*Supplement of*

# Resolving effects of leaf pigmentation changes and plant residue on the energy balance of winter wheat cultivation in the ORCHIDEE-CROP model

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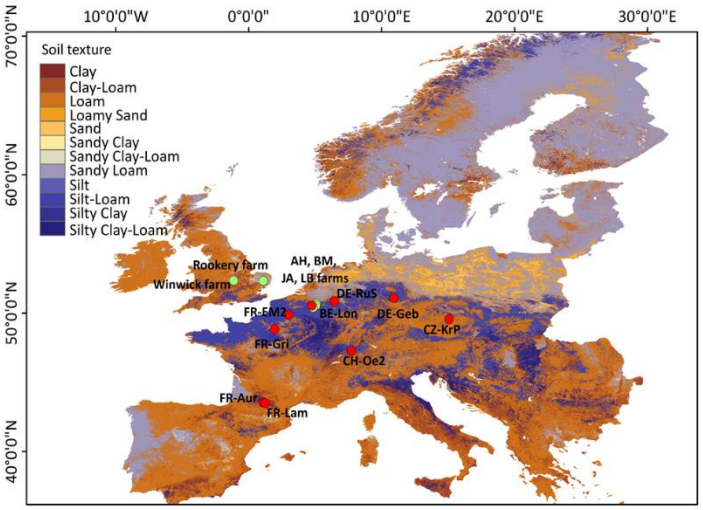
- Supplementary Figures
- Supplementary Tables

**Supplementary figures**




15 **Figure S1** Distribution of the 10 European cropland sites used in the analysis. Data is obtained from two eddy covariance datasets (ICOS (red) and ClienFarm project (green)). The background data is a 0.01° soil texture map.

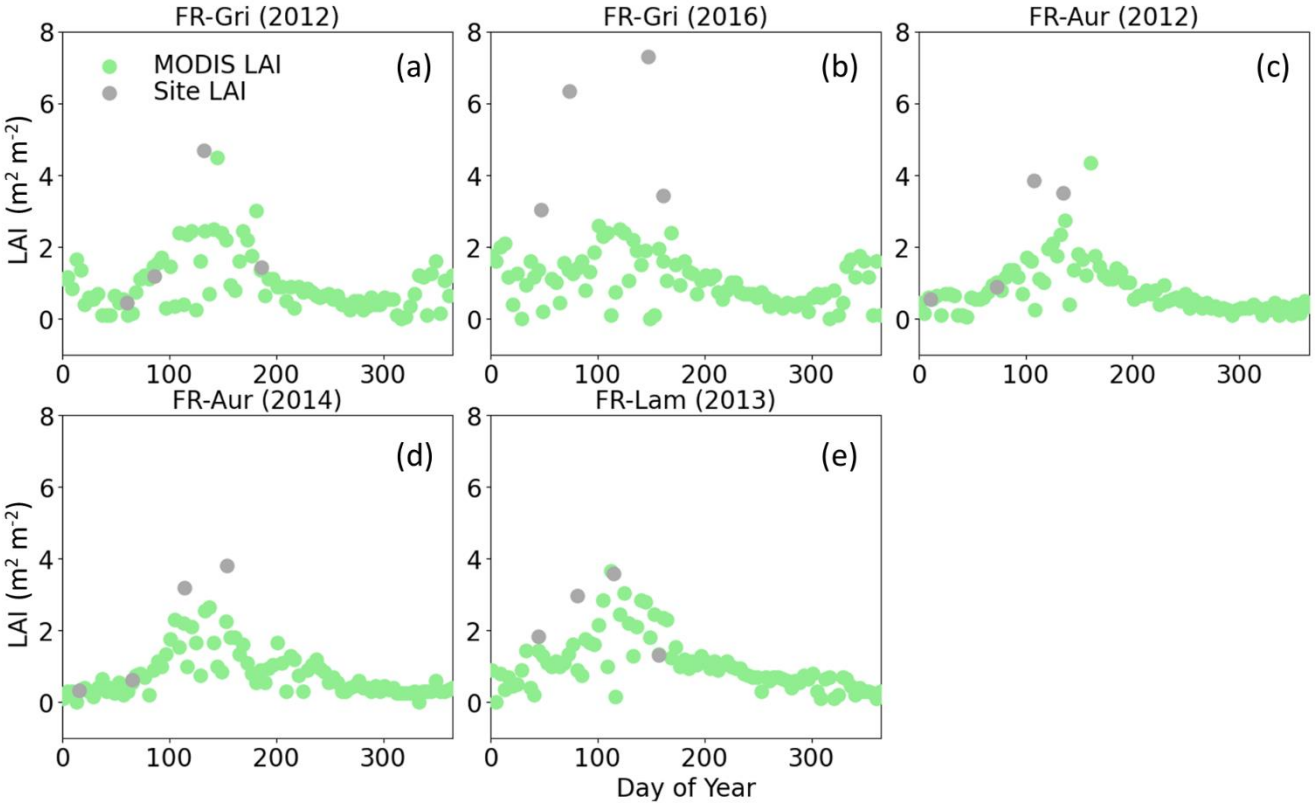



**Figure S2** Comparison of leaf area index (LAI) between daily satellite-based product (4-day, 500-m MCD15A3H) and site measurements at 3 ICOS sites in different years.

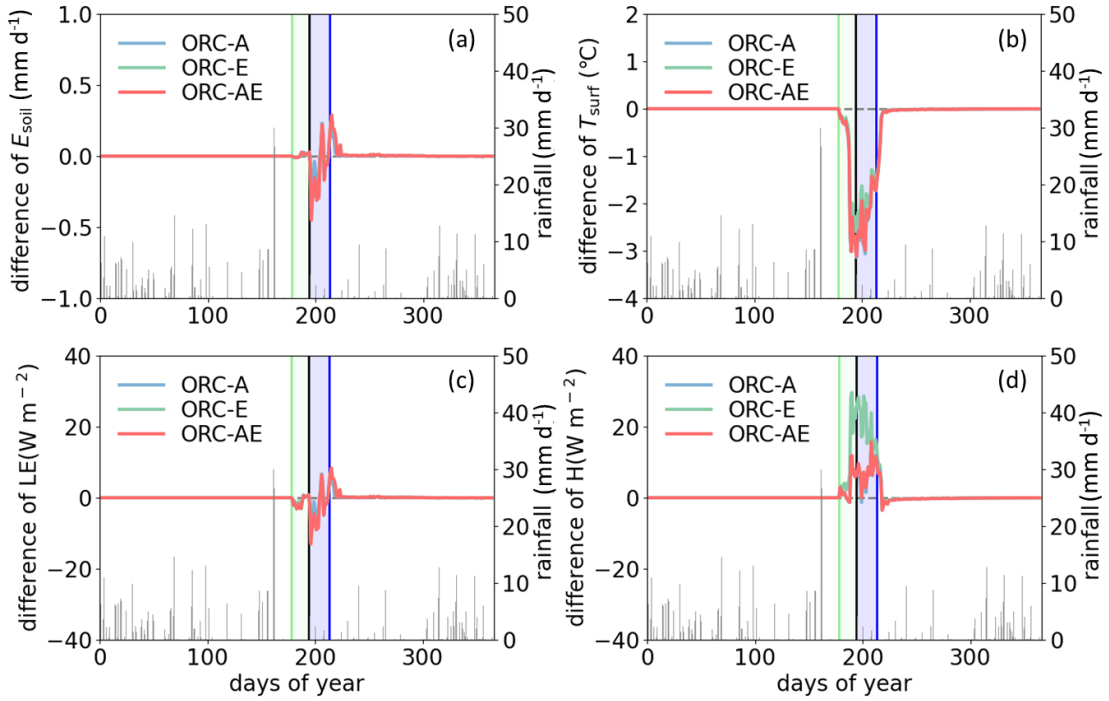



**Figure S3** The effect of model refinements on the (a) soil evaporation ($E_{soil}$), (b) surface temperature ($T_{surf}$), (c) latent heat flux (LE) and (d) sensible heat flux (H) among different experiments at the FR-Gri site in 2018. Shown are the differences between the new model and the old model. ORC-A (blue line) represents the modified surface albedo ($\alpha_{surf}$) in the ORCHIDEE-CROP model. In ORC-E (green line), both the soil conductance ($\beta_4$) and surface roughness ($Z_0$) were adjusted in the ORCHIDEE-CROP model. ORC-AE (red line) extends these modifications by adjusting $\alpha_{surf}$, $\beta_4$ and $Z_0$ together in the ORCHIDEE-CROP model. The green, black and blue solid lines are the simulated start of the foliar yellowing period (shallow green area), harvesting dates and the end of the residue covering period (shallow blue area), respectively. The gray bars in the right y-axis are the daily rainfall derived from site observation.

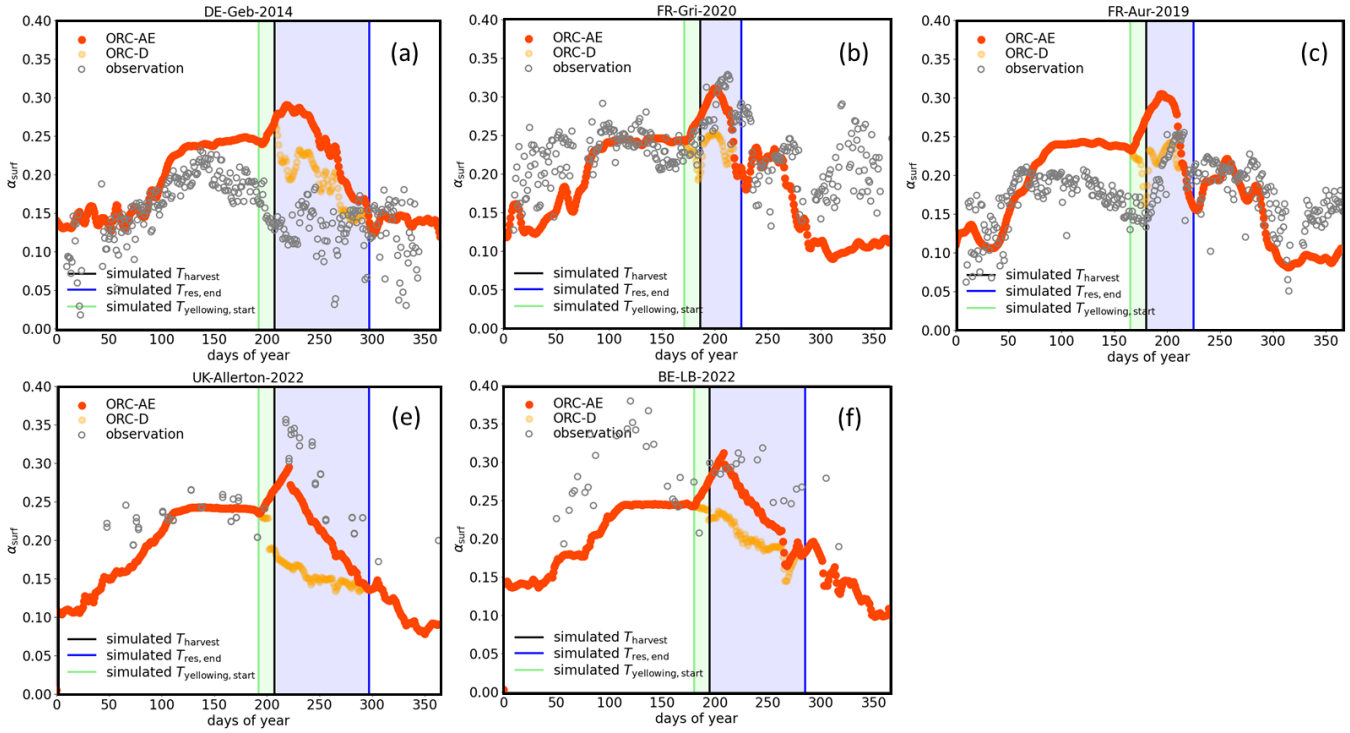



**Figure S4** The comparison of surface albedo ($\alpha_{surf}$) predicted from the old (orange dots) and new (red dots) ORCHIDEE-CROP models and observations (gray dots) at 5 test sites in Europe. The observed $\alpha_{surf}$ in (a), (b) and (c) is derived from site eddy covariance measurements through the Integrated Carbon Observation System (ICOS) Data Portal, while $\alpha_{surf}$ observation in (d) and (e) is derived from 5-day 300m Sentinel-2 $\alpha_{surf}$ product (Lin et al., 2023). The black and blue solid lines are the simulated harvesting dates ($T_{harvest}$) and the recorded tillage date ($T_{tillage}$), respectively. The green, black and blue solid lines are the simulated start of the foliar yellowing period (shallow green area), harvesting date and the end of residue covering period (shallow blue area), respectively.

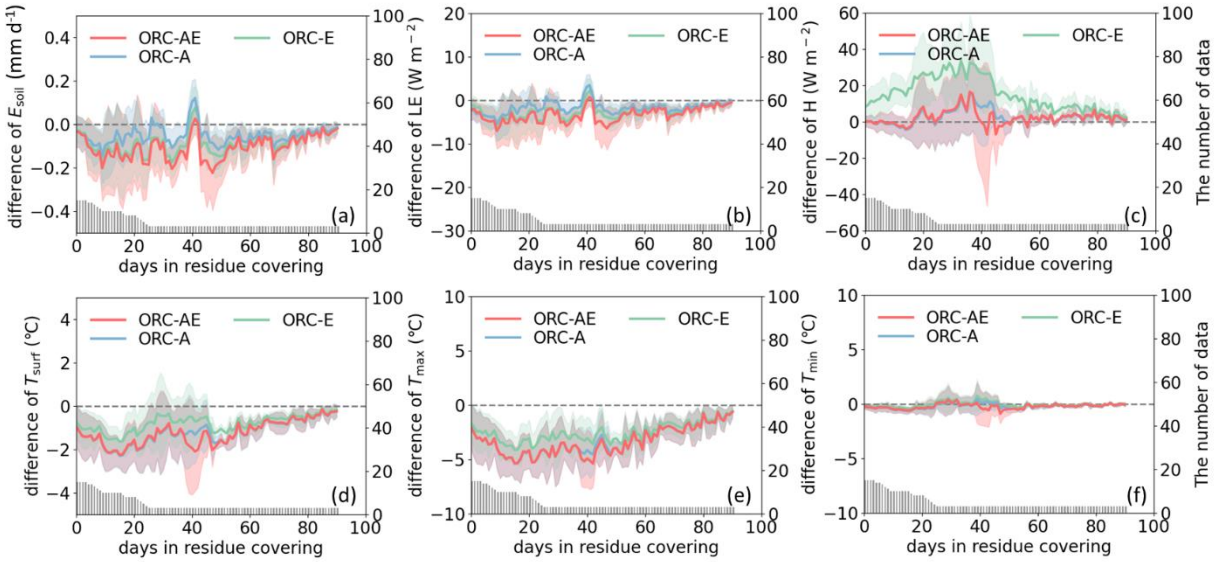



**Figure S5** Daily changes of soil evaporation ($E_{soil}$), surface temperature ($T_{surf}$), latent and sensible heat fluxes (LE and H), maximum and minimum surface temperature ($T_{max}$ and $T_{min}$) from the old model in ORC-A (blue line), ORC-E (green line), ORC-AE (orange line) experiments in 90 days during residue covering periods across 12 sites. ORC-A represents the modified surface albedo ($\alpha_{surf}$) in the ORCHIDEE-CROP model. In ORC-E, both the soil conductance ($\beta_4$) and surface roughness ($Z_0$) were adjusted in the ORCHIDEE-CROP model. ORC-AE extends these modifications by adjusting $\alpha_{surf}$, $\beta_4$ and $Z_0$ together in the ORCHIDEE-CROP model. Areas in different colors represent the standard deviation of variables across all sites in each experiment. Gray bars on the right y-axis indicate the number of data points per site.

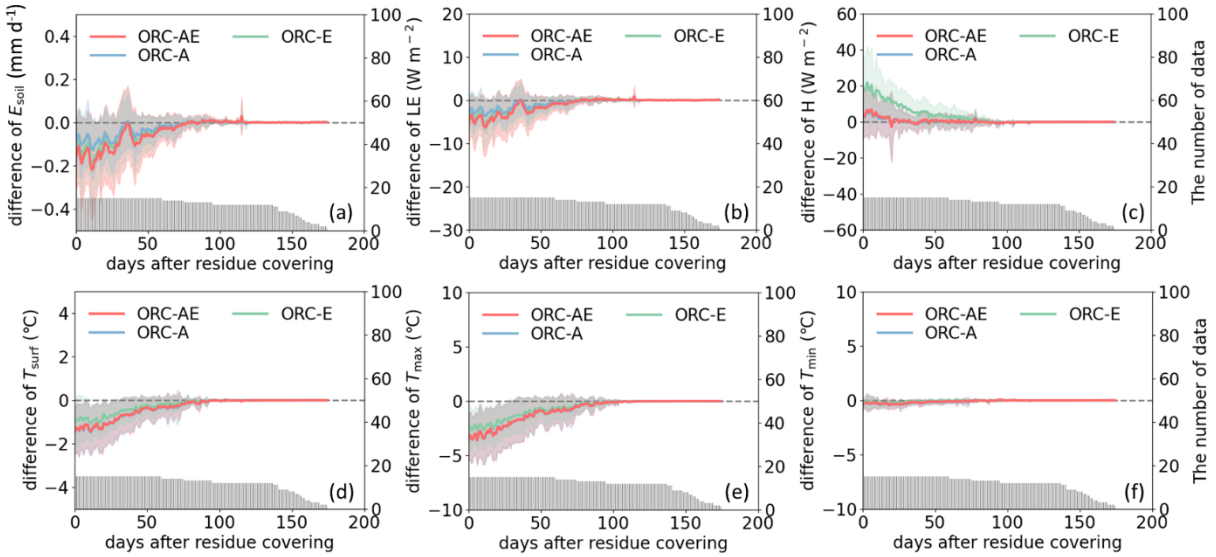



**Figure S6** Daily changes of soil evaporation ($E_{soil}$), surface temperature ($T_{surf}$), latent and sensible heat fluxes (LE and H), maximum and minimum surface temperature ($T_{max}$ and $T_{min}$) from the old model in ORC-A (blue line), ORC-E (green line), ORC-AE (orange line) experiments in days after residue covering periods in the harvest years across 12 sites. ORC-A represents the modified surface albedo ($\alpha_{surf}$) in the ORCHIDEE-CROP model. In ORC-E, both the soil conductance ($\beta_4$) and surface roughness ($Z_0$) were adjusted in the ORCHIDEE-CROP model. ORC-AE extends these modifications by adjusting $\alpha_{surf}$, $\beta_4$ and $Z_0$ together in the ORCHIDEE-CROP model. Areas in different colors represent the standard deviation of variables across all sites in each experiment. Gray bars on the right y-axis indicate the number of data points per site.

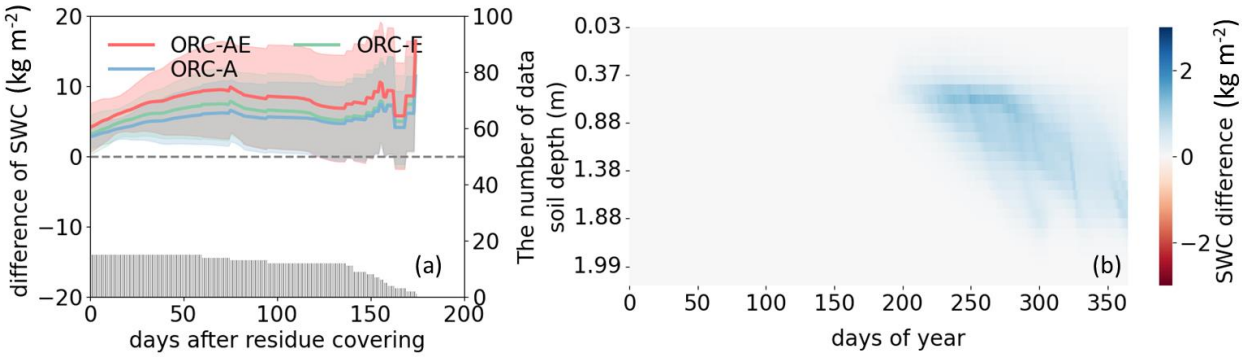



**Figure S7** Daily changes of total soil water content (SWC) (a) and SWC in different layers up to 2 m (b) in ORC-A (blue line), ORC-E (green line), ORC-AE experiments (orange line) compared with the old model in days after residue covering periods in the harvest years across 12 sites. ORC-A represents the modified surface albedo ($\alpha_{surf}$) in the ORCHIDEE-CROP model. In ORC-E, both the soil conductance ($\beta_4$) and surface roughness ($Z_0$) were adjusted in the ORCHIDEE-CROP model. ORC-AE extends these modifications by adjusting $\alpha_{surf}$, $\beta_4$ and $Z_0$ together in the ORCHIDEE-CROP model. Areas in different colors represent ranges of standard deviation of SWC across all sites. The gray bars on the right y-axis indicate the number of data points per day.

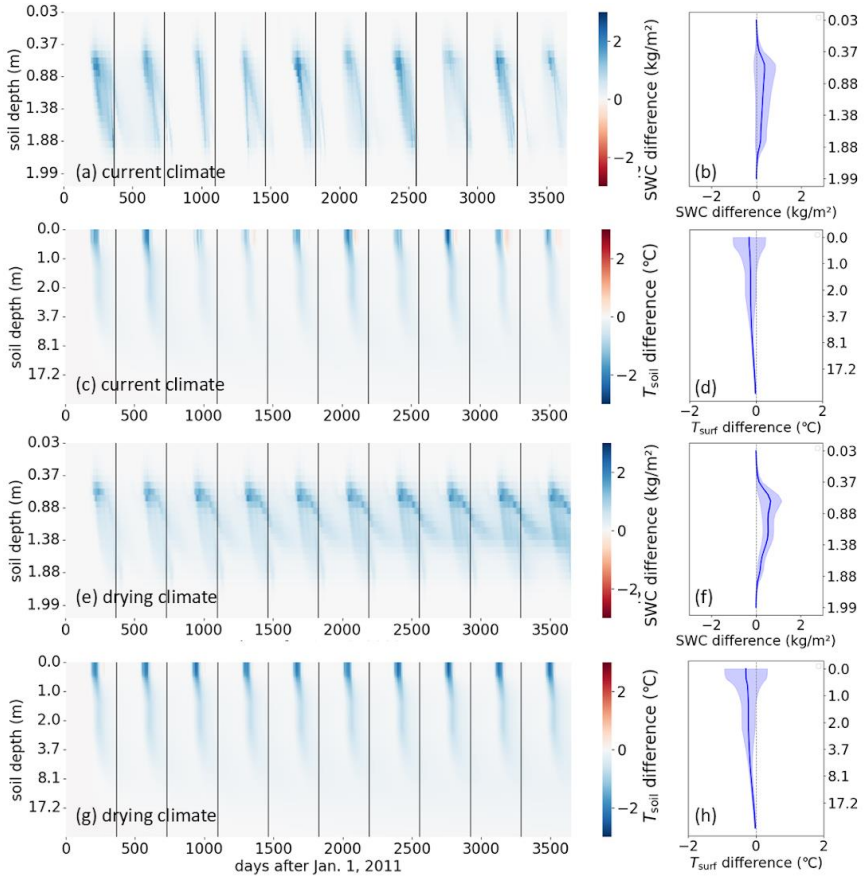



**Figure S8** Simulation of soil water content (SWC) and soil temperature ($T_{soil}$) differences between the new (ORC-AE) and old (ORC-D) models for winter wheat over a 10-year period (2010–2020) at 6 sites. ORC-AE extends these modifications by adjusting surface albedo ($\alpha_{surf}$), soil conductance ($\beta_4$) and surface roughness ($Z_0$) together in the ORCHIDEE-CROP model. Shows are only from the year of 2011 and residue cover persists for 60 days post-harvest each year. The SWC is within 2 m depths with 27 soil layers while $T_{soil}$ is within 10 m with 90 soil layers. (a)-(d) represent the current scenarios using climate forcing data from the Integrated Carbon Observation System (ICOS) Data Portal. While (e)-(h) shows drying scenarios using ICOS climate forcing data for the year with minimal annual rainfall. (a) and (e) show SWC differences by soil depth, with yearly averages at each soil depth shown in (b) and (f). (c) and (g) show $T_{soil}$ differences by soil depth, with yearly averages at each soil depth in (d) and (h). The blue areas in (b), (d), (f) and (h) represent the standard deviations. The vertical black solid lines in (a), (c), (e) and (g) are the beginning of each year.

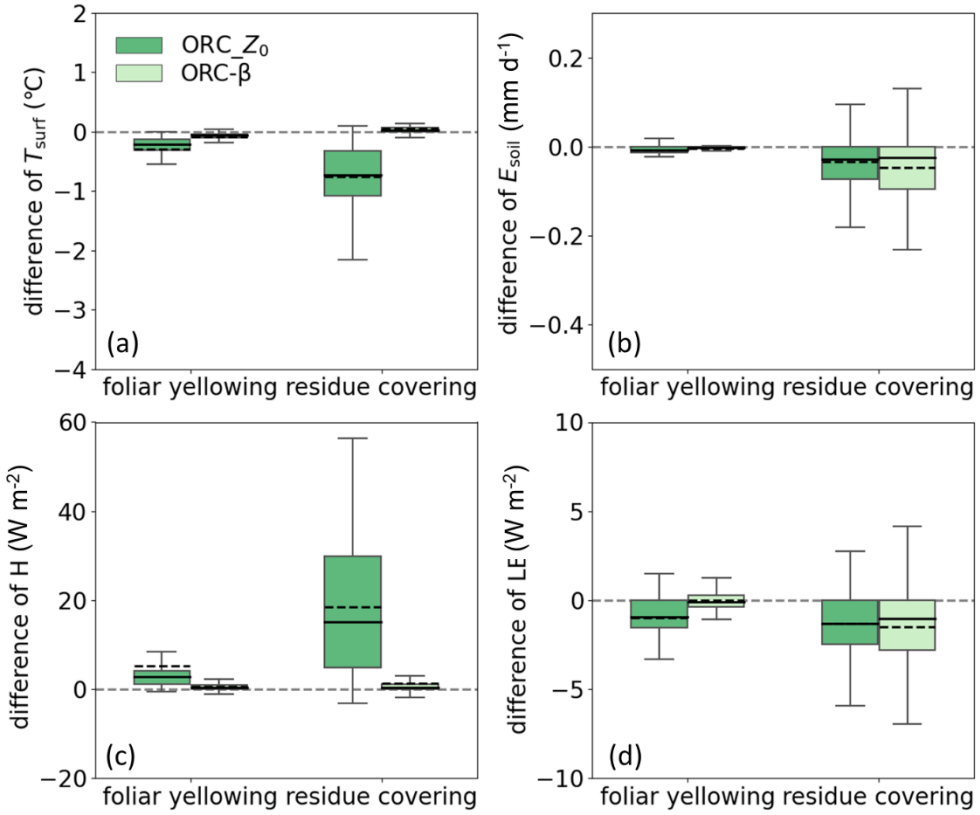



**Figure S9** The effect of model refinements on surface temperature ($T_{surf}$), soil evaporation ($E_{soil}$), latent and sensible heat fluxes (LE and H) during foliar yellowing and residue covering periods at 12 sites. Shown are the differences between the new model (ORC-β and ORC-$Z_0$) and the old model. ORC-$Z_0$ represents only the surface roughness ($Z_0$) was modified in the ORCHIDEE-CROP model. ORC-β refers to the modification of the soil conductance ($\beta_4$) in the ORCHIDEE-CROP model. The solid and dotted black lines within each box indicate the mean and median values, respectively. The box spans the interquartile range, covering the 25th percentile (lower bound) to the 75th percentile (upper bound). Black crossbars at the top and bottom represent the dataset's minimum and maximum values.

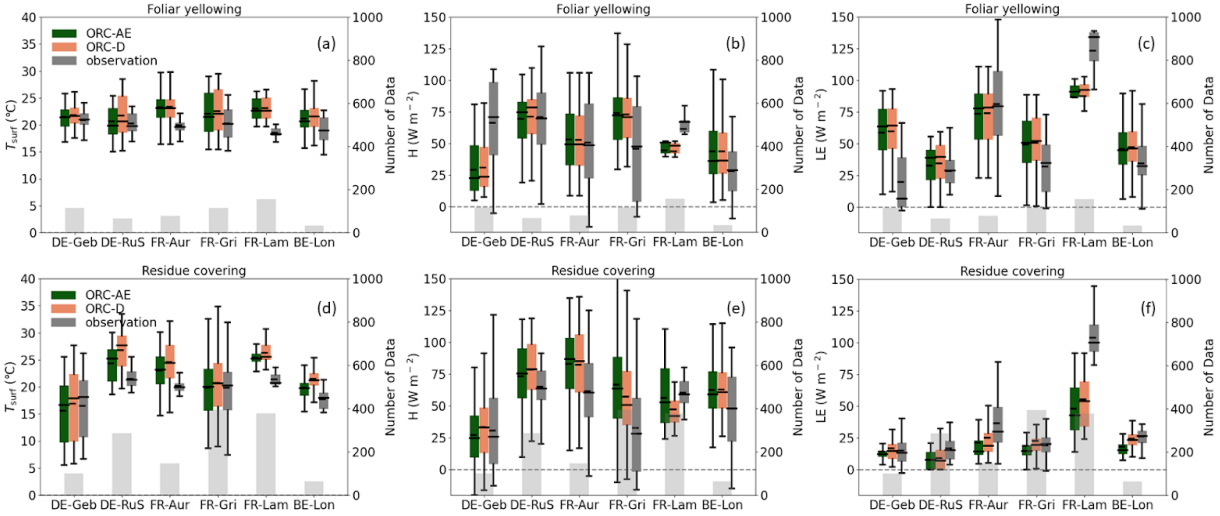



**Figure S10** The daily difference of surface temperature ($T_{surf}$), latent and sensible heat flux (LE and H) between model simulations and observations during the foliar yellowing (a,b,c) and residue covering (d,e,f) periods across 6 sites. ORC-AE (green boxes) extends these modifications by adjusting $\alpha_{surf}$, $\beta_4$ and $Z_0$ together in the ORCHIDEE-CROP model. ORC-D (orange boxes) is the old model. Observations (gray boxes) were obtained from daily eddy-covariance measurements via the Integrated Carbon Observation System (ICOS) Data Portal. The solid and dotted black lines within each box indicate the mean and median values, respectively. The box spans the interquartile range, covering the 25th percentile (lower bound) to the 75th percentile (upper bound). Black crossbars at the top and bottom represent the dataset's minimum and maximum values. The gray bars on the right y-axis show the number of data points per site.

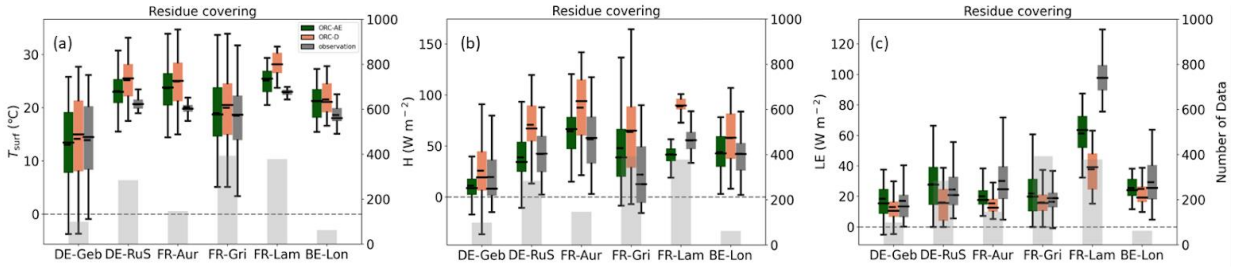



**Figure S11** The daily difference of surface temperature ($T_{surf}$), latent and sensible heat flux (LE and H) between model simulations and observations during residue covering periods across 6 sites. ORC-AE (green boxes) extends these modifications by adjusting $\alpha_{surf}$, $\beta_4$ and $Z_0$ together in the ORCHIDEE-CROP model. ORC-D (orange boxes) is the old model. Observations (gray boxes) were obtained from daily eddy-covariance measurements via the Integrated Carbon Observation System (ICOS) Data Portal. The solid and dotted black lines within each box indicate the mean and median values, respectively. The box spans the interquartile range, covering the 25th percentile (lower bound) to the 75th percentile (upper bound). Black crossbars at the top and bottom represent the dataset's minimum and maximum values. The gray bars on the right y-axis show the number of data points per site.

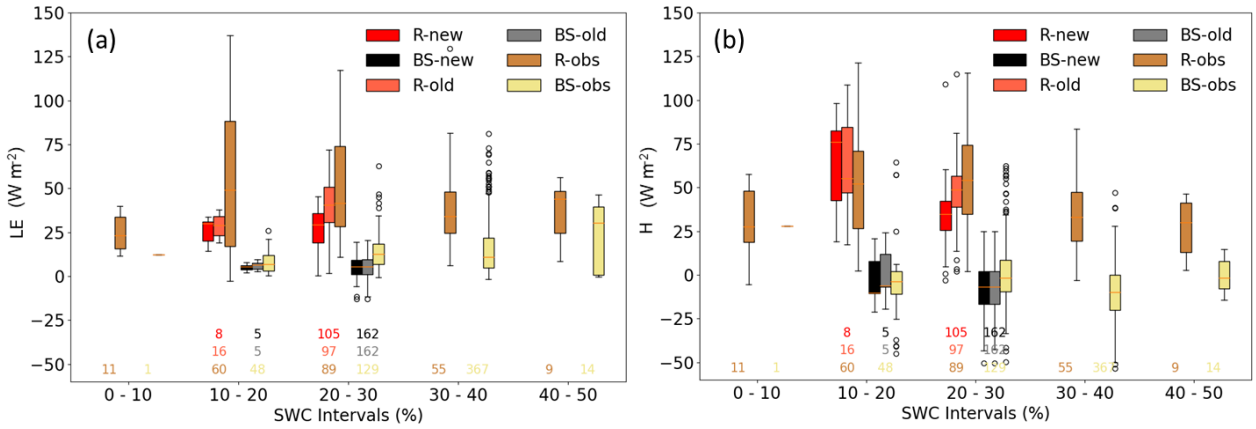



**Figure S12** The daily difference of latent and sensible heat flux (LE and H) between model simulations and observations across different soil water content intervals (SWC, %) during residue covering periods and the subsequent bare soil periods at 4 sites. ORC-AE (green boxes) extends these modifications by adjusting $\alpha_{surf}$, $\beta_4$ and $Z_0$ together in the ORCHIDEE-CROP model. ORC-D (orange boxes) is the old model. Observations were obtained from daily eddy-covariance measurements via the Integrated Carbon Observation System (ICOS) Data Portal. The periods of residue covering and bare soil were extracted by identifying site photos. 'R', 'BS' and 'obs' in each plot represent residues and bare soil. Numbers with different colors represent the number of data in each compared dataset. The solid and dotted black lines within each box indicate the mean and median values, respectively. The box spans the interquartile range, covering the 25th percentile (lower bound) to the 75th percentile (upper bound). Black crossbars at the top and bottom represent the dataset's minimum and maximum values. The black hollow circles are outliers.

**Supplementary Tables**

**Table S1** Site information

| Site | Sowing | Harvest | Tillage | Observed annual $T_{surf}$ | Observed annual SWC | Annual rainfall | Resource |
|---|---|---|---|---|---|---|---|
| BE-Lon | 2012/10/25 | 2013/8/12 | - | 10.53 | 33.98 | 1.70 | ICOS |
| | 2014/10/14 | 2015/8/2 | 20150821 | 10.89 | 31.22 | 1.74 | |
| | 2010/10/14 | 2011/8/16 | - | 11.56 | 29.83 | 1.21 | |
| CH-Oe2 | 2018/10/10 | 2019/8/1 | 20190807 | 10.78 | 28.77 | 1.92 | ICOS |
| | 2018/10/11 | 2019/7/23 | 20190809 | 11.54 | 24.35 | 3.22 | |
| DE-Geb | 2013/8/12 | 2014/8/8 | - | 11.37 | 19.24 | 1.47 | ICOS |
| | 2015/9/29 | 2016/8/7 | - | 10.56 | 18.40 | 1.32 | |
| DE-Kli | 2018/10/19 | 2019/7/24 | 20190727 | 12.09 | 14.24 | 0.96 | ICOS |
| | 2010/10/2 | 2011/8/22 | - | 8.83 | 38.14 | 2.12 | |
| | 2015/9/18 | 2016/8/24 | 20160901 | 8.58 | - | 2.09 | |
| DE-RuS | 2012/10/19 | 2013/8/11 | - | 9.81 | 32.42 | 1.30 | ICOS |
| | 2014/10/25 | 2015/8/2 | 20150805 | 11.22 | 26.75 | 1.42 | |
| | 2019/10/26 | 2020/7/28 | - | 12.22 | 25.56 | 1.67 | |
| | 2017/10/25 | 2018/7/16 | - | 11.61 | 17.19 | 1.20 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2011/10/21 | 2012/7/14 | - | 12.90 | 21.86 | 1.51 | |
| FR-Aur | 2013/10/26 | 2014/7/10 | - | 13.77 | 23.93 | 1.37 | ICOS |
| | 2016/12/2 | 2017/7/5 | 20170803 | 13.66 | 22.82 | 1.88 | |
| | 2015/10/21 | 2016/7/29 | 20160809 | 11.17 | 46.29 | 1.58 | |
| FR-Gri | 2013/10/8 | 2014/8/5 | - | 9.75 | 28.19 | 1.80 | ICOS |
| | 2011/10/20 | 2012/8/3 | - | 11.38 | 28.50 | 1.70 | |
| | 2010/11/3 | 2011/7/2 | - | 14.12 | 34.21 | 1.29 | |
| | 2012/10/29 | 2013/7/22 | - | 13.57 | 29.23 | 2.48 | |
| FR-Lam | | | | | | | ICOS |
| | 2015/10/20 | 2016/7/20 | 20160810 | 13.91 | 24.72 | 1.65 | |
| | 2017/11/16 | 2018/7/17 | 20180925 | 14.71 | 29.42 | 2.26 | |
| UK-Rookery | 2021/10/15 | 2022/8/2 | - | 10.16 | 22.51 | 1.32 | |
| UK-Winwick | 2021/10/13 | 2022/8/9 | - | - | - | - | ClieNFarm |
| UK-Allerton | 2021/10/16 | 2022/8/10 | - | - | - | - | |
| BE-AH | 2021/10/28 | 2022/7/28 | - | 9.11 | 1.44 | - | |
| BE-BM | 2021/11/1 | 2022/8/1 | - | 11.78 | 1.40 | - | ClieNFarm |
| BE-LB | 2021/10/18 | 2022/7/25 | | 11.73 | 1.32 | - | |

125 '-' represent there is no observation at site

**Table S2** Averaged meteorological variables in the year with the lowest annual rainfall at all sites for the drying climate scenario

| Site | Drying year | Ta (℃) | Pa (Pa) | VPD (hPa) | WS (mm $d^{-1}$) | Precipitation (mm $d^{-1}$) | SW_IN (W $m^{-2}$) | LW_IN (W $m^{-2}$) |
|---|---|---|---|---|---|---|---|---|
| BE-Lon | 2011 | 13.28±6.43 | 100.17±0.79 | 3.49±4.11 | 3.05±1.48 | 0.02±0.12 | 125.78±193.41 | 319.53±36.08 |
| FR-Aur | 2014 | 13.61±6.36 | 98.50±0.70 | 4.41±4.88 | 3.08±1.95 | 0.03±0.19 | 159.52±244.33 | 334.63±38.39 |
| DE-RuS | 2018 | 11.82±8.13 | 100.41±0.86 | 4.93±6.64 | 1.78±1.23 | 0.03±0.20 | 137.92±220.17 | 323.81±45.38 |
| DE-Geb | 2019 | 10.86±7.99 | 98.52±0.99 | 4.81±6.03 | 3.39±1.81 | 0.02±0.10 | 131.28±201.68 | 306.34±42.24 |
| FR-Lam | 2011 | 14.88±7.33 | 99.52±0.71 | 6.67±6.97 | 3.01±1.66 | 0.03±0.20 | 162.22±239.51 | 327.84±40.41 |
| FR-Gri | 2020 | 12.92±6.64 | 100.34±0.95 | 5.37±6.24 | 3.21±1.62 | 0.03±0.09 | 144.72±223.33 | 348.67±32.57 |

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**Table S3** Canopy height and LAI measurements of winter wheat at ICOS cropland sites

| Site | Year | Canopy height averaged during growing season (m) | Maximum canopy height (m) | LAI averaged during growing season (-) |
|---|---|---|---|---|
| BE-Lon | 2015 | 0.68±0.32 | 0.97 | - |
| DE-Geb | 2014 | 0.49±0.34 | 0.95 | - |
| | 2016 | 0.28±0.31 | 0.95 | - |
| FR-Aur | 2012 | 0.41±0.05 | 0.75 | 1.75±0.68 |
| | 2014 | 0.55±0.03 | 0.93 | 1.59±0.41 |
| | 2019 | 0.60±0.03 | 1.01 | - |
| FR-Lam | 2013 | 0.57±0.11 | 1.03 | 2.42±0.72 |
| | 2012 | 0.46±0.28 | 0.75 | 1.94±0.32 |
| FR-Gri | 2016 | 0.48±0.32 | 1.10 | 5.02±0.42 |
| | 2018 | 0.43±0.04 | 0.89 | - |
| | 2020 | 0.48±0.05 | 0.95 | - |

'-' represent there is no measurement at site

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