Table S1: Formulas for retrieving LSP using remote sensing data (with $NDVI_{SDC}$ as a specific example)

Phenological parameters	Formulas
$NDVI_{SOS}$	$NDVI_{\mathrm{SOS}} = NDVI_{min,up} + 0.2 \times (NDVI_{\max} - NDVI_{min,up})$
$NDVI_{MidGreenup}$	$NDVI_{\mathrm{MidGreenup}} = NDVI_{min,up} + 0.5 \times (NDVI_{\max} - NDVI_{min,up})$
$NDVI_{Maturity}$	$NDVI_{\mathrm{Maturity}} = NDVI_{min,up} + 0.9 \times (NDVI_{\max} - NDVI_{min,up})$
$NDVI_{Senescence}$	$NDVI_{\mathrm{Senescence}} = NDVI_{min,down} + 0.9 \times (NDVI_{\max} - NDVI_{min,down})$
$NDVI_{MidGreendown}$	$NDVI_{\mathrm{MidGreendown}} = NDVI_{min,down} + 0.5 \times (NDVI_{\max} - NDVI_{min,down})$
$NDVI_{EOS}$	$NDVI_{\mathrm{EOS}} = NDVI_{min,down} + 0.2 \times (NDVI_{\max} - NDVI_{min,down})$

*Note: ：$NDVI_{min,up}$ represents the minimum value of NDVI during the ascending phase in a year, $NDVI_{min,down}$ represents the minimum value of NDVI during the descending phase in a year, and $NDVI_{\max}$ represents the maximum value of NDVI in a year.

Table S2: The regression measurement statistics for the comparison between remote sensing phenology and actual phenology sites

Data	Vegetation type	Phenological parameter	$NDVI_{SDC}$			$EVI2_{SDC}$		
			R^2	RMSE(d)	Bias(d)	R^2	RMSE(d)	Bias(d)
PEP27	DBF	SOS	0.64	16.05	-13.38	0.68	9.36	-6.48
		MidGreendown	0.62	12.39	10.34	0.65	6.81	3.47
	ENF	SOS	0.69	11.57	-10.36	0.73	10.17	-8.57
USA-NPN	DTF	SOS	0.59	14.23	-10.16	0.65	10.80	-6.33
		MidGreendown	0.55	8.83	-0.9	0.61	11.45	-1.38

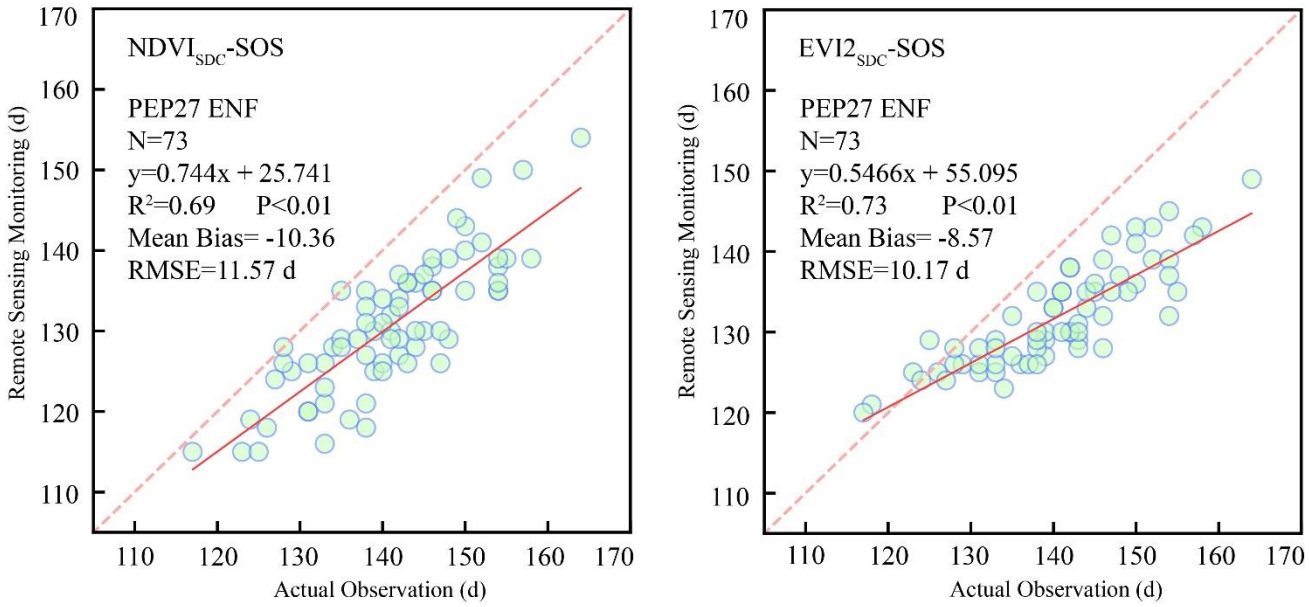

Figure S1: Comparison of phenological accuracy between remotely sensed retrievals and phenological observations derived from the PEP27 dataset for evergreen forests. The remotely sensed phenological results for the current year show temporal consistency with the observed phenological stations. ENF is an abbreviation for Evergreen Needleleaf Forest.

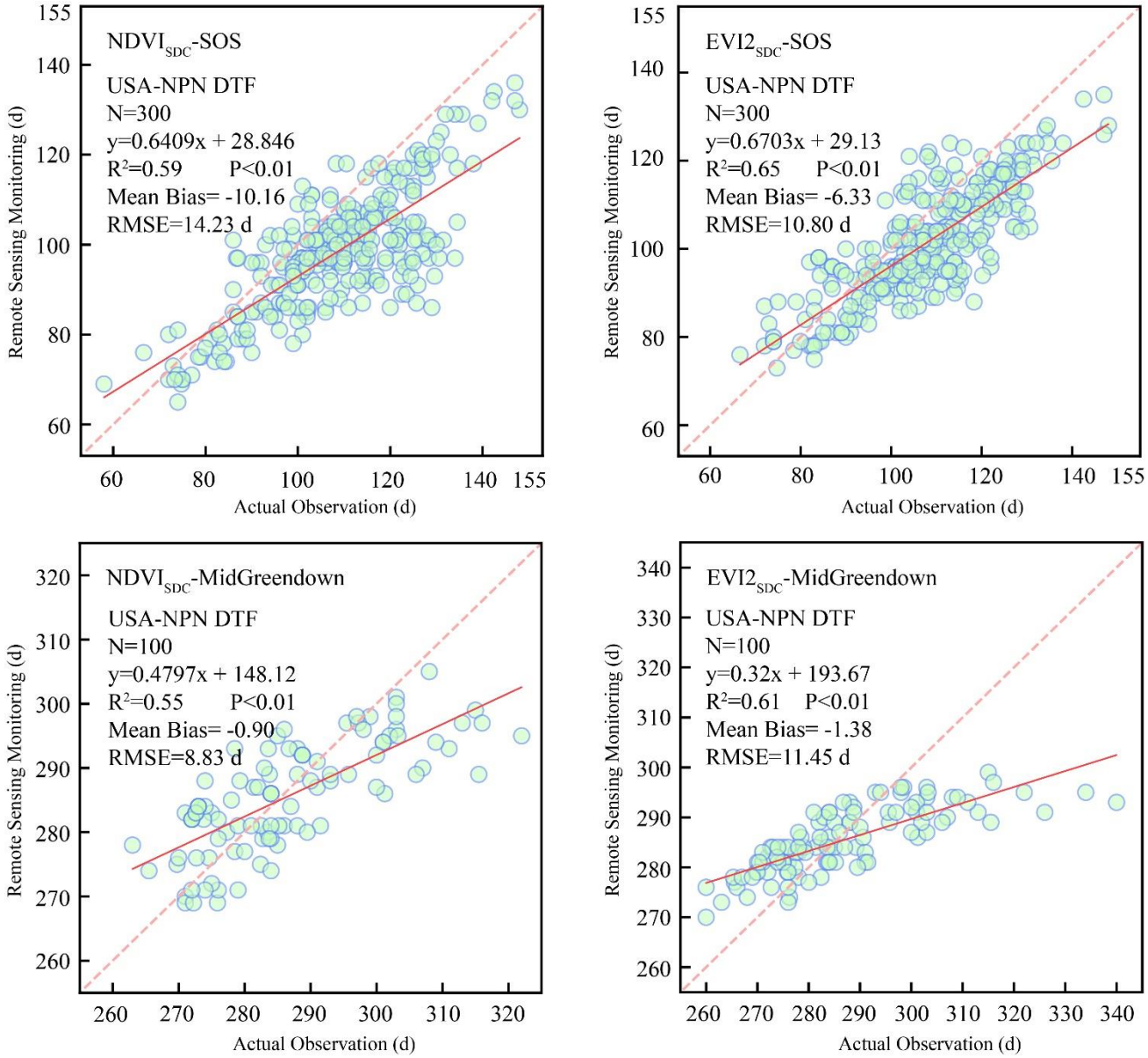

Figure S2: Comparison of phenological accuracy between remotely sensed retrievals and phenological observations derived from the USA National Phenology Network (USA-NPN) for deciduous forests. The remotely sensed phenological results for the current year demonstrate temporal consistency with the observed phenological stations. DTF represents deciduous type forest.

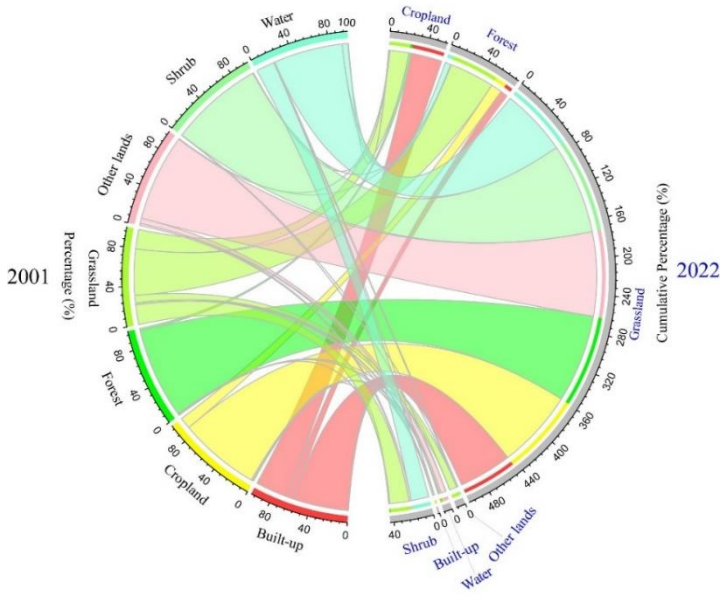

Figure S3: Flowchart of the percentage of land transfer area in the study area from 2001 to 2022.

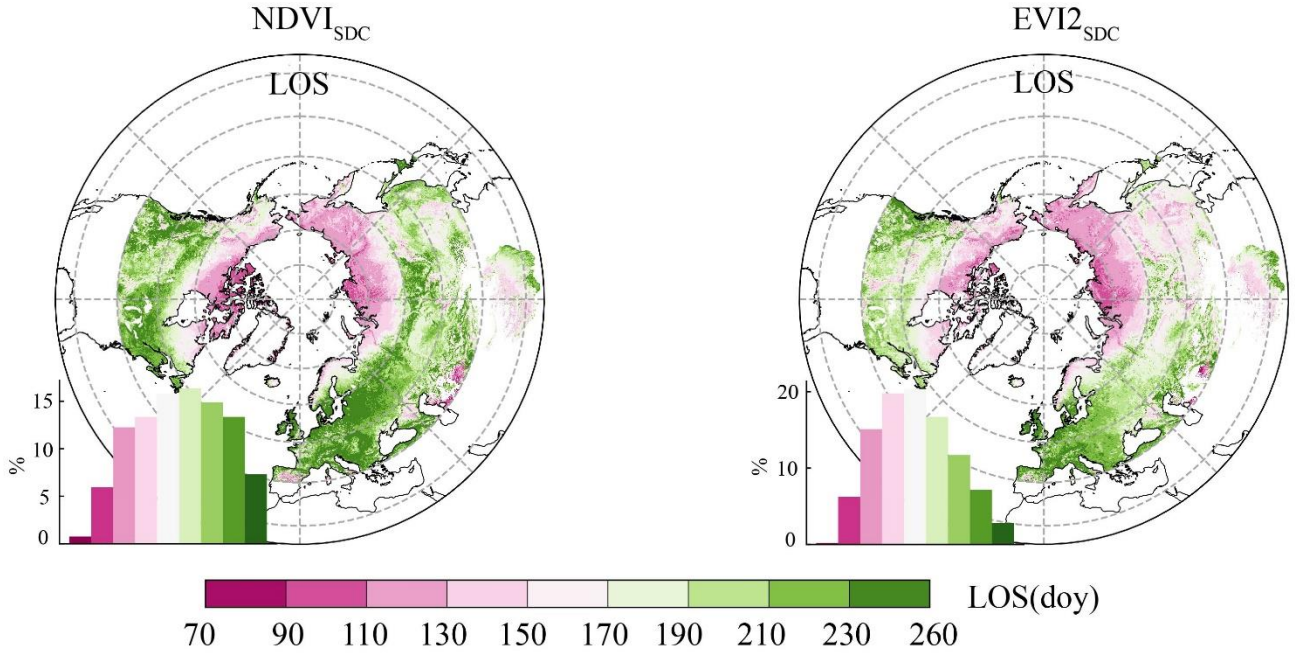

Figure S4: Spatial distribution of the long-term average of LOS derived from NDVI$_{SDC}$ and EVI2$_{SDC}$ in the study area from 2001 to 2022. Each histogram in the bottom left corner represents the frequency distribution of the corresponding phenological date.

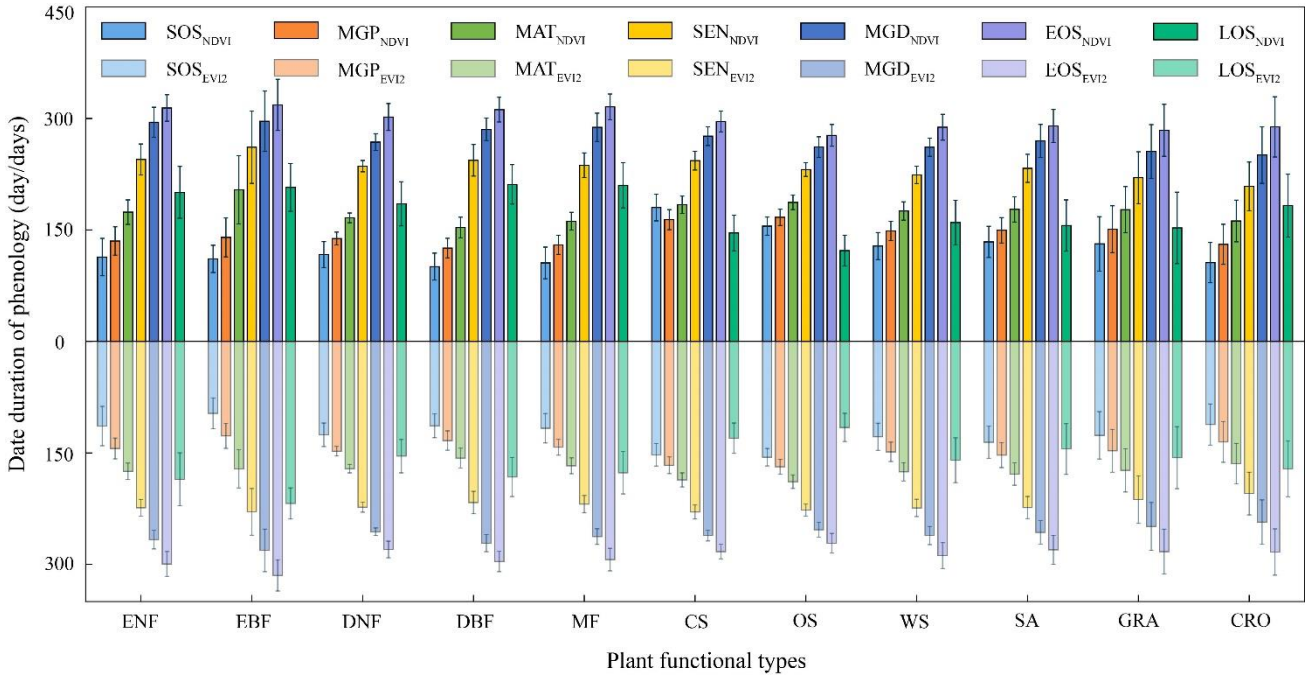

Figure S5: Vegetation phenology across different vegetation functional types. From left to right, the order of phenological parameters is SOS, MidGreenup (MGP), Maturity (MAT), Senescence (SEN), MidGreendown (MGD), EOS, and LOS. ENF: Evergreen Needleleaf Forest; EBF: Evergreen Broadleaf Forests; DNF: Deciduous Needleleaf Forests; DBF: Deciduous Broadleaf Forests; MF: Mixed Forests; CS: Closed Shrublands; OS: Open Shrublands; WS: Woody Savannas; SA: Savannas; GRA: Grasslands; CRO: Croplands. The NDVI and EVI2 for each phenological parameter refer to NDVI$_{SDC}$ and EVI2$_{SDC}$ datasets, respectively.

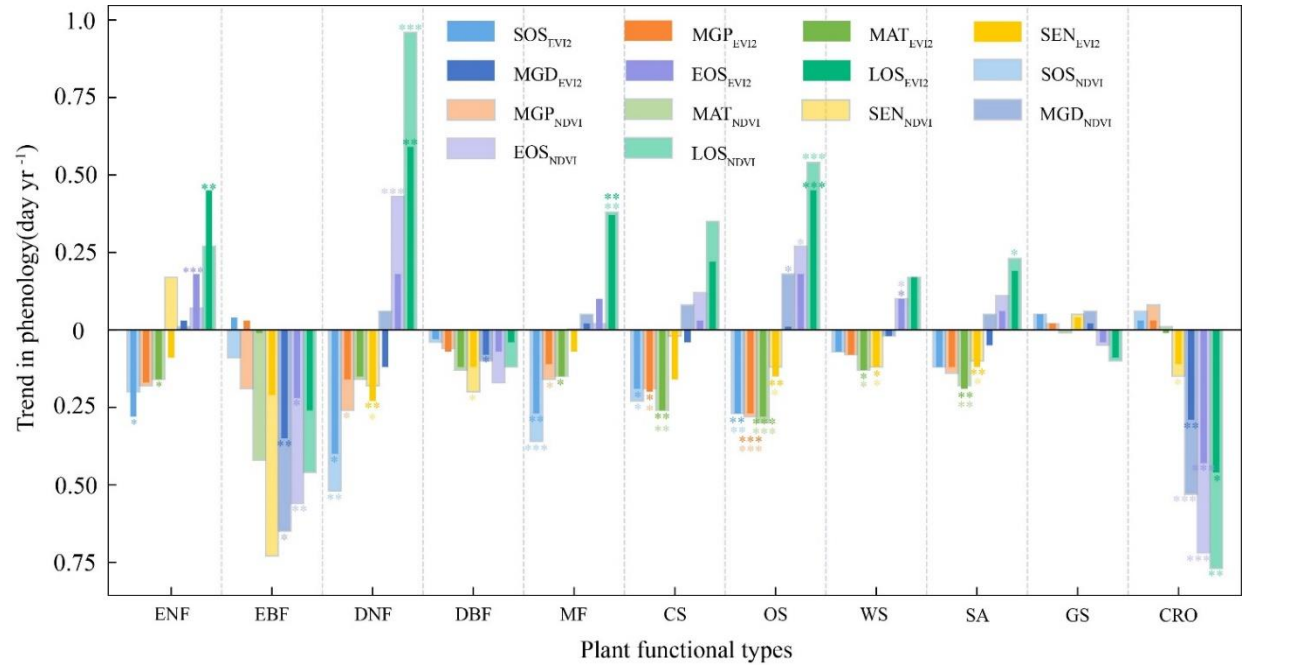

Figure S6: Vegetation phenological trends across different vegetation functional types. The order of phenological parameters from left to right and the definitions of the abbreviations on the x-axis are the same as in Figure S5. The significance levels are represented by symbols (*), where *, **, and *** correspond to significance at the 95% level ($P<0.05$), 99% level ($P<0.01$), and 99.9% level ($P<0.001$), respectively.

Table S3: Pixel statistics and the percentage of significant pixels for each phenological parameter trend from 2001 to 2022

Data sources	Phenological parameters	Positive trend	Negative trend	Significant positive ratio(P<0.05)	Significant negative ratio(P<0.05)
NDVI$_{SDC}$	SOS	39.80	60.20	5.91	15.93
	MidGreenup	31.25	68.75	8.99	16.96
	Maturity	27.15	72.85	7.37	17.58
	Senescence	41.27	58.73	6.87	10.29
	MidGreendown	58.47	41.53	10.49	10.77
	EOS	61.72	38.28	11.29	11.60
	LOS	65.01	34.99	18.06	13.29
EVI2$_{SDC}$	SOS	30.33	69.67	9.47	15.92
	MidGreenup	27.76	72.24	9.47	15.97
	Maturity	23.50	76.50	7.55	18.23
	Senescence	32.34	67.66	6.08	12.48
	MidGreendown	52.89	47.11	8.78	12.35
	EOS	59.36	40.64	10.76	11.28
	LOS	65.20	34.80	17.33	13.17

*Note: "Positive Trend" represents the proportion of positive pixels out of the total pixels. "Negative Trend" represents the proportion of negative pixels out of the total pixels. "Significant Positive Ratio (P<0.05)" represents the proportion of significant positive pixels out of the total positive pixels. "Significant Negative Ratio (P<0.05)" represents the proportion of significant negative pixels out of the total negative pixels.

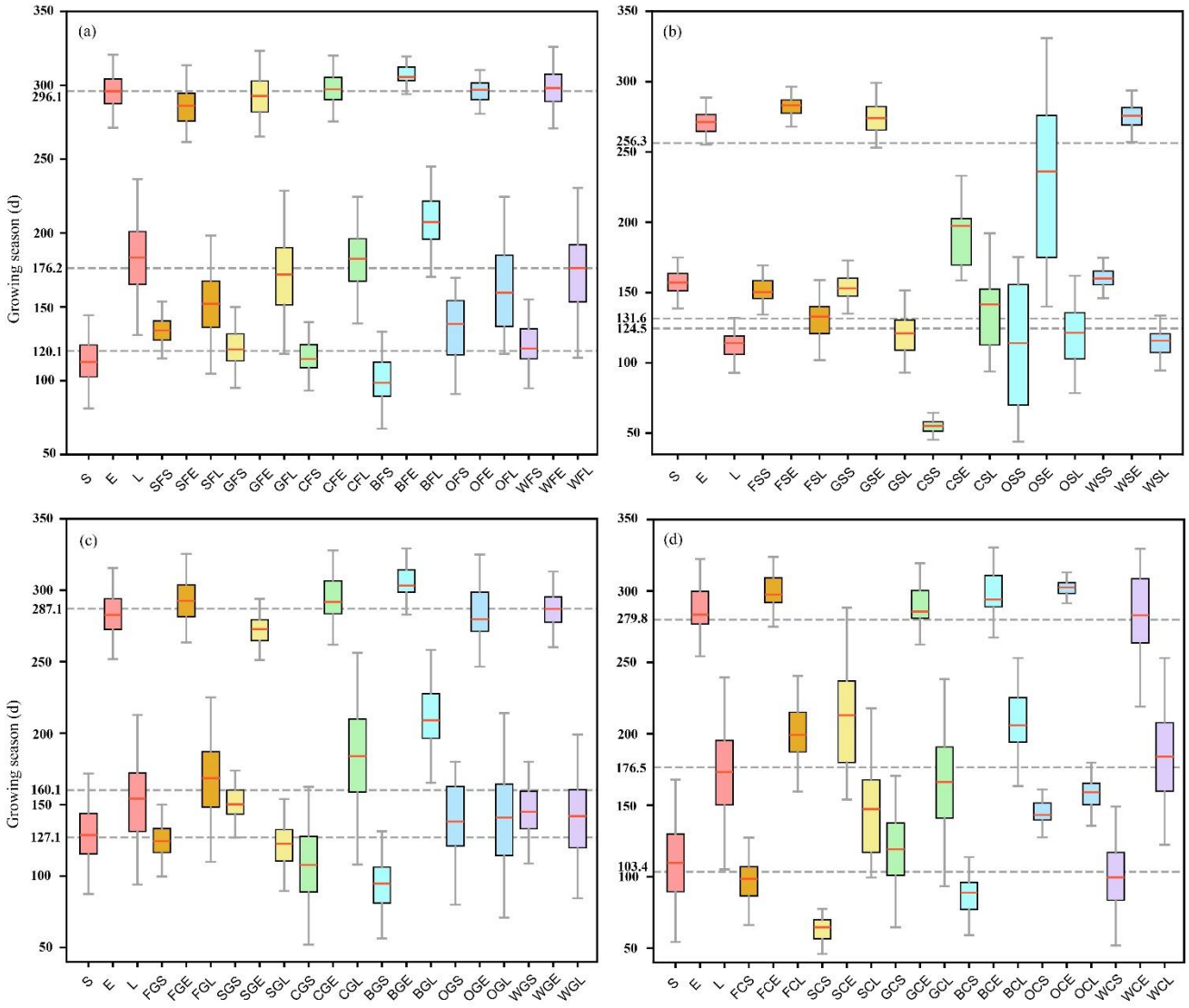

Figure S7: Land use change patterns in forest(a), shrub(b), grassland(c), and cropland(d) based on the phenological differences of LSP (SOS, EOS, LOS) retrieved from EVI2$_{SDC}$. Panels (a), (b), (c), and (d) represent the land use change patterns in forest, shrub, grassland, and cropland, respectively. The x-axis naming convention in each panel follows the same convention as Figure 6(a,b,c,d). In each panel, the three gray dashed lines from top to bottom indicate the average values of EOS, LOS, and SOS under each land use change pattern.

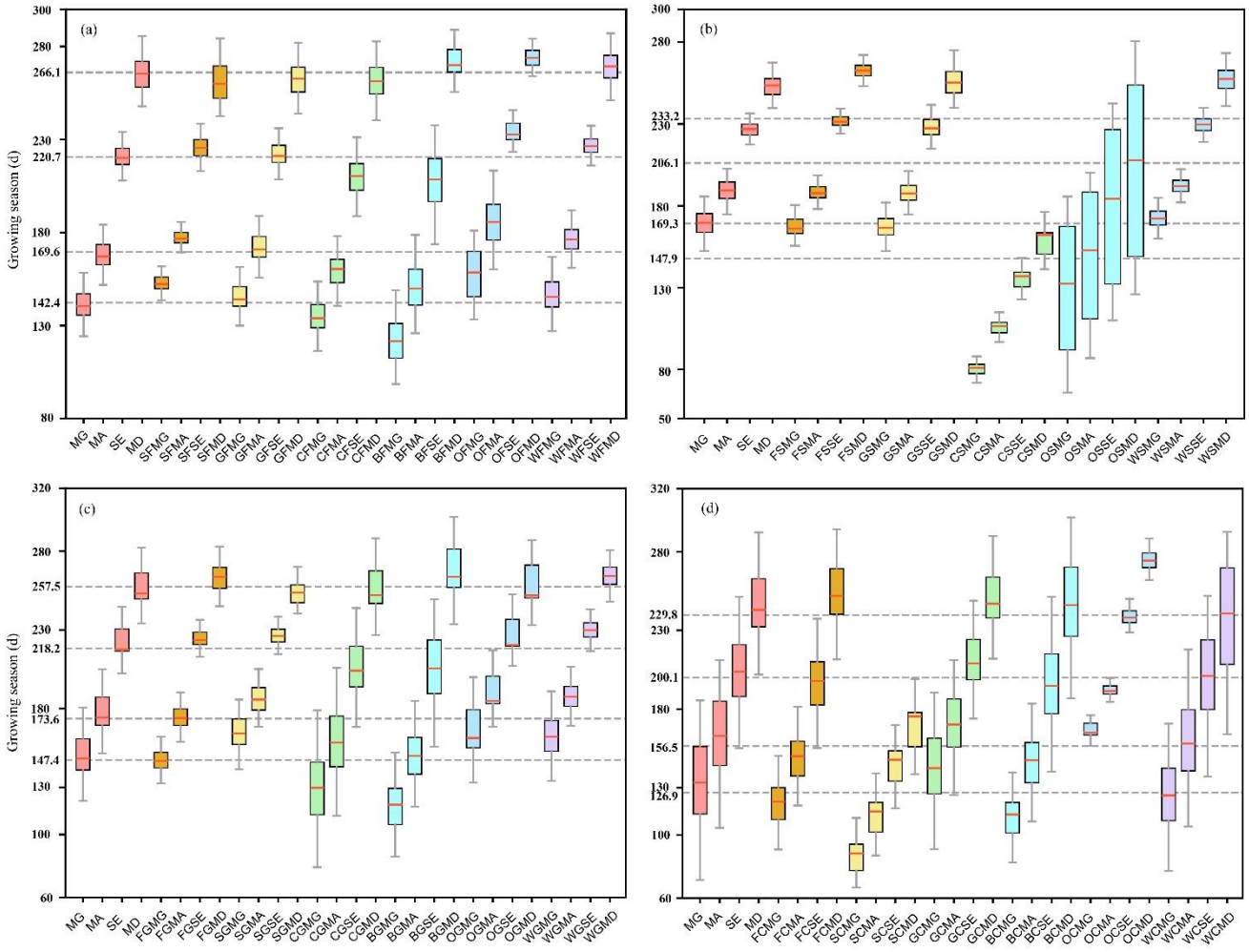

Figure S8: Land use change patterns in forest(a), shrub(b), grassland(c), and cropland(d) based on the phenological differences of LSP (MidGreenup, Maturity, Senescence, and MidGreendown) retrieved from EVI2SDC. Panels (a), (b), (c), and (d) represent the land use change patterns in forest, shrub, grassland, and cropland, respectively. The x-axis naming convention in each panel follows the same convention as Figure 6(e,f,g,h). In each panel, the four gray dashed lines from top to bottom indicate the average values of MidGreendown, Senescence, Maturity, and MidGreenup under each land use change pattern.

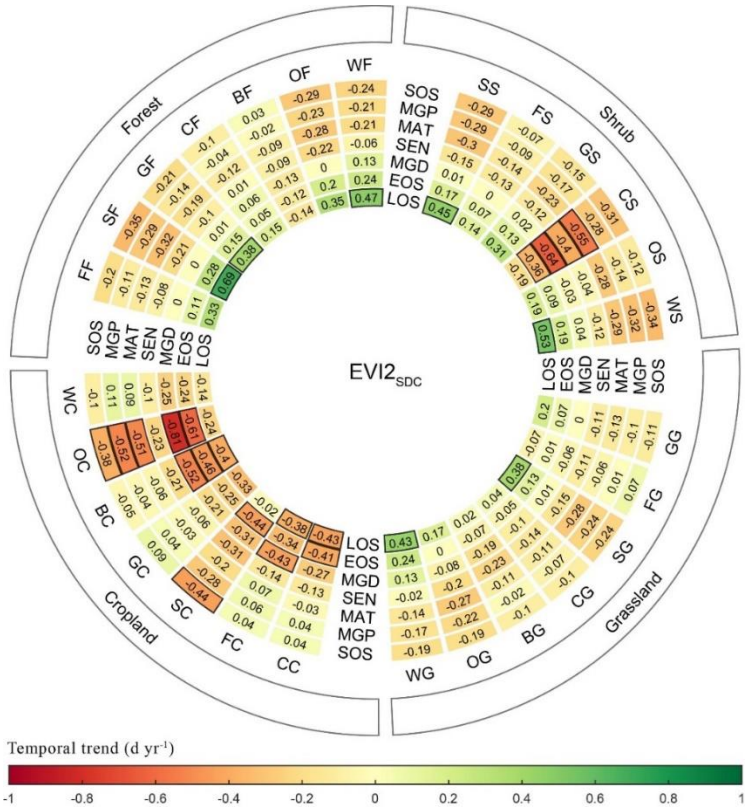

Figure S9: Land use change patterns in forest, shrub, grassland, and cropland based on the phenological trend retrieved from EVI2SDC. The abbreviations used in each column and row of the figure are consistent with Figure 7.

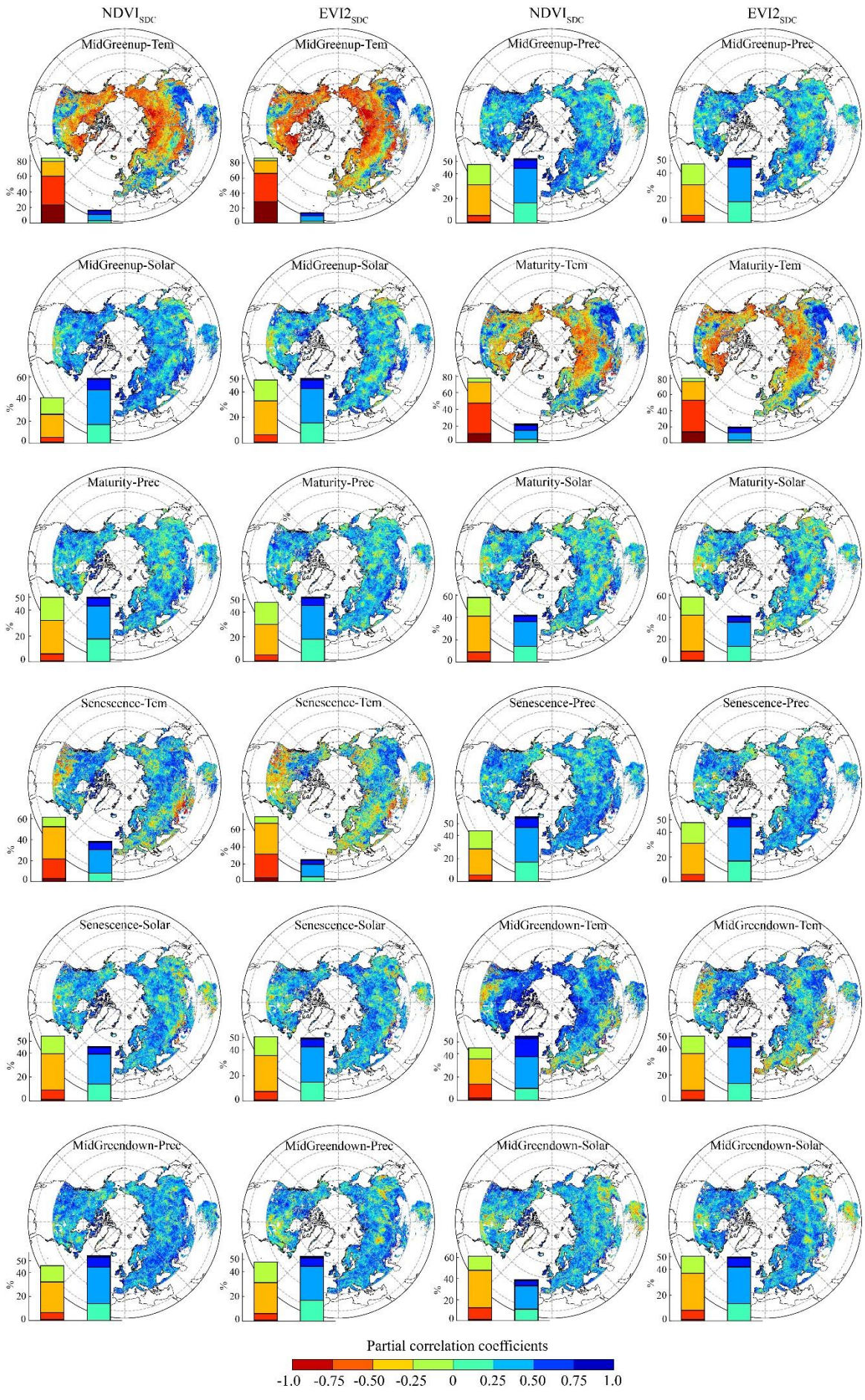
NDVI$_{SDC}$
EVI2$_{SDC}$
NDVI$_{SDC}$
EVI2$_{SDC}$
MidGreenup-Tem
MidGreenup-Tem
MidGreenup-Prec
MidGreenup-Prec
MidGreenup-Solar
MidGreenup-Solar
Maturity-Tem
Maturity-Tem
Maturity-Prec
Maturity-Prec
Maturity-Solar
Maturity-Solar
Senescence-Tem
Senescence-Tem
Senescence-Prec
Senescence-Prec
Senescence-Solar
Senescence-Solar
MidGreendown-Tem
MidGreendown-Tem
MidGreendown-Prec
MidGreendown-Prec
MidGreendown-Solar
MidGreendown-Solar
%
Partial correlation coefficients
-1.0 -0.75 -0.50 -0.25 0 0.25 0.50 0.75 1.0

Figure S10: Spatial distribution of partial correlation coefficients between climate variables (temperature, precipitation, and solar radiation) and phenological parameters (Midgreenup, Maturity, Senescence, and MidGreendown). The histograms in the lower left corner of each picture represent the frequency distribution of corresponding partial correlations.

Table S4: Percentage contribution of major climatic factors driving for phenological parameters

	NDVI$_{SDC}$			**EVI2$_{SDC}$**		
	Tem(%)	**Prec(%)**	**Solar(%)**	**Tem(%)**	**Prec(%)**	**Solar(%)**
SOS	79.20	10.66	10.14	83.39	8.63	7.99
MidGreenup	81.40	9.18	9.41	85.19	6.96	7.85
Maturity	74.95	11.39	13.66	78.33	9.60	12.07
Senescence	51.00	23.88	25.12	59.03	20.04	20.93
MidGreendown	48.07	24.79	27.14	44.16	26.92	28.92
EOS	56.42	20.94	22.64	44.15	27.51	28.34

*Note: Tem refers to temperature, Prec refers to precipitation, and Solar refers to solar radiation.

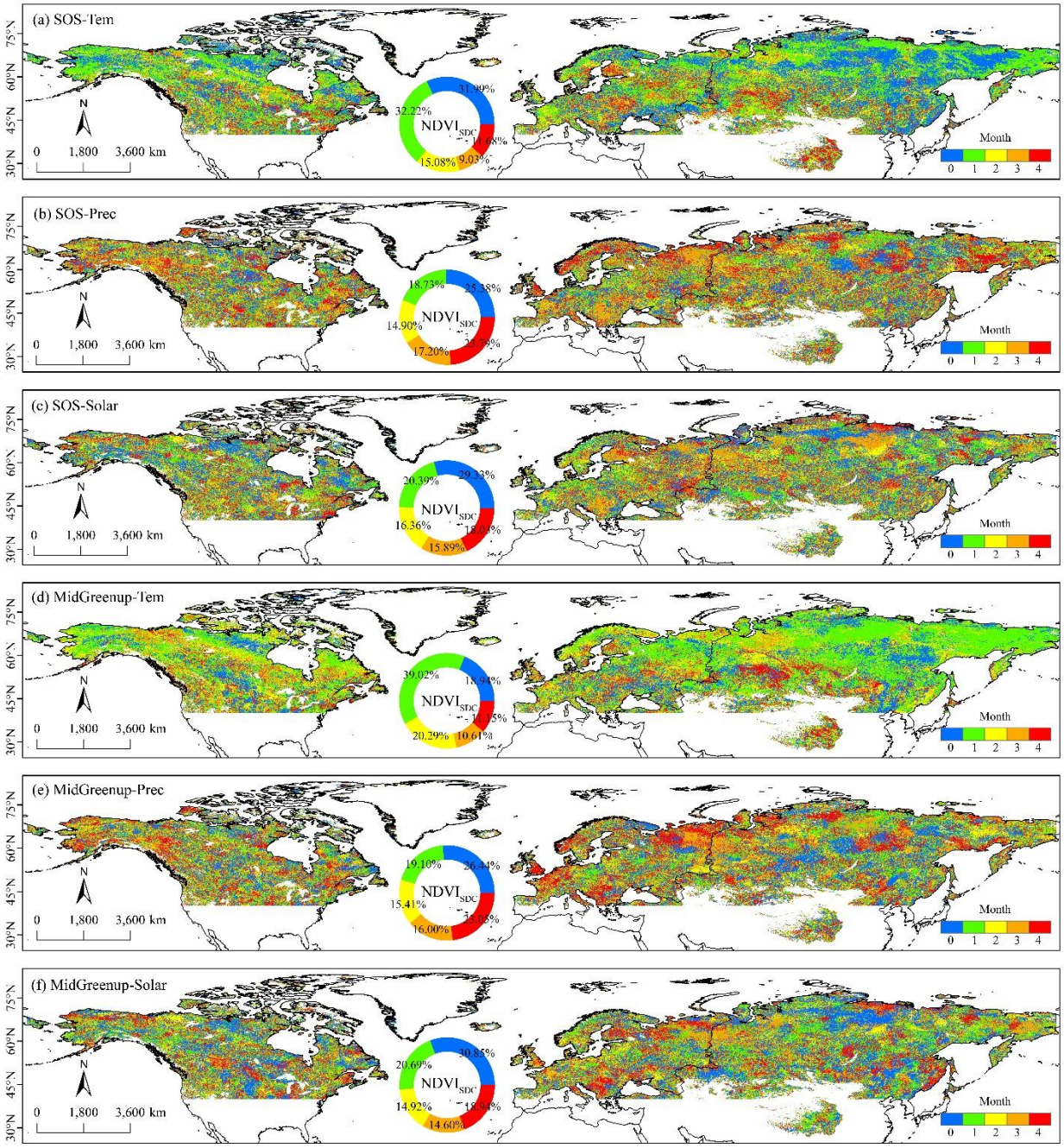

Figure S11: The spatial distribution of preseason length for SOS and MidGreenup based on the NDVI$_{SDC}$ dataset. The preseason length is defined as the period with the highest partial correlation coefficient between phenological parameters and climate variables（temperature (Tem), precipitation (Prec) and solar radiation (Solar) for the months preceding the phenological parameters-corresponding month.

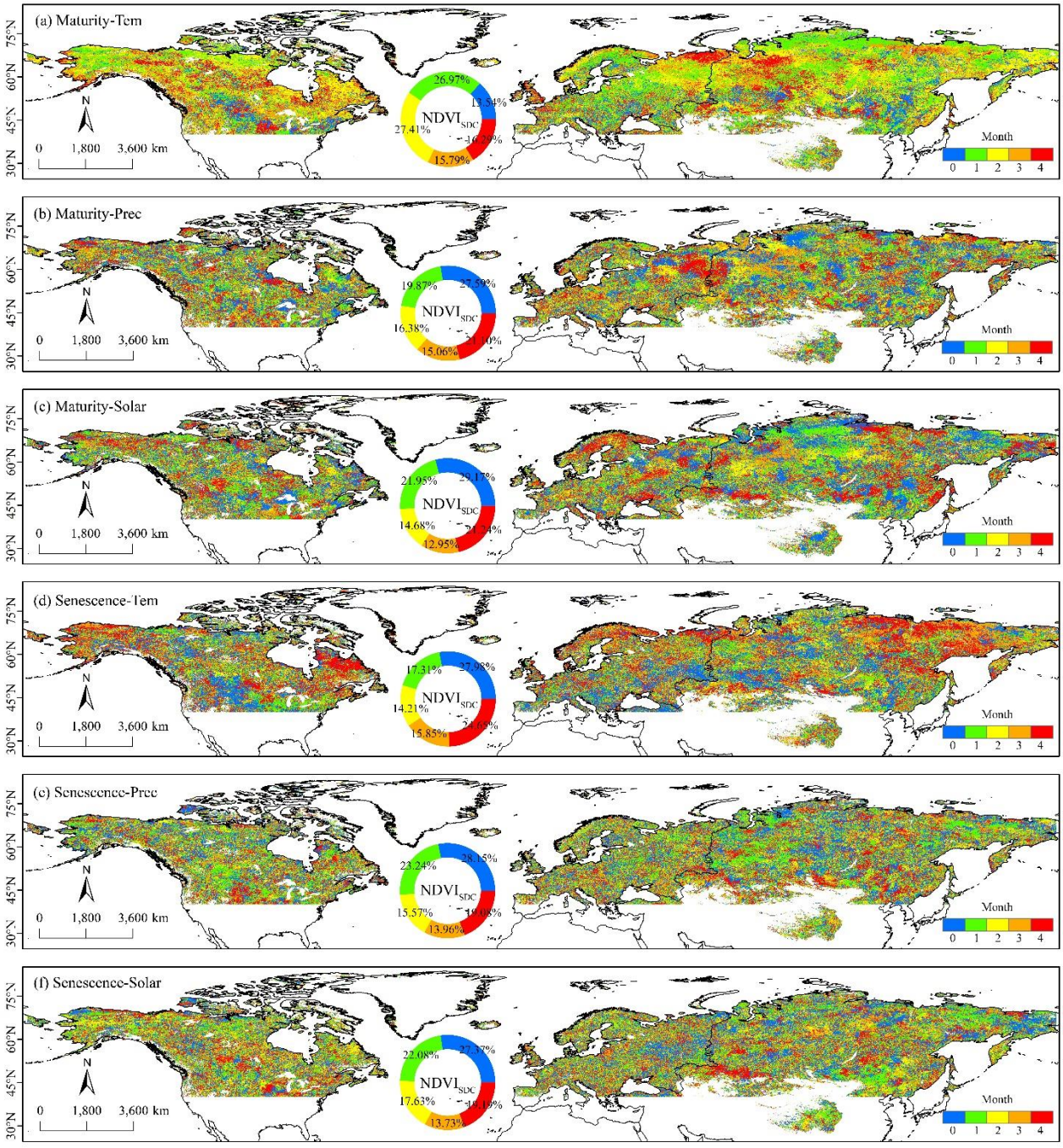

Figure S12: The spatial distribution of preseason length for Maturity and Senescence based on the NDVI$_{SDC}$ dataset.

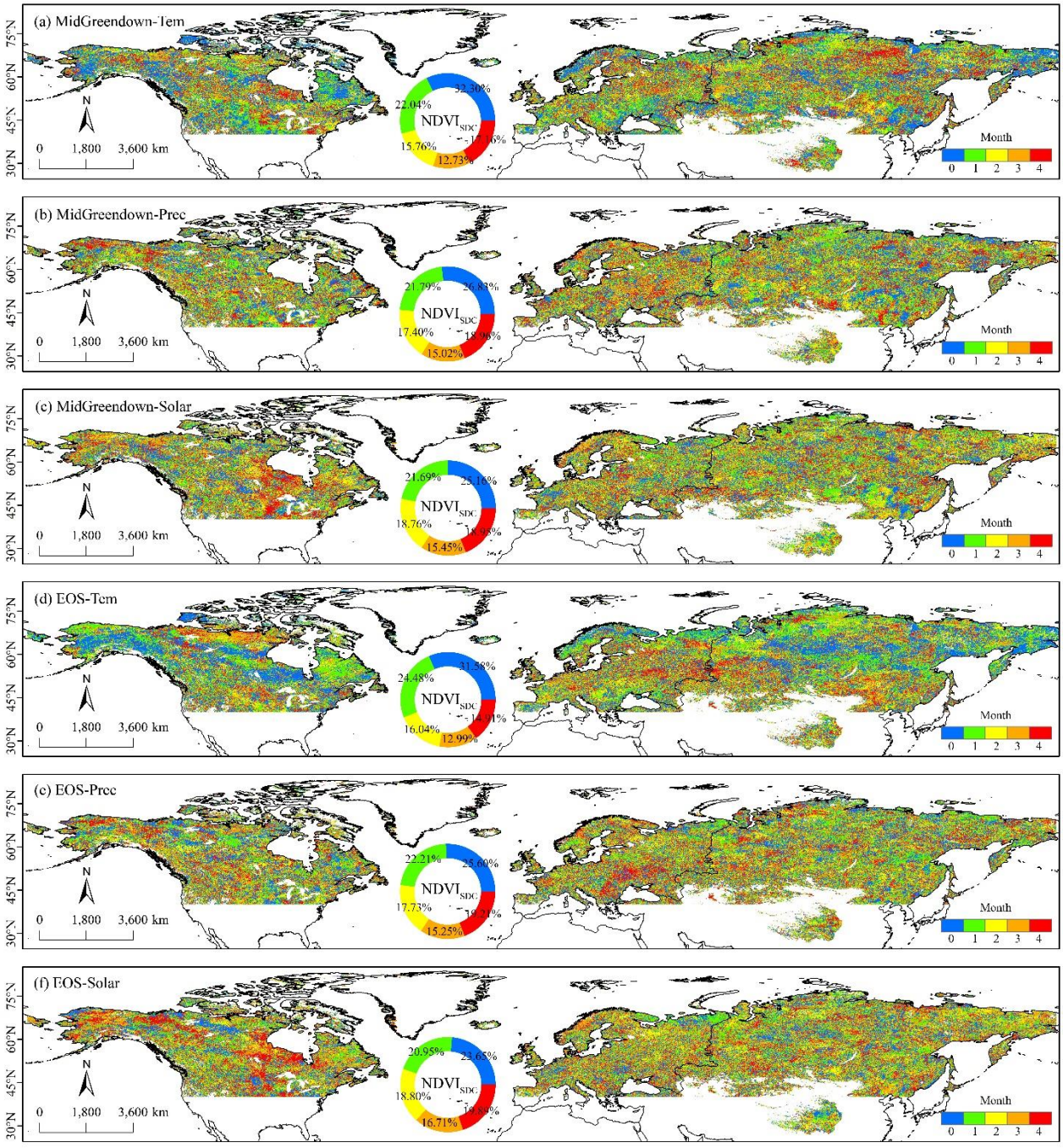

Figure S13: The spatial distribution of preseason length for MidGreenupdown and EOS based on the NDVI$_{SDC}$ dataset.

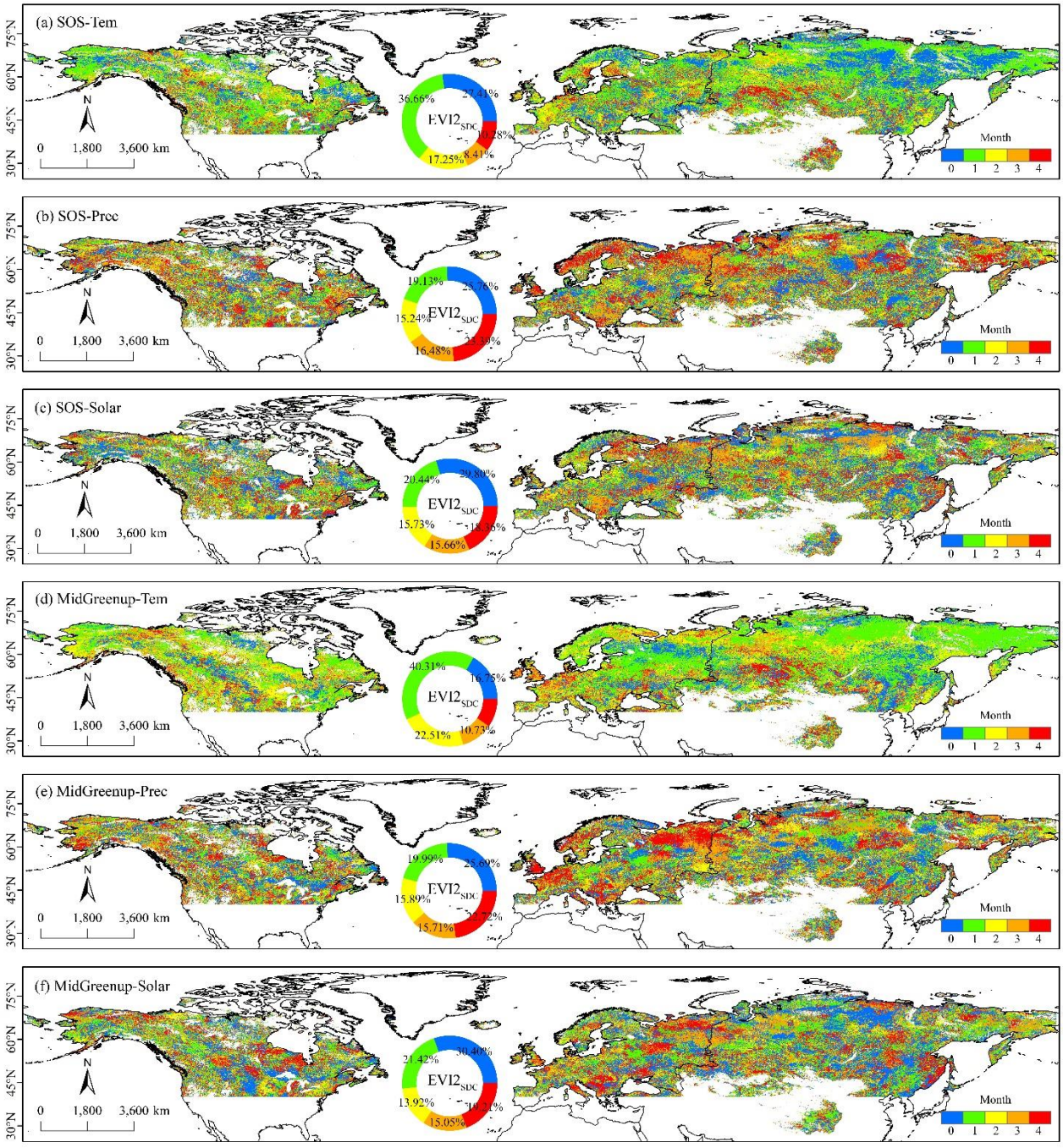

Figure S14: The spatial distribution of preseason length for SOS and MidGreenup based on the EVI2SDC dataset.

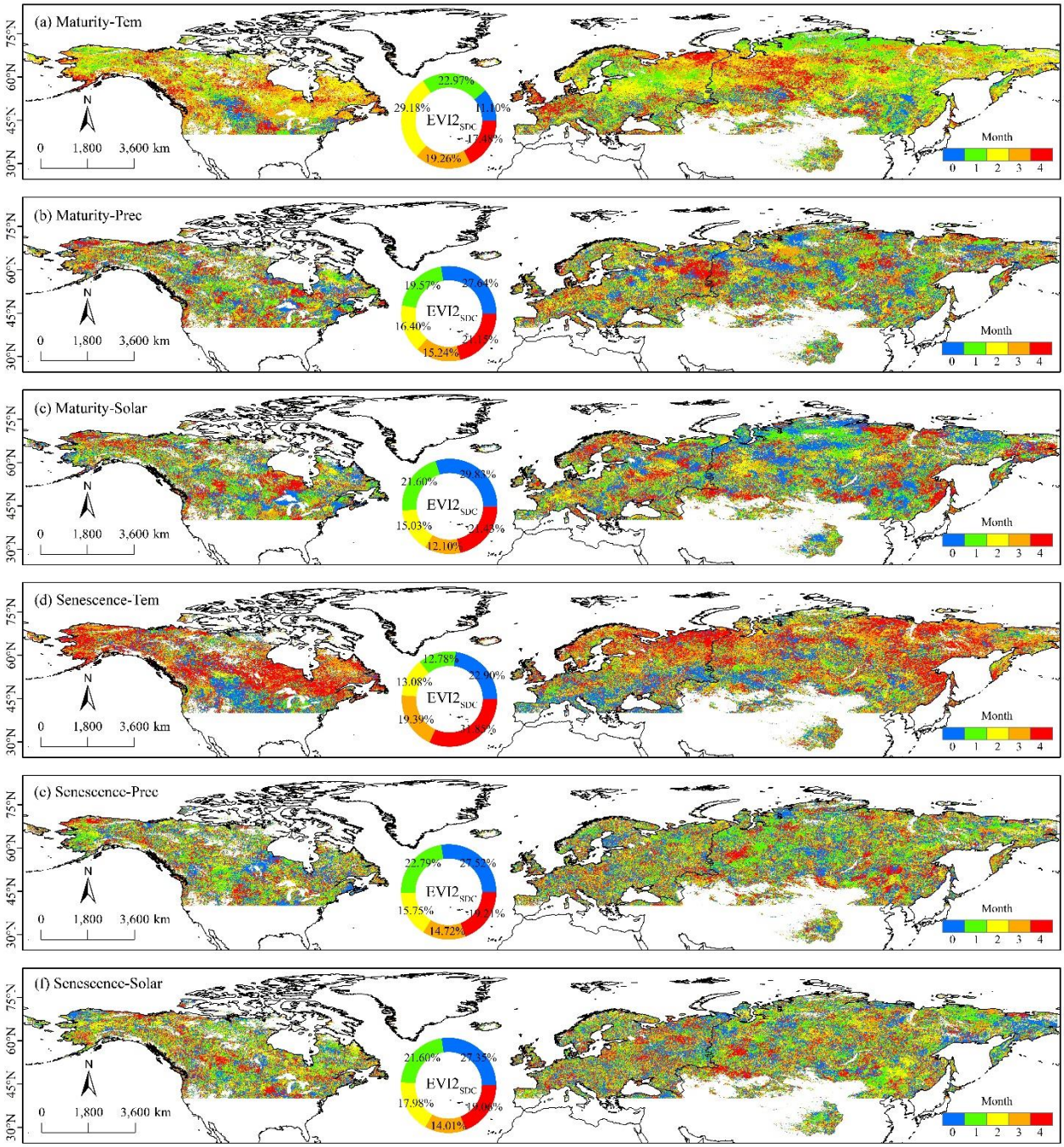

Figure S15: The spatial distribution of preseason length for Maturity and Senescence based on the EVI2SDC dataset.

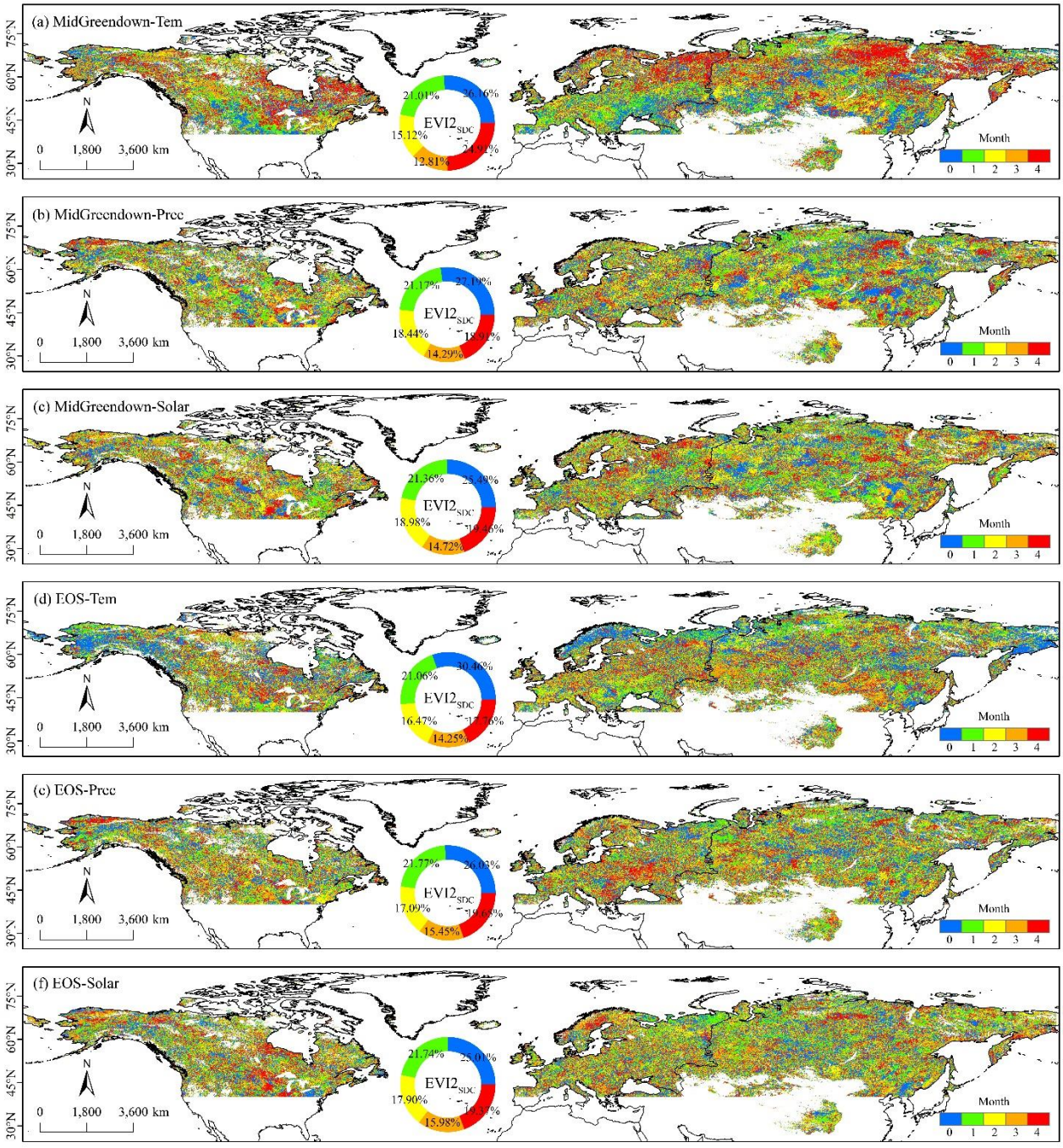

Figure S16: The spatial distribution of preseason length for MidGreenupdown and EOS based on the EVI2SDC dataset.

Table S5: Phenology and trends under different human footprints and vegetation types.

Unit:(d)&(d·year^{-1})

Vegetation type	Phenology	HFP(0-10) (NDVI/EVI2)	HFP(10-20) (NDVI/EVI2)	HFP(20-30) (NDVI/EVI2)	HFP(30-40) (NDVI/EVI2)	HFP(40-50) (NDVI/EVI2)
Forest	SOS&trends	108.69&0.32**/116.90&-0.29***	98.37&-0.06 /106.49&-0.07	94.42&0.10/ 100.36&-0.03	93.85&0.06/ 98.75&-0.06	93.60&0.14/ 96.63&-0.01
Forest	MidGreenup &trends	132.74&-0.18 */143.94&-0.15*	122.50&0.004 /131.25&-0.01	118.75&0.07/ 125.69&-0.01	117.62&0.04 /123.39&-0.03	116.83&0.07 /120.74&-0.02
Forest	Maturity &trends	166.53&-0.17 */170.53&-0.17*	155.29&-0.06 /158.38&-0.08	151.61&0.01 /153.38&-0.07	149.61&-0.03 /151.33&-0.09	148.23&-0.03 /148.88&-0.10
Forest	Senescence &trends	241.60&0.001 /221.68&-0.09	234.14&-0.14 /214.06&-0.05	228.20&-0.33*/21 0.05&-0.11	225.68&-0.32*/20 8.65&-0.13	221.64&-0.34 ./206.55&-0.15
Forest	Midgreendown &trends	289.66&0.13 /263.94&0.02	289.04&-0.23*/269.19&-0.06	285.86&-0.46 **/269.78&-0.14	284.56&-0.50**/27 0.00&-0.17	282.19&-0.46 */270.02&-0.16
Forest	EOS&trends	314.06&0.08 /294.10&0.14**	316.66&-0.24**/302. 73&-0.04	314.88&-0.49***/3 04.87&-0.11	314.15&-0.53***/3 05.15&-0.10	312.27&-0.51 **/306.09&-0.09
Forest	LOS&trends	205.37&0.39**/177.20&0.43***	218.28&-0.18 /196.24&0.03	220.46&-0.59**/20 4.51&-0.08	220.30&-0.59**/20 6.41&-0.04	218.67&-0.64 **/209.45&-0.09
Grassland	SOS&trends	135.41&-0.06 /135.27&-0.05	106.08&-0.03 /110.02&-0.04	95.13&0.08/ 97.98&-0.04	94.10&0.07/ 96.08&-0.10	94.10&0.07/ 96.08&-0.10
Grassland	MidGreenup &trends	151.61&-0.07 /153.33&-0.68	129.60&0.007 /133.76&-0.02	118.97&0.10/ 122.41&-0.01	118.72&0.06/ 121.10&-0.04	118.72&0.06/ 121.06&-0.04
Grassland	Maturity &trends	179.17&-0.13**/178. 83&-0.13**	161.23&-0.02 /162.53&-0.05	152.88&0.03/ 152.41&-0.07	154.29&-0.07 /152.03&-0.13	154.29&-0.07 /152.03&-0.13
Grassland	Senescence &trends	231.44&-0.05 /222.55&-0.07	213.23&-0.02 /206.34&-0.03	214.43&-0.15 /203.36&-0.12	219.22&-0.28*/20 5.85&-0.23*	219.22&-0.28 */205.85&-0.23*
Grassland	Midgreendown &trends	267.33&0.08 /255.88&-0.001	260.48&-0.07 /251.38&-0.02	269.19&-0.48 **/259.15&-0.23	274.27&-0.47 */263.02&-0.26	274.27&-0.47* /263.02&-0.26
Grassland	EOS&trends	289.71&0.07/282.30&0.05	297.00&-0.19 /290.60&-0.06	303.85&-0.53 **/299.84&-0.19	307.29&-0.51 **/302.83&-0.16	307.29&-0.51 **/302.83&-0.16
Grassland	LOS&trends	154.29&0.13./147.03&0.10	190.92&-0.15 /180.59&-0.02	208.73&-0.61 */201.86&-0.15	213.19&-0.58 */206.75&-0.01	213.19&-0.58 */206.75&-0.07
Shrub	SOS&trends	155.44&-0.27***/156.28&-0.27**	146.28&-0.29./149.86&-0.32	123.71&-0.38 /127.44&-0.39	95.15&-0.31/ 94.58&-0.59	97.56&-0.19 /109.59&-0.48
Shrub	MidGreenup &trends	167.37&-0.27***/168.99&-0.27***	159.20&-0.28./163.90&-0.32	139.63&-0.33 /145.31&-0.34	116.42&-0.45 /117.48&-0.73	115.39&-0.01/ 127.87&-0.37
Shrub	Maturity &trends	187.29&-0.30***/189.00&-0.28***	180.83&-0.28./185.66&-0.30	162.97&-0.35 /168.42&-0.35	145.01&-0.46 /144.97&-1.07	139.20&-0.27 /151.30&-0.53
Shrub	Senescence &trends	231.19&-0.11* /226.90&-0.14*	226.67&-0.07 /225.27&-0.16	204.14&-0.26 /206.20&-0.24	180.59&-0.53 /181.19&-1.14	186.88&-0.10 /193.21&-0.46
Shrub	Midgreendown &trends	261.55&0.16*/253.40&0.01	260.76&0.24/ 254.78&0.001	238.35&-0.01 /240.20&-0.16	210.25&-0.58 /218.09&-0.94	227.35&-0.87 /243.06&-0.61
Shrub	EOS&trends	277.20&0.25*/271.60&0.17	277.83&0.33./ 275.50&0.23	259.17&0.03 /270.12&-0.02	235.00&-0.44 /258.94&-0.54	256.08&-0.63 /285.72&-0.19

Shrub	LOS&trends	121.76&0.52***/115.32&0.44**	146.28&-0.29./125.65&0.55**	135.46&0.40/146.41&0.36	139.85&-0.13/164.36&0.05	158.53&-0.44/176.12&0.29
Cropland	SOS&trends	117.70&-0.15/124.87&-0.10	112.30&0.04/119.81&0.10	99.72&0.12/103.88&0.04	92.64&0.1/93.48&-0.07	92.37&0.01/93.82&-0.12
Cropland	MidGreenup&trends	139.46&-0.05/145.46&-0.04	136.76&0.09/142.51&0.10	125.16&0.09/128.72&0.03	119.20&0.05/120.47&-0.05	119.49&-0.02/120.86&-0.13
Cropland	Maturity&trends	167.62&-0.03/171.42&-0.07	166.67&-0.01/170.09&-0.02	158.93&-0.02/160.04&-0.03	156.67&-0.07/155.90&-0.09	157.86&-0.08/157.04&-0.12
Cropland	Senescence&trends	213.97&-0.05/209.12&-0.10	212.38&-0.08/208.62&-0.08	207.86&-0.21**/203.52&-0.13	205.97&-0.31**/201.71&-0.19	207.66&-0.32**/203.29&-0.21*
Cropland	Midgreendown&trends	258.97&-0.15/246.26&-0.10	254.53&-0.38**/244.78&-0.20*	250.90&-0.60***/245.35&-0.30 *	247.28&-0.76***/244.92&-0.40*	250.50&-0.78**/247.31&-0.38
Cropland	EOS&trends	298.22&-0.27*/285.45&-0.16	293.03&-0.55/283.65&-0.36**	287.24&-0.92***/285.80&-0.48	282.98&-1.20***/287.06&-0.51*	287.36&-1.21***/290.58&-0.52**
Cropland	LOS&trends	180.52&-0.12/160.58&-0.10	180.73&-0.60**/163.84&-0.44**	187.51&-1.04***/181.91&-0.53*	190.34&-1.30**/193.58&-0.45	194.99&-1.23**/196.76&-0.40

*Note: The symbol * indicates significance, and the symbols *, **, and *** represent significance levels at the 95% (P<0.05), 99% (P<0.01), and 99.9% (P<0.001) levels, respectively.

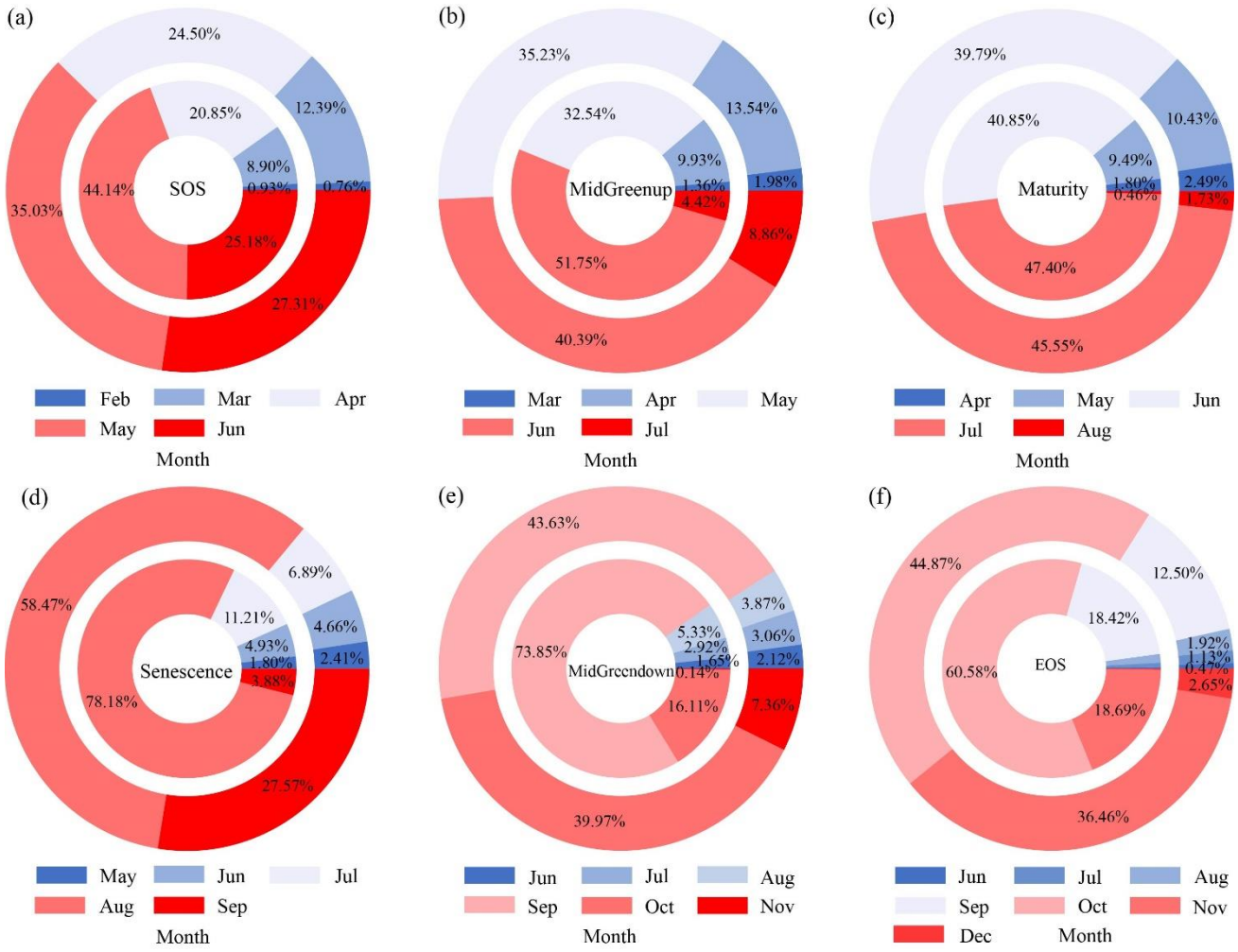

Figure S17: Monthly pixel percentage statistics of phenological parameters retrieved by NDVI$_{SDC}$ and EVI2$_{SDC}$. The outer circle represents the pixel percentage statistics of each phenological parameter per month for NDVI$_{SDC}$, while the inner circle represents the pixel percentage statistics of each phenological parameter per month for EVI2$_{SDC}$. (a), (b), (c), (d), (e), (f) sequentially display the phenological parameters SOS, MidGreenup, Maturity, Senescence, MidGreendown, and EOS.

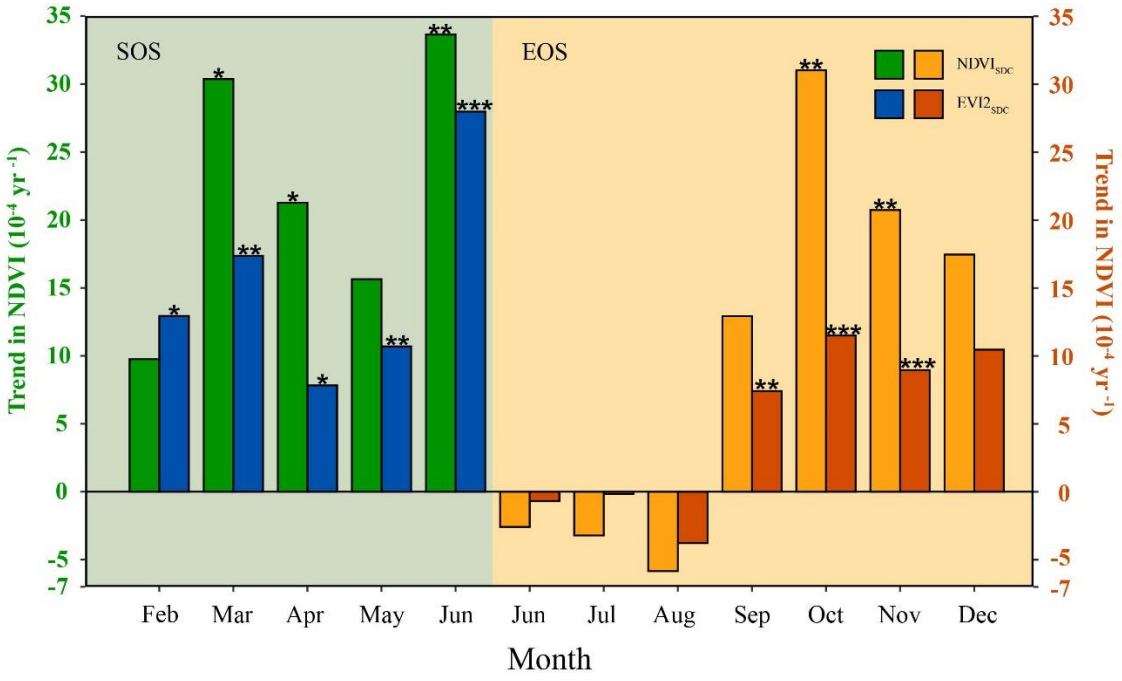

Figure S18: Monthly trends in SDC$_{NDVI}$ and SDC$_{EVI2}$ for SOS and EOS. Symbols *, **, and *** represent the significance levels at 95 % ($p < 0.05$), 99 % ($p < 0.01$), and 99.9 % ($p < 0.001$), respectively.

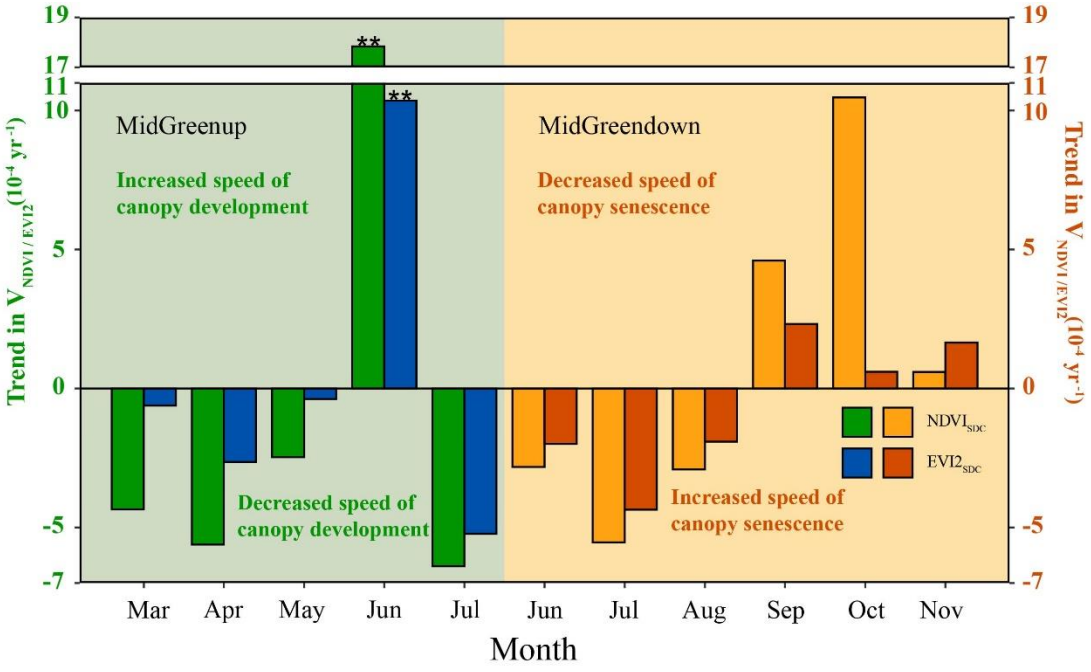

Figure S19: Monthly trends in V$_{NDVI/EVI2}$ for MidGreenup and MidGreendown. Symbols *, **, and *** represent the significance levels at 95 % ($p < 0.05$), 99 % ($p < 0.01$), and 99.9 % ($p < 0.001$), respectively.

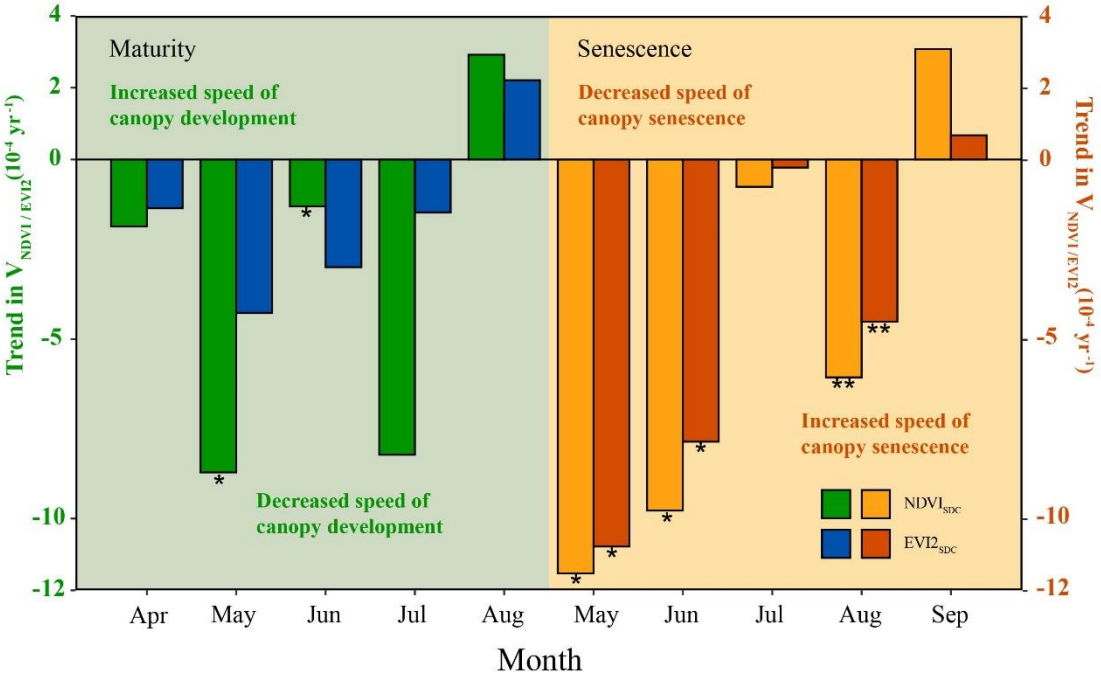

Figure S20: Monthly trends in $V_{NDVI/EVI2}$ for Maturity and Senescence. Symbols *, **, and *** represent the significance levels at 95 % ($p < 0.05$), 99 % ($p < 0.01$), and 99.9 % ($p < 0.001$), respectively.

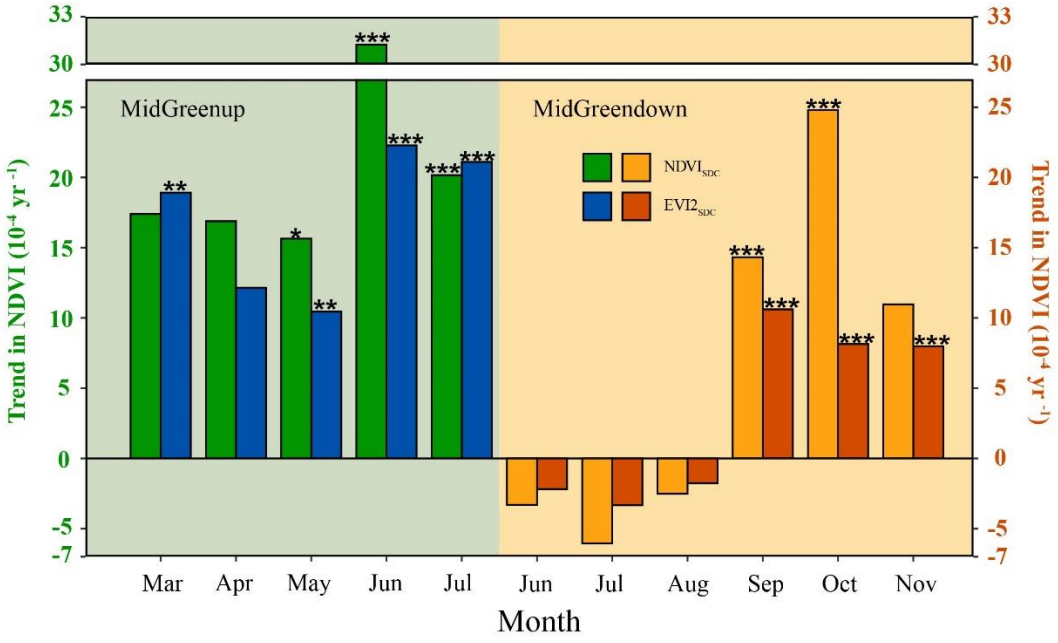

Figure S21: Monthly trends in $NDVI_{SDC}$ and $EVI2_{SDC}$ for MidGreenup and MidGreendown. Symbols *, **, and *** represent the significance levels at 95 % ($p < 0.05$), 99 % ($p < 0.01$), and 99.9 % ($p < 0.001$), respectively.

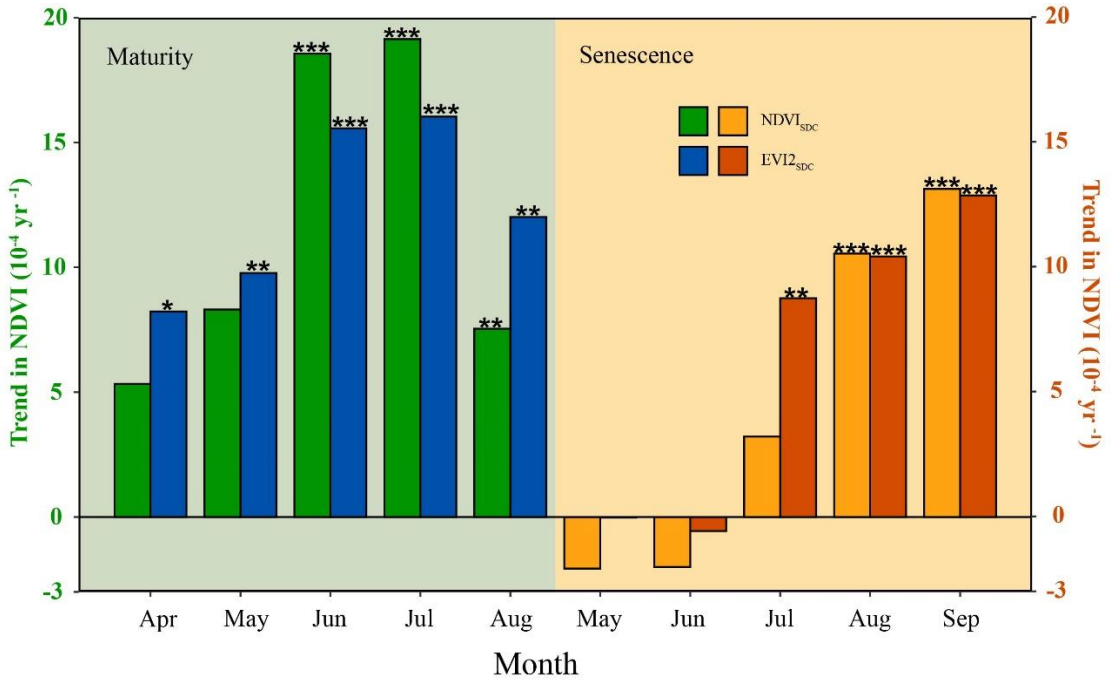

Figure S22: Monthly trends in NDVI$_{SDC}$ and EVI2$_{SDC}$ for Maturity and Senescence. Symbols *, **, and *** represent the significance levels at 95 % ($p < 0.05$), 99 % ($p < 0.01$), and 99.9 % ($p < 0.001$), respectively.

Table S6: Contribution rates of vegetation greening rate in different vegetation types for China and India.

Country	Vegetation type	Positive contribution（NDVI$_{SDC}$ /EVI2$_{SDC}$,unit:%）
India	Forest	5.77/5.87
	Shrub	4.5/4.78
	Grassland	20.37/20.45
	Cropland	69.30/68.90
China	Forest	9.94/11.63
	Shrub	0.64/0.52
	Grassland	66.31/64.42
	Cropland	22.11/23.43

Table S7: Russia 's land use transfer matrix from 2001 to 2022(×10^4 km^2)

2001 / 2022	Grassland	Forest	Shrub	Cropland	Built-up	Other lands	Water	Total
Grassland	749.4	54.1	64.7	15.5	0.17	5.4	36.8	926.07
Forest	53.3	359.9	0.2	3.5	0.02	----	2.5	419.42
Shrub	36.8	0.9	421.9	---	---	0.2	13.9	473.70
Cropland	8.0	0.4	----	117.0	0.04	---	0.04	125.48
Built-up	0.1	0.02	---	0.06	2.3	0.0011	0.0038	2.48
Other lands	1.7	---	0.0078	---	----	31.4	0.2	33.30
Water	1.2	0.4	0.09	0.02	---	0.3	84.1	86.11
Total	850.5	415.72	486.90	136.08	2.53	37.30	136.54	2065.57

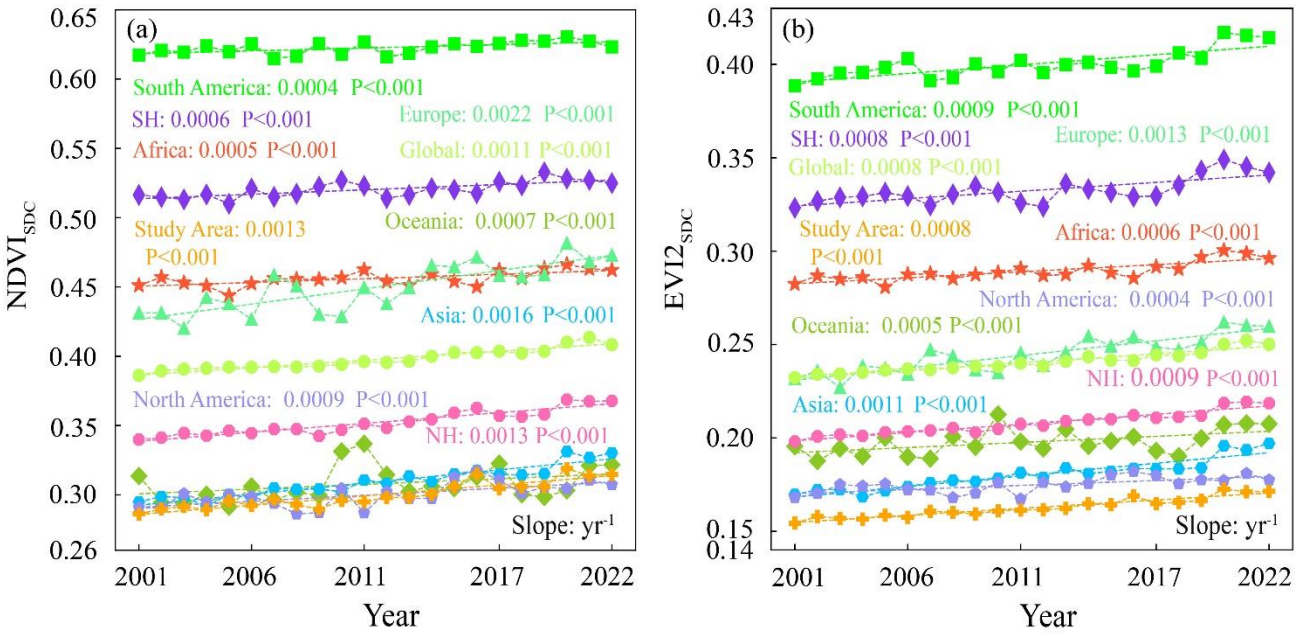

Figure S23: The interannual variations of $NDVI_{SDC}$ and $EVI2_{SDC}$ for different continents from 2001 to 2022. SH represents the Southern Hemisphere, and NH represents the Northern Hemisphere.

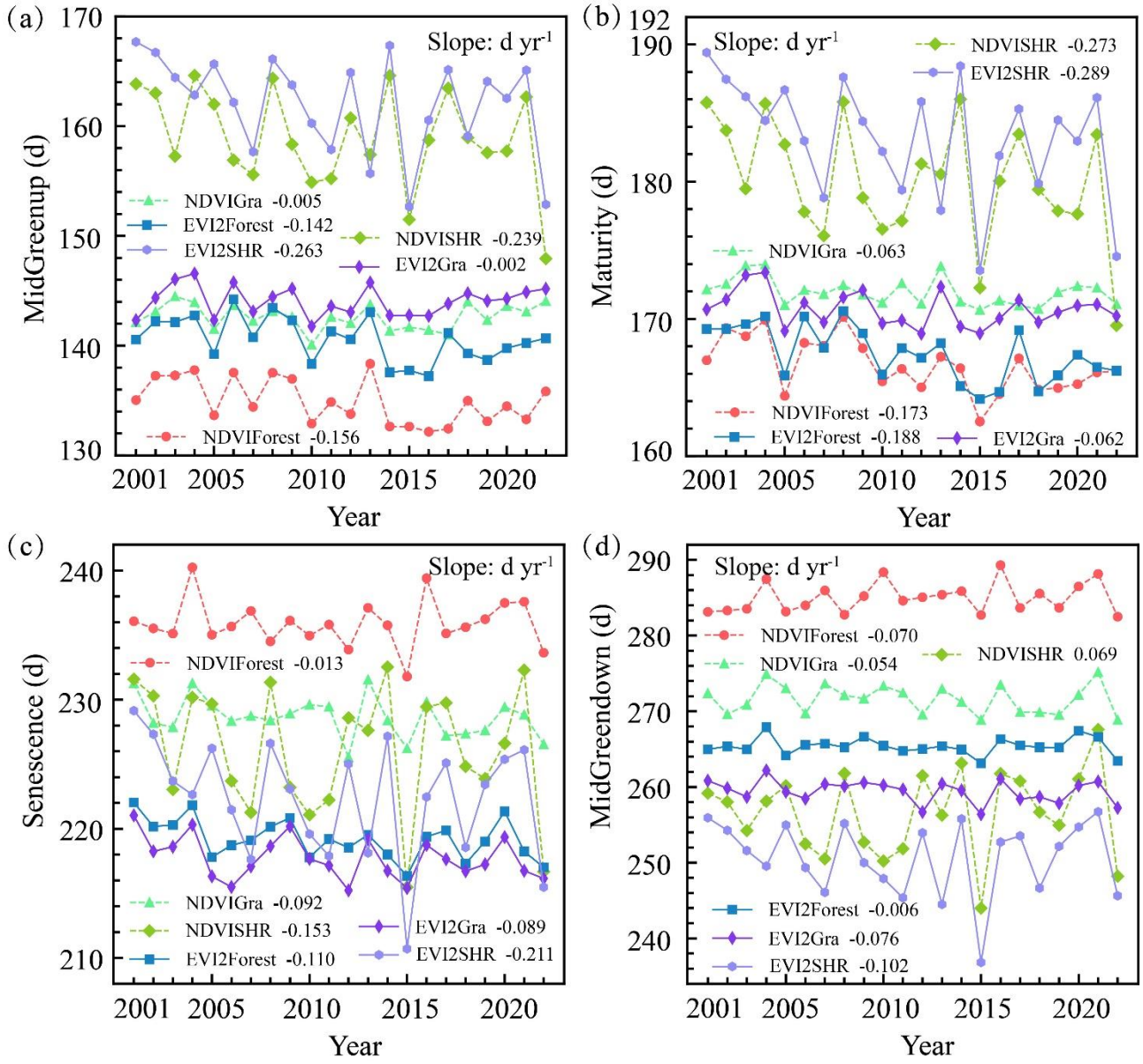

Figure S24: Interannual phenological changes in forest, shrub, and grassland from 2001 to 2022. (a), (b), (c), and (d) represent the interannual phenological changes of MidGreenup, Maturity, Senescence, and MidGreendown for forest, shrub, and grassland, respectively. "Gra" represents grassland, and "SHR" represents shrub.