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Biogeosciences Discussions

Divergent climate feedbacks in the growing period and the dormancy period to sowing date shift of winter wheat in the North China Plain

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Abstracts: The land cover and management changes have strong feedbacks to climate through surface biophysical and biochemical processes. Agricultural phenology dynamic exerted measurable impacts on land surface properties, biophysical process and climate feedback in particular times at local/regional scale. But the responses of climate feedback through surface biophysical process to sowing date shift in the winter wheat ecosystem have been overlooked, especially at winter dormancy period. Considering the large

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cultivation area, unique surface property and phenology shift of winter wheat in the North China Plain, we first validated the SiBcrop model. Then, we used it to investigate the dynamics of leaf area index (LAI) and canopy temperature (T_c) under two planting date scenarios (Early Sowing: EP; Late Sowing: LP) of winter wheat at 10 selected stations. Finally, the surface energy budget was analyzed and interpreted. The results showed that the SiBcrop with a modified crop phenology scheme better simulated the seasonal dynamic of LAI, T_c, phenology, and surface heat fluxes. Earlier sowing date had higher LAI with earlier development than later sowing date. But the response of T_c to sowing date exhibited opposite patterns during the dormancy and active growth periods: EP led to higher T_c (0.05 K) than LP in the dormancy period and lower T_c (-0.2K) in the growth period. The highest difference (0.6 K) between EP and LP happened at the time when wheat was sown in EP but wasn't in LP. The higher LAI captured more net radiation with lower surface albedo for warming, whist surface energy partitioning exerted cooling effect. The relative contributions of albedo-radiative process and partitioning-non-radiative process determined the climate effect of sowing date shift. The spatial pattern of the climate response to sowing date was influence by precipitation and air temperature. The study highlight that the climate effects of the sowing date shift in winter dormancy period are worthy of attention.

Key words: sowing date, canopy temperature, phenology, leaf area index, winter wheat, land surface model, North China Plain

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1. Introduction

Land-atmosphere interactions are key components of the climate system. The land cover and management changes have strong feedbacks with climate through surface biophysical and biochemical processes (Mahmood et al. 2014). Cropland surface characteristic had been and will continue to be changed through agricultural management, such as cropping system (Jeong et al. 2014; Cui et al. 2018), sowing date and phenology shifts (Sacks et al. 2011; Richardson et al. 2013), and bio-geoengineering (Seneviratne et al. 2018), to keep high yield under climate change condition. The changed surface properties in farmland further generate feedback to regional climate through surface energy partitioning and albedo (α) mechanisms (Cooley et al. 2005; Zhang et al. 2015). It is important to quantify the climate feedback of crop phenology shift for regional climate prediction and agriculture sustainable development.

There are evidences that crop phenology has been shifts substantially in the major cultivation areas worldwide (Sacks and Kucharik 2011; Tao et al. 2012; Tao et al. 2014; Liu et al. 2017). In the North China Plain (NCP), the dates of seeding, dormancy, green-up, anthesis, and maturity in wheat system were changed by 1.5, 1.5, -1.1, -2.7, and -1.4 days/decade (a positive value indicates delay and a negative value indicates advance), respectively. The vegetative stages (including periods from dormancy to greenup, greenup to anthesis) was shortened and reproductive stage was prolonged (Xiao et al. 2013). The main contributors including climate change and crop management. Global warming induced-higher temperature resulted in longer photosynthetic-active period but faster development rate and shorter growth stages. Crop management reduced the lengths of vegetative stage, but increased the length of reproductive stage (Liu et al. 2010; Liu et

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al. 2018). The phenology change is beneficial for high-yielding. The strategies adapting to warmer environment include adopting cultivars with higher accumulated growing degree days (GDD) and later planting. The prolonged grain-filling period of winter wheat benefits the accumulation of organic matter in grain (Reynolds et al. 2012; Liu et al. 2018), and the adjusted sowing date reduces the risks such as insect and viral infection, adverse meteorological conditions, and soil depletion, et al.(Sacks et al. 2010). Model simulation indicated that yield increase of winter wheat was benefitted from cultivars renewal by 12.2-22.6% and fertilization management by 2.1-3.6%; climate change damaged yield by -15.0% for rain-fed type, in the NCP (Xiao et al. 2014).

The phenology shifts change the seasonal rhythm of crop development and affect the greenness coverage of land surface and energy and water exchanges in the boundary layer. For example, maize growth duration prolonged and reached maturity and senesced a couple of weeks later, and the maximum change can reach 47 W m^{-2} and -20 W m^{-2} for latent heat flux (*LH*) and sensible heat flux (*SH*), respectively, when the NDVI is increased by 0.1 in the Agro-IBIS model (Bagley et al. 2015). Earlier planting date and longer grain-filling period increased (decreased) the *LH* (*SH*) by 0.3 (0.2) mm/year in June and enhanced the net radiation (R_n) in October by reducing the interval time from maturity to harvest in American maize belt (Sacks and Kucharik 2011). The change of surface coverage also shows a certain regional climate feedback. The increased spring surface greenness at farmland, due to the advanced re-greening stage of winter wheat (Xiao et al. 2013; Liu et al. 2017), significantly impacted the patterns of *LH* and *SH* and then the changes of moderate to light rainfall (Zhang et al. 2015). Harvest shifted the key influence factors of the radiative balance and evaporative fraction from leaf area and

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soil-atmosphere temperature difference to soil moisture in U.S. winter wheat (Bagley et al. 2017), and warming future atmosphere by 1~1.4 ℃ through decreasing evapotranspiration in the NCP (Cho et al. 2014). So, the influence of phenology on climate feedback through surface biophysical process at local/regional scale is worthy of further studies (Liu et al. 2017).

Despite previous studies showed the critical role of crop phenology dynamic to surface energy and water balance, there is an important potential sensitive period that has been ignored in the winter wheat system. During the dormancy period in winter, aboveground canopy of winter wheat remained constant for more than 2 months (Xiao et al. 2013). In view of the close relationships between surface biophysical processes and surface characteristic (Boisier et al. 2012; Chen et al. 2015; Liu et al. 2017), the length from sowing date to start of dormancy would be the determinant factor to surface biophysical process in winter where winter wheat wildly distributed, such as NCP, Pacific Northwest (Wuest 2010) and Southern Great Plains of USA (Bagley et al. 2017)，Australia, and numerous countries surrounding the Mediterranean Sea (Mahdi et al. 1998; Schillinger 2011). Compared with climate feedback of other phenology dynamics, such as earlier re-greening stage(Xiao et al. 2013; Zhang et al. 2013), longer reproductive period (Sacks and Kucharik 2011) and inter-cropping period (Cho et al. 2014; Bagley et al. 2017), the effects of sowing date on land surface characteristic in dormancy period of winter wheat and other winter crops are relatively indirect and the effects last longer. Recognition of the impacts of sowing date on land surface characteristics and climate feedback would be beneficial to the understanding of human influence on climate change. Therefore, it is necessary to investigate whether dormancy period of winter wheat is

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sensitive to sowing date. And if so, how sensitivities are surface biophysical process and climate effect?

2. Data and methods

2.1. Study stations

The NCP is the largest winter wheat production region in China, including Hebei, Henan, Shandong, Jiangsu, and Anhui provinces, and Beijing and Tianjin municipalities (Fig.1). Summer maize - winter wheat rotation is the main cropping system， except Anhui and Jiangsu where winter wheat-rice rotation system is dominated. Two stations with surface fluxes were used for model calibration (Fig.1, blue triangles). Ten randomly distributed stations with complete meteorology and phenology information were selected for this study (Fig.1, green dots). The natural conditions and agricultural production level of the selected stations are typical to the NCP. The stations maintain good records on both meteorological and winter wheat phenology data since 1981.

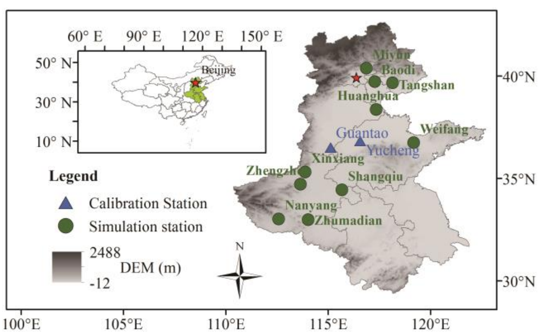

Fig.1 Distribution map of the study area and observation sites.

The 30 m resolution digital elevation model (DEM), provided by the GlobeLand30 in 2010, and the administrative map were download from the National Catalogue Service For Geographic Information.

2.2 Data

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2.2.1 Meteorology

The quality-controlled meteorological data, including air temperature (T_a), precipitation (P), atmosphere pressure, relative humidity, and wind speed was obtained from the Chinese Meteorological Administration. Summer monsoon climate dominates the region with an uneven distribution of annual precipitation (Table 1). In the 1980-2012, the average annual P at the selected stations ranged between 550-990 mm, mainly happened in summer. The mean yearly T_a varied between 11-15 ℃. In the growing season of winter wheat (11-12 and 1-6 month), the T_a varied between 7-11 ℃ among stations and P ranged between 170-420 mm. Meteorological data was also used to drive the model in the selected 10 stations (Fig.1).

Table 1 Climate conditions of the selected stations in 1980-2012

	Station	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Average Wheat Season
T_a (℃)	Baodi	-5	-1.4	5.3	13.6	19.5	24	26.1	24.8	19.8	12.7	3.7	-2.7	7.1
	Huanghua	-3.4	-0.2	5.9	14.1	20.3	25	26.9	25.8	21.2	14.2	5.5	-1.2	8.3
	Miyun	-5.9	-2.2	4.8	13.5	19.6	24	25.8	24.5	19.3	12	3	-3.7	6.6
	Nanyang	1.6	4.4	9.1	15.8	21.2	25.5	27	26	21.7	16.1	9.4	3.5	11.3
	Shangqiu	0.1	3.1	8.3	15.1	20.6	25.4	26.9	25.7	21.1	15.3	8.1	2	10.3
	Tangshan	-4.8	-1.3	5.1	13.4	19.4	23.7	25.9	25	20.3	13	4.1	-2.5	7.1
	Weifang	-2.8	0.1	5.8	13.2	19.2	23.9	26.2	25.2	20.7	14.4	6.4	-0.3	8.2
	Xinxiang	0	3.3	8.7	15.8	21.2	25.8	27	25.9	21.3	15.3	7.9	1.8	10.6
	Zhengzhou	0.5	3.5	8.7	16	21.5	26	27.1	25.7	21.2	15.5	8.4	2.5	10.9
	Zhumadian	1.5	4.2	9	15.7	21.2	25.7	27.2	25.9	21.6	16.3	9.6	3.6	11.3
(mm)	Baodi	2.7	3.7	9	20.1	36.2	82.4	169.7	142.6	49.7	27.5	10.1	3.6	167.8

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Huanghua	3.2	5.5	10.1	21.3	42.8	84.2	177.2	111.6	41.5	31	11.9	3.5	182.5
Miyun	2.2	4	9.7	19.9	43.1	86.7	180.7	172.6	62.9	25.5	9.4	2.3	177.3
Nanyang	13.2	15.6	35.2	41.7	78.8	124.5	183.7	131.7	76.3	51.1	30	12.8	351.8
Shangqiu	14.3	16.3	29.3	33	65	85.2	166.8	144.8	68.5	38.2	23.4	12.7	279.2
Tangshan	3.5	4.1	9.4	22.4	47	83.2	169.7	154.3	50.8	28.2	9.5	3.4	182.5
Weifang	6	10.3	14.9	24.5	45.4	80	136.5	132.1	56.1	32.8	18.8	8.9	208.8
Xinxiang	4.6	7.1	19.2	25	49.9	65	150	119.5	59.8	32	14.9	5	190.7
Zhengzhou	9.6	12.4	27.1	30.9	63.6	67.8	146.6	134.7	75.6	40.5	21.1	9.1	241.6
Zhumadian	21.9	24.8	51	50.9	93	128.6	227.7	176.3	98.2	63.9	35.2	18.5	423.9

T_a means air temperature, and P means precipitation.

2.2.2 Verification data

To verify the applicability of the model, surface flux data was collected from Yucheng and Guantao stations (Fig.1; Table 2). The two stations used the same eddy covariance instruments to measure the surface latent heat flux (LI7500, LI-COR Inc., Lincoln, NE, USA) and sensible heat flux (CSAT-3, Campbell Scientific Inc., Logan, UT, USA), but at different heights (Yucheng:3.3 m; Guantao: 15.6 m). The post-processing software (Yucheng: Eddypro; Guantao: EdiRe) was used to process the raw data such as spike detection, lag correction of H_2O/CO_2 relative to the vertical wind component, sonic virtual temperature correction, coordinating rotation using the planar fit method, corrections for density fluctuation (WPL-correction), and frequency response correction (Liu et al. 2011). The REddyProc was used for gap-filling by method of the look-up table and the mean diurnal variations method (Falge et al. 2001; Wutzler et al. 2018). More details could be refered to (Lei et al. 2010; Liu et al. 2013). Totally 10 complete winter wheat season flux data were used to validate the model (Table 2).

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The meteorology conditions were also synchronously measured during flux observation (Table 2). The measurement included T_a, P, atmosphere pressure, relative humidity, wind speed, and sunshine. These data was the inputs of the model. According to the T_a and P, the meteorological conditions were similar between the 10 stations for simulation and the two stations for calibration. More variables were observed at Yucheng station, such as wheat phenology and leaf area index (LAI) and canopy temperature (T_c). The observed durations of phenology, LAI, and fluxes at Yucheng station were in 2003-2006, 2004-2006, and 2003-2010, respectively.

Table 2 General information about model verification data

Station	Period	Wheat growing season T_a (K)	Wheat growing season P (mm)	Measured variables
Yucheng	2003-2010	282.15	226.7	Meteorology, Phenology, LAI, *LH*, *SH*, T_c
Guantao	2008-2010	282.75	134.4	Meteorology, *LH*, *SH*

T_a means air temperature, P means precipitation, LAI means leaf area index (m^2 m^{-2}), *LH* means latent heat flux (W m^{-2}), *SH* means sensible heat flux (W m^{-2}). T_c means the simulated canopy temperature (K).

2.2.3 Phenology of winter wheat

The phenology information was manually recorded and available in the period of 1981-2009, except for 2003 at Zhumadian and 1986 and 1988 at Miyun station (Table 3). Phenological statistics showed that the sowing time of winter wheat is generally between DOY (Day Of Year) 270-290 (early and middle October) in the NCP. After sowing, it generally takes about 6-10 days for germination. Winter wheat dormancy stage generally begins in December and ends in late February and early March, and reaches maturity in

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mid-June. The standard deviation shows that the inter-annual fluctuations of dormant and re-greening period is larger, and harvest period is relatively stable.

For the past 30 years, winter wheat phenology at some stations showed a significant linear trend (Table 4). The sowing and germination periods were significantly delayed in 4 out of 10 stations, and the trend in the dormant and re-greening period was not obvious. Winter wheat matured significantly earlier at five stations. Generally, the autumn and winter phenophases, including sowing, germination and dormancy, are mainly delayed, while spring and summer phenophases, including re-greenning and maturity, are primarily advanced. According to the fitting coefficient (a), the duration were changed by 5.7, 8.1, 4.9, -3.5, and -5.5 in the period of 1981-2009, respectively, for the stages of sowing, germination, dormancy re-greenning and maturity of winter wheat. These results were consistent with previous studies (Tao et al. 2012; Xiao et al. 2013; Xiao et al. 2015), and indicating that the selected stations were good representation of the NCP.

Table 3 General information on the phenology of winter wheat in the selected stations (unit: DOY)

Station	Period	Sowing	Germination	Dormancy	Re-greening	Maturity
Baodi	1981-2009	272.83±4.33	281.55±5.5	335.62±6.86	59.19±42.72	165.97±2.57
Huanghua	1981-2009	274.17±7.83	280.32±7.03	340.38±8.65	62.45±6.56	157.14±3.25
Miyun	1981-2009	275.52±7.55	284.96±9.03	331.93±6.41	73.59±15.1	168.26±3.46
Nanyang	1981-2009	297.21±7.81	306.83±9.03	7.54±14.64	48.22±8.9	149.21±4.99
Shangqiu	1981-2009	287.59±4.07	295.31±4.79	359.21±32.4	47.03±6.43	151.59±2.99
Tangshan	1981-2009 (except 2003)	271.86±4.83	279.59±6.04	335.55±6.6	66.62±7.98	169.97±3.23

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Weifang	1981-2009	274.1±5.75	284.62±17.93	343.72±7.76	59.59±7.29	160.41±3.42
Xinxiang	1981-2009	283.59±4.21	291.64±5.14	351.9±10.56	47.55±7.16	152.03±3.3
Zhengzhou	1981-2009	289.76±5.67	298.45±6.65	360.5±14.08	44.21±7.43	151.34±3.88
Zhumadian	1981-2009 (except 1986, 1988)	289.54±9.33	298.29±11.11	5.46±10.35	49.15±6.84	146.21±4.76

the data was shown in average ± standard deviation.

Table 4 Linear trends in winter wheat phenology

Station	Sowing		Germination		Dormancy		Re-greening		Maturity	
	a	p	a	p	a	p	a	p	a	p
Baodi	0.31	0.00	0.41	0.00	0.14	0.36	-0.67	0.52	-0.05	0.35
Huanghua	0.18	0.31	0.17	0.31	0.38	0.05	-0.07	0.64	-0.13	0.07
Miyun	0.62	0.00	0.69	0.00	0.17	0.27	-0.51	0.15	-0.20	0.01
Nanyang	-0.18	0.30	-0.11	0.60	-0.13	0.71	0.12	0.60	-0.38	0.00
Shangqiu	0.03	0.77	0.04	0.68	0.39	0.59	0.10	0.51	-0.07	0.28
Tangshan	0.41	0.00	0.51	0.00	0.43	0.00	-0.29	0.11	-0.20	0.00
Weifang	0.20	0.11	0.61	0.13	0.11	0.55	0.14	0.38	-0.12	0.11
Xinxiang	0.07	0.46	0.12	0.34	0.27	0.26	-0.16	0.33	-0.12	0.10
Zhengzhou	-0.16	0.21	-0.21	0.17	-0.28	0.41	0.11	0.52	-0.25	0.00
Zhumadian	0.49	0.02	0.56	0.02	0.21	0.37	0.02	0.89	-0.36	0.00

a was the coefficient of linear fitting equation (d/year); p was the significance level

2.3 Methods

2.3.1 Model calibration and verification

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The SiBcrop model was selected in this study. SiBcrop is a process-based land surface model adapted from the Simple Biosphere model version 3 (Lokupitiya et al. 2009). The SiB series models (version 1, 2, 3 refers to SiB1, SiB2, SiB3, respectively) are widely adopted land surface model for computing surface energy, water, momentum and CO_2 exchange in the boundary layer. The SiBcrop version added the simulation of maize, soybean, winter and spring wheats cropping system (Lokupitiya et al. 2009). The crop-specific submodel replaces remotely-sensed NDVI information by simulated LAI and the fraction of photosynthetically active radiation. SiBcrop simulated fast response processes that vary sub-hourly such as energy, water, carbon and momentum balance of the canopy and soil, as well as the processes that vary daily such as LAI. Surface energy and water fluxes are calculated at each time step on a grid cell basis according to physiologically based formulations of leaf-level photosynthesis, stomatal conductance and respiration (Farquhar et al. 1980; Collatz et al. 1990).

The model was first modified according to the actual situation of winter wheat in the NCP (Chen et al. 2020). The SiBcrop model was originally calibrated in winter wheat – summer fallow system in which the growth time of wheat is relative abundant (Lokupitiya et al. 2009). However, the NCP is dominated by winter wheat – summer maize system in which the development of wheat is strictly restricted. There are great differences in the varieties, planting date, growth environment and physiological characteristics of winter wheat between the two systems. The modifications including: (1) the sowing date was postponed to October from original August. (2) The cold tolerance was reduced to 8℃ from original 18℃, above which the seven consecutive days for wheat sowing was counted. (3) The harsh condition of delayed sowing also reduced the

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daily growth rate, which was modified from 0.07 to 0.03 g m^{-2} when GDD was 105-310 ºC d. (4) Wheat grows faster when GDD is 769-1074 ºC d with maximum dry weight increased from 8 to 12 g and daily rate enlarged from 0.015 to 0.15 g m^{-2}. (5) Specific leaf area was changed from 0.02 to 0.025 m^2 g^{-1} (Najeeb et al. 2016). (6) A subroutine was added to describe the senescence process of canopy when GDD was larger than 1074 ºC d according to Tao et al. (Tao et al. 2009). More details could be referred to Chen et al (2020).

2.3.2 Model simulation

Two simulations with different sowing dates were performed to examine the responses of surface biophysical processes to shifts in sowing dates at the selected 10 stations (Fig.1). The planting date was classified into two scenarios: after DOY 265 (early sowing scenario, EP) and after DOY 275 (late sowing scenario, LP). The early and late sowing scenarios were established by artificially limiting the starting time of the sowing date. The early sowing scenario means that the sowing will not be allowed until DOY 265. Similarly, the late sowing scenario is only allowed after DOY 275. In both scenarios, wheat was sowed at the seventh consecutive days when temperature ranged 5~25℃, which means the real sowing date was seven days later.

The simulations were driven by the same meteorological data, initial condition, and soil texture from 1980 to 2009. The 1980-1984 was not analyzed as the spin-up time. The difference in the simulation results was mainly ascribed to the sowing date. The analyses focused on the dynamics of LAI and T_c, and the surface energy balance components such as R_n, *LH*, and *SH*, which was used to explain the climate feedback mechanism.

2.3.3. Methods to relate the surface energy balance components with T_c

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The Boisier method (Boisier et al. 2012) was adopted to relate the surface energy balance components with T_c. The energy partitioning of a terrestrial surface is expressed as

$$(1-\alpha)\, S_d + L_d - L_u = LH + SH + R \qquad (1)$$

Where S_d, L_d, and L_u are the downward short-wave radiation, downward long-wave radiation, and upward long-wave radiation, respectively. In order to have a closed surface energy balance, the residual term R was derived explicitly from the other terms in equation (1), and principally accounts for the soil heat flux and canopy storage flux.

The T_c change simulated by model is affected by both radiative (surface albedo effect) and non-radiative processes (surface energy partitioning effect). In order to separate temperature variation caused by the sole change in absorbed short-wave radiation (radiative process), the following equation (Boisier et al. 2012) was used:

$$\Delta T_c = (\varepsilon\sigma)^{-1/4}\left[\left(L_u + \Delta L_u\right)^{1/4} - L_u^{\ 1/4}\right] \qquad (2)$$

Where ΔT_c is the anomaly of canopy temperature (K). The σ is Stefan-Boltzmann constant (=5.67×10 -8 W m^{-2} K^{-4}). The ε is surface emissivity (= 1). A disturbance in S_d, L_d, LH, SH or R can be expressed as ΔL_u by fixing non-perturbed terms using equation (1). More details can be found in Boisier et al. (2012).

3 Results

3.1 SiBcrop simulation accuracy

The SiBcrop model had been modified to improve the simulation accuracy of wheat growth and surface fluxes in our previous study (Chen et al. 2020). After modifications, the simulated biases were within 10 days for wheat emergency and harvest dates, the

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determination coefficient, root mean square error, and agreement index between simulated and observed LAI were obviously improved from 0.26, 1.89 m^2 m^{-2}, and 0.7 to 0.80, 0.99 m^2 m^{-2}, and 0.91, respectively. And they were 0.66, 32.37 W m^{-2}, and 0.84, respectively, for the simulated *LH* (Chen et al. 2020).

The simulation accuracy for T_c was analyzed by comparing the observation with simulation at Yucheng station over 2003-2010 (data not shown). The linear regression equation (simulated T_c = 1.02 * measured T_c - 4.22, R^2 = 0.91, $p < 0.001$) showed good linear relationship between the simulated T_c and the observed T_c. The coefficients of linearly fitted equations indicating that the simulated T_c was slightly higher than the measured (slope =1.02) and was negative deviated (intercept =-4.22). So the model can well simulate the dynamic of T_c with relatively smaller error. In this paper, we focused on the T_c difference between two sowing dates, which could reduce the influence of low numerical simulation value.

The simulation error for wheat phenology at Yucheng station was within 10 days (Chen et al. 2020). The sowing time under the two sowing scenarios was further compared with observation at the selected 10 stations. The simulated sowing date was stable, generally around DOY278.66 ± 1.15, and DOY 290.34 ± 2.08 for EP and LP scenario, respectively. The observed phenology fluctuated greatly. Wheat was prone to sow later or early generally due to geographical location at some specific stations. In the EP scenario, the stations in the north had a positive difference compared to the actual phenological period, whereas the stations in the south had a negative difference, because the stations in the north had earlier sowing date than those in the south. In the LP scenario, the stations in the south were relatively close to the actual phenology, but the stations

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near the north had a larger positive difference. Overall, the simulation difference of phenology was within 15 days. The selected scenario covers the actual situation of winter wheat sowing in the NCP. The comparisons improved the representativeness and reliability of the simulation results.

Table 5 The difference between simulated and observed sowing dates under two scenarios at each station

Station	Scenario	
	Early sowing	Late sowing
Baodi	6.59±4.62	19.59±4.49
Huanghua	4.41±8.02	16.31±7.55
Miyun	4.19±7.82	17.48±7.55
Nanyang	-19.07±7.87	-8.41±8.08
Shangqiu	-9.34±3.84	1.48±3.85
Tangshan	7.41±4.95	20.38±5.47
Weifang	4.34±5.6	15.86±5.55
Xinxiang	-5.31±4.24	5.59±4.24
Zhengzhou	-11.41±5.47	-0.38±5.53
Zhumadian	-11.36±8.91	-0.57±9.07
All	-2.98±10.96	8.7±11.66

data was show in average ± standard deviation.

3.2 Seasonal dynamics of LAI and T_c in scenarios

Wheat LAI curves for the two sowing dates were obviously not overlapped (Fig.2a). The LAI in the EP scenario was larger with earlier development. With the sowing in the LP scenario, LAI difference between the two scenarios gradually narrowed until the spring of the next year when the disparity increased again (Fig.3a). The LAI difference between two scenarios had a valley after the reproductive period. With the approaching of harvest, the difference gradually decreased to 0.

The LAI difference of winter wheat in two scenarios is mainly attributed to the difference in the accumulation of organic matter. In the EP scenario, earlier sowing means advanced assimilation process and better temperature conditions, more photosynthetic carbon was produced and distributed into leaf. The impact of sowing time on LAI displayed great dissimilarity among stations (Fig.3a). Based on linear regression, the seasonal average of wheat LAI difference between scenarios was highly related with precipitation in the growth period (LAI anomaly = 0.0011 * P - 0.12，R^2 = 0.59). The more precipitation, the greater influence of sowing date on growth. The T_a contributed little to the LAI difference between the two scenarios.

The most obvious disparity in T_c between two scenarios occurred in the period when wheat had been sown in the EP but hadn't in the LP (Fig.2b). The development of early sown winter wheat resulted in higher T_c, with a peak of up to 0.6 K. The growth of wheat in the LP sharply reduced the warming effect in EP, and eventually the EP scenario had lower temperatures (-0.2K) before entering the dormancy period. The temperature change process during this period was relatively consistent across the selected stations (Fig.3b).

Another special period is the dormancy period, when EP had higher T_c than LP with average of 0.05 K (Fig.3b). With the start of the re-greening period, the EP T_c was

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gradually lower than LP T_c and dropped to 0 at the harvest time. The T_c dynamics during this period was highly heterogeneous among the stations, varying between -0.25~0.25 K.

In the dormancy period, the T_c anomaly between scenarios was significantly affected by the T_a in winter (T_c anomaly = -0.023 * T_a + 0.062, R^2 = 0.6, p = 0.005). The lower the T_a, the bigger the T_c difference, which indicating that the influence of sowing date is more important in northern farmland. The linear relationship between P and T_c difference in winter was not obvious. The linear fitting equation between P and T_c anomaly in the growing period: T_c anomaly = -0.0013 * P + 0.057, R^2 = 0.8, p < 0.001. So more rainfall increased the T_c anomaly in the growing period. The linear fitting equation between T_a and T_c anomaly in the growing period: T_c anomaly = -0.017 * T_a + 0.2, R^2 = 0.53, p = 0.01. Since the T_c anomaly was negative, the higher the T_a, the greater the T_c anomaly. Considering the low temperature and less precipitation at the northern stations, the high temperature and more precipitation at the southern stations, the climate feedback of sowing date shift was more obvious in winter in the northern areas, and in the growing period in the southern areas.

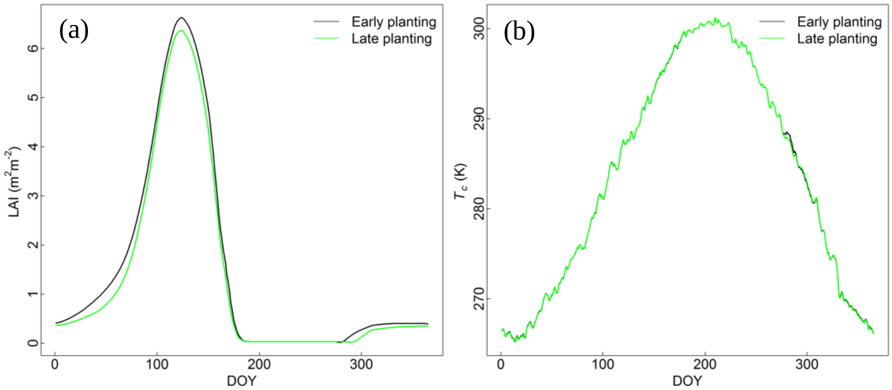

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Fig.2 Dynamics of (a) LAI and (b) T_c under two sowing scenarios in winter wheat growing season

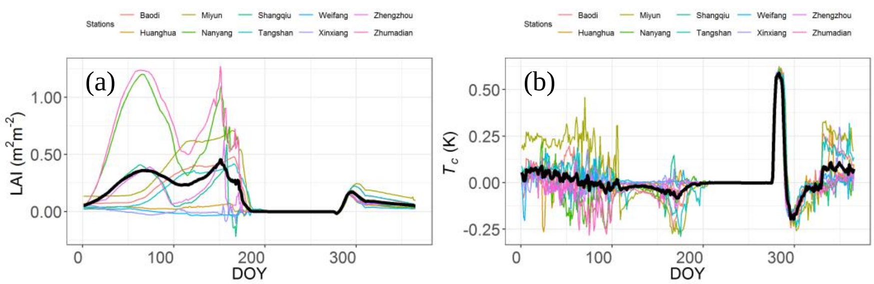

Fig.3 Seasonal differences in (a) LAI and (b) T_c of EP-LP at each station. The average across the stations was shown in bold black line

3.3 Contributions of surface energy balance components to scenario difference in T_c

According to the seasonal dynamics of LAI and T_c, winter wheat growth could not explain the difference in climate effect of sowing time. Specifically, the T_c anomaly between the two scenarios were reversed between the dormancy (December, January, and February) and active growth periods (other wheat development period with active physiological activity), but with both positive LAI difference (Fig.3). In this section, surface energy balance was used to explain the response of T_c to sowing date.

The flux anomalies of R_n, LH, SH and R were shown in Fig.4a. The EP scenario always maintained higher R_n and LH. Especially winter wheat-covered ground captured more than 10 W m^{-2} R_n than bare land. The anomaly of R_n in different sowing dates was maintained within 2 W m^{-2}. LH generally was covariant with the change in R_n. However, the anomaly of LH in the late growth period was greater than that of R_n, resulting in negative SH, indicating that the EP scenario had stronger LH distribution tendency and

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less *SH* was partitioned. Bigger anomaly of *SH* was happened in the initial and dormant stages. *R* anomaly fluctuated obviously only in the initial phase.

The contributions of surface energy balance components to T_c were shown in Fig.4b. Stronger radiation absorption provided more energy for the thermal motion of air and causing positive T_c differences of EP-LP. Correspondingly, higher distribution into *LH*, *SH*, and *R* was conducive to cooling T_c. Therefore, positive *LH* and *SH* differences of EP-LP showed negative T_c effects, and negative *R* difference of EP-LP showed positive T_c effect. The positive T_c anomaly of EP-LP reflected that the radiative process played the major role in the dormancy period. In the active growth time, the cooling effect of *LH* partitioning dominated the T_c anomaly.

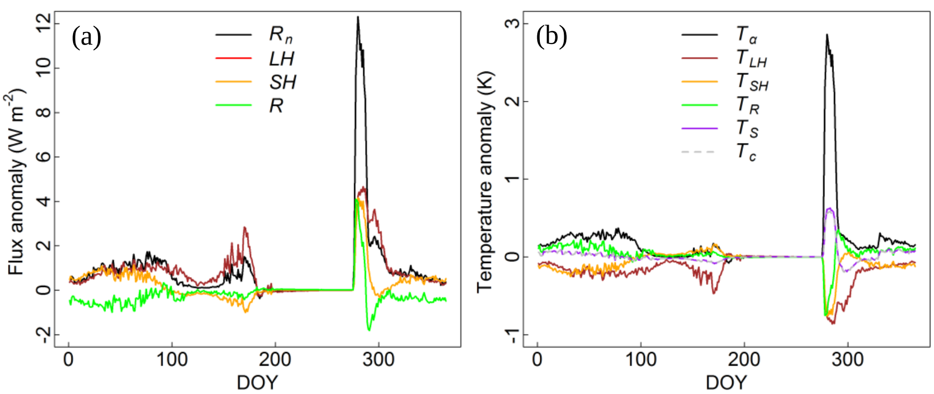

Fig.4 (a) The differences in the surface fluxes between the sowing scenarios of EP and LP, (b) its contributions to T_c anomaly.

R_n means net radiation, T_a represents the temperature anomaly induced by changes in absorbed solar radiation. T_{LH} represents the temperature anomaly induced by changes in latent flux. T_{SH} represents the temperature anomaly induced by changes in sensible flux. T_R represents the temperature anomaly induced by changes in residual term. T_S represents

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the temperature anomaly induced by changes in solar radiation, latent, sensible and residual fluxes.

4 Discussion

4.1 The diverse shift in sowing date of winter wheat in the NCP

The spatiotemporal changes of winter wheat phenology had been examined. In the period of 1981-2009, sowing date delayed significantly at 13 station and advanced at 8 stations out of the 36 agro-meteorological experiment stations (Xiao et al. 2013). In the NCP, the sowing date were on average delayed by 1.5 day/decade. The diverse trends in sowing date were also existed at the national scale, where 6 stations significantly advanced by up to 9.1 day/decade, and 11 stations significantly delayed by up to 10 days/decade (Tao et al. 2012).

The main reasons for agricultural phenology shifts include climate warming and variety renewal (Mirschel et al. 2005; Eyshi Rezaei et al. 2017; Liu et al. 2017). Climate warming mainly leads to the delay of sowing date, and variety renewal is more likely to affect the length of reproductive period. The management practices, photoperiod, and the time of summer maize harvest also contributed to the shift of winter wheat sowing date (Yuan et al. 2010).

The proper sowing date is key to ensure winter wheat survived through winter and reduce the freezing injury, insect pests and other harmful conditions (Sacks et al. 2010; Zhang et al. 2012; Newbery et al. 2016). With faster growth in warmer environment, the sowing date should be postponed to maintain the proper coverage of winter wheat in dormancy period. The warming of the NCP is regionally consistent (Shi et al. 2014), and

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the diverse change of sowing date will affect the coverage of winter wheat, especially one fifth stations advanced their sowing date. Earlier sowing may also benefited from the reduction in freezing damage and the increase in pest diseases caused by higher minimum temperature, since more above-ground biomass will not be subject to lethal freezing damage and will resist higher harms from pests and diseases. There are also management practices to counteract the effects of advanced sowing date, such as deep tillage and delayed irrigation, which reduce the development of leaves and stems.

Shifts in sowing date significantly affected land surface characteristic. And this affects probably more than we think especially in the early stage of winter wheat. As shown in Fig.5, there were several times of differences in surface coverage between the two sowing date. Differences in spectral characteristics, canopy structure and physiological activities between soil and winter wheat can significantly affect surface biophysical processes such as surface reflectivity, roughness, canopy resistance and surface energy budget (Richardson et al. 2013). In this study, the two sowing scenarios showed clear disparity in LAI (Fig.2a).

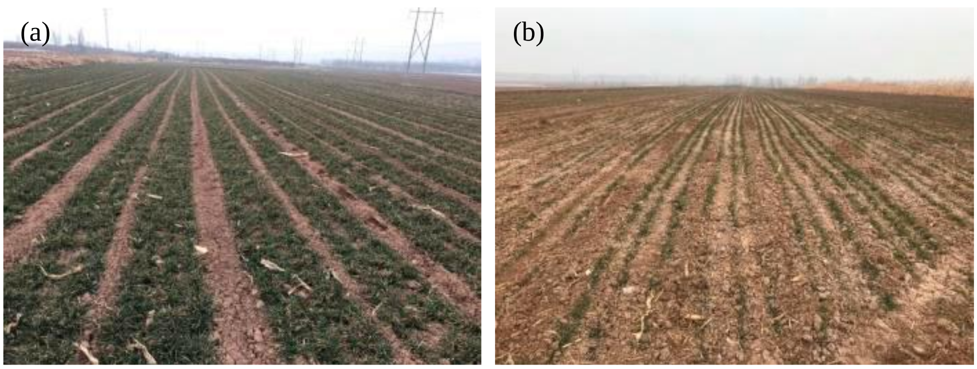

Fig.5 Land surface characteristics of winter wheat in re-greening period for (a) early and (b) late sowing date

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4.2 Warming effect of EP-LP in the dormancy period

Although there were literatures reporting that the albedo process in winter is relatively important (Richardson et al. 2013; Lombardozzi et al. 2018), fewer studies directly addressed the influence of different surface characteristics and climate effect through biophysical process in the dormancy period. In the Oklahoma's winter wheat belt, the rapid crop growth during November exhibited a distinct cool anomaly against adjacent regions of dormant grassland. Over the period of December through April, the cool bias was visibly diminished although the greenness difference between grassland and wheat was more distinct (McPherson et al. 2004). The biophysical impacts between maize and perennial grass were simulated using Agro-IBIS model in US corn belt (Bagley et al. 2015). The results showed that much higher LAI of perennial scenario was existed in winter December–February (3 vs 0 m^2 m^{-2}) and in summer June–August (10 vs 4 m^2 m^{-2}). Perennial grass had smaller surface albedo (coupling snow effect) than maize in winter, but showed quite small difference in summer. During winter and summer, the perennial scenario had slightly higher *LH* than the maize scenario, but the difference in R_n between two scenarios was more than 10W m^{-2} in winter (Bagley et al. 2015). The results of this current study indicate that higher LAI in winter has a warming effect, which is different from the conclusion above. The main reason was due to the relative contributions of surface albedo mechanism and surface flux distribution process.

Previous studies showed that the increase of vegetation cover caused warming feedback by destroying the high albedo of snow in the case of snow cover (Richardson et al. 2013; Bagley et al. 2015; Lombardozzi et al. 2018). But the simple increased crop

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coverage in the bare ground would substantially alter surface albedo results from the decreasing contribution of the soil to the canopy reflectance (Hammerle et al. 2008). The soil reflectance is apparently high at our simulation (Fig.6a), which is favorable to the sharp reduction after crop covered. The measured surface albedo in winter could drop to 0.14 (Liu et al. 2019). The surface albedo was computed based on surface energy budget at Weishan station, the bare ground albedo can be higher than 0.3 and the winter wheat lower than 0.15 (data not shown). Therefore, early sowing in EP scenario results in higher LAI, which can significantly affect the surface albedo at the initial stage and continuously have lower albedo than that in LP scenario. The effect of the soil on the canopy reflectance is negligible at LAI > 2 m^2 m^{-2} (Goudriaan 1977), which explained why the R_n anomaly of EP-LP was small after the re-greening stage. In the model, the senescence of winter wheat is a process in which LAI decreases rapidly, and the disparity in LAI variations between the two scenarios further led to the difference in surface albedo and R_n during the late growth period.

Low soil water content also contributed to the high surface albedo (Seneviratne et al. 2010)(Fig.6b). With the decrease of surface soil moisture, surface albedo increased in winter, which explained why albedo in the winter was higher than that in the growth period. The increase in soil reflectivity caused by soil drying enhanced the role of low winter wheat reflectivity in surface albedo, the albedo disparity between the two scenarios increased in winter, so the albedo-radiative mechanism strengthened. Low soil moisture also contributed to the disparity in warming effect between EP and LP during dormancy period (Fig.6b). The lack of precipitation in winter made soil moisture unable to be replenished effectively, thus reducing soil evaporation and crop transpiration. But

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during the growing season, soil moisture is high enough to supply transpiration. The lower the T_a, the lower the transpiration vitality, thus unable to offset the warming effect of increased R_n absorption, which explained why the winter T_c disparity among stations was controlled by T_a.

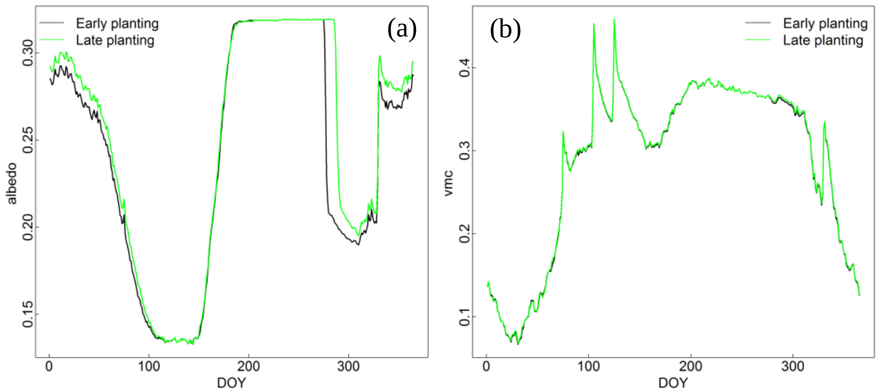

Fig.6 Dynamics of (a) surface albedo and (b) surface soil moisture content under two sowing scenarios in winter wheat growing season

4.3 Cooling effect of EP-LP during the growing period

The phenological shifts, such as earlier leaf unfolding, delayed leaf fall, and lengthening of the green-cover season have feedback on climate through biophysical and biogeochemical processes (Penuelas et al. 2009). Previous studies showed cooling effect in the photosynthetic active period through surface biophysical mechanism.

In the NCP, the increased spring surface greenness at farmland, benefited from advanced re-greening stage of winter wheat (Xiao et al. 2013; Liu et al. 2017), had cooling and wetting effects (Zhang et al. 2013) and suppressed the moderate to light rainfall (Zhang et al. 2015). The analysis found that surface greening increased the partitioning into *LH* and reduced *SH* to cooling surface air and suppression of rainfall

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(Zhang et al. 2013; Zhang et al. 2015). Distinguished difference between early-covering crops (winter wheat, winter rapeseed, winter barley) and late-covering crops (corn, silage maize, sugar beet) in central Europe caused impacts on simulated surface energy fluxes and temperature in the Noah-MP model, the higher LAI led to an increase in *LH*, decreased in *SH* and eventually surface cooling in May-September (Bohm et al. 2020). The Agro-IBIS model was used to study the impacts on surface energy balance of advanced corn sowing date (10 days): Early sowing means earlier development and senescence of LAI, causing stronger disparity of *LH* than R_n with bigger LAI and probably a slight cooling of T_a in June (Sacks and Kucharik 2011). Similar conclusions were presented based on simulated T_c results.

5 Conclusions

The dynamics of winter wheat LAI and T_c under two sowing date scenarios were simulated by the SiBcrop model in the NCP, and the T_c disparity between the two scenarios was explained by the surface energy balance. The findings include:

(1) Earlier sowing date of winter wheat had higher LAI than later sowing date.

(2) The T_c disparity between EP and LP is divided into two periods: warming effect in the dormancy period, and cooling effect in the active growth period.

(3) Surface energy balance can interpret the climate feedback mechanism of sowing date shift, that is, the dominated role of albedo-radiative process in the dormancy period is surpassed by *LH* partitioning-non-radiative process in the growth period.

(4) The responses of LAI and T_c to sowing date at station scale were divergent: controlled by T_a in the dormancy period, and influenced by *P* and T_a in the growth period.

The study had some shortcomings. The single model simulation was highly dependent on the structure and parameterization scheme of the model. The climate feedback was reflected by the canopy temperature. In the SiBcrop model, the spatial distribution of stations was not fully considered in the determination of sowing date, which resulted in too early or too late sowing at some stations.

Nevertheless, the study quantified the climate effects of the sowing date shift in winter dormancy period. The simulation error of sowing date in land surface models is commonly higher than 10 days (Song et al. 2013; Chen et al. 2020), which may produce detectable climate effect especially in northern winter and then misestimate the variation of minimum temperature. The findings showed that even when land use/cover type remains unchanged, variations in surface properties caused by sowing date might still have detectable climatic effects by affecting the surface biophysical process. The conclusion implies that we need to consider not only conversions of land use/cover types but also changes in crop management to understand climate change.

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