Supplementary material

Fire-derived organic carbon turnover in soils on a centennial scale

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Methodology

1. Average turnover time: We calculated turnover times based on two data point for each study, the initial stock of PyC and final PyC remaining at the end of the experiment, using Eq. (1). Most studies had only these two data points and intermediate points that were reported in few studies (Hamer et al., 2004; Brodowski, 2005; Kuzyakov et al., 2009) were not included for consistency. The turnover time for compiled data set was then estimated by averaging individual turnover times. We observed that turnover time for PyC ranges from <1 to 750 years and average value of 88 y (Supplementary Figure 2).

$$C_t = C_0 e^{-kt} \quad (1)$$

where C_t is the remaining stock after time t (y), C_0 is the initial stock of PyC (t =0), k is the decay rate (y^{-1}) and turnover time τ (y) =1/k .

2. For model fit turnover time: The compiled data set (n = 54) was used to generate time series decrease in stock of PyC (with initial stock at time t = 0 being 100 % and the last point of each study correspond to remaining stock at time t in the time series) and two models used in this study were fitted to it using non linear regression.

a) One-pool model was fitted using constrained non-linear regression using chi-square minimization in IBM SPSS statistics software package for Mac.

b) Two-pool model was fit to the compiled data set using constrained non-linear parameter estimation procedures in IBM SPSS statistics software package for Mac. The curve fitting values were iterative and required initial starting values. To avoid errors due to convergence to local minima of residual sum of squares (RSS), we adopted convergence criteria used by Updegraff (Updegraff et al., 1995), where final parameter estimates were accepted only if equations converged to the same values given starting values up to 50% above and below them. The explained variance for two-pool model is given in Supplement Table 3.

Statistical analysis

Non-parametric test for comparison between factors were carried using Wilcoxon rank sum test. A three way ANOVA was done on the data set using R software to test the interaction between the variables (Supplement Table 4). Therefore, the imbalanced design of the grouped data (Supplement Table 5) does not introduce any significant error in the interpretation.

Supplement Table 1: Studies that calculated the mean residence time (and/or half life) of PyC using modelling approach. Most studies assume two-pool model approach with a fast mineralizable pool and a slow mineralizable pool.

References	Duration of experiment	Type of experiment	Type of char	Model used to predict MRT	Parameters	Assumptions	MRT calculated
(Baldock and Smerni 2002)	120 days	Incubation	Sap wood, *Pinus resinosa* (charred at <200° and 200-350º C)	No model used			Not calculated
(Hamer et al., 2004)(Hamer et al., 2004)	60 days	Incubation	Maize (at 350° C) Rye (at 350º) and wood at (at 800º C)	**Two-pool decay model**	1. Finely ground PyC material 2. Water holding capacity (WHC) was adjusted to 60% 3. Samples were incubated at 60°C. 4. pH value of maize/sand, rye/sand and wood/sand were 8.0, 6.7, and 6.5, respectively.	Twice as much PyC was mineralized in first 26 days compared to next 30 days suggested, one fast degradable pool and other slow degradable pool.	39 years for charred straw residues and 76 years for charred wood
(Brodowski, 2005)	2 years	Incubation	*Zea mays* (maize) and *Secale cereale* (rye straw) at 350° C	**One-pool decay model** $X_t = X_e + (100\text{-}Xe)\ \exp(-kt)$ where X_t is PyC concentration at incubation time t , X_e calculated end PyC concentration, k is rate constant(year^{-1})	1. Finely ground PyC 2. WHC = 70% 3. incubated at 20°C in dark	All PyC is degradable, $X_t = 100\ \exp(-kt)$	Turnover time of 8 years
(Hammes et al., 2008)	100 years	Field	Wildfire in a steppe land cover	**One pool, donor controlled model**	1. Mean annual temperature (MAT)	1) PyC is homogeneous with respect to turnover	Maximum turnover time

				$\tau = -t/[\ln(f-b)/(f-1)]$ where τ = turnover times(in years); t = time between samplings (years); f+ ratio of modern PyC flux to historic input flux; b = fraction of original PyC stock remaining	between 1989-1998 was 6.6°C while between 1893-1950 was 5.5°C. 2. Total annual rainfall between 1989-1998 iwas 507.7 mm and between 1893-1950 was 438.5 mm.	2) loss of PyC from soil is a first order decay process 3) after 1900 sampling , PyC inputs decreased in accord with the decrease in regional fire frequency	to be between 444-541 years and minimum to be between 212-262 years.
(Nguyen et al., 2008)(Nguyen et al., 2008)	100 years	Field	Slash and burn of native forest	Used **One pool model** with three parameters $f = Y_0 + ae^{-bt}$ $f = Y_0 + a(1-e^{-bt})$ where f = PyC content at time t (year); Y_0 = PyC content at time zero; a = constant, b = reaction rate constant	1. MAT = 19°C 2. MAP = 2000 mm 3. deep dark reddish soil with friable clay and thick humic topsoil with 45-49% clay, 15-25% silt and 26-40% sand. 4. PyC size particle ranged from 5 to 90 mm. 5. Stocks were calculated based on PyC content and bulk density in the top 0.1 m	1. Erosion losses presumed to be low since flat landscape positions were selected to minimize lateral soil export 2. Long term losses by erosion or vertical transport were low since PyC stocks did not decrease beyond 20 years.	8.3 years of MRT (a rate change of 0.12 $year^{-1}$ of total PyC)
(Liang et al., 2008)(Liang et al., 2008)	532 days (1.5 years)	Incubation	High-PyC containing Anthrosols soils	**Two-pool decay model** $X_t = X_1 (1-e^{-k1t}) + X_2 (1-e^{-k2t})$ where X_t =mineralizable C; X1 = size of the stable C pool; k1 and k2 = mineralization rates of the labile and stable pools, respectively; and t = time of incubation (days)	Turnover time of total SOC (calculated as the ratio of soil C and CO_2-C loss over 532 days at 30°C incubation temperature)	Two pool consisting of 1) a large stable pool with a slow turnover rate comprising PyC and /or stable SOM 2) a smaller and easily mineralizable C pool of higher turnover rate	Turnover time was between 44-52 years in BC rich soils as compared to 9-20 years in adjacent soils.

(Cheng et al., 2008a)	130 years	Field	Hardwood (chestnut, hickory, oak and sugar maple) produced similarly as wildfire	Not used	n/a	n/a	Not calculated
(Lehmann et al., 2008)	100 year	Modeling approach with different scenarios	Savannah region wildfire PyC	Using single exponential function for scenario 4 i.e. both biomass consumption by fire and the formation of PyC is considered and PyC disappears over time. PyC mineralization was calculated with a **first order decay** to CO_2	1. Equilibrium conditions were established for PyC and non-PyC pools for an average of each soil set 2. MAP= 887 mm and 738 mm, MAT for both is 27°C 3. Clay content is 13% and 21 %, respectively	1.60-90% biomass burned 2.Conversion of burnt biomass to PyC to be between 1-4.5% 3. Belowground C input from grass vegetation was not altered as a result of burning.	Between 718 to 9259 years Applying MRT of 1300 yr could SOC and PyC modelled equilibrium matched experimental observations
(Cheng et al., 2008b)	177 days for PyC conataing soil 50 days for isolated PyC particles	Incubation	PyC samples were collected from the remnants of historic charcoal blast furnances, which were deposited during 1870s. PyC were produced from woods of chestnut, hickory, oak and sugar maple	For PyC, a **one pool decay model** was used to fit OC mineralization kinetics $OC_{cum}(t) = OC_0\,(1\text{-}exp(\text{-}kt)$ where $OC_{cum}(t)$ = cumulative mineralized OC at time t; OC_0 = the amount of "potential" mineralizable OC (mg g^{-1} PyC-C); k = decomposition rate constant for potential C mineralization (day^{-1})	1. WHC = 60% 2. Incubated at 30°C 3. 130 year old PyC samples collected from soil.		Mean half life for potential mineralized OC was around 19 days (varied between 10-31 days)
(Cheng and Lehmann, 2009)	1 year	Incubation	Wood logs of white oak and red oak prepared similarly	Not used	1. Aerobic incubation 2. At temperature, -22°C, 4°C, 30°C and	n/a	Not calculated

			as furnance making charcoal		70°C. 3. In water medium		
(Hilscher et al., 2009)	48 days	Incubation	Rye grass (*Lolium perenne*), Pine wood (*Pinus sylvestris*) charred 350° C under oxic condition for 1 minute and 4 minutes	**Two pool decay model**	Controlled aerobic conditions	Used mean mineralization rate of last 10 days when the mineralization rate showed no decline	14 and 19 years for charred rye grass residues and upto 56 years for pine wood chars.
(Kuzyakov et al., 2009)	1089 days (3.9 years)	Incubation	^{14}C labeled *Lolium perenne* charred for 13 h at 400° C	Decomposition of PyC was estimated based on $^{14}CO_2$ efflux and mean **decomposition rate was calculated based on loss of PyC**	1. Soils were incubated at 70% water holding capacity 2. Incubated at 20°C 3. Two types of soil, one with low amount of organic C	Biological activity of a loamy soil in the field is about 10% of that under optimal conditions based on biological active time approach for loamy soil.	Observed MRT = 200 years and based on the assumption of field condition, MRT = 2000 years
(Liang et al., 2010)	532 days	Incubation	PyC rich Anthrosols with distinct ^{13}C isotopic composition using the C4 plant was added to originally C3 dominated soil	**Two-pool decay model** $X_t = X_1\,(1-e^{-k1t}) + X_2\,(1-e^{-k2t})$ where X_t =mineralizable C; X1 = size of the stable C pool; k1 and k2 = mineralization rates of the labile and stable pools, respectively; and t = time of incubation (days)		Two pool consisting of 1) a large stable pool with a slow turnover rate comprising PyC and /or stable SOM 2) a smaller and easily mineralizable C pool of higher turnover rate	Does not calculate MRT for PyC
(Major et al., 2010)	2 years	Field	Mango tree	**Two-pool decay model**	1. at 26°C mean annual		MRT of 600

			(*Mangifera indica L.*) charred between 400-600° C		temperature (MAT) 2. PyC was ground and < 0.9 mm 3. PyC applied at the onset of the dry season and incorporated to soil under native savanna vegetation that was never tilled or cropped.First order decay to CO_2		years [When normalized to MRT = 10°C (from 26°C using a Q_{10} of 3.4) the resulting MRT = 3264 years]
(Zimmerman, 2010)(Zimmerman, 2	1 year	Incubation	*Quercus laurifolia* (living wood oak); *Pinus taeda* (pine); *Juniperus virginiana* (cedar); *Guibourtia demusei* (tropical hardwood); *Tripsacum dactyloides* (mixed stems and blades of gamma grass); Sugarcane baggase charred at 250° C under oxic condition and at 400° C, 524° C and 650° C under N_2	$C_{lost} = C_0 – C_t$ $= [C_0\ e^b/(m+1)]\ x\ t^{m+1}$ $C_{1/2} = [(m+1)/2e^b]^{\{1/(m+1)\}}$ Where C0 = initial c amount at time t0; Ct = final C amount at final time t, m is slope and b is intercept	1) Coarse size fraction (0.25-2 mm) 2) Direct relationship was observed between the logarithmically transformed experimental degradation rate (k in units of $year^{-1}$) and time (in units of years)	1) Biphasic composition consisting of a more labile volatile component of relatively lower C and higher O content and a non-volatile, high C and low O material 2) time degradation rate relationship is maintained in future	Half life varies between 260-840 years for 250°C, 370-23,800 years for 400°C, 930-12,800 years for 525°C, 15,600- 2.0 x 10^7 years for 650°C.
(Hilscher and Knicke 2011)	28 months	Incubation	Rye grass (*Lolium perenne*), Pine wood (*Pinus sylvestris*) charred	**Two-pool decay model** $y = a\ .\ e^{(-k1.\ t1)} + b.\ e^{(-k2.\ t2)}$	1. The water content of the soil samples was adjusted to ca. 60% of the maximum water	1. linear regression model resulted in lower R^2 in the range 0.42–0.82, which supports the	The calculated $t_{1/2}$ implies mean residence

350° C under oxic condition for 1 minute and 4 minutes	where a = fast decomposable OM pool; b = slowly decomposable OM pool; k_1 and k_2 are turnover constant rate ($year^{-1}$) at respective time t	holding capacity 2. Incubated at 30 °C in the dark under aerobic conditions.	idea that the PyOM is composed of C pools with different decomposition kinetics.	times between 26 and 31 years for the more stable Pool B.

Supplement Table 2: Studies used in the meta-analysis to calculate the turnover time of PyC in terrestrial systems using mono-exponential decay model.

Reference	Experimental set up	Matrix	Soil type	Climate/ moisture/ temperature	Type of substrate	Pyrolysis temp	Study duration (year)	% of the initial PyC	Individual k ($year^{-1}$)	Individual MRT, first order decay (year)
(Baldock and Smernik, 2002)	Incubation	Sand	Sand (packed at 1.6 bulk density	At 25º C and volumetric water content of 0.29 cm^3 water cm^{-3} soil	Wood	150°C	0.33	87	0.4260	2.35
					Wood	>200°C	0.33	98	0.0618	16.18
(Hamer et al., 2004)	Incubation	Sand	Sand + 1ml inoculum + 0.5ml nutrient solution	At 20º C and 60% water holding capacity (WHC)	Maize (Grass)	350°C	0.16	99.22	0.0479	20.87
					Rye (Grass)	350°C	0.16	99.28	0.0442	22.62
					Wood	800°C	0.16	99.74	0.0159	62.79
(Brodowski, 2005)	Incubation	Soil	Top soil; Ap horizon; 0-25 cm: Haplic Phaeozem	At 20º C and 70% WHC	Maize (Grass)	350°C	2.00	78.73	0.1196	8.36
		sand			Maize (Grass)	350°C	2.00	48.04	0.3666	2.73
		Soil			Rye (Grass)	350°C	2.00	77.91	0.1248	8.01
(Cheng et al., 2008a)	Field	Soil	Soil	Incubated at 30º C and70º C	Oak wood	450-600°C	130.00	77.64	0.0019	513.66

(Bruun et al., 2008)	Incubation	Soil	Sandy loam	25º C	14C labelled Barley root (Hordeum vulgare)	225°C	0.08	98.1	0.2494	4.01
						300°C	0.08	98.6	0.1833	5.46
						375°C	0.08	91.8	1.1123	0.90
(Major et al., 2010)	Field	Soil	Isohypertherm ic kaolinitic Typic Haplustox sandy clay loam	MAT = 26º C MAP = 2200 mm (95% of precipitation falls between April and December)	prunings of mango tree	600°C	2.00	97.8	0.0111	89.91
(Hilscher et al., 2009)	Incubation	Soil	Bw horizon of Cambisol under Spruce	Incubated at 30º C	Lolium perenne (Grass)	350°C, 1 minutes	0.13	96.9	0.2408	4.15
					Lolium perenne (Grass)	350°C, 4 minutes	0.13	97.5	0.1936	5.17
					Pinus sylvestris (Wood)	350°C, 1 minutes	0.13	99.34	0.0506	19.75
					Pinus sylvestris (Wood	350°C, 4 minutes	0.13	99.54	0.0353	28.36
(Kuzyakov et al., 2009)	Incubation	Soil	Ap horizon of a loamy Haplic Luvisol	Incubated at 20º C and 70% WHC	shoot litter of L perenne	400°C	3.23	95.5	0.0143	70.17
(Zimmerman , 2010)	Incubation	Sand	Quartz Sand	Incubated in the dark at 32 °C	Oak (Wood)	250°C	1.00	97.8	0.0222	44.95
					Pine (wood)	250°C	1.00	97.07	0.0297	33.63
					Cedar (Wood)	250°C	1.00	98.72	0.0129	77.62
					Bubinga (wood)	250°C	1.00	98.6	0.0141	70.93
					Gamma grass	250°C	1.00	98.8	0.0121	82.83
					Sugar Cane (Grass)	250°C	1.00	98.3	0.0171	58.32
					Oak (Wood)	450°C	1.00	97.93	0.0209	47.81
					Pine (wood)	450°C	1.00	98.88	0.0113	88.78

					Cedar (Wood)	450°C	1.00	98.95	0.0106	94.74
					Bubinga (Wood)	450°C	1.00	99.11	0.0089	111.86
					Gamma grass	450°C	1.00	96.98	0.0307	32.61
					Sugar Cane (Grass)	450°C	1.00	98.17	0.0185	54.14
					Oak (Wood)	525°C	1.00	99.22	0.0078	127.70
					Pine (Wood)	525°C	1.00	99.16	0.0084	118.55
					Cedar (Wood)	525°C	1.00	99.07	0.0093	107.03
					Gamma grass	525°C	1.00	98.43	0.0158	63.19
					Sugar Cane (Grass)	525°C	1.00	98.83	0.0118	84.97
					Oak (Wood)	650°C	1.00	99.15	0.0085	117.15
					Pine (wood)	650°C	1.00	99.09	0.0091	109.39
					Cedar (Wood)	650°C	1.00	99.45	0.0055	181.32
					Bubinga (Wood)	650°C	1.00	99.38	0.0062	160.79
					Gamma grass	650°C	1.00	98.75	0.0126	79.50
					Sugar Cane (Grass)	650°C	1.00	99.4	0.0060	166.17
(Nocentini et al., 2010)	Incubation	Sand	Sand	Incubated at 20º C and 50% WHC	Pine needles	350°C	0.08	99.53	0.0612	16.33
					Pine wood	350°C	0.08	99.43	0.0743	13.46
(Singh et al., 2010)	Incubation	Soil	top Cambisol soil	Incubated at 25º C and 60% WHC	Pinus ponderosa (wood)	450°C	0.15	99.86	0.0091	109.81
(Bird et al., 1999)	Field	Soil	Coarse sand derived from gneissic granite bedrock	Sub-humid MAT =17.7º C MAP = 630 mm		Wildfire	100.00	50	0.0069	144.27

(Hammes et al., 2008)	Field	Soil	Chernozem soil	MAT = 6.6º C (1989-1998) and 5.3ºC (1893-1950); MAP = 507.7 mm (1989-1998) and 438.5 mm (1893-1950)	Grassland	Wildfire	100.00	75	0.0029	347.61
(Nguyen et al., 2008)	Field	Soil	Humic Nitosols (FAO/UNESCO)	Tropical MAT = 19º C MAP = 2000 mm	Forest	Wildfire	100.00	68.52	0.0038	264.51
(Cheng et al., 2008a)	Incubation	Soil	Subsurface soil for incubation	Aged charcoal from areas with MAT ranging between 3.9º C to 17.2º C and MAP between 940 mm to 1500 mm	Hardwood (chestnut, hickory, oak and sugar maple)	450-600°C	130.00	77.7	0.0019	515.23
(Vasilyeva et al., 2010)	Field	Soil	Chernozem	MAT = +5.5 ˚C MAP = 600 mm/year	Grassland	Wildfire	55.00	93	0.0013	757.88
(Bruun et al., 2011)	Incubation	Soil	Sandy Loam (Typic Hapludalf)	Incubated at room temperature (20-23º C) at constant water content (30%)	Wheat straw	475 500 525 550 575	0.32 0.32 0.32 0.32 0.32	88.10 92.10 94.60 96.00 96.90	0.4022 0.2613 0.1762 0.1296 0.1000	2.49 3.83 5.67 7.72 10.00

Supplement Table 3: ANOVA for two-pool model

	Sum of Squares (SS)	df	Mean squares (MS)
Regression	473627.92	3	157875.97
Residual	3897.936	51	76.43
Uncorrected Total	477525.86	54	
Corrected Total	7010.12	53	

R squared = 1 – (Residual Sum of Squares)/(Corrected Sum of Squares) = 0.444

Supplement Table 4: Three-way ANOVA for interactions between variables

	Df	**Sum sq**	**Mean sq**	**F value**	**Pr(>F)**
Matrix	2	24838	12419	11.7306	0.0001418 ***
Temperature of pyrolysis	1	35051	35051	33.1074	1.992e-06 ***
Initial biomass	2	3915	1958	1.8490	0.1733280
Medium: Temperature of pyrolysis	1	240	240	0.2263	0.6374453
Medium: initial biomass	1	34	34	0.0321	0.8588546
Temperature of pyrolysis: initial biomass	1	3440	3440	3.2488	0.0806158
Residuals	33	34937	1059		

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

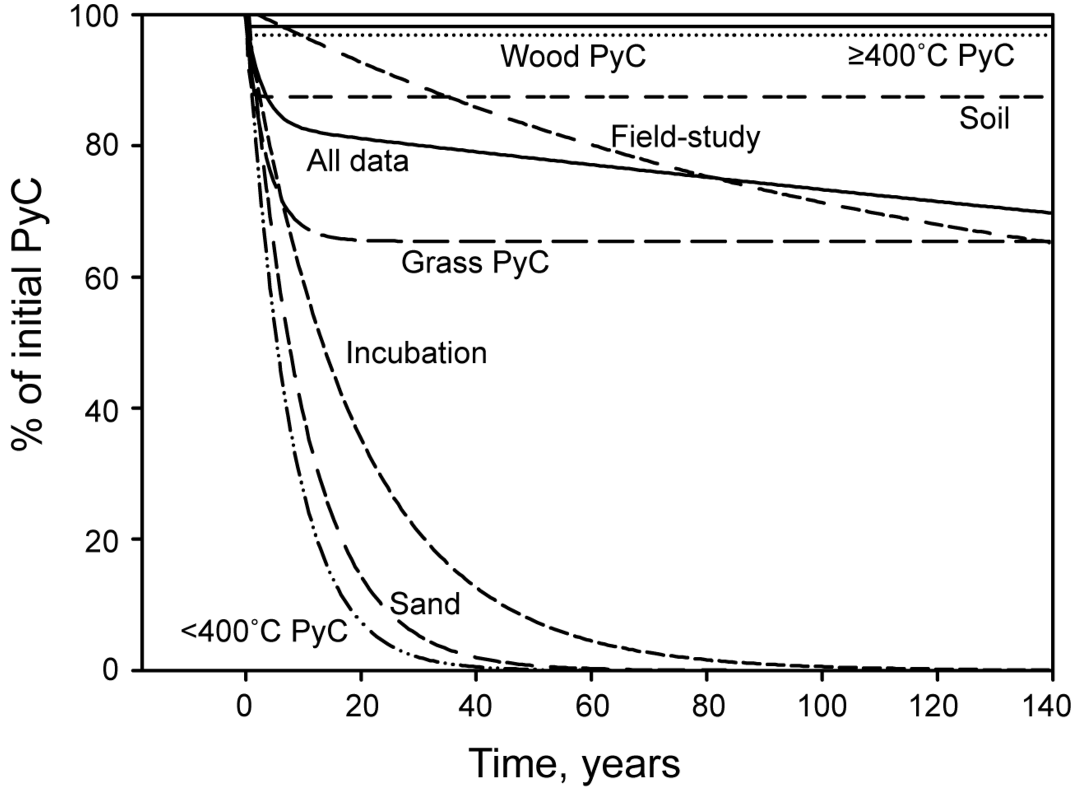
Supplement Table 5: Number of data point for each factor in the study

	Incubation	**Field study**	**Grass PyC**	**Wood PyC**	**<400ºC pyrolysis temperature**	**≥400ºC pyrolysis temperature**	**Sand medium**	**Soil medium**
Incubation	**47**	0	22	22	22	25	31	16
Field study	0	**6**	0	3	0	1	0	6
Grass PyC	22	0	**22**	0	10	12	12	10
Wood PyC	22	0	0	**22**	9	13	19	3
<400ºC pyrolysis temperature	22	0	10	9	**22**	0	13	9
≥400ºC pyrolysis temperature	25	1	12	14	0	**26**	18	8
Sand	31	0	12	19	13	18	**31**	0
Soil	16	6	10	3	9	8	0	**17**

Supplement Table 6: Turnover time calculated for grouped factors using one pool model, either average of individual study or model fit using non-linear regression.

Grouped factors	One pool	
	Average	Model fit
Incubation study (n = 47)	τ = 55 y; Stdv.[1] = 58	τ = 18 y; RSME[2] = 7.8
Field Study (n = 6)	τ = 353 y; Stdv.[1] = 249	τ = 300 y; RSME[2] = 11.2
Grass PyC (n = 22)	τ = 37 y; Stdv.[1] = 41	τ = 12 y; RSME[2] =10.1
Wood PyC (n = 22)	τ = 79 y; Stdv.[1] = 50	τ = 64 y; RSME[2] =2.8
<400°C Pyrolysis temperature (n = 22)	τ = 25 y; Stdv.[1] = 26	τ = 8 y; RSME[2] = 8.6
≥400°C Pyrolysis temperature (n = 26)	τ = 81y ; Stdv.[1] = 51	τ = 79 y; RSME[2] = 3.0
Quartz sand (n = 36)	τ = 73 y; Stdv.[1] = 48	τ = 20 y; RSME[2] = 8.5
Soil medium (n = 17, excluding field studies)	τ = 23 y; Stdv.[1] = 33	τ = 19 y; RSME[2] = 5.6

Note: [1] standard deviation; [2] root mean square error



Supplementary Figure 1: Two-pool double exponential model on grouped data namely, (a) Incubation studies (C_{fast} = 46 %, r^2 = 0.16); (b) Field Study(C_{fast} = 49.8 %, r^2 = 0.51); (c) Grass PyC* (C_{fast}= 46%, r^2 = 0.23); (d) Wood PyC* (C_{fast} = 6%, r^2 = 0.03); (e) <400° C PyC*(C_{fast}= 49.8%, r^2 = 0.46); (f) ≥400° C PyC* (C_{fast} = 46%, r^2=0.23); (g) Quartz Sand medium* (C_{fast} = 50%, r^2 = 0.20); (h) Soil medium* (C_{fast} = 12%, r^2 = 0.34). (* denotes only incubation studies included).

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