Supplemental Information:

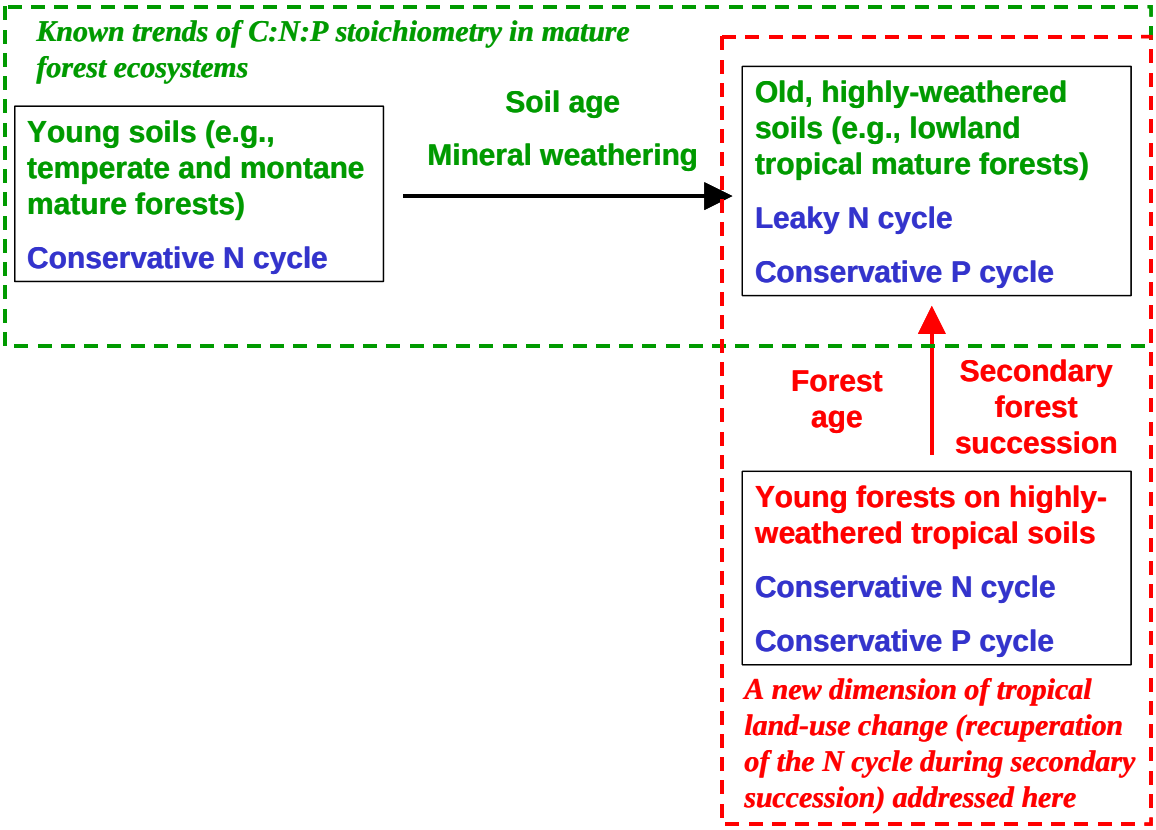

Figure S1. Simple schematic that summarizes the main finding of the paper. The patterns of N and P cycling for secondary succession, shown here in red font, are integrated conceptually with those previously demonstrated for primary succession, shown here in green font. Actively cycling N in terrestrial ecosystems can be lost either by land-use change, such as forest clearing, burning and agricultural practices (the present study), or by natural processes such as fires, landslides, glaciers, and volcanic activity (previous studies). Just as accumulation of total ecosystem N alleviates a N limitation as soils age over thousands and millions of years, we show here that actively cycling N accumulates over decades and centuries during secondary forest succession, resulting in a similar successional trajectory from a conservative N cycle following agricultural abandonment to the leaky-N and conservative-P cycles expected in mature lowland tropical forests on old soils.

Table S1. Physical and chemical characteristics of the top 10 cm of mineral soil of São Francisco do Pará (SF), Capitão Poço (CP) and Paragominas (PG) chronosequences.

Site & Age (years)	Bulk density ($g\ cm^{-3}$)	Clay ($g\ kg^{-1}$)	Sand ($g\ kg^{-1}$)	pH_{H20}	C ($g.kg^{-1}$)	N ($g.kg^{-1}$)	$P_{Mehlich}$ ($mg\ kg^{-1}$)	P_{total} ($mg\ kg^{-1}$)
SF3	1.35 (0.03)	65 (17)	898 (27)	5.3 (0.2)	10.5 (0.4)	0.74 (0.03)	1.2 (0.2)	33 (3)
SF6	1.37 (0.03)	85 (17)	785 (28)	5.1 (0.2)	11.9 (0.6)	0.70 (0.10)	2.0 (0.3)	47 (8)
SF10	1.30 (0.04)	60 (18)	873 (31)	5.3 (0.2)	9.5 (0.5)	0.73 (0.05)	1.3 (0.1)	32 (3)
SF20	1.29 (0.05)	110 (10)	775 (26)	4.9 (0.4)	11.4 (0.6)	0.82 (0.07)	3.2 (1.1)	49 (7)
SF40	1.29 (0.04)	65 (17)	830 (25)	4.9 (0.3)	10.9 (1.3)	0.63 (0.11)	1.0 (0.1)	30 (4)
SF70	1.29 (0.04)	90 (13)	790 (15)	4.9 (0.3)	11.3 (0.6)	0.89 (0.16)	1.6 (0.2)	30 (3)
SFmature	1.25 (0.03)	100 (00)	755 (25)	4.4 (0.4)	14.7 (1.4)	1.11 (0.04)	2.0 (0.1)	62 (2)
CP3		149 (10)	799 (20)	5.4 (0.1)	13.5 (1.4)	0.85 (0.15)	4.2 (0.7)	87 (2)
CP10		100 (13)	819 (12)	5.1 (0.1)	11.6 (0.1)	0.80 (0.00)	6.5 (1.5)	67 (6)
CP20		117 (08)	840 (02)	5.5 (0.2)	8.9 (1.0)	0.65 (0.05)	10.3 (0.8)	54 (8)
CPmature		160 (19)	749 (32)	4.5 (0.1)	20.7 (4.1)	1.18 (0.15)	17.3 (1.6)	100 (15)
PG6	0.92 (0.03)	750 (10)	58 (08)	5.4 (0.1)	19.2 (1.7)	2.36 (0.16)	2.9 (0.4)	213 (16)
PG20	1.01 (0.06)			5.5 (0.1)	29.0 (4.0)	2.57 (0.35)	0.8 (0.1)	209 (7)
PGmature	1.02 (0.02)	785 (13)	90 (08)	4.4 (0.1)	23.9 (0.4)	2.19 (0.04)	1.6 (0.1)	189 (1)

Means are followed by standard errors in parentheses. Soil analyses for SF and CP the followed standard procedures of Embrapa (*Embrapa 1997. Manual de métodos de análise de solo. Ministério da Agricultura e do Abastecimento, Embrapa, Centro Nacional de Pesquisa de Solos, Rio de Janeiro, 212p.)* Soil pH was measured in a 1:2.5 water slurry. Total-N concentrations were determined by micro-Kjeldahl digestions (SF) or from isotopic analyses with a mass

spectrometer (CP). An index of plant-available-P was measured using the Mehlich-I dilute double acid extraction procedure. Total-P concentrations were determined by digestion in sulfuric acid and hydrogen peroxide. Concentrations of all P extracts were determined colorimetrically. Data for PG are from refs 22 and 24.

25 **Table S2.** Foliar analyses of C and N concentrations and isotope ratios at São Francisco do Pará.

Family	Species	Forest age	$\delta^{13}C$ (‰)	C (%)	$\delta^{15}N$ (‰)	N (%)
Annonaceae	*Guatteria poeppigiana*	6	-33.63	45.97	-1.62	1.64
Annonaceae	*Rollinia exsucca*	6	-30.61	46.41	-2.34	1.66
Annonaceae	*Rollinia exsucca*	6	-29.38	45.06	-4.02	1.62
Annonaceae	*Guatteria poeppigiana*	6	-30.98	46.48	-1.19	1.56
Annonaceae	*Guatteria poeppigiana*	6	-32.50	45.70	-1.49	1.68
Annonaceae	*Rollinia exsucca*	6	-30.51	45.64	-3.06	1.70
Caesalpiniaceae	*Sclerolobium paraense*	6	-31.41	48.00	1.96	2.81
Dichapetalaceae	*Tapura amazonica*	6	-32.68	35.82	1.01	1.26
Dichapetalaceae	*Tapura amazonica*	6	-30.77	37.23	2.61	1.09
Dichapetalaceae	*Tapura amazonica*	6	-31.93	36.10	-0.84	1.18
Euphorbiaceae	*Croton matourensis*	6	-29.08	48.28	0.00	1.97
Euphorbiaceae	*Croton matourensis*	6	-28.34	48.49	0.20	2.65
Euphorbiaceae	*Mabea speciosa*	6	-32.48	44.81	-0.73	1.81
Euphorbiaceae	*Mabea speciosa*	6	-33.00	46.10	-1.42	1.72
Fabaceae	*Dipteryx odorata*	6	-29.87	49.24	2.07	2.23
Fabaceae	*Dipteryx odorata*	6	-28.93	49.34	0.00	2.25
Fabaceae	*Dipteryx odorata*	6	-28.08	49.55	2.58	2.46
Fabaceae	*Dipteryx odorata*	6	-28.29	48.73	0.88	2.33
Guttiferae	*Vismia guianensis*	6	-31.85	49.53	-2.07	1.81
Mimosaceae	*Abarema jupunba var. jupunba*	6	-28.09	49.04	0.70	2.16
Mimosaceae	*Abarema jupunba var. jupunba*	6	-31.47	47.99	-0.21	2.13
Mimosaceae	*Inga flageliformis*	6	-29.53	48.82	0.21	2.00
Mimosaceae	*Inga flageliformis*	6	-29.88	48.20	-0.57	2.63
Mimosaceae	*Inga flageliformis*	6	-28.88	48.17	-0.29	2.17
Mimosaceae	*Inga flageliformis*	6	-29.71	47.24	-0.70	2.25
Mimosaceae	*Inga thibaudiana*	6	-30.26	48.61	1.21	2.30
Mimosaceae	*Inga rubiginosa*	6	-29.32	45.19	-0.08	2.30
Mimosaceae	*Inga thibaudiana*	6	-31.11	46.89	-0.36	2.08
Mimosaceae	*Inga thibaudiana*	6	-30.39	46.55	-0.88	1.99
Mimosaceae	*Inga thibaudiana*	6	-30.87	48.23	0.51	2.28
Myrtaceae	*Myrcia cuprea*	6	-33.66	42.33	-0.24	1.17
Myrtaceae	*Myrcia cuprea*	6	-33.20	43.08	-1.87	1.16
Anacardiaceae	*Tapirira guianensis*	20	-32.19	46.51	2.22	1.85
Anacardiaceae	*Tapirira guianensis*	20	-32.10	45.82	2.62	1.68
Annonaceae	*Guatteria poeppigiana*	20	-31.49	47.63	-1.18	1.59
Annonaceae	*Guatteria poeppigiana*	20	-33.39	44.33	2.25	1.64
Annonaceae	*Guatteria poeppigiana*	20	-33.18	44.31	2.64	1.83
Connaraceae	*Connarus perrottetii var. angustifolius*	20	-31.76	52.87	2.05	1.49
Connaraceae	*Connarus perrottetii var. angustifolius*	20	-32.04	50.90	1.99	1.29
Connaraceae	*Connarus perrottetii var. angustifolius*	20	-30.58	49.35	1.12	1.28
Euphorbiaceae	*Croton matourensis*	20	-30.70	45.59	2.51	2.53
Euphorbiaceae	*Croton matourensis*	20	-28.70	45.83	1.57	2.83
Euphorbiaceae	*Croton matourensis*	20	-29.30	46.02	2.28	2.70

Guttiferae	*Vismia guianensis*	20	-30.90	49.92	-1.88	1.56
Guttiferae	*Vismia guianensis*	20	-30.71	48.52	-1.16	1.68
Guttiferae	*Vismia guianensis*	20	-32.19	40.19	0.77	1.58
Lauraceae	*Ocotea guianensis*	20	-29.73	48.28	-1.98	1.30
Lauraceae	*Ocotea guianensis*	20	-30.29	48.00	-4.10	1.41
Lauraceae	*Ocotea guianensis*	20	-30.44	50.03	2.00	1.77
Lecythidaceae	*Lecythis lurida*	20	-31.09	46.72	2.95	2.16
Lecythidaceae	*Lecythis lurida*	20	-29.90	49.39	2.21	2.23
Mimosaceae	*Inga flageliformis*	20	-30.16	45.23	0.10	2.39
Mimosaceae	*Inga flageliformis*	20	-30.39	47.71	-0.18	2.04
Mimosaceae	*Inga stipularis*	20	-32.47	48.79	0.63	2.05
Mimosaceae	*Inga thibaudiana*	20	-31.92	46.49	-0.23	2.54
Mimosaceae	*Inga thibaudiana*	20	-31.03	46.84	0.12	2.34
Mimosaceae	*Inga thibaudiana*	20	-32.08	46.49	-0.49	2.30
Mimosaceae	*Inga flageliformis*	20	-30.21	46.25	0.08	2.20
Mimosaceae	*Inga thibaudiana*	20	-33.19	47.35	1.70	3.18
Moraceae	*Maquira guianensis*	20	-32.19	41.77	2.16	2.13
Myrtaceae	*Myrcia cuprea*	20	-33.33	44.20	2.13	1.44
Annonaceae	*Guatteria schomburgkiana*	40	-32.48	45.58	1.62	2.12
Apocynaceae	*Ambelania acida*	40	-32.14	52.36	1.73	1.17
Apocynaceae	*Ambelania acida*	40	-32.39	51.44	2.05	1.05
Burseraceae	*Protium subserratum*	40	-33.94	46.79	0.28	1.65
Caesalpiniaceae	*Hymenaea parvifolia*	40	-30.44	49.51	0.06	1.91
Caesalpiniaceae	*Hymenaea parvifolia*	40	-31.05	49.37	-0.02	1.93
Caesalpiniaceae	*Chamaecrista bahiae*	40	-31.14	50.60	1.80	2.41
Caesalpiniaceae	*Chamaecrista bahiae*	40	-31.07	50.04	-0.56	2.65
Caesalpiniaceae	*Chamaecrista bahiae*	40	-31.10	49.94	0.53	2.53
Caesalpiniaceae	*Chamaecrista bahiae*	40	-30.66	48.37	-0.19	2.24
Euphorbiaceae	*Croton matourensis*	40	-27.06	49.28	0.89	3.01
Euphorbiaceae	*Croton matourensis*	40	-29.79	47.68	1.25	2.95
Fabaceae	*Swartzia arborescens*	40	-30.92	47.85	1.57	3.21
Lacistemaceae	*Lacistema pubescens*	40	-31.96	49.30	0.96	2.12
Lacistemaceae	*Lacistema pubescens*	40	-32.61	47.11	1.94	2.40
Lauraceae	*Ocotea guianensis*	40	-29.34	48.84	-0.29	1.63
Lecythidaceae	*Lecythis lurida*	40	-30.56	48.99	2.45	2.83
Lecythidaceae	*Lecythis lurida*	40	-31.35	49.72	4.18	2.87
Mimosaceae	*Inga auristellae*	40	-32.87	47.12	1.76	2.54
Mimosaceae	*Inga gracilifolia*	40	-30.20	46.89	1.17	3.10
Mimosaceae	*Inga rubiginosa*	40	-30.28	47.62	2.83	2.79
Mimosaceae	*Inga rubiginosa*	40	-30.14	47.98	1.21	2.65
Mimosaceae	*Stryphnodendron pulcherrimum*	40	-27.73	47.36	2.94	4.23
Myrtaceae	*Myrcia fallax*	40	-33.57	45.36	-1.16	1.43
Myrtaceae	*Myrcia fallax*	40	-33.73	45.15	-0.09	1.47
Anacardiaceae	*Tapirira guianensis*	mature	-29.57	45.65	1.14	2.11
Anacardiaceae	*Tapirira guianensis*	mature	-29.07	45.38	1.43	2.10
Annonaceae	*Guatteria poeppigiana*	mature	-31.04	47.89	2.11	1.87
Apocynaceae	*Lacmellia aculeata*	mature	-33.56	47.68	1.08	1.54
Bignoniaceae	*Jacaranda copaia*	mature	-31.94	48.18	1.41	2.47

Burseraceae	*Protium pallidum*	mature	-29.16	44.51	0.76	1.31
Buseraceae	*Protium tenulfolium*	mature	-31.63	49.08	1.27	1.80
Cecropiaceae	*Pourouma velutina*	mature	-30.93	45.56	2.10	2.73
Flacourtiaceae	*Laetia procera*	mature	-28.29	50.14	1.72	3.04
Flacourtiaceae	*Laetia procera*	mature	-28.86	50.77	2.55	2.95
Guttiferae	*Vismia guianensis*	mature	-32.59	48.48	2.56	1.67
Mimosaceae	*Inga thibaudiana*	mature	-32.17	48.44	3.42	2.95
Mimosaceae	*Pseudopiptadenia suaveolens*	mature	-32.40	48.85	3.11	2.83
Mimosaceae	*Stryphnodendron pulcherrimum*	mature	-30.57	49.06	2.72	3.40
Mimosaceae	*Abarema jupunba var. jupunba*	mature	-33.92	48.92	1.83	2.91
Mimosaceae	*Abarema jupunba var. jupunba*	mature	-32.64	48.74	1.30	2.99
Mimosaceae	*Inga alba*	mature	-32.16	50.55	2.43	3.73
Mimosaceae	*Inga alba*	mature	-32.18	50.46	2.58	3.34
Mimosaceae	*Inga alba*	mature	-34.70	48.43	4.59	3.21
Mimosaceae	*Inga thibaudiana*	mature	-33.81	49.11	3.11	3.27
Sapotaceae	*Pouteria oblanceolata*	mature	-29.10	49.63	2.17	1.84
Tiliaceae	*Apeiba burchellii*	mature	-29.91	45.98	2.15	2.04
Tiliaceae	*Apeiba burchellii*	mature	-29.36	46.02	2.56	2.08
Tiliaceae	*Apeiba burchellii*	mature	-33.15	44.35	1.22	2.55

Analysis of variance shows that there was no difference in foliar ^{15}N enrichments between legume and non-legume species ($p = 0.19$), although leguminous species had significantly higher foliar N concentrations ($p = .0001$) and significantly lower C:N ratios ($p = 0.0001$).

Table S3. P-values of site (chronosequence) and forest age effects in analyses of variance (ANOVA). To address uncertainty in the ages of the mature forests, three approaches were used. One ANOVA was conducted with data from all forest ages, using rankings of 1-7 for the 3, 6, 10, 20, 40, and 70 year-old forests and mature forests, respectively. A second ANOVA was conducted on all data, using the logarithm of forest age as a continuous variable and conservatively assuming an age of 200 years for the mature forests. A third ANOVA omitted the data of the mature forests, and used the logarithm of known forest ages as a continuous variable for all secondary forests only. P-values ≤0.05 are in bold font.

Dependent variable	All data				Mature forests excluded	
	age as rank		log age		log age	
	site effect	age rank effect	site effect	log age effect	site effect	log age effect
foliar ^{15}N	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.002**	**0.021**
foliar N conc.	0.081	**0.007**	0.078	**0.006**	0.255	**0.037**
litterfall mass:N	**0.004**	**<0.001**	**0.002**	**<0.001**	**0.003**	**<0.001**
litterfall N:P	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.014**
soil NO_3^-	0.117	**<0.001**	0.151	**0.002**	**0.037**	**0.025**
soil NO_3^-:NH_4^+	0.071	**0.005**	0.072	**0.005**	0.210	0.057
nitrous oxide	**0.048**	**0.022**	0.052	**0.031**	0.243	0.119