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Long-term carbon turnover rates in natural topsoils

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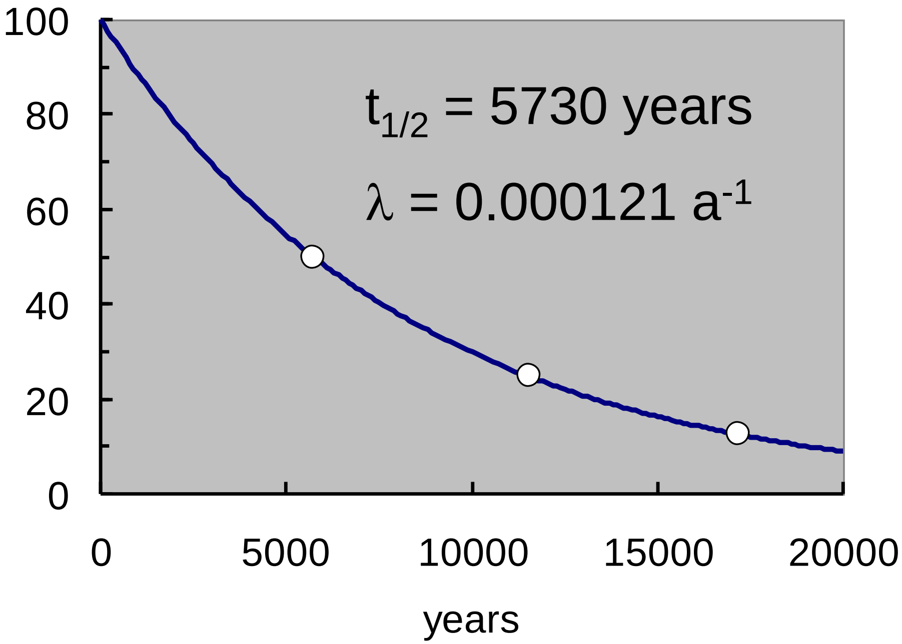
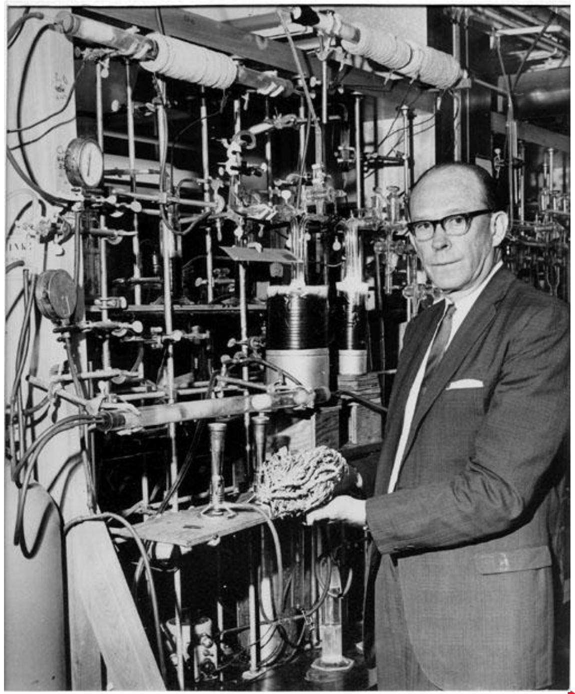
Radiocarbon

^{12}C	6 protons	6 neutrons	98.9 %
^{13}C	6 protons	7 neutrons	1 in 90
^{14}C	6 protons	8 neutrons	1 in 10^{12}

$$n + {}^{14}_{7}N \rightarrow {}^{14}_{6}C + p$$





Willard F Libby

1908-1980

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Measuring radiocarbon

Scintillation counter

radioactive emissions (β)

needs ~ 1 gC

Accelerator

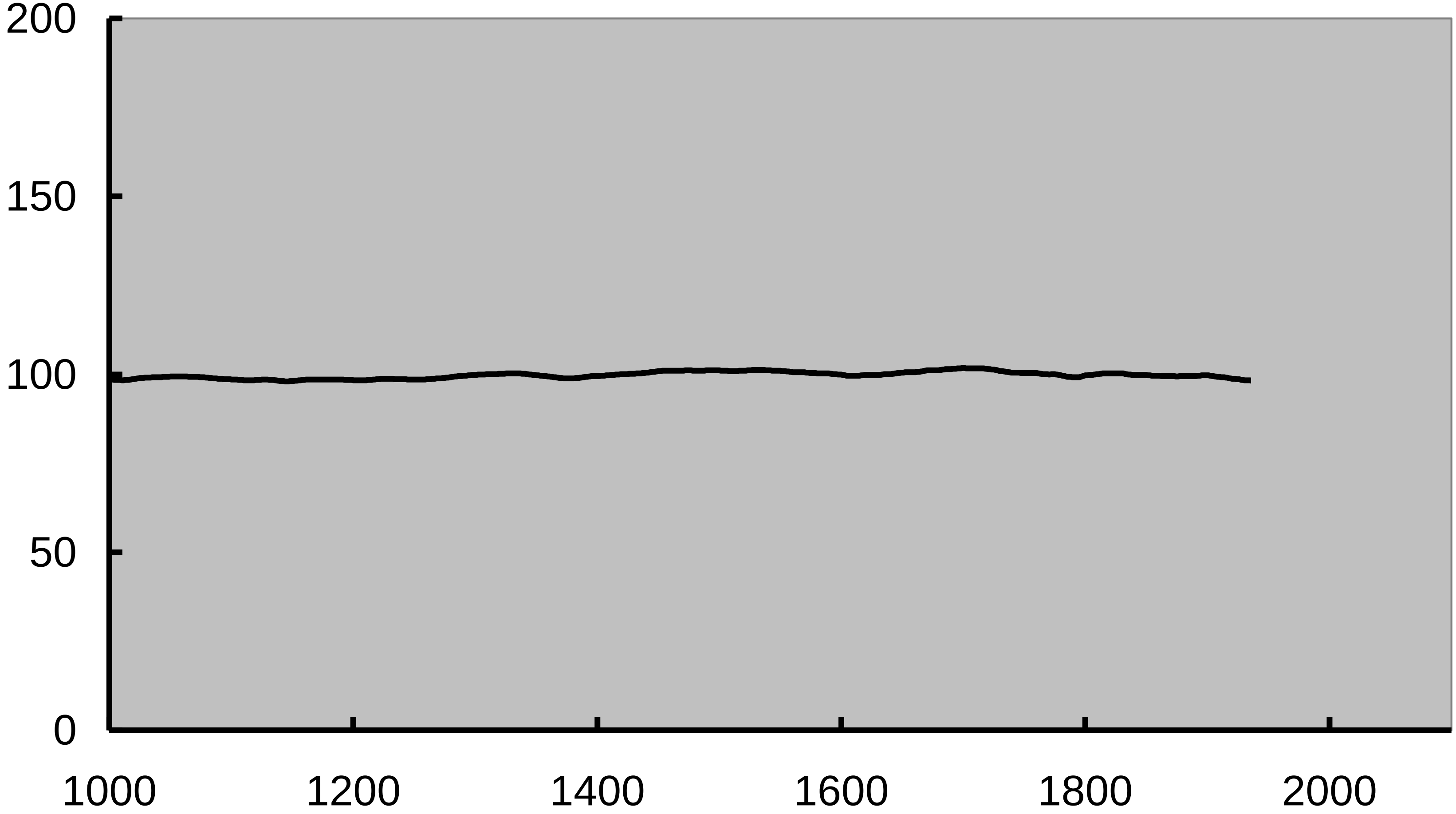
Mass

Spectrometer

at SUERC East Kilbride

Needs ~ 5 mg C

Atmospheric ^{14}C, expressed as % modern



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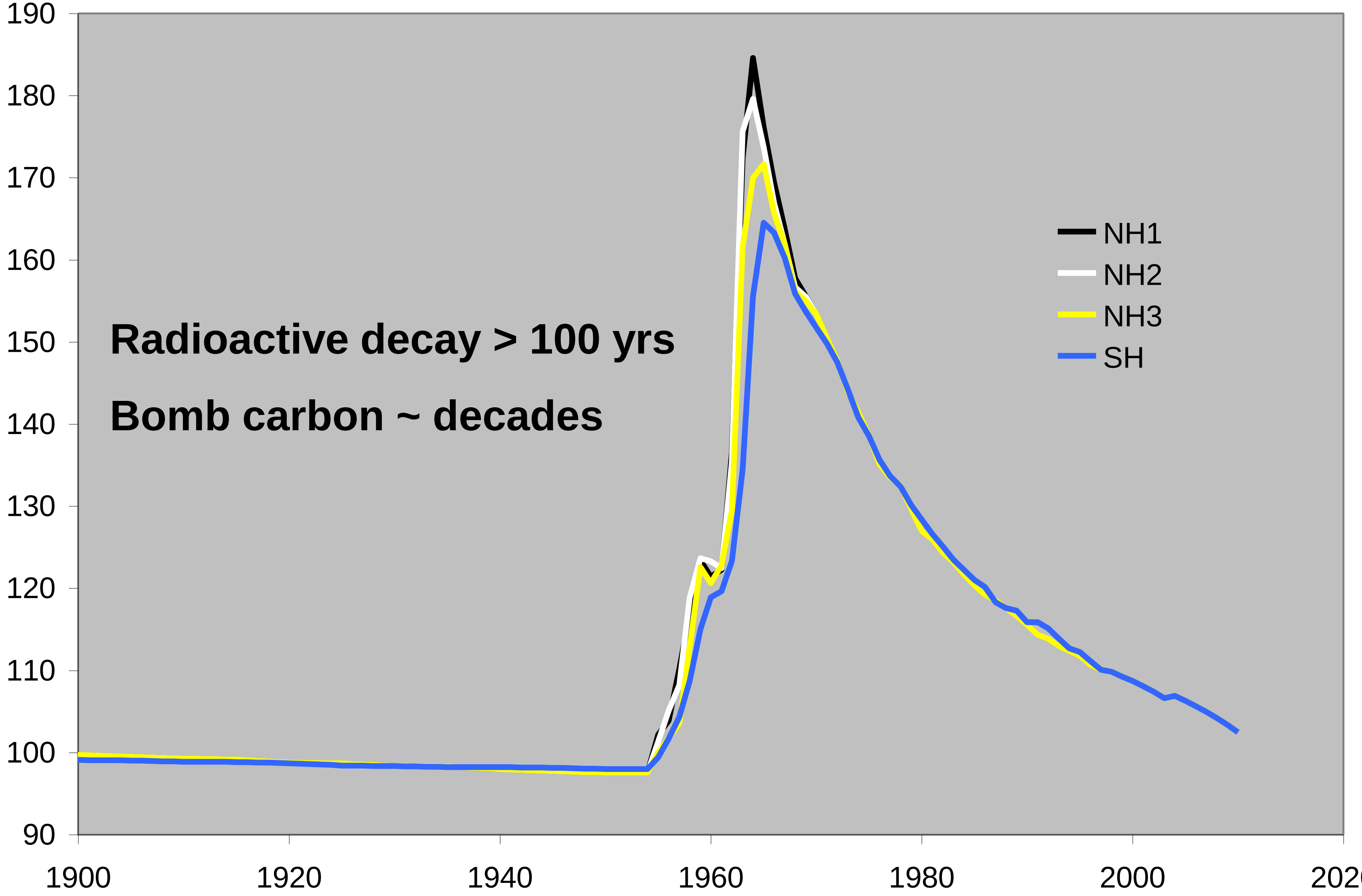
The "bomb peak"



The database and its use

<u>The database</u> *(a valuable resource)*

247 sites with data on topsoil ^{14}C (237 usable)

85% have only a single ^{14}C value

Subdivided into forest and non-forest

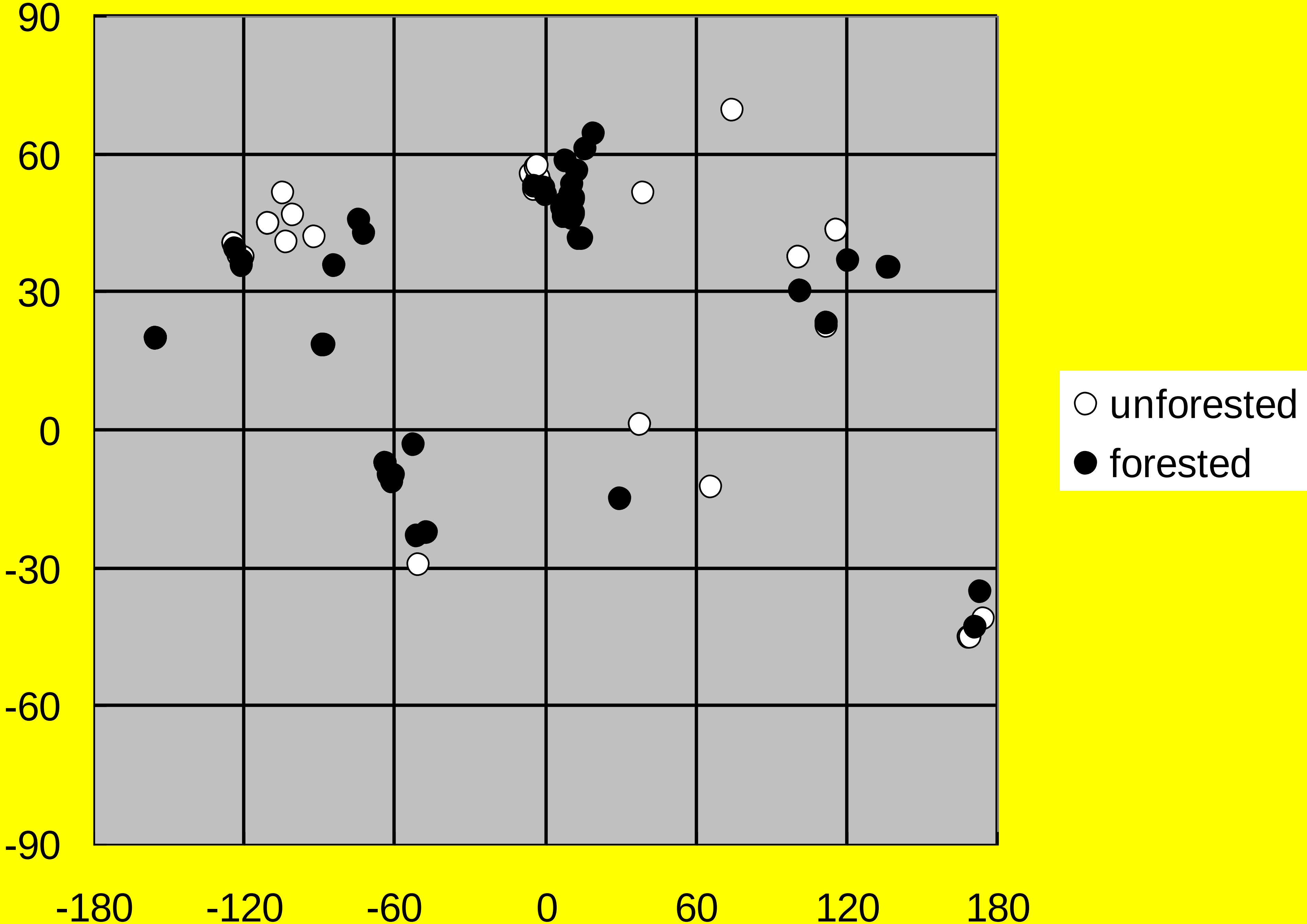
<u>Aims</u>

- Ranges and representative topsoil turnover rates
- Difference between soils under trees and non-trees
- Relationships with MAT, MAP, pH, soil type

Numbers of sites in geographical regions

	Forest	Non-forest	Total
Africa	1	2	3
Asia	7	11	18
Australasia	2	3	5
Europe	63	109	172
North America	11	23	34
Central & South America	11	4	15
latitude ranges (deg)			
0 - 22.5	15	6	21
22.5 - 45	18	32	50
45 - 67.5	61	112	173
67.5 - 90	1	2	3

7 Swiss sites
128 UK sites



90
60
30
0
-30
-60
-90
-180
-120
-60
0
60
120
180
unforested
forested

Summary of soil properties

		all	forest	non-forest	sig
depth	n	237	94	143	
cm	mean	15.2	15.2	15.2	NS
	SD	3.2	3.9	2.6	
%C	n	201	72	129	
	mean	14.5	14.5	14.5	NS
	SD	14.0	11.7	15.4	
	median	9.4	11.2	8.1	
pH	n	180	65	115	
	mean	5.3	5.4	5.3	NS
	SD	1.1	1.2	1.0	
	median	5.1	5.4	5.0	
C pool	n	237	94	143	
kg m-2	mean	6.90	6.00	7.49	$p < 0.001$
	SD	2.98	2.24	3.25	
	median	6.78	5.94	7.23	

Trends in SOC (kgC m^{-2})

Mean annual temperature

-10 to 27°C

SOC pool declines by 0.17 kg m^{-2} $°C^{-1}$

$r^2 = 0.07$, $p < 0.001$

Soil pH

3.4 to 7.8

SOC pool declines by 0.74 kg m^{-2} pH^{-1}

$r^2 = 0.08$, $p < 0.001$

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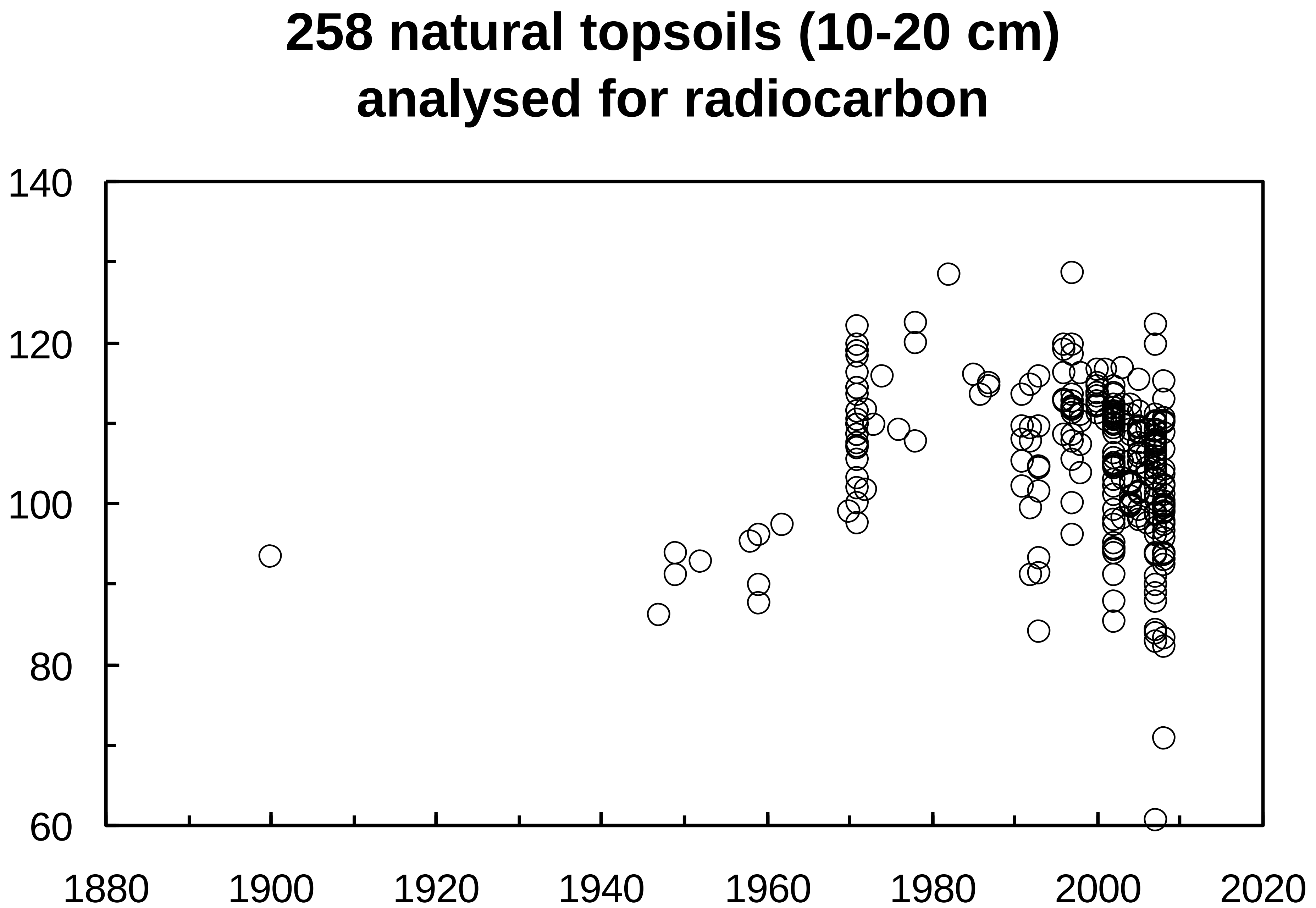
258 natural topsoils (10-20 cm)
analysed for radiocarbon
140
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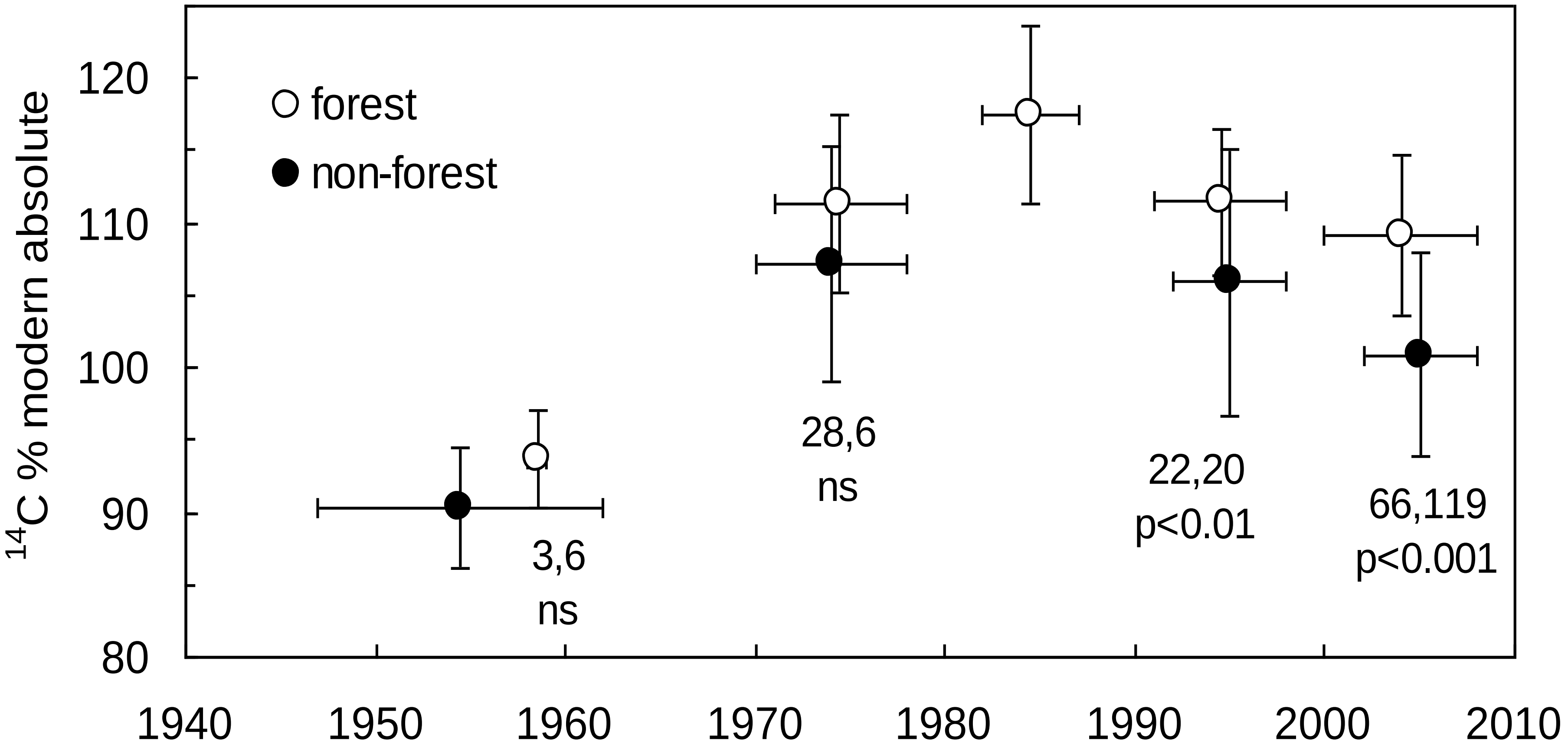
2020

forest vs non-forest



More "bomb carbon" in the forest soils indicates faster C turnover

Simplest soil carbon model (**Model I**)

- one homogeneous pool, ***in steady state***

^{14}C input =

^{14}C-litter × Y

new ^{14}C-soil =

old ^{14}C-soil +

^{14}C input - ^{14}C output

- radioactive decay

^{14}C output =

^{14}C-soil × Y

Y

gC m^{-2} a^{-1}

SOM

X gC m^{-2}

Y

gC m^{-2} a^{-1}

Mean Residence Time

MRT = X / Y years

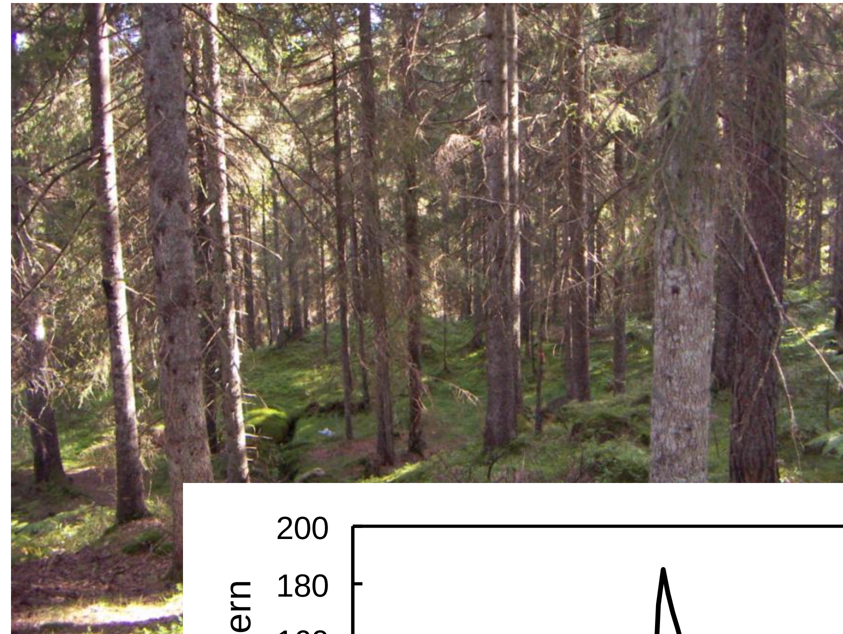
Spruce forests, Sweden

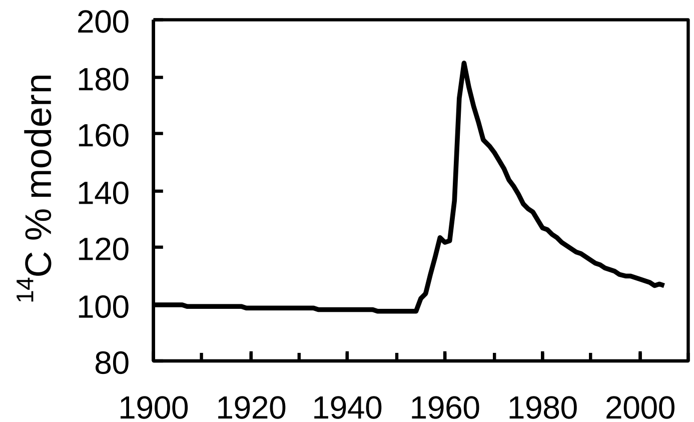
<u>O-horizon</u>

C pool ~ 2000 gC m^{-2}

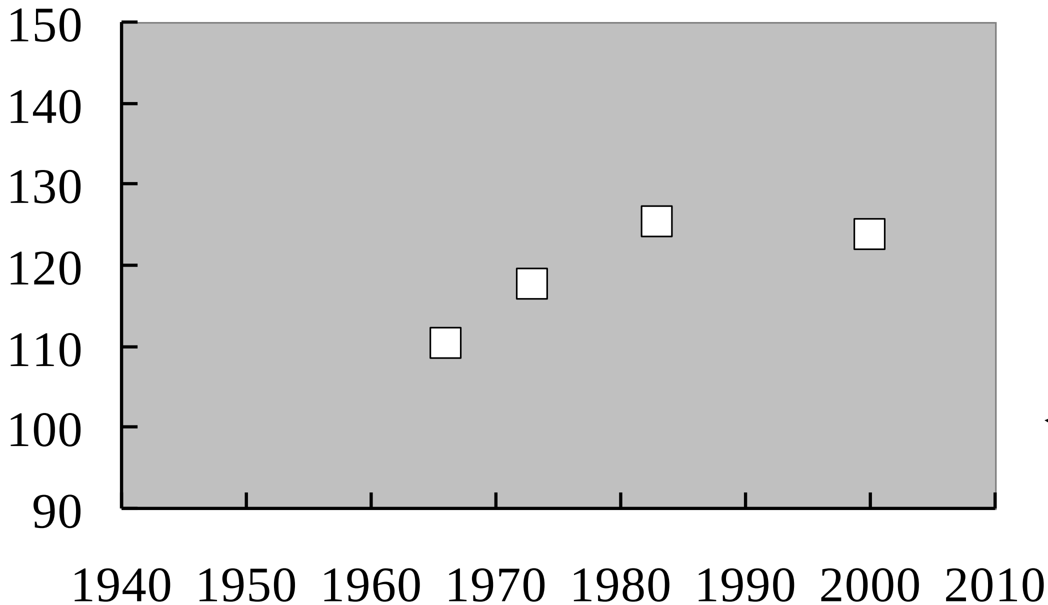
Litter input ~ 200 gC m^{-2} a^{-1}

MRT = 10 years





^{14}C data (M Fröberg, C Bryant)



5-year delay of ^{14}C in tree

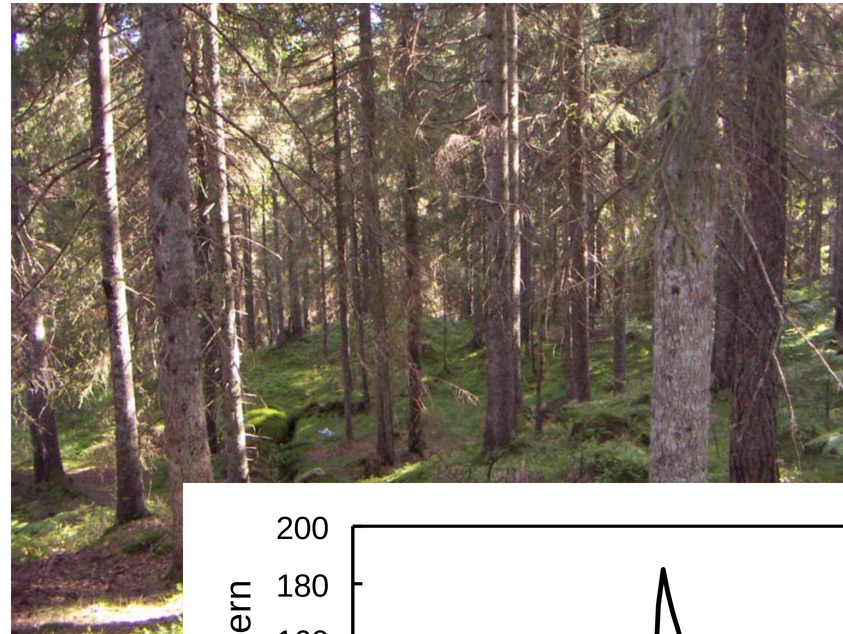
Spruce forests, Sweden

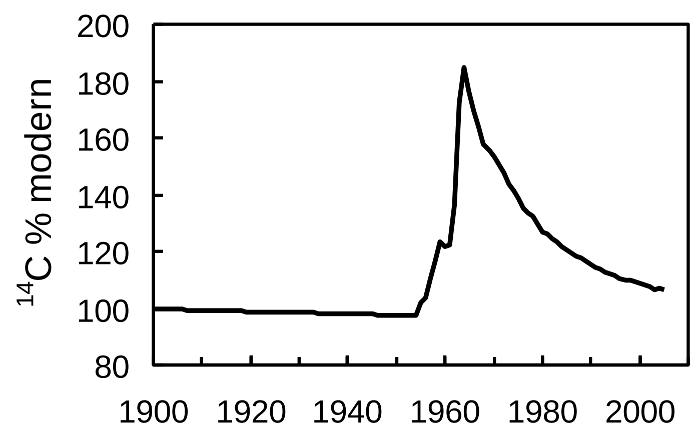
<u>O-horizon</u>

C pool ~ 2000 gC m^{-2}

Litter input ~ **200** gC m^{-2} a^{-1}

MRT = **10** years





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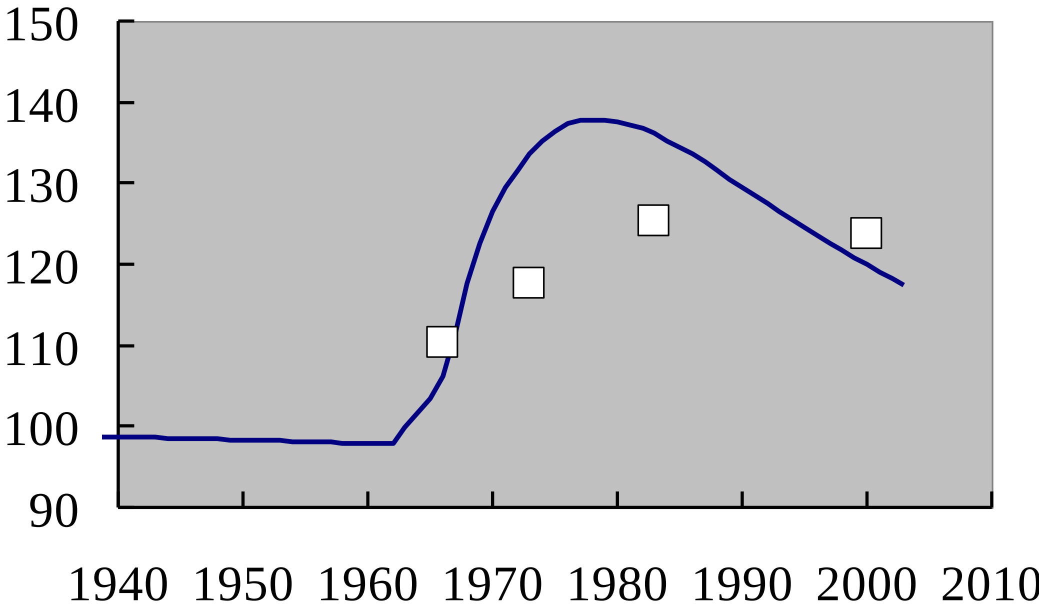


5-year delay of ^{14}C in tree

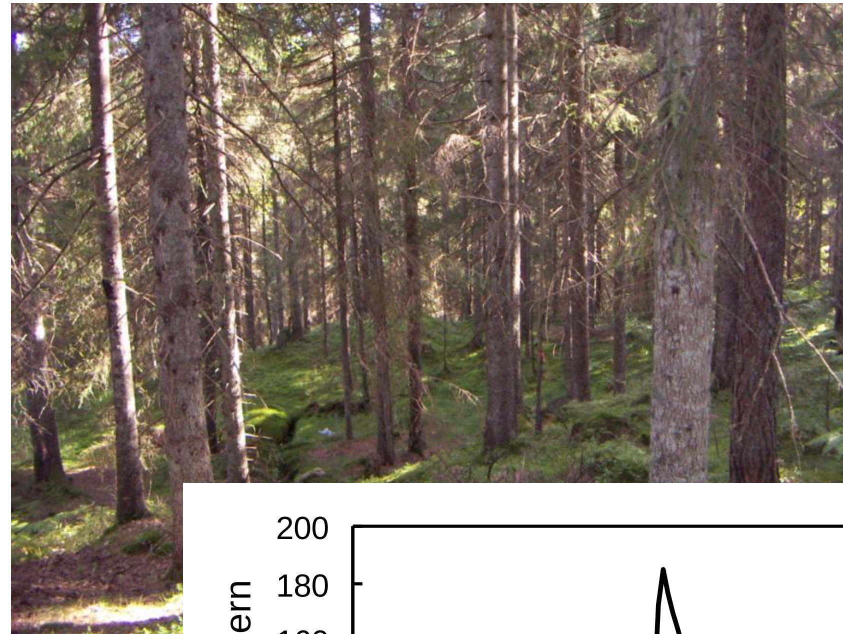
Spruce forests, Sweden

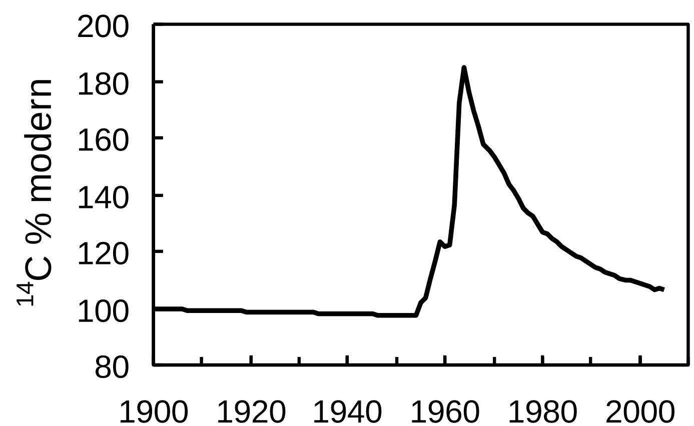
<u>O-horizon</u>

C pool ~ 2000 gC m^{-2}

Litter input ~ **100** gC m^{-2} a^{-1}

MRT = **20** years





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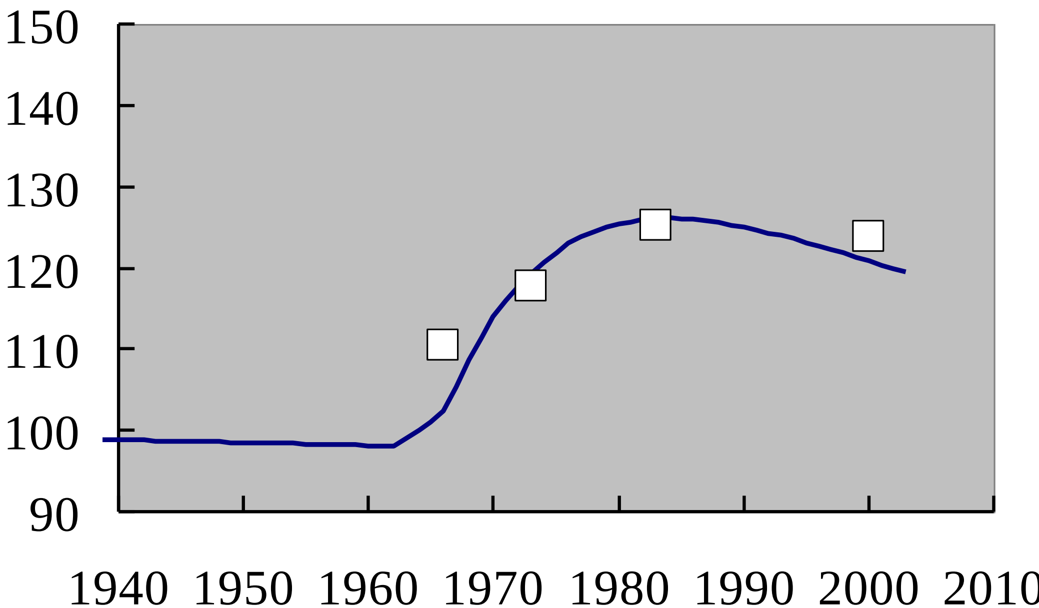
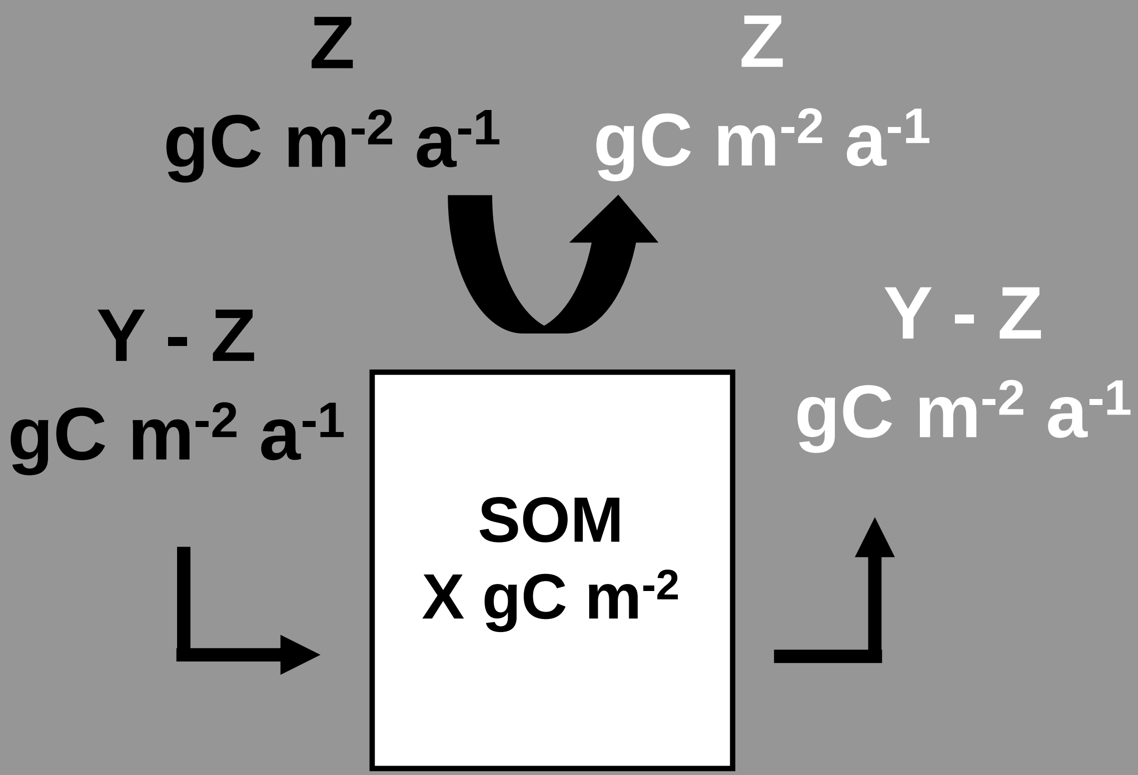


5-year delay of ^{14}C in tree

Next-simplest soil carbon model (**Model II**)

- one fast pool
- one homogeneous soil pool, ***in steady state***

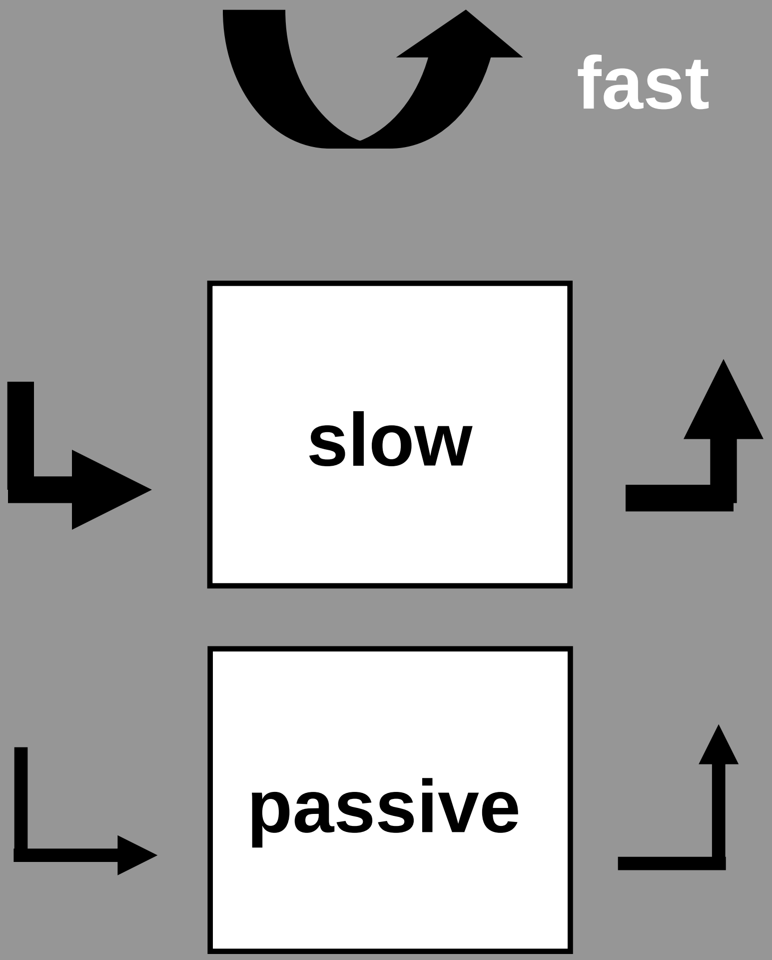


soil MRT =

X / (Y-Z) years

Three-pool soil carbon model (**Model III**)

fast - slow - passive pools (Amundson, 2001)



Requires MRTs of slow and passive pools to be specified & fixed

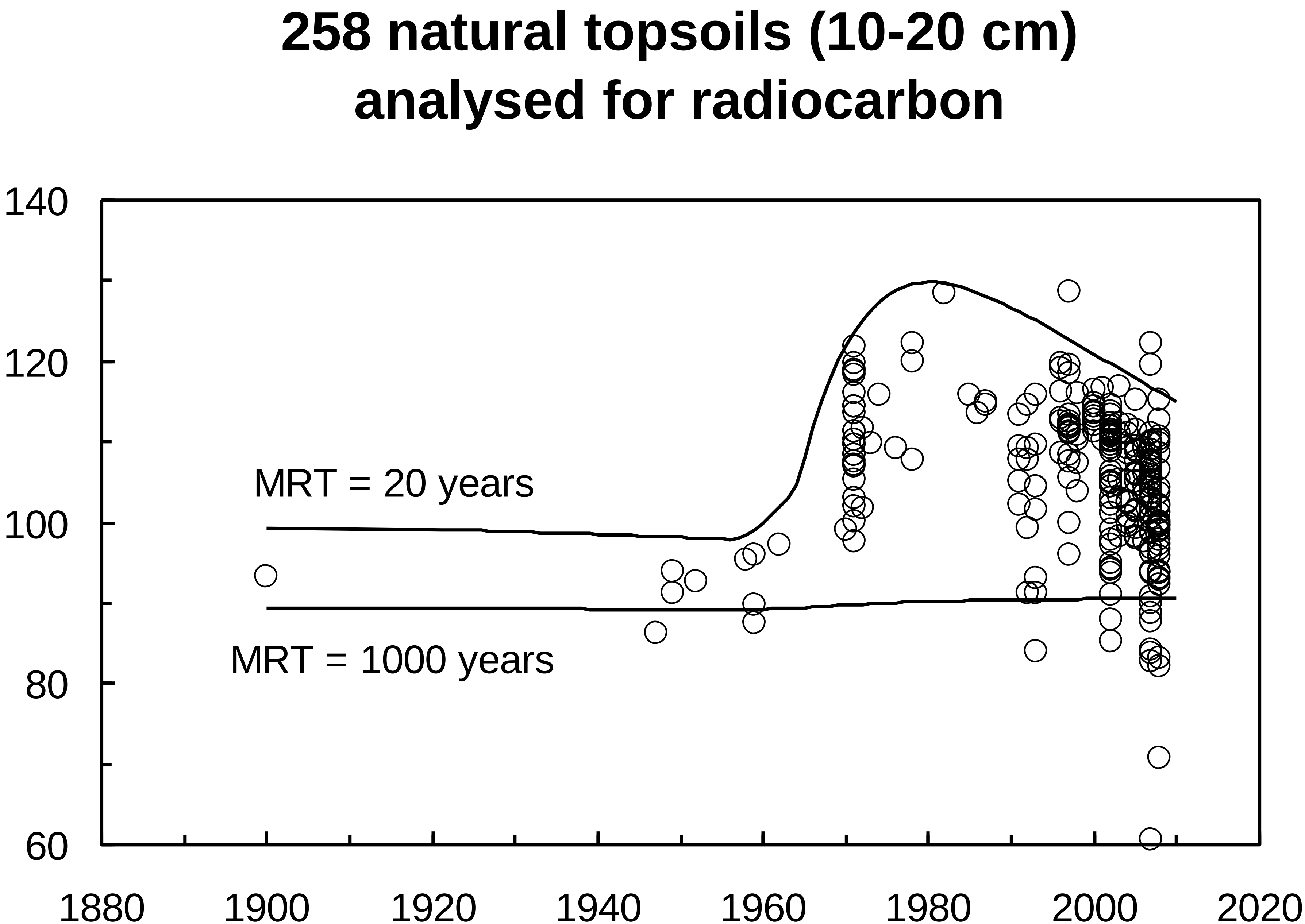
MRT slow = 20 yr

MRT passive = 1000 yr

Swiss meadow soil OC fractions

		0 - 4 cm	4 - 16/20 cm
^{14}C	SOC	105.6	101.4
	light	109.9	109.4
	micro-aggregates	106.7	101.5
	silt + clay	103.0	99.5
MRT (yr)	light	5.5	90
	micro-aggregates	125	265
	silt + clay	210	339

Leifeld & Fuhrer, EJSS, 2009



258 natural topsoils (10-20 cm)
analysed for radiocarbon
140
120
100
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60
MRT = 20 years
MRT = 1000 years
1880
1900
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2020

Data fitting

Model II

^{14}C only $\longrightarrow$ MRT

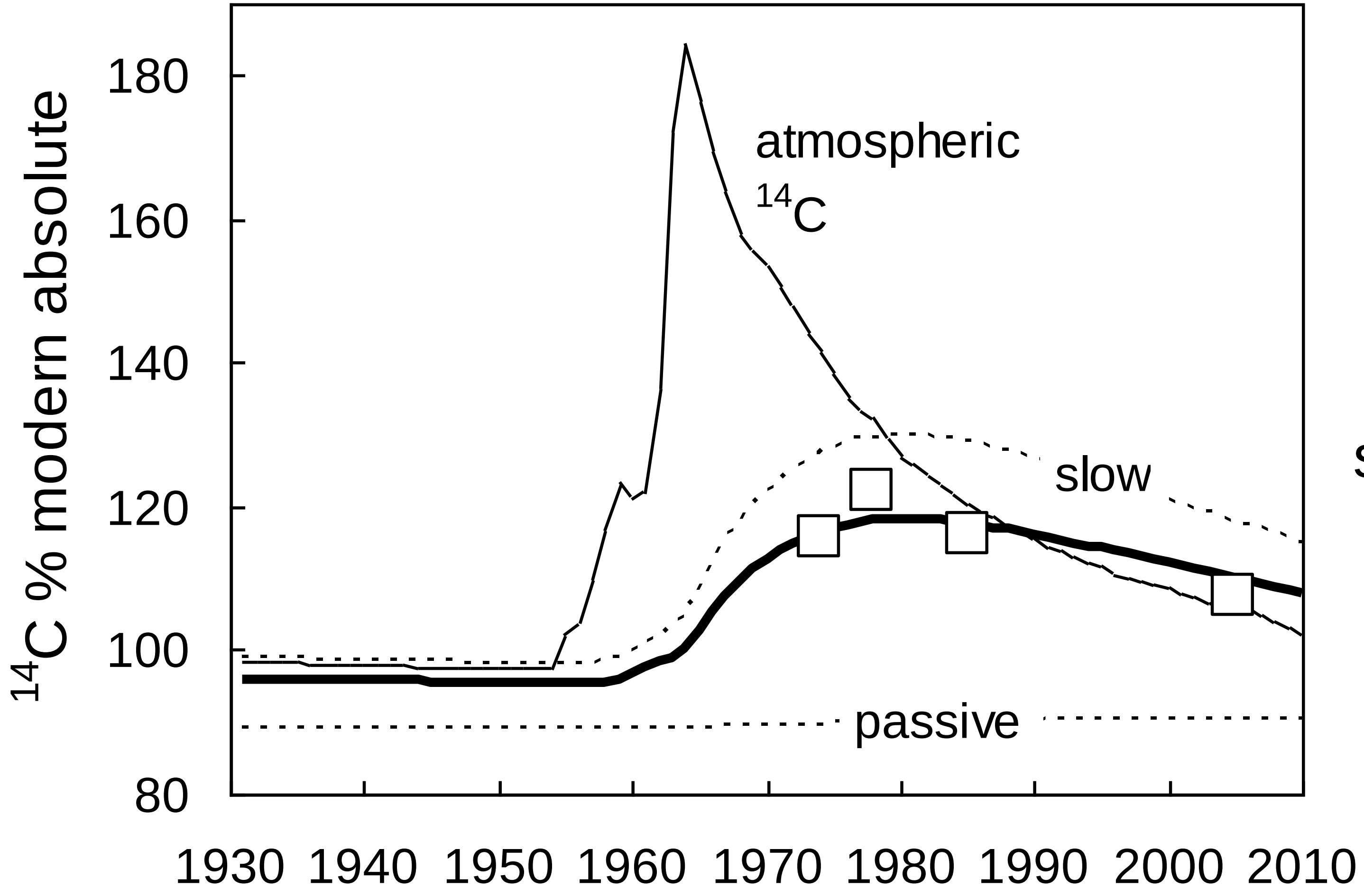
^{14}C + soil C pool $\longrightarrow$ MRT + C flux (g m^{-2} a^{-1})

Model III

^{14}C only $\longrightarrow$ slow / passive fractions

^{14}C + soil C pool $\longrightarrow$ slow / passive fractions + C flux (g m^{-2} a^{-1})

Model III forest example



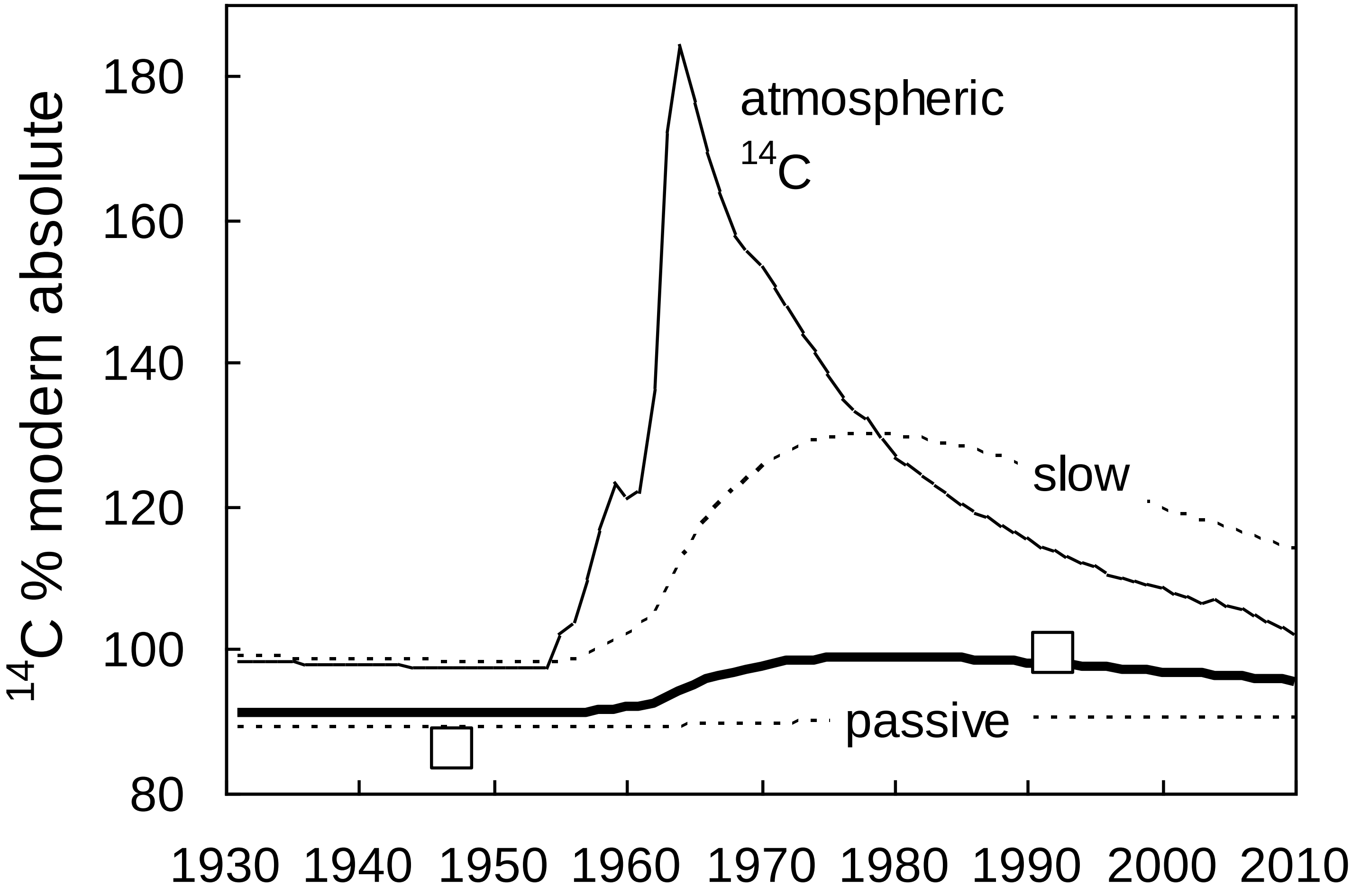
SOC

6.0 kg m^{-2}

slow fraction

0.71

Model III non-forest example



SOC

4.0 kg m^{-2}

slow fraction

0.23

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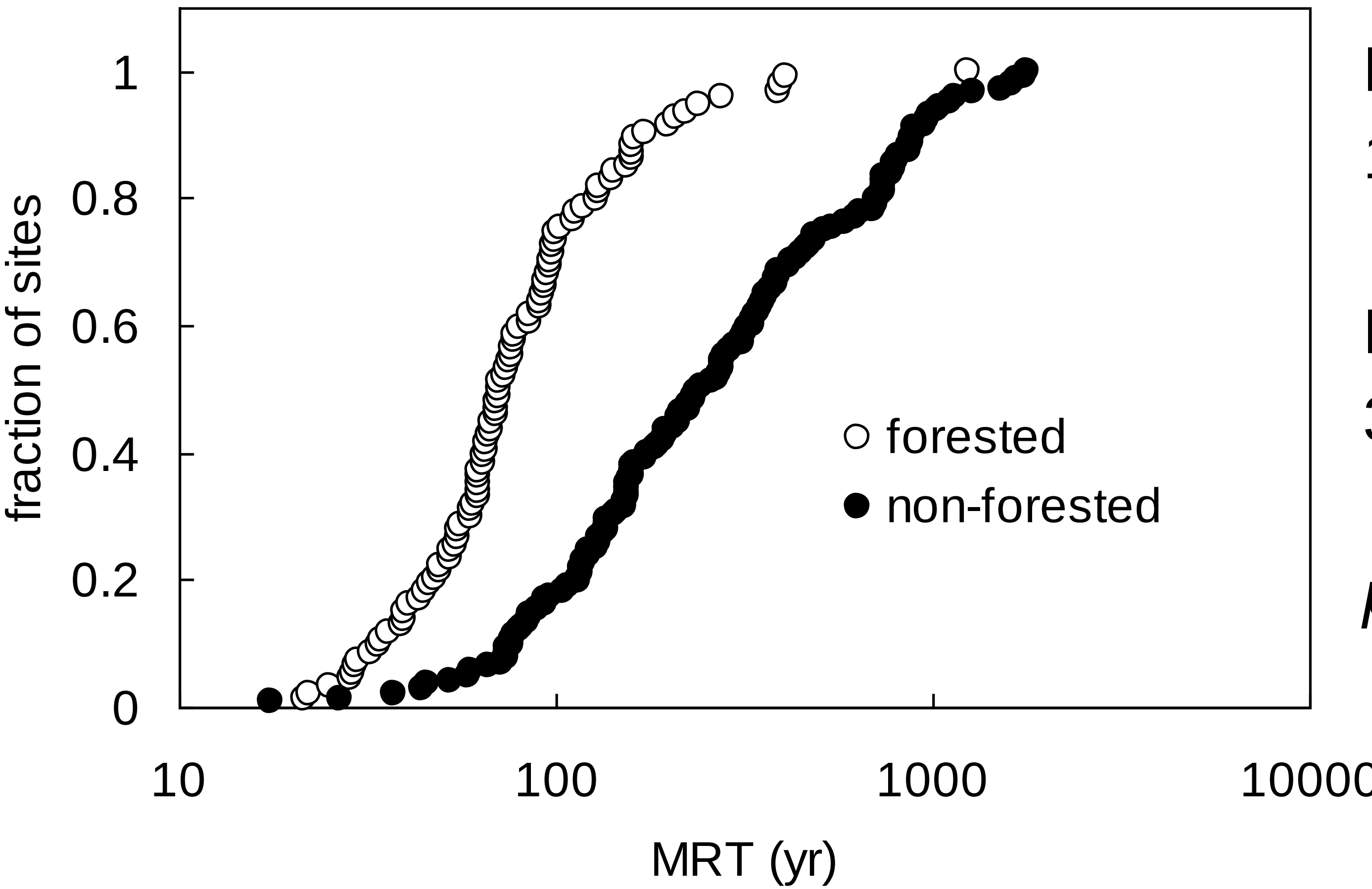
Model II MRT values for 237 sites



Mean forest

107 yr

Mean non-forest

395 yr

p < *0.001*

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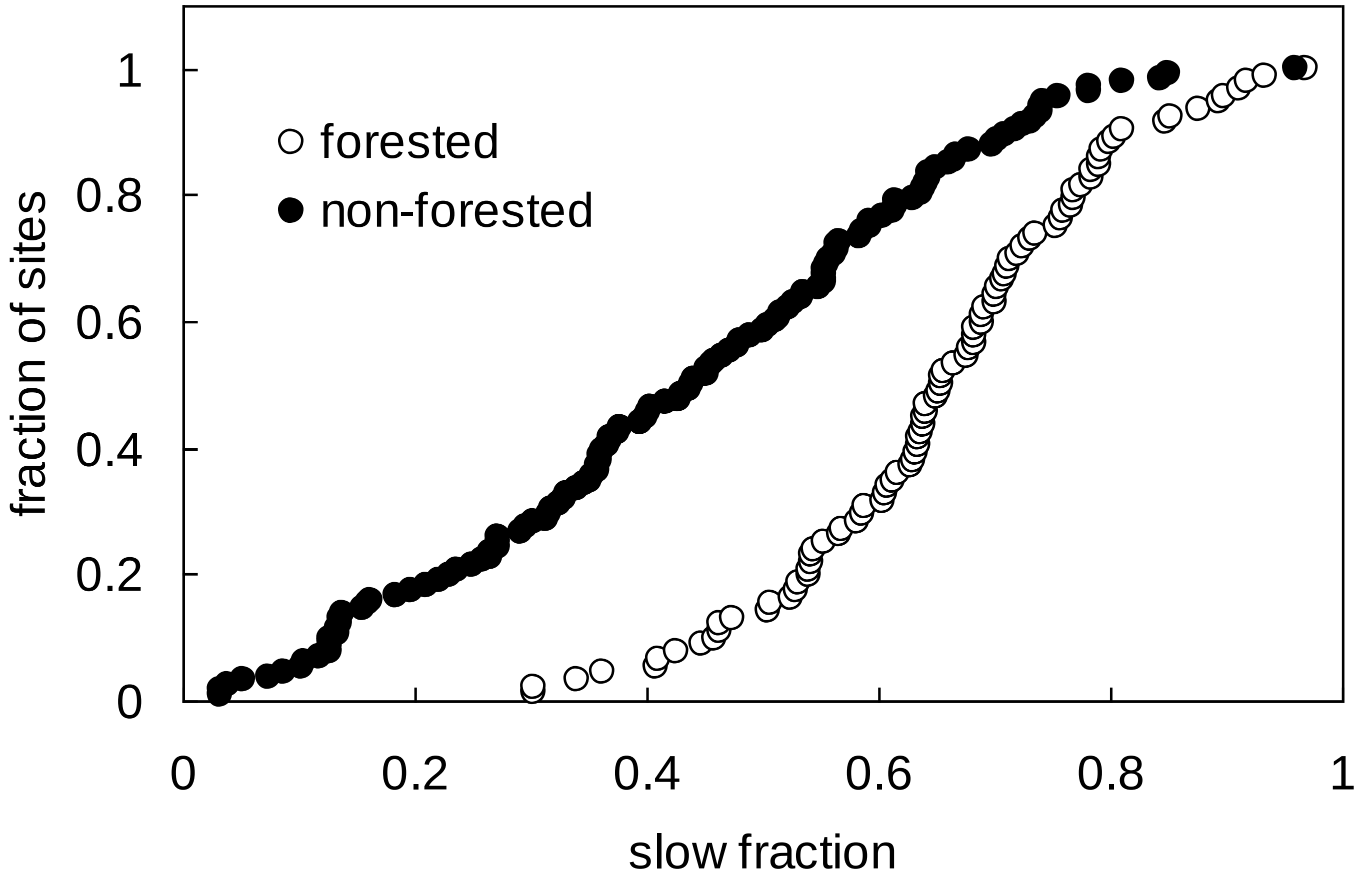
Model III slow fractions for 227 sites



Mean forest
0.654

Mean non-forest
0.436

$p < 0.001$

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SOC fractions and fluxes

		all sites
	n	224
slow fraction	mean	0.525
	SD	0.215
	median	0.554
slow C flux	mean	168
$g\ m^{-2}\ a^{-1}$	SD	88
	median	167
passive C flux	mean	3.5
$g\ m^{-2}\ a^{-1}$	SD	2.5
	median	2.8

SOC fractions and fluxes

		all sites	forest	non-forest
	n	224	92	132
slow fraction	mean	0.525	0.654	0.436
	SD	0.215	0.142	0.212
	median	0.554	0.655	0.441
slow C flux	mean	168	193	151
g m^{-2} a^{-1}	SD	88	76	92
	median	167	193	142
passive C flux	mean	3.5	2.2	4.4
g m^{-2} a^{-1}	SD	2.5	1.4	2.8
	median	2.8	1.9	3.8

Sensitivity analysis

Factor	**Apparent turnover**
Grassland from forest	⇧
Fertilisation by N-dep	⇧
Young soil	⇧
Charcoal	⬇
Black carbon	⬇
“Hot” material	⇧

Bioturbation - needs a two-depth model

- if significant, higher fluxes of slow and passive C

Possible explanations : forest vs non-forest

Not an artefact of non-steady state

Not an artefact of sampling depth (different C pool size)

- Litter quality – more intrinsically recalcitrant SOC from non-forest vegetation?
- Difference in decomposer communities?
- Windthrow disturbs the soil in forests?
- Forest microclimate?

Trends in turnover variables

MRT (normalised)

Decreases with temperature, 2.7% per ^{o}C
$r^2 = 0.03, p < 0.01$

Decreases with pH, 11% per pH
$r^2 = 0.02, p < 0.05$

Slow fraction (normalised)

No relation with temperature

Increases with pH, 6% per pH
$r^2 = 0.03, p < 0.05$

Slow fraction and soil type

Forest soils

	n	mean	SD
Acrisol	9	0.65	0.18
Cambisol	25	0.63	0.11
Leptosol	17	0.72	0.12
Luvisol	8	0.63	0.11
Podsol	17	0.59	0.14

Non-forest soils

	n	mean	SD
Cambisol	25	0.46	0.16
Gleysol	20	0.31	0.16
Histosol	12	0.48	0.22
Leptosol	13	0.55	0.22
Luvisol	26	0.48	0.22
Podsol	20	0.33	0.20

Wider context / global soil OC

Terrestrial surface	**%**
Forest	20.5
Non-forest vegetation	40.9
Cropland	14.3
Barren etc	24.2

Loveland et al. 2000

Soil pools data from ***Batjes 1996***

Jobbagy & Jackson 2000

Global NPP = ***61.25 Pg*** $\boldsymbol{a^{-1}}$ ***Atjay et al 1979***

Saugier et al 2001

Scharpenseel's data (WASP 1993

Sub-soil samples to 3 metres

^{14}C measurements → soil age

Regressions: age = $\boldsymbol{m} \times$depth + $\boldsymbol{c}$

	m	***c***
Inceptisols	26.7	2303
Spodosols	11.8	896
Vertisols	23.8	1537
Alfisols	38.7	1125
Mollisols	42.3	509

57.5 cm	***150 cm***	***250 cm***
3836	6302	8968
1574	2666	3846
2907	5110	7492
3347	6922	10787
2944	6860	11094

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MEAN AGES: 2922   5572   8438   yr

Global soil OC steady-state budget (Pg)

	C pool	Pool %
topsoil fast	48.1	2.1
topsoil slow	248	10.6
topsoil passive	253	10.8
15-100 cm	1001	42.7
100-200 cm	491	20.9
200-300 cm	351	15.0
total	2344	100

1 petagram $= 10^{15}$ *g*

$= 10^{9}$ *tonnes*

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Global soil OC steady-state budget (Pg)

	C pool	MRT	Flux	Pool %	Flux %
topsoil fast	48.1	1	48.1	2.1	78.6
topsoil slow	248	20	12.4	10.6	20.2
topsoil passive	253	1000	0.25	10.8	0.4
15-100 cm	1001	2922	0.34	42.7	0.6
100-200 cm	491	5572	0.09	20.9	0.1
200-300 cm	351	8438	0.04	15.0	0.1
total	2344	-	61.25	100	100

1 petagram $= 10^{15}$ *g*

$= 10^{9}$ *tonnes*

Summary and conclusions

Topsoil MRT	90% in range 36-970 yr, median 126 yr
	forest median 71 yr, non-forest 243 yr

Topsoil slow:passive fractions	forest	0.66:0.34
	non-forest	0.44:0.56

Topsoil fluxes (g m^{-2} a^{-1})		<u>forest</u>	<u>non-forest</u>
	slow	193	142
	passive	1.9	3.8

Long term topsoil OC turnover rate increases with MAT & pH

Globally, 99% of C flux is through fast (~1 yr) & slow (20 yr) pools
87% of whole-soil OC supplies 1% of the C flux

Thanks to NERC and Defra for funding