrease marginally to 57.2 Mha by 2032 (EUROSTAT, 2022), it is plausible to assume that the total amount of grain maize used for feeding livestock will remain at a high level in the future. This is because the livestock population in Europe is expected to increase slightly from 9,415 kg-per animal per year in 2012 to 10,394 kg per animal per year by 2050 (FAO, 2018).

Given these challenges in maize production and livestock feed requirements, we explored the possibility of replacing grain maize with locally-produced sorghum for feeding livestock in Europe. To this end, we followed a four-step procedure. Firstly, we assumed that one kilogram of sorghum has an equivalent nutritional value as one kilogram of maize since different studies show that sorghum can serve as a suitable alternative to grain maize for feeding livestock, as it contains comparable amounts of essential nutrients (including proteins) required for maintaining a healthy diet (Ronda et al., 2018; Liaqat, et al., 2024). Secondly, we restricted sorghum cultivation to existing cropland in the year 2000 (Ramankutty et al., 2008), excluding permanent pastures protected by the European Union’s Common Agricultural Policy (Guilpart et al., 2022). We then explored one year out of three years scenario for sorghum frequency in crop rotations, which is equivalent to 33% of the cropland area under sorghum. Finally, we assumed that, in the future, sorghum will be preferentially grown in “suitable area” (defined in the last section)

Table 1 summarizes our projections of total sorghum production in Europe in future scenarios with sorghum frequency of one year out of three in crop rotations, which corresponds to 33% of cropland area under sorghum. SSP5-RCP8.5 scenarios resulted in higher sorghum production levels compared to SSP1-RCP2.6 scenarios over both time horizons

(2041–2060 and 2081–2100). Under SSP1-RCP2.6, the projected annual sorghum production was 79 Mt at mid-century, which falls short of the 86 Mt needed for livestock feed, with a deficit of 7 Mt. However, by the end-century, sorghum production increases to 98 Mt, with a surplus of about 13 Mt above livestock feed requirements. In contrast, under SSP5-RCP8.5, sorghum production would be sufficient to replace maize for livestock feed, with a surplus of 9 Mt in the 2041–2060 period and 25 Mt in the 2081–2100 period. Under both scenarios, the sorghum production increased from the mid-century to the end-of-century period. Notably, under SSP5-RCP8.5, the increase is much more obvious and there is no shortfall in both time periods. At present and through the 21st century, regardless of the scenario, if sorghum was grown in one out of three years, at least 90% of maize used as livestock feed could be replaced by sorghum in Europe (Table S4). These findings suggest that sorghum cultivation could be a viable alternative to grain maize for feeding livestock in Europe.

### Impact of expanding sorghum on other crops

Potential changes in sorghum-suitable areas and the possible expansion of sorghum cultivation in Europe could have significant implications for land use in Europe. For instance, achieving 50% (feed self-sufficiency) in sorghum production (i.e., approximately 42.5 Mt) would likely impact the cultivation of other crops. Our analysis indicates that four crops currently dominate the suitable area for sorghum cultivation. If sorghum were grown in one out of three years, for the mid-century period (2041–2060), under the SSP1-RCP2.6 scenario, sorghum cultivation could lead to reductions in the area used for wheat (29%), maize (44%), barley (18%), and sunflower (25%) (Table S5). Under the more extreme SSP5-RCP8.5 scenario for the same period, these losses are projected to increase to 35% for wheat, 54% for maize, 22% for barley, and 33% for sunflower. By the end of the century (2081–2100), the SSP1-RCP2.6 scenario projects land reallocation of 47% for wheat, 57% for maize, 22% for barley, and 31% for sunflower. Under the SSP5-RCP8.5 scenario, these figures are expected to reach 44% for wheat, 49% for maize, 34% for barley, and 36% for sunflower (Table S5).

These projections highlight that maize, being the primary summer crop, is most affected across all scenarios, aligning with the focus on replacing maize with sorghum for livestock feed. Moreover, since wheat and a large part of barley are most often winter crops and as sorghum is often proposed as an alternative crop to replace maize for feeding livestock, we discuss here mainly the consequences of a substitution of maize for sorghum. Based on the suitable area estimates in Fig. 4, our results suggest that the sorghum production could reach 98.5 Mt (SSP1-RCP2.6 by the end of the century) and 111.1 Mt (SSP5-RCP8.5 by the end of the century) if sorghum is grown one year in three and if the aim is to use it as a replacement of maize. These values correspond to 114–130% feed self-sufficiency in sorghum. However, assuming sorghum production area to expand at the expense of maize only, this would lead to a dramatic reduction in the European maize production area of 8 to 9 Mha (-44% to -57%) which is unlikely as Europe is currently not self-sufficient in maize (average self-sufficiency ratio of 82% over 2018–2022, FAOSTAT, 2023). These results highlight the need to identify where, and under which conditions a maize-to-sorghum substitution would lead to the higher benefits.

### Environmental impacts of sorghum expansion in Europe

Sorghum is considered a drought-tolerant crop with high water-use efficiency. The cultivation of sorghum may permit saving water consumption for irrigation, depending on the types of crops replaced by sorghum. For example, in France, about 30% of the maize production area is irrigated while this value is only 5% for sorghum (Agreste 2024). However, conflicting evidence exists regarding the relative performance of rainfed sorghum and maize under water-limited conditions. Some studies suggest that modern rainfed maize hybrids may be more productive than sorghum in regions like the US and Argentina under drought (Rotundo et al., 2024; Parra et al., 2020; Parra et al., 2022), while others indicate that sorghum productivity is less sensitive to water limitation compared to maize in Europe (Lemaire et al., 1996; Farré and Faci, 2006; Schittenhelm and Schroetter, 2014; Kunrath et al., 2020). Further investigation specific to European conditions may be necessary to assess the potential impact on crop water demand and irrigation requirements of an expansion of sorghum areas, especially in regions frequently impacted by drought. Sorghum expansion may also provide

benefits associated with less nitrogen fertilization, pesticide use, and crop diversification. Indeed, sorghum nitrogen fertilization is usually much lower than for maize, which is expected to reduce risks of nitrate leaching and GHG emissions (due to synthetic fertilizer manufacture and field application of fertilizers). For example, in France in 2021, a comprehensive farmers survey revealed that the average nitrogen fertilization rate was 111 kgN ha<sup>-1</sup> for sorghum and 199 kgN ha<sup>-1</sup> for maize (Agreste, 2024). Moreover, some studies suggest that sorghum has a higher capacity to absorb nitrogen from the soil and maintain its nitrogen nutrition than maize, especially under drought (Lemaire et al. 1996; Kunrath et al. 2020). Pesticide use intensity on sorghum is among the lowest of all field crops, with a treatment frequency index of 2.0 compared to 2.9 for maize, 5.1 for wheat, and 6.4 for rapeseed (Agreste 2024). An expansion of sorghum production area is therefore expected to contribute to pesticide use reduction in Europe. Sorghum expansion would also contribute to diversify the crop sequences in Europe that are dominated by cereals and winter crops (Ballot et al, 2023), with a range of associated benefits (Beillouin et al. 2021)

### Limitations of the model

Our model has some limitations because it doesn't consider all variables that might affect sorghum growth and yield, including soil properties, atmospheric CO<sub>2</sub> levels, and changes in management practices. Soil properties can be an important local driver of crop growth, affecting availability of moisture and nutrients in the root zone as well as root development (Correa et al., 2022; Rroço et al., 2003). However, reliable global data on soil properties that matter for crop production (especially rootable soil depth) are not available to our knowledge (Folberth et al., 2016; Guilpart et al., 2017). Thus, we did not include soil properties as predictors in our model. Nevertheless, a recent study at the global scale suggests that root growth is not a major limiting factor in European soils (Shangguan et al., 2017).

We also chose not to include the effects of increasing atmospheric CO<sub>2</sub> levels on sorghum yields in our model. C4 crops such as sorghum are generally considered to be less responsive to CO<sub>2</sub> than C3 crops. The interactions effect between CO<sub>2</sub> levels, plant growth, and other environmental factors on sorghum yields are complex and not well understood (Asadi & Eshghizadeh, 2021; Gleadow et al., 2016; Ellis et al., 1995; Ottman et al., 2001; De Souza et al., 2015). However, some recent studies suggest that higher CO<sub>2</sub> levels might increase yields of C4 crops such as sorghum (Li et al., 2019; Vijayalakshmi et al., 2024). Fu et al. (2016) found that when CO<sub>2</sub> concentrations rose from 200 to 480 parts per million (ppm), there was a substantial increase in grain yield, amounting to an additional 1.7 t ha<sup>-1</sup>. However, further increases in CO<sub>2</sub> from 480 to 950 ppm resulted in only a modest yield gain of 0.2 t ha<sup>-1</sup>. This might further support our finding that large opportunities exist to improve sorghum production in Europe under climate change.

In our model, we considered a sorghum growing period of eight months, from April to November. In reality, the length of the growing season from sowing to harvest is often no longer than five months, although early and late sowing generates some variations in the duration of the growing periods. However, examining the possibilities of earlier and later planting would be very challenging because accurate data on sowing dates are lacking. Because these climate change adaptation options are not considered in our approach, our results likely underestimate the potential production of sorghum in Europe under climate change.

For future research, it would be valuable to use more detailed crop models that can capture these complex processes. These models could account for variable planting dates, different sorghum varieties, and the intricate interactions between plants and their environment (Carcedo et al. 2023; Raymundo et al. 2021). Comparing results from these detailed models with our current predictions would give us a more complete picture of how climate change might affect sorghum production in Europe.

## Conclusion

Our analysis shows that sorghum could play a critical role in feeding livestock in the future, particularly as a substitute for maize, which is widely used for livestock feed in Europe. Sorghum is already utilized in several livestock systems, including pigs, cattle, and poultry production. They demonstrated that animals fed with sorghum grains showed the same weight gain as those that fed by maize grains.

The use of sorghum in livestock feed offers several advantages. It provides comparable nutritional value to maize, with some studies suggesting even higher protein content and energy provision. Moreover, sorghum's adaptability to various climatic conditions, particularly its high heat tolerance and resilience to water stress compared to other crops, makes it an attractive option for ensuring feed security in the face of climate change.

Our analysis indicates that expanding sorghum production in Europe could significantly contribute to meeting livestock feed demand, reducing reliance on maize. If sorghum were grown in one out of three years, it could replace at least 90% of the maize currently used for livestock feed across Europe, regardless of the climate change scenario considered. This finding suggests that transitioning to sorghum-based feed could be a viable strategy for maintaining or even improving feed security in Europe as climate conditions evolve.

## Method

### Sorghum yield and climate data

Our training dataset was built from national databases, including grain yield data at the county level covering a time period of at least 10 years since 2000. We collected sorghum grain yield data from 2000 to 2020 in France, Italy, Spain, and the USA, resulting in a total of 11,644 yield data points (Table S6). The inclusion of the USA data was relevant, given its climatic conditions and agricultural practices that are similar to many European regions. Moreover, the larger climatic variability in the USA allowed us to train our machine learning model with data that are representative of both current and future climatic conditions projected for Europe. In contrast, we avoided data from tropical sorghum-producing nations such as those in Africa, India, Brazil, and Bolivia, as their growing conditions differ significantly from those in Europe. Furthermore, to maintain consistency in crop calendars and seasonal patterns, we focused solely on northern hemisphere countries, omitting data from southern hemisphere nations like Argentina and Mexico. It is important to note that we specifically focused on grain sorghum data and excluded silage sorghum data from our analysis, as our study aims to assess grain production potential. Sorghum grain yield ( $\text{t ha}^{-1}$ ) statistics of each country are available at the subnational administrative level (department, NUTS3 (<http://ec.europa.eu/eurostat/web/nuts/overview>)) in European countries (with an average area of 5,961  $\text{km}^2$  in France, of 2,663  $\text{km}^2$  in Italy, and of 11,264  $\text{km}^2$  in Spain), and at the county level in the USA (with an average area of 2,320  $\text{km}^2$ ) (Figures S7 and S8). However, for Italy, sorghum data is available from 2006 only (Table S6). As we focus on only rainfed sorghum production, we treated our dataset as follows: For the USA and Spain, where official statistics distinguish between rainfed and irrigated sorghum, we excluded all data flagged as irrigated from these databases. For France and Italy, the official databases do not make this distinction for sorghum. However, since the majority of sorghum in these countries is grown under rainfed conditions, we assumed all data from France (Agreste, 2022, 7% of agricultural land in France irrigated in 2020) and Italy (Todorovic et al., 2007, 4.5% of the total cultivation of cereal crops in Italy is irrigated) to be rainfed.

An enhanced global dataset for the land component of the fifth generation of European reanalysis (ERA5-land) was used for current climate data (2000–2020) (Muñoz-Sabater et al., 2021). This dataset provides gridded values of various climate variables at a spatial resolution of  $0.25^\circ$  and a temporal resolution of three hours. We first aggregated these values to daily averages. Then, we aggregated the daily averages to monthly averages. This way, we reduced the dimensionality and noise of the data and obtained a smoother representation of the seasonal climate patterns (Chen et al., 2024). The set of climate predictors are solar radiation ( $\text{rsds}$ ,  $\text{MJ m}^{-2} \text{day}^{-1}$ ), minimum ( $\text{tasmin}$ ,  $^\circ\text{C}$ ) and maximum

(tasmax, °C) temperature, total precipitation (pr, mm day<sup>-1</sup>), and relative humidity (hurs, %). To align the climate data with yield statistics, we used shapefiles (GADM, 2018) representing the boundaries of each NUTS3 region for European countries and each county for the USA. By applying these shapefiles, we masked the climate data to keep only the information relevant for each NUTS3 and county. Next, we identified the grid-cells within each NUTS3 region and county that were considered cropland in 2000 (Ramankutty et al., 2008). A grid-cell can have from 0 to 100% cropland. Therefore, we performed a cropland area-weighted average where a pixel with 100% cropland would not have the same weight when calculating the average than a pixel with 5% cropland. The remaining grid-cells were used to calculate the monthly average value for each climate predictor within each NUTS3 region or county.

#### Climatic zones unsuitable for sorghum production

To allow the model to better discriminate between suitable and unsuitable areas for sorghum, we added data points to the training data representing sites where yields can be assumed zero due to climate conditions. It was shown, in a previous study, that this approach was able to improve model predictive performances (Guilpart et al., 2022). This procedure involved adding grid-cells located in climatic zones generally known to be unsuitable for crop production, such as deserts and arctic areas. We selected six climate zones based on the Köppen–Geiger classification (Kottek et al., 2006), including polar tundra (EF), polar frost (ET), snow with fully humid with cool summer (Dfc), snow with fully humid with extremely continental (Dfd), hot arid desert (BWh), and cold arid desert (BWk) (Figure S9). In each selected climate zone, 15 grid-cells were randomly chosen and added as zero yield values, so that 20% of the final dataset represented zero yield values. The final dataset (including zero yield values) comprised a total of 11,644 yield data.

#### Random forest model

A random forest model was developed to predict sorghum yields from 5 climate variables averaged for each of the eight months of the sorghum growing season (April–November) (USDA IPAD, 2024). The random forest model was fitted using the R v4.3.0 software. The *ranger()* function of the *ranger* package (Wright and Ziegler, 2017) was used to train the random forest with 500 trees, 5-fold cross-validation, and default values for other parameters. We used a mean decrease in impurity (Gini importance) (Breiman, 2001) to compare the variable importance of climate variables. Gini importance evaluates the feature's contribution to reducing impurity in decision trees, indicating its significance in splitting nodes to improve model performance. To show the effects of each climate variable on the random forest predictions while keeping all other climate variables constant, partial dependence plots and accumulated local effects (Apley and Zhu, 2020) were produced. The *model\_profile()* function of the *DALEX* package was used to plot partial dependence plots and accumulated local effects.

#### Transferability in time and space

Two additional sets of cross-validation analyses were performed to assess the random forest model's predictive ability in time and space. The normalized root-mean-squared error (NRMSE, unitless), the Nash–Sutcliffe model efficiency (NSE, unitless), and R<sup>2</sup> were used to measure the transferability of the random forest model in space and time. For transferability in time, we first excluded yield data for one year from the dataset. Then, the random forest was trained on the remaining yield data to predict yields for the year excluded. To assess the transferability in space, we followed a five-step procedure. First, we randomly selected a department (county) in one of the European countries included in our dataset (France, Italy, or Spain). Then, six buffer zones of varying sizes (100, 200, 400, 600, 800, and 1,000 km) were defined around the barycenter of the selected department. For each buffer zone, neighboring departments within the buffer zone were removed to train the random forest model on the rest of the dataset outside the buffer zone. Next, we predicted yields for the randomly selected department and we computed R<sup>2</sup>, NSE, and NRMSE between observed and predicted yields for the selected department. We repeated this procedure over 10 departments in each European country

(France, Italy, and Spain) to estimate transferability in space for various degrees of spatial proximity between the training and test datasets.

### Sorghum yield projections

We applied the random forest model to 20 future climate change scenarios and five (near-present-day) historical scenarios using bias-corrected climate data of five Global Climate Models (UKESM1-0-LL, MRI-ESM2-0, MPI-ESM1-2-HR, IPSL-CM6A-LR, and GFDL-ESM4) produced by the Coupled Model Intercomparison Project phase 6 (CMIP6) (Eyring et al., 2016), following two combinations of Socio-economic pathways (SSPs) and Representative Concentration Pathways scenarios (RCPs) (SSP1-RCP2.6 and SSP5-RCP8.5 refers to high mitigation (moderate warming) and low mitigation (strong warming) scenarios, respectively) (O'Neill et al., 2016), and focusing on two future periods (2041–2060 and 2081–2100) and the recent historical period 1995–2014. A more detailed description of the bias-correction method and combination of Socio-economic pathways (SSPs) and Representative Concentration Pathways scenarios (RCPs) can be found in Eyring et al. (2016) and O'Neill et al. (2016), respectively. Here, we present the difference between the average predicted sorghum yields of future scenarios and a historical scenario (1995–2014) over five climate models. For both historical and future scenarios, we projected sorghum yield in grid-cells considered to contain cropland in the year 2000 (Ramankutty et al., 2008).

In our initial analysis, we used vapor pressure deficit (VPD) as a predictor of sorghum yield instead of relative humidity (RH). However, to maintain consistency with climate parameters included in the future climate projections (CMIP6 ensemble), RH was used instead of VPD. Both variables are highly correlated, and despite this change, our model showed the same performance (VPD vs RH) (Figure S4). Therefore, we used RH instead of VPD.

### Estimation of livestock feed demand

To assess the potential for replacing maize with sorghum in livestock feed, we estimated the current and future demand for grain maize as animal feed in Europe. We used data from FAOSTAT (2023) to determine the average domestic supply in Europe over the last five years. Based on Erenstein et al. (2022), we assumed that 75% of this maize production is used for livestock feed.

To account for future changes, we considered that although the total EU cereal area, including maize, is projected to decrease marginally to 57.2 million hectares by 2032 (EUROSTAT, 2022), it is plausible to assume that the total amount of maize for feeding livestock will remain at a high level in the future. This is because the livestock population in Europe is expected to increase slightly from 9,415 kg-per animal per year in 2012 to 10,394 kg per animal per year by 2050 (FAO, 2018). Consequently, we considered the same quantity for maize production for livestock feed in our future projections.

We used these figures to estimate the amount of sorghum that would be needed to replace maize in livestock feed. Several studies suggest that sorghum offers similar nutritional benefits to maize, providing comparable energy and protein levels, allowing for a 1:1 replacement ratio based on nutritional equivalence (Ronda et al., 2018; Liaqat et al., 2024). We further analyzed the potential for replacing maize with locally-produced sorghum across different climate scenarios.

### Scenarios of sorghum expansion in Europe

We explored the possibility of replacing maize with locally-produced sorghum for feeding livestock in Europe. To this end, we followed a four-step procedure. Firstly, we assumed that one kg of sorghum has an equivalent nutritional value to one kg of maize since different studies show that sorghum can serve as a suitable alternative to maize for feeding livestock, as it contains comparable amounts of essential nutrients (including proteins) required for maintaining a healthy diet (Ronda et al., 2018; Liaqat, et al., 2024). Secondly, we restricted sorghum cultivation to existing cropland in the year 2000

(Ramankutty et al., 2008), excluding permanent pastures protected by the European Union's Common Agricultural Policy (Guilpart et al., 2022). We then explored one year out of three years scenario for sorghum frequency in crop rotations, which is equivalent to 33% of sorghum cropland area in each grid-cell.

Finally, to identify suitable areas for sorghum cultivation, for each combination of climate scenario and time period, we first calculated the ensemble mean of the five climate models and computed the inter-annual mean yield and standard variation for each grid cell. We established two primary selection criteria: an average inter-annual yield higher than  $4 \text{ t ha}^{-1}$  (the average sorghum yield in Europe in the last 20 years, (FAOSTAT, 2023)) and an inter-annual yield standard variation less than  $0.5 \text{ t ha}^{-1}$ .

While the standard variation criterion was consistently applied across all models, we retained only those grid cells that met the average yield threshold in at least 4 out of 5 models, ensuring a robust and conservative selection of suitable sorghum cultivation areas.

The selection of a  $0.5 \text{ t ha}^{-1}$  standard variation threshold for yield stability was informed by existing research on crop yield variability. Cernay et al. (2015) showed that the standard deviation of yield anomalies for sorghum in Europe and the Americas over the period 1961–2013 was less than 0.10. Consequently, we established a conservative threshold that allows for some variability while ensuring overall crop stability. This approach provides a robust method for identifying reliable sorghum cultivation areas that can maintain consistent productivity across different environmental conditions. Suitable areas were identified separately for the historical period and the current climate condition and for the different climate change scenarios in each of the two future periods (2041–2060 and 2081–2100).

## Declarations

Code availability

Code availability The R code to reproduce key results of this paper is available at:  
[https://github.com/mdavoudkhani/Sorghum\\_yield\\_projections\\_Europe](https://github.com/mdavoudkhani/Sorghum_yield_projections_Europe)

## References

1. Agreste (2022). Annual Agricultural Statistics 2022. <https://agreste.agriculture.gouv.fr/agreste-web/download/publication/publie/MemSta2022-en/Handbook2022.pdf> (Accessed 28 February 2024).
2. Agreste (2024). Enquête Pratiques culturelles en grandes cultures 2021. [https://www.agreste.agriculture.gouv.fr/agreste-web/download/publication/publie/Chd2413/cd2024-13\\_PK-GC2021.pdf](https://www.agreste.agriculture.gouv.fr/agreste-web/download/publication/publie/Chd2413/cd2024-13_PK-GC2021.pdf) (Accessed 28 February 2024).
3. Apley, D. W., & Zhu, J. (2020). Visualizing the effects of predictor variables in black box supervised learning models. *J. R. Statist. Soc. B*, 82. <https://academic.oup.com/jrssb/article/82/4/1059/7056085>
4. Asadi, M., & Eshghizadeh, H. R. (2021). Response of sorghum genotypes to water deficit stress under different CO<sub>2</sub> and nitrogen levels. *Plant Physiology and Biochemistry*, 158, 255–264. <https://doi.org/10.1016/j.plaphy.2020.11.010>
5. Ballot, R., Guilpart, N., & Jeuffroy, M. H. (2023). The first map of crop sequence types in Europe over 2012–2018. *Earth System Science Data*, 15(12), 5651–5666.
6. Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V., & Makowski, D. (2021). Positive but variable effects of crop diversification on biodiversity and ecosystem services. *Global change biology*, 27(19), 4697–4710.
7. Breiman L. (2001). Random forests. *Mach. Learn.*, 45, 5–32.
8. Carcedo, A. J., & Ciampitti, I. A. (2023). Sorghum producer yield contest: A synthesis-analysis of major management and environmental drivers. *Field Crops Research*, 296, 108922.

9. Cernay, C., Ben-Ari, T., Pelzer, E., Meynard, J. M., & Makowski, D. (2015). Estimating variability in grain legume yields across Europe and the Americas. *Scientific reports*, 5(1), 11171.
10. Chen, M., Guilpart, N., & Makowski, D. (2024). Comparison of methods to aggregate climate data to predict crop yield: an application to soybean. *Environmental Research Letters*, 19(5), 054049.
11. Choudhary, S., Mutava, R. N., Shekoofa, A., Sinclair, T. R., & Prasad, P. V. (2013). Is the stay-green trait in sorghum a result of transpiration sensitivity to either soil drying or vapor pressure deficit?. *Crop Science*, 53(5), 2129-2134.
12. Ciurescu, G., Vasilachi, A., Idriceanu, L., & Dumitru, M. (2023). Effects of corn replacement by sorghum in broiler chickens diets on performance, blood chemistry, and meat quality. *Italian Journal of Animal Science*, 22(1), 537–547. <https://doi.org/10.1080/1828051X.2023.2212695>
13. Correa, J., Postma, J. A., & Wojciechowski, T. (2022). Phenotypic response to soil compaction varies among genotypes and correlates with plant size in sorghum. *Plant and Soil*, 472(1–2), 59–76. <https://doi.org/10.1007/s11104-021-05160-z>.
14. Cosentino, S. L., Testa, G., Scordia, D., & Alexopoulou, E. (2012). Future yields assessment of bioenergy crops in relation to climate change and technological development in Europe. *Italian Journal of Agronomy*, 7(2), 154–166. <https://doi.org/10.4081/ija.2012.e22>
15. De Souza, A. P., Cocuron, J. C., Garcia, A. C., Alonso, A. P., & Buckeridge, M. S. (2015). Changes in whole-plant metabolism during the grain-filling stage in sorghum grown under elevated CO<sub>2</sub> and drought. *Plant Physiology*, 169(3), 1755–1765. <https://doi.org/10.1104/pp.15.01054>
16. Didenko, N., Mosiichuk, Y., Islam, R., Zosymchuk, M., Mazurenko, B., Lavrenko, S., Kharytonov, M., & Babenko, M. (2023). Prospect of Growing Energy Crops on Biosolids-Amended Marginal Soils in Ukraine. *Advances in Transdisciplinary Engineering*, 38, 875–882. <https://doi.org/10.3233/ATDE230371>
17. Ellis, R. H., Craufurd, P. Q., Summerfield, R. J., & Roberts, E. H. (1995). Linear relations between carbon dioxide concentration and rate of development towards flowering in sorghum, cowpea and soyabean. *Annals of Botany*, 75(2), 193-198.
18. Emendack, Y., Sanchez, J., Hayes, C., Nesbitt, M., Laza, H., & Burke, J. (2021). Seed-to-seed early-season cold resiliency in sorghum. *Scientific Reports*, 11(1). <https://doi.org/10.1038/s41598-021-87450-1>
19. Erenstein, O., Jaleta, M., Sonder, K., Mottaleb, K., & Prasanna, B. M. (2022). Global maize production, consumption and trade: trends and R&D implications. In *Food Security* (Vol. 14, Issue 5, pp. 1295–1319). Springer Science and Business Media B.V. <https://doi.org/10.1007/s12571-022-01288-7>
20. EUROSTAT (2019). Irrigation in EU agriculture. [https://www.europarl.europa.eu/RegData/etudes/BRIE/2019/644216/EPRS\\_BRI\(2019\)644216\\_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2019/644216/EPRS_BRI(2019)644216_EN.pdf) (Accessed 28 February 2024).
21. EUROSTAT (2022). EU agricultural outlook for markets, income, and environment 2022 - 2032. [https://agriculture.ec.europa.eu/system/files/2023-04/agricultural-outlook-2022-report\\_en\\_0.pdf](https://agriculture.ec.europa.eu/system/files/2023-04/agricultural-outlook-2022-report_en_0.pdf) (Accessed 28 February 2024).
22. Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, 9(5), 1937–1958. <https://doi.org/10.5194/gmd-9-1937-2016>
23. FAO, FAOSTAT (FAO, 2023).
24. FAO. (2018). The future of food and agriculture—Alternative pathways to 2050.
25. Farré, I., & Faci, J. M. (2006). Comparative response of maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench) to deficit irrigation in a Mediterranean environment. *Agricultural Water Management*, 83(1–2), 135–143. <https://doi.org/10.1016/j.agwat.2005.11.001>

26. Folberth, C., Skalský, R., Moltchanova, E., Balkovič, J., Azevedo, L. B., Obersteiner, M., & Van Der Velde, M. (2016). Uncertainty in soil data can outweigh climate impact signals in global crop yield simulations. *Nature Communications*, 7. <https://doi.org/10.1038/ncomms11872>
27. Fu, T., Ko, J., Wall, G. W., Pinter, P. J., Kimball, B. A., Ottman, M. J., & Kim, H. Y. (2016). Simulation of climate change impacts on grain sorghum production grown under free air CO<sub>2</sub> enrichment. *International Agrophysics*, 30(3), 311–322. <https://doi.org/10.1515/intag-2016-0007>.
28. GADM. (2018). Global Administrative Areas Version 3.6. University of California, Berkley. Global Available online: <http://www.gadm.org> (accessed on 07/10/2024).
29. Gleadow, R. M., Ottman, M. J., Kimball, B. A., Wall, G. W., Pinter, P. J., LaMorte, R. L., & Leavitt, S. W. (2016). Drought-induced changes in nitrogen partitioning between cyanide and nitrate in leaves and stems of sorghum grown at elevated CO<sub>2</sub> are age dependent. *Field Crops Research*, 185, 97–102. <https://doi.org/10.1016/j.fcr.2015.10.010>
30. Gouel, C., & Guimbard, H. (2019). Nutrition transition and the structure of global food demand. *American Journal of Agricultural Economics*, 101(2), 383-403.
31. Graß, R., Thies, B., Kersebaum, K. C., & Wachendorf, M. (2015). Simulating dry matter yield of two cropping systems with the simulation model HERMES to evaluate impact of future climate change. *European Journal of Agronomy*, 70, 1–10. <https://doi.org/10.1016/j.eja.2015.06.005>
32. Guilpart, N., Grassini, P., Van Wart, J., Yang, H., Van Ittersum, M. K., Van Bussel, L. G. J., Wolf, J., Claessens, L., Leenaars, J. G. B., & Cassman, K. G. (2017). Rooting for food security in Sub-Saharan Africa. *Environmental Research Letters*, 12(11). <https://doi.org/10.1088/1748-9326/aa9003>
33. Guilpart, N., Iizumi, T., & Makowski, D. (2022). Data-driven projections suggest large opportunities to improve Europe's soybean self-sufficiency under climate change. *Nature Food*, 3(4), 255–265. <https://doi.org/10.1038/s43016-022-00481-3>
34. Hao, B., Xue, Q., Bean, B. W., Rooney, W. L., & Becker, J. D. (2014). Biomass production, water and nitrogen use efficiency in photoperiod-sensitive sorghum in the Texas High Plains. *Biomass and Bioenergy*, 62, 108–116. <https://doi.org/10.1016/j.biombioe.2014.01.008>.
35. Hariprasanna, K., & Rakshit, S. (2016). Economic Importance of Sorghum (pp. 1–25). [https://doi.org/10.1007/978-3-319-47789-3\\_1](https://doi.org/10.1007/978-3-319-47789-3_1)
36. Hoffman, A. L., Kemanian, A. R., & Forest, C. E. (2020). The response of maize, sorghum, and soybean yield to growing-phase climate revealed with machine learning. *Environmental Research Letters*, 15(9), 094013.
37. Hossain, M. S., Islam, M. N., Rahman, M. M., Mostofa, M. G., & Khan, M. A. R. (2022). Sorghum: A prospective crop for climatic vulnerability, food and nutritional security. In *Journal of Agriculture and Food Research* (Vol. 8). Elsevier B.V. <https://doi.org/10.1016/j.jafr.2022.100300>
38. IPCC, (2023). Climate change 2023: synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647.
39. Iqbal, F., Lucieer, A., & Barry, K. (2018). Poppy crop capsule volume estimation using UAS remote sensing and random forest regression. *International Journal of Applied Earth Observation and Geoinformation*, 73, 362–373. <https://doi.org/10.1016/j.jag.2018.06.008>
40. Jeong, J. H., Resop, J. P., Mueller, N. D., Fleisher, D. H., Yun, K., Butler, E. E., Timlin, D. J., Shim, K. M., Gerber, J. S., Reddy, V. R., & Kim, S. H. (2016). Random forests for global and regional crop yield predictions. *PLoS ONE*, 11(6). <https://doi.org/10.1371/journal.pone.0156571>
41. Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, 15(3), 259–263. <https://doi.org/10.1127/0941-2948/2006/0130>

42. Kunrath, T. R., Lemaire, G., Teixeira, E., Brown, H. E., Ciampitti, I. A., & Sadras, V. O. (2020). Allometric relationships between nitrogen uptake and transpiration to untangle interactions between nitrogen supply and drought in maize and sorghum. *European Journal of Agronomy*, 120, 126145.
43. Labeyrie, V., Renard, D., Aumeeruddy-Thomas, Y., Benyei, P., Caillon, S., Calvet-Mir, L., ... & Reyes-García, V. (2021). The role of crop diversity in climate change adaptation: Insights from local observations to inform decision making in agriculture. *Current Opinion in Environmental Sustainability*, 51, 15-23.
44. Lemaire, G., Charrier, X., & Hébert, Y. (1996). Nitrogen uptake capacities of maize and sorghum crops in different nitrogen and water supply conditions. *Agronomie*, 16(4), 231-246.
45. Li, P., Li, B., Seneweera, S., Zong, Y., Li, F. Y., Han, Y., & Hao, X. (2019). Photosynthesis and yield response to elevated CO<sub>2</sub>, C<sub>4</sub> plant foxtail millet behaves similarly to C<sub>3</sub> species. *Plant Science*, 285, 239–247. <https://doi.org/10.1016/j.plantsci.2019.05.006>
46. Liaqat, W., Altaf, M. T., Barutçular, C., Mohamed, H. I., Ahmad, H., Jan, M. F., & Khan, E. H. (2024). Sorghum: a Star Crop to Combat Abiotic Stresses, Food Insecurity, and Hunger Under a Changing Climate: a Review. *Journal of Soil Science and Plant Nutrition*, 1-28.
47. Lidea Seeds., (2023). Brochure Sorghum Animal Feed 2023. [https://api-com.lidea-seeds.com/uploads/2023/04/brochure\\_sorghum\\_animal\\_feed\\_2023.pdf](https://api-com.lidea-seeds.com/uploads/2023/04/brochure_sorghum_animal_feed_2023.pdf).
48. Lunduka, R., Fisher, M., & Snapp, S. (2012). Could farmer interest in a diversity of seed attributes explain adoption plateaus for modern maize varieties in Malawi? *Food Policy*, 37(5), 504–510. <https://doi.org/10.1016/j.foodpol.2012.05.001>
49. Mengistu Urge, A. M. (2015). Effects of Replacing Maize with Sorghum on Growth and Feed Efficiency of Commercial Broiler Chicken. *Journal of Veterinary Science & Technology*, 06(03). <https://doi.org/10.4172/2157-7579.1000224>
50. Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., & Thépaut, J. N. (2021). ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data*, 13(9), 4349–4383. <https://doi.org/10.5194/essd-13-4349-2021>
51. Negri, L., Bosi, S., Fakaros, A., Ventura, F., Magagnoli, S., Masetti, A., ... & Dinelli, G. (2024). Millets and sorghum as promising alternatives to maize for enhancing climate change adaptation strategies in the Mediterranean Basin. *Field Crops Research*, 318, 109563.
52. O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J. F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., & Sanderson, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, 9(9), 3461–3482. <https://doi.org/10.5194/gmd-9-3461-2016>
53. Olesen, J. E., Trnka, M., Kersebaum, K. C., Skjelvåg, A. O., Seguin, B., Peltonen-Sainio, P., Rossi, F., Kozyra, J., & Micale, F. (2011). Impacts and adaptation of European crop production systems to climate change. In *European Journal of Agronomy* (Vol. 34, Issue 2, pp. 96–112). <https://doi.org/10.1016/j.eja.2010.11.003>
54. Onunkwo, D., Anyaegbu, C., Odukwe, C., & Adedokun, O. (2015). Evaluation of Dietary Substitution of Yellow Maize with White Sorghum on the Performance of Broiler Starter. *International Journal of Livestock Research*, 5(11), 31. <https://doi.org/10.5455/ijlr.20151125064842>
55. Ottman, M. J., Kimball, B. A., Pinter, P. J., Wall, G. W., Vanderlip, R. L., Leavitt, S. W., Lamorte, R. L., Matthias, A. D., & Brooks, T. J. (2001). Elevated CO<sub>2</sub> increases sorghum biomass under drought conditions. *New Phytologist*, 150(2), 261–273. <https://doi.org/10.1046/j.1469-8137.2001.00110.x>
56. Parra, G., Borrás, L., & Gambin, B. L. (2022). Crop attributes explaining current grain yield dominance of maize over sorghum. *Field Crops Research*, 275, 108346.

57. Pettigrew, W. T., Hesketh, J. D., Peters, D. B., & Woolley, J. T. (1990). A vapor pressure deficit effect on crop canopy photosynthesis. *Photosynthesis research*, 24, 27-34.
58. Pohle, I., Koch, H., Conradt, T., Gädeke, A., & Grünewald, U. (2015). Impacts potentiels des changements climatiques et des activités anthropiques régionales dans les bassins versants de méso-échelle d'Europe centrale. *Hydrological Sciences Journal*, 60(5), 912–928. <https://doi.org/10.1080/02626667.2014.968571>
59. Prasad, P. V. V., Djanaguiraman, M., Perumal, R., & Ciampitti, I. A. (2015). Impact of high temperature stress on floret fertility and individual grain weight of grain sorghum: Sensitive stages and thresholds for temperature and duration. *Frontiers in Plant Science*, 6(OCTOBER). <https://doi.org/10.3389/fpls.2015.00820>
60. Prasad, P. V., Bheemanahalli, R., & Jagadish, S. K. (2017). Field crops and the fear of heat stress—opportunities, challenges and future directions. *Field Crops Research*, 200, 114-121.
61. Ramankutty, N., Evan, A. T., Monfreda, C., & Foley, J. A. (2008). Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochemical Cycles*, 22(1). <https://doi.org/10.1029/2007GB002952>
62. Ray, D. K., West, P. C., Clark, M., Gerber, J. S., Prishchepov, A. V., & Chatterjee, S. (2019). Climate change has likely already affected global food production. *PLoS ONE*, 14(5). <https://doi.org/10.1371/journal.pone.0217148>
63. Raymundo, R., Sexton-Bowser, S., Ciampitti, I. A., & Morris, G. P. (2021). Crop modeling defines opportunities and challenges for drought escape, water capture, and yield increase using chilling-tolerant sorghum. *Plant direct*, 5(9), e349.
64. Rezaei, E. E., Webber, H., Asseng, S., Boote, K., Durand, J. L., Ewert, F., ... & MacCarthy, D. S. (2023). Climate change impacts on crop yields. *Nature Reviews Earth & Environment*, 4(12), 831-846.
65. Ronda, V., Visarada, K. B. R. S., & Bhat, B. V. (2018). Sorghum for animal feed. In *Breeding Sorghum for Diverse End Uses* (pp. 229–238). Elsevier. <https://doi.org/10.1016/B978-0-08-101879-8.00014-0>
66. Rooney, W. L., Blumenthal, J., Bean, B., & Mullet, J. E. (2007). Designing sorghum as a dedicated bioenergy feedstock. In *Biofuels, Bioproducts and Biorefining* (Vol. 1, Issue 2, pp. 147–157). <https://doi.org/10.1002/bbb.15>
67. Rotundo, J. L., Salinas, A., Gomara, N., Borrás, L., & Messina, C. (2024). Maize outyielding sorghum under drought conditions helps explain land use changes in the US. *Field Crops Research*, 308, 109298.
68. Rroço, E., Kosegarten, H., Harizaj, F., Imani, J., & Mengel, K. (2003). The importance of soil microbial activity for the supply of iron to sorghum and rape. *European Journal of Agronomy*, 19(4), 487–493. [https://doi.org/10.1016/S1161-0301\(02\)00185-5](https://doi.org/10.1016/S1161-0301(02)00185-5)
69. Sloat, L. L., Davis, S. J., Gerber, J. S., Moore, F. C., Ray, D. K., West, P. C., & Mueller, N. D. (2020). Climate adaptation by crop migration. *Nature communications*, 11(1), 1243.
69. Schaffasz, A., Windpassinger, S., Friedt, W., Snowdon, R., & Wittkop, B. (2019). Sorghum as a novel crop for Central Europe: Using a broad diversity set to dissect temperate-adaptation. *Agronomy*, 9(9). <https://doi.org/10.3390/agronomy9090535>
70. Schittenhelm, S., & Schroetter, S. (2014). Comparison of Drought Tolerance of Maize, Sweet Sorghum and Sorghum-Sudangrass Hybrids. *Journal of Agronomy and Crop Science*, 200(1), 46–53. <https://doi.org/10.1111/jac.12039>
71. Shangguan, W., Hengl, T., Mendes de Jesus, J., Yuan, H., & Dai, Y. (2017). Mapping the global depth to bedrock for land surface modeling. *Journal of Advances in Modeling Earth Systems*, 9(1), 65-88.
72. Shekoofa, A., Balota, M., & Sinclair, T. R. (2014). Limited-transpiration trait evaluated in growth chamber and field for sorghum genotypes. *Environmental and Experimental Botany*, 99, 175-179.
73. Shoemaker, C., Bransby, D., Shoemaker, C. E., & Bransby, D. I. (2010). The Role of Sorghum as a Bioenergy Feedstock. <https://www.researchgate.net/publication/228518249>
74. Tack, J., Lingenfelser, J., & Jagadish, S. K. (2017). Disaggregating sorghum yield reductions under warming scenarios exposes narrow genetic diversity in US breeding programs. *Proceedings of the National Academy of*

Sciences, 114(35), 9296-9301.

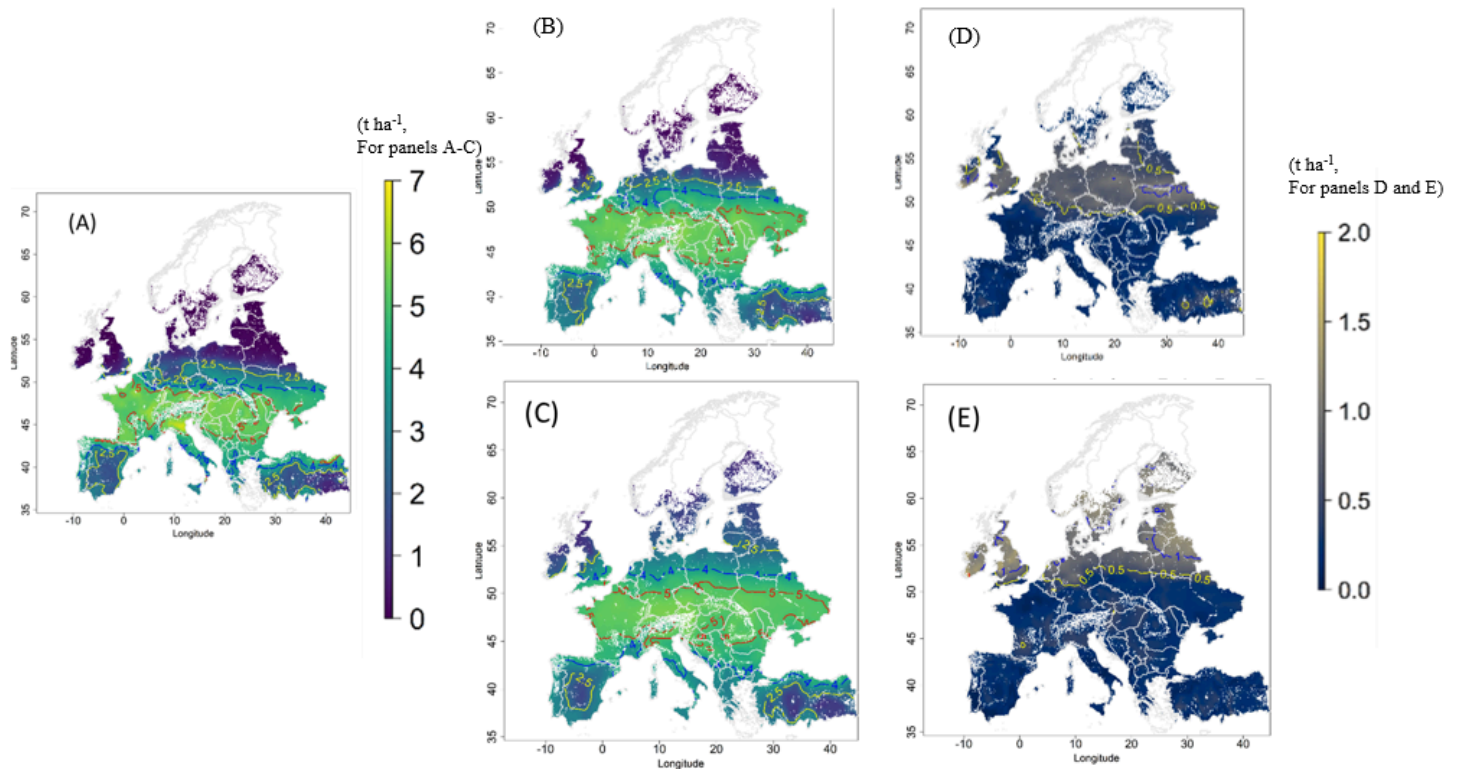
75. Todorovic, M., Caliandro, A., & Albrizio, R. (2007). Irrigated agriculture and water use efficiency in Italy. Shatanawi M. (ed.), Todorovic M.(ed.), Bogliotti C.(ed.), Albrizio R.(ed.). Water use efficiency and water productivity: WASAMED project. Bari: CIHEAM, 101-136.
76. Tóth, Š., Tancik, J., Šoltysová, B., & Porvaz, P. (2023). A case study - The occurrence of pests in stands of newly introduced energy crops in large-scale pilot experiments in conditions of Central Europe. *Agriculture (Pol'nohospodarstvo)*, 69(2), 47–65. <https://doi.org/10.2478/agri-2023-0005>
77. Tubiello, F. N., Donatelli, M., Rosenzweig, C., & Stockle, C. O. (2000). Effects of climate change and elevated CO<sub>2</sub> on cropping systems: model predictions at two Italian locations. In *European Journal of Agronomy* (Vol. 13). [www.elsevier.com/locate/eja](http://www.elsevier.com/locate/eja)
78. United Nations (2022). *World Population Prospects 2022: Summary of Results*. [https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/undesa\\_pd\\_2022\\_wpp\\_key-messages.pdf](https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/undesa_pd_2022_wpp_key-messages.pdf) (Accessed 28 February 2024).
79. USDA IPAD (2024). International Production Assessment Division. <https://ipad.fas.usda.gov/ogamaps/cropcalendar.aspx> (Accessed 28 February 2024)
80. Van Dijk, M., Morley, T., Rau, M. L., & Saghai, Y. (2021). A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nature Food*, 2(7), 494-501.
81. Vautard, R., Cattiaux, J., Hap  , T., Singh, J., Bonnet, R., Cassou, C., ... & Yiou, P. (2023). Heat extremes in Western Europe increasing faster than simulated due to atmospheric circulation trends. *Nature Communications*, 14(1), 6803.
82. Vijayalakshmi, D., Priya, J. R., Vinitha, A., & Ramya, G. (2024). Interactive effects of elevated CO<sub>2</sub> with combined heat and drought stresses on the physiology and yield of C3 and C4 plants. *Journal of Crop Science and Biotechnology*, 27(1), 1-16.
83. Von Cossel, M., Lewandowski, I., Elbersen, B., Staritsky, I., Van Eupen, M., Iqbal, Y., Mantel, S., Scordia, D., Testa, G., Cosentino, S. L., Maliarenko, O., Eleftheriadis, I., Zanetti, F., Monti, A., Lazdina, D., Neimane, S., Lamy, I., Ciadamidaro, L., Sanz, M., ... Alexopoulou, E. (2019). Marginal agricultural land low-input systems for biomass production. *Energies*, 12(16). <https://doi.org/10.3390/en12163123>
84. Wright, M. N., & Ziegler, A. (2017). Ranger: A fast implementation of random forests for high dimensional data in C++ and R. *Journal of Statistical Software*, 77(1). <https://doi.org/10.18637/jss.v077.i01>
85. Yang, M., Zhao, H., Xian, X., Qi, Y., Li, Q., Guo, J., Chen, L., & Liu, W. (2023). Reconstructed Global Invasion and Spatio-Temporal Distribution Pattern Dynamics of Sorghum halepense under Climate and Land-Use Change. *Plants*, 12(17). <https://doi.org/10.3390/plants12173128>

## Table

Table 1. Potential production of sorghum in Europe under future climate scenarios. These estimates assume 33% of cropland area in a grid-cell cultivated with sorghum (i.e., sorghum one year out of three in crop rotation). The suitable area for growing sorghum is defined as grid-cells with an average inter-annual yield higher than 4 t ha<sup>-1</sup> (the average sorghum yield in Europe in the last 20 years) and an inter-annual yield standard variation less than 0.5 t ha<sup>-1</sup>. While the standard variation criterion was consistently applied across all models, we retained only those grid cells that met the average yield threshold in at least 4 out of 5 models.

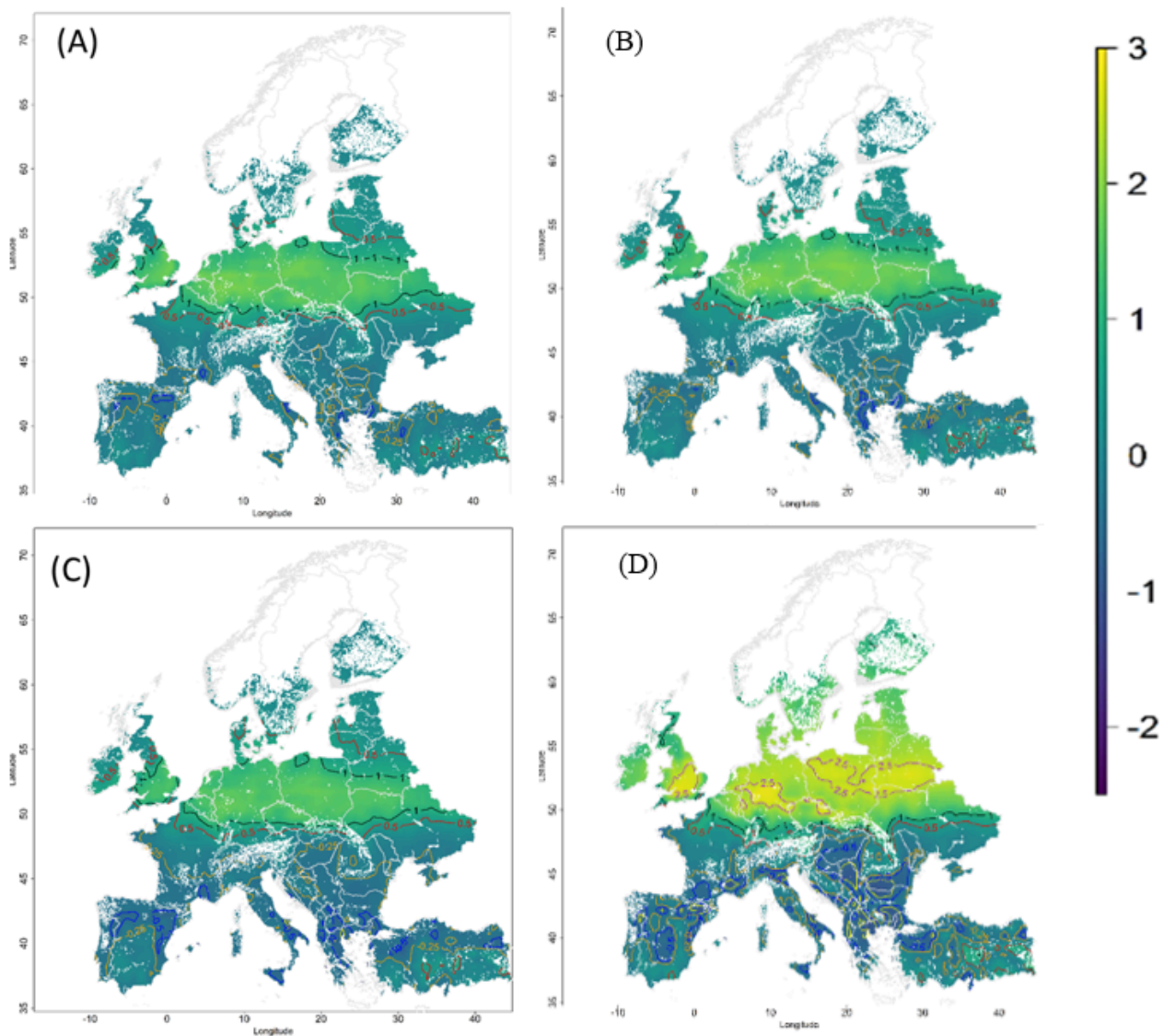
Scenario	Time period	Potential sorghum production (Mt)
Historical	1995-2014	72
SSP1-RCP2.6	mid-century (2041-2060)	79
SSP5-RCP8.5	mid-century (2041-2060)	95
SSP1-RCP2.6	end-century (2081-2100)	98
SSP5-RCP8.5	end-century (2081-2100)	111

## Figures



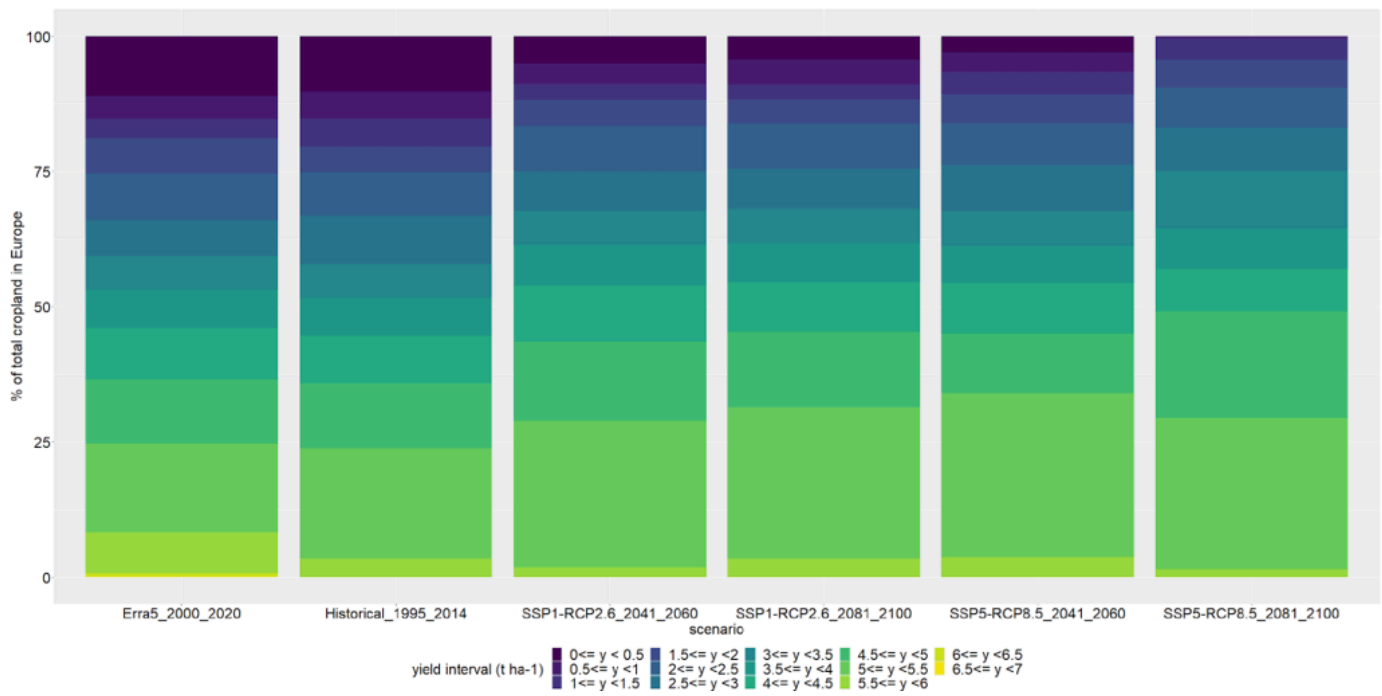
**Figure 1**

Sorghum yield projections in Europe under current and future climates. (A) Mean projected sorghum yield ( $t\ ha^{-1}$ ) using ERA5-land dataset for current climate (2000-2020). Mean (B, C) and standard variation (D, E) of projected sorghum yield ( $t\ ha^{-1}$ ) over the five global climate models for future climate scenarios by end-century (2081-2100) under SSP1-RCP2.6 (B, D) and SSP5-RCP8.5 (C, E), respectively. The higher the standard variation over the five global climate models, the higher the disagreement between sorghum yield projections using climate projections from the different climate models. See text for details.



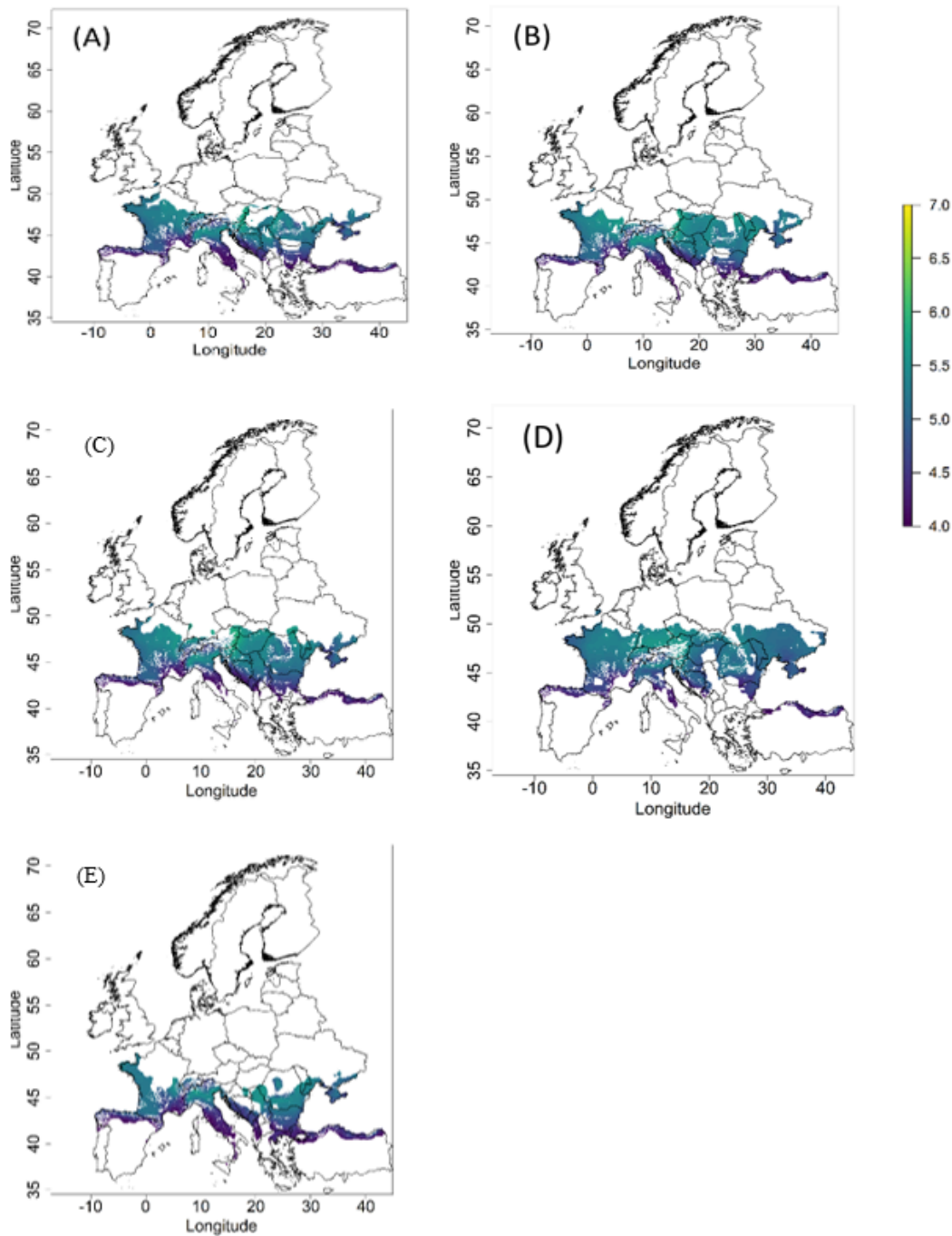
**Figure 2**

Difference in projected mean yields ( $\text{t ha}^{-1}$ ) between future and historical conditions (1995-2014). (A, B) Differences in mean projected sorghum yield over the five global climate models for future climate scenarios between mid-century (2041-2060) (A), end-century (2081-2100) (B), under SSP1-RCP2.6, and historical climate (1995-2014). Differences in mean projected sorghum yield over the five global climate models for future climate scenarios between mid-century (2041-2060) (C), end-century (2081-2100) (D) under SSP5-RCP8.5, and historical climate (1995-2014).



**Figure 3**

Percentage of total cropland area (198 Mh, based on the cropland area reported for the year 2000) with different average yield levels under current and historical (current (Erra5)\_2000-2020, historical\_1995-2014) and future climates (SSP1-RCP2.6 and SSP5-RCP8.5 for two time periods: mid-century (2041-2060) and end-century (2081-2100)).



**Figure 4**

Cropland area with high and consistent sorghum yield (an average inter-annual yield higher than  $4 \text{ t ha}^{-1}$  and an inter-annual yield standard variation less than  $0.5 \text{ t ha}^{-1}$ ). While the standard variation criterion was consistently applied across all models, we retained only those grid cells that met the average yield threshold in at least 4 out of 5 models, ensuring a robust and conservative selection of suitable sorghum cultivation areas. (A, B) suitable area over the five global climate models (Eyring et al., 2016) for future climate scenarios for mid-century (2041-2060) under SSP1-RCP2.6 and SSP5-RCP8.5 with 24% and 29% of the total cropland, respectively. (C, D) suitable areas over the five global climate models for future climate scenarios for the end-century (2081-2100) under SSP1-RCP2.6 and SSP5-RCP8.5 with 29% and 34% of the total cropland, respectively. (E) suitable areas over the five global climate models for historical climate between 1995-2014 with 22% of the total cropland.

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryMaterialDavoudkhanietal.docx](#)