Spatiotemporal variation of single-season rice phenology in the Three Gorges Reservoir Area, China, during 1991–2010

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Studying the spatiotemporal changes in crop phenology across the Three Gorges Reservoir Area, China, is important to understand how crops adapt to climate changes. Here, the single-season rice crop phenology at 27 national agro-meteorological experimental stations during 1991–2010 was examined. The sowing, emerging, tillering and maturity dates were delayed in 11, 13, 13 and 23 stations respectively, from the set of 27 studied stations. Additionally, the length of growth duration (GD) and the period from tillering to maturity (TTM) were elongated in 18 and 16 stations respectively. The tendency of TTM is similar with that of the GD. In-depth comparative analyses of the impact of climate changes were conducted between stations in the south of the reservoir. Correlation between the GD days and precipitation was occasionally found in Lichuan ($R^2 = 0.43$) and Yuqing ($R^2 = 0.57$). The results are of great significance to formulate national and regional socio-economic development plans and agricultural product import and export plans, and to guide and regulate macro-planting structures.

Keywords: Climate change, growth duration, phenology, spatiotemporal variation, Three Gorges Reservoir Area.

PHENOLOGY, the science that studies the inter-relationship in plants (including crops), animals and environmental conditions (climate, hydrology, soil)[1,2], has an extensive history rooted in biological sciences. Vegetation phenology mainly includes a series of periodic phenomena such as germination, regreening, flowering, fruiting, senescence and dormancy, which is a rhythm formed by vegetation growth and development with seasonal changes. Phenological events are found to be of those mechanisms wherein organisms synchronize their development and behaviour with the impact of local and global environmental conditions, such as temperature and soil moisture[3–5]. Thus, it is of utmost importance to study the temporal and spatial variations in order to fully comprehend the responses of the vegetation to climate changes.

Accordingly, extensive efforts have been made to understand the phenological variations occurring in several countries, such as USA[6–8], Japan[9,10] and China[11,12]. Phenology not only reflects the changes in the natural season, but also shows the response and adaptation of ecosystems to global changes[8]. It was found that the vegetation phenological seasons showed spatial–temporal changes subject to variations in climate trends in the mid-high latitudes of the Northern Hemisphere[13–15]. An earlier onset of spring and significant extension of the growing season, particularly, have been documented due to climate warming in the Northern Hemisphere[16–18]. Apart from changes in temperature, ecosystem processes are influenced by other factors like elevated CO_2 and N in soil in different seasons[19,20].

However, there are relatively fewer studies involving phenology changes of agricultural and horticultural plants than changes of the natural vegetation[21,22]. At present, about 11% (1.5 billion ha) of the globe's land surface (13.4 billion ha) is used in crop production (arable land and land under permanent crops), and cultivated land is the basic resource and condition for human survival[23]. By defining the key periods of crop planting, seedling, filling, flowering, maturity and harvest, crop phenology provides an objective basis for the study of cultivated land under human control. Crop phenology is closely related to the agro-ecosystem surface dynamic process, surface water heat balance and crop-atmosphere exchange, which provide a regular research basis for the interaction between agriculture and climate[24,25]. It is interconnected with the farming cycle, agricultural productivity, and natural weather variation, which consequently influence our daily lives and have national economic implications. Therefore, there is a need to conduct scientific research on crop phenology, as it is also related to the betterment of people's quality of life and national economy. Current research studies have investigated the phenology of maize, winter wheat and rice crops in major agriculture regions in China[26,27] and USA[28,29]. Crop phenology is significantly affected by climate change and agricultural

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*For correspondence. (e-mail: chenjilong@cigit.ac.in) management practices. Studies have shown that rainfall and temperature are critical factors affecting crop yields. Both natural climatic changes, such as warming temperatures and increase in annual rainfall; and agricultural management practices (e.g. increasing applications of fertilizer and mechanization) can potentially increase crop yield.

The China Three Gorges Project (TGP), officially launched in 1994 and fully implemented in 2008, ranked as the biggest hydropower project in the world[30]. The ecological and environmental impacts of TGP on the Three Gorges Reservoir Area (TGRA) and its surrounding regions have been attracting considerable attention since 1950s and remain so to this day[31], with the agricultural impact always being one of the most important focal and academic issues. A better understanding of the growth of crops with seasonal change through the study of crop phenology, will help in the effective cultivation of crops. Although there are several works reported on crop phenology in China till date, yet it is still not clear about how the growing period of crops has changed in the past few decades and how the crop phenology varied before and after the completion of TGP.

Thus, the present study addressed the issue of how seasonal (phenological) variations in the timing (start, tiller, ripe and length of growing season) of various agricultural vegetation types have been affected in the TGRA and its surrounding regions. This study aimed to: (i) Examine the long-term trends in phenology dynamics in southwestern China, especially in areas surrounding the Three Gorges Reservoir (TGR), and (ii) Identify the spatial areas and explain the land surface phenological responses combined with the climate patterns in this region.

Materials and methods

Study area

The study area covers about 300 km farther from the administrative division of TGR, which largely encompasses the provinces of Chongqing, Sichuan, Guizhou, Hunan, Hubei (Figure 1). The TGR extends 193 km on the Yangtze River, with complex terrain – from deep valleys to mountainous. The climate in this area is subtropical monsoon; cold in winter and hot in summer[32,33]. The study area is rich in precipitation and has a high annual average relative humidity. The annual precipitation is abundant, but unevenly distributed in seasons. The rainy season begins in April and ends in October. The temperature is high in July and August, when drought often occurs. The main crops are spring corn, winter wheat, single-season rice and rapeseed. We chose the most widely distributed crop, i.e. single-season rice, as the main research object in this study.

Site and data

A total of 27 stations with long-term phenology and meteorological data were considered in this work. The catchment area ranged from 27.23° to 32.32°N, from 103.13° to 113.45°E. Detailed information of the stations are shown in Table 1. The records covered a period of 10 to 20 years (Table 1). The data were collected from the China agro-meteorological experimental stations. Phenological data included the dates of sowing, emergence, tillering and maturity (physiological maturity). We chose two phenological events for our study, which included growth duration (GD) and the period from tillering to maturity (TTM).

Analytical methods

Descriptive statistical analysis and ordinal linear regression methods were used for processing the experimental data. The ordinal linear regression equation is: $y = Ax + b$, where A is defined as the slope of regression equation. Here, $10A$ indicates the climate tendency rate, which is the quantitative description of the time variation trend, and the unit is days per ten year (d/dec or d dec^{-1}). Positive means 'postponing', and negative denotes 'in advance'.

We tabulated the station name, latitude, longitude and seasonal timing period (time interval between sowing and maturing) of every studied station, and the main phenology period (sowing, emerging, tillering and maturing), as shown in Table 1. The value of 10A, range and total average of 10A are listed in Table 2. Empirical regression was conducted to detect the changes of the timings of phenological events (Table 2) and for the correlation between the timing and environmental factors such as temperature and precipitation.

Hierarchical clustering is used to group similar objects into a 'cluster'. The endpoint is a set of clusters, where

Figure 1. Location of the meteorological stations (stations' identifications correspond with those in Table 1).

Table 1. Basic data of all the studied stations

Station name	Latitude (°N)	Longitude (°E)	Data period	Sowing stage	Emerging stage	Tillering stage	Mature stage
Jiangjin	29.97	106.28	1992.3–2010.12	3.5–3.18	3.13–3.25	5.14–5.29	8.5–8.23
Wanzhou	30.76	108.40	1991.10–2010.12	3.10–3.21	3.10–3.30	5.20–6.20	8.4–8.18
Fengdu	29.88	107.70	1992.3–2010.12	3.22–4.6	3.27–4.12	5.22–6.24	8.10–9.3
Youyang	28.83	108.77	1991.9–2010.12	4.4–4.15	4.14–5.7	6.4–6.30	9.8–10.4
Zunyi	27.53	106.81	1991.10–2010.12	3.29–4.9	4.4–4.16	4.28–6.18	9.14–10.2
Jiangkou	27.70	108.85	1991.10–2010.12	4.12–4.29	4.18–5.18	6.5–7.10	9.6–9.23
Yuqing	27.23	107.88	1991.10–2010.12	4.13–4.21	4.18–4.26	6.7–6.24	9.2–9.20
Sangzhi	29.40	110.17	1992.4–2010.12	4.5–4.20	4.5–4.28	6.3–6.23	8.19–9.1
Guzhang	28.56	109.76	1991.9–2010.12	4.9–4.22	4.20–4.28	5.26–6.15	8.25–9.17
Huaihua	27.55	109.96	1991.9–2002.12	4.15–4.27	4.23–5.2	5.30–6.14	8.17–9.9
Zhuxi	32.32	109.68	2002.9–2010.12	4.5–4.13	4.10–4.17	6.8–6.28	9.9–9.24
Jiangling	30.33	112.18	1991.9–2010.12	4.17–5.2	4.21–5.7	6.4–6.22	8.30–9.20
Fangxian	32.03	110.77	1992.4–2010.12	4.13–4.19	4.11–4.23	5.24–6.18	9.5–9.21
Lichuan	30.28	108.93	1991.9–2010.12	4.1–4.17	4.12–4.22	6.4–6.24	9.7–10.3
Zhongxiang	31.17	112.57	1991.9–2010.12	4.22–5.2	4.26–5.10	6.14–6.30	9.5–9.19
Honghu	29.82	113.45	1991.9–2010.12	4.28–5.11	5.4–5.13	6.14–7.8	9.8–10.10
Suizhou	31.72	113.38	1991.9–2010.12	4.13–4.24	4.18–4.28	5.10–6.22	9.4–9.22
Dazhu	30.80	107.25	1992.3–2010.12	3.11–3.30	3.14–4.8	4.19–5.7	8.16–8.30
Xuanhan	31.37	107.72	1992.3–2010.12	3.13–3.30	3.18–4.7	5.25–6.20	8.10–9.6
Daxian	31.20	107.50	1992.3–2010.12	3.13–4.2	3.24–4.14	5.14–6.20	8.20–9.8
Nanchong	30.80	106.08	1992.3–2010.12	3.12–3.21	3.22–3.30	5.18–6.6	8.16–8.24
Anyue	30.11	105.33	1992.3–2010.12	3.21–3.30	3.25–4.5	5.28–6.19	8.14–8.30
Yibin	28.80	104.60	1991.10–2010.12	3.2–3.15	3.10–3.25	5.6–5.26	8.9–8.26
Leshan	29.56	103.75	1991.10–2010.12	3.23–4.9	3.29–4.19	5.12–6.2	8.14–8.26
Mingshan	30.10	103.13	1991.10–2010.12	3.28–4.2	3.30–4.5	5.20–6.9	8.25–9.10
Wenjiang	30.70	103.86	1991.9–2010.12	4.1–4.8	4.6–4.18	6.2–6.14	8.29–9.17
Guanxian	30.98	103.66	1991.9–2010.12	3.26–4.11	3.29–4.20	5.30–6.18	8.29–9.19

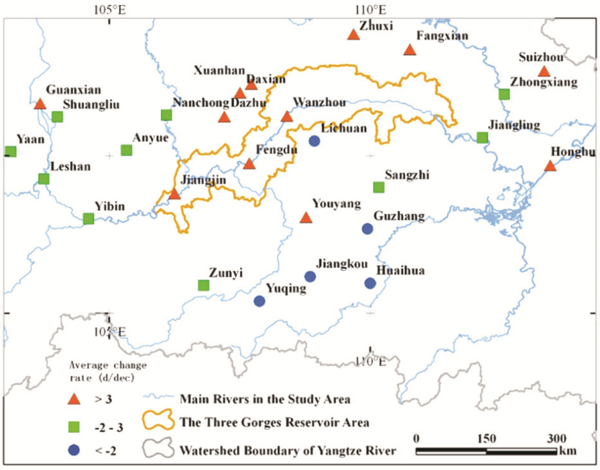

Figure 2. Result of cluster analysis about the growth duration.

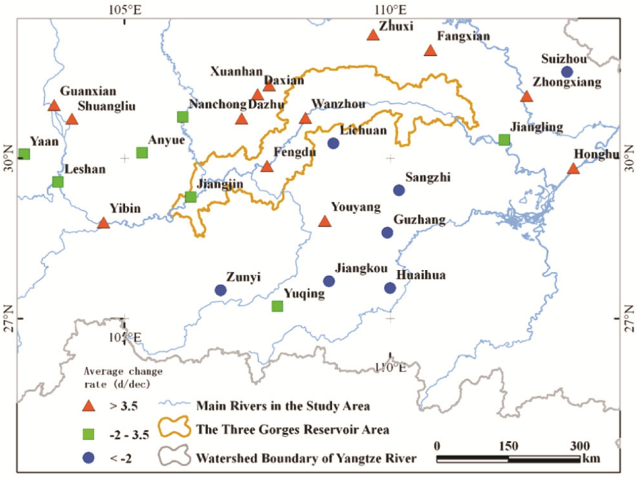

Figure 3. Result of cluster analysis about the period from tillering to maturity.

each cluster is distinct from each other, and the objects within each cluster are broadly similar to each other. This allows for exploratory analysis to see how the microarrays cluster together based on similarity of features. In this study, it is used for spatial analysis. The 10A values of GD and TTM (Table 2) are ranked in descending order. The data were then clustered into three categories using SPSS software (IBM Corp., Armonk, NY, USA) as shown in Figures 2 and 3.

Results

Single-season rice in the TGRA and surrounding regions is generally sown in mid-March to late April (Table 2). Overall, the sowing dates were advanced, on an average, by 1.33 d/dec during 1991 to 2010. The temporal variation of the sowing dates varied greatly from site to site. Specifically, advancement trend was observed in a total of 16 stations, accounting for 59% of the all the

Table 2. Rate of change of phenology period for each station

Station name	Average rate of change (d dec^{-1}) Sowing	Emerging	Tillering	Maturity	GD	TTM
Jiangjin	–3.34	0.55	0.49	3.01	7.31	2.49
Wanzhou	4.61	9.75	–6.84	2.69	7.4	10.25
Fengdu	–2.26	–2.71	–6.15	7.50	8.87	12.49
Youyang	–8.75	–8.48	–5.76	4.32	17.91	7.92
Zunyi	–1.64	0.26	14.93	5.27	3.19	–9.29
Jiangkou	2.66	4.48	7.01	–0.14	–4.49	–7.62
Yuqing	–1.41	–0.12	0.19	0.45	–3.43	0.88
Sangzhi	–0.20	–1.34	4.58	1.12	–1.25	–4.44
Guzhang	1.87	2.39	2.19	–5.98	–7.96	–6.96
Huaihua	–8.49	–7.55	–3.27	–13.09	–3.76	–9.82
Zhuxi	–6.07	–0.38	–22.62	0.50	8.93	25.48
Jiangling	2.88	2.99	3.04	1.76	–0.28	0.30
Fangxian	10.00	12.43	–16.54	13.73	8.00	23.20
Lichuan	0.91	–1.01	6.49	3.77	–10.18	–11.48
Zhongxiang	–0.65	–2.84	–5.29	0.01	–0.99	3.70
Honghu	–1.28	–0.32	–9.50	11.50	9.63	21.26
Suizhou	1.19	1.86	20.14	6.50	6.02	–13.36
Dazhu	–7.63	0.95	–2.46	0.20	7.07	6.28
Xuanhan	–9.75	–5.64	–5.62	3.87	17.29	5.58
Daxian	–4.67	–3.16	–14.80	3.37	8.98	18.61
Nanchong	1.92	1.65	8.63	2.86	2.62	–5.77
Anyue	–3.22	–2.20	–3.08	–5.50	1.45	–0.04
Yibin	–3.70	–0.24	–5.18	2.05	3.36	7.70
Leshan	2.66	0.92	0.52	2.21	–0.64	–11.48
Mingshan	1.41	0.25	2.03	2.05	0.50	–0.21
Wenjiang	0.19	–3.33	–3.10	3.04	3.08	5.00
Guanxian	–3.12	10.74	0.77	6.81	4.95	6.04
Adv number	16	14	14	4	18	16
Advave	–4.14	–2.81	–7.87	–6.18	7.03	9.70
Dly number	11	13	13	23	9	11
Dlyave	2.75	3.79	5.46	3.85	–3.66	–7.32
Range	–9.75 ~10	–8.48 ~12.43	–22.62~20.14	–13.09 ~13.73	–10.18~17.91	–13.36~25.48
Ave	–1.33	0.37	–1.45	2.37	3.47	2.84

studied stations, and showed a negative relation, averaging –4.14 d/dec. On the contrary, sowing dates were delayed, on an average by 2.75 d/dec, at the remaining 11 sites.

Emergence and tillering of single-season rice in the study area generally occur in April and June respectively. The 10A values of the emergence dates (Table 2) varied from –8.48 to 12.43 d/dec with an average of 0.37 d/dec. The emergence dates were advanced on an average by –2.81 d/dec in 14 stations. The tillering dates (Table 2) in all stations were advanced on an average by 1.45 d/dec, with the 10A values varying between –22.62 d/dec and 20.14 d/dec. There were 14 stations that were significantly advanced, with an average of –7.87 d/dec, while the emergence and tillering dates were delayed in the remaining stations, with average 10A values of 3.79 and 5.46 d/dec respectively. The maturity dates (Table 2) were delayed on an average of 2.37 d/dec, ranging from –13.09 to 13.73 d/dec. A total of 23 stations were delayed (on an average by 3.85 d/dec) and 4 stations were advanced on average by –6.18 d/dec.

The advancement of sowing and delay of maturity elongated the GD in 18 sites, with the 10A varying between –10.18 d/dec and 17.91 d/dec (on an average by 3.47 d/dec). Overall, the period of TTM increased by an average of 2.84 d/dec from 1991 to 2010, with an advancement in 16 stations (on an average by 9.70 d/dec) (Table 2).

The temporal distributions of all stations are shown in Figures 2 and 3. The spatial trends of GD (Figure 2) showed that 12 stations within the TGRA and northern areas were significantly elongated, with GD greater than 3 d/dec on an average. Eight stations in the west and east of the TGR were essentially unchanged. Changes in the Zunyi and Sangzhi stations were also not significant. Five stations in the south of the reservoir decreased by more than 2 d/dec. In general, the tendency of TTM was similar with GD. The stations in Yibin, Shuangliu, Zhongxiang and Yuqing exhibited a more significant trend towards elongating the number of days during TTM stage, whereas stations in Jiangjin, Zunyi and Sangzhi had a relatively lower change rate. In comparison, the

Suizhou station changed considerably, with a highly increased GD, but a heavily decreased TTM. The TTM variation was important for assessing agricultural production and the variation was significant.

Discussion

Crop phenology is established as one of the major components of ecological construction in TGRA. The changes in phenology for single-season rice were obviously affected by multiple meteorological factors, such as increasing temperature over the recent decades and sunshine hours[34,35].

The sowing date can be influenced by agricultural management and climate changes[36,37]. Soil moisture might also affect the date. The change of the sowing dates in southwestern China is generally a strategy to cope with the climate change, which also influences the emerging date.

The period from sowing to tillering is determined by many factors, including natural and human factors. It is difficult to detect the impacts of climate change due to the diversified sowing dates and introduction of new cultivars[37–39]. The influence of technology and strategy could disrupt the trend analysis to some extent. The TGRA and its northern areas (Chongqing and Shanxi) had significantly elongated the GD. However, the trends of rice GD showed various patterns among different areas[40,41]. There was a slight change in the stations of eastern and western areas of the reservoir within Sichuan and Hubei. In contrast to other regions, the southern areas of the reservoir in Hunan exhibited a completely opposite trend.

Given the importance of climate change in controlling plant development, our primary hypothesis was that the spatial variation in phenology would be correlated with temperature and precipitation[42,43]. However, we found mixed results. Additionally, no significant relationships existed between GD and air temperature, while significant relationships between GD and precipitation were occasionally found in two stations (Lichuan and Yuqing).

A comparison of the data shown in Figures 2 and 3 reveals that the general trend of the TTM and GD periods are similar except for some stations. Uncertainties too, may occur due to the limited number of stations and the cultivars changing during the period of the study[44–46]. The time period of two decades would be relatively short for such a study. There may be other factors that could influence the analysis, like terrain variation. However, since many factors keep changing simultaneously, it is difficult to separate their effects. These imperfections need to be kept in mind while planning for future studies.

Conclusion

It is of high importance to investigate the changes of crop phenology in TGRA for understanding the agricultural impacts of the TGP. This work studied the spatiotemporal variation of the single-season rice crop phenology at 27 national agro-meteorological experimental stations in TGRA. Four typical phenology including the sowing, emerging, tillering and maturity dates were studied and compared. The results showed that sowing, emerging, tillering and maturity dates were delayed in 11, 13, 13 and 23 stations respectively. The length of growth duration and the period from tillering to maturity were elongated in 18 and 16 stations respectively. The length of growth duration did not show significant relationship with air temperature, while it was correlated significantly with precipitation in Lichuan and Yuqing stations.

Conflict of Interest: The authors declare no conflict of interest.

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1. Fu, Y. *et al.*, Declining global warming effects on the phenology of spring leaf unfolding. *Nature*, 2015, **526**(7571), 104–107.
2. Gross, E. M., Lahkar, B. P., Subedi, N., Nyirenda, V. R., Lichtenfeld, L. L. and Jakoby, O., Seasonality, crop type and crop phenology influence crop damage by wildlife herbivores in Africa and Asia. *Biodivers. Conserv.*, 2018, **27(8)**, 2029-–2050.
3. Keenan, T. F. *et al.*, Net carbon uptake has increased through warming-induced changes in temperate forest phenology. *Nat. Clim. Change*, 2014, **4**(7), 598–604.
4. Wagner, M. R., Lundberg, D. S., Colemanderr, D., Tringe, S. G., Dangl, J. L. and Mitchellolds, T., Natural soil microbes alter flowering phenology and the intensity of selection on flowering time in a wild arabidopsis relative. *Ecol. Lett.*, 2014, **17**(6), 717–726.
5. Rezaei, E. E., Siebert, S. and Ewert, F., Climate and management interaction cause diverse crop phenology trends. *Agr. Forest Meteorol.*, 2017, **233**, 55–70.
6. Atzberger, C., Eilers and Paul, H. C., A time series for monitoring vegetation activity and phenology at 10-daily time steps covering large parts of South America. *Int. J. Digit. Earth*, 2011, **4**, 365–386.
7. Tang, J. M., Dynamic linkages between vegetation phenology and seasonal changes in water quality in the Choptank watershed, USA. *Int. J. Remote Sens*., 2015, **36**, 3041–3057.
8. Koster, R. D. and Walker, G., Interactive vegetation phenology, soil moisture, and monthly temperature forecasts. *J. Hydrometeorol.*, 2015, **16**, 1456–1465.
9. Kamruzzaman, M., Osawa, A., Mouctar, K. and Sharma, S., Comparative reproductive phenology of subtropical mangrove communities at Manko wetland, Okinawa island, Japan. *J. For. Res.-JPN*, 2017, **22**(2), 118–125.
10. Hasegawa, K., Izumi, T., Matsuyama, H., Kajiwara, K. and Honda, Y., Seasonal change of bidirectional reflectance distribution function in mature Japanese larch forests and their phenology at the foot of Mt. Yatsugatake, Central Japan. *Remote Sens. Environ.*, 2018, **209**, 524–539.
11. Liu, Y., Chen, Q., Ge, Q. and Dai, J., Spatiotemporal differentiation of changes in wheat phenology in china under climate change from 1981 to 2010. *Sci. China Earth Sci*., 2018, **61**(8), 1088–1097.
12. Chen, H., Zhang, Y., Peng, Y. and Corlett, R. T., Latitudinal effects on phenology near the northern limit of figs in china. *Sci. Rep.-UK*, 2018, **8**(1), 4320.
13. Zhao, J. J., Zhang, H. Y. and Zhang, Z. X., Spatial and temporal changes in vegetation phenology at middle and high latitudes of the northern hemisphere over the past three decades. *Remote Sens.-BASEL*, 2015, **7**(8), 10973–10995.

14. Wang, L. and Fensholt, R., Temporal changes in coupled vegetation phenology and productivity are biome-specific in the northern hemisphere. *Remote Sens.-BASEL*, 2017, **9**(12), 1277.
15. König, P., Tautenhahn, S., Cornelissen, J., Kattge, J., Bönisch, G. and Römermann, C., Advances in flowering phenology across the northern hemisphere are explained by functional traits. *Global Ecol. Biogeogr.*, 2018, **27**(3), 310–321.
16. Parmesan, C. and Yohe, G., A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, 2003, **421**, 37–42.
17. Wang, S., Yang, B., Yang, Q., Lu, L., Wang, X. and Peng, Y., Temporal trends and spatial variability of vegetation phenology over the northern hemisphere during 1982–2012. *PLoS ONE*, 2016, **11**(6), e0157134.
18. Chen, X., Liang, S. and Cao, Y., Satellite observed changes in the northern hemisphere snow cover phenology and the associated radiative forcing and feedback between 1982 and 2013. *Environ. Res. Lett.*, 2016, **11**(8), 084002.
19. Zelikova, T. J., Williams, D. G., Hoenigman, R., Blumenthal, D. M., Morgan, J. A. and Pendall, E., Seasonality of soil moisture mediates responses of ecosystem phenology to elevated CO_2 and warming in a semi-arid grassland. *J. Ecol.*, 2015, **103**(5), 1119–1130.
20. Xue, B. L., Guo, Q., Gong, Y., Hu, T., Liu, J. and Ohta, T., The influence of meteorology and phenology on net ecosystem exchange in an eastern Siberian boreal larch forest. *J. Plant Ecol.-UK*, 2016, **318**(1), 393–404.
21. Muhuddin, R. A. *et al.*, Climate change impacts on phenology and yields of five broadacre crops at four climatologically distinct locations in Australia. *Agr. Syst.*, 2015, **132**, 133–144.
22. Liang, H. *et al.*, Impacts of recent climate warming, cultivar changes, and crop management on winter wheat phenology across the Loess Plateau of China. *Agr. Forest Meteorol.*, 2015, **200**, 135–143.
23. Schmitz, C., Meijl, H. V., Kyle, P., Nelson, G. C., Fujimori, S. and Gurgel, A., Land-use change trajectories up to 2050: insights from a global agro-economic model comparison. *Agr. Econ.-Blackwell*, 2014, **45**(1), 69–84.
24. Meiyappan, P., Dalton, M., Neill, B. C. and Jain, A. K., Spatial modeling of agricultural land use change at global scale. *Ecol. Model.*, 2014, **291**, 152–174.
25. Ma, X., Huete, A., Moran, S., Ponce, C. G. and Eamus, D., Abrupt shifts in phenology and vegetation productivity under climate extremes. *J. Geophys. Res.-Biogeo.*, 2015, **120**(10), 2036–2052.
26. Guo, E., Zhang, J., Wang, Y., Si, A., Wang, R. and Li, D., Assessing non-linear variation of temperature and precipitation for different growth periods of maize and their impacts on phenology in the Midwest of Jilin province, china. *Theor. Appl. Climatol.*, 2017, **132**(3–4), 1–15.
27. Liu, Y., Qin, Y., Ge, Q., Dai, J. and Chen, Q., Reponses and sensitivities of maize phenology to climate change from 1981 to 2009 in Henan province, China. *J. Geogr. Sci.*, 2017, **27**(9), 1072–1084.
28. Augustine, K. E. and Kingsolver, J. G., Biogeography and phenology of oviposition preference and larval performance of pieris virginiensis, butterflies on native and invasive host plants. *Biol. Invasions*, 2018, **2**(20), 413–422.
29. Sharifi, H., Hijmans, R. J., Hill, J. E. and Linquist, B. A., Water and air temperature impacts on rice (*Oryza sativa*) phenology. *Paddy Water Environ.*, 2018, **16**(3), 1–10.
30. Xu, X. B., Yan, T. and Yang, G., Environmental impact assessments of the Three Gorges Project in China: issues and interventions. *Earth-Sci. Rev.*, 2013, **124**, 115–125.
31. Fu, B. *et al.*, Three Gorges Project: efforts and challenges for the environment. *Prog. Phys. Geog.*, 2010, **34**(6), 741–754.
32. Chen, J. *et al.*, Assessing the transferability of support vector machine model for estimation of global solar radiation from air temperature. *Energ. Convers. Manage.*, 2015, **89**, 318–329.
33. Zhang, J. *et al.*, Carbon storage by ecological service forests in Zhejiang Province, subtropical China. *Forest Ecol. Manage.*, 2007, **245**(1–3), 64–75.
34. Shen, X. *et al.*, Asymmetric effects of daytime and nighttime warming on spring phenology in the temperate grasslands of China. *Agr. Forest Meteorol.*, 2018, **259**, 240–249.
35. Huang, J. and Hao, H., Detecting mismatches in the phenology of cotton bollworm larvae and cotton flowering in response to climate change. *Int. J. Biometeorol.*, 2018, **3**, 1–14.
36. Bargiel, D., A new method for crop classification combining time series of radar images and crop phenology information. *Remote Sens. Environ.*, 2017, **198**, 369–383.
37. Tariq, M. *et al.*, The impact of climate warming and crop management on phenology of sunflower-based cropping systems in Punjab, Pakistan. *Agr. Forest Meteorol.*, 2018, 256–257, 270–282.
38. Rezaei, E., Siebert, S., Hüging, H. and Ewert, F., Climate change effect on wheat phenology depends on cultivar change. *Sci. Rep.-UK*, 2018, **8**(1), 4891.
39. Luo, Q., OLeary, G., Cleverly, J. and Eamus, D., Effectiveness of time of sowing and cultivar choice for managing climate change: wheat crop phenology and water use efficiency. *Int. J. Biometeorol.*, 2018, **62**(6), 1049–1061.
40. Shuai, Z., Fulu, T. and Zhao, Z., Rice reproductive growth duration increased despite of negative impacts of climate warming across China during 1981–2009. *Eur. J. Agron.*, 2014, **54**, 70–83.
41. Liu, Q., Fu, Y., Zeng, Z., Huang, M., Li, X. and Piao, S., Temperature, precipitation, and insolation effects on autumn vegetation phenology in temperate china. *Global Change Biol.*, 2016, **22**(2), 644–655.
42. Tao, F., Zhang, S., Zhang, Z. and Rotter, R., Temporal and spatial changes of maize yield potentials and yield gaps in the past three decades in China. *Agr. Ecosyst. Environ.*, 2015, **208**, 12–20.
43. Liu, L., Wang, E., Zhi, Y. and Tang, L., Contrasting effects of warming and autonomous breeding on single-rice productivity in China. *Agr.. Ecosyst. Environ.*, 2012, **149**, 20–29.
44. Wang, J., Wang, E., Feng, L., Yin, H. and Yu, W., Phenological trends of winter wheat in response to varietal and temperature changes in the North China Plain. *Field Crop. Res.*, 2013, **144**, 135–144.
45. Zheng, Z. and Zhu, W., Uncertainty of remote sensing data in monitoring vegetation phenology: a comparison of modis c5 and c6 vegetation index products on the Tibetan plateau. *Remote Sens.-BASEL*, 2017, **9**(12), 1288.
46. Liu, L. *et al.*, Uncertainty in wheat phenology simulation induced by cultivar parameterization under climate warming. *Eur. J. Agron.*, 2018, **50**(3), 46–53.

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