

# Supplementary Material

## Critical climate periods explain large fraction of the observed variability in vegetation state

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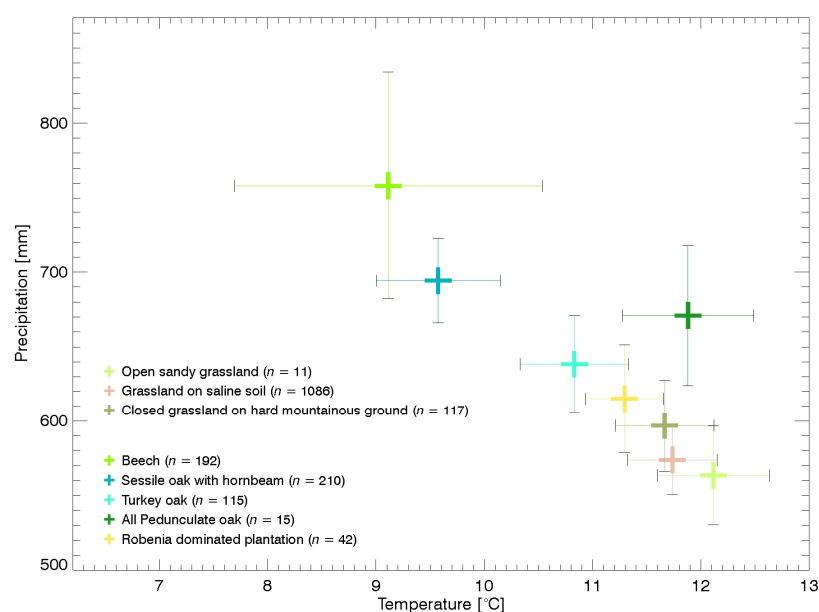
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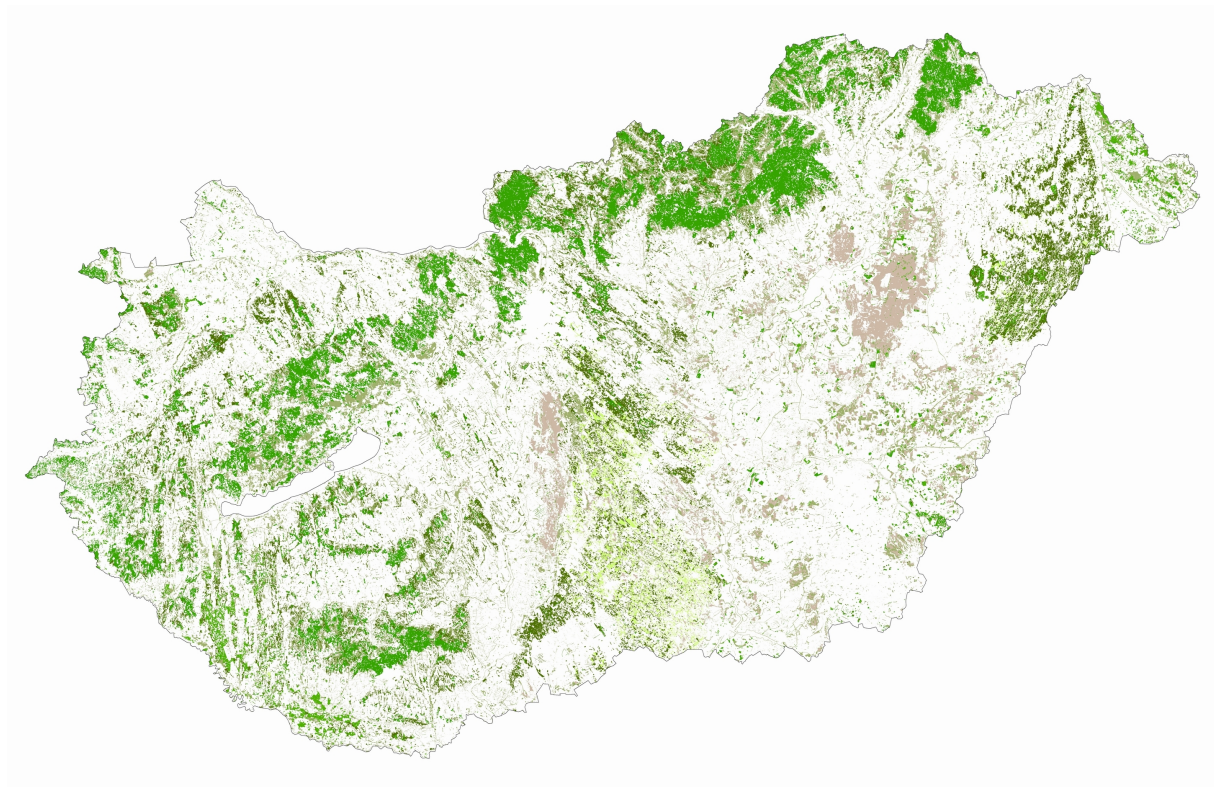
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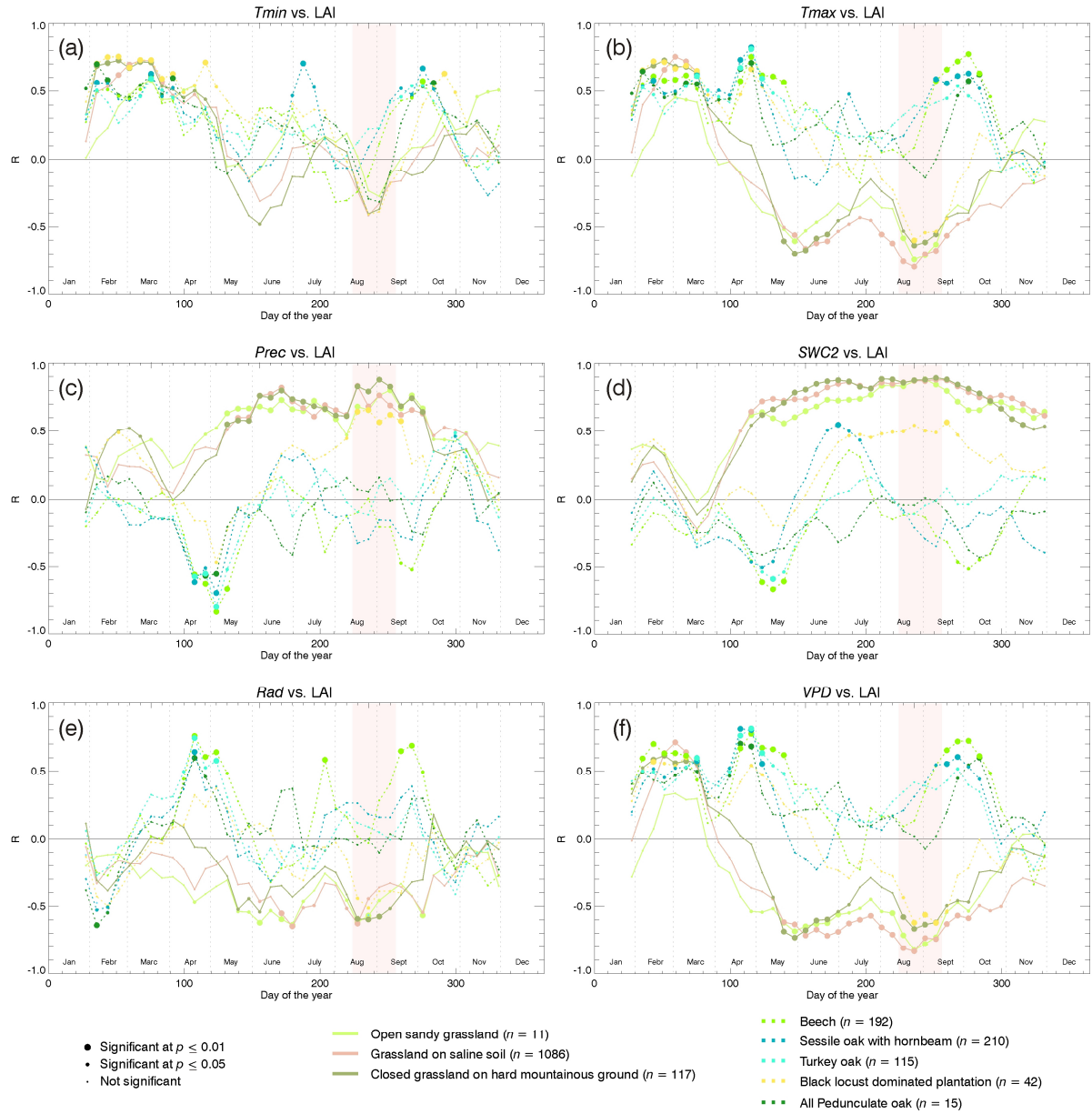
**Figure S1.** Thermopluviograms of the investigated ecosystem categories in Hungary. The values indicate the mean meteorological conditions ( $T_{mean}$  and  $Prec$ ) of the selected pixels and also their standard deviation. Additional climate maps about Hungary based on the used FORESEE v3.2 dataset are available at: [https://nimbus.elte.hu/FORESEE/index-maps\\_v3.2.html](https://nimbus.elte.hu/FORESEE/index-maps_v3.2.html)



**National Ecosystem Base Map land cover categories - Level-3**

Grasslands and other herbaceous vegetation	3110: Open sandy grasslands
	3200: Grasslands on saline soil
	3400: Closed grasslands on hard mountainous ground
Forests and woodlands	4101: Beeches
	4102: Sessile oak with hornbeam
	4103: Turkey oaks
	4109: Pedunculate oaks with hornbeams
	4110: Only Pedunculate oaks, or, pedunculate oaks mixed with ashes
	4301: Only Pedunculate oaks, or, pedunculate oaks mixed with ashes
	4303: Pedunculate oaks with hornbeam with extra soil water
	4402: Black locust dominated plantations

**Figure S2.** Geographical location of all grasslands and forests of the studied categories from the NÖSZTÉP ecosystem map dataset in Hungary, based on the native dataset with  $20 \text{ m} \times 20 \text{ m}$  resolution. The studied categories are listed in **Table 1** of the main paper. Categories 4109, 4110, 4301 and 4303 were used to create the “merged” *All pedunculate oak* category. The colors correspond to the original colortable of the NÖSZTÉP dataset (Tanács *et al.*, 2019). (Note that the resolution of the image is too coarse to distinguish all pixels with 20 meters resolution for the country with an area of  $90\,030 \text{ km}^2$ ).

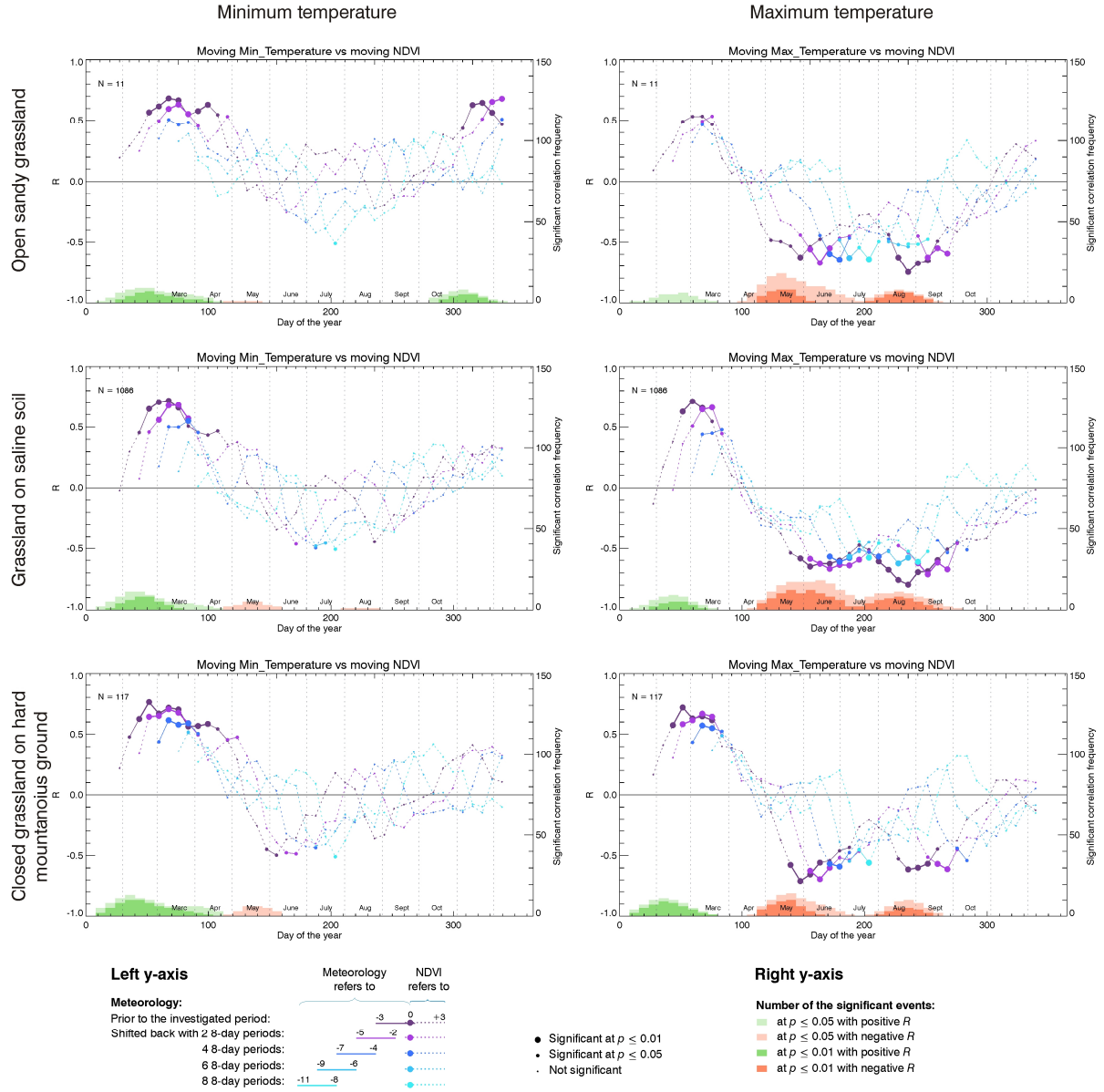


**Figure S3.** Pearson's  $R$  values between the area-averaged LAI and the area-averaged climate variables during 2000–2020. Both the LAI (after the indicated period) and the climate variables (before the indicated period) refer to 32 days long intervals, with 8-day overlap. Pink rectangles/columns indicate the period of interest (PI) in late summer (DOY 225–256, 13<sup>th</sup> of August – 13<sup>th</sup> of September).

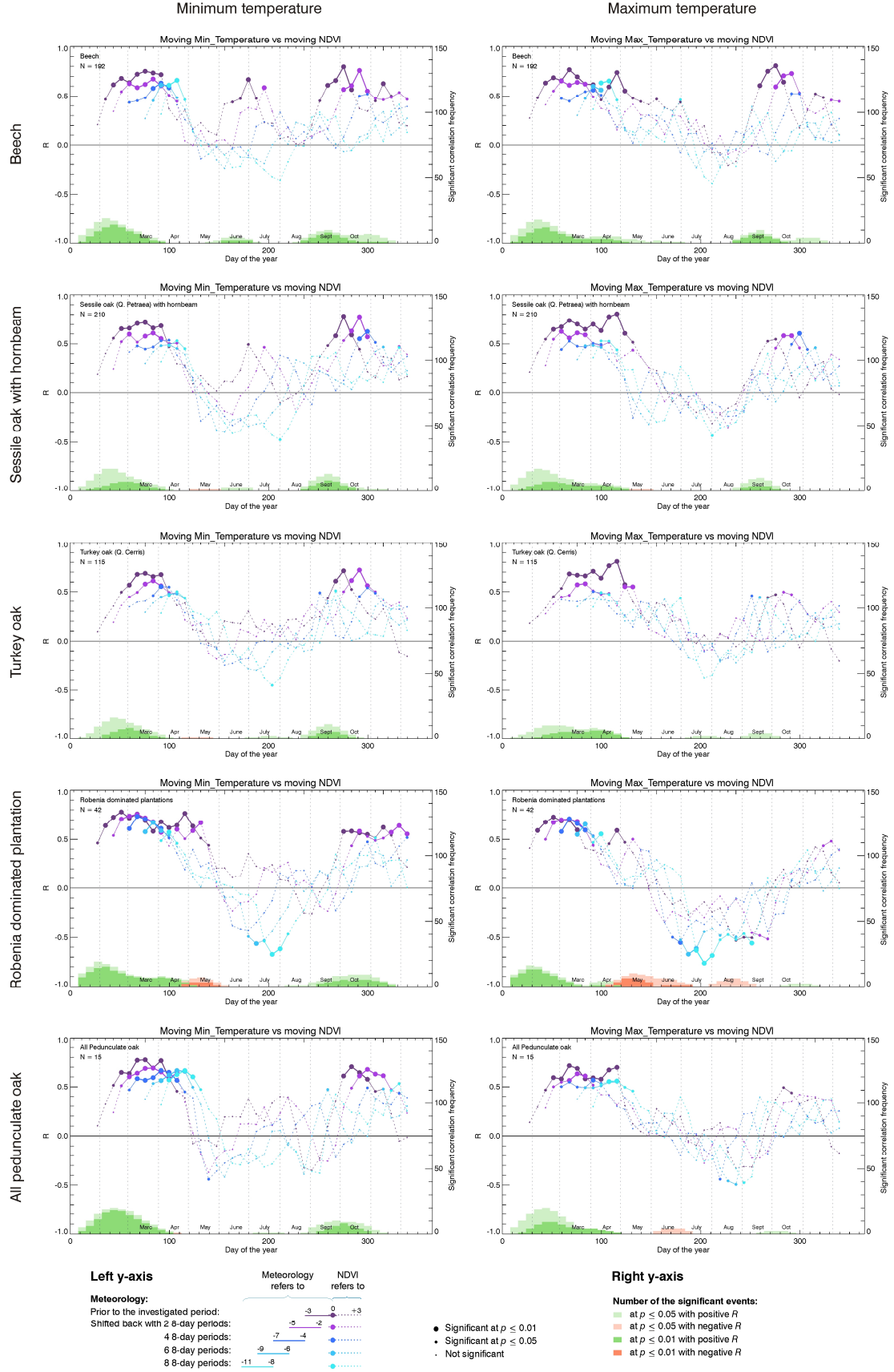
**Table S1.** Maximum and minimum significant ( $p \leq 0.01$ )  $R$  values representing correlation between LAI and the used climate variables during the year, based on the first  $R$ -curve (see also Figure 5). The months associated with the maximum and minimum significant  $R$  values are also indicated, referring to the 32-day long period of the investigated vegetation state. The  $R$  value with the greatest absolute value of each climate variable is marked with bold. In the case of no significant correlation ( $p > 0.01$ ) the  $R$  values are not indicated.  $SWC2$  is soil water content, and  $VPD$  is vapour pressure deficit.

Ecosystem categories	<i>Tmin</i>		<i>Tmax</i>		<i>Precipitation</i>		<i>SWC2</i>		<i>Radiation</i>		<i>VPD</i>	
	$R$	Month	$R$	Month	$R$	Month	$R$	Month	$R$	Month	$R$	Month
<b>Positive correlation with LAI</b>												
Open sandy grassland	0.56	III–IV	-	-	0.80	IX	0.88	IX	-	-	-	-
Grassland on saline soil	0.73	III–IV	0.75	II–III	0.83	VIII–IX	0.88	VII	-	-	0.71	II–III
Closed grassland on hard m. ground	0.73	II–III	0.73	II–III	<b>0.88</b>	IX	<b>0.89</b>	IX–X	-	-	0.61	II–III
Beech	0.60	III–IV	0.77	X	-	-	-	-	<b>0.76</b>	IV–V	0.77	IV–V
Sessile oak with hornbeam	0.71	VI–VII	<b>0.82</b>	IV–V	-	-	0.55	VI	0.64	IV–V	<b>0.81</b>	IV–V
Turkey oak	0.60	III–IV	0.81	IV–V	-	-	-	-	0.74	IV–V	0.81	IV–V
Black locust dominated plantation	0.76	II–III	0.72	II	0.66	IX	0.57	IX–X	-	-	0.60	III
All pedunculate oak	0.70	II	0.71	IV–V	-	-	-	-	0.60	IV–V	0.70	IV–V
<b>Negative correlation with LAI</b>												
Open sandy grassland	-	-	-0.75	VIII–IX	-	-	-	-	-0.64	VI–VII	<b>-0.83</b>	VIII–IX
Grassland on saline soil	-	-	<b>-0.80</b>	VIII–IX	-	-	-	-	<b>-0.65</b>	VI–VII	-0.83	VIII–IX
Closed grassland on hard m. ground	-	-	-0.70	V–VI	-	-	-	-	-0.60	VIII–IX	-0.73	V–VI
Beech	-	-	-	-	<b>-0.84</b>	V	<b>-0.67</b>	V–VI	-	-	-	-
Sessile oak with hornbeam	-	-	-	-	-0.70	V	-	-	-	-	-	-
Turkey oak	-	-	-	-	-0.80	V	-0.59	V–VI	-	-	-	-
Black locust dominated plantation	-	-	-0.60	VIII–IX	-	-	-	-	-	-	-0.62	IX
All pedunculate oak	-	-	-	-	-0.57	V	-	-	-0.64	II	-	-

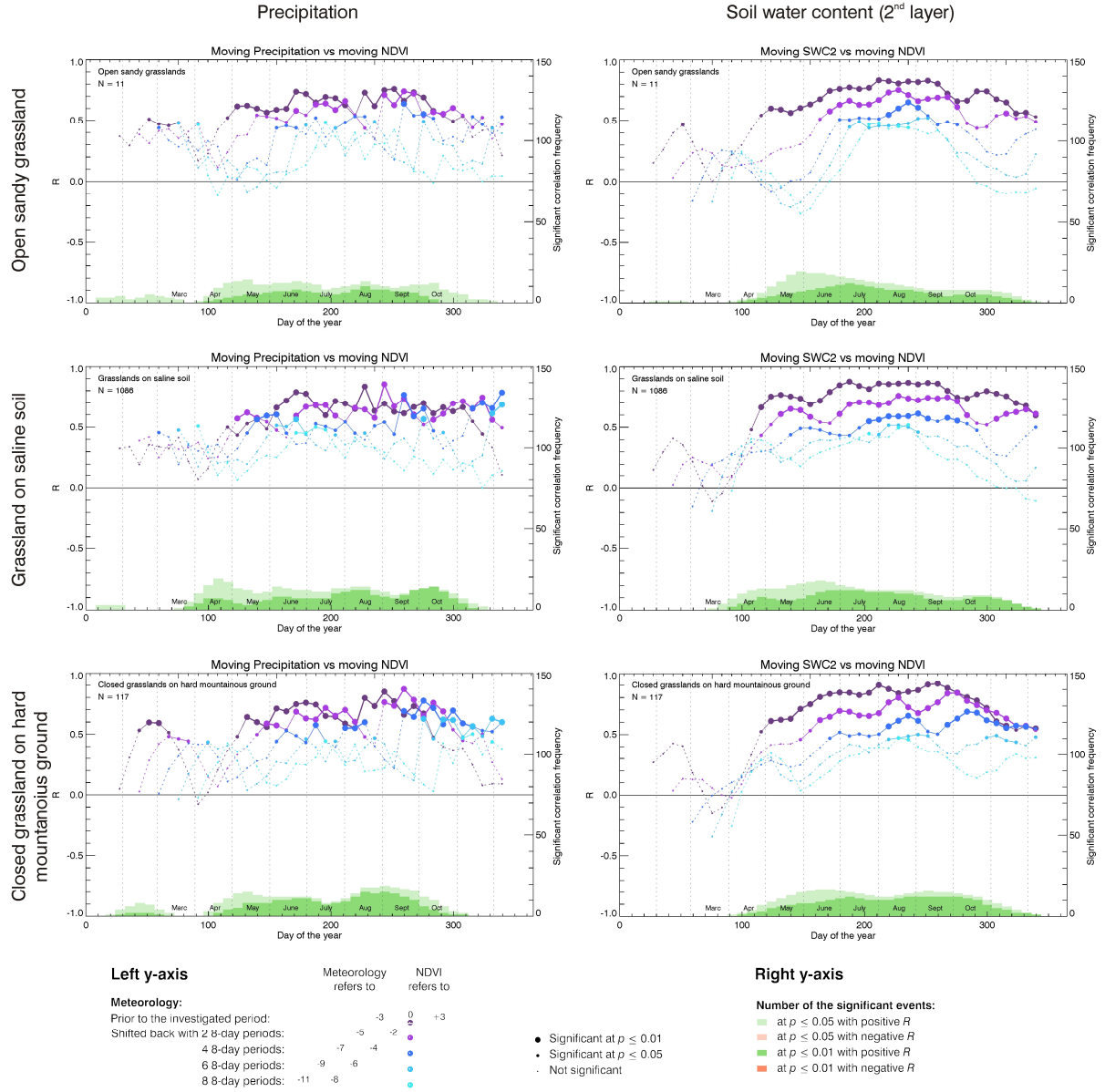




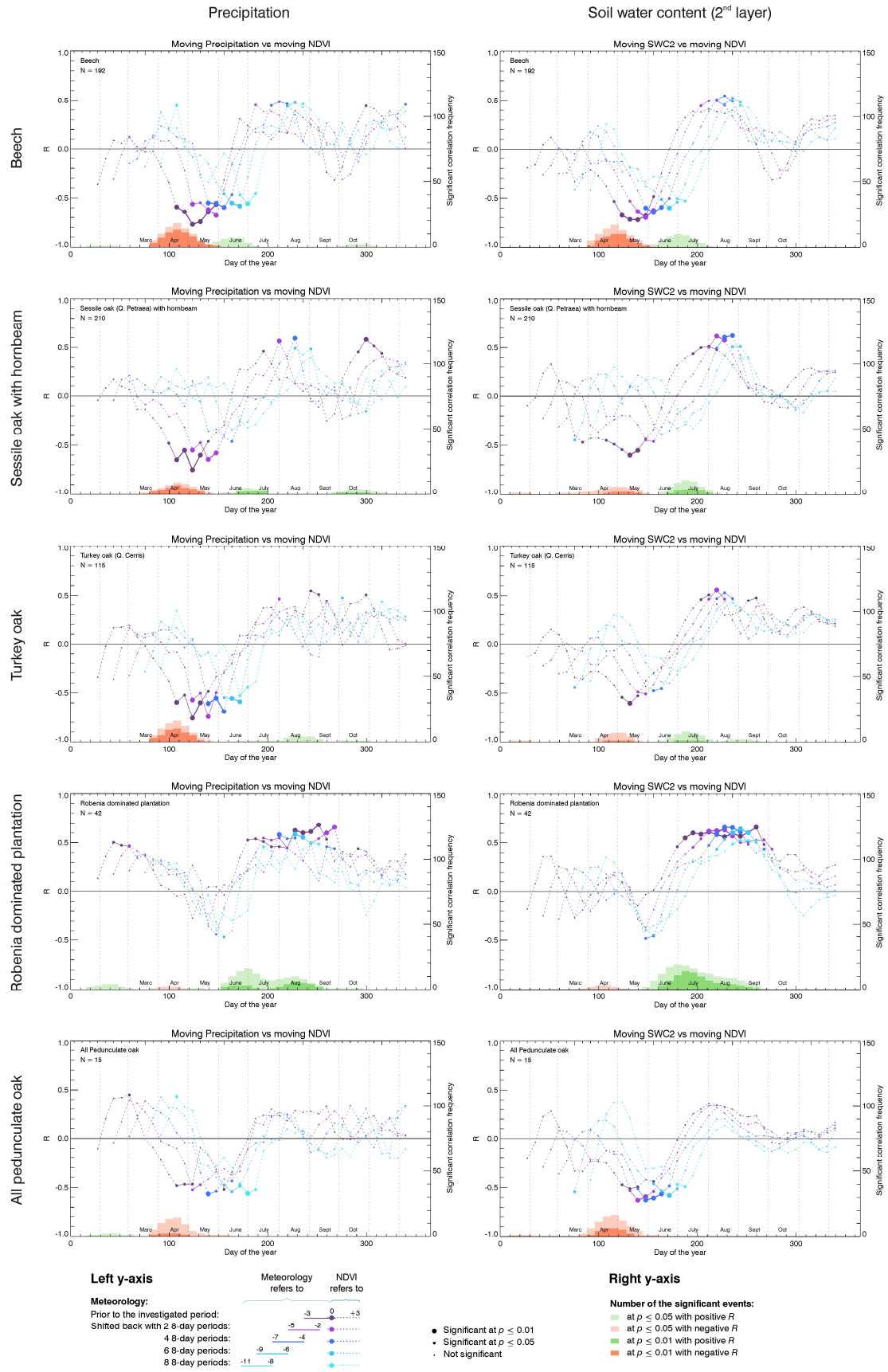
**Figure S4.** Pearson's  $R$  values between the NDVI and the climate variables (temperatures) for grasslands. NDVI refers to the investigated moving period after the indicated period, while the climate variables refer to the moving period before the indicated period. Both the NDVI and climate variables refer to 32 days ( $4 \times 8$ -day periods). In the case of NDVI the 32 days are starting uniformly after the indicated period, while in the case of climate variables 5 different backward shifts are shown with different colours. The secondary y-axis presents the number of the cases of those periods of the climate variables, where the presented 5 curves have any significant  $R$  value during the corresponding 32-32 days (i.e. the maximum number of the events is 20). Periods with positive  $R$  values are indicated with greenish, while with negative  $R$ -values are indicated with reddish colours.



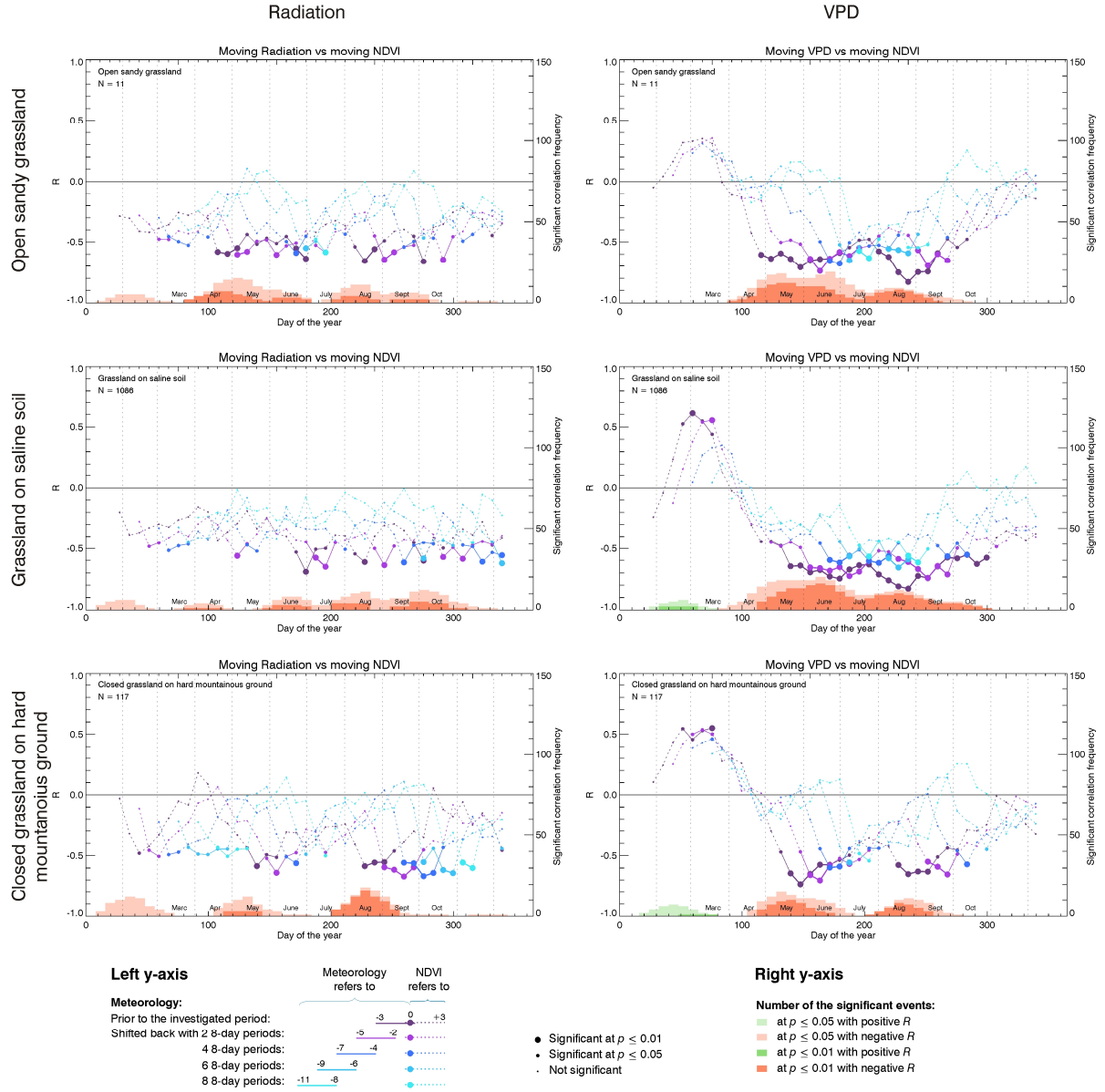
**Figure S5.** Pearson's  $R$  values between the NDVI and the climate variables (temperatures) for woody vegetation (forests). NDVI refers to the investigated moving period after the indicated period, while the climate variables refer to the moving period before the indicated period. For more details see the caption of **Figure S4**.



**Figure S6.** Pearson's  $R$  values between the NDVI and the climate variables (precipitation and SWC) for grasslands. NDVI refers to the investigated moving period after the indicated period, while the climate variables refer to the moving period before the indicated period. For more details see the caption of **Figure S4**.

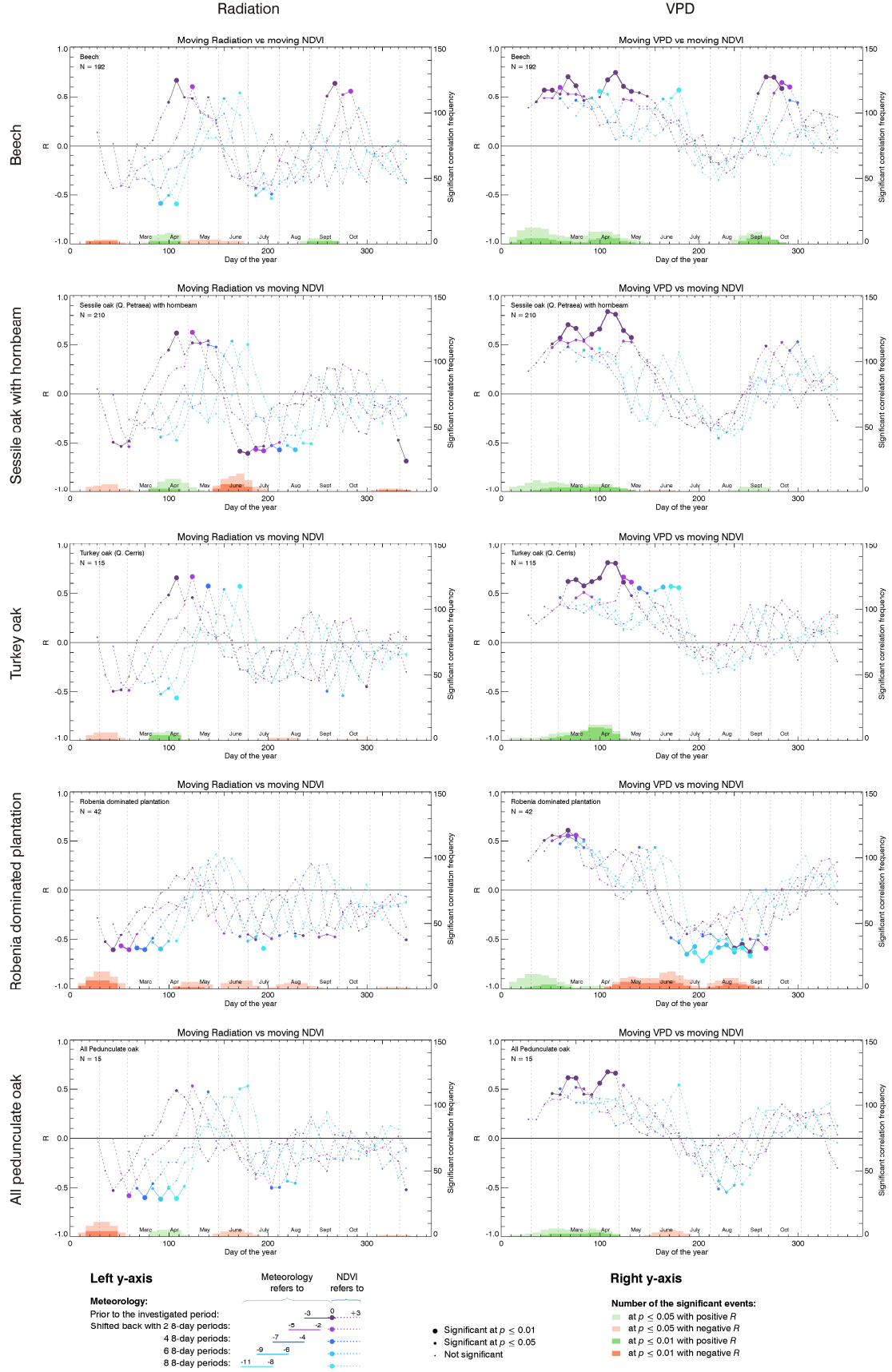


**Figure S7.** Pearson's  $R$  values between the NDVI and the climate variables (precipitation and SWC) for woody vegetation (forests). NDVI refers to the investigated moving period after the indicated period, while the climate variables refer to the moving period before the indicated period. For more details see the caption of **Figure S4**.



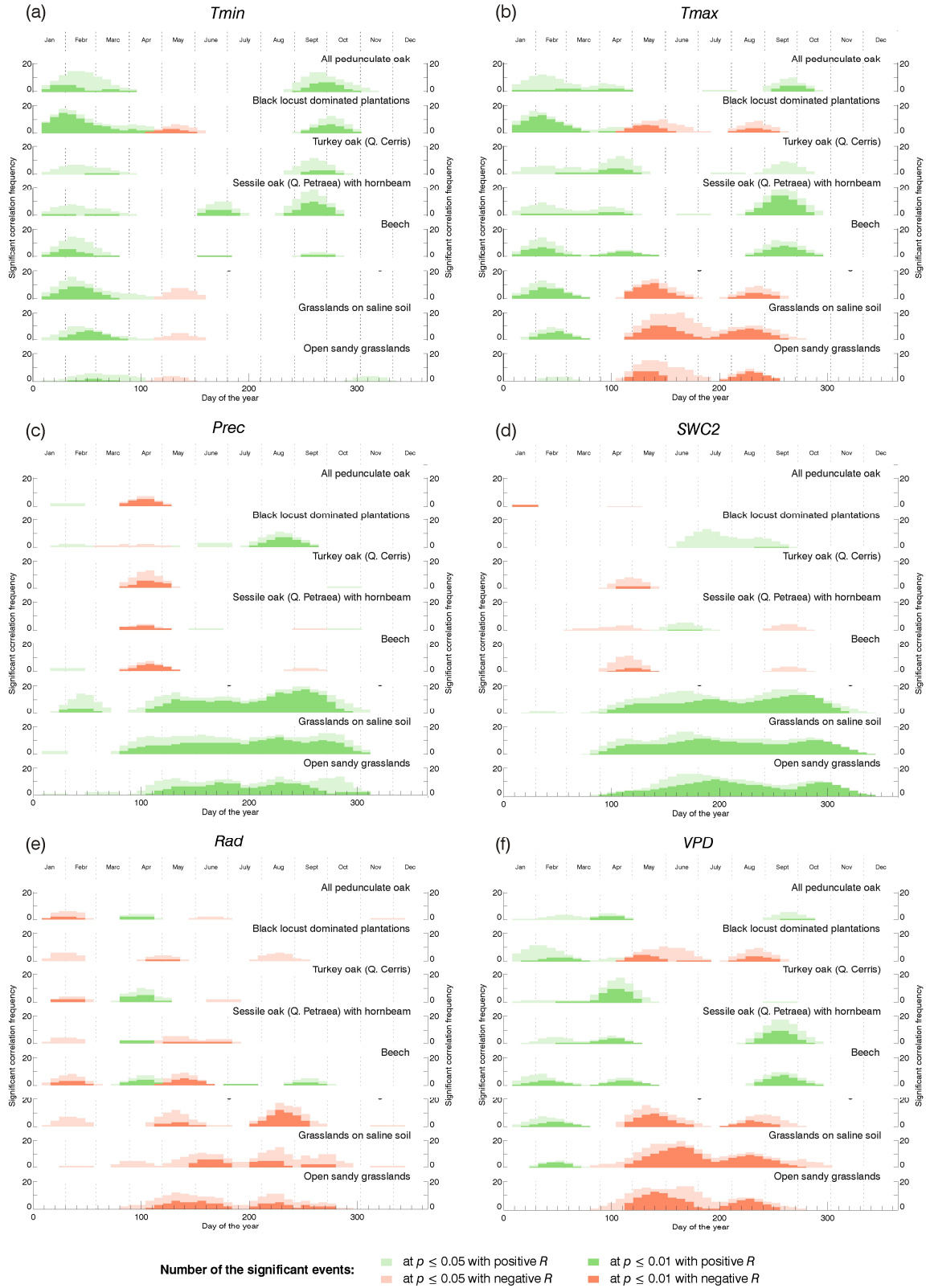
**Figure S8.** Pearson's  $R$  values between the NDVI and the climate variables (radiation and VPD) for grasslands. NDVI refers to the investigated moving period after the indicated period, while the climate variables refer to the moving period before the indicated period. For more details see the caption of **Figure S4**.





**Figure S9.** Pearson's  $R$  values between the NDVI and the climate variables (radiation and VPD) for woody vegetation (forests). NDVI refers to the investigated moving period after the indicated period, while the climate variables refer to the moving period before the indicated period. For more details see the caption of **Figure S4**.

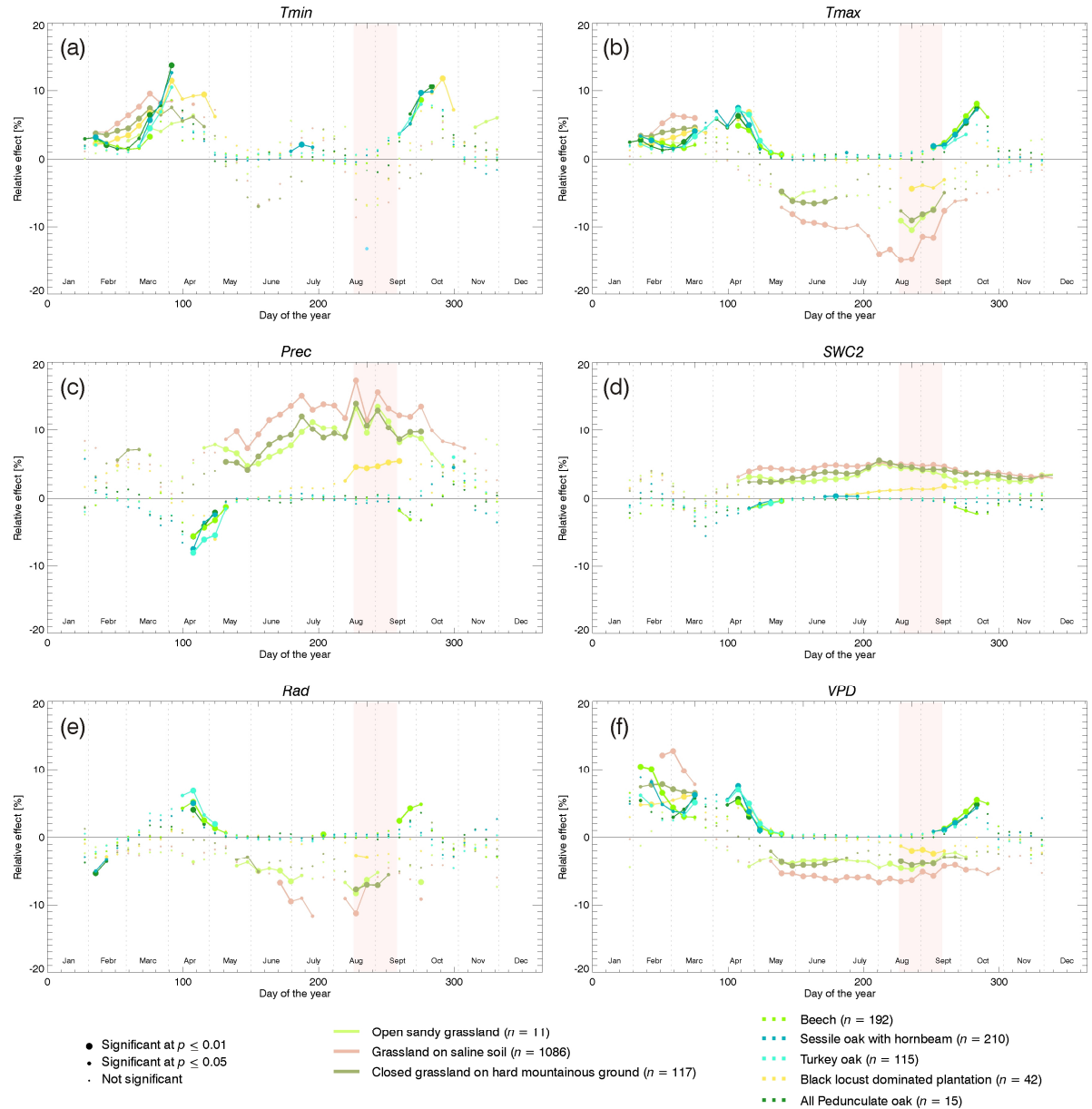




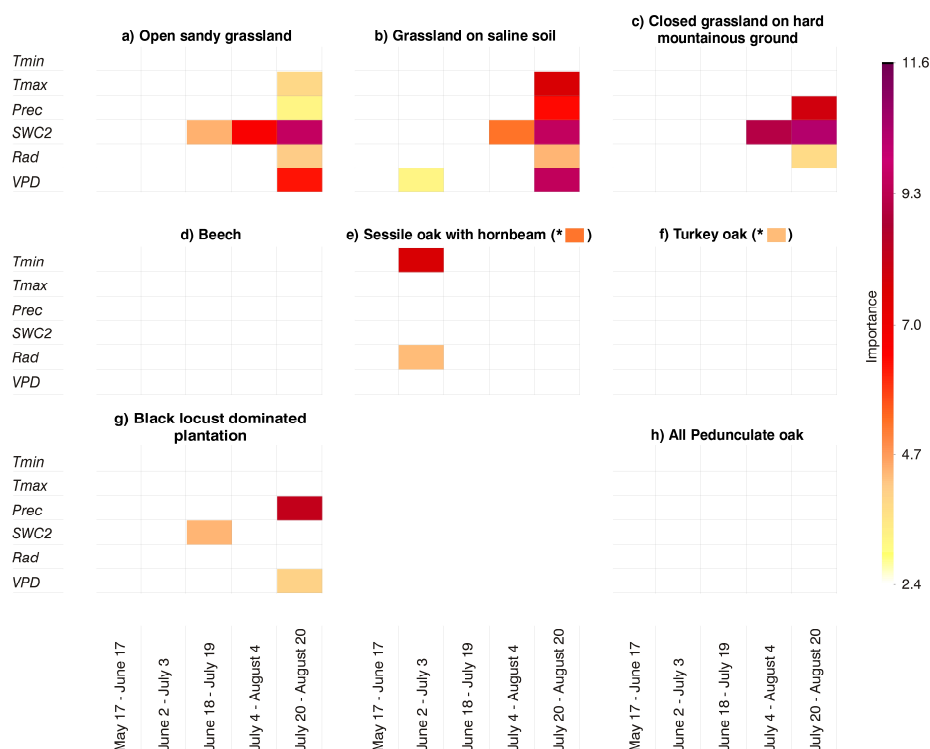
**Figure S10.** Critical climate periods within the year, when  $T_{min}$ ,  $T_{max}$ ,  $Prec$ ,  $SWC2$ ,  $Rad$  and  $VPD$  significantly influence the state of the vegetation (LAI). The significant correlation frequency (i.e., the numbers of the events, maximum 20; five time lags & four 8-day periods; see methods) associated with significant  $R$  are shown for all 8-day periods during the year. Periods corresponding to positive  $R$  values are indicated with green, while those with negative  $R$  values are indicated with red colour where those significant at  $p \leq 0.01$  are shown in darker shades while those with  $p \leq 0.05$  are shown with lighter shades.

**Table S2.** The average length of the time lags (*lag*, expressed in number of days) between LAI and the used climate variables for the time lags with the greatest significant *R*. The share of time between 25<sup>th</sup> Jan and 10<sup>th</sup> Dec (forty 8-day periods; the peak of the winter was discarded to minimise the snow effects) when the correlation was highly significant ( $p \leq 0.01$ ; *STSC* – share of time with significant correlation) is also indicated, according to the sign of the correlation.

Ecosystem categories	Correlation	<i>Tmin</i>		<i>Tmax</i>		<i>Precipitation</i>		<i>SWC2</i>		<i>Radiation</i>		<i>VPD</i>	
		<i>lag</i> (days)	<i>STSC</i>	<i>Lag</i> (days)	<i>STSC</i>	<i>lag</i> (days)	<i>STSC</i>	<i>lag</i> (days)	<i>STSC</i>	<i>lag</i> (days)	<i>STSC</i>	<i>lag</i> (days)	<i>STSC</i>
Open sandy grassland	negative	-	0%	46.2	33%	-	0%	-	0%	40.0	33%	41.0	40%
	positive	24.0	3.0%	-	0%	30.5	55%	25.7	73%	-	0%	-	0%
Grassland on saline soil	negative	-	0%	33.1	35%	-	0%	-	0%	43.7	33%	33.3	48%
	positive	27.2	13.0%	28.0	10%	38.3	70%	26.2	73%	-	0%	28.0	10%
Closed grassland on hard m. ground	negative	-	0%	40.0	30%	-	0%	-	0%	39.8	33%	33.3	30%
	positive	28.6	18.0%	30.9	18%	41.6	75%	29.7	70%	-	0%	24.0	13%
Beech	negative	-	0%	-	0%	27.2	13%	24.0	8%	67.4	18%	-	0%
	positive	56.0	20%	37.6	50%	-	0%	-	0%	24.0	15%	27.0	40%
Sessile oak with hornbeam	negative	-	0%	-	0%	24.0	5%	-	0%	64.0	5%	-	0%
	positive	46.0	33%	43.2	38%	-	0%	24.0	3%	32.0	5%	48.7	28%
Turkey oak	negative	-	0%	-	0%	33.6	13%	32.0	8%	80.0	5%	-	0%
	positive	40.0	10%	27.2	13%	-	0%	-	0%	48.0	10%	48.0	25%
Black locust dominated plantation	negative	88.0	8%	66.0	20%	-	0%	-	0%	88.0	3%	56.0	20%
	positive	34.7	38%	38.2	23%	29.3	15%	24.0	3%	-	0%	24.0	8%
All pedunculate oak	negative	-	0%	-	0%	32.0	10%	64.0	5%	48.0	10%	-	0%
	positive	48.4	28%	27.6	23%	-	0%	-	0%	32.0	5%	28.0	10%



**Figure S11.** Relative effects of  $T_{min}$ ,  $T_{max}$ ,  $Prec$ ,  $SWC2$ ,  $Rad$  and  $VPD$  on the investigated ecosystem groups based on LAI. It expresses that for one reference unit change of the climate variable the VRC will change the indicated percent. The reference units are 1 °C, 1 °C, 5 mm, 0.01 m<sup>3</sup> m<sup>-3</sup>, 10 MJ m<sup>-2</sup> day<sup>-1</sup> and 50 Pa in the case of  $T_{min}$ ,  $T_{max}$ ,  $Prec$ ,  $SWC2$ ,  $Rad$  and  $VPD$  respectively. Pink rectangles/columns indicate the period of interest (PI) in late summer (DOY 225–256, 13<sup>th</sup> of August – 13<sup>th</sup> of September).



**Figure S12.** Relevant climate variables affecting the vegetation state (expressed by LAI) during the PI based on the results of the *Boruta* algorithm. PI was selected as the period between August 13 and September 13. The colours are expressing the “importance” value as the result of the *Boruta* feature selection. The \* and the following coloured rectangles indicate that in the case of the given ecosystem category the *Year* variable was also found to be relevant.