Supplementary Information for the manuscript

Natural and human-based alterations affect long-term light properties at forest understory in Southern Europe

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Appendix S1. Detailed information of material and methods

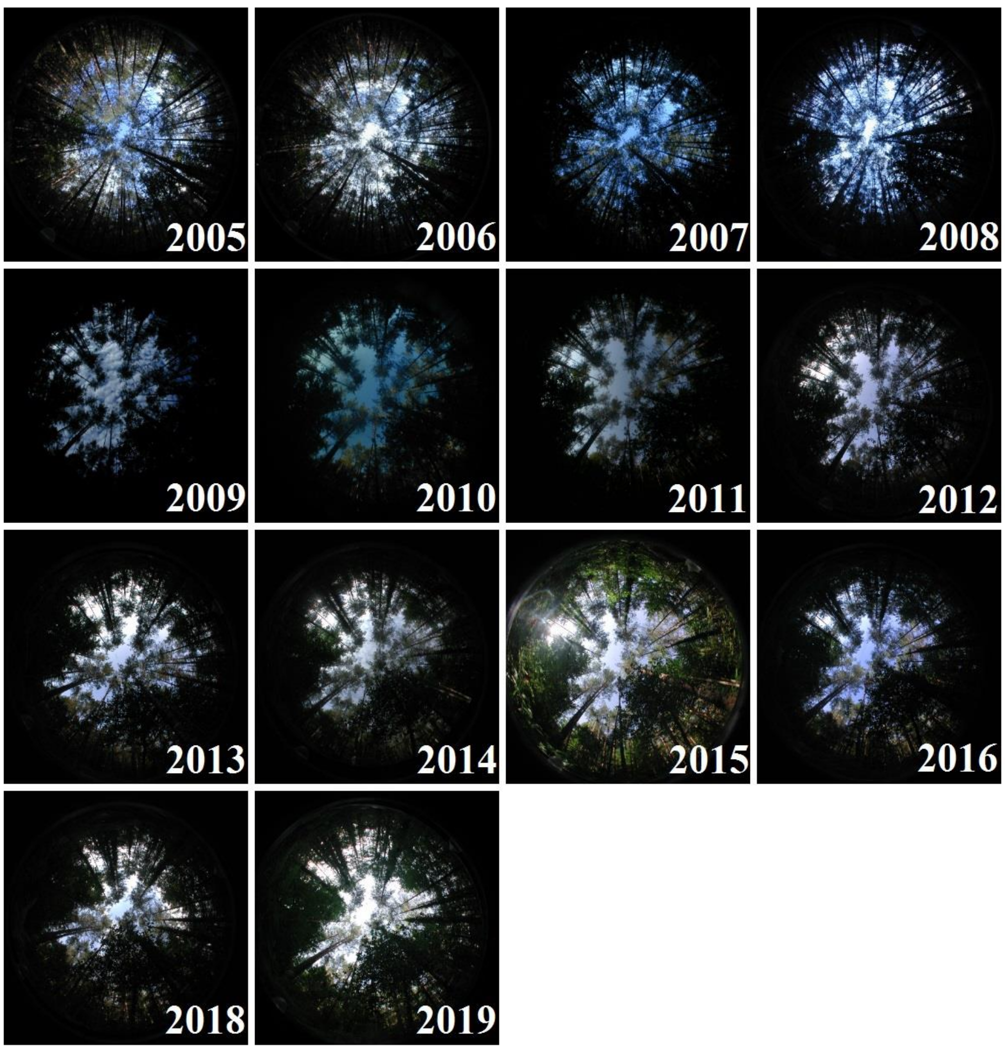

Figure S1. Example of raw (unprocessed) hemispherical photographs (HP). Here we only show a sample of a HP for the sampling point 7 in plot 7 (heavy thinning). Dark areas correspond to the vegetation whereas lighter areas to the vegetation and sky.

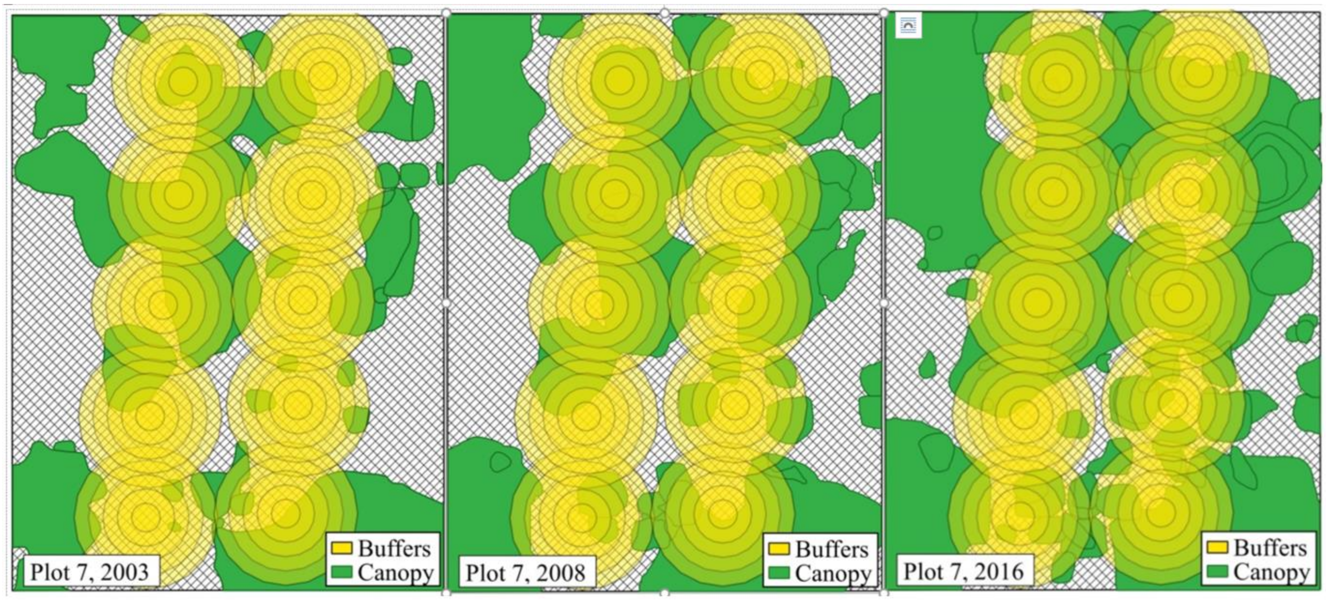

Figure S2. Example of maps of the broadleaved canopies and buffer areas around each sampling point for the years 2003, 2008 and 2016 and for the plot 7 (heavy thinning). Broadleaved canopy (represented by green polygons) were assumed to be under a continuous and homogenous layer of Scots pine (top canopy). Areas of increasing radius (buffer) around each sampling point where hemispherical photographs were taken as shown as yellow circles. In order to avoid calculation errors, those buffer areas exceeding the plot limits were cut to fit each plot limits. Calculations were performed with GIS software (QGIS Desktop, version 3.12.3).

Table S1. Pair-correlation between light variables, averaged across our studied years. Cross-correlation values between pairs of variables higher than 0.7 are highlighted in red. Empty values showed variables with a fixed value for the whole site, and were not included in calculations. In particular, *DirectAbove* and *DiffAbove* is a light index that depends exclusively on each location and was not variable.

	CanOpen	LAI	DirectAbove	DiffAbove	DirectBelow	DiffBelow	N.Sunflecks	Mdn.Sunflecks	Max.Sunflecks	DirectAbove.Yr	DiffAbove.Yr	DirectBelow.Yr	DiffBelow.Yr
CanOpen		-0.03			0.44	0.86	0.33	0.07	0.16			0.33	0.86
LAI					-0.18	-0.30	-0.26	0.00	0.10			-0.23	-0.30
DirectAbove													
DiffAbove													
DirectBelow						0.55	0.71	0.33	0.66			0.58	0.55
DiffBelow							0.40	0.13	0.26			0.44	1.00
N.Sunflecks								-0.08	0.18			0.49	0.40
Mdn.Sunflecks									0.29			0.11	0.13
Max.Sunflecks												0.30	0.26
DirectAbove.Yr													
DiffAbove.Yr													
DirectBelow.Yr													0.44
DiffBelow.Yr													

Table S2. Results of the Ljung-Box test for independence analysis of light variables. For each variable, tow which *p-values* suggest non-stationary time series. Calculations were performed with the "*stats*" library and the "*box.test*" function in R statistical language (R Core Team, 2020).

Variable	x-squared	df	p-value
CanOpen	15.03	14	0.38
LAI	13.50	14	0.49
DirectBelow.Yr	14.44	14	0.42
N.Sunflecks	24.16	14	0.04
Mdn.Sunflecks	7.99	14	0.89
Max.Sunflecks	6.10	14	0.96

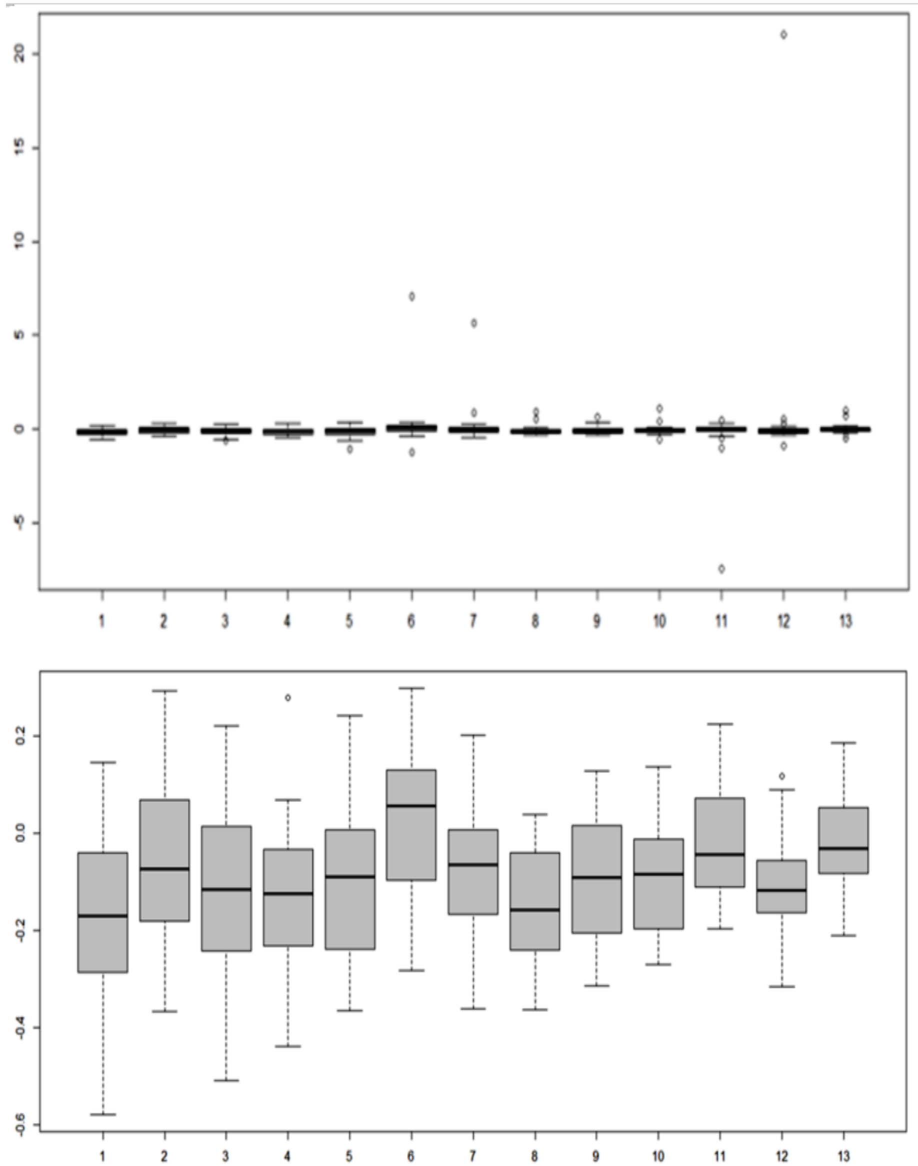

Figure S3. Boxplot of value of LAI values, representing lags in the horizontal axis, from 2006 to 2019 (data for the year 2017 were lost), for a tolal of 13 years since the first year does not count for the analysis (it starts in lag1). To check the effect of latter imputation on the time series, we checked the PACF values prior and post imputations with the aim to weight the importance of outliers in the PACF. When checking the boxplots without mean imputation, outliers weight for the years 2012 (where NAs values was high), 2013 (following a year with little data), and 2018 (followed by a year with missing data, and 2018 having some missing data as well), was too high. This affected further PACF analysis, and induced to think that our results were biased due to NAs weight. On the other side, boxplots with corrected mean were correct and provided stability for the further analysis. Mean was calculated and imputed for each thinning treatment in each year.

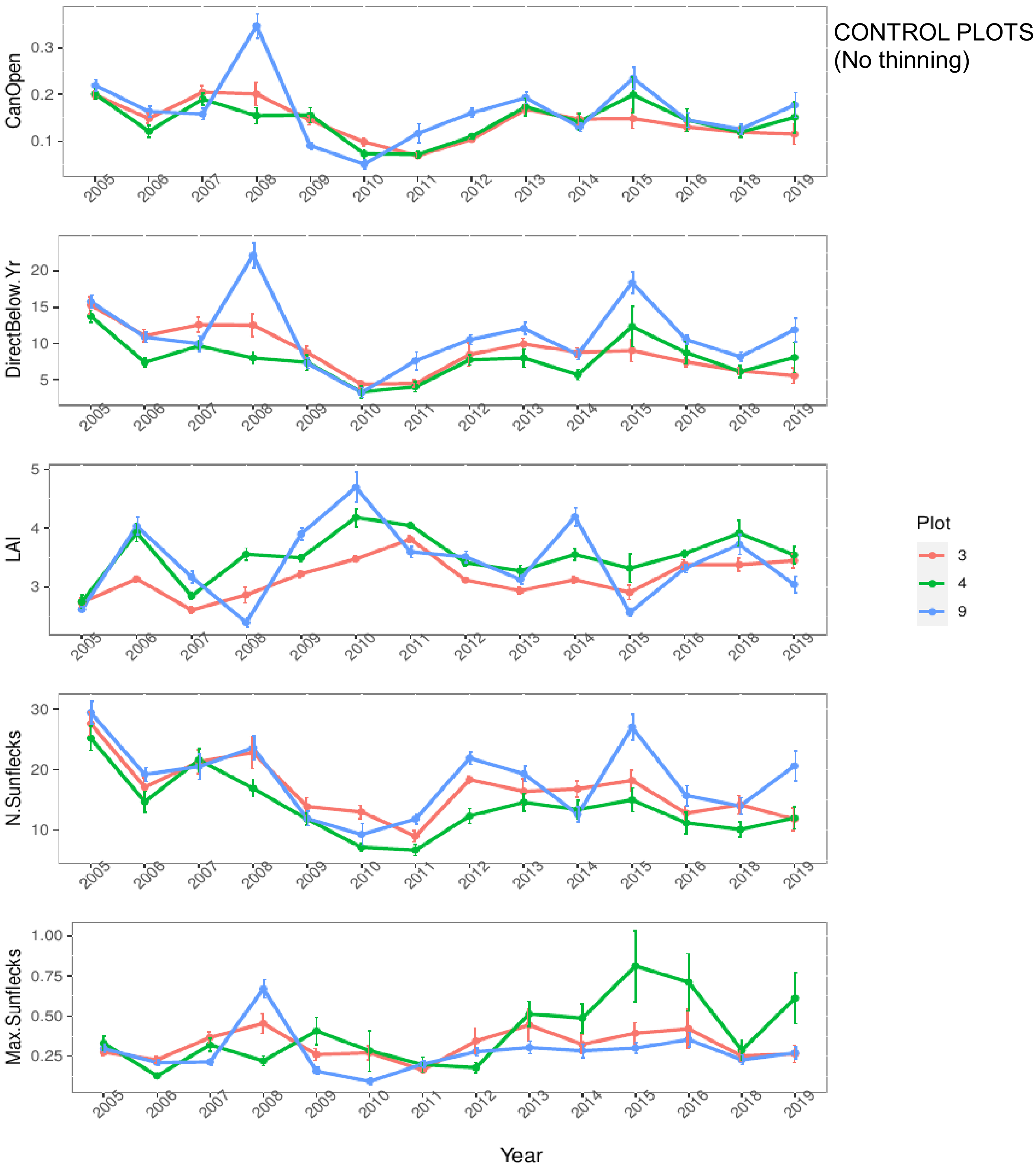

Figure S4. Light variables obtained from the hemispherical pictures over the studied years at the control plots. Each line corresponds to a different plot (identified by its number, see Figure 1 in the manuscript). For each light variable and plot, horizontal lines represent the mean values for each year whereas the vertical lines the standard error for each year. *CanOpen* (parts per unit); LAI (m^2 m^{-2}); *DirectBelow.Yr* (µmol m^{-2} s^{-1}); *N.Sunflecks* (µmol m^{-2} s^{-1}); *Max.Sunflecks* (minutes).

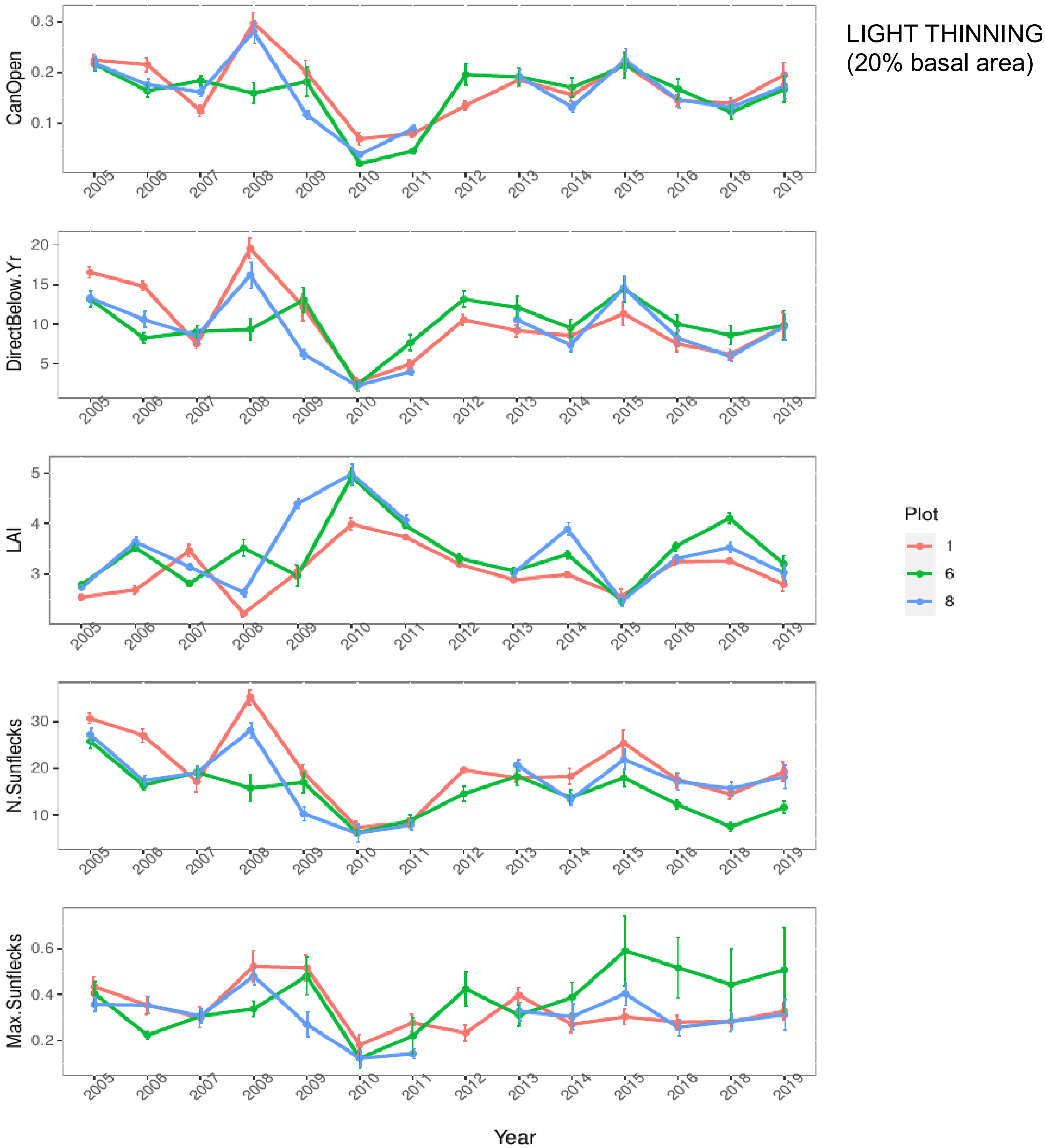

Figure S5. Light variables obtained from the hemispherical pictures over the studied years at the light thinning plots (20% basal area removed in 1999 and 2009). Each line corresponds to a different plot (identified by its number, see Figure 1 in the manuscript). For each light variable and plot, horizontal lines represent the mean values for each year whereas the vertical lines the standard error for each year. *CanOpen* (parts per unit); LAI (m^2 m^{-2}); *DirectBelow.Yr* (μmol m^{-2} s^{-1}); *N.Sunflecks* (μmol m^{-2} s^{-1}); *Max.Sunflecks* (minutes).

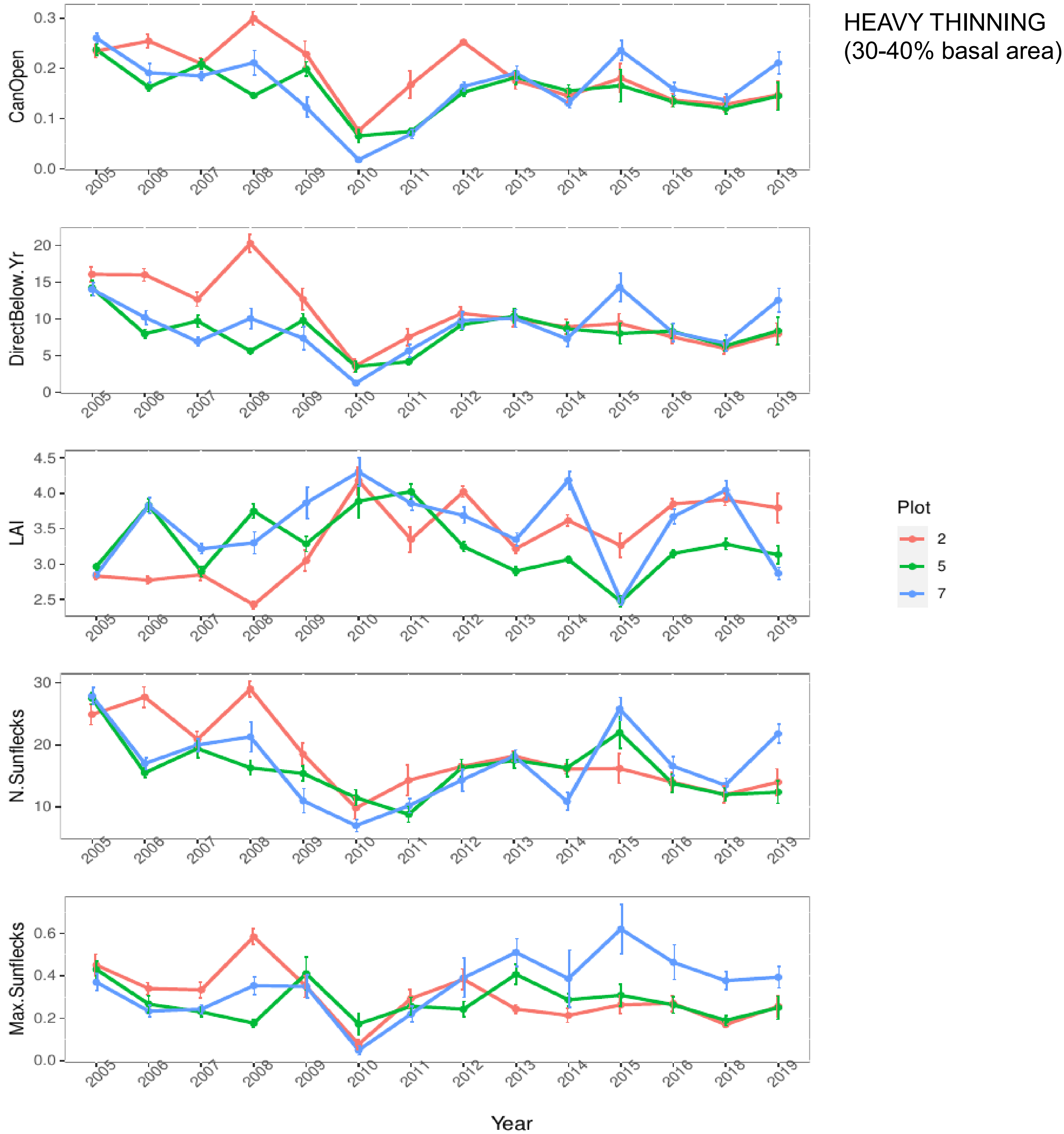

Figure S6. Light variables obtained from the hemispherical pictures over the studied years at the control plots (30% and 40% basal area removed in 1999 and 2009, respectively). Each line corresponds to a different plot (identified by its number, see Figure 1 in the manuscript). For each light variable and plot, horizontal lines represent the mean values for each year whereas the vertical lines the standard error for each year. *CanOpen* (parts per unit); LAI (m^2 m^{-2}); *DirectBelow.Yr* (μmol m^{-2} s^{-1}); *N.Sunflecks* (μmol m^{-2} s^{-1}); *Max.Sunflecks* (minutes).

Table S3. Results of pairwise contrasts between consecutive years for light variables. The number in the "treatment" and "plot" lines indicate the total number of significant pairwise contrasts obtained for the whole monitoring period, whereas the number between brackets besides each year indicates the number of significant pairwise contrast in which that year was involved. Only the five years with the highest number of significant contrasts are shown for each variable.

	CanOpen	LAI	DirectBelow.Yr	N.Sunflecks	Max.Sunflecks
Treatment	15	32	15	14	4
	2009 (8)	2015 (11)	2009 (8)	2008 (6)	2010 (4)
	2008 (5)	2009 (9)	2010 (5)	2009 (6)	2009 (3)
	2010 (4)	2006 (9)	2015 (5)	2005 (3)	2011 (1)
	2005 (2)	2010 (7)	2008 (4)	2006 (3)	-
	2006 (2)	2005 (7)	2016 (3)	2011 (2)	-
Plot	33	126	34	12	3
	2008 (22)	2009 (44)	2008 (26)	2008 (11)	2010 (3)
	2009 (19)	2010 (43)	2009 (14)	2009 (8)	2009 (2)
	2010 (11)	2015 (31)	2007 (10)	2014 (2)	2011 (1)
	2007 (8)	2014 (28)	2010 (5)	2015 (2)	-
	-	2008 (23)	2015 (5)	2007 (1)	-

Table S4. Results of pairwise contrasts between consecutive years for PACFs. The number in the "treatment" and "plot" lines indicate the total number of significant pairwise contrasts obtained for the whole monitoring period, whereas the number between brackets besides each year indicates the number of significant pairwise contrast in which that year was involved. Only the five years with the highest number of significant contrast are shown for each variable.

	CanOpen	LAI	DirectBelow.Yr	N.Sunflecks	Max.Sunflecks
Treatment	24	5	27	5	5
	2006 (14)	2006 (4)	2006 (12)	2012 (6)	2006 (4)
	2011 (9)	2005 (2)	2005 (9)	2005 (3)	2005 (3)
	2012 (9)	2007 (2)	2011 (9)	2006 (3)	2007 (2)
	2005 (5)	2011 (1)	2012 (8)	2007 (1)	2008 (1)
	2007 (3)	-	2010 (5)	2008 (1)	-
Plot	71	27	75	1	5
	2006 (42)	2006 (15)	2006 (38)	2005 (1)	2005 (5)
	2005 (39)	2007 (11)	2005 (28)	2006 (1)	2006 (4)
	2011 (23)	2005 (6)	2011 (19)	-	2007 (1)
	2012 (22)	2008 (6)	2007 (18)	-	-
	2009 (3)	2009 (5)	2012 (16)	-	-

Table S5. Results of univariate GLMMs showing the relationship between (a) thinning treatment or (b) plots as fixed (independent) factors to explain *CanOpen*. In both groups of models, we included year as fixed factor. In both models, sampling point (S.Point) was included as within-subject random factor. In bold, significant probability (P<0.05).

a) Results including Thinning treatment

Variability source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Thinning	2	0.048	0.024	0.681	0.509
Year	2	0.110	0.055	1.560	0.216
Thinning:Year	3	0.024	0.008	0.225	0.879
Residuals	82	2.901	0.035		
Error: S.Point					

Variability source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Year	13	2.698	0.208	65.908	**<0.001**
Thinning:Year	26	0.189	0.007	2.312	**<0.001**
Residuals	1078	3.395	0.003		
Error: S.Point:Year					

b) Results including Plot

Variability source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Plot	8	0.174	0.022	0.616	0.762
Year	2	0.101	0.050	1.425	0.247
Plot:Year	6	0.235	0.039	1.113	0.363
Residuals	73	2.573	0.035		
Error: S.Point					

Variability source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Year	13	2.698	0.208	81.021	**<0.001**
Plot:Year	103	1.020	0.010	3.865	**<0.001**
Residuals	1001	2.564	0.003		
Error: S.Point:Year					

Table S6. Results of univariate GLMMs showing the relationship between (a) thinning treatment or (b) plots as fixed (independent) factors to explain *LAI*. In both groups of models, we included year as fixed factor. In both models, sampling point (S.Point) was included as within-subject random factor. In bold, significant probability (P<0.05).

a) Results including Thinning treatment

Variability source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Thinning	2	3.190	1.596	2.070	0.134
Year	8	8.640	1.080	1.400	0.211
Thinning:Year	7	8.170	1.167	1.513	0.177
Residuals	72	55.520	0.771		
Error: S.Point					

Variability source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Year	13	200.600	15.432	54.720	**<0.001**
Thinning:Year	26	15.400	0.592	2.100	**0.001**
Residuals	1050	296.100	0.282		
Error: S.Point:Year					

b) Results including Plot

Variability source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Plot	8	26.840	3.355	6.288	**<0.001**
Year	8	4.260	0.533	0.998	0.447
Plot:Year	11	11.350	1.032	1.933	0.052
Residuals	62	33.080	0.534		
Error: S.Point					

Variability source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Year	13	200.600	15.432	76.630	**<0.001**
Plot:Year	103	115.500	1.122	5.571	**<0.001**
Residuals	973	195.900	0.201		
Error: S.Point:Year					

Table S7. Results of univariate GLMMs showing the relationship between (a) thinning treatment or (b) plots as fixed (independent) factors to explain *DirectBelow.Yr*. In both groups of models, we included year as fixed factor. In both models, sampling point (S.Point) was included as within-subject random factor. In bold, significant probability (P<0.05).

a) Results including Thinning treatment

Variability source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Thinning	2	51.000	25.480	0.168	0.846
Year	2	254.000	126.860	0.836	0.437
Thinning:Year	3	529.000	176.270	1.161	0.330
Residuals	82	12444.000	151.760		
Error: S.Point					

Variability source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Year	13	11291.000	868.600	54.350	**<0.001**
Thinning:Year	26	588.000	22.600	1.414	0.082
Residuals	1078	17227.000	16.000		
Error: S.Point:Year					

b) Results including Plot

Variability source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Plot	8	1395.000	174.320	1.132	0.352
Year	2	28.000	13.980	0.091	0.913
Plot:Year	6	619.000	103.170	0.670	0.674
Residuals	73	11236.000	153.920		
Error: S.Point					

Variability source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Year	13	11291.000	868.600	68.590	**<0.001**
Plot:Year	103	5139.000	49.900	3.940	**<0.001**
Residuals	1001	12676.000	12.700		
Error: S.Point:Year					

Table S8. Results of univariate GLMMs showing the relationship between (a) thinning treatment or (b) plots as fixed (independent) factors to explain *N.Sunflecks*. In both groups of models, we included year as fixed factor. In both models, sampling point (S.Point) was included as within-subject random factor. In bold, significant probability (P<0.05).

a) Results including Thinning treatment

Variability source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Thinning	2	288.000	144.200	0.751	0.475
Year	7	2303.000	329.000	1.714	0.119
Thinning:Year	5	293.000	58.500	0.305	0.909
Residuals	75	14399.000	192.000		
Error: S.Point					

Variability source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Year	13	28109.000	2162.200	52.030	**<0.001**
Thinning:Year	26	1560.000	60.000	1.444	0.070
Residuals	1037	43095.000	41.600		
Error: S.Point:Year					

b) Results including S.Point

Variability source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Plot	8	3491.000	436.400	2.895	**0.009**
Year	7	1620.000	231.500	1.535	0.173
Plot:Year	14	3124.000	223.200	1.480	0.147
Residuals	60	9047.000	150.800		
Error: S.Point					

Variability source	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Year	13	28109.000	2162.200	57.723	**<0.001**
Plot:Year	103	8694.000	84.400	2.253	**<0.001**
Residuals	960	35961.000	37.500		
Error: S.Point:Year					

Table S9. Results of univariate GLMMs showing the relationship between (a) thinning treatment or (b) plots as fixed (independent) factors to explain *Max.Sunflecks*. In both groups of models, we included year as fixed factor. In both models, sampling point (S.Point) was included as within-subject random factor. In bold, significant probability (P<0.05).

a) Results including Thinning treatment

Variability source	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Thinning	2	0.170	0.085	0.284	0.753
Year	7	1.798	0.257	0.856	0.545
Thinning:Year	7	2.882	0.412	1.373	0.230
Residuals	73	21.890	0.300		
Error: S.Point					

Variability source	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Year	13	7.150	0.550	8.854	**<0.001**
Thinning:Year	26	2.000	0.077	1.239	0.190
Residuals	1067	66.300	0.062		
Error: S.Point:Year					

b) Results including S.Point

Variability source	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Plot	8	1.863	0.233	0.748	0.649
Year	7	2.446	0.350	1.122	0.360
Plot:Year	9	2.192	0.244	0.782	0.634
Residuals	65	20.240	0.311		
Error: S.Point					

Variability source	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Year	13	7.150	0.550	9.401	**<0.001**
Plot:Year	103	10.370	0.101	1.720	**<0.001**
Residuals	960	35961.000	37.500		
Error: S.Point:Year					

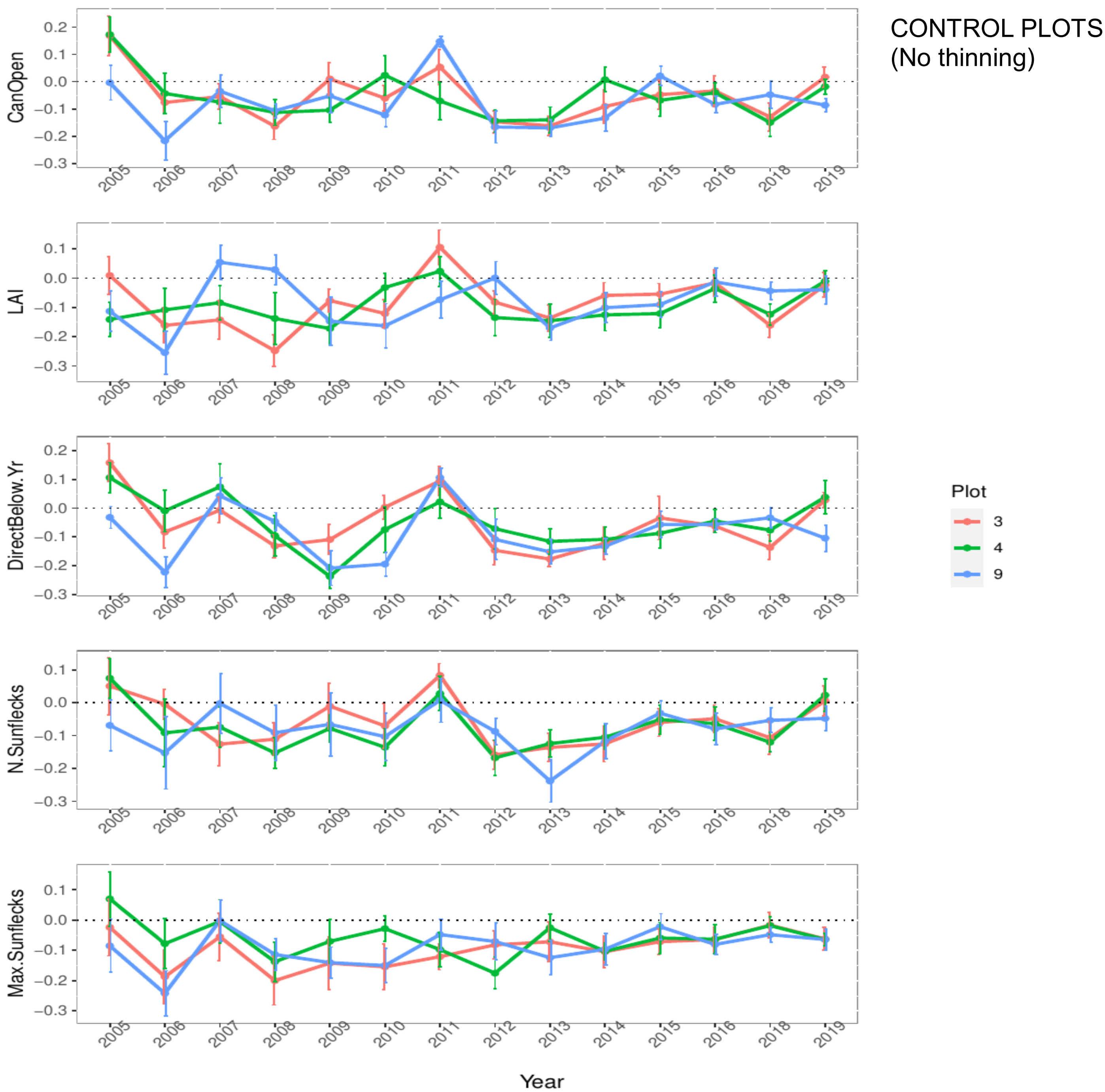

Figure S7. PACF for the light variables along the study years in the control plots. The vertical axis represents the values the PACF, and the horizontal axis represents the years. Each line corresponds to a different plot (see Figure 1 in the manuscript). For the vertical axis, values close to zero (dashed lines) show that there is no temporal autocorrelation of the values of each light variable in respect to the previous year, whereas values close to 1.0 or -1.0 indicates positive or negative autocorrelation values, respectively. For each light variable and plot, horizontal lines represent the mean values for each year whereas the vertical lines the standard error for each year.

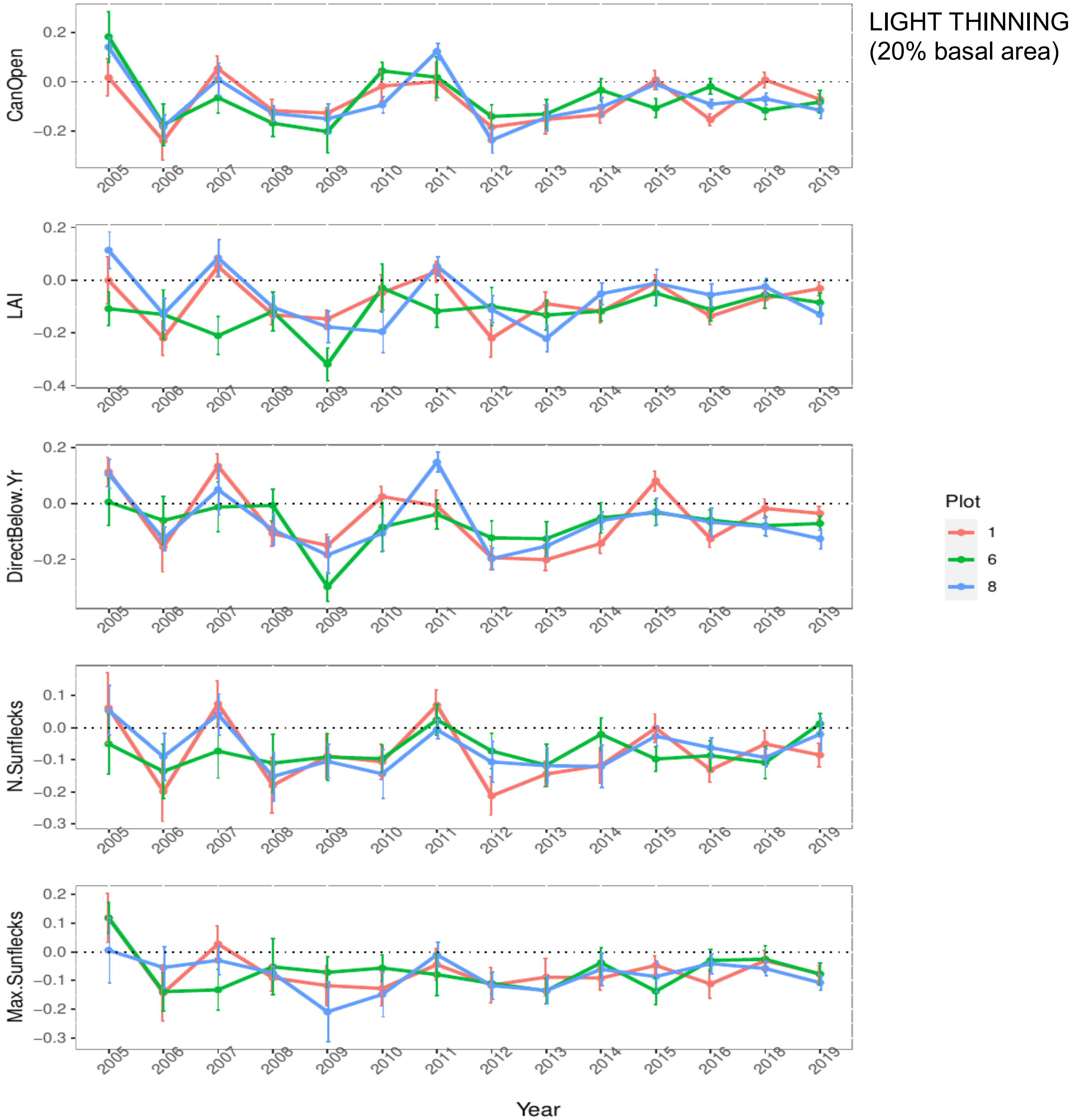

Figure S8. PACF for the light variables along the study years in the light thinning plots. The vertical axis represents the values the PACF, and the horizontal axis represents the years. Each line corresponds to a different plot (see Figure 1 in the manuscript). For the vertical axis, values close to zero (dashed lines) show that there is no temporal autocorrelation of the values of each light variable in respect to the previous year, whereas values close to 1.0 or -1.0 indicates positive or negative autocorrelation values, respectively. For each light variable and plot, horizontal lines represent the mean values for each year whereas the vertical lines the standard error for each year.

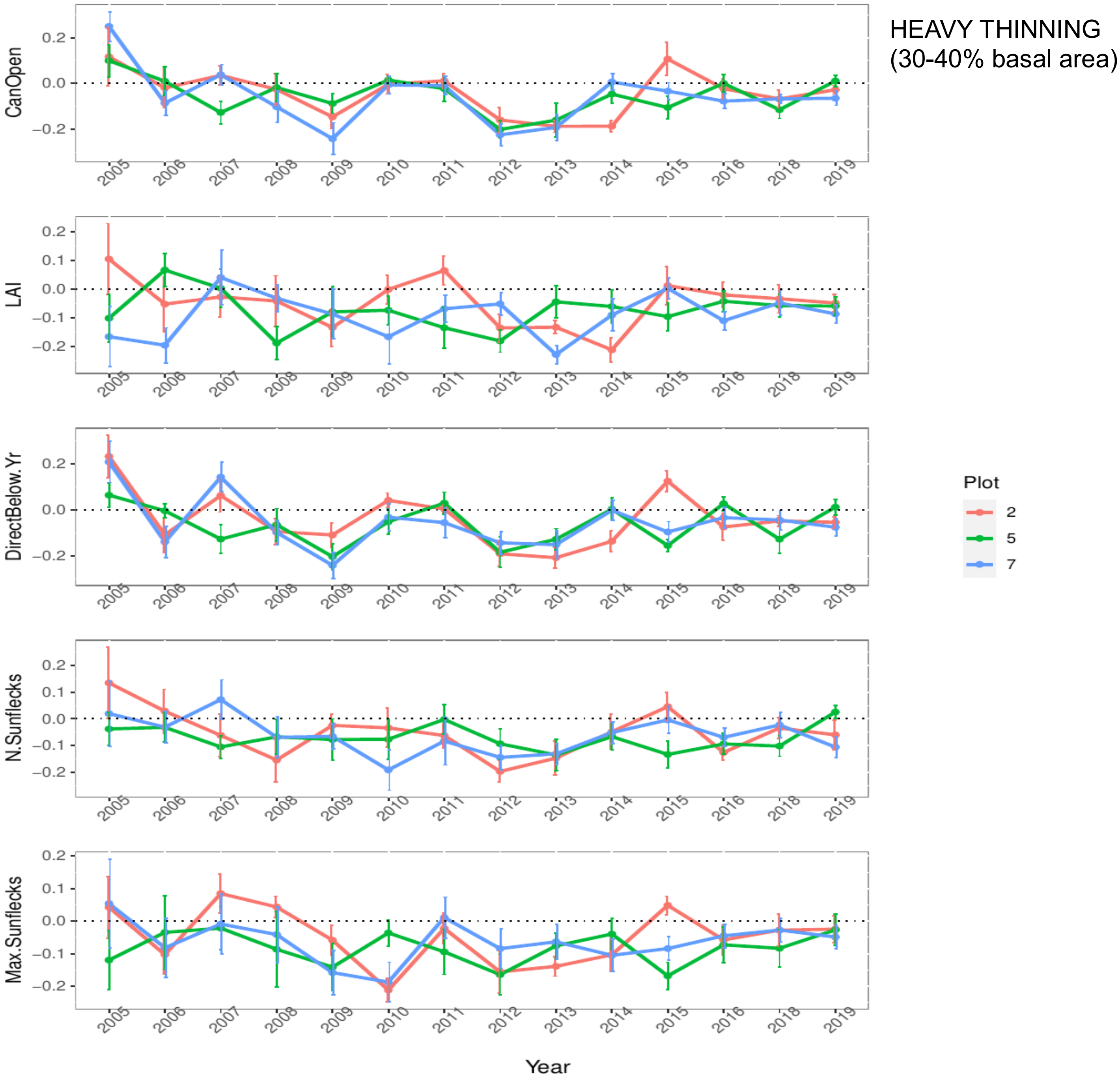

Figure S9. PACF for the light variables along the study years in the heavy thinning plots. The vertical axis represents the values the PACF, and the horizontal axis represents the years. Each line corresponds to a different plot (see Figure 1 in the manuscript). For the vertical axis, values close to zero (dashed lines) show that there is no temporal autocorrelation of the values of each light variable in respect to the previous year, whereas values close to 1.0 or -1.0 indicates positive or negative autocorrelation values, respectively. For each light variable and plot, horizontal lines represent the mean values for each year whereas the vertical lines the standard error for each year.

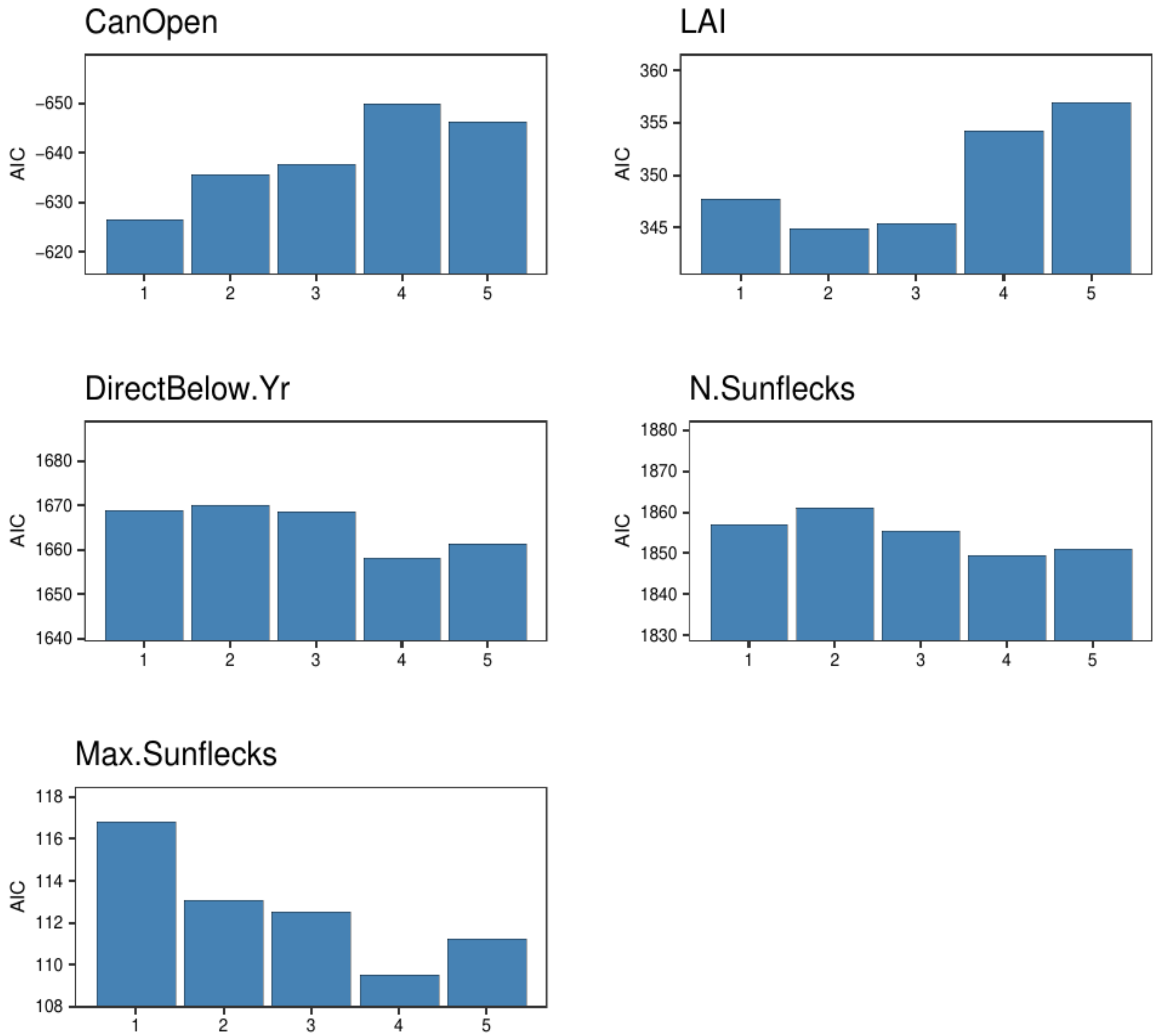

Figure S10. Performance of the "best models" explaining the light variables by the proportion of forest canopy and richness at increasing areas or buffers. For each panel, the horizontal axis represent the amount of area extracting the proportion of forest canopy and richness, which ranged from 1.0 to 5.0 m from the centroid of each sampling point, whereas the vertical axis represent the performance (in AIC values) to explain the "best model" which accounted for the lower complexity and higher fit of the model to the data (see Material and Methods in the manuscript for details). For each light variable, we considered the model with the highest performance models as that with the lowest AIC values.

Table S10. Co-variance of canopy structural variables, showing correlations between broadleaves canopy cover and riches for the different years of the study and considering different buffer areas around each sampling point.

Year	Plot	Radius around sampling point				
		1 m	2 m	3 m	4 m	5 m
2003	1	0.883	0.699	0.453	0.368	0.019
2003	2	0.961	0.781	0.547	0.439	0.671
2003	3	0.883	0.811	0.767	0.741	0.610
2003	4	0.693	0.472	0.085	-0.141	-0.540
2003	5	0.770	0.699	0.782	0.270	0.377
2003	6	0.877	0.534	0.500	0.729	0.673
2003	7	0.961	0.234	0.125	-0.534	-0.405
2003	8	0.883	0.469	-0.337	-0.389	-0.407
2003	9	0.929	0.699	0.542	0.445	0.646
2008	1	0.814	0.374	0.317	0.362	0.087
2008	2	0.869	0.618	0.667	0.241	0.094
2008	3	0.862	0.811	0.953	0.802	0.559
2008	4	0.866	0.676	0.178	0.248	-0.275
2008	5	0.967	0.801	0.801	0.480	0.125
2008	6	0.560	0.084	0.451	0.655	0.305
2008	7	0.338	0.142	-0.117	-0.108	0.172
2008	8	0.701	0.453	0.025	-0.137	-0.356
2008	9	0.928	0.880	0.808	0.529	0.269
2016	1	0.524	0.547	0.288	0.485	0.141
2016	2	0.877	0.781	0.650	0.702	0.537
2016	3	0.840	0.459	-0.234	-0.190	0.000
2016	4	0.835	0.644	0.619	-0.144	0.194
2016	5	0.780	0.486	0.608	0.514	0.038
2016	6	0.711	-0.130	0.329	-0.054	0.104
2016	7	0.190	-0.163	-0.138	-0.298	0.180
2016	8	0.816	0.388	-0.321	-0.663	-0.671
2016	9	0.699	0.498	-0.326	-0.317	-0.062

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