Supplemental Materials

Title: The carbon economics of vegetative phase change

Authors: Erica H. Lawrence, Clint J. Springer, Brent R. Helliker and R. Scott Poethig

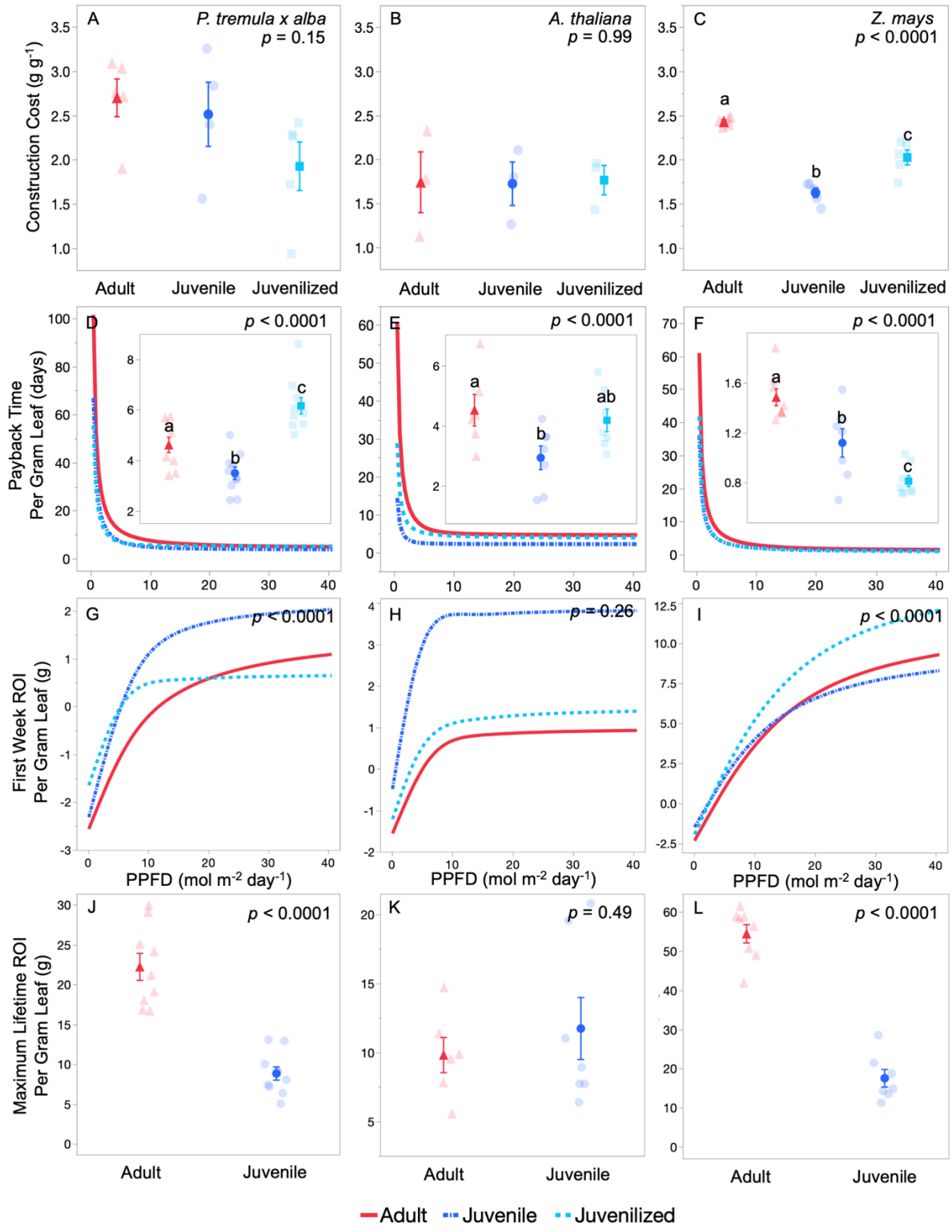

Figure S1. Payback time per gram of leaf tissue (A-C), and return on investment (ROI) per gram of leaf tissue in grams of glucose (D-F) for adult (red solid lines), juvenile (blue dash-dotted lines), and juvenilized (light blue dashed lines) leaves of *P. tremula x alba* (A, D), *A. thaliana* (B, E), and *Z. mays* (C, F). Payback time and ROI are modeled using photosynthetic light response parameters and 12-hour light periods with constant PAR levels between 10 and 2000 μmol m^2 s^1 and are plotted against the resulting daily integrated photosynthetic photon flux density (PPFD). *P*-values determined by ANCOVA.

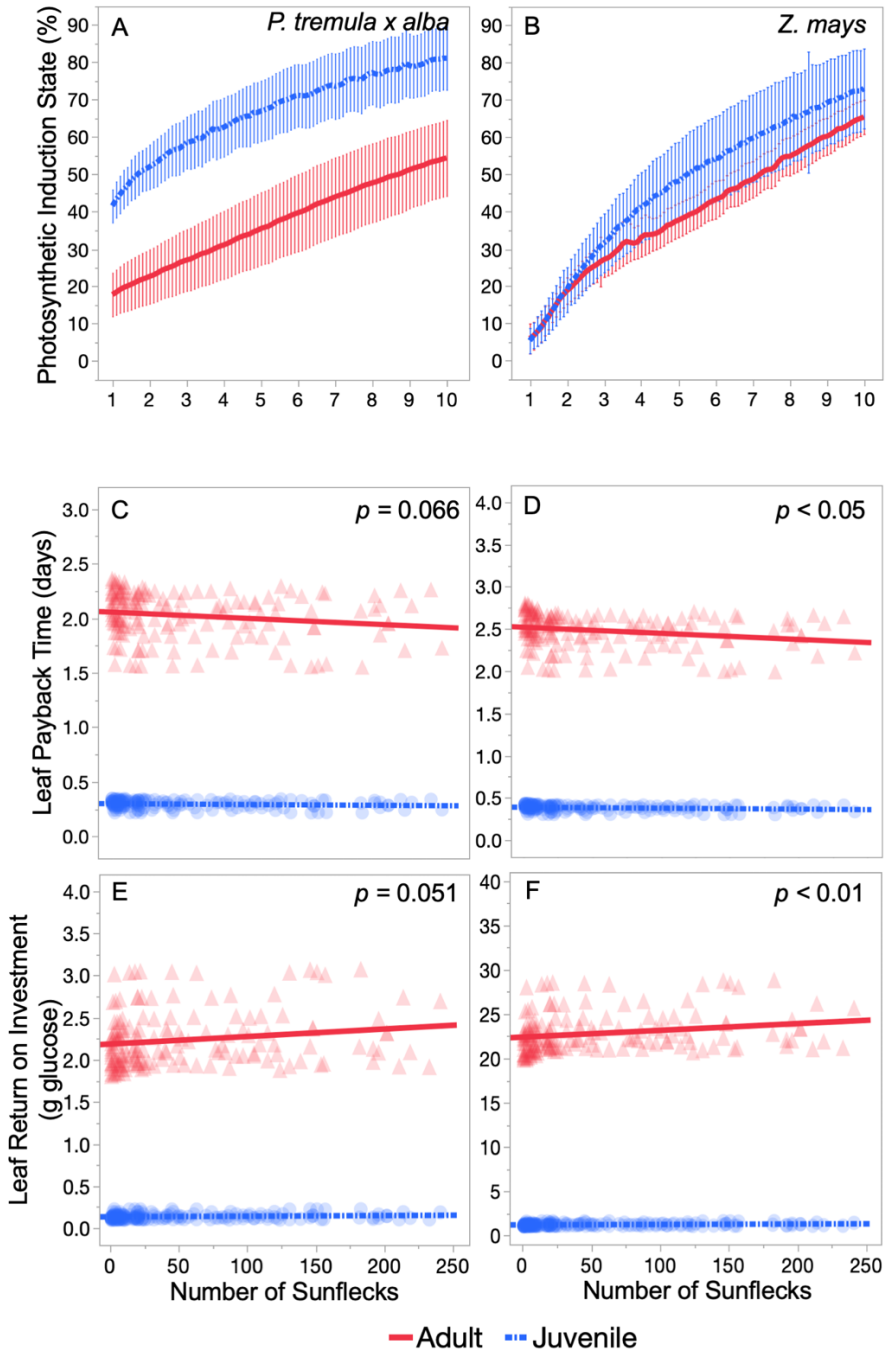

Figure S3. Photosynthetic induction state during minutes 1-10 of exposure to saturating light (A, B), leaf payback time (C, D) and leaf lifetime return on investment (E, F) for adult (solid, red) and juvenile (dash-dotted, blue) leaves of *P. tremula x alba* (A, C, E) and *Z. mays* (B, D, F) for adult (red triangles and solid lines) and juvenile (blue circles and dash-dotted lines). Payback time and ROI modeled from simulated dynamic light environments plotted against daily number of sunflecks. Photosynthetic induction data presented as the mean ± s.e.m and payback time and ROI data presented as individual replicates by transparent symbols and linear line of best-fit. *P*-values determined by *ANCOVA*.

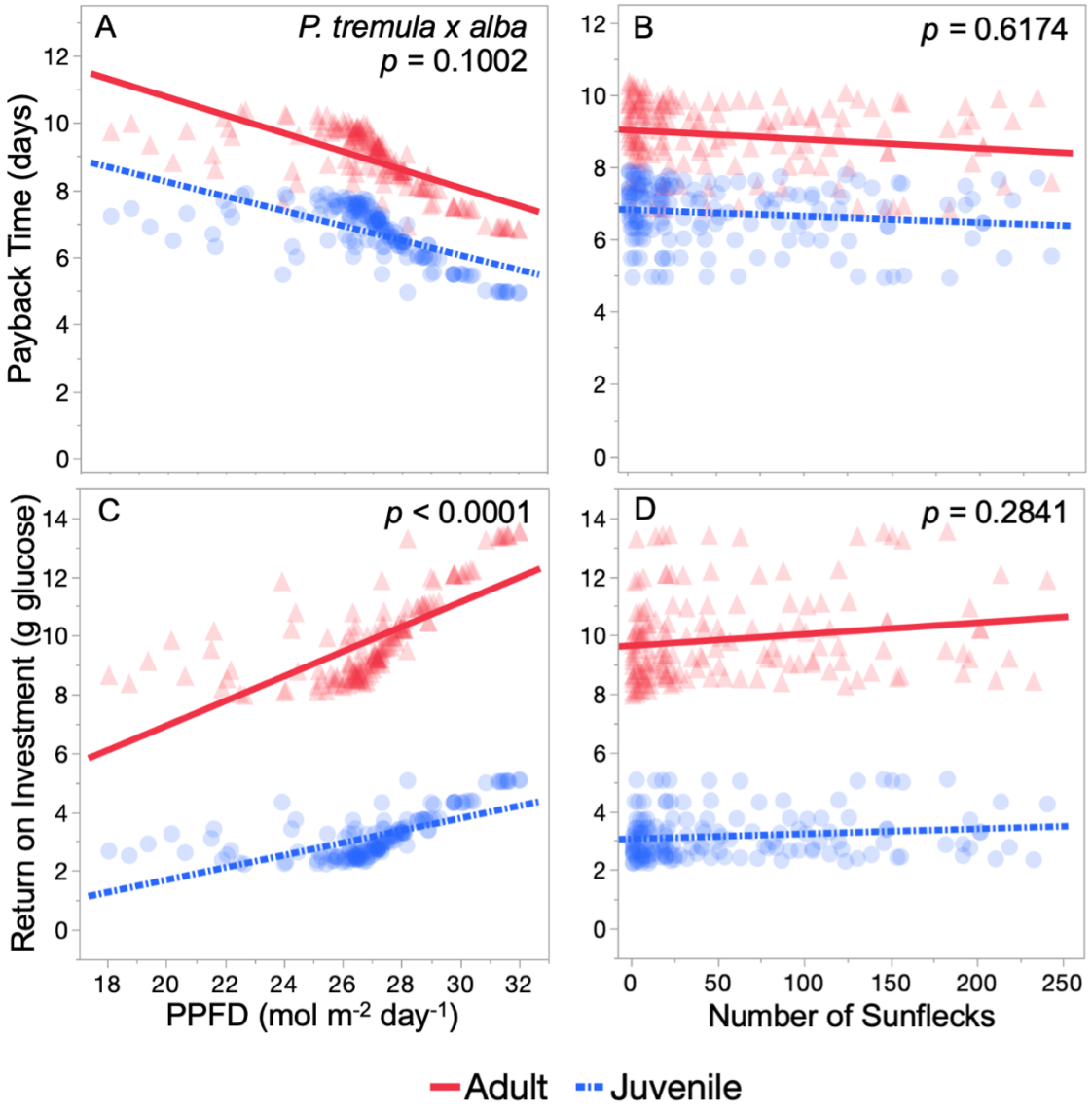

Figure S4. Payback time per gram of leaf tissue (A-B) and lifetime return on investment per gram of leaf tissue (C-D) for adult (red triangles and solid lines) and juvenile (blue circles and dash-dotted lines) leaves from simulated dynamic light environments in *P. tremula x alba* plotted against daily integrated PPFD (A, C) and number of sunflecks across the day (B, D). Data presented as individual replicates by transparent symbols and linear line of best-fit. *P*-values determined by ANCOVA.

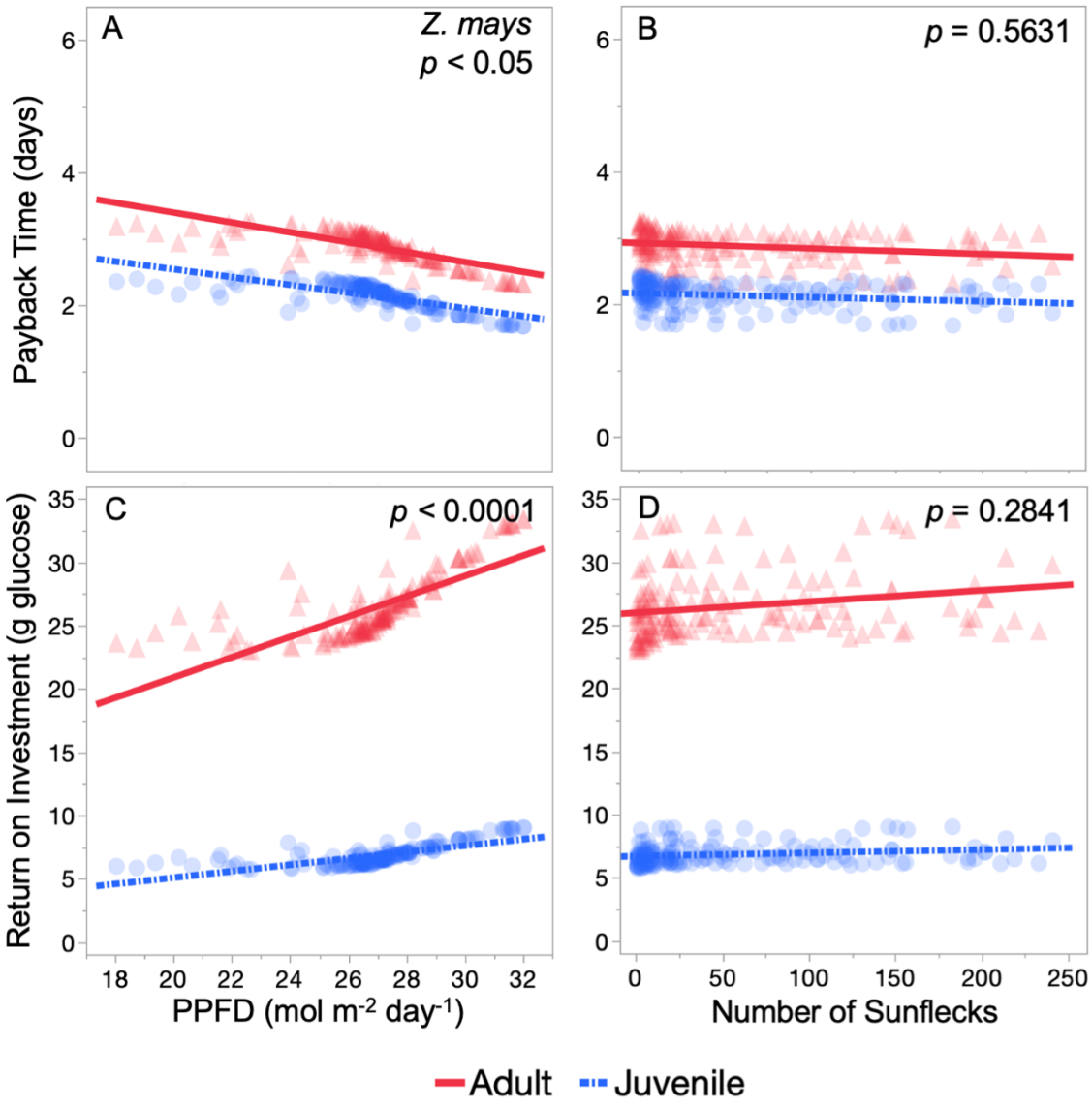

Figure S5. Payback time per gram of leaf tissue (A-B) and lifetime return on investment per gram of leaf tissue (C-D) for adult (red triangles and solid lines) and juvenile (blue circles and dash-dotted lines) leaves from simulated dynamic light environments in *Z. mays* plotted against daily integrated PPFD (A, C) and number of sunflecks across the day (B, D). Data presented as individual replicates by transparent symbols and linear line of best-fit. *P*-values determined by ANCOVA.

Table S1. Leaf morphological traits for adult, juvenile and juvenilized leaves of *P. tremula x alba, A. thaliana, and Z. mays.* Parameters presented as the median with interquartile range in parenthesis. Where one-way ANOVA showed significant differences (p<0.05), a Student's t test was performed to determine significant differences between developmental groups (p<0.05), shown by different lowercase letters. SLA = specific leaf area, LMA = leaf mass per area.

Species	Development	Leaf Area (cm^2)	Leaf Mass (mg)	SLA ($cm^2\ g^{-1}$)	LMA ($mg\ cm^{-2}$)	n
P. tremula x alba	Adult	69.06 (12.65)^a	226.85 (53.40)^a	330.04 (103.66)^c	3.04 (0.90)^a	10
	Juvenile	20.05 (14.49)^c	43.81 (64.16)^c	547.48 (94.41)^a	1.83 (0.31)^c	10
	Juvenilized	57.27 (11.16)^b	119.34 (30.83)^b	467.58 (63.04)^b	2.14 (0.29)^b	10
A. thaliana	Adult	1.32 (0.41)^a	3.28 (1.66)^a	432.99 (156.24)^c	2.35 (0.95)^a	6
	Juvenile	0.88 (0.40)^b	0.74 (0.39)^b	1212.61 (522.06)^a	0.82 (0.53)^c	7
	Juvenilized	0.75 (0.27)^b	1.21 (0.59)^b	615.51 (144.35)^b	1.62 (0.34)^b	7
Z. mays	Adult	436.13 (56.28)^a	861.95 (465.63)^a	476.50 (75.26)^c	2.10 (0.31)^a	8
	Juvenile	95.18 (18.22)^b	179.40 (46.63)^b	516.61 (110.71)^b	1.94 (0.38)^b	7
	Juvenilized	65.89 (25.18)^c	108.09 (73.00)^c	710.73 (84.33)^a	1.41 (0.16)^c	8

Table S2. Light response curve parameters for adult, juvenile and juvenilized leaves of *P. tremula x alba, A. thaliana, and Z. mays.* Parameters are light saturated net photosynthetic rate (A_{sat}), light use efficiency (Phi), dark respiration (Rd), and curvature (theta). Parameters presented as the median with interquartile range in parenthesis. Where one-way ANOVA showed significant differences (p<0.05), a Student's t test was performed to determine significant differences between developmental groups (p<0.05), shown by different lowercase letters.

Species	Development	Asat ($\mu mol\ m^{-2}\ s^{-1}$)	Phi	Rd ($\mu mol\ m^{-2}\ s^{-1}$)	Theta	n
P. tremula x alba	Adult	15.72 (2.48)^a	0.07 (0.02)	0.40 (0.20)^b	0.50 (0.18)^b	6
	Juvenile	11.5 (3.42)^b	0.06 (0.06)	0.94 (0.21)^c	0.79 (0.05)^a	5
	Juvenilized	6.02 (1.38)^c	0.05 (0.01)	0.12 (0.18)^a	0.88 (0.19)^a	6
A. thaliana	Adult	7.47 (1.60)^a	0.05 (0.02)	0.38 (0.33)	0.89 (0.04)	7
	Juvenile	5.19 (2.69)^b	0.07 (0.07)	0.83 (1.63)	0.89 (0.36)	7
	Juvenilized	5.86 (0.46)^b	0.08 (0.02)	0.71 (1.28)	0.62 (0.28)	6
Z. mays	Adult	28.10 (2.90)^{ab}	0.06 (0.01)	1.04 (0.44)	0.78 (0.12)	12
	Juvenile	24.07 (5.81)^b	0.07 (0.01)	0.84 (0.48)	0.65 (0.22)	15
	Juvenilized	30.70 (5.74)^a	0.07 (0.01)	0.97 (0.65)	0.68 (0.10)	10

Table S3. Light induction parameters for adult and juvenile leaves of *P. tremula x alba* and *Z. mays*. Relaxation time for Rubisco activation (tau) determined from the slope of the linear relationship between $\ln(A_f^* - A^*)$ vs. time during minutes 1-10 of induction described in the table below. Data presented as the median with interquartile range in parenthesis. A student's *t* test was performed to determine significant differences between developmental groups ($p<0.05$), the intercept in *P. tremula x alba* was the only significantly different trait.

Species	Development	tau (min)	slope	intercept	R^2	n
P. tremula x alba	Adult	11.40 (12.41)	-1.58e-3 (1.59e-3)	2.61 (0.34)	0.98 (0.04)	6
	Juvenile	5.73 (0.32)	-2.91e-3 (1.68e-4)	1.88 (1.03)	0.93 (0.24)	5
Z. mays	Adult	2.06 (1.32)	-8.35e-3 (5.3e-3)	4.96 (0.22)	0.83 (0.07)	4
	Juvenile	2.08 (2.12)	-8.41e-3 (5.77e-3)	4.70 (0.35)	0.88 (0.11)	4

Table S4. Linear relationships for carbon economic traits in simulated dynamic light environments depicted in figures 4, 5, S2, and S3 for adult and juvenile leaves of *P. tremula x alba* and *Z. mays*. *P*-values determined by ANCOVA.

Species	Development	dependent variable	independent variable	slope	intercept	R^2	*P*-value
P. tremula x alba	Adult	Leaf payback time	PPFD	-0.06	3.66	0.49	<0.0001
			Sunflecks	-5.7e-4	2.05	0.03	<0.05
	Juvenile		PPFD	-9.5e-3	0.55	0.41	<0.0001
			Sunflecks	-7.6e-5	0.3	0.02	0.0963
	Adult	Leaf ROI	PPFD	0.1	-0.32	0.49	<0.0001
			Sunflecks	8.9e-4	2.2	0.03	<0.05
	Juvenile		PPFD	9.2e-3	-0.11	0.43	<0.0001
			Sunflecks	7.5e-5	0.14	0.02	0.0832
	Adult	Payback time per gram	PPFD	-0.27	16.12	0.49	<0.0001
			Sunflecks	-2.52e-3	9.02	0.02	<0.05
	Juvenile		PPFD	-0.22	12.57	0.41	<0.0001
			Sunflecks	-1.7e-3	6.82	0.02	0.0963
	Adult	ROI per gram	PPFD	0.42	-1.41	0.49	<0.0001
			Sunflecks	3.93e-3	9,7	0.03	<0.05
	Juvenile		PPFD	0.21	-2.46	0.43	<0.0001
			Sunflecks	1.7e-3	3.1	0.02	0.0832
Z. mays	Adult	Leaf payback time	PPFD	-6.3e-2	4.17	0.6	<0.0001
			Sunflecks	-7.1e-4	2.5	0.05	<0.01
	Juvenile		PPFD	-0.01	0.66	0.56	<0.0001
			Sunflecks	-1.1e-4	0.39	0.04	<0.01
	Adult	Leaf ROI	PPFD	0.69	4.37	0.58	<0.0001
			Sunflecks	7.6e-3	22.6	0.05	<0.01
	Juvenile		PPFD	0.05	0.01	0.55	<0.0001
			Sunflecks	4.7e-4	1.21	0.04	<0.05
	Adult	Payback time per gram	PPFD	-0.07	4.83	0.6	<0.0001
			Sunflecks	-8.2e-4	2.9	0.05	<0.01
	Juvenile		PPFD	-0.06	3.68	0.56	<0.0001
			Sunflecks	-6.1e-4	2.15	0.04	<0.01
	Adult	ROI per gram	PPFD	0.8	5.07	0.58	<0.0001
			Sunflecks	8.9e-3	26.22	0.05	<0.01
	Juvenile		PPFD	0.25	0.08	0.55	<0.0001
			Sunflecks	2.6e-3	6.75	0.04	<0.05

Table S5. Inputs for each dynamic light simulation and the daily integrated PPFD and number of sunflecks resulting for that simulation.

	Inputs						Outputs	
Simulation	**LAI**	**Initial Sunfleck Length**	**day**	**latitude**	**off**	**random # range**	**Daily integrated PPFD**	**# of sunflecks**
S1	2	0.001	180	0.697	6	0.8-1.2	25.49	6
S2	2	0.002	180	0.697	6	0.8-1.2	20.18	3
S3	2	0.0009	180	0.697	6	0.8-1.2	26.21	6
S4	2	0.0008	180	0.697	6	0.8-1.2	26.40	7
S5	2	0.0006	180	0.697	6	0.8-1.2	26.84	8
S6	2	0.0004	180	0.697	6	0.8-1.2	27.10	11
S7	2	0.0002	180	0.697	6	0.8-1.2	27.82	20
S8	2	0.00009	180	0.697	6	0.8-1.2	28.04	43
S9	2	0.00007	180	0.697	6	0.8-1.2	27.99	51
S10	2	0.00005	180	0.697	6	0.8-1.2	28.08	71
S11	2	0.00003	180	0.697	6	0.8-1.2	27.99	116
S12	2.2	0.00003	180	0.697	6	0.8-1.2	27.62	53
S13	2.2	0.00005	180	0.697	6	0.8-1.2	27.71	33
S14	2.2	0.00009	180	0.697	6	0.8-1.2	27.77	21
S15	2.2	0.0004	180	0.697	6	0.8-1.2	26.08	6
S16	2.2	0.0008	180	0.697	6	0.8-1.2	21.53	3
S17	2.2	0.002	180	0.697	6	0.8-1.2	27.53	2
S18	2.5	0.002	180	0.697	6	0.8-1.2	27.53	1
S19	2.5	0.0004	180	0.697	6	0.8-1.2	19.38	2
S20	2.5	0.00005	180	0.697	6	0.8-1.2	26.66	11
S21	2.5	0.00003	180	0.697	6	0.8-1.2	27.33	19
S22	2.5	0.00001	180	0.697	6	0.8-1.2	27.33	50
S23	2.5	0.000008	180	0.697	6	0.8-1.2	27.81	58
S24	2.5	0.000006	180	0.697	6	0.8-1.2	27.41	83
S25	2.5	0.000004	180	0.697	6	0.8-1.2	27.48	121
S26	2.8	0.000004	180	0.697	6	0.8-1.2	26.99	41
S27	2.8	0.000002	180	0.697	6	0.8-1.2	27.35	78
S28	2.8	0.0000008	180	0.697	6	0.8-1.2	27.03	220
S29	2.8	0.000006	180	0.697	6	0.8-1.2	27.06	25
S30	2.8	0.000008	180	0.697	6	0.8-1.2	27.09	21
S31	2.8	0.00001	180	0.697	6	0.8-1.2	27.13	18
S32	2.8	0.0008	180	0.697	6	0.8-1.2	27.30	1
S33	3	0.00001	180	0.697	6	0.8-1.2	26.20	9

S34	3	0.0008	180	0.697	6	0.8-1.2	27.18	1
S35	3	0.00003	180	0.697	6	0.8-1.2	22.20	4
S36	3	0.00005	180	0.697	6	0.8-1.2	18.05	2
S37	3	0.000008	180	0.697	6	0.8-1.2	26.26	10
S38	3	0.000006	180	0.697	6	0.8-1.2	26.55	13
S39	3	0.000004	180	0.697	6	0.8-1.2	27.22	20
S40	3	0.000002	180	0.697	6	0.8-1.2	27.20	36
S41	3	0.0000008	180	0.697	6	0.8-1.2	27.21	85
S42	3.2	0.0000008	180	0.697	6	0.8-1.2	27.31	42
S43	3.2	0.0000006	180	0.697	6	0.8-1.2	26.65	52
S44	3.2	0.0000004	180	0.697	6	0.8-1.2	27.20	80
S45	3.2	0.0000002	180	0.697	6	0.8-1.2	28.19	183
S46	3.2	0.000002	180	0.697	6	0.8-1.2	26.81	19
S47	3.2	0.000004	180	0.697	6	0.8-1.2	26.23	10
S48	3.2	0.000008	180	0.697	6	0.8-1.2	25.21	6
S49	3.2	0.00001	180	0.697	6	0.8-1.2	24.48	5
S50	3.2	0.00003	180	0.697	6	0.8-1.2	20.64	2
S51	3.5	0.00003	180	0.697	6	0.8-1.2	26.94	2
S52	3.5	0.00001	180	0.697	6	0.8-1.2	22.07	2
S53	3.5	0.000008	180	0.697	6	0.8-1.2	18.74	2
S54	3.5	0.000002	180	0.697	6	0.8-1.2	25.60	7
S55	3.5	0.0000008	180	0.697	6	0.8-1.2	26.35	14
S56	3.5	0.0000006	180	0.697	6	0.8-1.2	26.56	19
S57	3.5	0.0000004	180	0.697	6	0.8-1.2	26.42	24
S58	3.5	0.0000001	180	0.697	6	0.8-1.2	27.18	93
S59	3.8	0.0000001	180	0.697	6	0.8-1.2	26.42	29
S60	3.8	0.00000008	180	0.697	6	0.8-1.2	27.04	39
S61	3.8	0.00000005	180	0.697	6	0.8-1.2	26.10	55
S62	3.8	0.00000002	180	0.697	6	0.8-1.2	26.46	155
S63	3.8	0.0000003	180	0.697	6	0.8-1.2	25.81	11
S64	3.8	0.0000005	180	0.697	6	0.8-1.2	25.71	8
S65	1.8	0.001	180	0.697	6	0.8-1.2	27.36	10
S66	1.8	0.002	180	0.697	6	0.8-1.2	26.44	6
S67	1.8	0.003	180	0.697	6	0.8-1.2	24.26	4
S68	1.8	0.004	180	0.697	6	0.8-1.2	21.62	3
S69	1.8	0.0008	180	0.697	6	0.8-1.2	27.41	11
S70	1.8	0.0006	180	0.697	6	0.8-1.2	28.12	15
S71	1.8	0.0004	180	0.697	6	0.8-1.2	27.92	22
S72	1.8	0.0002	180	0.697	6	0.8-1.2	28.05	42
S73	1.8	0.00008	180	0.697	6	0.8-1.2	27.89	98

S74	1.5	0.0008	180	0.697	6	0.8-1.2	28.53	33
S75	1.5	0.0006	180	0.697	6	0.8-1.2	28.72	45
S76	1.5	0.0004	180	0.697	6	0.8-1.2	28.80	62
S77	1.5	0.0002	180	0.697	6	0.8-1.2	29.29	127
S78	1.5	0.001	180	0.697	6	0.8-1.2	28.72	25
S79	1.5	0.003	180	0.697	6	0.8-1.2	28.19	10
S80	1.5	0.005	180	0.697	6	0.8-1.2	27.41	8
S81	1.5	0.007	180	0.697	6	0.8-1.2	26.35	6
S82	1.5	0.01	180	0.697	6	0.8-1.2	24.40	4
S83	1	0.01	180	0.697	6	0.8-1.2	29.80	21
S84	1	0.008	180	0.697	6	0.8-1.2	29.80	24
S85	1	0.006	180	0.697	6	0.8-1.2	29.76	31
S86	1	0.004	180	0.697	6	0.8-1.2	30.21	47
S87	1	0.002	180	0.697	6	0.8-1.2	30.44	89
S88	1	0.0009	180	0.697	6	0.8-1.2	29.11	242
S89	1	0.01	180	0.697	6	0.8-1.2	29.80	21
S90	1	0.03	180	0.697	6	0.8-1.2	29.01	8
S91	1	0.05	180	0.697	6	0.8-1.2	27.34	5
S92	1	0.08	180	0.697	6	0.8-1.2	23.94	3
S93	0.5	0.08	180	0.697	6	0.8-1.2	31.49	19
S94	0.5	0.06	180	0.697	6	0.8-1.2	31.62	23
S95	0.5	0.03	180	0.697	6	0.8-1.2	31.60	46
S96	0.5	0.009	180	0.697	6	0.8-1.2	30.88	158
S97	0.5	0.1	180	0.697	6	0.8-1.2	31.35	15
S98	0.5	0.4	180	0.697	6	0.8-1.2	28.22	4
S103	2	0.00002	180	0.697	6	0.8-1.2	28.10	203
S104	2	0.000025	180	0.697	6	0.8-1.2	28.92	149
S105	2	0.000035	180	0.697	6	0.8-1.2	27.81	102
S106	2	0.00004	180	0.697	6	0.8-1.2	27.65	87
S107	1.5	0.00015	180	0.697	6	0.8-1.2	28.56	197
S108	1.5	0.00025	180	0.697	6	0.8-1.2	28.83	103
S109	1.5	0.00027	180	0.697	6	0.8-1.2	28.97	93
S110	1.5	0.00023	180	0.697	6	0.8-1.2	29.09	111
S111	1	0.001	180	0.697	6	0.8-1.2	30.10	215
S112	1	0.0015	180	0.697	6	0.8-1.2	30.36	121
S113	1	0.0025	180	0.697	6	0.8-1.2	30.05	75
S114	0.5	0.0085	180	0.697	6	0.8-1.2	32.01	184
S115	0.5	0.0092	180	0.697	6	0.8-1.2	31.67	152
S116	0.5	0.0094	180	0.697	6	0.8-1.2	32.03	147
S117	0.5	0.01	180	0.697	6	0.8-1.2	31.30	132

S118	0.5	0.02	180	0.697	6	0.8-1.2	31.41	64
S119	2	0.00002	180	0.697	6	0.8-1.2	28.10	203
S120	2	0.000025	180	0.697	6	0.8-1.2	28.92	149
S121	2.5	0.000003	180	0.697	6	0.8-1.2	27.10	193
S122	2.5	0.0000035	180	0.697	6	0.8-1.2	27.24	147
S123	2.5	0.0000045	180	0.697	6	0.8-1.2	27.65	110
S124	3	0.0000007	180	0.697	6	0.8-1.2	26.76	98
S125	3	0.00000065	180	0.697	6	0.8-1.2	27.21	106
S126	3	0.00000055	180	0.697	6	0.8-1.2	26.99	123
S127	3	0.0000004	180	0.697	6	0.8-1.2	27.19	197
S128	3.5	0.00000009	180	0.697	6	0.8-1.2	27.34	106
S129	3.5	0.00000008	180	0.697	6	0.8-1.2	26.53	116
S130	3.5	0.00000007	180	0.697	6	0.8-1.2	26.61	140
S131	4	0.00000007	180	0.697	6	0.8-1.2	26.45	21
S132	4	0.00000009	180	0.697	6	0.8-1.2	26.31	18
S133	4	0.0000002	180	0.697	6	0.8-1.2	25.82	9
S134	4	0.0000003	180	0.697	6	0.8-1.2	25.30	7
S135	4	0.00000007	180	0.697	6	0.8-1.2	26.60	21
S136	4	0.00000005	180	0.697	6	0.8-1.2	26.49	26
S137	4	0.00000002	180	0.697	6	0.8-1.2	26.25	64
S138	4	8E-09	180	0.697	6	0.8-1.2	26.94	193
S139	4	9E-09	180	0.697	6	0.8-1.2	26.84	157
S140	4	0.00000001	180	0.697	6	0.8-1.2	26.33	132
S141	4.5	0.00000001	180	0.697	6	0.8-1.2	26.53	21
S142	4.5	0.00000004	180	0.697	6	0.8-1.2	25.15	7
S143	4.5	0.00000008	180	0.697	6	0.8-1.2	21.90	4
S144	4.5	7E-09	180	0.697	6	0.8-1.2	26.06	26
S145	4.5	4E-09	180	0.697	6	0.8-1.2	26.58	47
S146	4.5	1E-09	180	0.697	6	0.8-1.2	26.50	212
S147	4.5	2.5E-09	180	0.697	6	0.8-1.2	26.65	74
S148	5	2.5E-09	180	0.697	6	0.8-1.2	25.64	12
S149	5	3E-09	180	0.697	6	0.8-1.2	25.73	10
S150	5	8E-09	180	0.697	6	0.8-1.2	24.08	5
S151	5	8E-10	180	0.697	6	0.8-1.2	26.48	33
S152	5	2E-10	180	0.697	6	0.8-1.2	26.00	125
S153	6	2E-10	180	0.697	6	0.8-1.2	22.52	4
S154	6	2E-11	180	0.697	6	0.8-1.2	26.21	24
S155	7	2E-12	180	0.697	6	0.8-1.2	25.14	7
S156	8	2E-13	180	0.697	6	0.8-1.2	22.67	2
S157	8	2E-14	180	0.697	6	0.8-1.2	25.44	11

S158	8	2E-15	180	0.697	6	0.8-1.2	26.71	88
S159	8	9E-16	180	0.697	6	0.8-1.2	26.82	234
S160	8	2.1E-13	180	0.697	6	0.8-1.2	24.02	2