Characterizing spatiotemporal patterns of crop phenology across North America during 2000-2016 using satellite imagery and agricultural survey data

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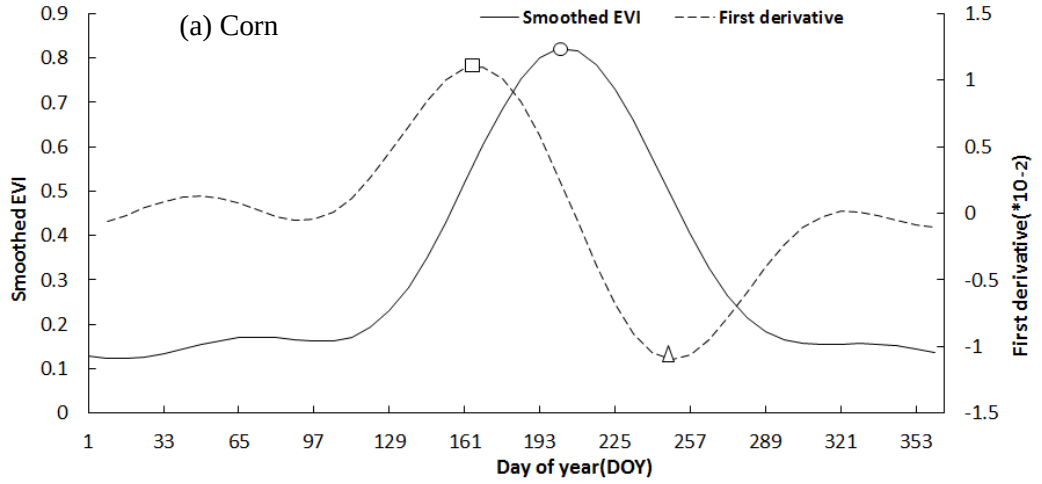
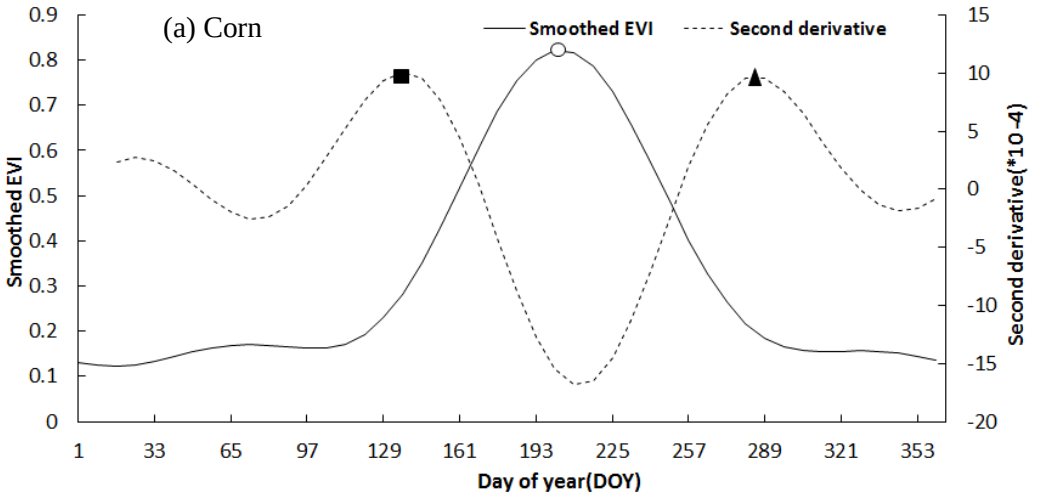
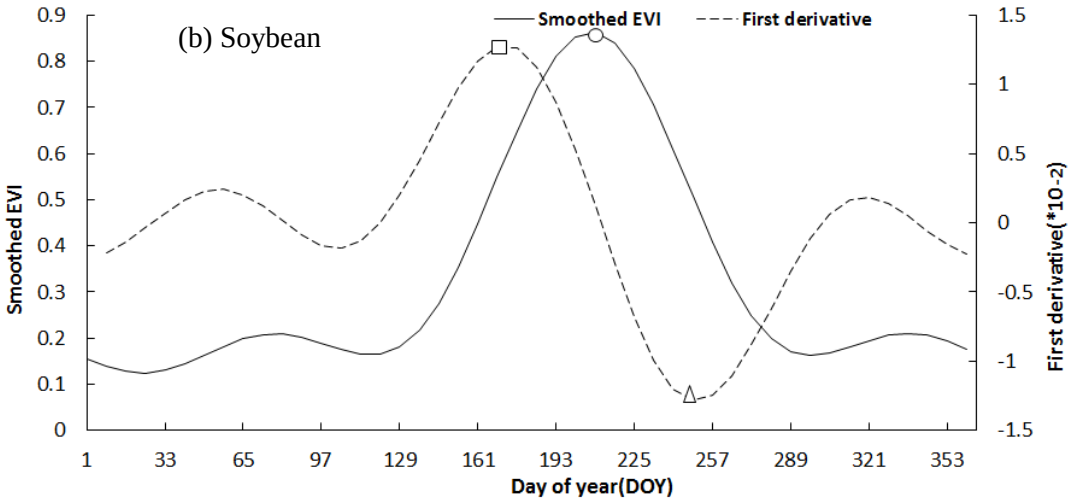
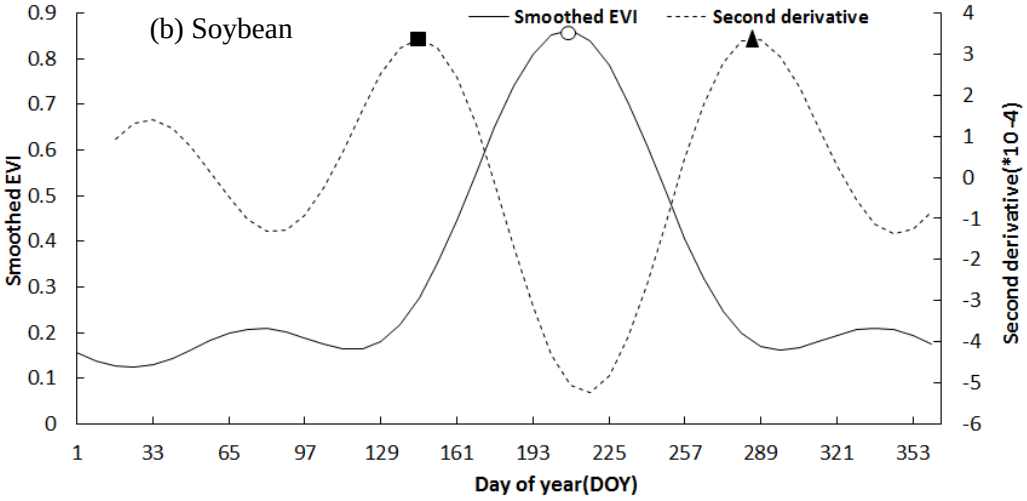
Introduction

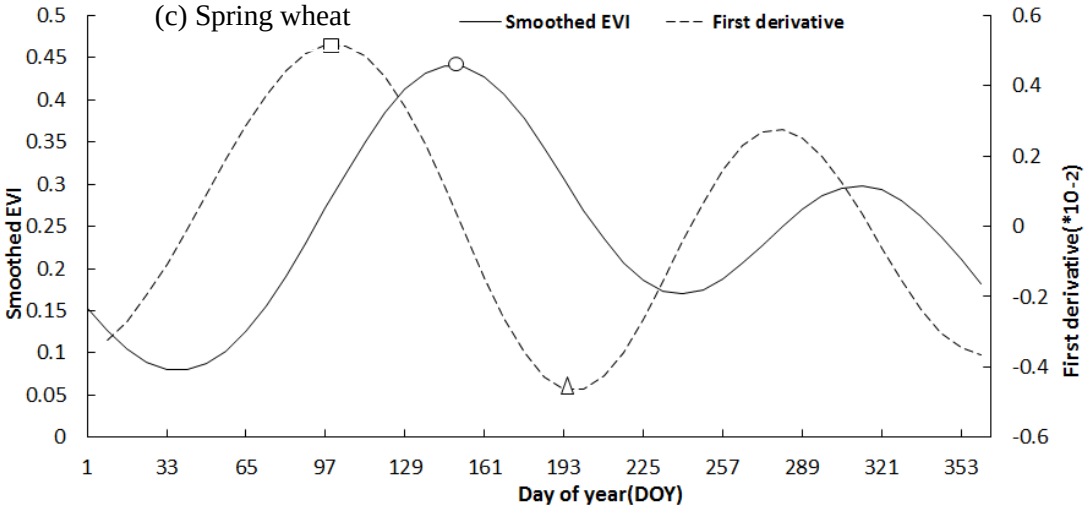
This supporting information provides the same figures and tables, and exhibits all initial data related as seen in the main article.

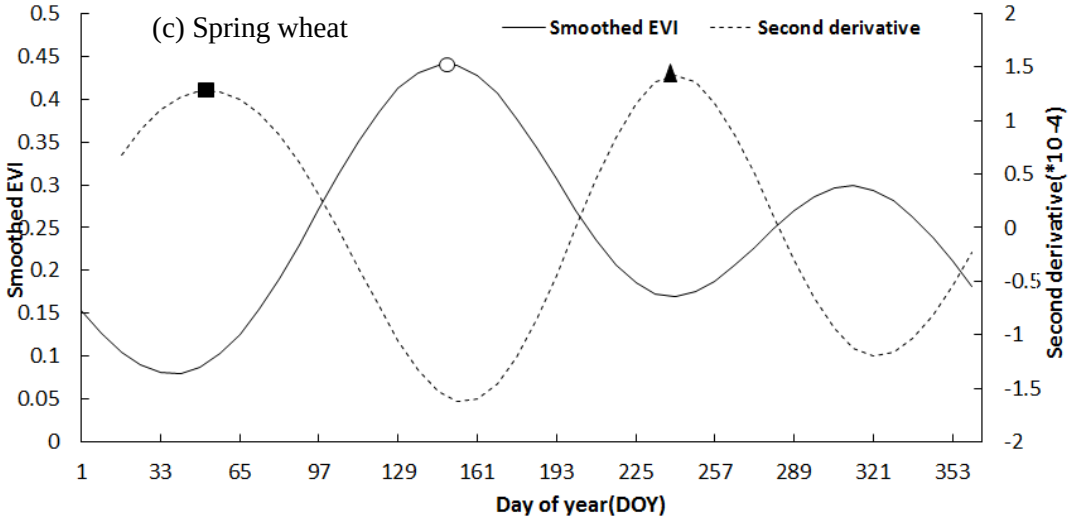

(a) Corn
Smoothed EVI
First derivative
Smoothed EVI
First derivative(*10-2)
Day of year(DOY)

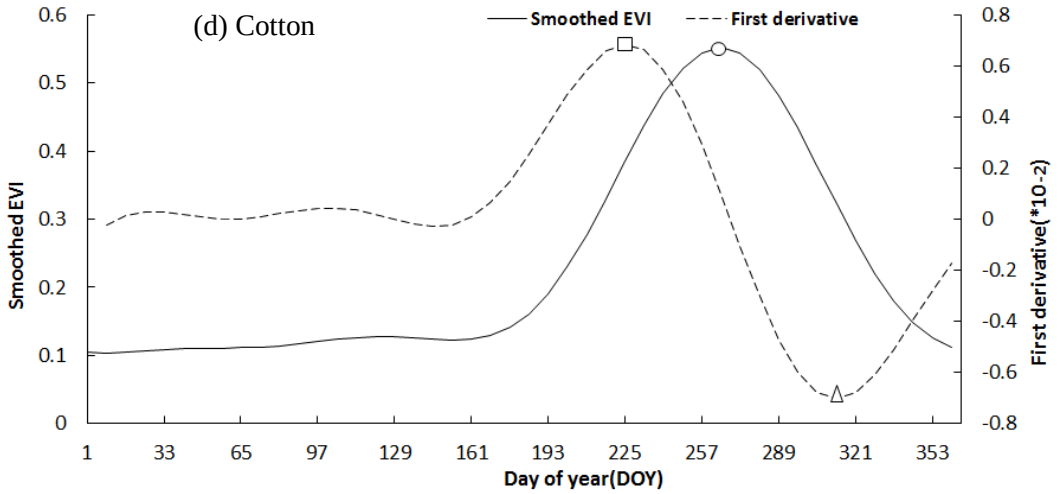

(a) Corn
Smoothed EVI
Second derivative
Smoothed EVI
Second derivative(*10-4)
Day of year(DOY)

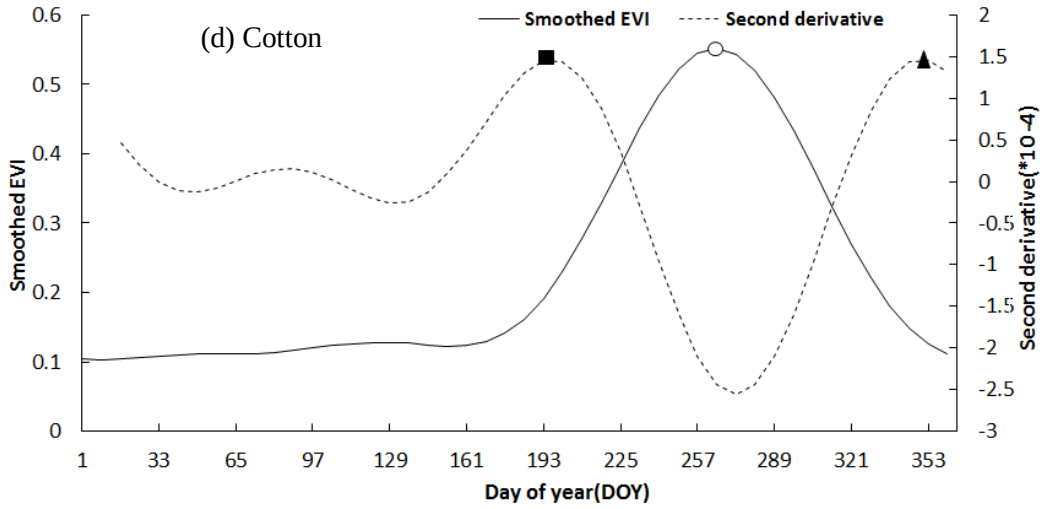

(b) Soybean
Smoothed EVI
First derivative
Smoothed EVI
First derivative(*10-2)
Day of year(DOY)

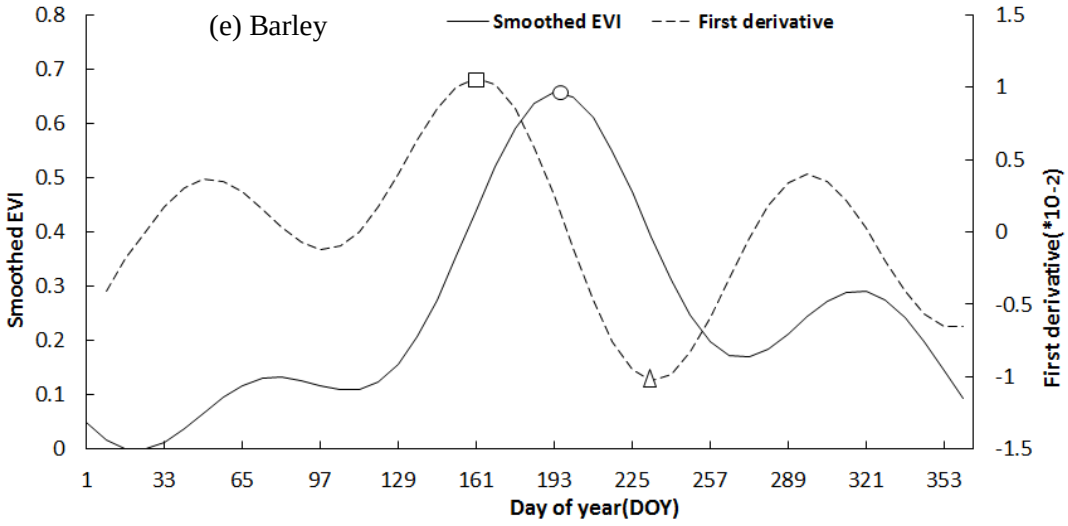

(b) Soybean
Smoothed EVI
Second derivative
Smoothed EVI
Second derivative(*10-4)
Day of year(DOY)

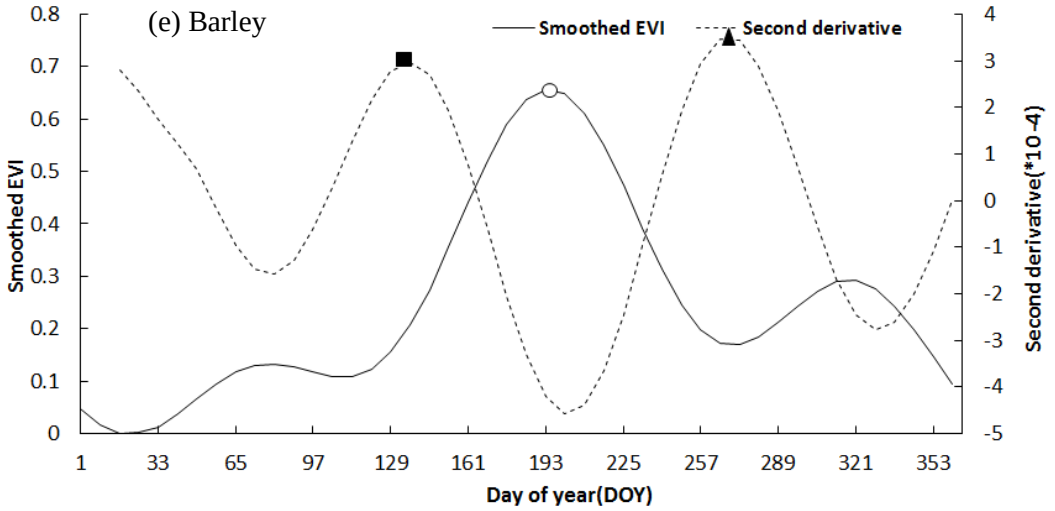

(c) Spring wheat
Smoothed EVI
First derivative
Smoothed EVI
First derivative(*10-2)
Day of year(DOY)

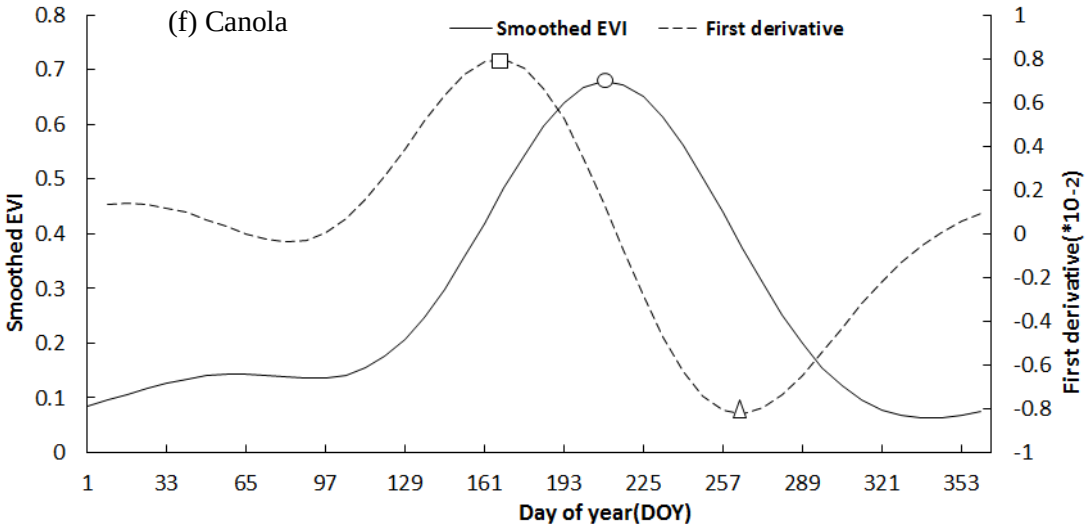

(c) Spring wheat
Smoothed EVI
Second derivative
Smoothed EVI
Second derivative(*10-4)
Day of year(DOY)


(d) Cotton
Smoothed EVI
First derivative
Smoothed EVI
First derivative(*10-2)
Day of year(DOY)


(d) Cotton
Smoothed EVI
Second derivative
Smoothed EVI
Second derivative(*10-4)
Day of year(DOY)


(e) Barley
Smoothed EVI
First derivative
Smoothed EVI
First derivative(*10-2)
Day of year(DOY)


(e) Barley
Smoothed EVI
Second derivative
Smoothed EVI
Second derivative(*10-4)
Day of year(DOY)


(f) Canola
Smoothed EVI
First derivative
Smoothed EVI
First derivative(*10-2)
Day of year(DOY)

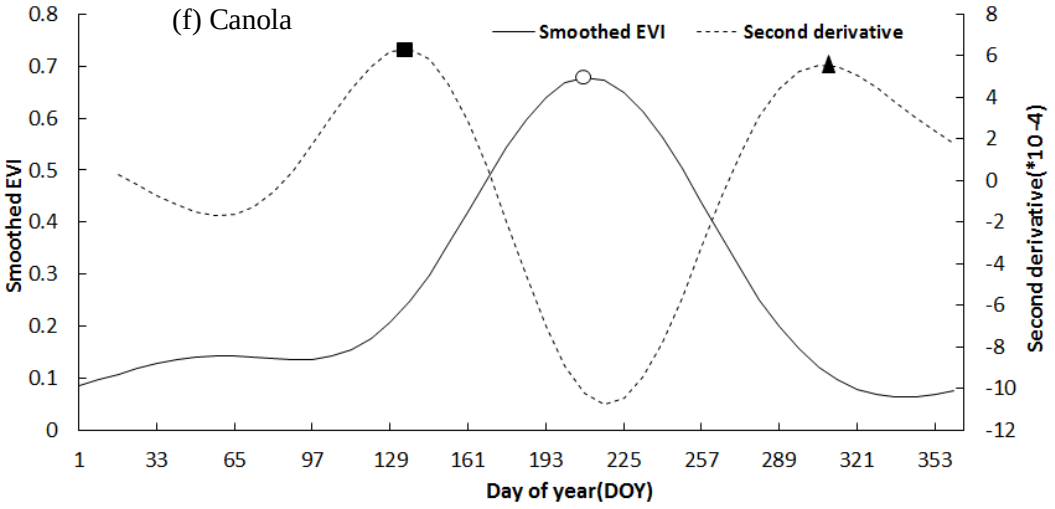

(f) Canola
Smoothed EVI
Second derivative
Smoothed EVI
Second derivative(*10-4)
Day of year(DOY)

Figure S1. Smoothed EVI curve, first derivative and second derivative for each main crop type at five stages with key points ((a) Corn, (b) Soybean, (c) Spring wheat, (d) Cotton, (e) Barley, (f) Canola).

Note.

○ Heading date, EVI curve peak

□ Jointing date, First derivative peak

△ Mature, First derivative trough

■ Planting date, Second derivative peak

▲ Harvesting date, Second derivative peak

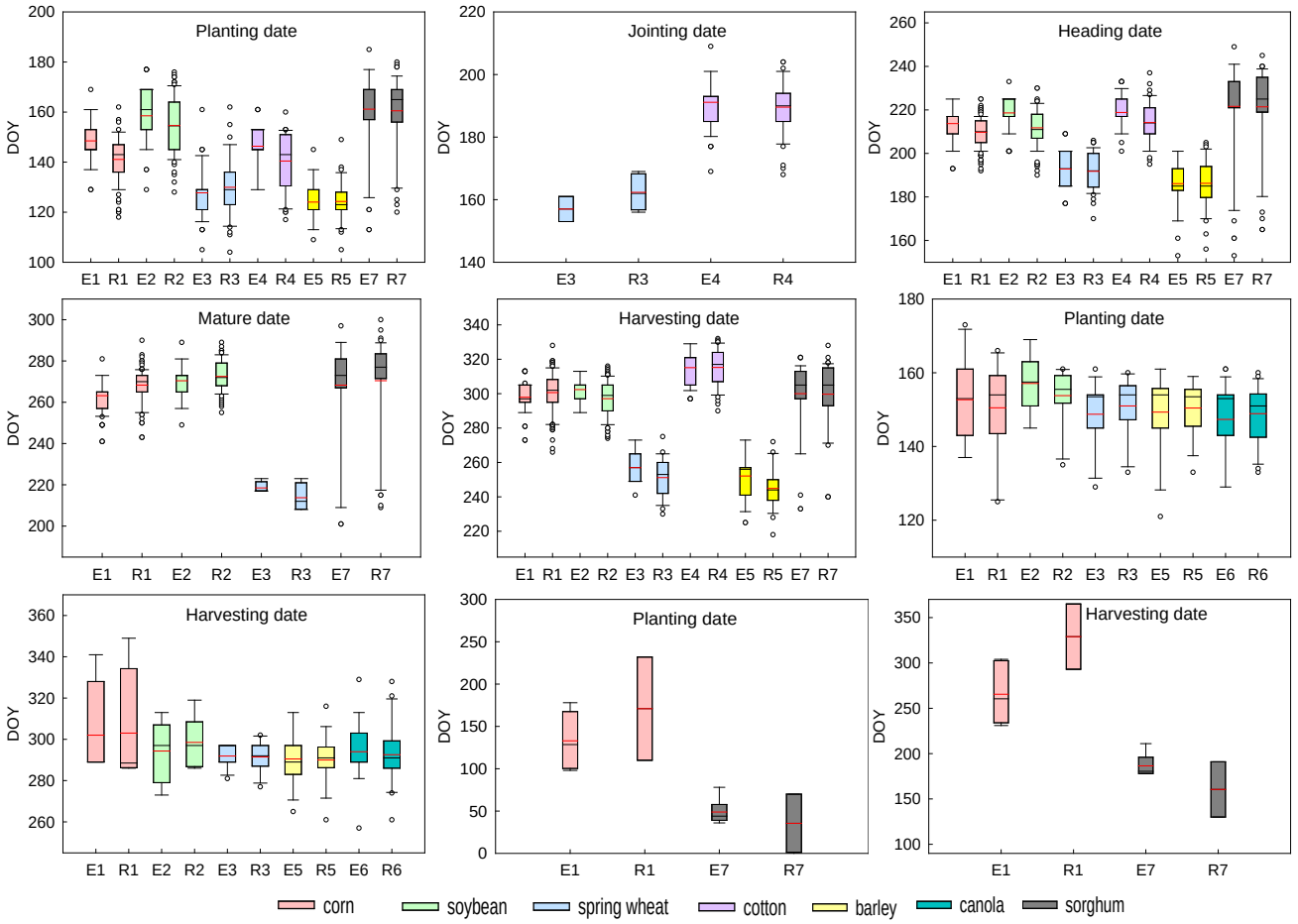
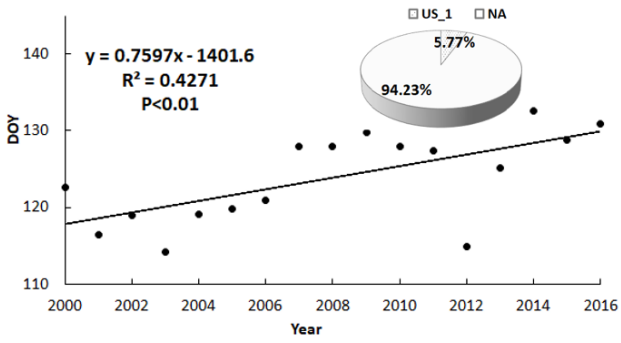
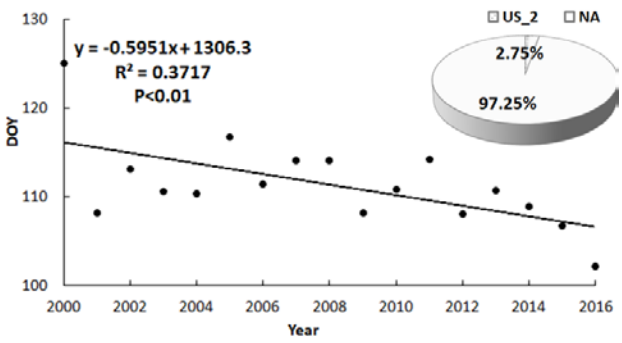
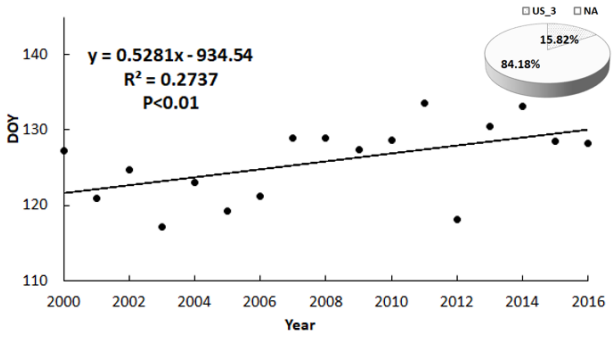
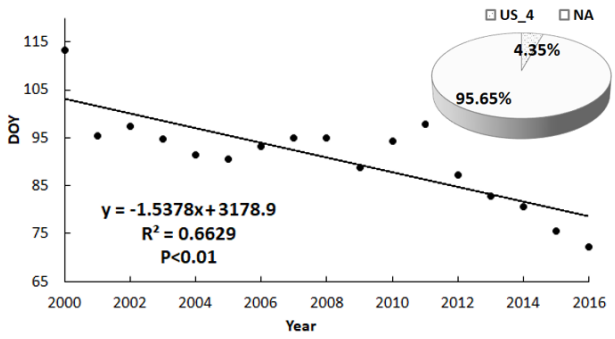


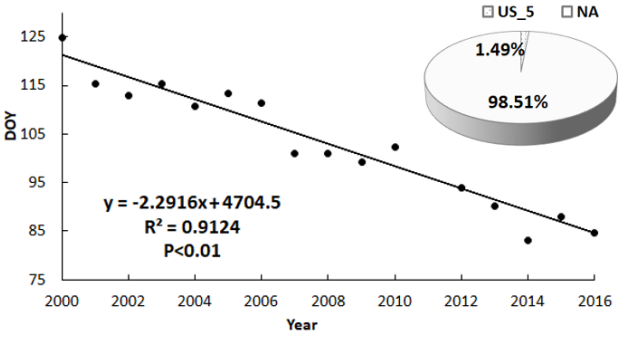
Fig. S2. Comparison of the satellite-based crop phenological dates with those from the ground crop reports across North America (A ~ E: The U.S., F, and G: Canada, H, and I: Mexico. *Note*. E1- E7 represent estimated phenological stages of seven crop types using MODIS data. R1-R7 represent the phenological stages of seven crop types collected from the ground crop reports. Numbers from 1 to 7 represent corn, soybean, spring wheat, cotton, barley, canola, and sorghum, respectively (i.e., E1 means estimated crop phenology for corn, R1 means ground-based crop phenology for corn). Only spring corn was considered in Mexico. Sorghum in Mexico refers to winter sorghum.

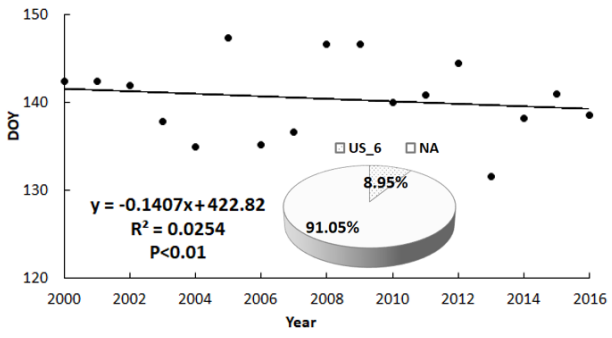

US_1
NA
5.77%
94.23%
y = 0.7597x - 1401.6
R² = 0.4271
P<0.01
DOY
Year

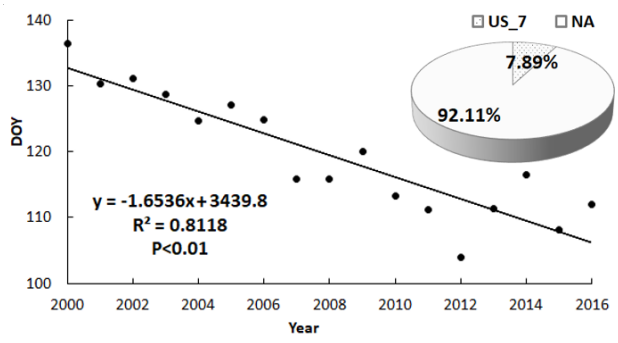

US_2
NA
2.75%
97.25%
y = -0.5951x + 1306.3
R² = 0.3717
P<0.01
DOY
Year

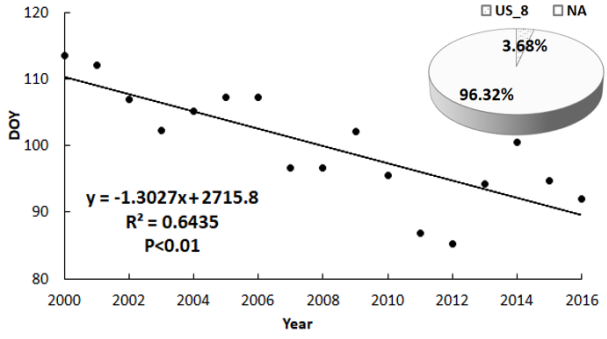

US_3
NA
15.82%
84.18%
y = 0.5281x - 934.54
R² = 0.2737
P<0.01
DOY
Year


US_4
NA
4.35%
95.65%
y = -1.5378x + 3178.9
R² = 0.6629
P<0.01
DOY
Year


US_5
NA
1.49%
98.51%
y = -2.2916x + 4704.5
R² = 0.9124
P<0.01
DOY
Year


US_6
NA
8.95%
91.05%
y = -0.1407x + 422.82
R² = 0.0254
P<0.01
DOY
Year


US_7
NA
7.89%
92.11%
y = -1.6536x + 3439.8
R² = 0.8118
P<0.01
DOY
Year


US_8
NA
3.68%
96.32%
y = -1.3027x + 2715.8
R² = 0.6435
P<0.01
DOY
Year

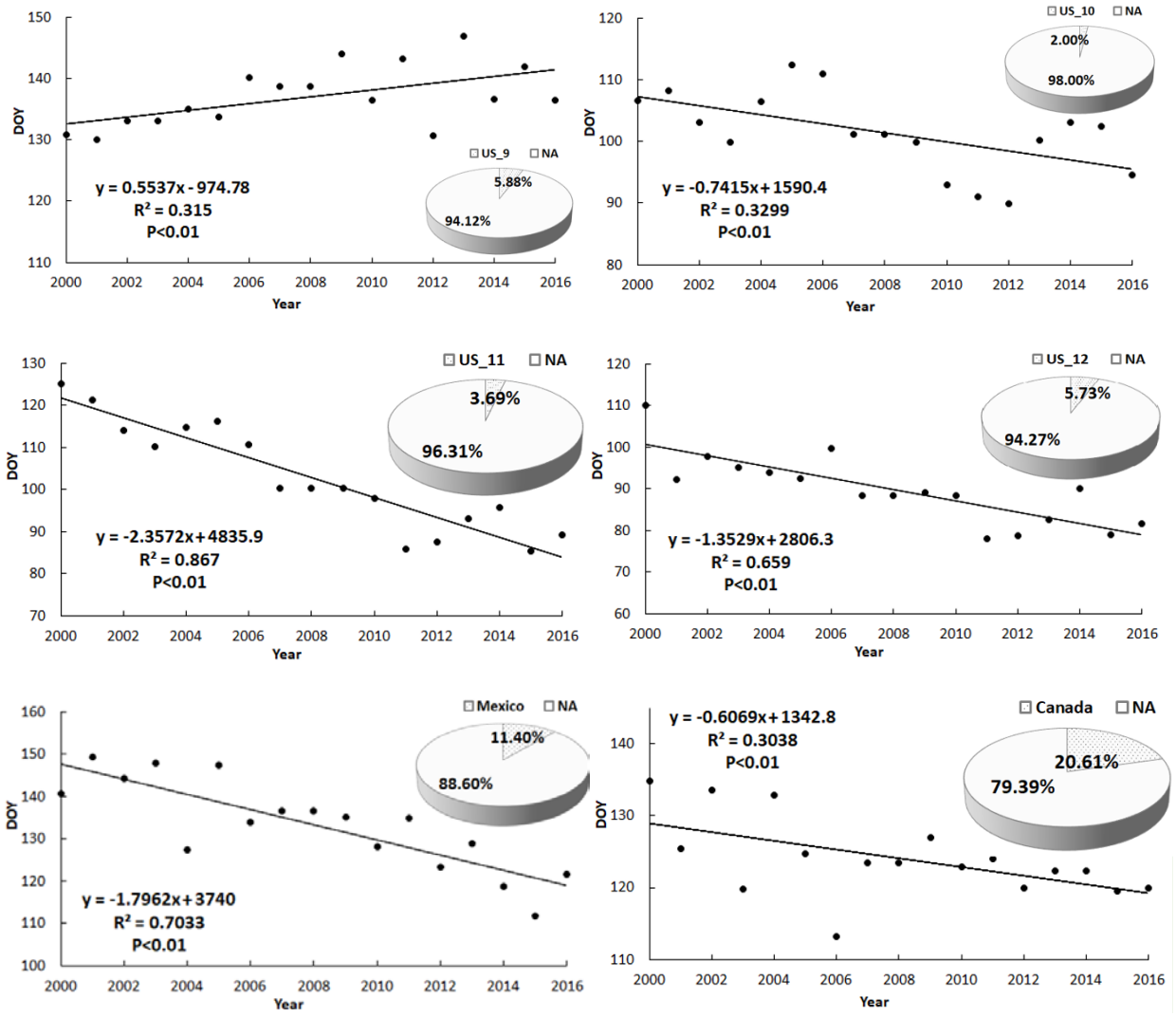
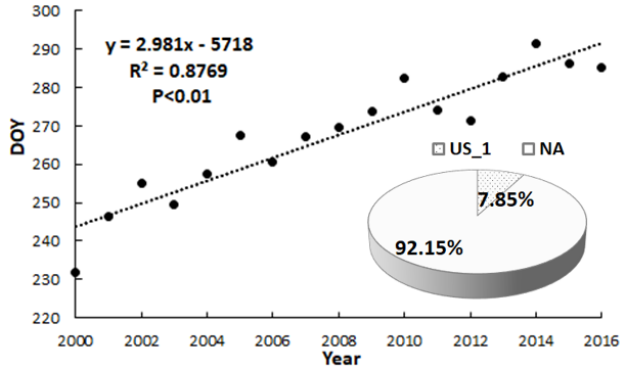
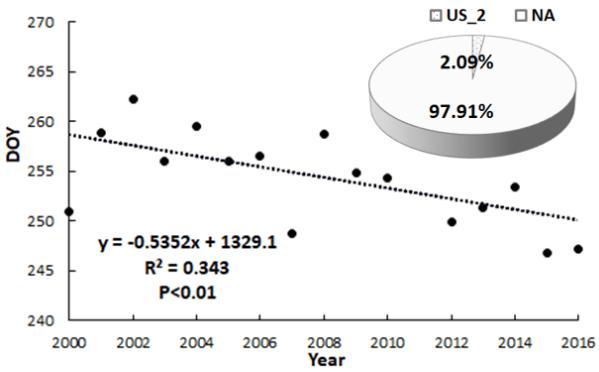
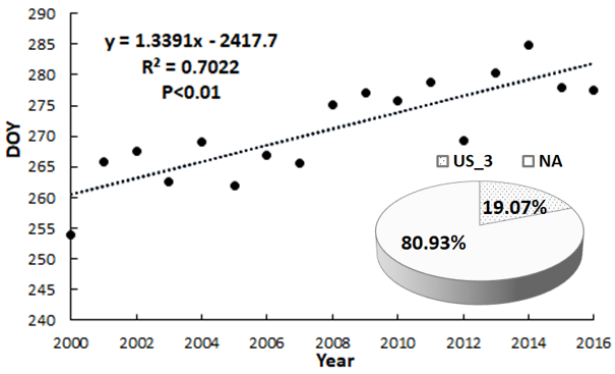
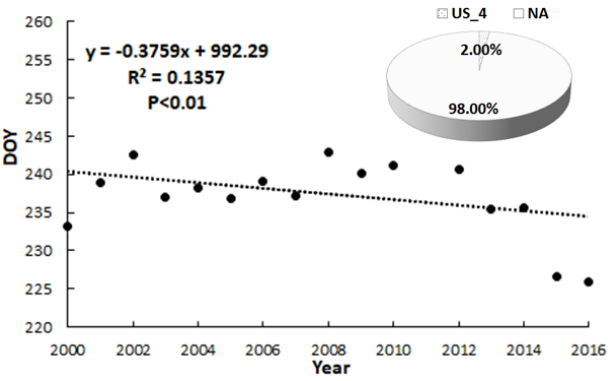


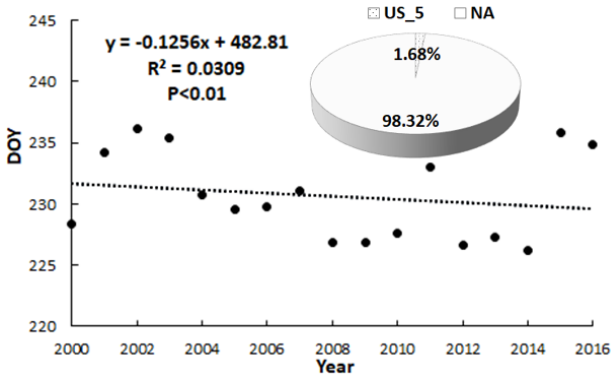
Figure S3. Dynamic change trend planting date in 14 regions of North America. The pie chart represents the percentage of pixels with 95% significance of each region in North America cropland. The numbers of regions in the U.S. are the same as in Table 3.

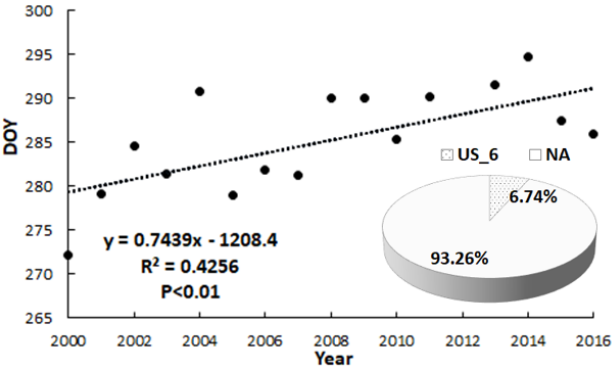

y = 2.981x - 5718
R² = 0.8769
P<0.01
US_1
NA
7.85%
92.15%
DOY
Year

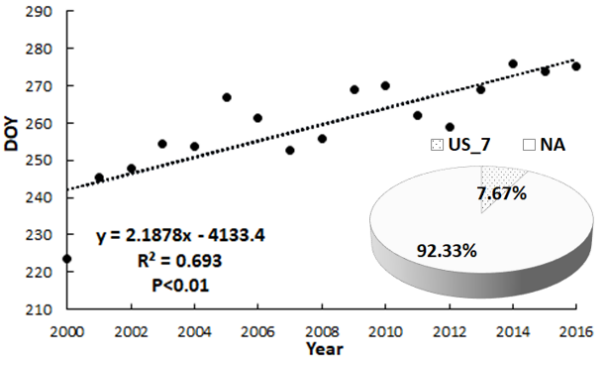

US_2
NA
2.09%
97.91%
y = -0.5352x + 1329.1
R² = 0.343
P<0.01
DOY
Year

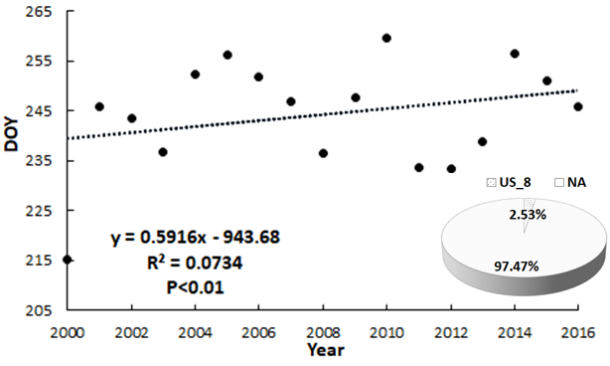

y = 1.3391x - 2417.7
R² = 0.7022
P<0.01
US_3
NA
19.07%
80.93%
DOY
Year


y = -0.3759x + 992.29
R² = 0.1357
P<0.01
US_4
NA
2.00%
98.00%
DOY
Year


y = -0.1256x + 482.81
R² = 0.0309
P<0.01
US_5
NA
1.68%
98.32%
DOY
Year


y = 0.7439x - 1208.4
R² = 0.4256
P<0.01
US_6
NA
6.74%
93.26%
DOY
Year


y = 2.1878x - 4133.4
R² = 0.693
P<0.01
US_7
NA
7.67%
92.33%
DOY
Year


y = 0.5916x - 943.68
R² = 0.0734
P<0.01
US_8
NA
2.53%
97.47%
DOY
Year

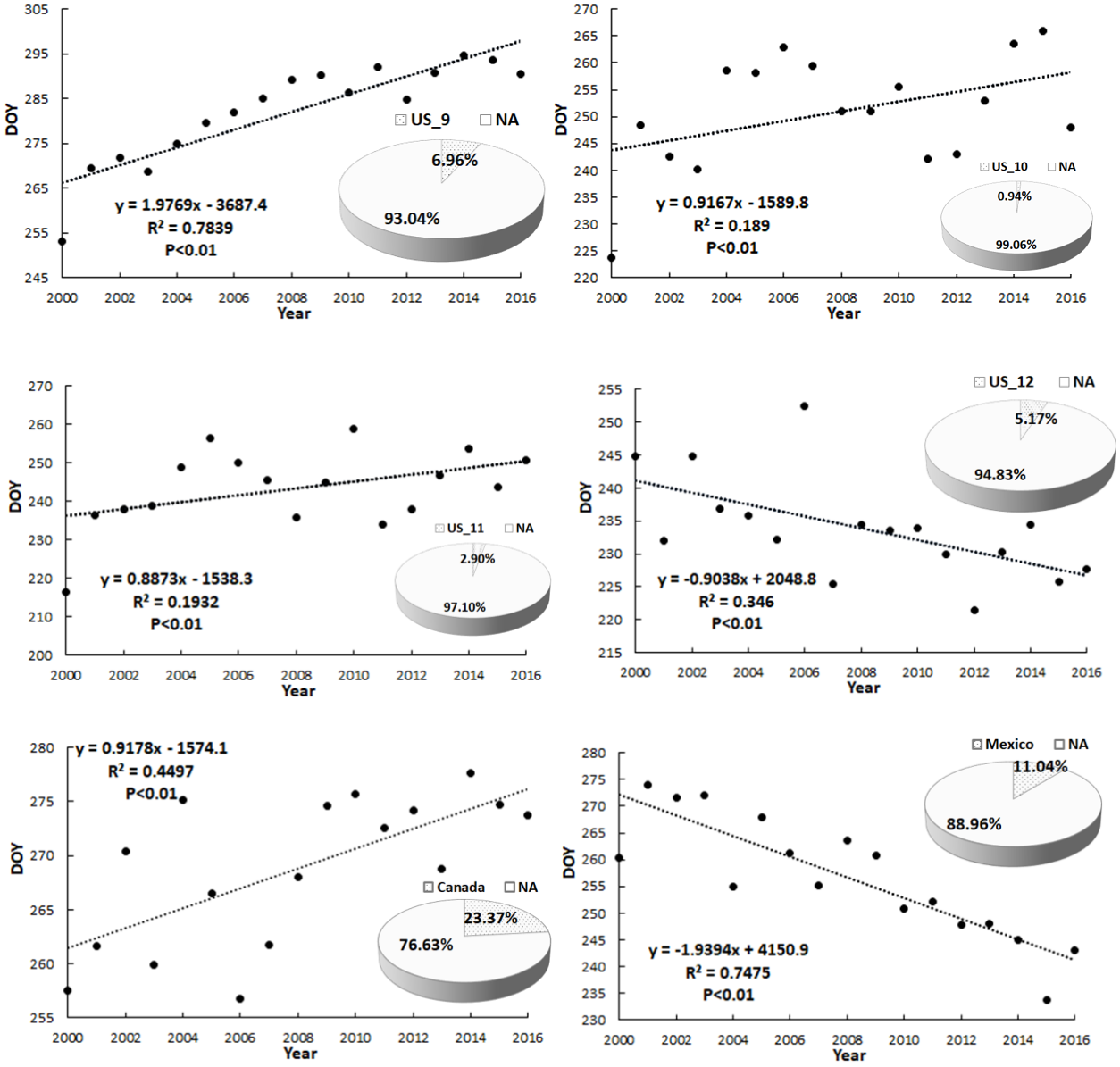


Figure S4. Dynamic change trend harvesting date in 14 regions of North America. The pie chart represents the percentage of pixels with 95% significance of each region in North America cropland. The numbers of regions in the U.S. are the same as Table S1.

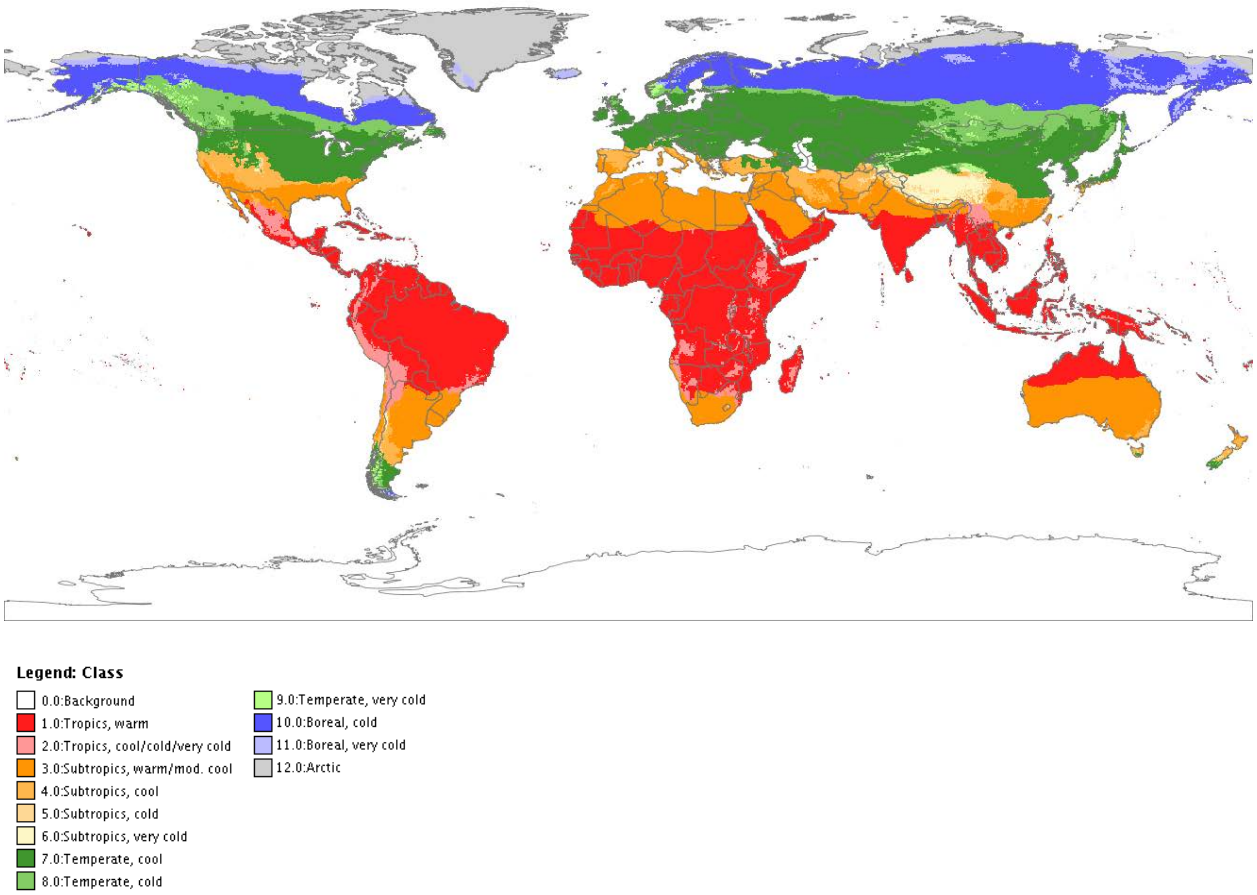


Figure S5. Thermal Zones: used in trend analysis of crop growth period in North America FAO/IIASA, 2011. Global Agro-ecological Zones (GAEZ v3.0). FAO Rome, Italy and IIASA, Laxenburg, Austria.

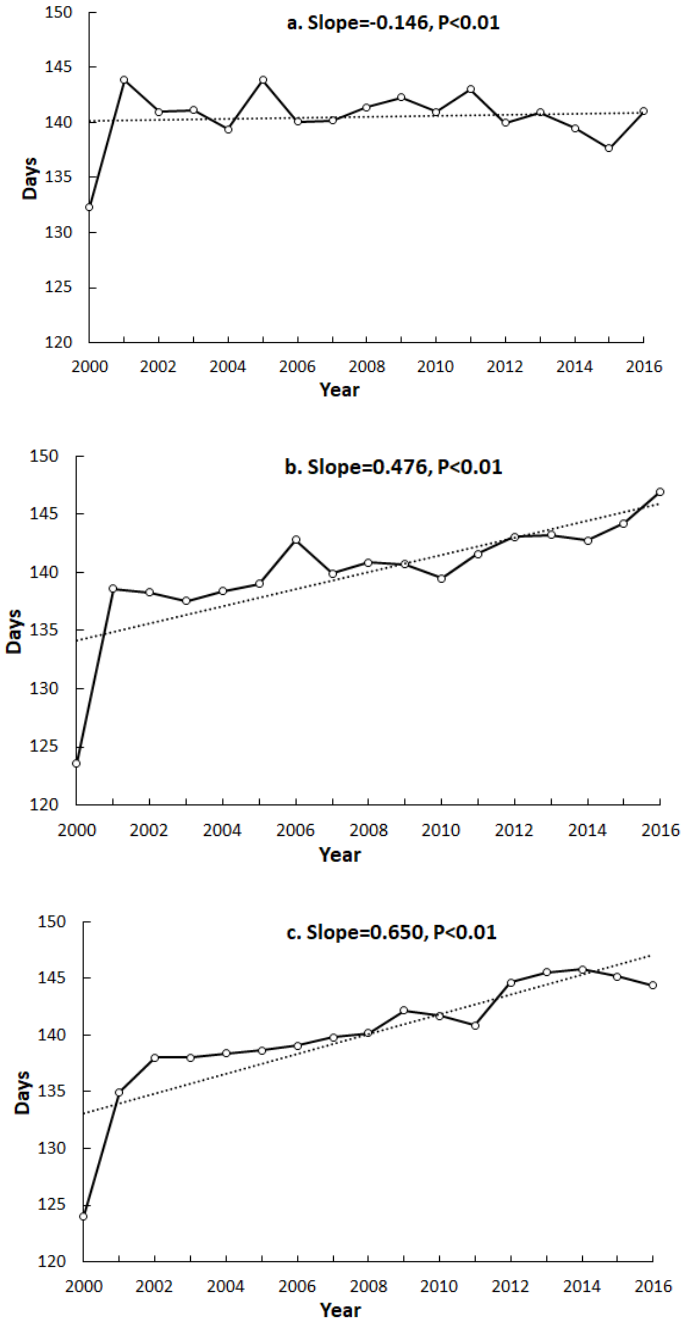


Figure S6. The trends of the crop growth period in six main regions in North America (a. Tropics; b. Subtropics; c. Temperature). Crop-growing season length is the average of pixels with a p-value of less than 0.05 significance measured by Mann-Kendall analysis. (We excluded the year 2000 when calculating the slopes and P values due to the underestimated growing season resulted from incomplete MODIS EVI time series.)

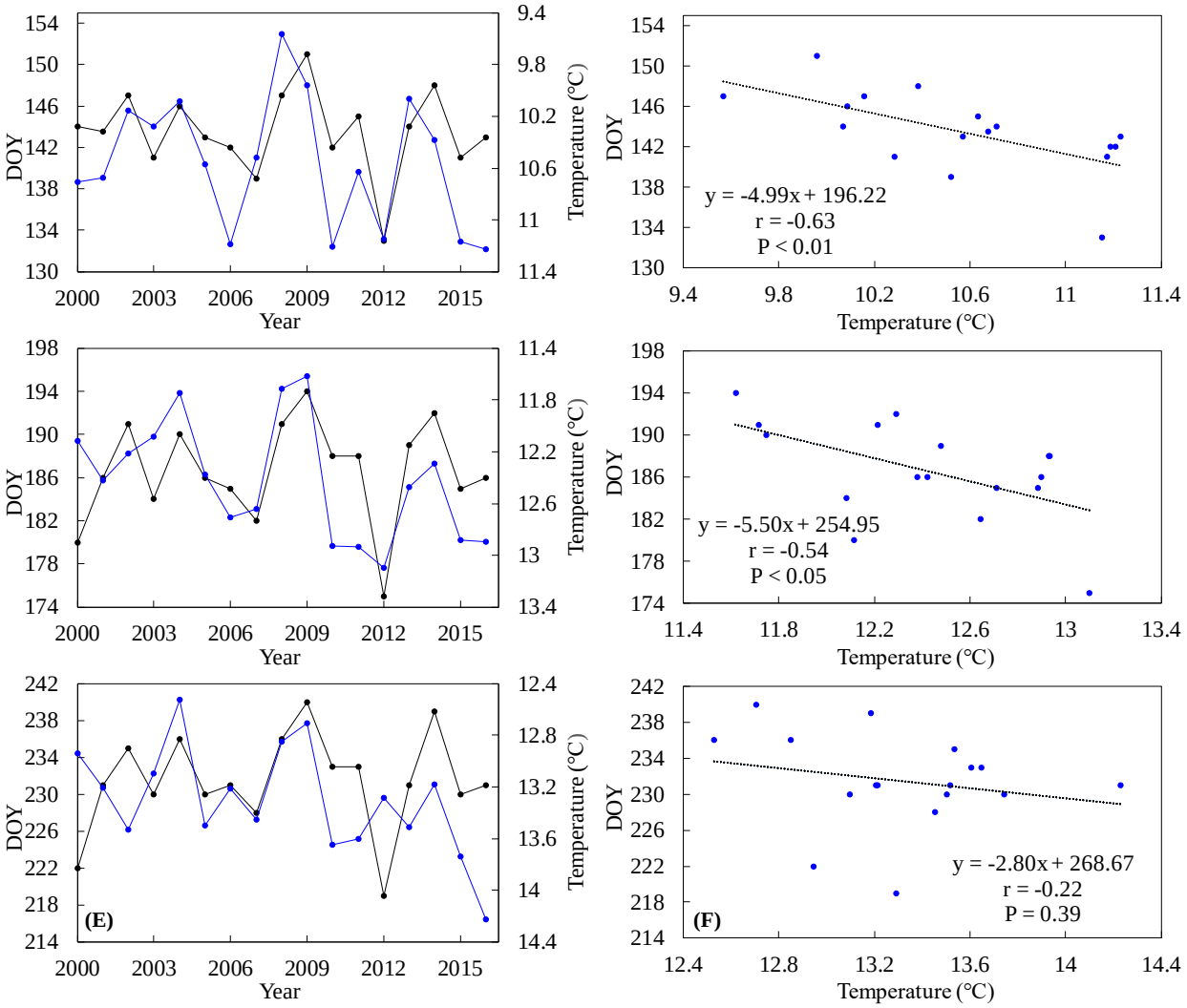


Figure S7. Interannual changes in estimated jointing, heading, and maturity dates and average daily minimum temperatures for jointing (A, B: April to June), heading dates (C, D: May to July), and maturity seasons (E, F: July to September) in North America during 2000-2016.

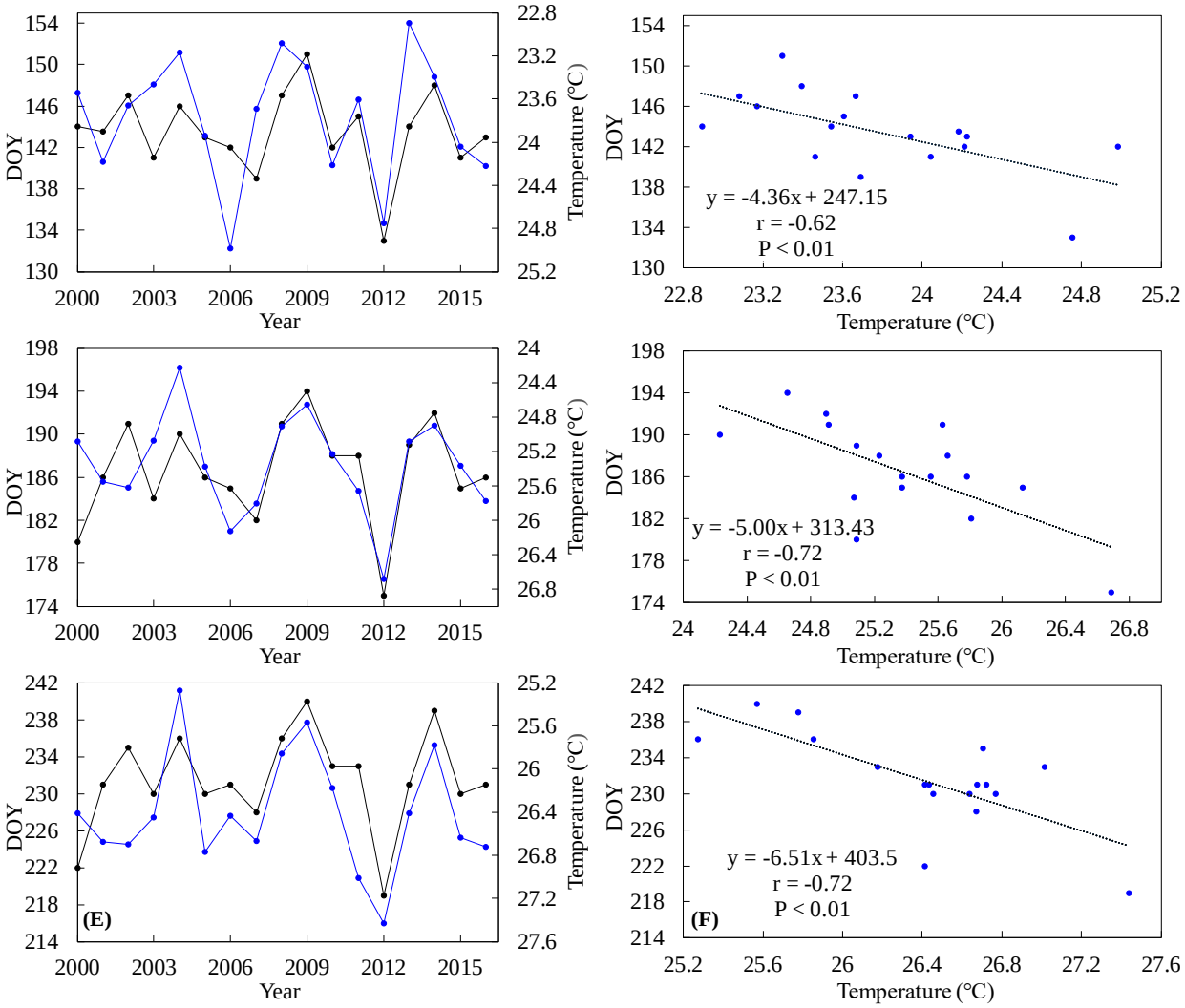


Figure S8. Interannual changes in estimated jointing, heading, and maturity dates and average daily maximum temperatures for jointing (A, B: April to June), heading dates (C, D: May to July), and maturity seasons (C, D: July to September) in North America during 2000-2016.

Table S1. Time Ranges (Day of Year, DOY) of Major Crop Types at Different Phenological Stages in North America.

Country	Phenological stages	Crop types							
		Barley	**Canola**	**Corn**	**Cotton**	**Soybean**	**Spring wheat**	**Sorghum**	**Time ranges**
U.S.	Planting	(90, 150)	-	(100, 140)	(90, 170)	(110, 170)	(90, 150)	(80, 180)	(90, 180)
	Jointing	-	-	-	(140, 220)	-	(120, 180)	-	(120, 220)
	Heading	(155, 210)	-	(160, 235)	(165, 235)	(170, 230)	(160, 210)	(150, 260)	(150, 260)
	Mature	-	-	(225, 280)	-	(235, 285)	(180, 240)	(220, 310)	(180, 310)
	Harvesting	(210, 270)	-	(245, 330)	(250, 330)	(250, 320)	(210, 290)	(240, 330)	(210, 330)
Canada	Planting	(120, 165)	(97, 165)	(130, 165)	-	(130, 165)	(130, 165)	-	(97, 165)
	Harvesting	(260, 330)	(260, 330)	(280, 365)	-	(280, 365)	(260, 330)	-	(260, 365)
Mexico	Planting	-	-	(120, 180)	-	-	-	(30, 105)	(30, 180)
	Harvesting	-	-	(270, 365)	-	-	-	(140, 180)	(140, 365)
North America	Crop growth period	(90, 330)	(97, 330)	(100, 365)	(90, 330)	(110, 320)	(90, 330)	(30, 330)	(30, 365)

Table S2. Site distribution for cropping intensity evaluation.

I.D.	Region*	ROI	The U.S. state
1	Heartland	101	Illinois; Missouri
2	Mountain	106	Montana; Wyoming; Utah; Colorado; Arizona; New Mexico
3	Northern Plain	113	North Dakota; South Dakota; Nebraska; Kansas
4	Northwest	35	Washington; Oregon; Idaho
5	Pacific	61	California; Nevada
6	Upper Midwest	34	Iowa; Minnesota; Wisconsin
7	Delta	87	Arkansas; Louisiana; Mississippi
8	Eastern Mountain	106	Kentucky; West Virginia; Virginia; North Carolina; Tennessee
9	Great Lakes	82	Michigan; Ohio; Indiana
10	Northeastern	91	Maine; Vermont; New Hampshire; Massachusetts; Rhode Island; Connecticut; New York; New Jersey; Pennsylvania; Maryland; Delaware
11	Southern	115	Alabama; Florida; Georgia; South Carolina
12	Southern Plains	75	Oklahoma; Texas

**Note.* Regions in the United States are divided according to the USDA Crop Data Layer (https://nassgeodata.gmu.edu/CropScape/).

Table S3. Crop phenology evaluations of our estimates and SACRA (Kotsuki and Tanaka, 2015).

Crop types	Phenology products	MAE (days)		RMSE (days)		States	Time period
		Planting	Harvesting	Planting	Harvesting		
Corn	Our study	9.50	8.00	10.97	9.77	Illinois; Michigan; Minnesota; Nebraska	2004-2006
	SACRA	37.50	43.25	38.04	44.10		
Soybean	Our study	4.33	10.81	5.93	14.06	Arkansas; Indiana; Louisiana; Mississippi; Missouri; North Carolina; Ohio; South Carolina; South Dakota;	
	SACRA	54.15	24.85	55.40	28.10		
Wheat	Our study	4.67	10.33	-	-	North Dakota	
	SACRA	12.33	22.67	-	-		
Cotton	Our study	5.86	9.93	-	-	Georgia	
	SACRA	45.44	29.45	-	-		

Table S4. Comparison of the estimations detected from the improved EVI-curve-based approach with and without thresholds in 2015 and 2016 *.

Crop types	Methods	Statistics (days)	Planting	Jointing	Heading	Mature	Harvesting
Corn	With-threshold	RMSE	12.70	-	6.54	7.69	6.90
		MAE	9.54	-	4.96	6.29	5.17
	No-threshold	RMSE	15.90	-	8.98	11.54	9.26
		MAE	14.00	-	7.71	11.21	7.33
Soybean	With-threshold	RMSE	8.73	-	4.04	5.81	10.30
		MAE	6.65	-	3.40	4.85	7.50
	No-threshold	RMSE	11.18	-	6.28	10.81	11.55
		MAE	9.45	-	5.30	9.30	9.20
Spring wheat	With-threshold	RMSE	4.04	5.40	6.18	3.67	8.00
		MAE	3.30	5.17	4.60	2.50	6.50
	No-threshold	RMSE	4.93	10.20	11.90	5.87	33.36
		MAE	4.30	9.17	9.40	5.00	25.20
Cotton	With-threshold	RMSE	10.06	4.39	8.71	-	3.15
		MAE	7.30	3.90	7.50	-	2.70
	No-threshold	RMSE	22.42	4.91	16.90	-	29.83
		MAE	19.30	4.50	16.10	-	22.50
Barley	With-threshold	RMSE	2.94	-	2.66	-	9.51
		MAE	2.00	-	2.25	-	8.00
	No-threshold	RMSE	6.98	-	10.79	-	41.43
		MAE	5.33	-	8.75	-	32
Sorghum	With-threshold	RMSE	3.29	-	4.48	4.07	3.86
		MAE	2.40	-	3.50	3.00	3.10
	No-threshold	RMSE	7.67	-	12.10	13.73	29.07
		MAE	5.00	-	8.10	12.60	18.70
Canola	With-threshold	RMSE	6.77	-	-	-	4.40
		MAE	6.50	-	-	-	3.67
	No-threshold	RMSE	19.5	-	-	-	17.67
		MAE	20.91	-	-	-	22.38
All crops	With-threshold	Mean RMSE	6.93	4.90	5.43	5.31	6.59
		Mean MAE	5.38	4.54	4.37	4.16	5.23
	No-threshold	Mean RMSE	12.65	7.56	11.16	10.49	24.60
		Mean MAE	11.18	6.84	9.23	9.53	19.62

**Note.* Three provinces (Alberta; Saskatchewan; Manitoba) in Canada were used for the comparison for Canola. The U.S. states used for the comparison of other six crops are same with the states in Table 4.