



UNIVERSITY OF LEEDS

This is a repository copy of *Climate change enhances stability of wheat-flowering-date*.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/211652/>

Version: Accepted Version

Article:

He, Y., Xiong, W., Hu, P. et al. (10 more authors) (2024) Climate change enhances stability of wheat-flowering-date. *Science of The Total Environment*, 917. 170305. ISSN 0048-9697

<https://doi.org/10.1016/j.scitotenv.2024.170305>

© 2024 Elsevier. This manuscript version is made available under the CC-BY-NC-ND 4.0 license <http://creativecommons.org/licenses/by-nc-nd/4.0/>. This is an author produced version of an article published in *Science of the Total Environment*. Uploaded in accordance with the publisher's self-archiving policy.

Reuse

This article is distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs (CC BY-NC-ND) licence. This licence only allows you to download this work and share it with others as long as you credit the authors, but you can't change the article in any way or use it commercially. More information and the full terms of the licence here: <https://creativecommons.org/licenses/>

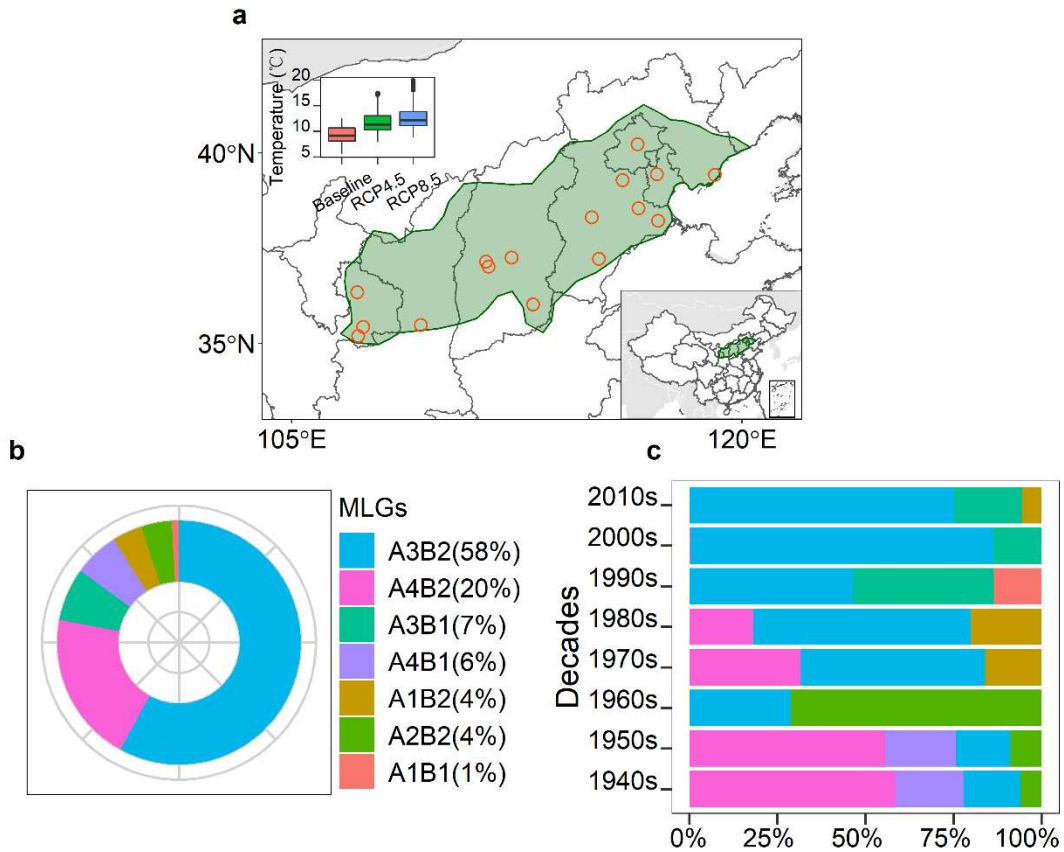
Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.



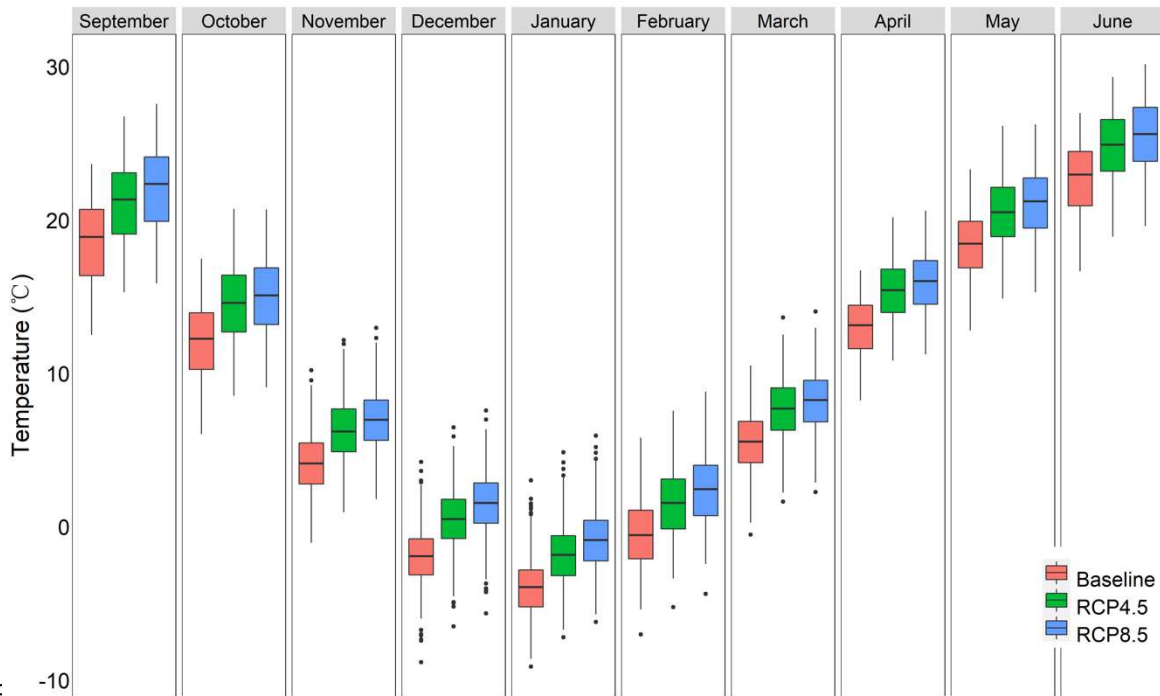
eprints@whiterose.ac.uk
<https://eprints.whiterose.ac.uk/>

1



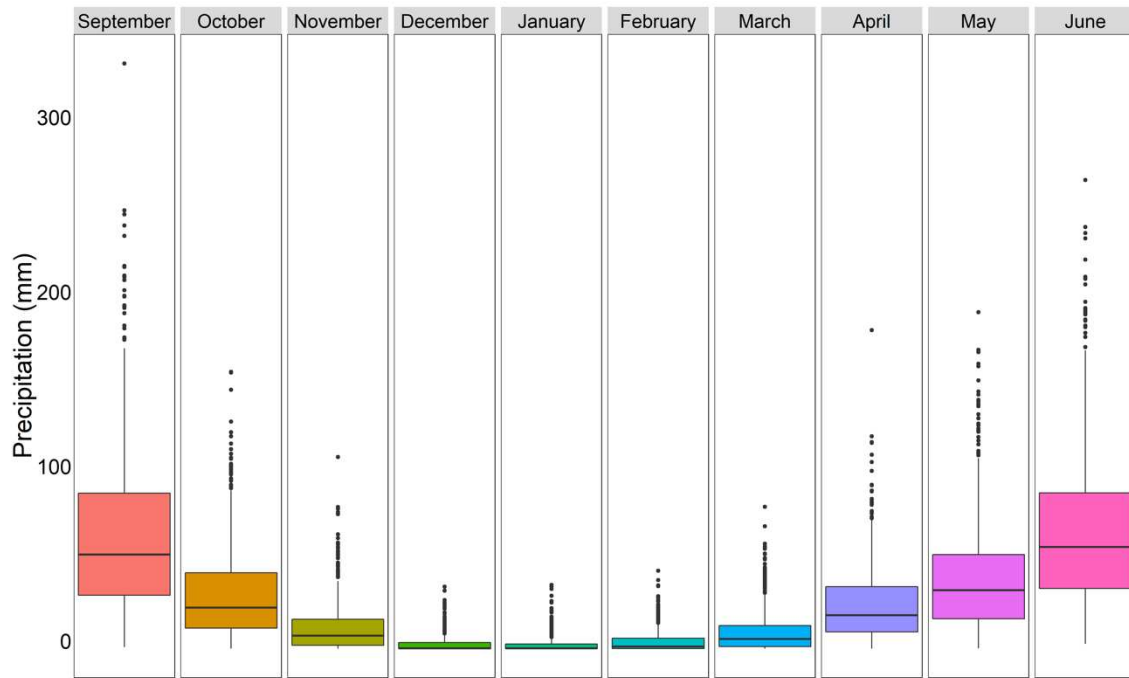
2

3 **Figure 1. Study area, climate change, and genetic diversity.** a, Map of the 16
 4 locations of the Northern China Winter Wheat Region (NCWWR), where this study
 5 was conducted (light green area); Target mean air temperature of wheat growing season
 6 under baseline (1981–2010) and RCP4.5 and RCP8.5 projected climates (2036–2065).
 7 Boxes in a show the median, an upper and lower hinge corresponding to the 25th and
 8 75th percentiles of the distribution (first and third quartiles) and the whiskers, which
 9 show data dispersion up to 1.5 times the inter-quantile range; filled black circles are
 10 outliers. b, Multi-locus genotypes (MLGs) identified among 100 adapted wheat
 11 varieties and landraces. The photoperiod and vernalization loci were combined to
 12 construct haplotypes in which A1 (*Ppd-A1a+Ppd-D1a*), A2 (*Ppd-A1a+Ppd-D1b*), A3
 13 (*Ppd-A1b+Ppd-D1a*), and A4 (*Ppd-A1b+Ppd-D1b*) in which the a and b alleles
 14 represent different photoperiod insensitivity and sensitivity, respectively. While B1
 15 (*Vrn-D1*) and B2 (*vrn-D1*) represent the spring and winter vernalization alleles,
 16 respectively. See Supplementary Table 1 for details. c, Era-wise distribution of release
 17 of the MLGs. Note: 1940s represents the varieties dating during and prior to the 1940s.
 18 The inset in 1a shows the Nanhai zhudao.



19
 20 **Figure 2. Distribution of mean monthly air temperature of wheat growing-season**
 21 **at 16 locations of the Northern China Winter Wheat Region (NCWWR) under**
 22 **baseline (1981–2010), RCP4.5 and RCP8.5 projected climates (2036–2065) of the**
 23 **16 locations of the Northern China Winter Wheat Region (NCWWR). Boxes show**
 24 **the median, an upper and lower hinge corresponding to the 25th and 75th percentiles of**
 25 **the distribution (first and third quartiles) and the whiskers, which show data dispersion**
 26 **up to 1.5 times the inter-quantile range; filled black circles are outliers.**

19
 20
 21
 22
 23
 24
 25
 26
 27
 28
 29
 30
 31
 32
 33
 34
 35
 36
 37
 38
 39
 40
 41
 42
 43
 44
 45



46

47 **Figure 3. Distribution of monthly accumulated precipitation of growing-season**
 48 **at 16 locations of the Northern China Winter Wheat Region (NCWWR) for the**
 49 **period 1961–2015.** Boxes show the median, an upper and lower hinge corresponding
 50 to the 25th and 75th percentiles of the distribution (first and third quartiles) and the
 51 whiskers, which show data dispersion up to 1.5 times the inter-quantile range; filled
 52 black circles are outliers.

53

54

55

56

57

58

59

60

61

62

63

64

65

66

67

68

69

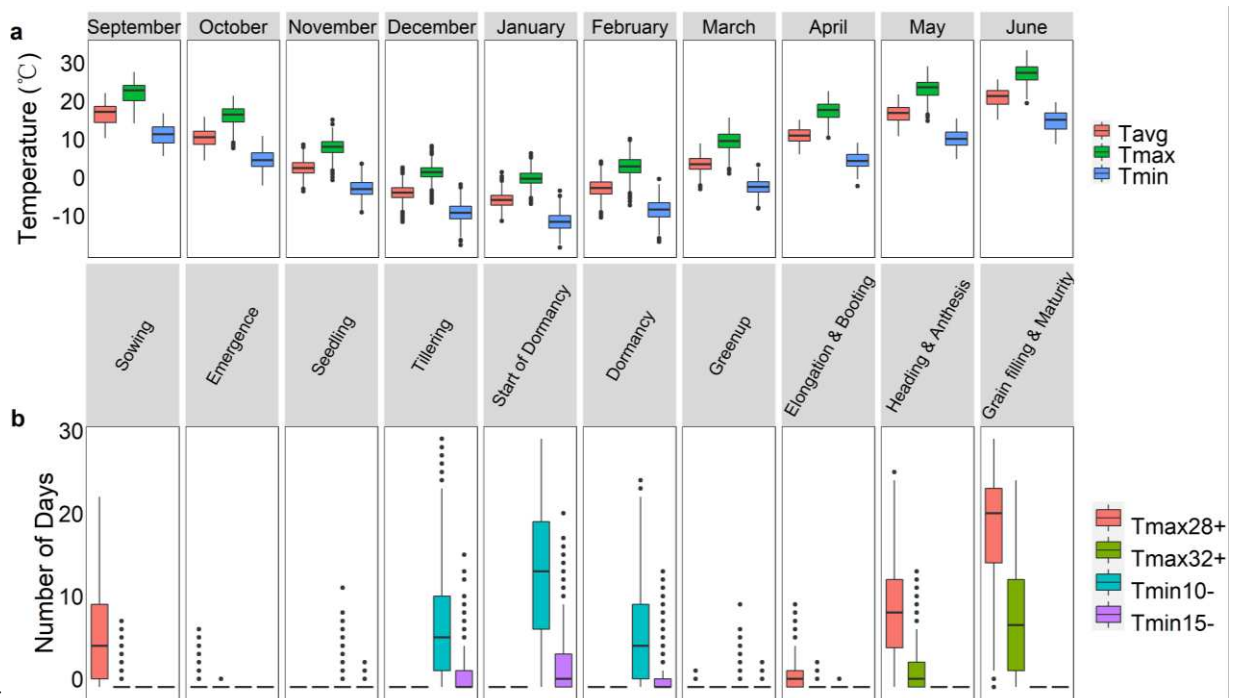
70

71

72

73

74



75

76 **Figure4. Variation in monthly air temperature of growing-season at 16 locations**
 77 **of the Northern China Winter Wheat Region (NCWWR) for the period 1961–2015.**

78 **a**, Boxplot of averaged monthly temperature (Tavg), maximum temperature (Tmax),
 79 and minimum temperature (Tmin). **b**, Boxplot of averaged number of days with daily
 80 maximum temperature over 28 °C (Tmax28+), daily maximum temperature over 32 °C
 81 (Tmax32+), daily minimum temperature less than -10 °C (Tmin10-), and daily
 82 minimum temperature less than -15 °C (Tmin15-) for each month. Boxes in **a** and **b**
 83 show the median, an upper and lower hinge corresponding to the 25th and 75th
 84 percentiles of the distribution (first and third quartiles) and the whiskers, which show
 85 data dispersion up to 1.5 times the inter-quantile range; filled black circles are outliers.

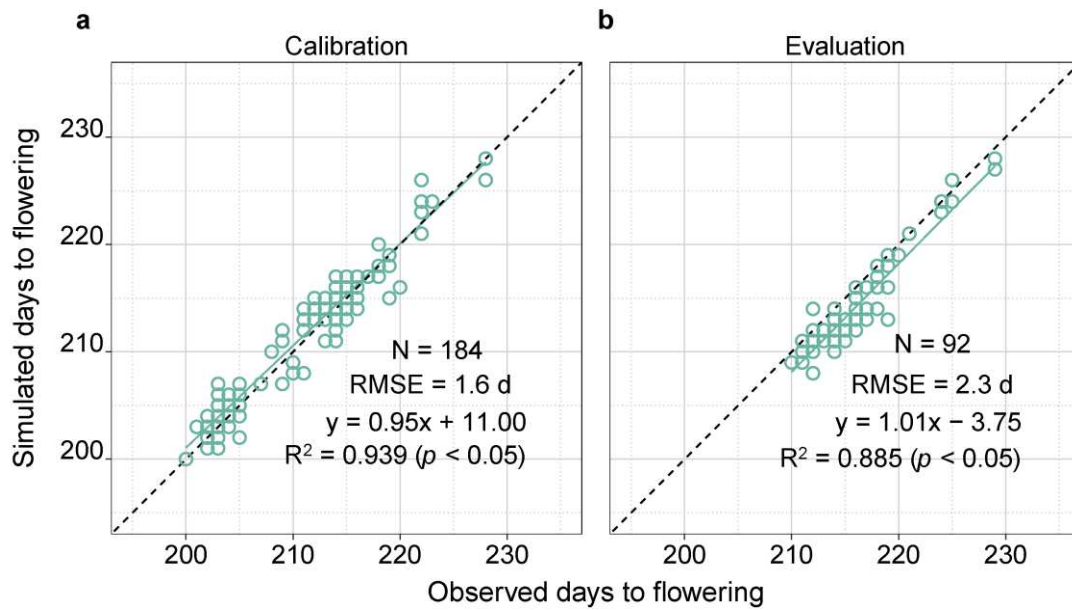
86

87

88

89

90



91

92 **Figure 5. Calibration and evaluation of the MLG-based model for modeling**
 93 **wheat-flowering-date. a,** Comparison of observed and simulated flowering dates for
 94 the calibration datasets using the MLG-based model. **b,** Comparison of observed and
 95 simulated flowering dates for the evaluation datasets using the MLG-based model
 96 (1:1, dashed line). The trial was conducted over three years in Beijing, China. Field
 97 test for calibrating and evaluating the MLG-based model was performed from 2016 to
 98 2019 at the Beijing Shunyi Experimental Base (40°15'N, 116°55'E) of the Institute of
 99 Environment and Sustainable Development in Agriculture, Chinese Academy of
 100 Agricultural Sciences. Calibration datasets (2016-2017 and 2017-2018 growing
 101 seasons); Evaluation datasets (2018-2019 growing season).

102

103

104

105

106

107

108

109

110

111

112

113

114

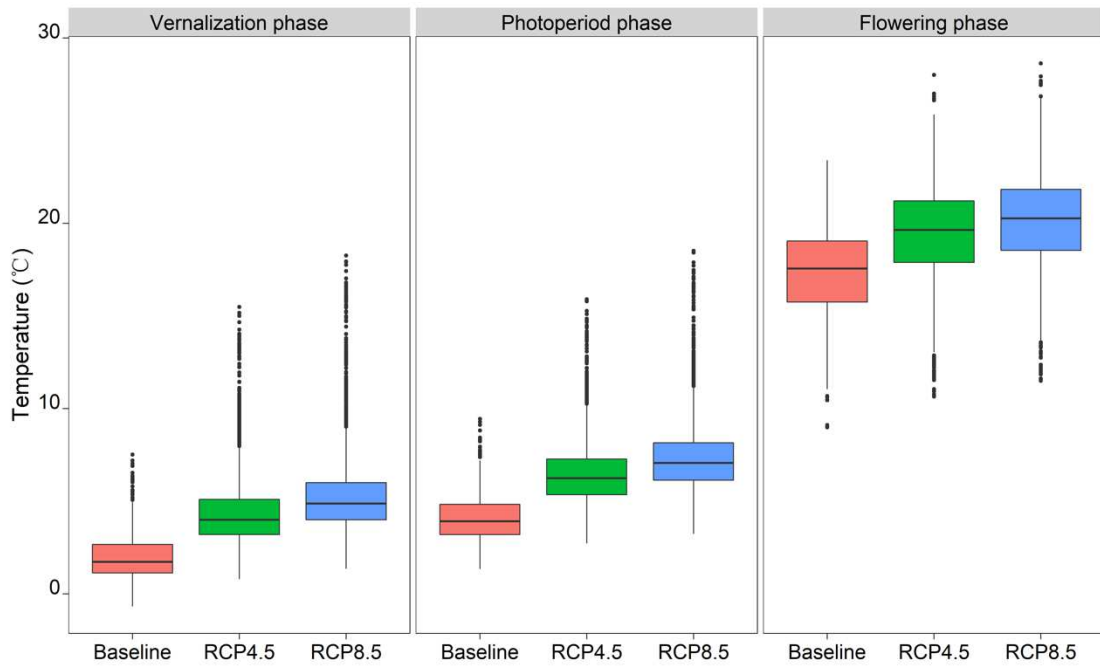
115

116

117

118

119



121

122

123

124

125

126

127

128

129

130

131

132

133

134

135

136

137

138

139

140

141

142

143

144

145

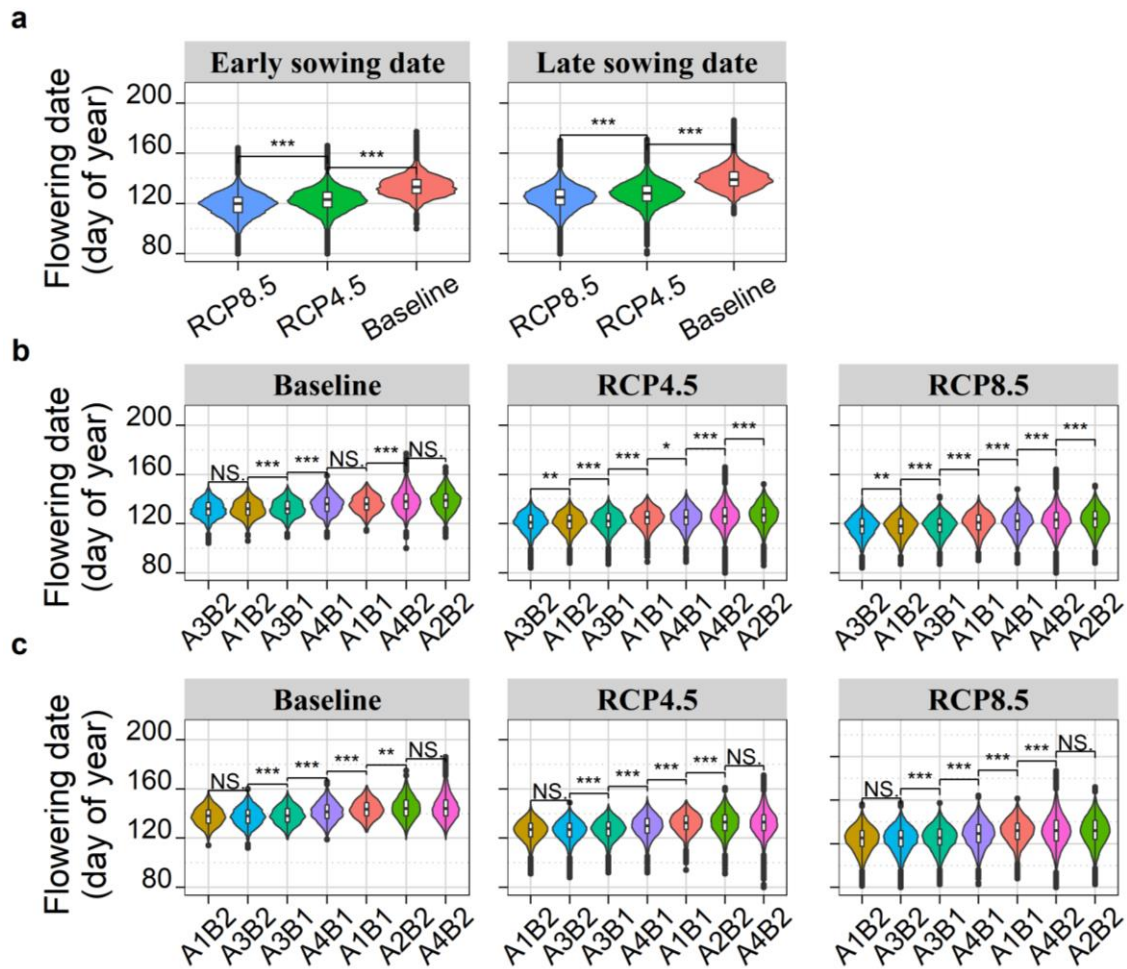
146

147

148

149

Figure 6. Variation in air temperature for vernalization phase (emergence to floral initiation), photoperiod phase (emergence to start of flowering), and flowering phase (heading to start of flowering) under baseline (1981–2010), RCP4.5 and RCP8.5 projected climates (2036–2065) of the 16 locations of the Northern China Winter Wheat Region (NCWWR). Boxplot of averaged temperature (T_{avg}). Boxes show the median, an upper and lower hinge corresponding to the 25th and 75th percentiles of the distribution (first and third quartiles) and the whiskers, which show data dispersion up to 1.5 times the inter-quantile range; filled black circles are outliers. The phenological dates including emergence, floral initiation and start of flowering were obtained from a dataset of wheat phenology collected from agrometeorological stations in China.

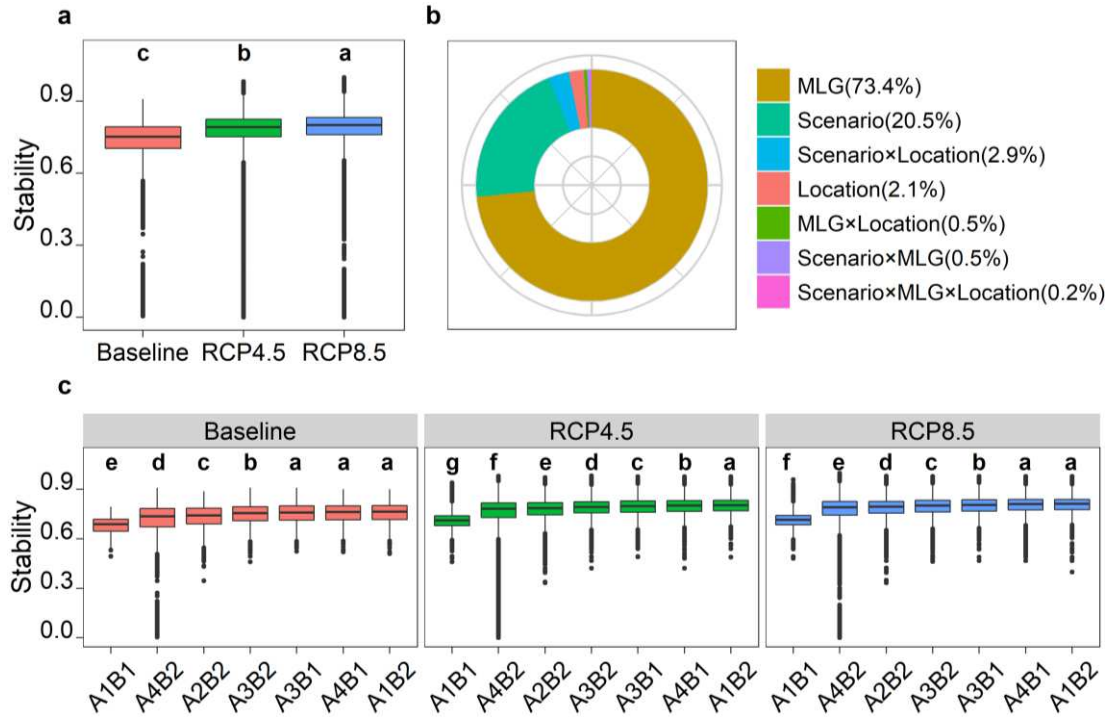


150

151 **Figure 7. Violin plots showing the distribution of the predicted wheat-flowering-**
 152 **date across the 16 locations in the Northern China Winter Wheat Region**
 153 **(NCWWR) using starting and ending sowing dates under baseline and RCP4.5**
 154 **and RCP8.5 projected climates (multi-climate model ensemble), respectively, for**
 155 **different multi-locus genotypes (MLGs). a, All MLGs, early sowing date, late**
 156 **sowing date. b, Early sowing date, baseline climate, RCP4.5 climate and, RCP8.5**
 157 **climate. c, Late sowing date, baseline climate, RCP4.5 climate and, RCP8.5**
 158 **climate. The photoperiod and vernalization alleles were combined in haplotypes in which A1**
 159 **(*Ppd-A1a+Ppd-D1a*), A2 (*Ppd-A1a+Ppd-D1b*), A3 (*Ppd-A1b+Ppd-D1a*), and A4**
 160 **(*Ppd-A1b+Ppd-D1b*) represent different photoperiod alleles, while B1 (*Vrn-D1*) and**
 161 **B2 (*vrn-D1*) represent different vernalization alleles. The early sowing dates were set**
 162 **to a range between September 21 and September 29, and the late sowing date was set**
 163 **to October 21. In a, b and c, the central mark is the median, lower (Q1) and upper**
 164 **(Q3) quartiles and the whiskers, which show data dispersion up to 1.5 times the inter-**
 165 **quantile range; filled black circles are outliers. Asterisks indicate statistically**
 166 **significant differences (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$) or not significant (NS)**
 167 **($p > 0.05$) based on the two-sided t-tests.**

168

169



170

171 **Figure 8. The effect of climate change, multi-locus genotype (MLG), and location**
 172 **on the stability of the wheat-flowering-date across the 16 locations in the Northern**
 173 **China Winter Wheat Region (NCWWR). a, Predicted stability of the wheat-**
 174 **flowering-date under baseline and RCP4.5 and RCP8.5 projected climates, respectively.**
 175 **b, Fraction of variance in the stability of the wheat-flowering-date according to MLG,**
 176 **temperature scenario, location, and the corresponding two- and three-way interactions**
 177 **for predicting flowering date stability. c, Predicted stability of the wheat-flowering-date**
 178 **for different MLGs under baseline and RCP4.5 and RCP8.5 projected climates,**
 179 **respectively (higher number indicates more stable). The photoperiod and vernalization**
 180 **alleles were combined in haplotypes in which A1 (*Ppd-A1a+Ppd-D1a*), A2 (*Ppd-***
 181 ***A1a+Ppd-D1b*), A3 (*Ppd-A1b+Ppd-D1a*), and A4 (*Ppd-A1b+Ppd-D1b*) represent**
 182 **different photoperiod alleles, while B1 (*Vrn-D1*) and B2 (*vrn-D1*) represent different**
 183 **vernalization alleles. In a and c, the central mark is the median, lower (Q1) and upper**
 184 **(Q3) quartiles and the whiskers, which show data dispersion up to 1.5 times the inter-**
 185 **quantile range; filled black circles are outliers, treatments (MLGs) sharing a letter do**
 186 **not significantly differ (Tukey-adjusted LSMeans comparisons; $p < 0.05$).**

187

188

189

190

191

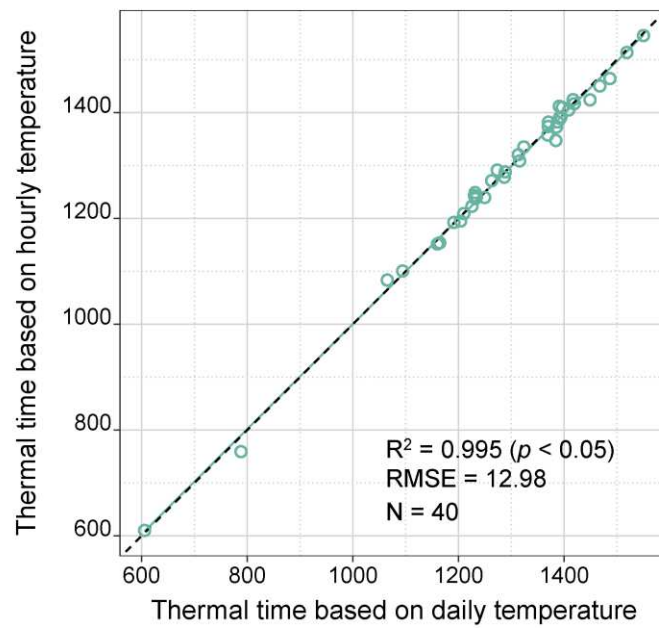
192

193

194

195

196



197

198 **Figure 9. Comparison of thermal time from 1 October (sowing date) to 1 May**
 199 **(flowering date) calculated by APSIM-Wheat-M using daily and hourly**
 200 **temperature (1:1, dashed line), respectively, from 1981 to 2020 in Beijing Shunyi**
 201 **Experimental Base (40°15'N, 116°55'E) of the Institute of Environment and**
 202 **Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences.**
 203 **Field test for calibrating and evaluating the APSIM-Wheat-M model was performed**
 204 **from 2016 to 2019 at this site. Calibration datasets (2016-2017 and 2017-2018**
 205 **growing seasons); Evaluation datasets (2018-2019 growing season).**