Global warming increases the chance of success of maize-wheat double cropping in Europe

Authors

Yang Su [a, b], Ronny Lauerwald [a], David Makowski [c], Nicolas Viovy [b], Nicolas Guilpart [d], Peng Zhu [b, e], Benoit Gabrielle [a], Philippe Ciais [b]

Affiliations

[a] UMR ECOSYS, INRAE AgroParisTech, Université Paris-Saclay, 91120 Palaiseau, France

[b] Laboratoire des Sciences du Climat et de l'Environnement, CEA CNRS UVSQ Orme des Merisiers, 91190 Gif-sur-Yvette, France

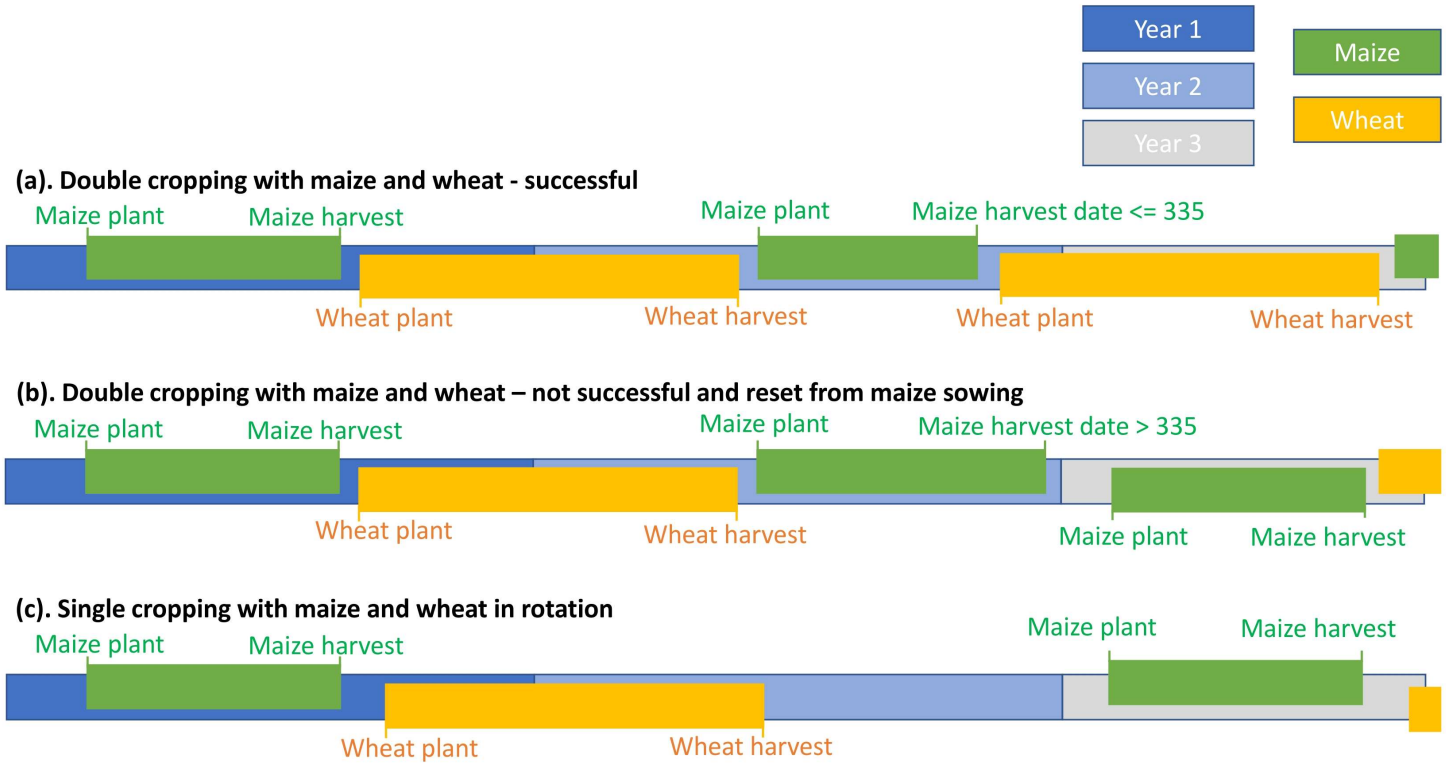
[c] Unit Applied mathematics and computer science (MIA 518), INRAE AgroParisTech, Université Paris-Saclay, 91120 Palaiseau, France

[d] UMR Agronomie, INRAE AgroParisTech, Université Paris-Saclay, 91120 Palaiseau, France

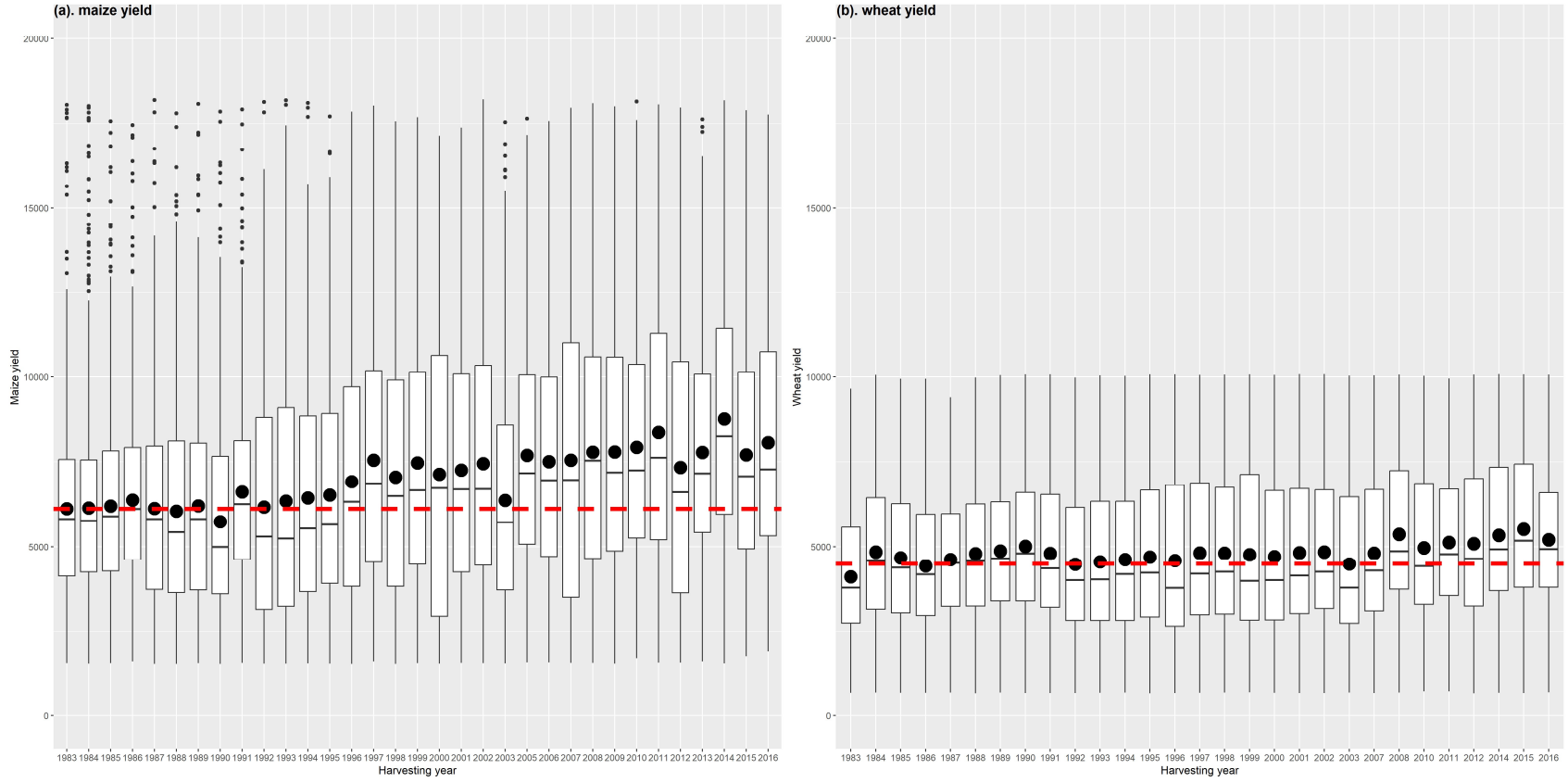
[e] Department of Geography, The University of Hong Kong, Hong Kong SAR, China

Corresponding Author

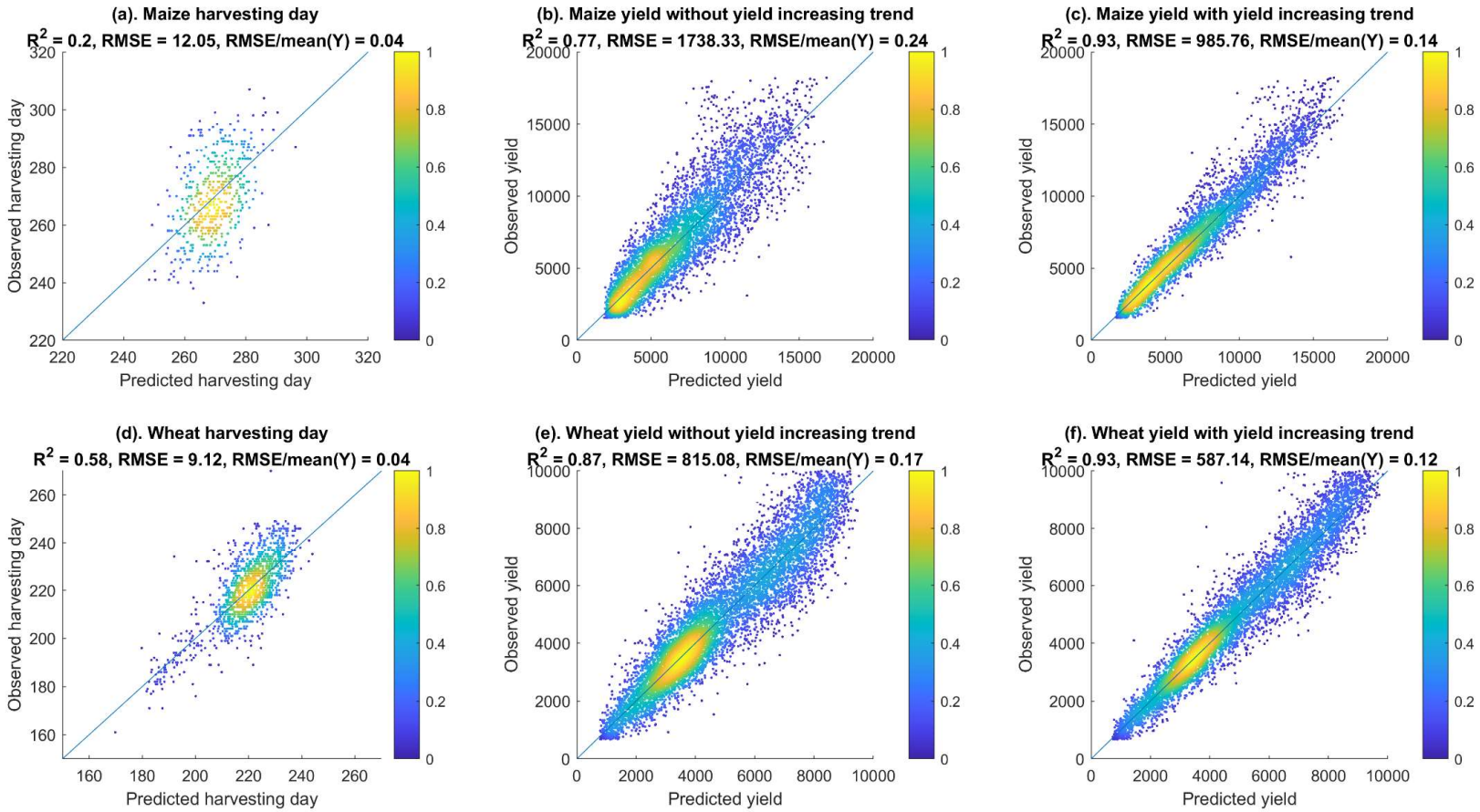
Yang Su yang.su@inrae.fr +33 1 89 10 07 67 INRAE AgroParisTech



Supplementary figure 1 | Cropping scheme setting. In this study, we defined two cropping schemes: plot a, b for double cropping with maize and wheat, plot c for single cropping with maize and wheat in rotation. For the double cropping with maize and wheat, we initialized the crop sequence with maize, the initial plant date of maize is based on the crop calendar dataset [1]. The time interval between the harvest and the subsequent crop planting is set at 14 days. After the maize harvest, there is a 14-day gap before the planting of wheat, and the same applies in the opposite direction. Plot a, double cropping is successfully implemented when maize is predicted to harvest before 335 Julian day (1st December) [2]. Plot b, if the predicted maize harvest date is later than 335 Julian day, we define this as a failure of maize-wheat double, and we set the maize yield at this year to zero and restart the double cropping from maize on the initial planting date next year. Plot c, for single cropping with maize and wheat in rotation, we set the plant date of both maize and wheat based on the crop calendar dataset [1].

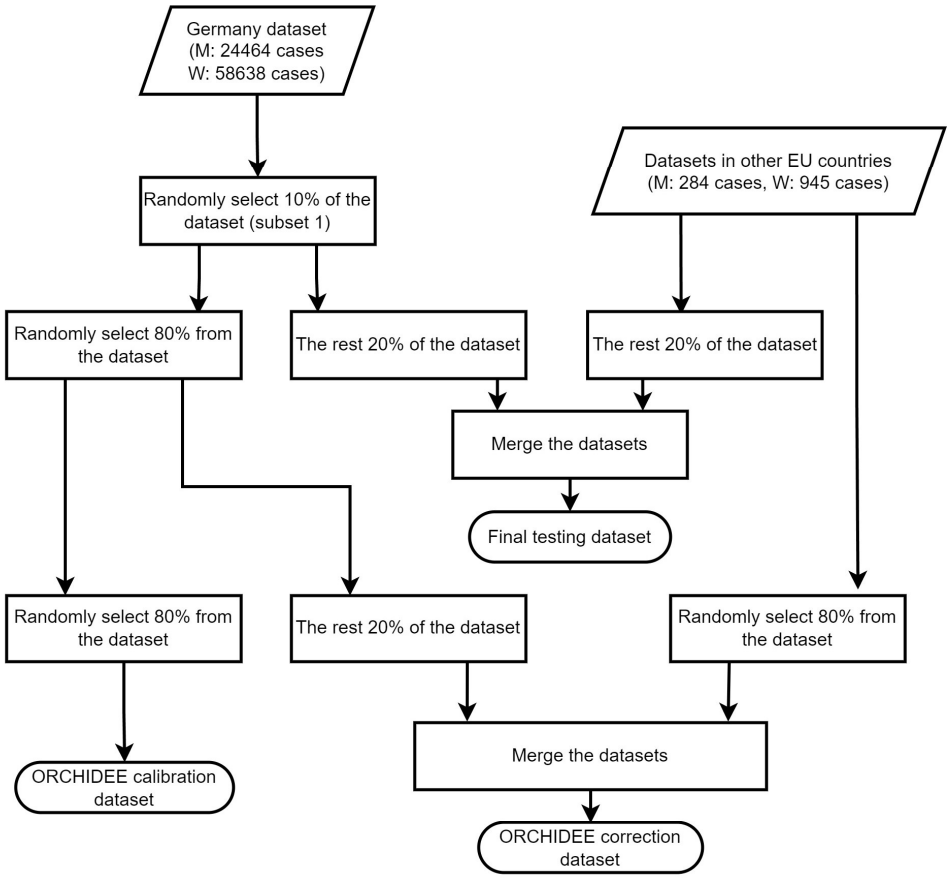


Supplementary figure 2 | Boxplots of historical maize and wheat yield used in this study [3]**.** Plot a is the boxplot of maize yield from 1983 to 2016, plot b is the boxplot of wheat yield from 1983 to 2016. The horizontal line in the box is the median yield in the year, while the black dot is the mean yield. The red dash line is the reference line, which equals to the mean yield of the first two years.

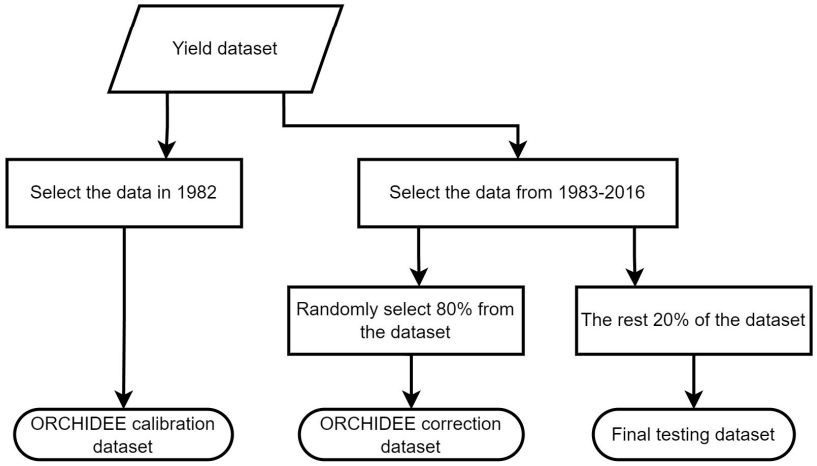


Supplementary figure 3 | Final model performance – scatterplot of observations versus prediction from different hybrid models. Plot a is the performance of the maize harvest date model. Plot b is the performance of the maize yield model without considering the yield increasing trend. Plot c is the performance of the maize yield model that considers the yield increasing trend. Plot d is the performance of the wheat harvest day model. Plot e is the performance of the wheat yield model without considering the yield increasing trend. Plot f is the performance of the wheat yield model that considers the yield increasing trend. The yellow color indicates a higher density, while the bluish color indicates a lower data density.

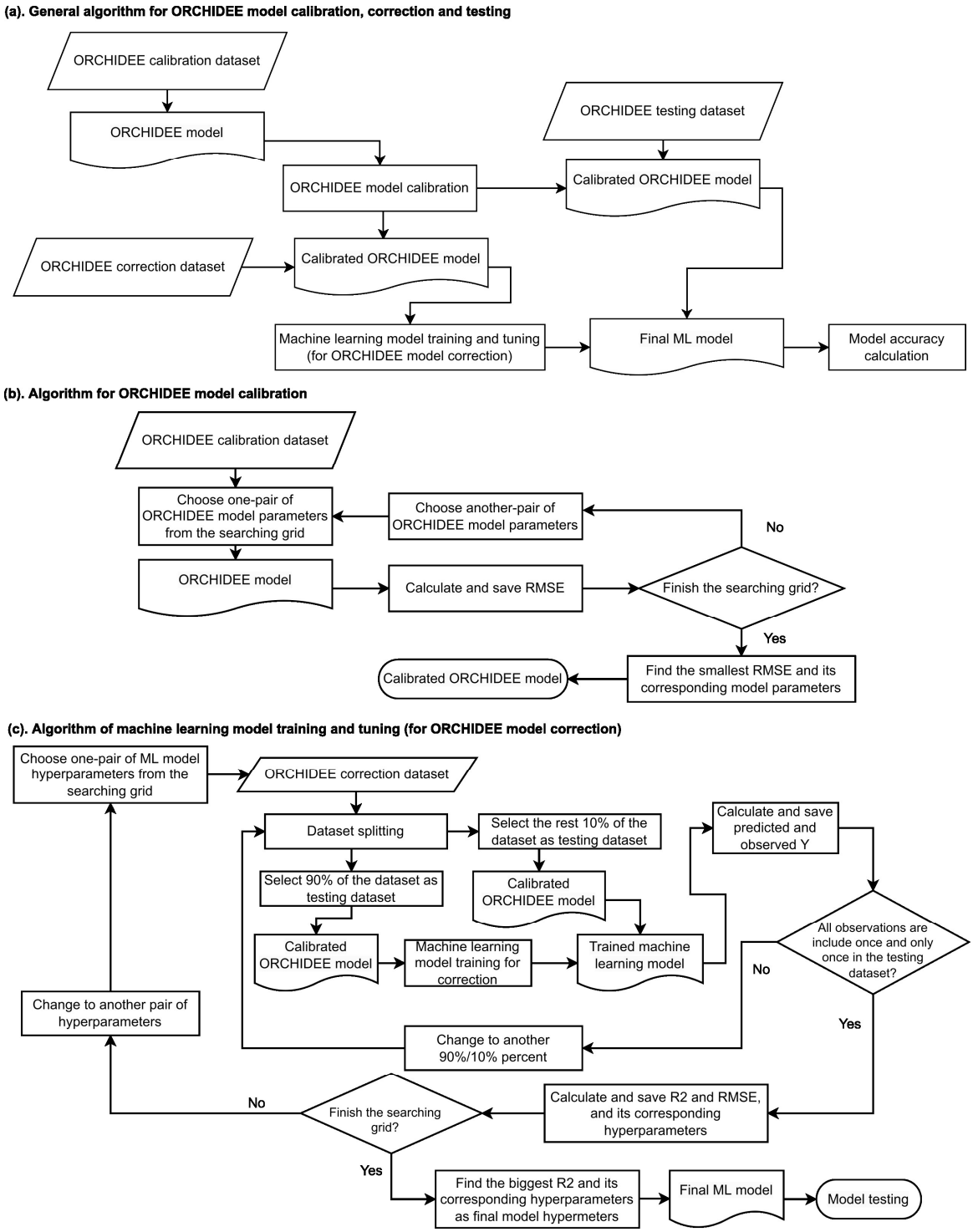
(a). Phenology dataset splitting of maize and wheat



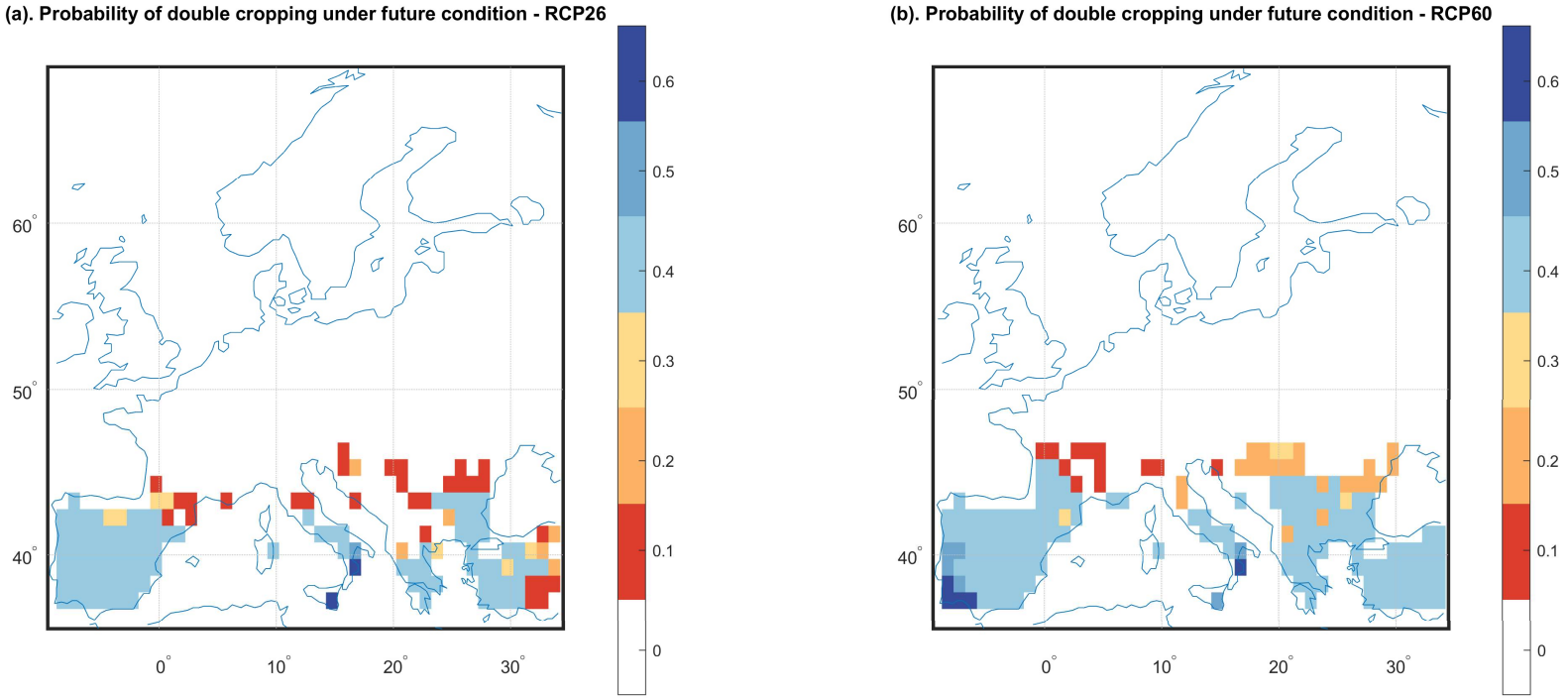
(b). Yield dataset splitting of maize and wheat



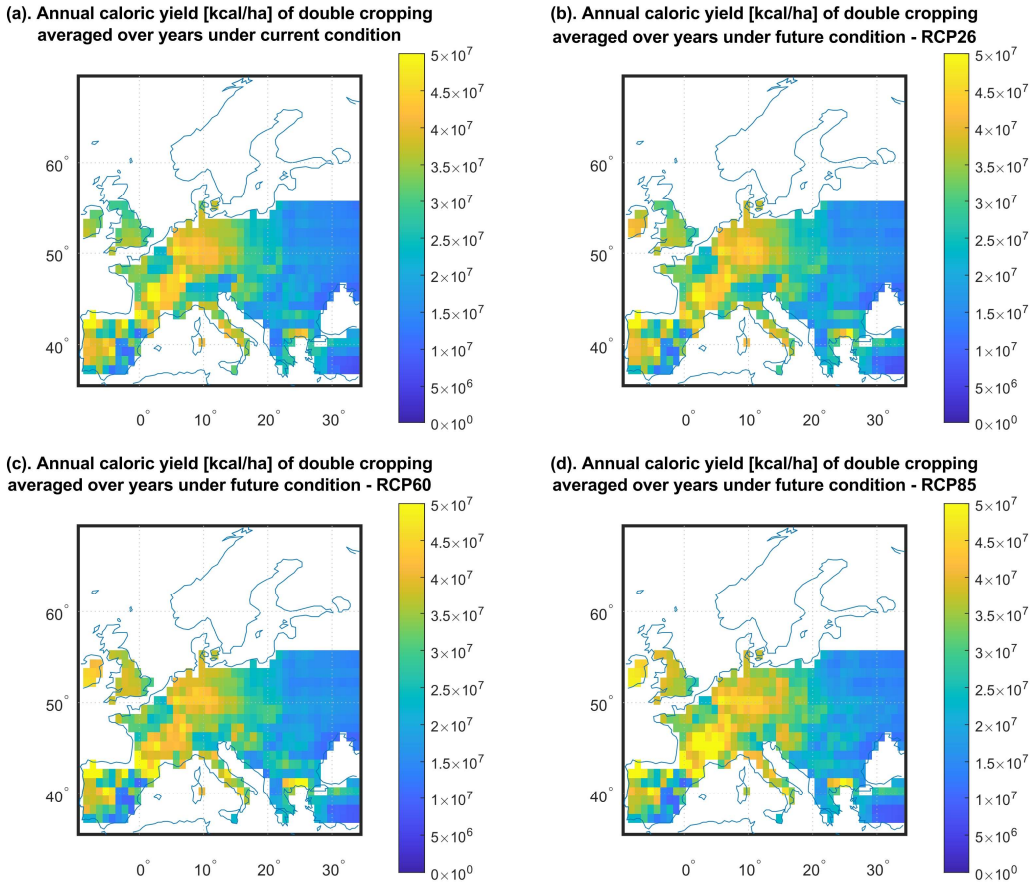
Supplementary figure 4 | Dataset splitting. The maize and wheat phenology [4,5] (plot a) and yield [3] (plot b) datasets are split into three sub-datasets, one for ORCHIDEE-CROP calibration; one for machine learning model training and tuning for ORCHIDEE-CROP output adjustment; and one for model testing.



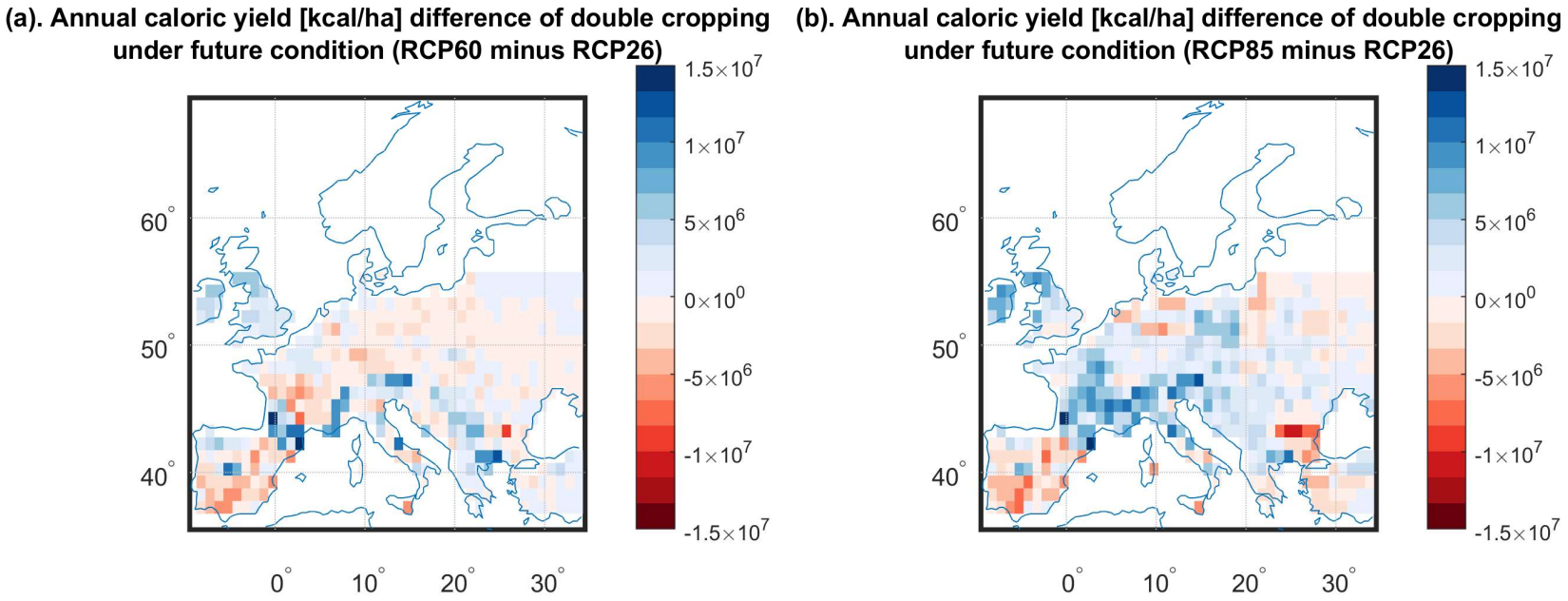
Supplementary figure 5 | Algorithms for ORCHIDEE-CROP calibration, adjustment, and testing. Plot a is the overall algorithm for model calibration, adjustment, and testing. Plot b is the algorithm for ORCHIDEE-CROP calibration. Plot c is the algorithm for machine learning training and tuning, which is used to adjust ORCHIDEE-CROP prediction.



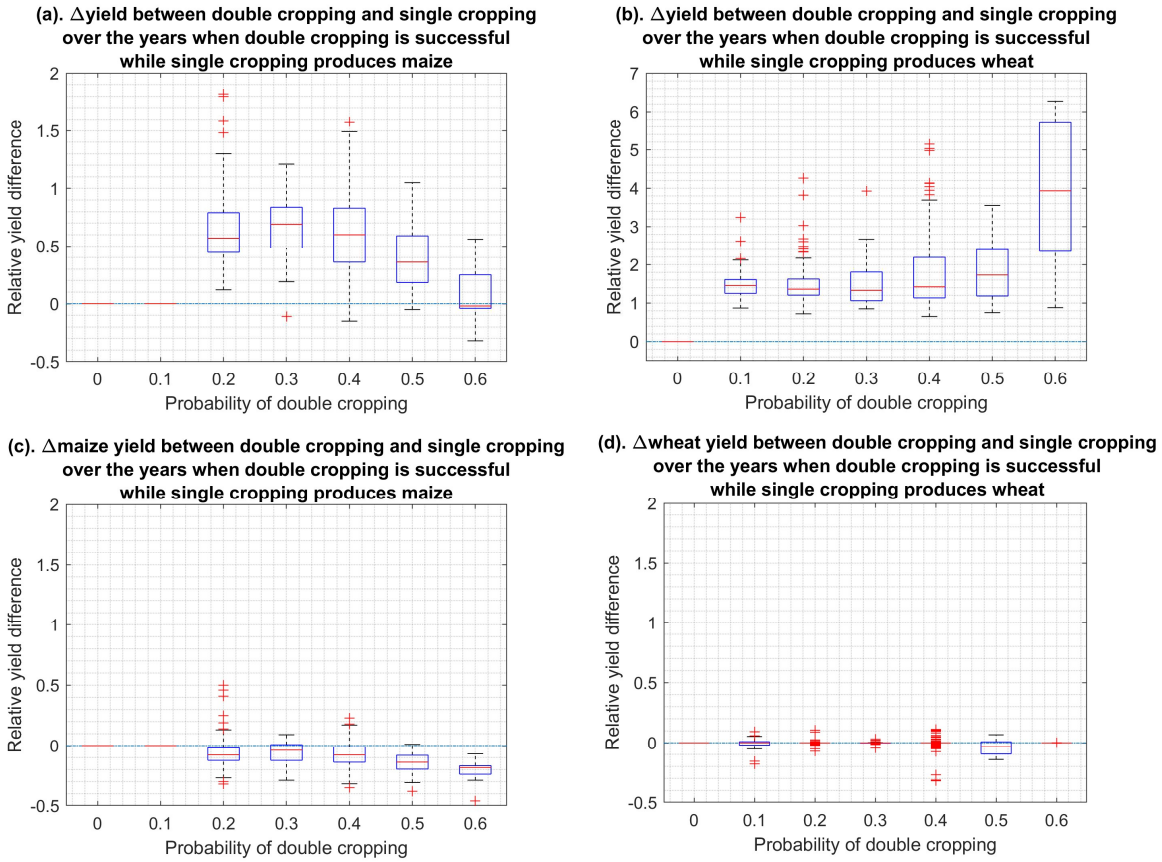
Supplementary figure 6 | Probability of successfully implementing maize-wheat double cropping under future RCP 2.6 and RCP 6.0 climate conditions. Plot a represents the probability of successfully implementing double cropping under future RCP 2.6 climate conditions (from 2089 to 2100). Plot b represents the probability of successfully implementing double cropping under future RCP 6.0 climate conditions (from 2089 to 2100). The reddish color indicates that there is less chance of successful implementation of double cropping, while the bluish color indicates that there is higher chance of successful implementation of double cropping.



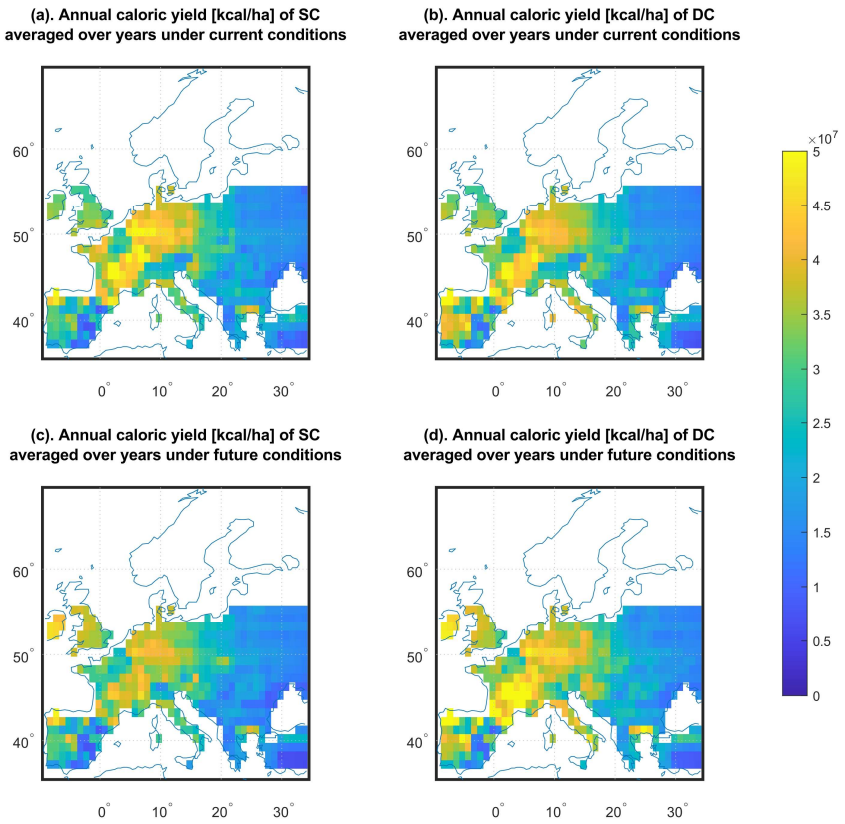
Supplementary figure 7 | Annual caloric yield of maize-wheat double cropping under current and future climate conditions. Plot a represents the annual caloric yield of double cropping averaged over years under current climate conditions (from 2009 to 2020). Plot b represents the annual caloric yield of double cropping averaged over years under future RCP 2.6 climate conditions (from 2089 to 2100). Plot c represents the annual caloric yield of double cropping averaged over years under future RCP 6.0 climate conditions (from 2089 to 2100). Plot d represents the annual caloric yield of double cropping averaged over years under future RCP 8.5 climate conditions (from 2089 to 2100). All results are from the yield model without considering the yield increasing trend. The yellow color indicates that the caloric production is higher, while the bluish color indicates that the caloric production is lower.



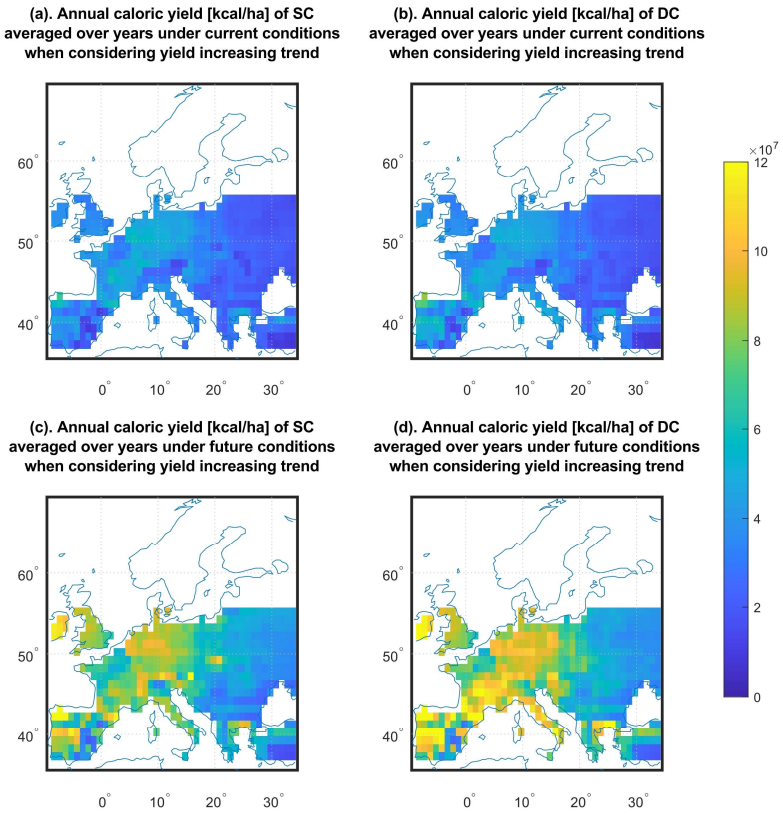
Supplementary figure 8 | Annual caloric yield difference of double cropping under RCP 6.0/ RCP 8.5 scenarios versus RCP 2.6 scenario. Plot a represents the annual caloric yield difference of double cropping under RCP 6.0 versus RCP 2.6 scenario. Plot b represents the annual caloric yield difference of double cropping under RCP 8.5 versus RCP 2.6 scenario. All results are from the yield model without considering the yield increasing trend. The bluish color indicates that the annual caloric yield from RCP 6.0 or RCP 8.5 is higher, while the reddish color indicates that the annual caloric yield from RCP 6.0 or RCP 8.5 is lower compared to RCP 2.6 scenario.



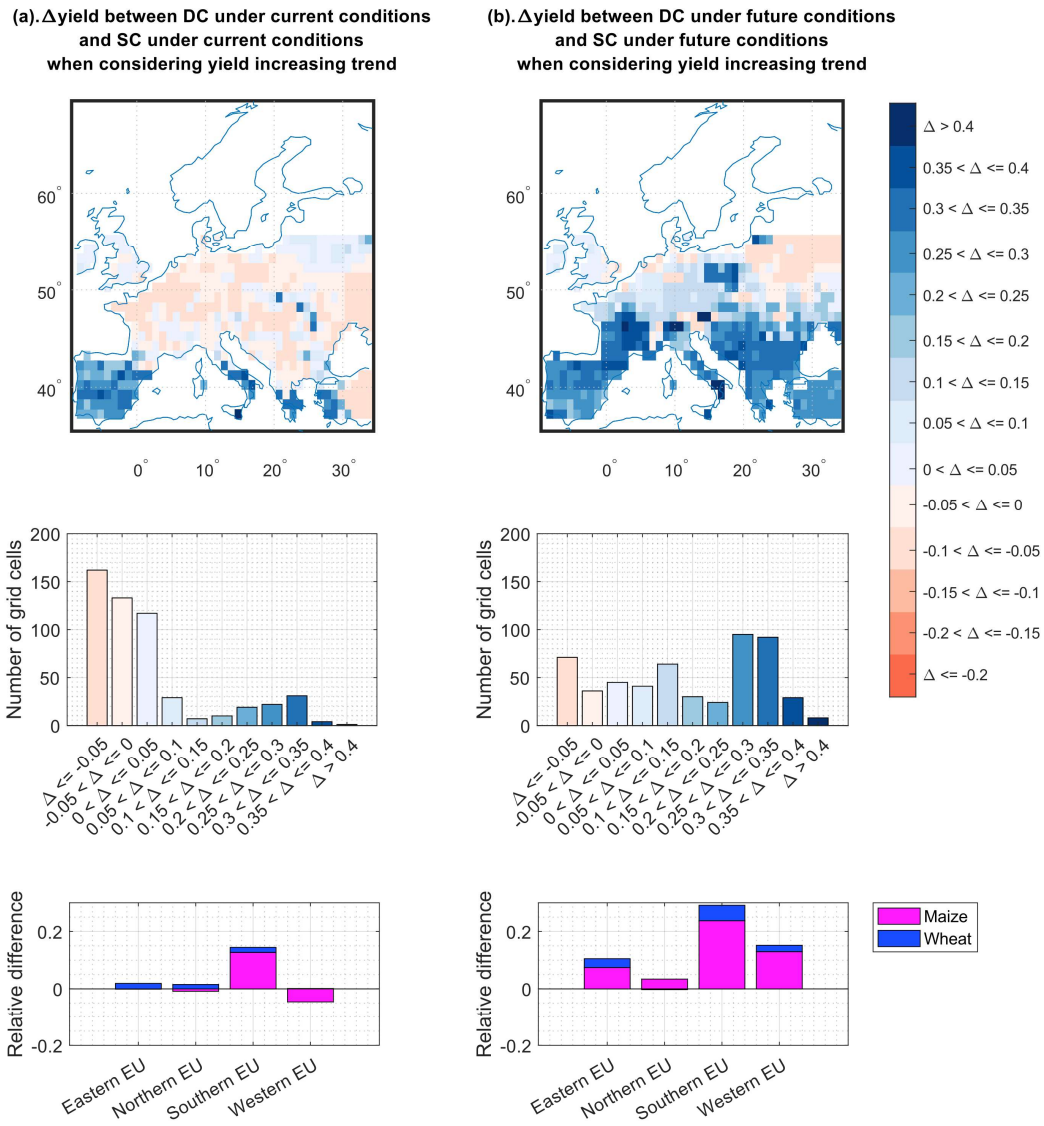
Supplementary figure 9 | Comparison of calorie production of double cropping versus single cropping under future climate conditions (RCP 8.5) under different probability of successful implementation probability of double cropping. *Plot a is the relative caloric yield difference (*$\Delta yield$*) of double cropping and single cropping* $\left(\frac{Yield_{double\ cropping} - Yield_{single\ cropping}}{Yield_{single\ cropping}}\right)$ *while the single cropping produces maize simultaneously. Plot b is the relative caloric yield difference of double cropping and single cropping while the single cropping produces wheat simultaneously. Plot c is the relative maize caloric yield difference of double cropping and single cropping while the single cropping produces wheat simultaneously. Plot d is the relative wheat caloric yield difference of double cropping and single cropping while the single cropping produces wheat simultaneously.*



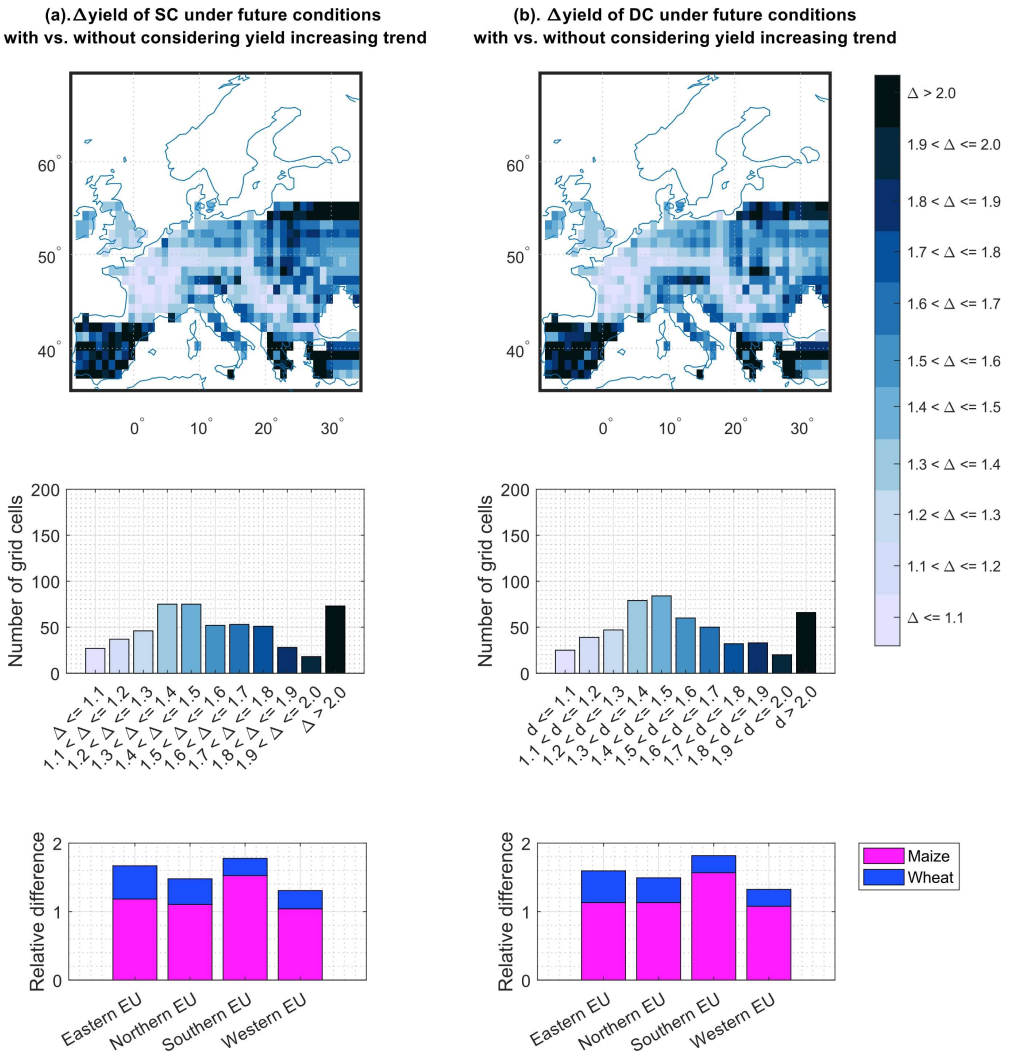
Supplementary figure 10 | Calorie production of double cropping with maize and wheat vs. single cropping with maize and wheat in rotation under current and future (RCP 8.5) climate conditions. Plot a represents the annual caloric yield of single cropping (SC) with maize and wheat in rotation averaged over years under current climate conditions (from 2009 to 2020). Plot b represents the annual caloric yield of double cropping (DC) with maize and wheat averaged over years under current climate conditions (from 2009 to 2020. Plot c represents the annual caloric yield of single cropping (SC) with maize and wheat in rotation averaged over years under future climate conditions (RCP 8.5 scenario from 2089 to 2100). Plot d represents the annual caloric yield of double cropping (DC) with maize and wheat averaged over years under future climate conditions (RCP 8.5 from 2089 to 2100). All results are from the yield model without considering the yield increasing trend. The yellow color indicates that the caloric production is higher, while the bluish color indicates that the caloric production is lower.



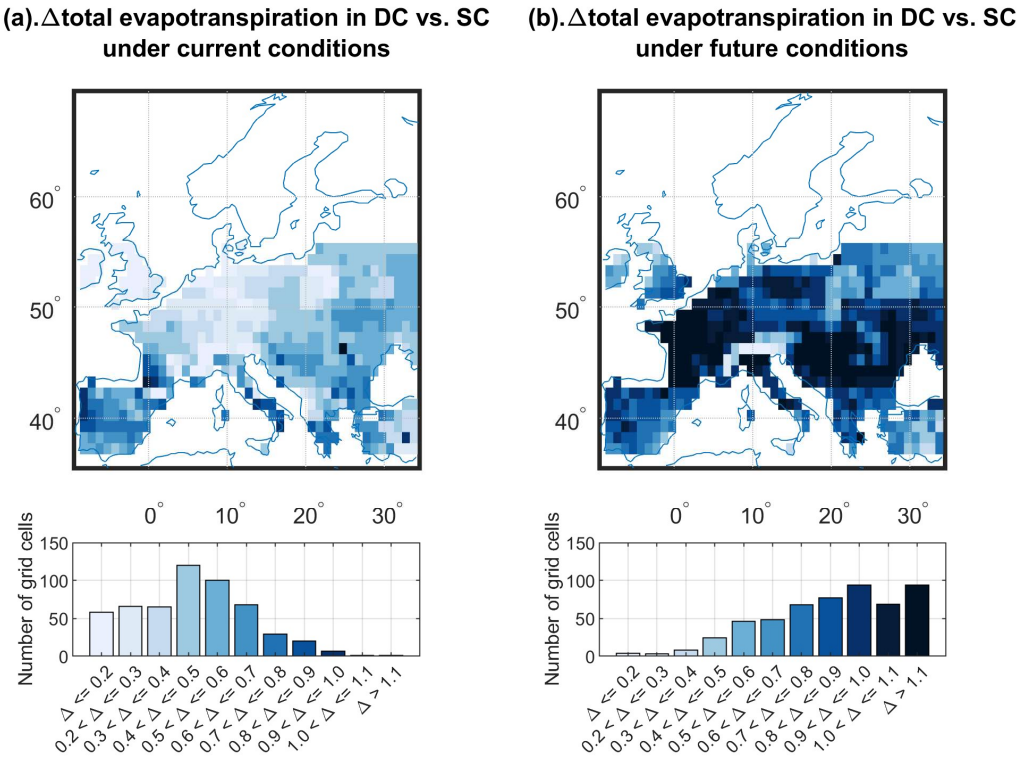
Supplementary figure 11 | Calorie production of double cropping with maize and wheat vs. single cropping with maize and wheat in rotation under current and future (RCP 8.5) climate conditions when considering the yield increasing trend. Plot a represents the annual caloric yield of single cropping (SC) with maize and wheat in rotation averaged over years under current climate conditions (from 2009 to 2020). Plot b represents the annual caloric yield of double cropping (DC) with maize and wheat averaged over years under current climate conditions (from 2009 to 2020. Plot c represents the annual caloric yield of single cropping (SC) with maize and wheat in rotation averaged over years under future climate conditions (RCP 8.5 scenario from 2089 to 2100). Plot d represents the annual caloric yield of double cropping (DC) with maize and wheat averaged over years under future climate conditions (RCP 8.5 from 2089 to 2100). All results are from the yield model with considering the yield increasing trend. The yellow color indicates that the caloric production is higher, while the bluish color indicates that the caloric production is lower.



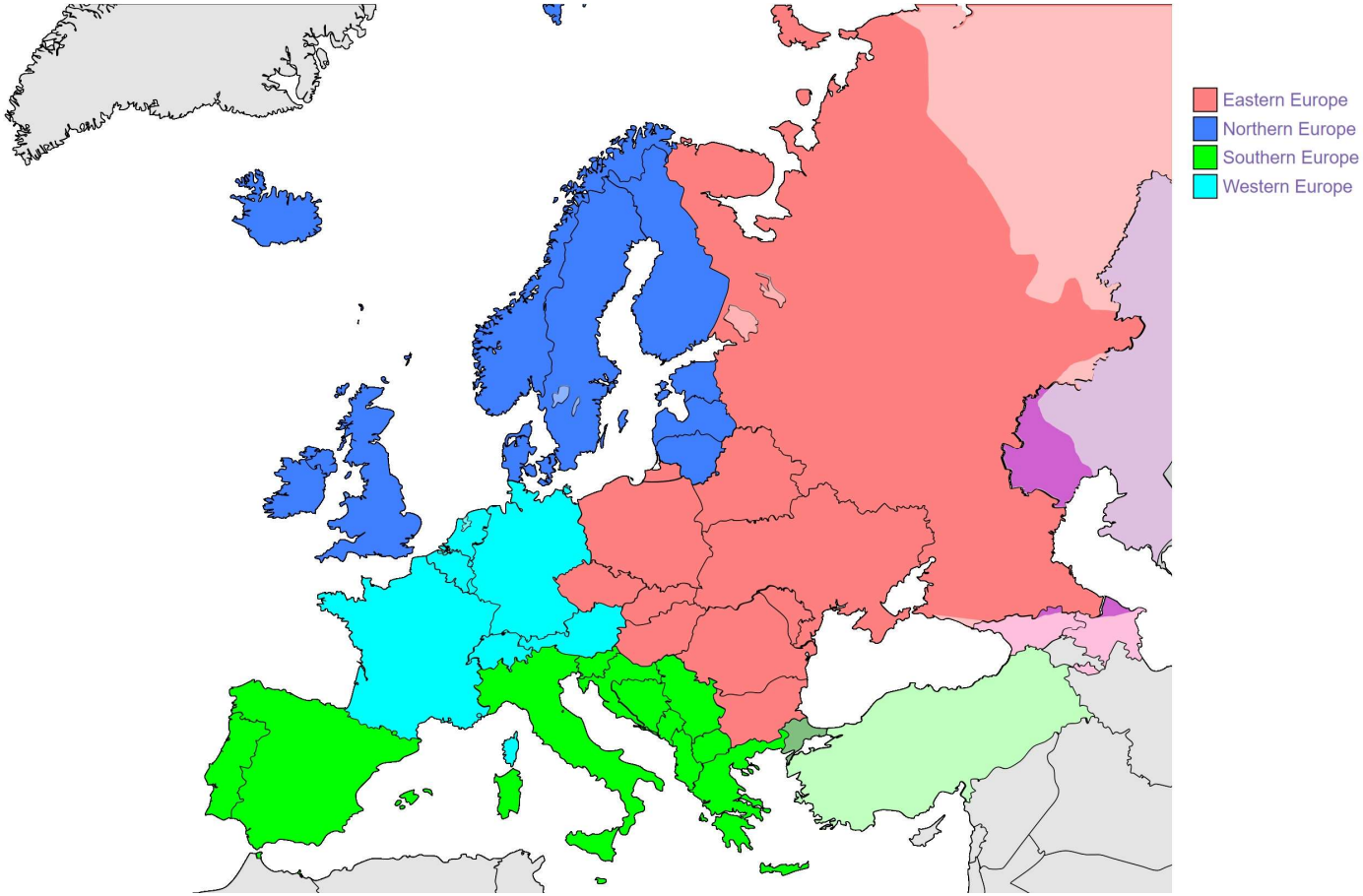
Supplementary figure 12 | Analysis of the caloric yield of double cropping and single cropping systems in Europe under different climate conditions when considering the yield increasing trend. *Plot a represents the relative caloric yield of double cropping (DC) with maize and wheat versus single cropping (SC) with maize and wheat in rotation* $\left(\Delta yield = \frac{Yield_{DC,\ current} - Yield_{SC,\ current}}{Yield_{SC,\ current}}\right)$ *under current climate conditions (2009-2020) when considering the yield increasing trend, the bar plot in the second row shows the number of grid cells as a function of different relative difference of caloric yield of double cropping and single cropping, the bar plot in the third row shows the relative difference on the caloric yield of maize* $\left(\frac{Maize\ Yield_{DC,\ current} - Maize\ Yiel_{SC,\ current}}{Maize\ Yield_{SC,\ current}}\right)$ *and wheat* $\left(\frac{Wheat\ Yield_{DC,\ current} - Whe\quad Yiel_{SC,\ current}}{Wheat\ Yield_{SC,\ current}}\right)$ *under current climate conditions. Plot b represents the relative caloric yield of double cropping system (DC) versus single cropping system (SC) under future climate conditions (2089-2100, RCP 8.5 scenario)* $\left(\Delta yield = \frac{Yiel_{DC,\ future} - Yiel_{SC,\ future}}{Yield_{SC,\ future}}\right)$ *when considering the yield increase trend, the bar plot in the second row shows the number of grid cells as a function of different relative difference of caloric yield of double cropping versus single cropping under future climate conditions, the bar plot in the third row shows the relative difference on the caloric yield of maize* $\left(\frac{Maize\ Yield_{DC,\ future} - Maize\ Yield_{SC,\ future}}{Maize\ Yield_{SC,\ future}}\right)$ *and wheat* $\left(\frac{Wheat\ Yield_{DC,\ future} - Wheat\ Yield_{SC,\ future}}{Wheat\ Yield_{SC,\ future}}\right)$ *from double cropping versus single cropping under current climate conditions.*



Supplementary figure 13 | Analysis of the caloric yield of double cropping and single cropping systems in Europe under future climate conditions when considering the yield increasing trend versus without considering the yield increasing trend. *Plot a represents the relative caloric yield of single cropping (SC) with maize and wheat in rotation* $\left(\Delta yield = \frac{Yield_{SC,\ with\ yield\ increasing\ trend} - Yield_{SC,\ witho\quad yield\ increasing\ trend}}{Yield_{SC,\ without\ yield\ increasing\ tren}}\right)$*, under future climate conditions (2089-2100, RCP 8.5) when considering the yield increasing trend versus when without considering the yield increasing trend, the bar plot in the second row shows the number of grid cells as a function of different relative difference of caloric yield of single cropping with and without considering yield increasing trend, the bar plot in the third row shows the relative difference on the caloric yield of maize* $\left(\frac{Maize\ Yield_{SC,\ with\ yield\ increasing\ trend} - Maize\ Yield_{SC,\ without\ yield\ increasing\ trend}}{Maize\ Yield_{SC,\ witho\quad yield\ increasing\ trend}}\right)$ *and wheat* $\left(\frac{Wheat\ Yield_{SC,\ with\ yield\ increasing\ trend} - Wheat\ Yield_{SC,\ without\ yield\ increasing\ trend}}{Wheat\ Yiel\ _{SC,\ without\ yiel\quad increasing\ trend}}\right)$ *under future climate conditions. Plot b represents the relative caloric yield of double cropping (DC)* $\left(\Delta yield = \frac{Yield_{double\ cropping,\ with\ yield\ increasing\ trend} - Yield_{double\ cropping,\ without\ yield\ increasing\ trend}}{Yield_{double\ cropping,\ without\ yield\ increasing\ trend}}\right)$*, under future climate conditions (2089-2100, RCP 8.5) when considering the yield increasing trend versus when without considering the yield increasing trend, the bar plot in the second row shows the number of grid cells as a function of different relative difference of caloric yield of double cropping with and without considering yield increasing trend, the bar plot in the third row shows the relative difference on the caloric yield of maize* $\left(\frac{Maize\ Yield_{DC,\ with\ yield\ increasing\ trend} - Maize\ Yiel\ _{DC,\ without\ yield\ increasing\ trend}}{Maize\ Yield_{DC,\ without\ yield\ increasing\ trend}}\right)$ *and wheat* $\left(\frac{Wheat\ Yiel\ _{DC,\ with\ yield\ increasing\ trend} - Wheat\ Yiel\ _{DC,\ without\ yield\ increasing\ trend}}{Wheat\ Yiel\ _{DC,\ without\ yield\ increasing\ trend}}\right)$ *under future climate conditions.*



Supplementary figure 14 | Relative difference in total evapotranspiration in double cropping vs. single cropping under current and future conditions. Plot a is the relative difference in total evapotranspiration of double cropping (DC) with maize and wheat vs. single cropping (SC) with maize and wheat in rotation under current climate conditions. Plot b is the relative difference in total evapotranspiration of double cropping (DC) with maize and wheat vs. single cropping (SC) with maize and wheat in rotation under future climate conditions. Note that even though the double cropping is not always successfully implemented, the maize is always planted after wheat.



Supplementary figure 15 | Subregions of Europe. We split Europe into Eastern, Western, Southern and Northern Europe based on United Nations geoscheme [6]. Northern Europe was restricted to regions where maize and wheat are both cultivated [7,8], and it only includes the UK, Ireland and a few areas in Denmark and Lithuania.

Reference

1. Sacks, W. J., Deryng, D., Foley, J. A. & Ramankutty, N. Crop planting dates: an analysis of global patterns. *Global Ecology and Biogeography* no-no (2010) doi:10.1111/j.1466-8238.2010.00551.x.

2. United States Department of Agriculture (USDA). Crop Calendars for Europe. https://ipad.fas.usda.gov/rssiws/al/crop_calendar/europe.aspx (2023).

3. Iizumi, T. & Sakai, T. The global dataset of historical yields for major crops 1981–2016. *Sci Data* **7**, 97 (2020).

4. PEP725. Pep725: Pan European Phenology Data. http://www.zamg.ac.at/pep725/index.php (2010).

5. Deutscher Wetterdienst. CDC (Climate Data Center). https://opendata.dwd.de/climate_environment/CDC/ (2020).

6. United Nations Statistics Division. Countries or areas / geographical regions. https://unstats.un.org/unsd/methodology/m49/ (1999).

7. Portmann, F. T., Siebert, S. & Döll, P. MIRCA2000-Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling. *Global Biogeochem Cycles* **24**, (2010).

8. Su, Y., Gabrielle, B. & Makowski, D. The impact of climate change on the productivity of conservation agriculture. *Nat Clim Chang* (2021) doi:10.1038/s41558-021-01075-w.