

Elevated Litterfall Phosphorus Reduces Litter and Soil Organic Matter Pools in Exotic-dominated Novel Forests in Singapore

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SUPPLEMENTARY MATERIAL

Note 1. Weibull residence time model

Using the values of α and β estimated from the Weibull model, the half-life of leaf litter is given by

$$t_{\frac{1}{2}} = \beta (\ln(2))^{\frac{1}{\alpha}} \quad (\text{Eq. 1})$$

and its mean residence time by

$$\bar{t} = \beta \Gamma \left(1 + \frac{1}{\alpha} \right) \quad (\text{Eq. 2})$$

where Γ is the gamma function, following Cornwell and Weedon (2014).

Note 2. Logit transformation and interpretation of model coefficients

The model coefficients of the explanatory factors were interpreted as follows: a single-unit increase in the explanatory factor leads to an increase in the odds ratio $p/(1-p)$ by a factor of e^β , where p is the proportion of leaf litter decomposed, $(1-p)$ is the proportion of leaf litter remaining, and β is the coefficient of the explanatory factor.

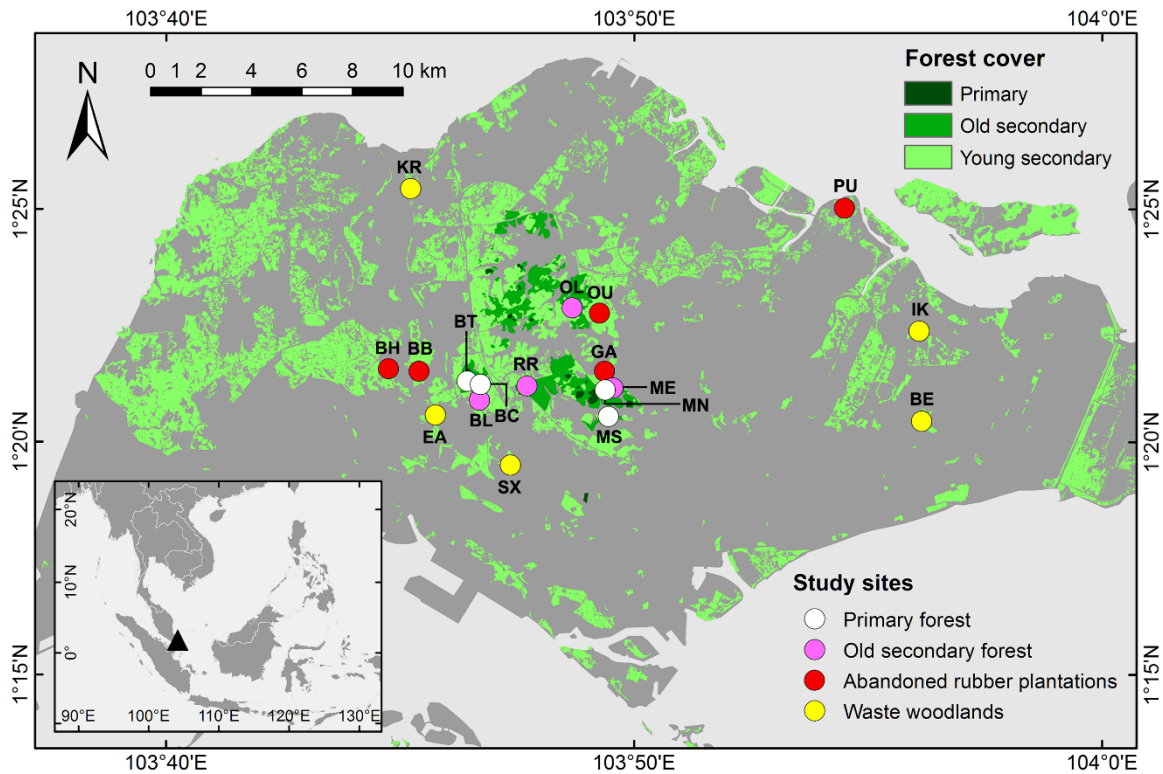


Figure S1. Location of study sites across forest successional types in Singapore. Site names and GPS coordinates are shown in Table S2. Inset map shows location of Singapore (triangle symbol) within Southeast Asia. Forest cover map adapted from Yee *et al.* (2011).

Table S1. Forest canopy structure, understorey microclimate, and soil nutrient content per forest type. Values in parentheses represent standard error of the mean.

	Primary forest	Old secondary forest	Abandoned rubber plantation	Waste woodland
Forest canopy structure				
Canopy openness (%)	10.89 (0.60)	12.72 (0.78)	12.52 (0.74)	21.87 (1.92)
Forest understorey microclimate				
Daily mean temperature (°C)	26.29 (0.05)	26.31 (0.05)	26.70 (0.05)	27.07 (0.05)
Daily mean relative humidity (%)	92.84 (0.21)	91.54 (0.21)	90.47 (0.24)	90.44 (0.23)
Daily mean volumetric soil moisture content (%)	0.244 (0.006)	0.205 (0.007)	0.255 (0.007)	0.246 (0.005)
Soil nutrient content				
Organic matter (%)	7.85 (0.77)	8.35 (0.93)	4.95 (1.041)	5.08 (0.53)
Total nitrogen (mg/kg)	1750 (210)	1995 (155)	2002 (333.95)	1890 (272.91)
Extractable phosphorus (mg/kg)	4.46 (0.70)	4.95 (0.73)	7.38 (3.33)	6.92 (1.33)
Extractable potassium (mg/kg)	44.43 (5.55)	42.63 (6.68)	57.10 (21.37)	85.42 (9.92)
Extractable calcium (mg/kg)	170.25 (19.51)	205.25 (14.91)	199.75 (18.98)	2087.25 (600.54)
Extractable magnesium (mg/kg)	45.78 (3.18)	53.15 (4.46)	52.50 (5.47)	163.75 (33.14)

Table S2. Annual litterfall production and leaf litter nutrient properties per study site, including nitrogen-use efficiency (NUE) and phosphorus-use efficiency (PUE). Values in parentheses represent standard error of the mean. (D.D.: Data deficient).

Forest type	Study site				Litterfall production (Mg/ha/yr)					Leaf litterfall nutrient properties							
	Name	Code	GPS Coordinates	Dominant Canopy Species	Total	Leaf	Wood	Reproductive	Debris	C (%)	C:N	C:P	N:P	NUE	PUE	N return (kg/ha/yr)	P return (kg/ha/yr)
Primary forest	Macritchie South	MS	1°20'33.0"N, 103°49'26.3"E	D.D.	11.76 (1.62)	8.02 (0.99)	1.40 (0.51)	2.04 (0.41)	0.30 (0.07)	50.67	33.45	2533.50	75.75	66.01	5000.00	121.54 (14.97)	1.60 (0.20)
	Macritchie North	MN	1°21'6.3"N, 103°49'22.6"E	D.D.	12.26 (1.04)	9.19 (0.38)	1.45 (0.55)	1.39 (0.34)	0.22 (0.03)	49.79	36.75	2489.50	67.75	73.80	5000.00	124.56 (5.10)	1.84 (0.08)
	Bukit Timah Jungle Fall	BT	1°21'17.8"N, 103°46'26.0"E	D.D.	10.54 (0.77)	8.13 (0.37)	0.88 (0.28)	1.25 (0.24)	0.27 (0.04)	51.39	40.31	3426.00	85.00	78.43	6666.67	103.71 (4.73)	1.22 (0.06)
	Bukit Timah Catchment Path	BC	1°21'14.1"N, 103°46'42.3"E	D.D.	9.35 (0.97)	6.84 (0.94)	0.91 (0.23)	1.41 (0.39)	0.19 (0.04)	49.55	35.14	2477.50	70.50	70.92	5000.00	96.42 (13.27)	1.37 (0.19)
Old secondary forest	Rifle Range	RR	1°21'11.4"N, 103°47'42.8"E	D.D.	9.31 (0.76)	6.60 (0.33)	1.18 (0.26)	1.36 (0.32)	0.18 (0.01)	51.63	39.11	2581.50	66.00	75.76	5000.00	87.07 (4.36)	1.32 (0.07)
	Old Upper Thomson Road (1)	OL	1°22'53.1"N, 103°48'40.1"E	D.D.	8.69 (0.91)	7.00 (0.72)	0.49 (0.14)	0.93 (0.33)	0.27 (0.06)	50.20	32.70	2008.00	61.40	65.15	4000.00	107.48 (11.08)	1.75 (0.18)
	Bukit Timah Taban Loop	BL	1°20'53.6"N, 103°46'41.5"E	D.D.	9.26 (1.48)	6.75 (0.76)	1.52 (0.52)	0.83 (0.37)	0.15 (0.04)	49.38	37.41	2469.00	66.00	75.76	5000.00	89.10 (9.99)	1.35 (0.15)
	Macritchie East	ME	1°21'9.0"N, 103°49'32.4"E	D.D.	12.65 (1.89)	8.42 (1.08)	2.28 (0.89)	1.65 (0.39)	0.30 (0.06)	49.45	34.10	1648.33	48.33	68.97	3333.33	122.09 (15.65)	2.53 (0.32)

Forest type	Study site				Litterfall production (Mg/ha/yr)					Leaf litterfall nutrient properties							
	Name	Code	GPS Coordinates	Dominant Canopy Species	Total	Leaf	Wood	Reproductive	Debris	C (%)	C:N	C:P	N:P	NUE	PUE	N return (kg/ha/yr)	P return (kg/ha/yr)
Abandoned rubber plantation	Punggol End	PE	1°25'1.7"N, 103°54'29.7"E	<i>Hevea brasiliensis</i>	11.89 (1.24)	9.13 (1.11)	0.66 (0.19)	1.48 (0.66)	0.62 (0.07)	48.94	26.45	699.14	26.43	54.05	1428.57	169.00 (20.58)	6.39 (0.78)
	Bukit Batok Town Park	BB	1°21'30.7"N, 103°45'23.4"E	<i>Hevea brasiliensis</i>	8.31 (0.74)	6.22 (0.54)	1.36 (0.24)	0.47 (0.15)	0.26 (0.03)	52.06	34.48	1487.43	43.14	66.23	2857.14	93.85 (8.19)	2.18 (0.19)
	Bukit Batok Hillside Park	BH	1°21'33.4"N, 103°44'44.3"E	<i>Hevea brasiliensis</i>	6.44 (0.18)	5.08 (0.22)	0.86 (0.31)	0.34 (0.08)	0.16 (0.03)	50.94	31.84	2037.60	64.00	62.50	4000.00	81.34 (3.47)	1.27 (0.05)
	Windsor Park	GA	1°21'31.0"N, 103°49'21.4"E	<i>Hevea brasiliensis</i>	10.28 (1.41)	8.49 (1.03)	1.16 (0.42)	0.47 (0.13)	0.16 (0.01)	48.47	32.53	1384.86	42.57	67.11	2857.14	126.50 (15.32)	2.97 (0.36)
	Old Upper Thomson Road (2)	OU	1°22'45.1"N, 103°49'15.5"E	<i>Hevea brasiliensis</i>	10.29 (1.22)	7.01 (0.55)	2.22 (0.98)	0.83 (0.20)	0.22 (0.05)	50.34	32.58	2517.00	77.25	64.72	5000.00	108.34 (8.46)	1.40 (0.11)
Waste woodland	Sixth Avenue	SX	1°19'29.7"N, 103°47'21.6"E	<i>Falcataria moluccana</i>	16.09 (0.89)	12.11 (0.62)	1.38 (0.37)	1.72 (0.65)	0.87 (0.14)	49.27	26.49	1231.75	46.50	53.76	2500.00	225.24 (11.46)	4.84 (0.25)
	Bukit Batok East	EA	1°20'34.7"N, 103°45'45.7"E	<i>Falcataria moluccana</i>	11.30 (0.76)	10.01 (0.61)	0.40 (0.16)	0.28 (0.08)	0.61 (0.06)	43.47	19.28	621.00	32.21	44.35	1428.57	225.73 (13.77)	7.01 (0.43)
	Bedok Reservoir	BE	1°20'26.8"N, 103°56'7.9"E	<i>Acacia auriculiformis</i>	11.92 (1.11)	8.59 (0.79)	1.10 (0.18)	1.72 (0.38)	0.52 (0.14)	47.65	41.43	1058.89	25.56	86.96	2222.22	98.80 (9.13)	3.87 (0.36)
	Kranji	KR	1°25'25.8"N, 103°45'12.6"E	<i>Falcataria moluccana</i>	13.70 (0.96)	10.69 (0.47)	1.63 (0.50)	0.70 (0.34)	0.69 (0.15)	47.55	23.31	1056.67	45.33	49.02	2222.22	218.12 (9.62)	4.81 (0.21)

Forest type	Study site				Litterfall production (Mg/ha/yr)					Leaf litterfall nutrient properties							
	Name	Code	GPS Coordinates	Dominant Canopy Species	Total	Leaf	Wood	Reproductive	Debris	C (%)	C:N	C:P	N:P	NUE	PUE	N return (kg/ha/yr)	P return (kg/ha/yr)
	IKEA Tampines	IK	1°22'22.8"N, 103°56'5.7"E	<i>Acacia auriculiformis</i>	10.89 (0.81)	7.77 (0.65)	0.83 (0.23)	1.86 (0.59)	0.44 (0.04)	49.11	34.95	1637.00	46.83	71.17	3333.33	109.10 (9.09)	2.33 (0.19)

Table S3. Model selection from a list of candidate models using an Akaike Information Criterion approach for annual *total* and *leaf* litterfall production modelled using linear mixed effects models. Study site was modelled as a random effect. k = number of estimated parameters. The most parsimonious model and its predictor(s) is highlighted in bold.

Model response	Model predictor(s)	k	AICc	ΔAICc	AICc Weight	Log likelihood
Annual <i>total</i> litterfall	Forest type + soil nitrogen content	7	517.2357	0	0.2611	-251.0221
	Forest type	6	517.9933	0.7576	0.1788	-252.5545
	Forest type + soil phosphorus content	7	518.5688	1.3331	0.1341	-251.6887
	Forest type + soil nitrogen content + canopy openness	8	518.8712	1.6355	0.1153	-250.6614
	Forest type + canopy openness	7	520.0832	2.8475	0.0629	-252.4458
	Forest type + soil phosphorus content + canopy openness	8	520.5781	3.3424	0.0491	-251.5149
	Soil nitrogen content	4	520.9577	3.722	0.0406	-256.2726
	Soil phosphorus content	4	521.0209	3.7852	0.0393	-256.3043
	Forest type + soil nitrogen content + soil phosphorus content + canopy openness	9	521.2214	3.9857	0.0356	-250.6324
	Canopy openness	4	521.5634	4.3278	0.03	-256.5755
	Soil nitrogen content + canopy openness	5	522.7691	5.5334	0.0164	-256.0721
	Soil phosphorus content + canopy openness	5	522.8307	5.595	0.0159	-256.1028
	Soil nitrogen content + soil phosphorus content	5	522.9529	5.7172	0.015	-256.1640
	Soil nitrogen content + soil phosphorus content + canopy openness	6	524.8340	7.5983	0.0058	-255.9749
Annual <i>leaf</i> litterfall	Forest type	6	434.5655	0	0.2764	-210.8406
	Forest type + soil phosphorus content	7	434.8479	0.2824	0.24	-209.8282
	Forest type + soil nitrogen content	7	435.9989	1.4335	0.135	-210.4037
	Forest type + canopy openness	7	436.8587	2.2933	0.0878	-210.8336
	Forest type + soil phosphorus content + canopy openness	8	437.0923	2.5268	0.0781	-209.7719
	Forest type + soil nitrogen content + canopy openness	8	438.256	3.6906	0.0437	-210.3538
	Canopy openness	4	438.9672	4.4018	0.0306	-215.2774
	Soil phosphorus content	4	439.3093	4.7438	0.0258	-215.4484
	Forest type + soil nitrogen content + soil phosphorus content + canopy openness	9	439.4928	4.9273	0.0235	-209.7681
	Soil phosphorus content + canopy openness	5	439.9794	5.4139	0.0184	-214.6772
	Soil nitrogen content	4	440.5598	5.9944	0.0138	-216.0737
	Soil nitrogen content + canopy openness	5	441.0752	6.5097	0.0107	-215.2251
	Soil nitrogen content + soil phosphorus content	5	441.3426	6.7771	0.0093	-215.3588
	Soil nitrogen content + soil phosphorus content + canopy openness	6	442.0026	7.4372	0.0067	-214.5592

Table S4. Leaf litter decomposition parameters as estimated by the Weibull residence model. Values in parentheses represent standard error of the mean.

Forest type	Study site	df	Weibull α	Weibull β	Half-life (days)	Mean residence time (days)	r^2	Mean squared error	Annual leaf litter mass loss (%)	
									Predicted Mean	95% CI
Primary forest	MS	10	2.995 (0.419)	324.91 (13.04)	287.48 (12.46)	290.11 (11.75)	0.9547	0.0049	75.82	[60.88, 92.13]
	MN	10	0.666 (0.185)	287.26 (59.24)	165.66 (33.77)	382.38 (160.34)	0.8513	0.0128	69.07	[61.73, 76.17]
	BT	10	1.227 (0.352)	303.00 (42.16)	224.77 (32.00)	283.43 (48.52)	0.8395	0.0167	71.57	[57.22, 90.24]
	BC	4	1.796 (0.016)	288.61 (1.03)	235.34 (0.88)	256.69 (0.94)	0.9999	0.0000	78.27	[78.11, 78.46]
Old secondary forest	RR	10	1.049 (0.325)	424.86 (83.10)	299.53 (44.09)	416.91 (119.36)	0.8103	0.0134	57.40	[47.31, 77.49]
	OL	10	0.727 (0.184)	270.63 (48.41)	163.42 (30.25)	331.03 (107.86)	0.8684	0.0119	71.16	[57.49, 79.14]
	BL	10	1.097 (0.423)	462.53 (113.81)	331.17 (58.27)	446.69 (156.53)	0.7328	0.0184	53.78	[38.16, 79.54]
	ME	10	1.663 (0.154)	245.49 (8.68)	196.92 (8.20)	219.39 (7.83)	0.9870	0.0017	85.57	[82.41, 91.97]
Abandoned rubber plantation	PE	10	2.105 (0.720)	175.88 (20.87)	147.77 (23.43)	155.77 (18.32)	0.9143	0.0157	99.05	[92.30, 100.00]
	BB	10	1.261 (0.194)	219.88 (16.37)	164.42 (14.31)	204.40 (16.72)	0.9498	0.0056	84.99	[77.43, 92.60]
	BH	10	1.547 (0.124)	195.81 (6.87)	154.51 (6.69)	176.15 (6.04)	0.9896	0.0014	92.74	[89.08, 96.14]
	GA	10	1.410 (0.244)	234.18 (16.59)	180.56 (15.61)	213.20 (15.78)	0.9470	0.0062	84.61	[77.14, 95.20]
	OU	6	1.812 (0.584)	271.94 (24.53)	222.15 (23.21)	241.76 (22.55)	0.9129	0.0093	81.85	[67.25, 94.97]
	SX	10	1.406 (0.272)	174.14 (17.37)	134.17 (16.11)	158.61 (15.62)	0.9343	0.0094	94.12	[86.45, 99.92]

Forest type	Study site	df	Weibull α	Weibull β	Half-life (days)	Mean residence time (days)	r^2	Mean squared error	Annual leaf litter mass loss (%)	
									Predicted Mean	95% CI
Waste woodland	EA	10	1.869 (0.282)	134.75 (12.61)	110.76 (11.06)	119.64 (11.17)	0.9708	0.0056	99.84	[97.40, 100.00]
	BE	10	1.735 (0.318)	275.27 (15.11)	222.85 (13.64)	245.28 (14.22)	0.9487	0.0052	80.48	[66.35, 91.87]
	KR	8	1.457 (0.199)	161.89 (13.21)	125.88 (11.40)	146.69 (12.10)	0.9721	0.0042	96.21	[91.05, 99.51]
	IK	10	1.828 (0.329)	233.96 (13.08)	191.45 (13.42)	207.91 (11.54)	0.9577	0.0055	89.54	[81.80, 97.79]

Table S5. Model selection from a list of candidate models using an Akaike Information Criterion approach for nutrient use efficiencies (as deduced from leaf litterfall nutrient concentrations) and annual leaf litterfall decomposition modelled using linear regression models. k = number of estimated parameters. Predictor(s) used in the most parsimonious model is highlighted in bold.

Model response	Model predictor(s)	k	AICc	Δ AICc	AICc Weight	Log likelihood
Nitrogen-use efficiency	Soil nitrogen content	3	143.2806	0	0.7792	-67.7832
	Forest type	5	145.9955	2.7149	0.2005	-65.4977
	Forest type + soil nitrogen content	6	150.5807	7.3001	0.0203	-65.4722
Phosphorus-use efficiency	Forest type	5	309.1824	0	0.5118	-147.0912
	Forest type + soil phosphorus content	6	309.4181	0.2357	0.4549	-144.8908
	Soil phosphorus content	3	314.6530	5.4707	0.0332	-153.4694
Soil phosphorus content	Annual phosphorus return via leaf litterfall	3	100.2419	0	0.9928	-46.2638
	Forest type + annual phosphorus return via leaf litterfall	6	110.3676	10.1256	0.0063	-45.3656
	Forest type	5	114.2004	13.9585	0.0009	-49.6002
Soil nitrogen content	Annual nitrogen return via leaf litterfall	3	281.3384	0	0.9607	-136.8121
	Forest type	5	287.9242	6.5858	0.0357	-136.4621
	Forest type + annual nitrogen return via leaf litterfall	6	292.478	11.1396	0.0037	-136.4208
Proportion of leaf litterfall mass loss annually (logit-transformed)	Leaf litterfall C:N + leaf litterfall C:P	4	47.3060	0	0.5504	-18.1145
	Leaf litterfall C:N	3	49.0325	1.7266	0.2322	-20.6591
	Leaf litterfall C:N + soil moisture content	4	50.299	2.993	0.1232	-19.611
	Leaf litterfall C:N + leaf litterfall C:P + soil moisture content	5	51.1542	3.8483	0.0804	-18.0771
	Forest type + leaf litterfall C:N	6	56.2769	8.9709	0.0062	-18.3203
	Leaf litterfall C:P + soil moisture content	4	57.8464	10.5405	0.0028	-23.3847
	Leaf litterfall C:P	3	58.1777	10.8717	0.0024	-25.2317
	Forest type + leaf litterfall C:N + leaf litterfall C:P	7	58.3356	11.0297	0.0022	-16.5678
	Forest type + leaf litterfall C:N + leaf litterfall C:P + soil moisture content	8	64.6236	17.3176	0.0001	-16.3118
	Forest type + leaf litterfall C:P	6	67.04	19.7341	0	-23.7018
	Forest type + leaf litterfall C:P + soil moisture content	7	69.1343	21.8284	0	-21.9672
	Forest type	5	70.9532	23.6472	0	-27.9766
	Soil moisture content	3	73.3903	26.0843	0	-32.8380

	Forest type + soil moisture content	6	75.546	28.2401	0	-27.9548
Soil organic matter content (%) (logit-transformed)	Estimated amount of leaf litterfall accumulated annually	3	14.2539	0	0.9766	-3.1269
	Forest type	5	22.1257	7.8718	0.0191	-3.0628
	Forest type + estimated amount of leaf litterfall accumulated annually	6	25.0719	10.8181	0.0044	-1.8693