Supplementary Figures and Tables for "Temperature is a dominant driver of distinct annual seasonality of leaf litter production of equatorial tropical rain forests"

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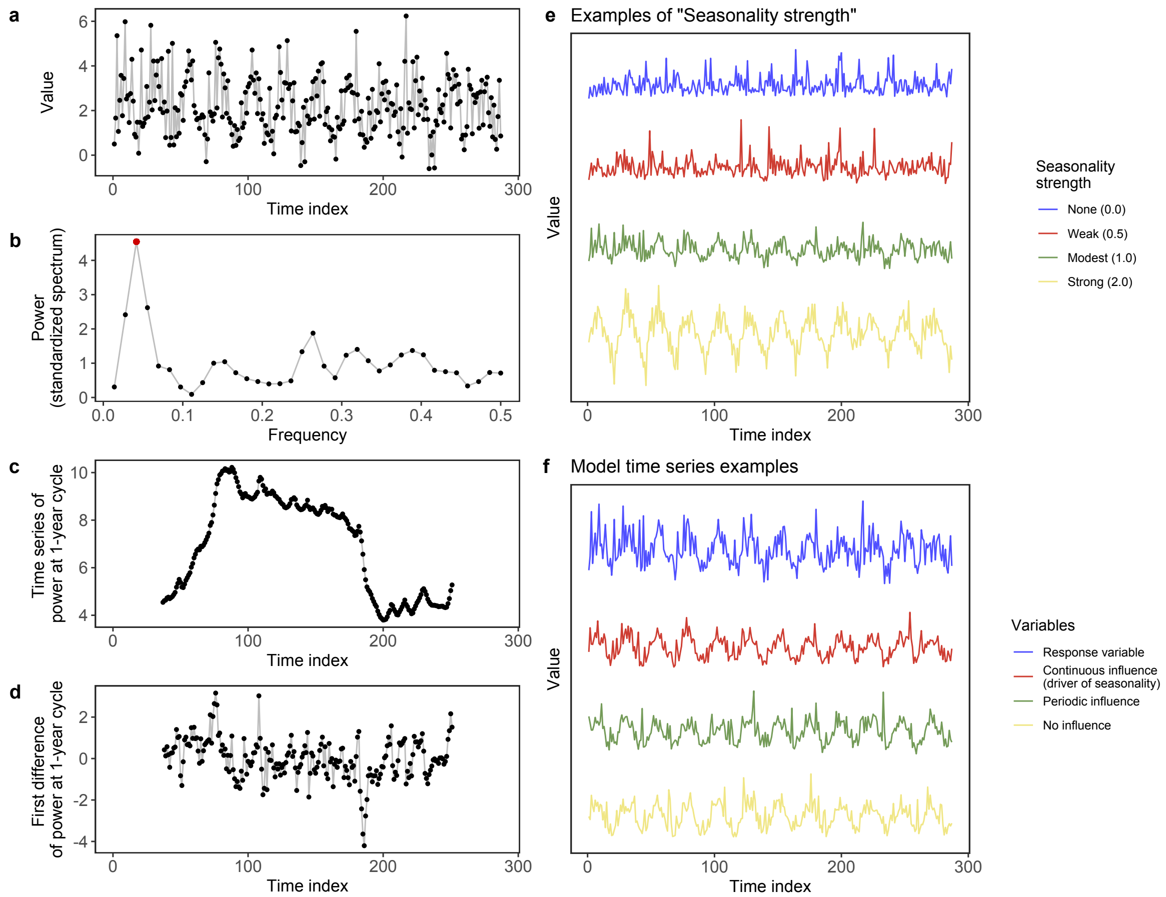

Figure S1 | Algorithm of spectrum convergent cross mapping (spectrum CCM) and examples of model time series used for the performance test of spectrum CCM. (**a**) Model time series that shows moderate seasonality (twelve-year time series with 2-week intervals). (**b**) Fourier analysis of the model time series, showing that the length of the dominant cycle is 12 months. Red point indicates the power of the 12-month cycle. (**c**) Time series of power of one-year cycle calculated as follows: (1) power of one-year cycle is calculated for a three-year window, (2) we slid the window one time-step forward, (3) power of one-year cycle is again calculated for the new three-year window, and (4) steps 2-3 were repeated until the end of the time series. (**d**) First difference of the time series of power of one-year cycle. CCM was performed for the first difference time series. (**e**) Examples of the model time series with different strengths of seasonality. Numbers in parentheses indicate the strength of seasonality (corresponding to $\beta_{2,i}$ in Eqn. (1) in Methods). (**f**) Examples of the model time series. Blue line indicates a response time series (e.g., leaf litter time series; Eqn. (2) in Methods). Red, green, and yellow lines indicate time series A, B and C (see Eqn. (1) in Methods). Time series A, B and C have continuous, periodic, and no influence on the response variable, respectively. The red time series is a true driver of the seasonality of the response variable.

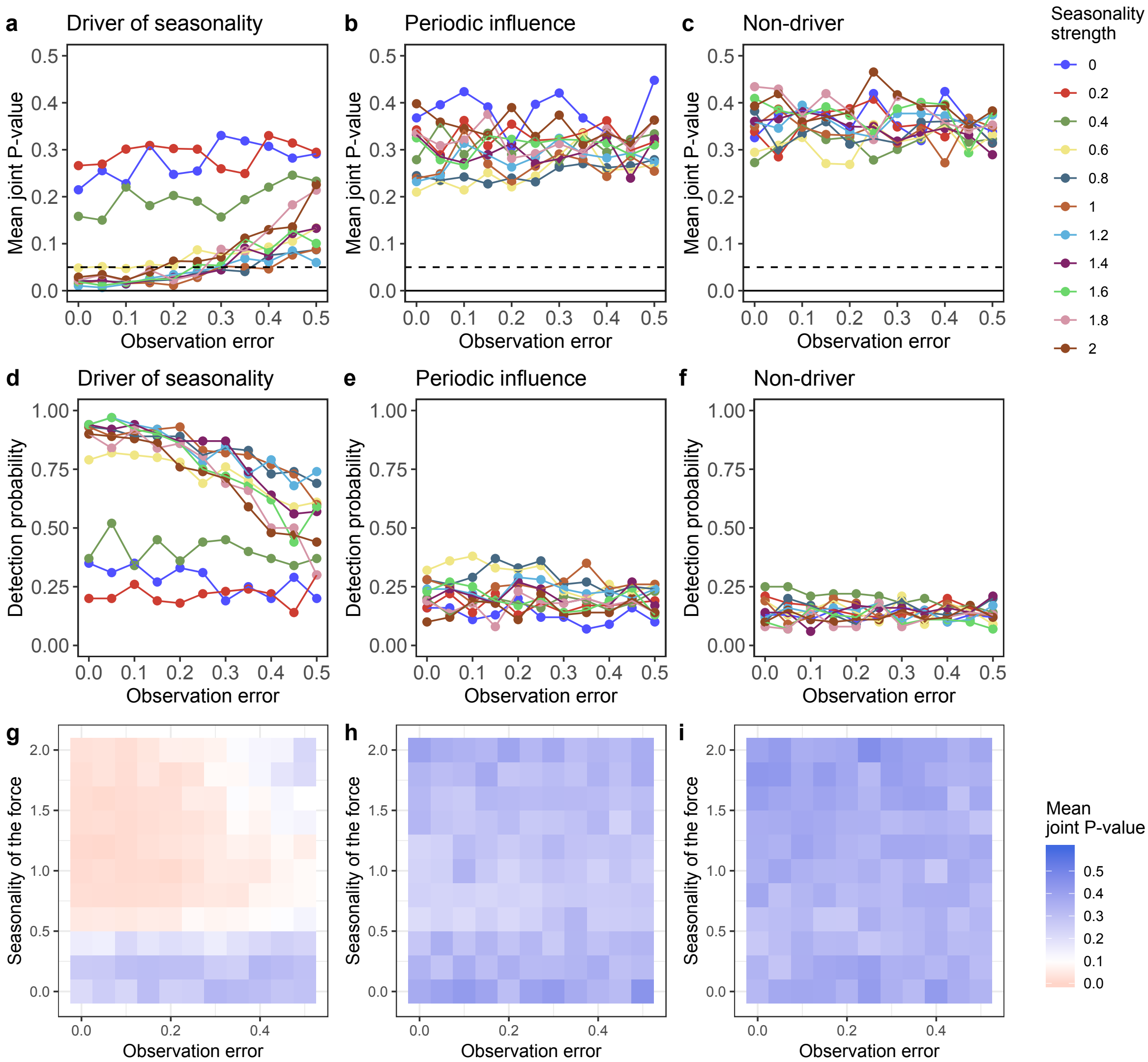

Figure S2 | The results of the performance test of spectrum convergent cross mapping (spectrum CCM). Seasonality strength, observation errors and mean joint P-values of spectrum CCM applied to time series that have (**a**) continuous influence (the true seasonality driver), (**b**) periodic influence, and (**c**) no influence on the target variable. Different colours indicate different strengths of seasonality. Dashed line indicates joint P-value = 0.05. Seasonality strength, observation errors and detection probability (as the true seasonality driver) of spectrum CCM applied to time series that have (**d**) continuous influence (the true seasonality driver), (**e**) periodic influence, and (**f**) no influence on the target variable. Different colours indicate different strengths of seasonality. Heat map of the seasonality strength, observation errors and mean joint P-values of spectrum CCM applied to time series that have (**g**) continuous influence (the true seasonality driver), (**h**) periodic influence, and (**i**) no influence on the target variable. Colours indicate mean joint P-value. If a time series has weak to strong seasonality and observation errors less than 20-30%, then spectrum CCM correctly distinguishes the true seasonality driver from non-driver (**a–c**), and the probability of false-positive detection is low (10–20%; **e–f**).

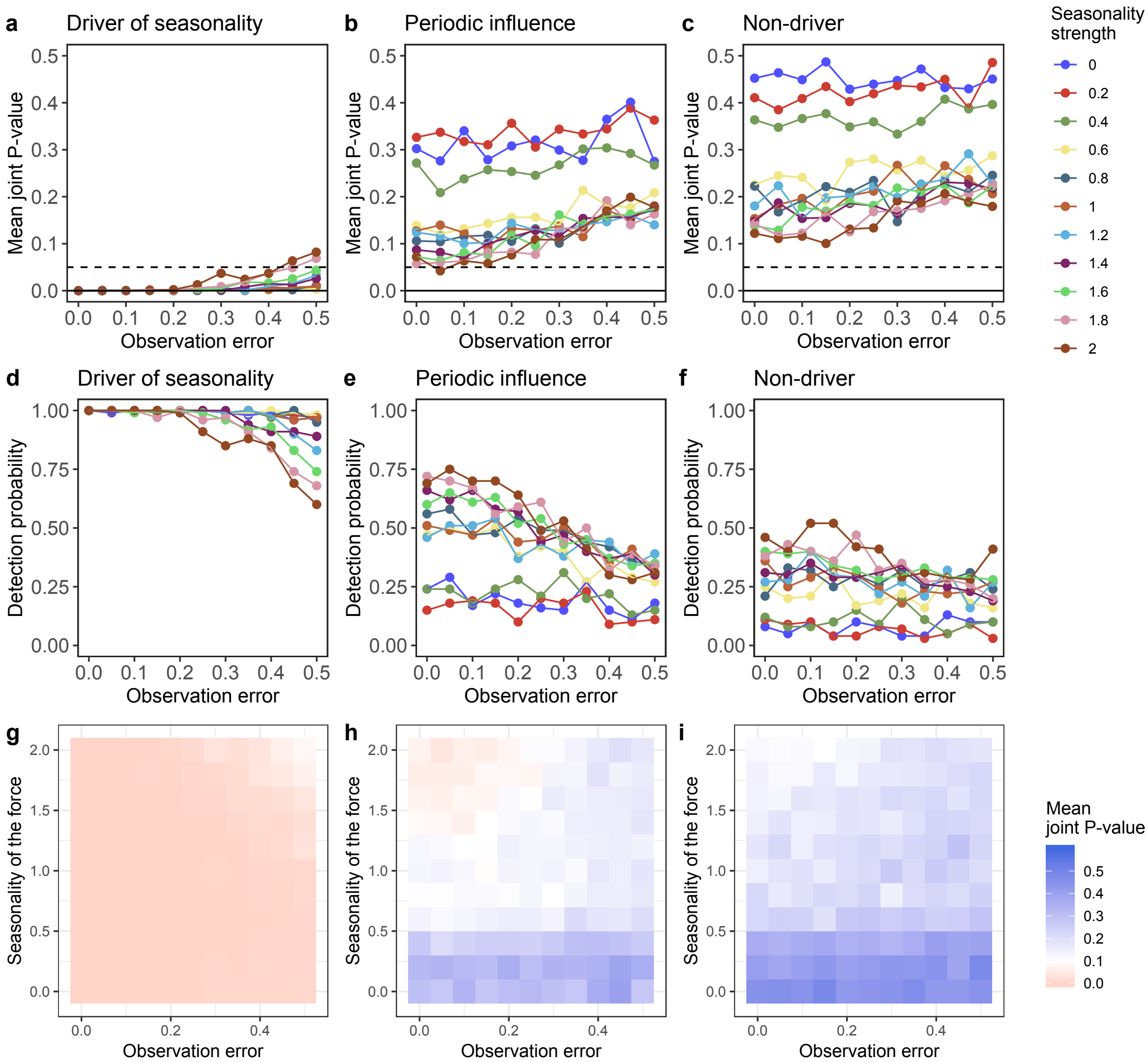

Figure S3 | The results of the performance test of convergent cross mapping (normal CCM). Seasonality strength, observation errors and mean joint P-values of normal CCM applied to time series that have (**a**) continuous influence (the true seasonality driver), (**b**) periodic influence, and (**c**) no influence on the target variable. Different colours indicate different strengths of seasonality. Dashed lines indicate joint P-value = 0.05. Seasonality strength, observation errors and detection probability (as the true seasonality driver) of normal CCM applied to time series that have (**d**) continuous influence (the true seasonality driver), (**e**) periodic influence, and (**f**) no influence on the target variable. Different colours indicate different strengths of seasonality. Heat map of the seasonality strength, observation errors and mean joint P-values of normal CCM applied to time series that have (**g**) continuous influence (the true seasonality driver), (**h**) periodic influence, and (**i**) no influence on the target variable. Colours indicate mean joint P-value. If time series has weak to strong seasonality, then normal CCM may incorrectly detect a non-driver as the driver (**b**–**c**). Also, even with weak to moderate strength of seasonality, the probability of false-positive detection is high for time series that have periodic influence (50–75%; **e**) and no influence (20–50%; **f**).

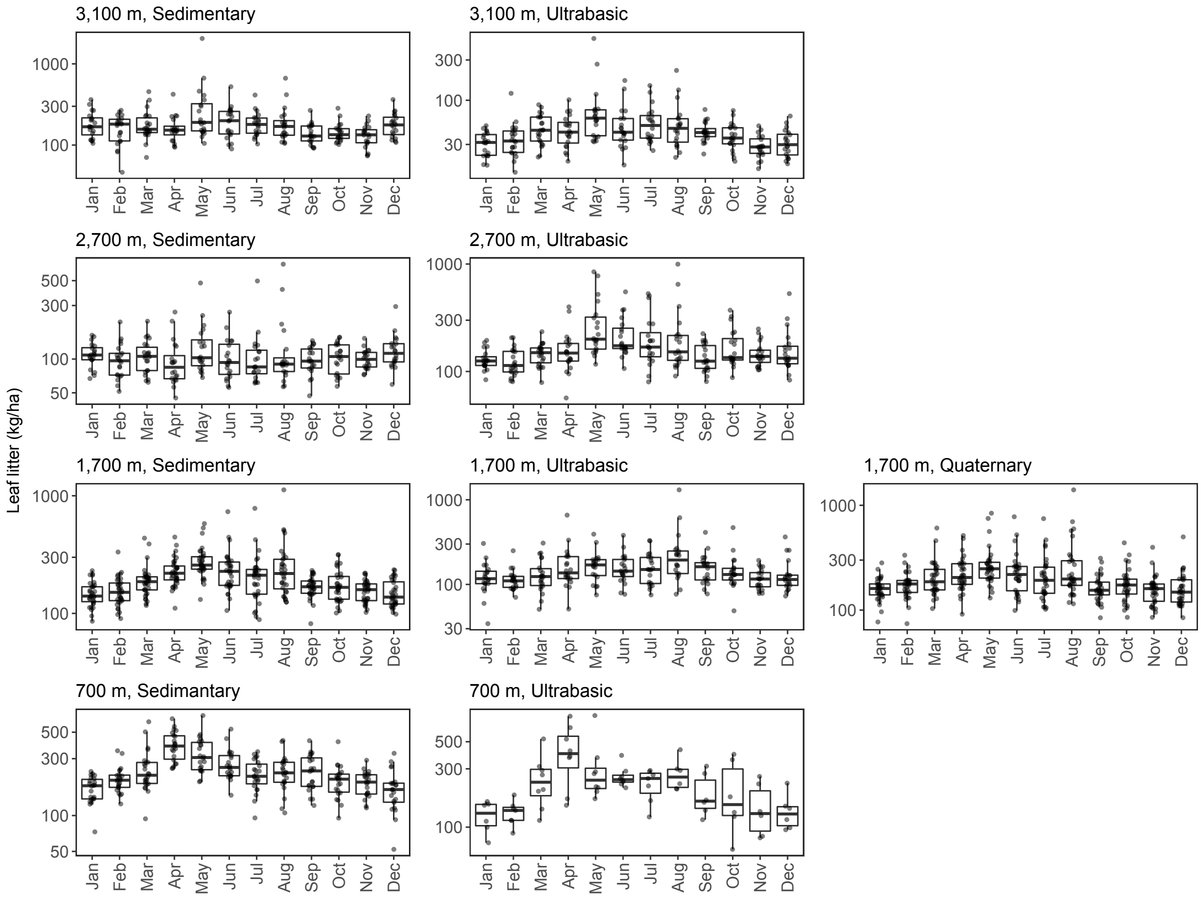

Figure S4 | Monthly patterns of leaf litter production in the tropical rain forests on Mt. Kinabalu. In general, leaf litter production is larger from March to June than in other months at most sites. This trend is detected as the one-year periodicity using Fourier analysis.

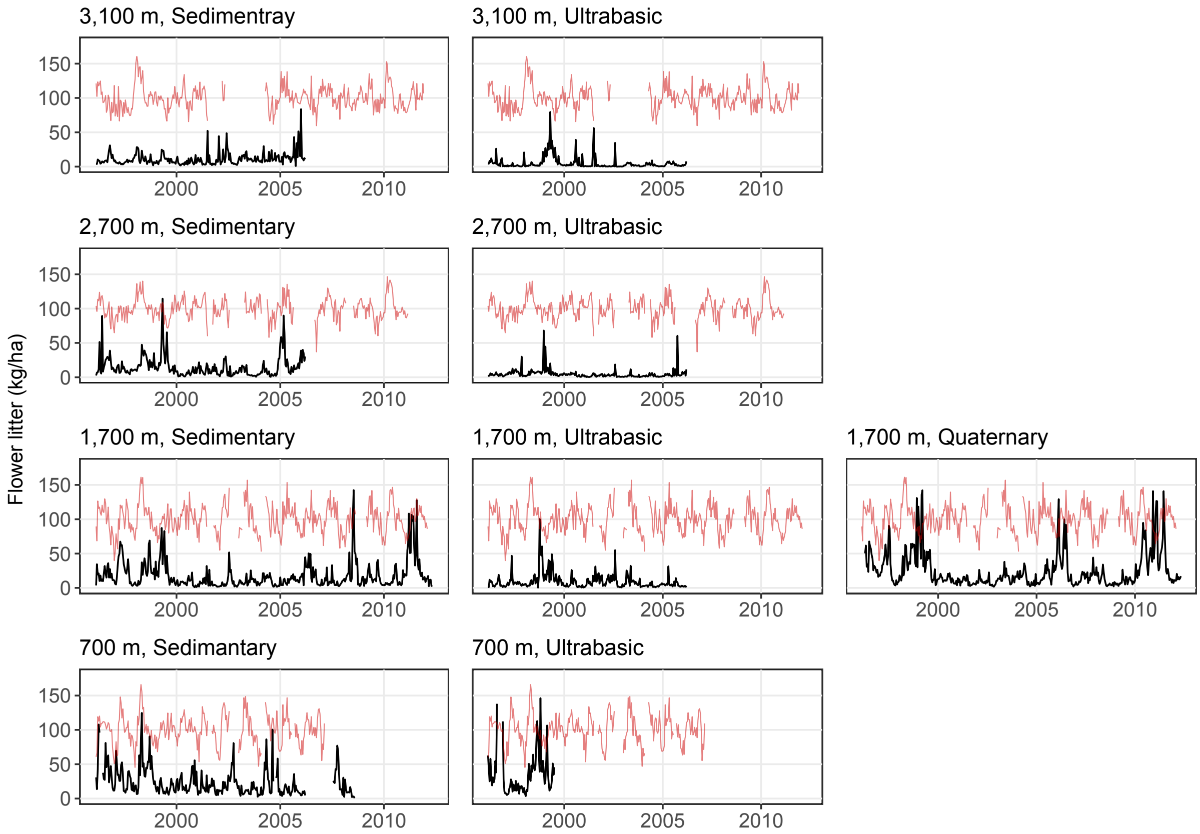

Figure S5 | Time series of flower litter production in tropical rain forests on Mt. Kinabalu. Black lines indicate flower litter production, and red lines indicate mean daily air temperature corrected by general additive model (only patterns are shown). The values on the y-axis are for flower litter production. Flower litter production does not show clear annual periodicity, unlike leaf litter production.

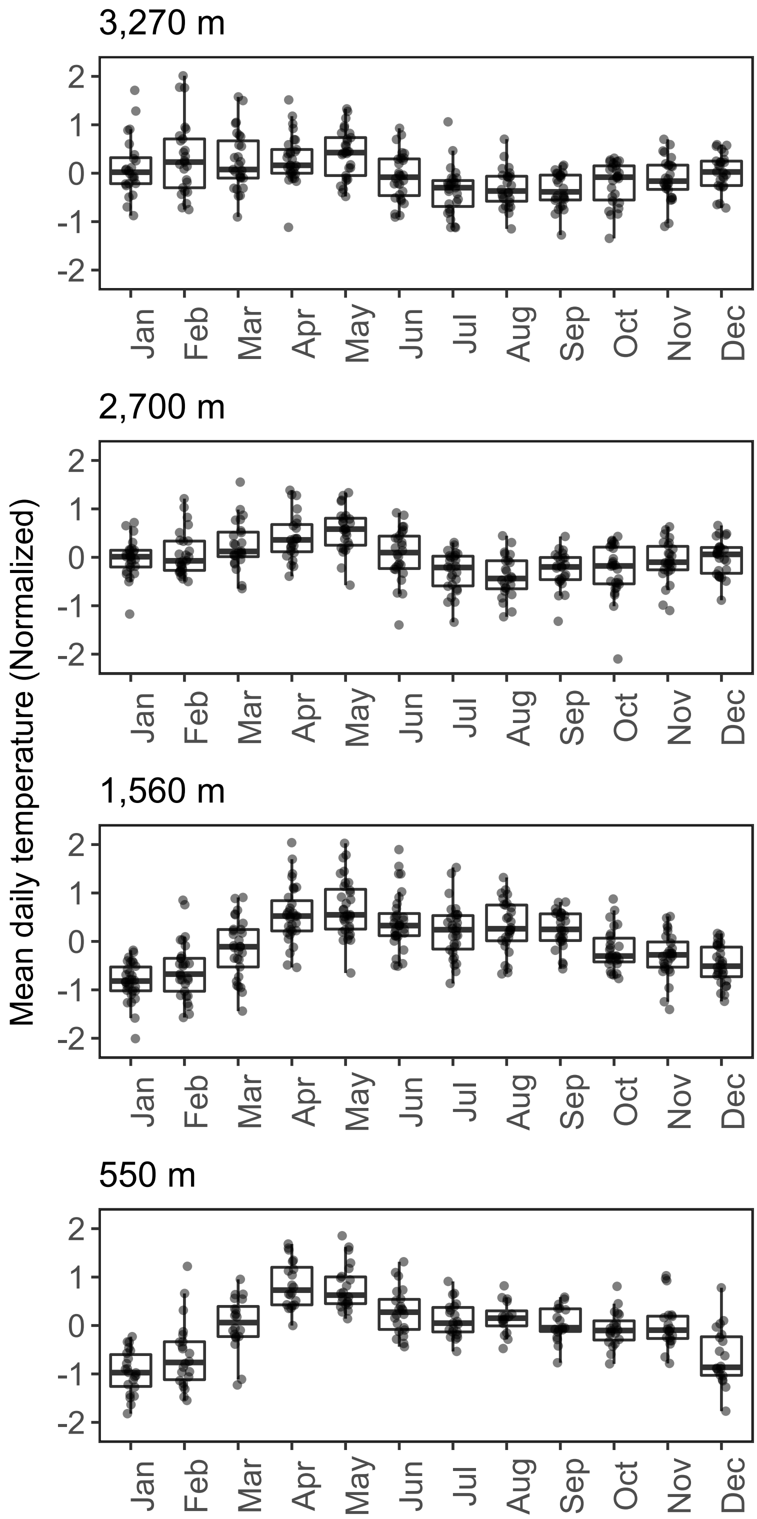

Figure S6 | Monthly patterns of daily mean air temperature. The original values were corrected by a general additive model and the residuals are shown. In general, daily mean air temperature is higher from March to June.

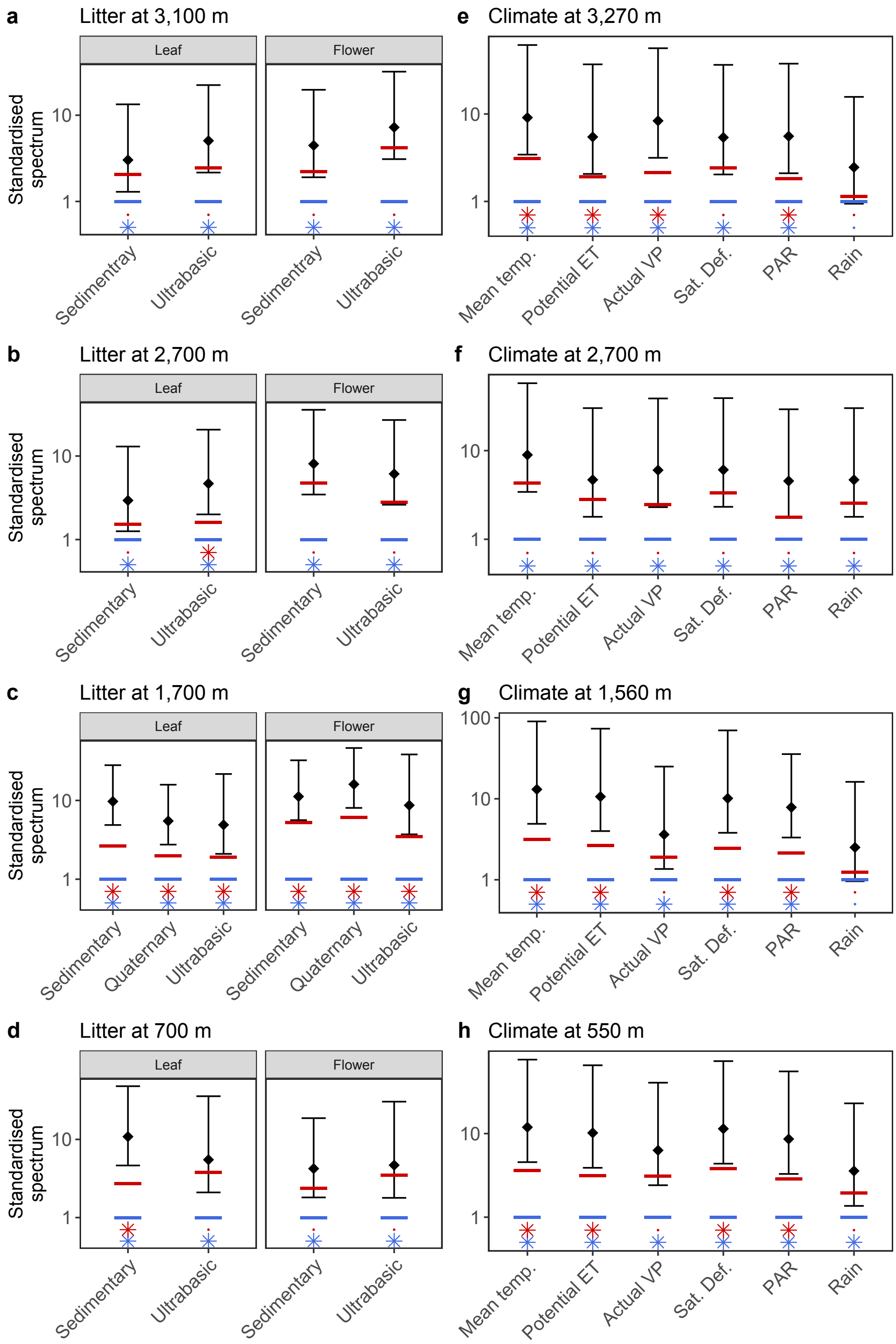

Figure S7 | Confidence intervals and significance of the dominant periodicity of litter and meteorological time series. Black points indicate the power of the dominant periodicity (note that the powers were not always for the 1-year periodicity). Bars indicate 95% confidence intervals calculated by assuming that spectral estimates approximate a chi-square distribution. Red and blue bars indicate null and average spectrum, respectively. Red and blue asterisks indicate the significance of the power based on the null and average spectrum, respectively. If the power is not significant, only "dot" is shown.

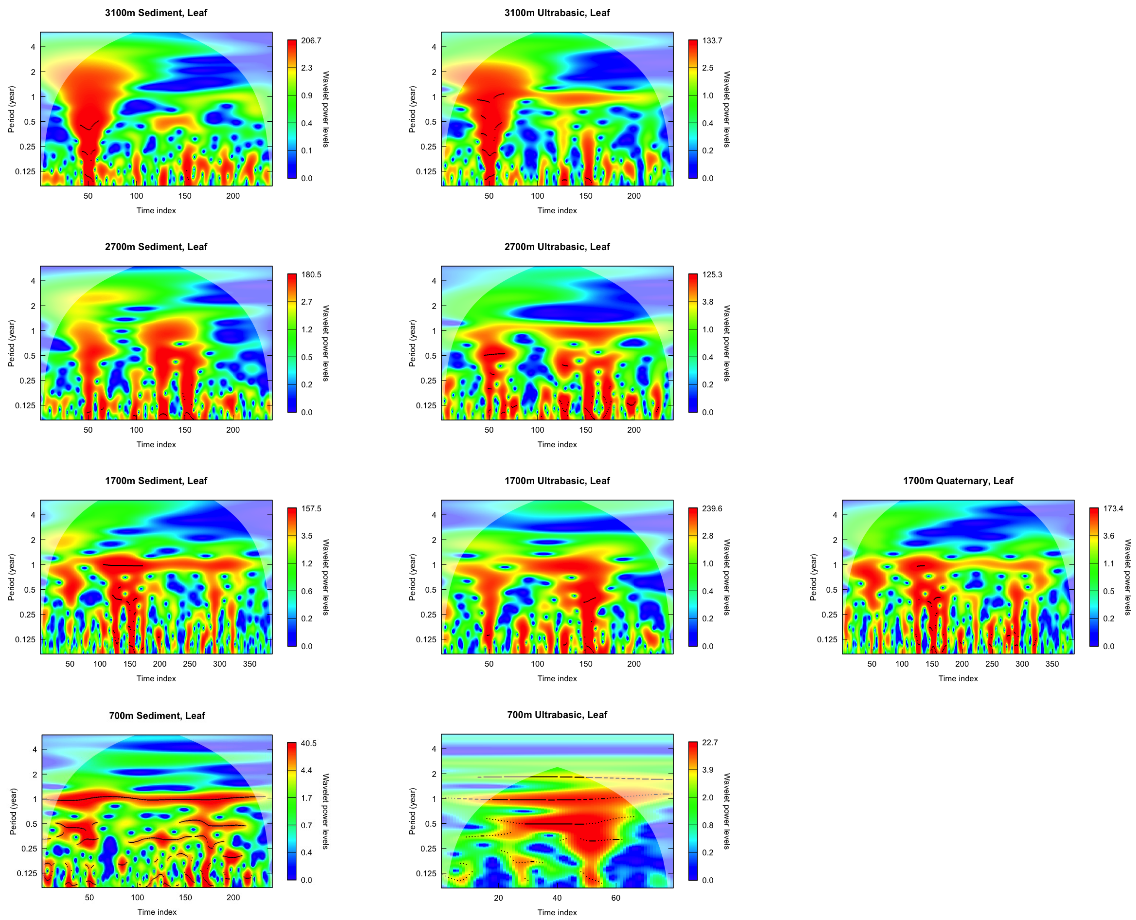

Figure S8 | Wavelet analysis of leaf litter production. *x*-axis and *y*-axis and color indicate time points, the length of periodicity and the strength of the periodicity at each frequency, respectively. Black lines indicate the ridge of wavelet power.

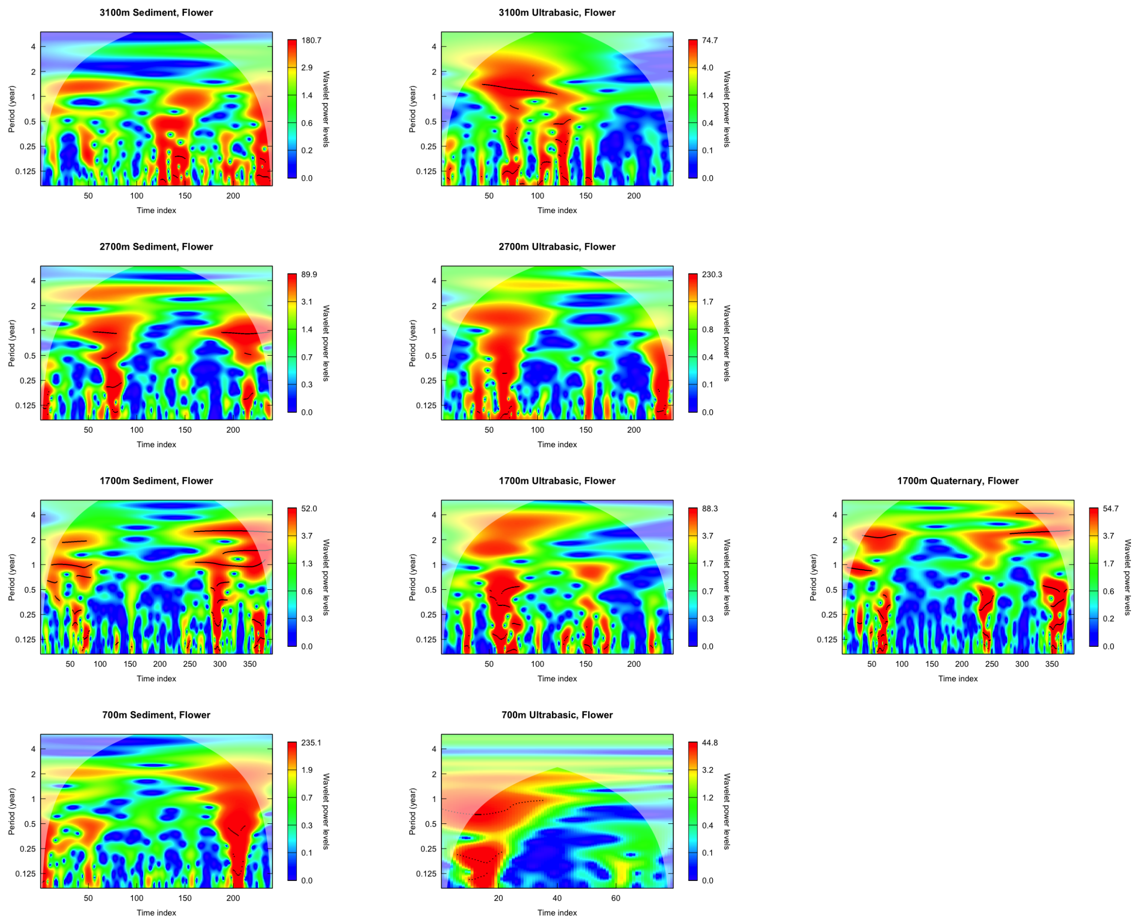

Figure S9 | Wavelet analysis of flower litter production. *x*-axis and *y*-axis and color indicate time points, the length of periodicity and the strength of the periodicity at each frequency, respectively. Black lines indicate the ridge of wavelet power.

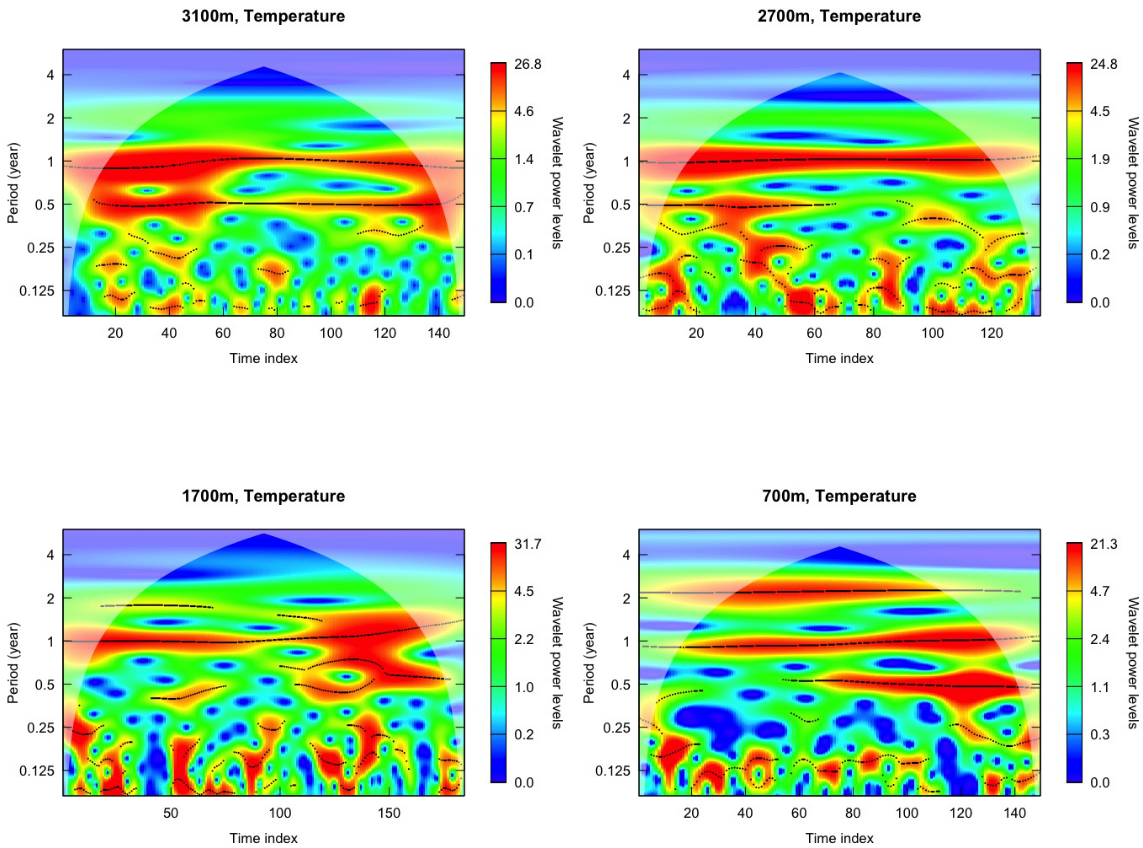

Figure S10 | Wavelet analysis of daily mean air temperature. x-axis and y-axis and color indicate time points, the length of periodicity and the strength of the periodicity at each frequency, respectively. Black lines indicate the ridge of wavelet power.

Table S1 | Time series length used for Fourier analysis

Altitude (m)	**Parent materia**	**Total monitoring duratio**	**For Fourier analysis** Start (year/month)	End (year/month)	**duration (mo)**	**Time poin (*N*)**
Climate site			(for air temperature*)			
3270		1996/2 – 2011/12	2004/4	2011/12	92.0	184
2700		1996/2 – 2011/3	1996/5	2002/7	74.5	149
1560		1996/2 – 2012/2	2003/1	2008/8	68.0	136
550		1996/2 – 2007/2	1996/5	2002/7	74.5	149
Litter site			(for leaf and flower litter)			
700	Sedimentary	1996/4 – 2006/3	1996/4	2006/3	120.0	240
1700	Sedimentary	1996/4 – 2012/5	1996/4	2012/5	193.5	387
2700	Sedimentary	1996/4 – 2006/3	1996/4	2006/3	120.0	240
3100	Sedimentary	1996/4 – 2006/3	1996/4	2006/3	120.0	240
700	Ultrabasic	1996/4 – 1999/7	1996/4	1999/7	39.5	79
1700	Ultrabasic	1996/4 – 2006/3	1996/4	2006/3	120.0	240
2700	Ultrabasic	1996/4 – 2006/3	1996/4	2006/3	120.0	240
3100	Ultrabasic	1996/4 – 2006/3	1996/4	2006/3	120.0	240
1700	Quaternary	1996/4 – 2012/5	1996/4	2012/5	193.0	386

*The duration may slightly change depending on meteorological variables.

Table S2 | Summary of Fourier analysis of litter

Site name	Altitude (m)	Parent material	Variable	Dominant cycle (month)	Significance of the cycl (null)	(average)	One-year cycle† (12 ± 1.5 month)
POR	700	Sedimantary	Leaf	12.0	*	*	One-year cycle
NAL	700	Ultramafic	Leaf	13.3	N.S.	*	7 / 9 sites
PHQ	1700	Sedimantary	Leaf	11.8	*	*	
BAB	1700	Ultramafic	Leaf	12.0	*	*	Significant one-year cycle
ULA	1700	Quaternary	Leaf	12.0	*	*	(null spectrum) 5 / 9 sites
RTM	2700	Sedimantary	Leaf	6.3	N.S.	*	(avr. spectrum) 7 / 9 sites
CAR	2700	Ultramafic	Leaf	12.0	N.S.	*	
PAK	3100	Sedimantary	Leaf	24.0	N.S.	*	
HEL	3100	Ultramafic	Leaf	11.8	*	*	
POR	700	Sedimantary	Flower	24.0	N.S.	*	One-year cycle
NAL	700	Ultramafic	Flower	20.0	N.S.	*	0 / 9 sites
PHQ	1700	Sedimantary	Flower	> 48	*	*	
BAB	1700	Ultramafic	Flower	40.0	*	*	Significant one-year cycle
ULA	1700	Quaternary	Flower	> 48	N.S.	*	(null spectrum) 0 / 9 sites
RTM	2700	Sedimantary	Flower	40.0	N.S.	*	(avr. spectrum) 0 / 9 sites
CAR	2700	Ultramafic	Flower	40.0	N.S.	*	
PAK	3100	Sedimantary	Flower	15.0	N.S.	*	
HEL	3100	Ultramafic	Flower	> 48	*	*	
POR	700	Sedimantary	Branch	4.0	N.S.	*	One-year cycle
NAL	700	Ultramafic	Branch	1.9	N.S.	*	4 / 9 sites
PHQ	1700	Sedimantary	Branch	11.8	*	*	
BAB	1700	Ultramafic	Branch	> 48	N.S.	*	Significant one-year cycle
ULA	1700	Quaternary	Branch	12.0	*	*	(null spectrum) 3 / 9 sites
RTM	2700	Sedimantary	Branch	12.0	N.S.	*	(avr. spectrum) 4 / 9 sites
CAR	2700	Ultramafic	Branch	12.0	*	*	
PAK	3100	Sedimantary	Branch	6.0	*	*	
HEL	3100	Ultramafic	Branch	1.6	N.S.	N.S.	
POR	700	Sedimantary	Epiphyte	40.0	N.S.	*	One-year cycle
NAL	700	Ultramafic	Epiphyte	13.3	N.S.	N.S.	3 / 9 sites
PHQ	1700	Sedimantary	Epiphyte	12.5	N.S.	*	
BAB	1700	Ultramafic	Epiphyte	30.0	N.S.	*	Significant one-year cycle
ULA	1700	Quaternary	Epiphyte	12.0	*	*	(null spectrum) 1 / 9 sites
RTM	2700	Sedimantary	Epiphyte	1.0	N.S.	*	(avr. spectrum) 2 / 9 sites
CAR	2700	Ultramafic	Epiphyte	> 48	N.S.	N.S.	
PAK	3100	Sedimantary	Epiphyte	17.1	N.S.	*	
HEL	3100	Ultramafic	Epiphyte	10.0	N.S.	*	
POR	700	Sedimantary	Bamboo	1.1	*	*	One-year cycle
NAL	700	Ultramafic	Bamboo	13.3	N.S.	*	2 / 9 sites
PHQ	1700	Sedimantary	Bamboo	> 48	*	*	
BAB	1700	Ultramafic	Bamboo	1.0	N.S.	N.S.	Significant one-year cycle
ULA	1700	Quaternary	Bamboo	12.0	N.S.	*	(null spectrum) 0 / 9 sites
RTM	2700	Sedimantary	Bamboo	> 48	N.S.	*	(avr. spectrum) 1 / 9 sites
CAR	2700	Ultramafic	Bamboo	> 48	N.S.	N.S.	
PAK	3100	Sedimantary	Bamboo	9.2	N.S.	N.S.	
HEL	3100	Ultramafic	Bamboo	> 48	*	*	
POR	700	Sedimantary	Dust	> 48	N.S.	*	One-year cycle
NAL	700	Ultramafic	Dust	40.0	N.S.	*	4 / 9 sites
PHQ	1700	Sedimantary	Dust	11.8	*	*	
BAB	1700	Ultramafic	Dust	> 48	N.S.	*	Significant one-year cycle
ULA	1700	Quaternary	Dust	12.0	*	*	(null spectrum) 4 / 9 sites
RTM	2700	Sedimantary	Dust	12.0	*	*	(avr. spectrum) 4 / 9 sites
CAR	2700	Ultramafic	Dust	> 48	*	*	
PAK	3100	Sedimantary	Dust	> 48	*	*	
HEL	3100	Ultramafic	Dust	11.8	*	*	

†This column indicates how many study sites exhibited annual seasonality (i.e., one-year cycle). "One-year cycle" indicates the number of study sites of which dominant cycle is 12 ± 1.5 months. "Significant one-year cycle" indicates the number of study sites which showed significant annual seasonality compared with null or average spectrum.

Table S3 | Summary of Fourier analysis of climate variables

Site name	Altitude (m)	Variable	Dominant cycle (month)	Significance of the cycl (null)	(average)	One-year cycle† (12 ± 1.5 month)
POR	550	Mean daily temperatu	12.5	*	*	One-year cycle
POR	550	Relative humidity	12.5	*	*	5 / 7 variables
POR	550	Acutual vapor pressur	15.0	N.S.	*	
POR	550	Saturation deficient	12.5	*	*	Significant one-year cycle
POR	550	PAR	12.5	*	*	(null spectrum) 5 / 7 variables
POR	550	Evapotranspiration	12.5	*	*	(avr. spectrum) 7 / 7 variables
POR	550	Rain	7.5	N.S.	*	
PHQ	1650	Mean daily temperatu	12.0	*	*	One-year cycle
PHQ	1650	Relative humidity	12.0	*	*	4 / 7 variables
PHQ	1650	Acutual vapor pressur	6.0	*	*	
PHQ	1650	Saturation deficient	12.0	N.S.	*	Significant one-year cycle
PHQ	1650	PAR	5.9	*	*	(null spectrum) 3 / 7 variables
PHQ	1650	Evapotranspiration	12.0	*	*	(avr. spectrum) 4 / 7 variables
PHQ	1650	Rain	1.7	N.S.	N.S.	
CAR	2700	Mean daily temperatu	25.0	N.S.	*	One-year cycle
CAR	2700	Relative humidity	12.5	N.S.	*	2 / 7 variables
CAR	2700	Acutual vapor pressur	6.3	N.S.	*	
CAR	2700	Saturation deficient	12.5	N.S.	*	Significant one-year cycle
CAR	2700	PAR	6.3	N.S.	*	(null spectrum) 0 / 7 variables
CAR	2700	Evapotranspiration	8.4	N.S.	*	(avr. spectrum) 2 / 7 variables
CAR	2700	Rain	25.0	N.S.	*	
LAB	3270	Mean daily temperatu	12.0	*	*	One-year cycle
LAB	3270	Relative humidity	12.0	N.S.	*	3 / 7 variables
LAB	3270	Acutual vapor pressur	6.0	*	*	
LAB	3270	Saturation deficient	12.0	N.S.	*	Significant one-year cycle
LAB	3270	PAR	6.0	*	*	(null spectrum) 1 / 7 variables
LAB	3270	Evapotranspiration	6.0	*	*	(avr. spectrum) 3 / 7 variables
LAB	3270	Rain	2.7	N.S.	N.S.	

†This column indicates how many study sites exhibited annual seasonality (i.e., one-year cycle). "One-year cycle" indicates the number of study sites of which dominant cycle is 12 ± 1.5 months. "Significant one-year cycle" indicates the number of study sites which showed significant annual seasonality compared with null or average spectrum.