Carbon sequestration in terrestrial ecosystems: facts and methods

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Carbon Sequestration in terrestrial ecosystems: facts and methods

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INRA

www.inra.fr/ephyse

- The carbon cycle updated 2007, natural and human- disturbed.

- Its terrestrial component
  - Generic scheme and important definitions
  - Land use types
  - Geographical distribution

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  - Land use changes
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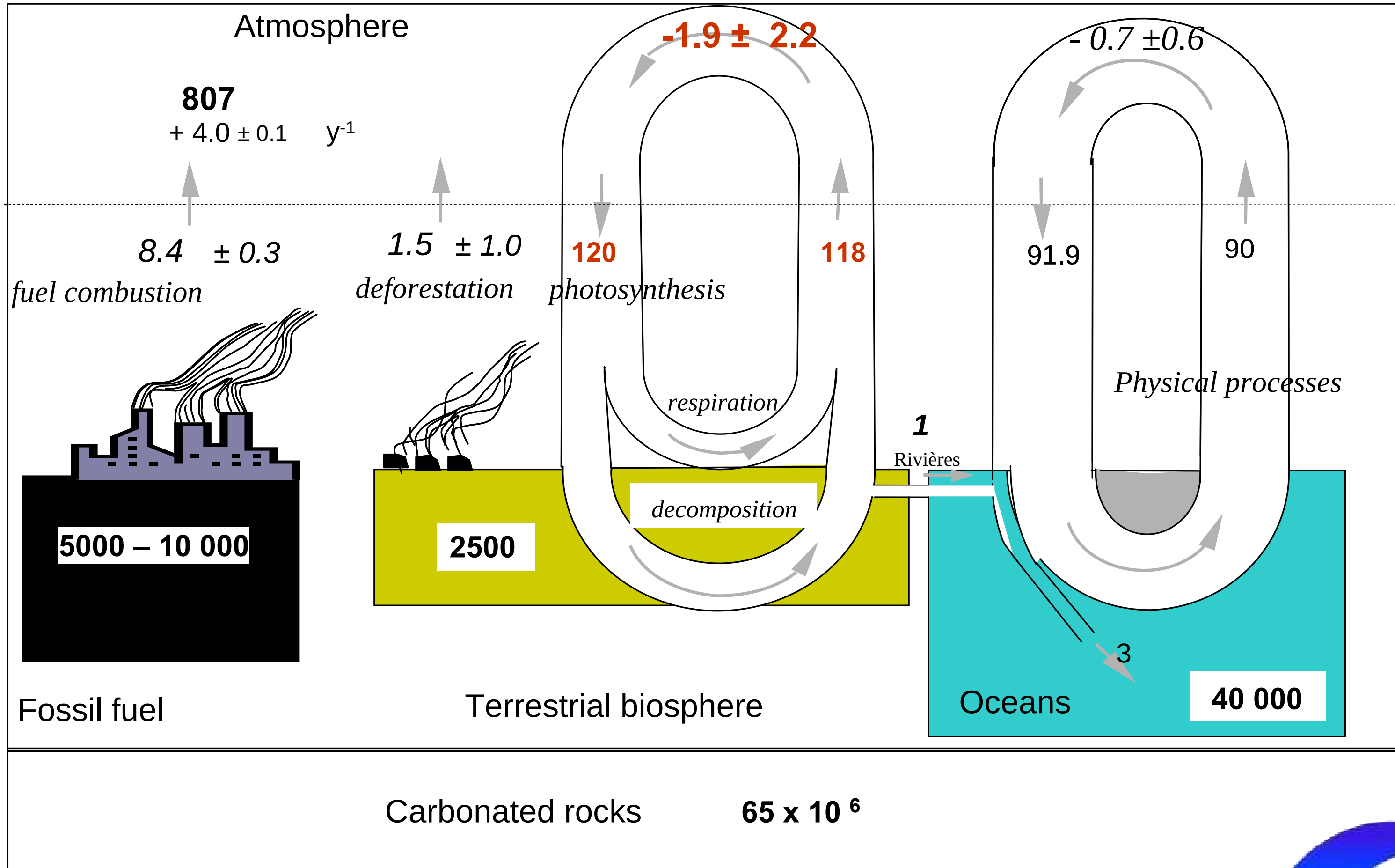
- Beyond carbon, managing the climate impacts
  - Carbon free greenhouse gases (N_2O, O_3)
  - Energy Balance: heat flux, evaporation
  - Global warming potential

- Diversity

- Conclusion



The global cycle of carbon 2005-2006

(stocks in GtC, flux in GtC.an-1, Canadell et al. 2007)

www.globalcarbonproject.org info@globalcarbonproject.org

Sources: anthropogenic C Emissions: Land Use Change

Borneo, Courtesy: Viktor Boehm

Tropical deforestation

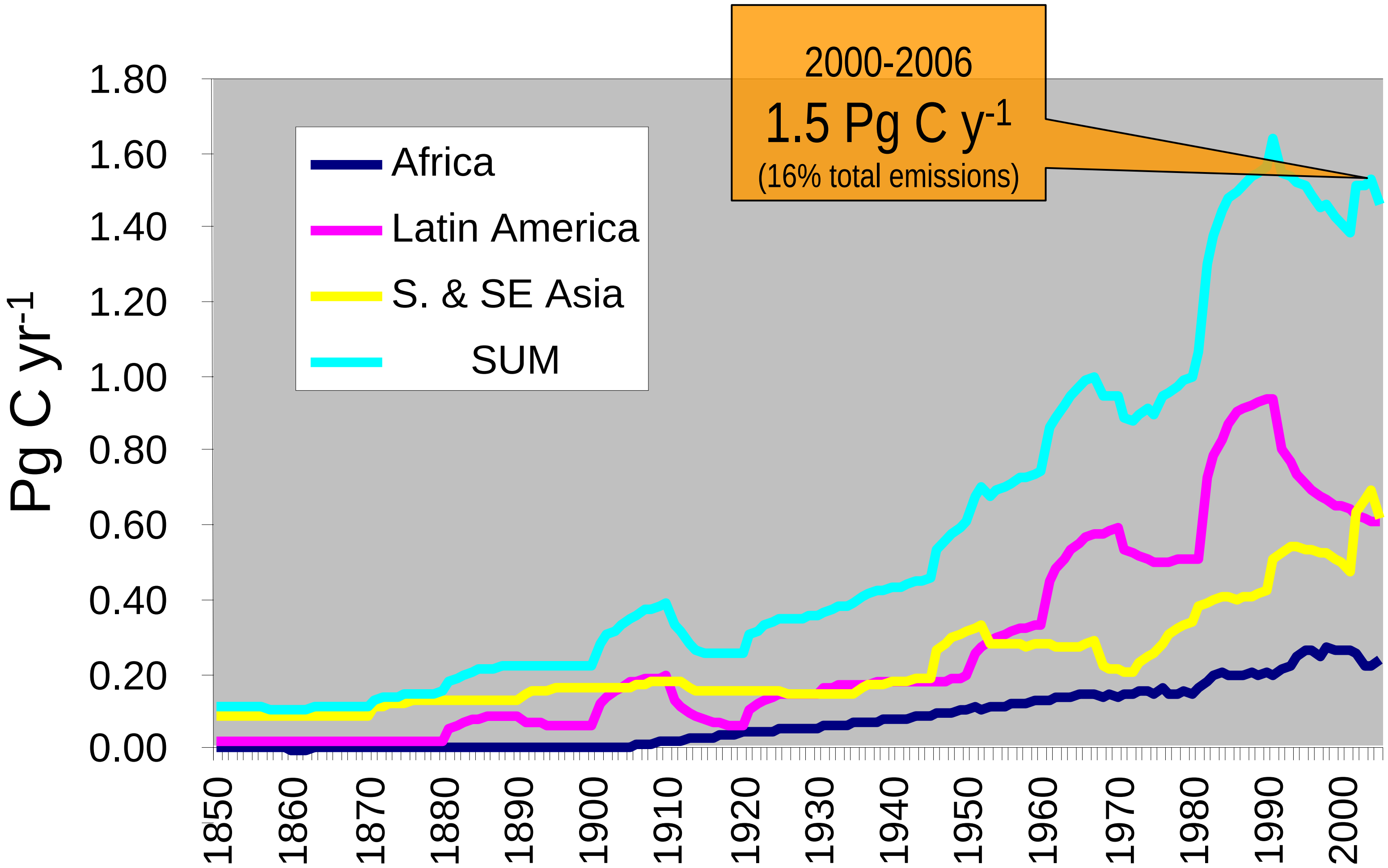
13 Million hectares each year

2000-2005

Tropical Americas	0.6 Pg C y^{-1}
Tropical Asia	0.6 Pg C y^{-1}
Tropical Africa	0.3 Pg C y^{-1}
	1.5 Pg C y^{-1}

FAO-Global Resources Assessment 2005; Canadell et al. 2007, PNAS

Anthropogenic C Emissions: Tropical Deforestation

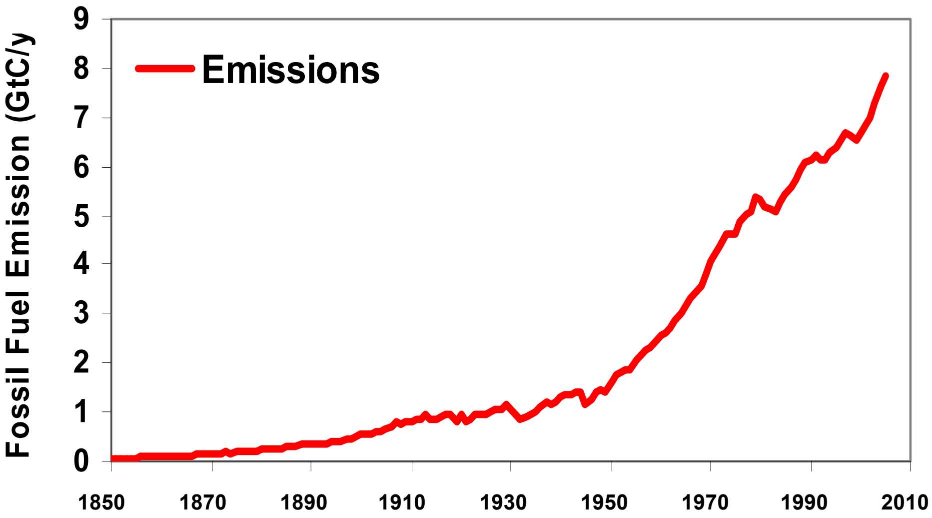


Houghton, unpublished

Sources: anthropogenic C Emissions, fossil fuel

2006 Fossil Fuel: 8.4 Pg C

[2006-Total Anthrop. Emissions:8.4+1.5 = 9.9 Pg]

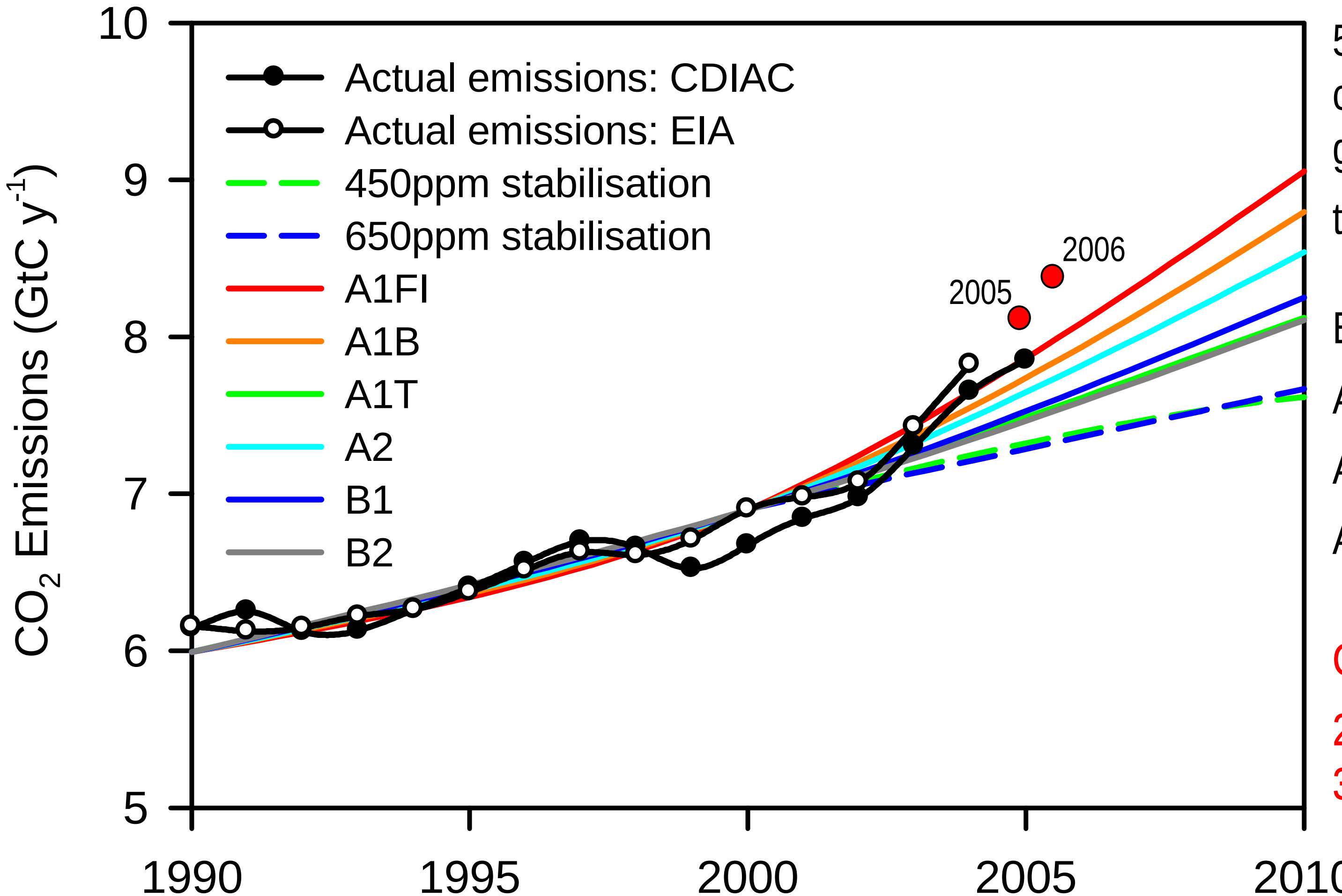


1990 - 1999: 1.3% y^{-1}

2000 - 2006: 3.3% y^{-1}

Raupach et al. 2007, PNAS; Canadell et al 2007, PNAS

Trajectory of Global Fossil Fuel Emissions



50-year constant growth rates to 2050

B1 1.1%,

A1B 1.7%,

A2 1.8%

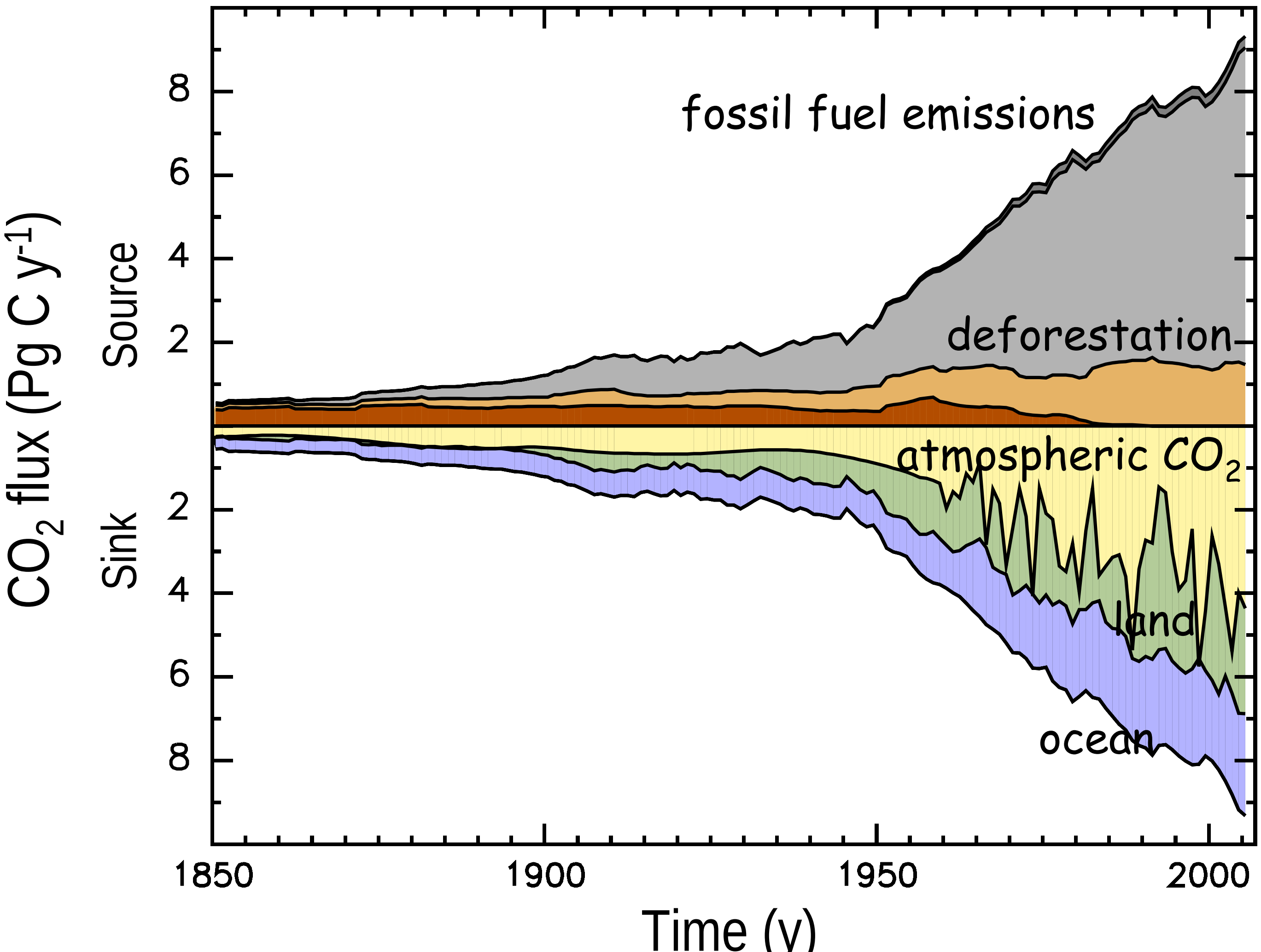
A1FI 2.4%

Observed

2000-2006 3.3%

Raupach et al. 2007, PNAS

Anthropogenic perturbation of global carbon budget (1850-2006)



Le Quéré, unpublished; Canadell et al. 2007, PNAS

Sink: partition of anthropogenic carbon emissions

[2000-2006]

45% of all CO_2 emissions accumulated in the atmosphere

Atmosphere

The Airborne Fraction

The fraction of the annual anthropogenic emissions that remains in the atmosphere

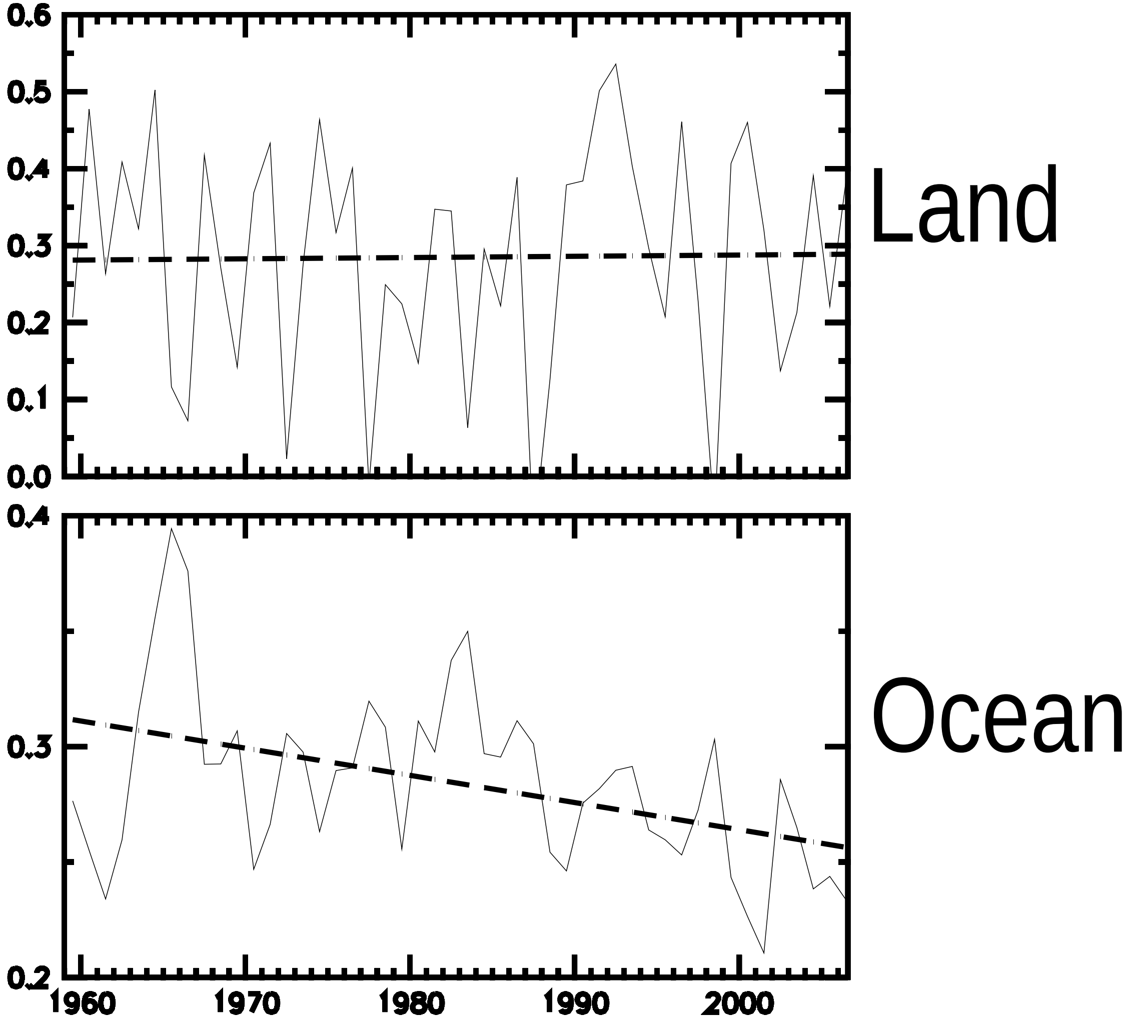
55% were removed by natural sinks

Ocean removes _ 24%

Land removes _ 30%

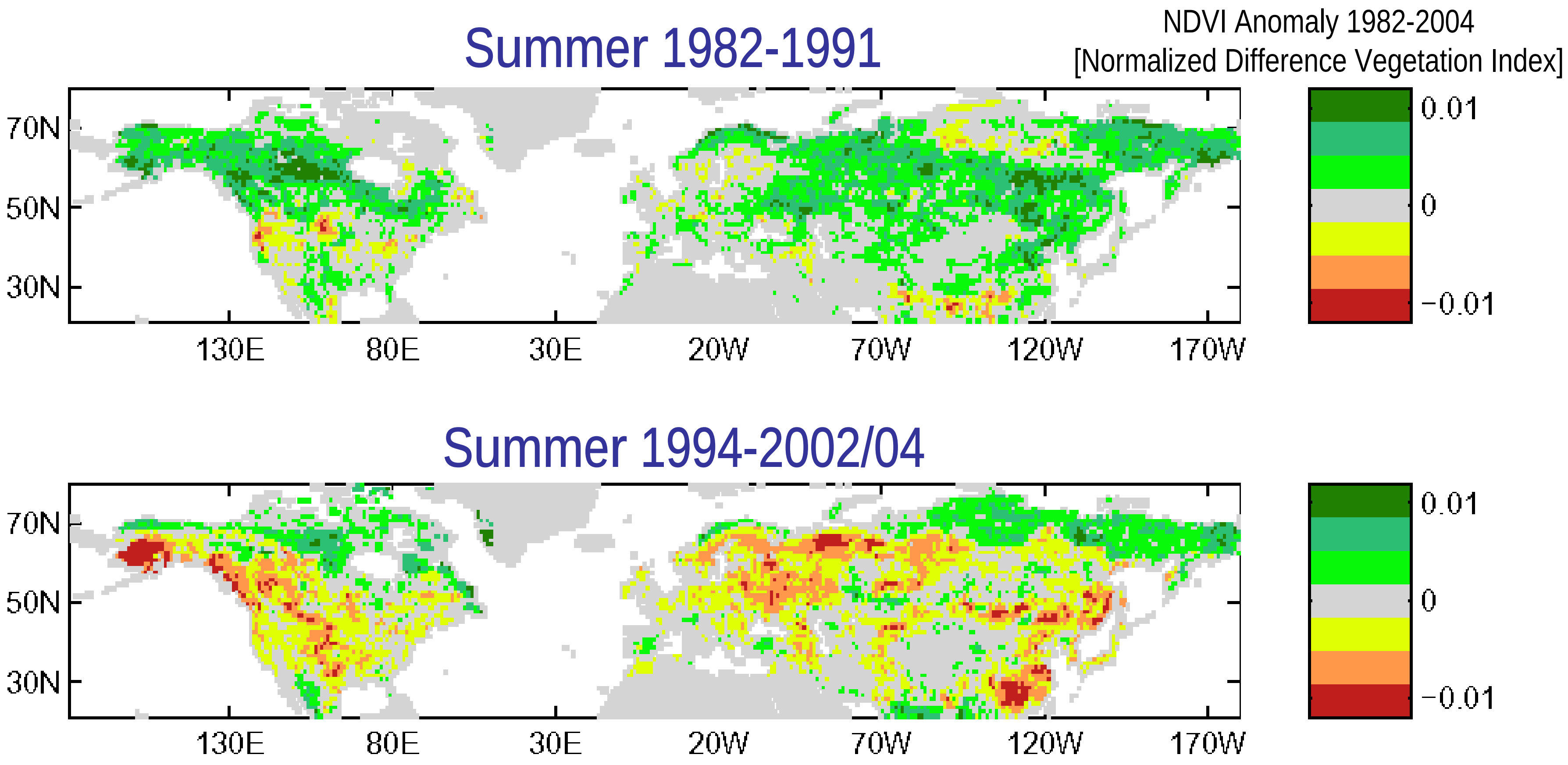
Canadell et al. 2007, PNAS

The Efficiency of Natural Sinks: Land and Ocean Fractions

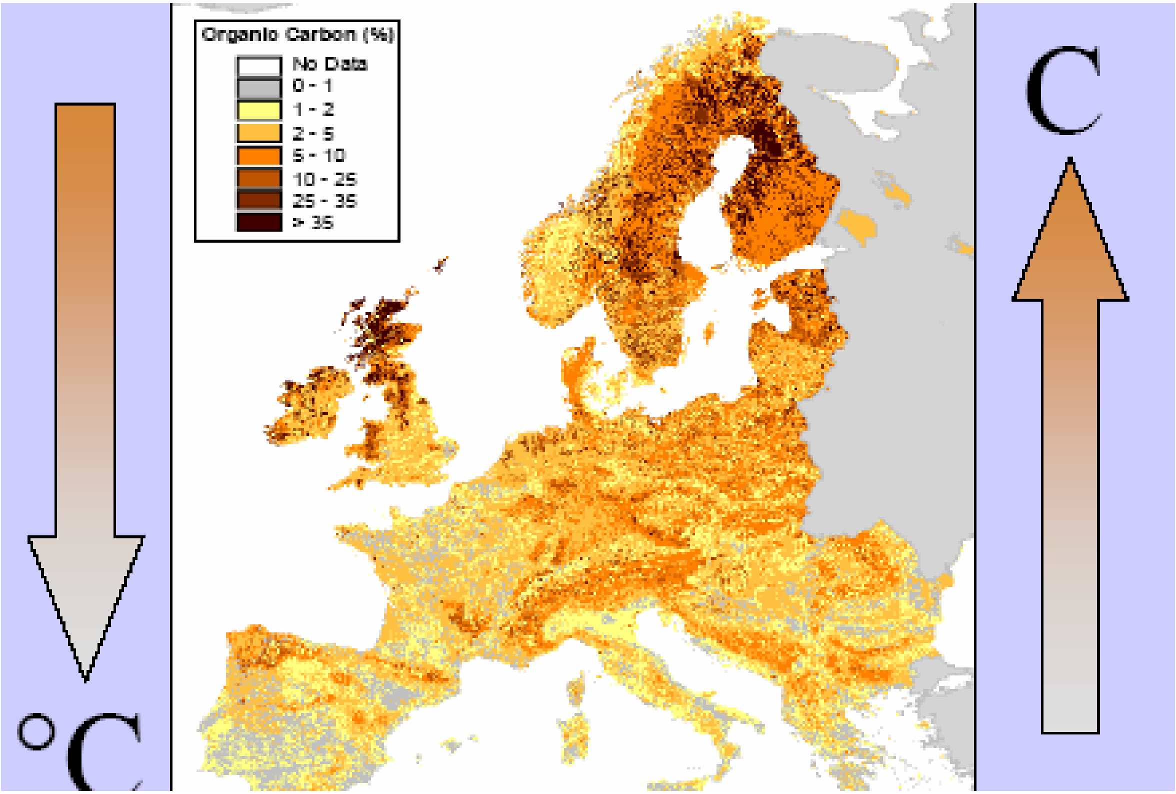


Canadell et al. 2007, PNAS

A number of major droughts in mid-latitudes have contributed to the weakening of the growth rate of terrestrial carbon sinks in mid latitude regions.



Angert et al. 2005, PNAS; Buermann et al. 2007, PNAS; Ciais et al. 2005, Science



- Large carbon stocks in soil are found in cold and wet climate on acidic soils where microbial activity is constrained by lack of O_2, N, Heat, liquid water.

- These conditions are changing rapidly: soils are getting warmer and drier, and N enriched through acidic deposition → .../...

C storage
in soil is not
given on long term

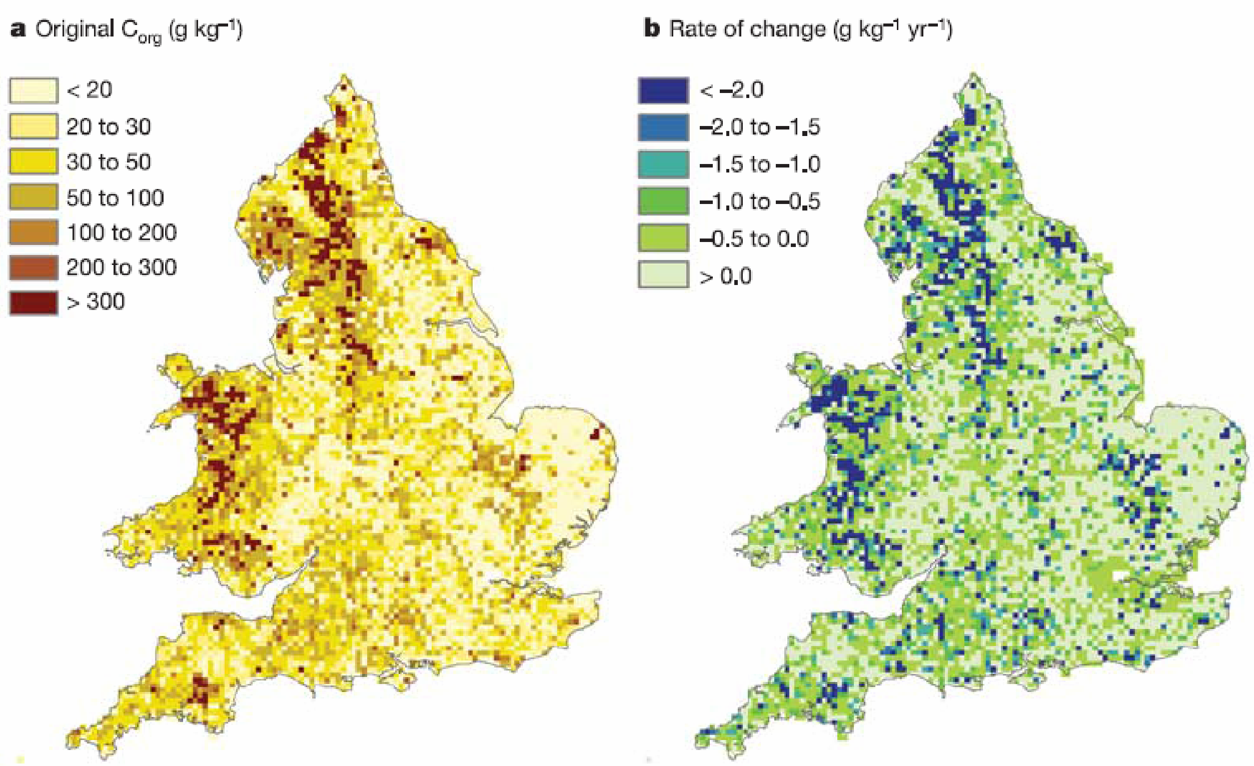


Figure 1 | Changes in soil organic carbon contents across England and Wales between 1978 and 2003. **a**, Carbon contents in the original samplings, and **b**, rates of change calculated from the changes over the different sampling intervals. Values at sites that were not resampled were calculated from their original organic carbon contents using equation (1). The changes were negative in all but 8% of the sites.

Bellamy et al., *Nature* 2006

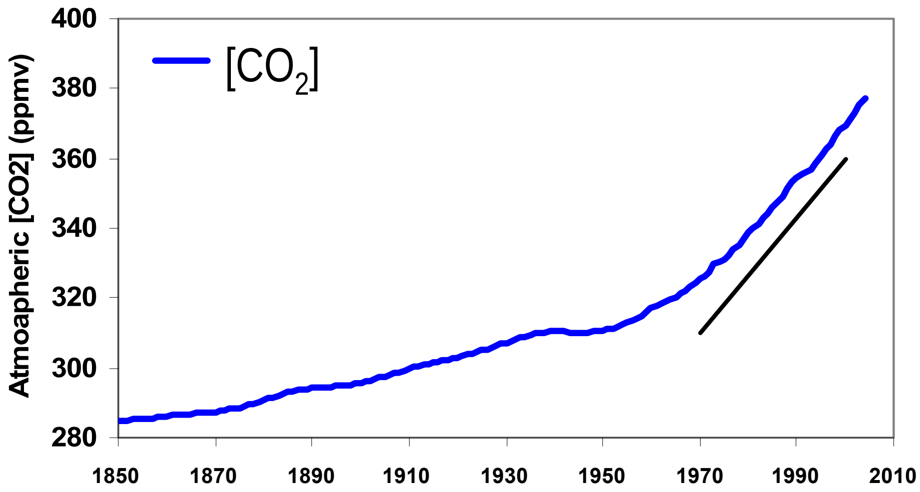
Ex. :Soil have released from 0 to 100-150 gC $m^{-2}.an^{-1}$ in UK between 1978 and 2003

Disequilibrium in net atmospheric balance :

Year 2006
Atmospheric CO_2
concentration:

381 ppm

35% above pre-industrial



1970 – 1979: 1.3 ppm y^{-1}
1980 – 1989: 1.6 ppm y^{1}
1990 – 1999: 1.5 ppm y^{-1}

2000 - 2006: 1.9 ppm y^{-1}

NOAA 2007; Canadell et al. 2007, PNAS

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Terrestrial ecosystems and the carbon cycle

Carbon stocks

(Gt)

(total ~2500 Gt C)

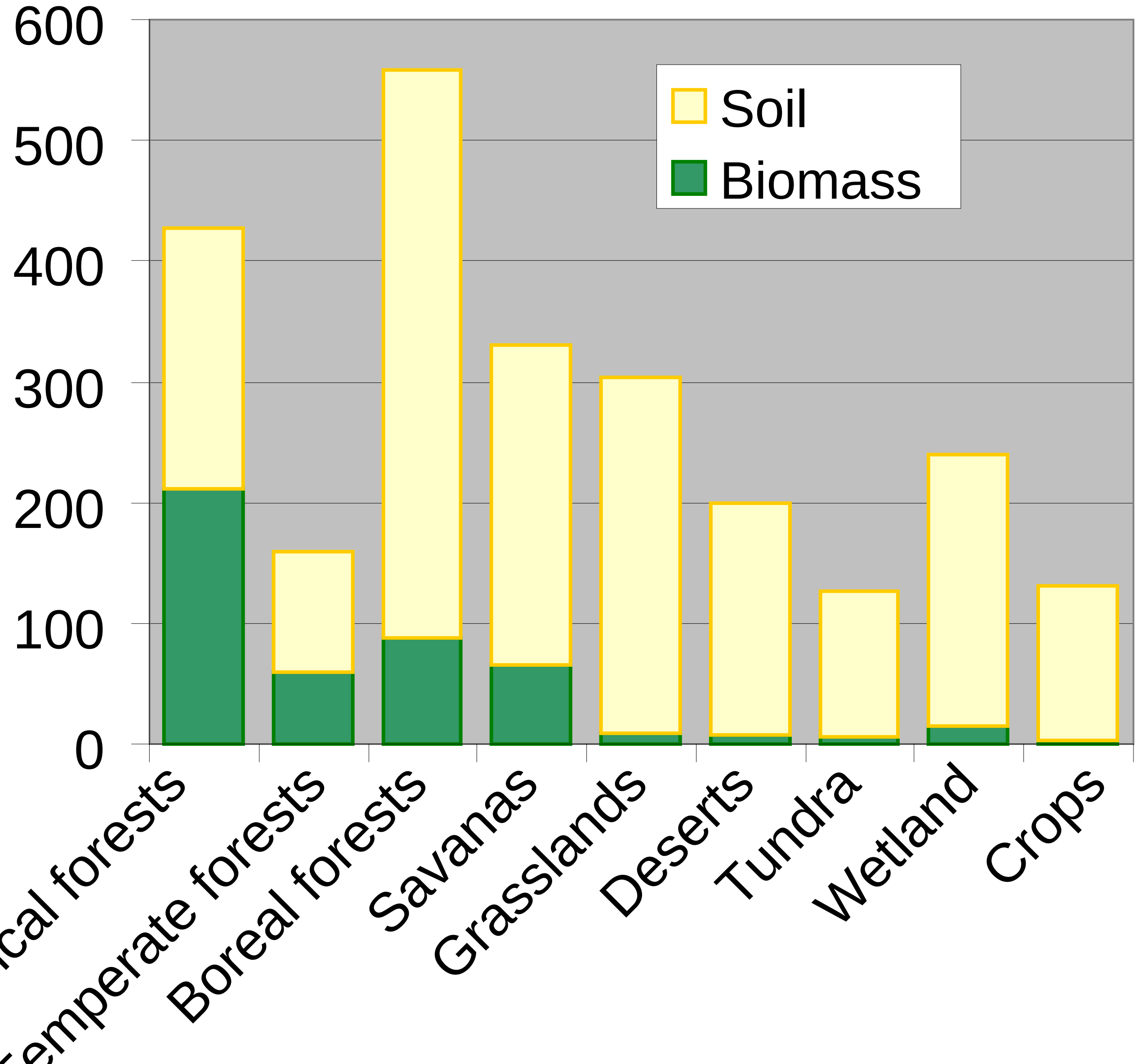


TABLE 3A.1.2

ABOVEGROUND BIOMASS STOCK IN NATURALLY REGENERATED FORESTS BY BROAD CATEGORY (tonnes dry matter/ha)

(To be used for Bw in Equation 3.2.9, for $L_{conversion}$ in Equation 3.3.8 in Cropland section and for $L_{conversion}$ in Equation 3.4.13. in Grassland section, etc. Not to be applied for C_{t_2} or C_{t_1} in Forest section Equation 3.2.3)

Tropical Forests [1]

	Wet	**Moist with Short Dry Season**	**Moist with Long Dry Season**	**Dry**	**Montane Moist**	**Montane Dry**
Africa	310 (131 - 513)	260 (159 – 433)	123 (120 - 130)	72 (16 - 195)	191	40
Asia & Oceania:						
Continental	275 (123 - 683)	182 (10 – 562)	127 (100 - 155)	60	222 (81 - 310)	50
Insular	348 (280 - 520)	290	160	70	362 (330 - 505)	50
America	347 (118 - 860)	217 (212 - 278)	212 (202- 406)	78 (45 - 90)	234 (48 - 348)	60

Temperate Forests

Age Class	**Coniferous**	**Broadleaf**	**Mixed Broadleaf-Coniferous**
Eurasia & Oceania			
≤20 years	100 (17 - 183)	17	40
>20 years	134 (20 - 600)	122 (18 -320)	128 (20-330)
America			
≤20 years	52 (17-106)	58 (7-126)	49 (19-89)
>20 years	126 (41-275)	132 (53-205)	140 (68-218)

Boreal Forests

Age Class	**Mixed Broadleaf-Coniferous**	**Coniferous**	**Forest-Tundra**
Eurasia			
≤20 years	12	10	4
>20 years	50	60 (12.3-131)	20 (21- 81)
America			
≤20 years	15	7	3
>20 years	40	46	15

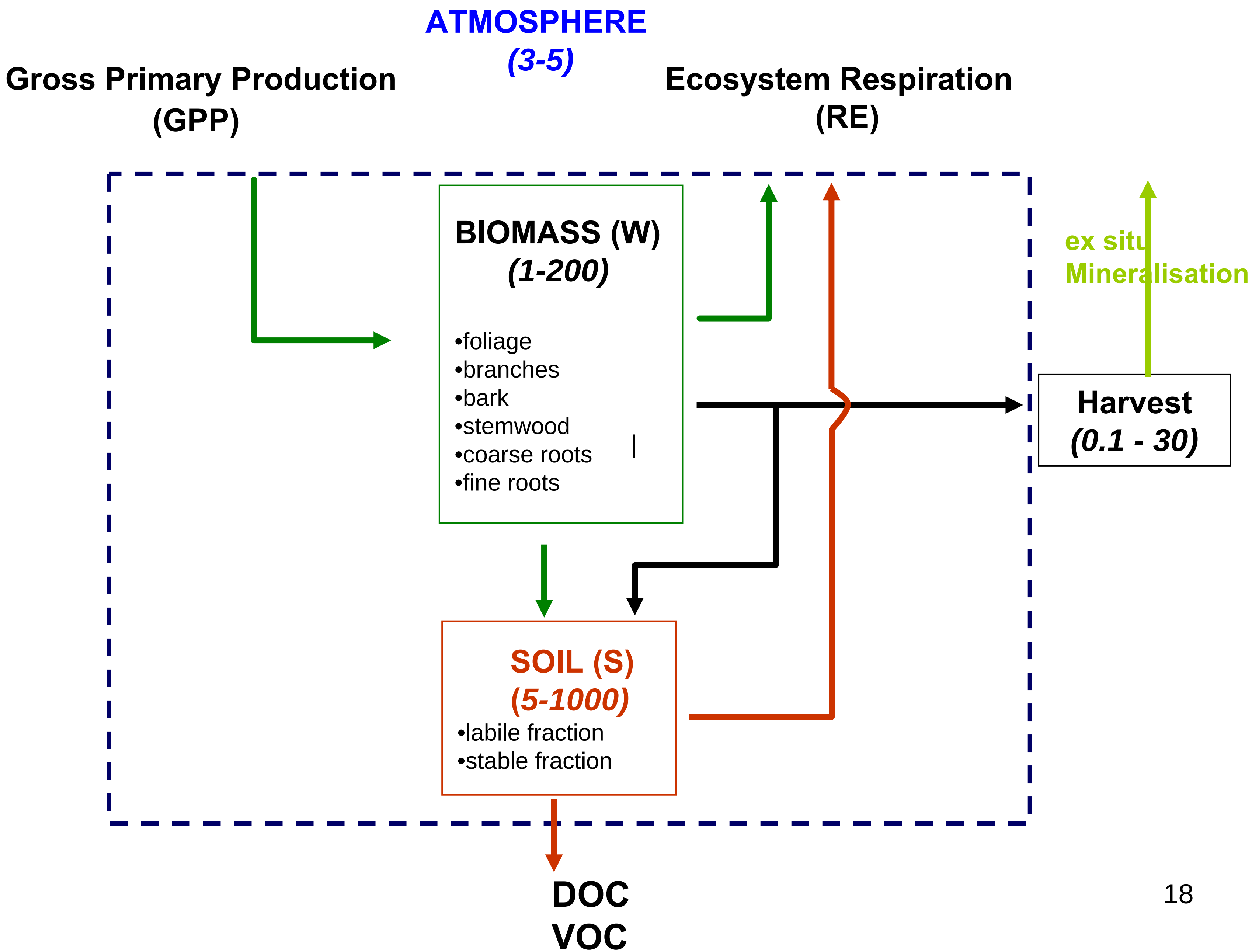
Note: Data are given in mean value and as range of possible values (in parentheses).

[1] The definition of forest types and examples by region are illustrated in Box 2 and Tables 5-1, p 5.7-5.8 of the *IPCC Guidelines* (1996).

Carbon and biomass stocks
In world's forests are well
documented by FAO and IPCC

Table A1.From
IPCC Report on Good Practice Guidance for Land Use, Land-Use Change and Forestry

Carbon cycle in terrestrial ecosystems : fluxes, pools and residence time (years)



Carbon sequestration in forest ecosystems: important definitions

Gross Primary Production

$$GPP = A - R_d$$

Net Primary Production

$$NPP = GPP - R_a - VOC$$

Net Ecosystem Exchange

$$NEE = GPP - R_a - VOC - R_h$$

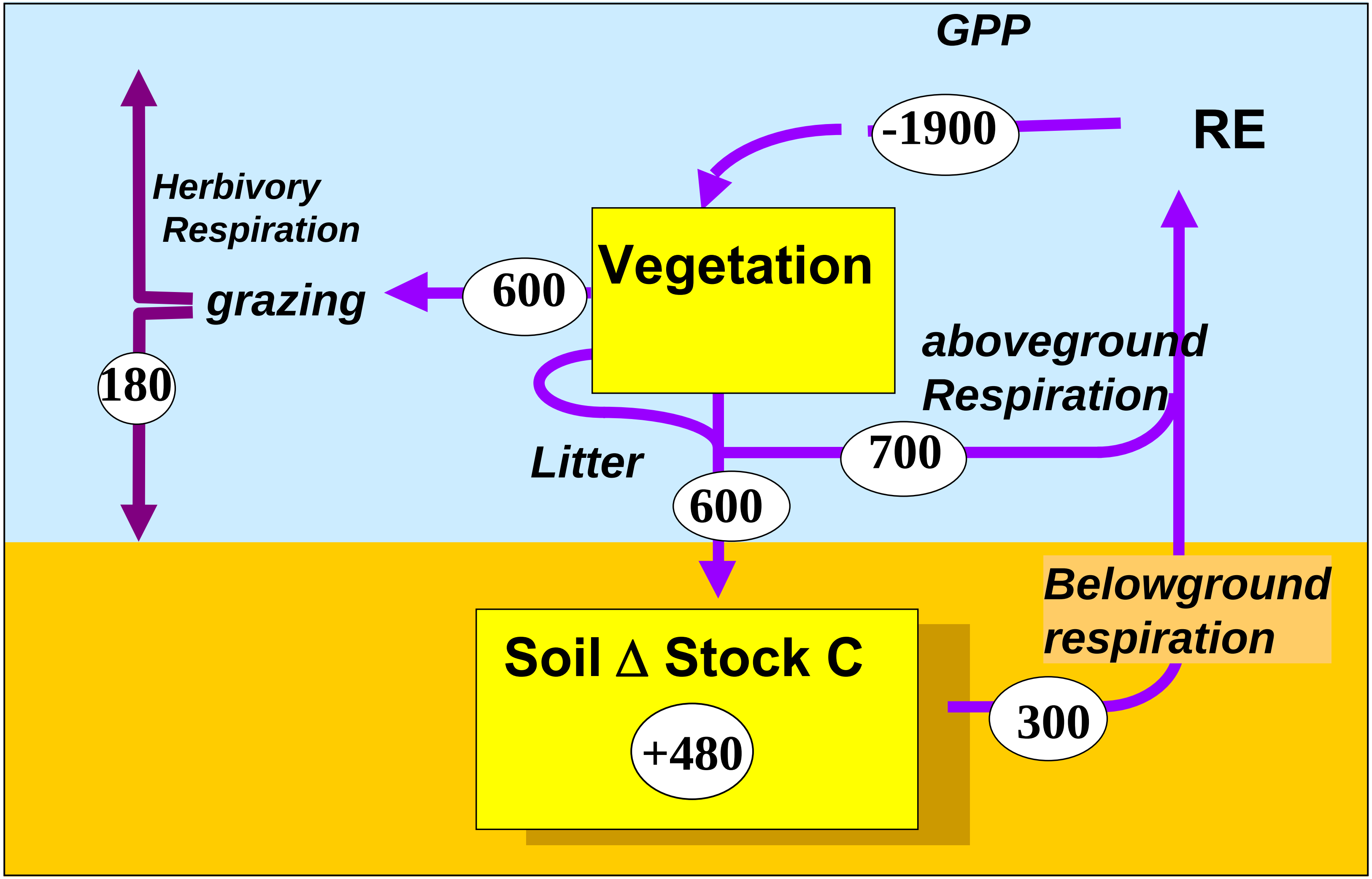
Net Ecosystem production

$$NEP = GPP - R_a - VOC - R_h - DOC - DIC$$

A	Net Assimilation
Rd	Day mitochondrial leaf respiration
Ra	Autotrophic Respiration
Rh	Heterotrophic Respiration
VOC	Volatile Organic Carbon
DOC	Dissolved Organic Carbon
DIC	Dissolved Inorganic Carbon

Carbon cycle: grasssland with grazing.

Annual balance of carbon (gC m-2 an-1)



Carbon balance of forest ecosystems.
Synthesis from a database including 513 forest sites.

Table 3 Mean carbon fluxes, NPP components, sum of closure terms [$\Sigma(\delta\text{Flux}) = |\delta\text{GPP}| + |\delta\text{NPP}| + |\delta R_e| + |\delta R_a| + |\delta R_h|$] and their standard deviation for the different biomes. The SD refer to the variability surrounding the mean values

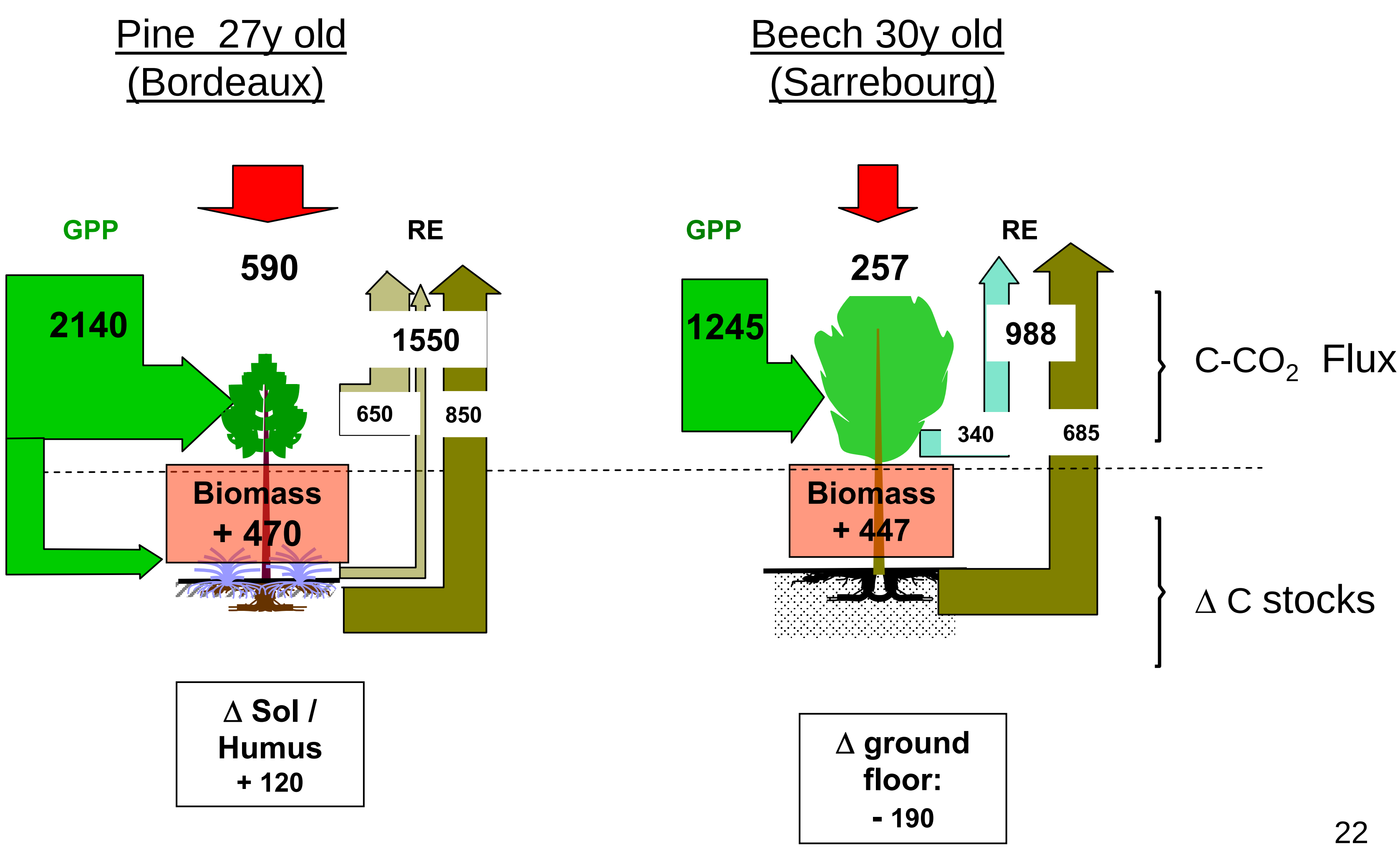
	Boreal humid	Boreal semiarid		Temperate humid		Temperate semiarid	Mediterranean warm	Tropical humid
	Evergreen	Evergreen	Deciduous	Evergreen	Deciduous	Evergreen	Evergreen	Evergreen
GPP	973 ± 83	773 ± 35	1201 ± 23	1762 ± 56	1375 ± 56	1228 ± 286	1478 ± 136	3551 ± 160
NPP	271 ± 17	334 ± 55	539 ± 73	783 ± 45	738 ± 55	354 ± 33	801 ± NA	864 ± 96
fNPP	73 ± 9	47 ± 5	109 ± 11	159 ± 19	235 ± 13	56 ± 11	134 ± NA	316 ± 32
wNPP	205 ± 28	110 ± 20	304 ± 36	280 ± 29	329 ± 47	117 ± 20	389 ± NA	212 ± 52
rNPP	69 ± 9	157 ± 31	112 ± 22	235 ± 14	207 ± 20	172 ± 19	278 ± NA	324 ± 56
NEP	131 ± 79	40 ± 30	178 ± NA	398 ± 42	311 ± 38	133 ± 47	380 ± 73	403 ± 102
R_e	824 ± 112	734 ± 37	1029 ± NA	1336 ± 57	1048 ± 64	1104 ± 260	1112 ± 100	3061 ± 162
R_a	489 ± 83	541 ± 35	755 ± 31	951 ± 114	673 ± 87	498 ± 58	615 ± NA	2323 ± 144
R_h	381 ± 40	247 ± 26	275 ± 31	420 ± 31	387 ± 26	298 ± 16	574 ± 98	877 ± 96
$\Sigma(\delta\text{Flux})$	439 ± 122	176 ± 81	163 ± 90	216 ± 102	206 ± 95	713 ± 314	359 ± 131	774 ± 225
R_e/GPP	0.88 ± 0.09	0.97 ± 0.04	0.86 ± 0.01	0.77 ± 0.03	0.77 ± 0.04	0.87 ± 0.22	0.76 ± 0.07	0.88 ± 0.04
R_e/GPP	0.85 ± 0.14	0.95 ± 0.06	0.86 ± 0.02	0.76 ± 0.04	0.76 ± 0.06	0.96 ± 0.38	0.76 ± 0.10	0.86 ± 0.06

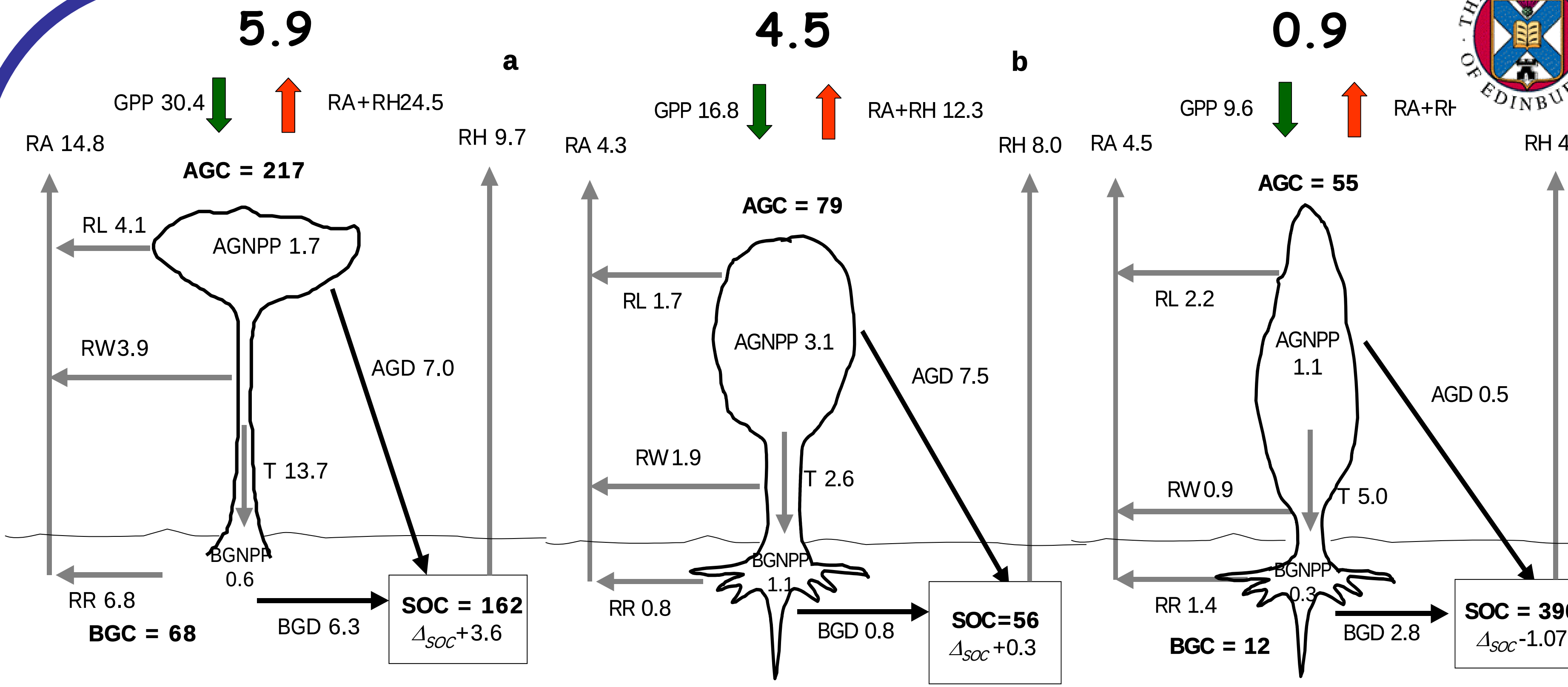
The R_e/GPP ratio was calculated for each bootstrap before and after balance closure.
NPP, net primary production; NEP, net ecosystem production; GPP, gross primary production.

Luyssaert et al . *Global Change biology, 2007*

Temperate forests: broadleaf & coniferous have ~ the same NPP

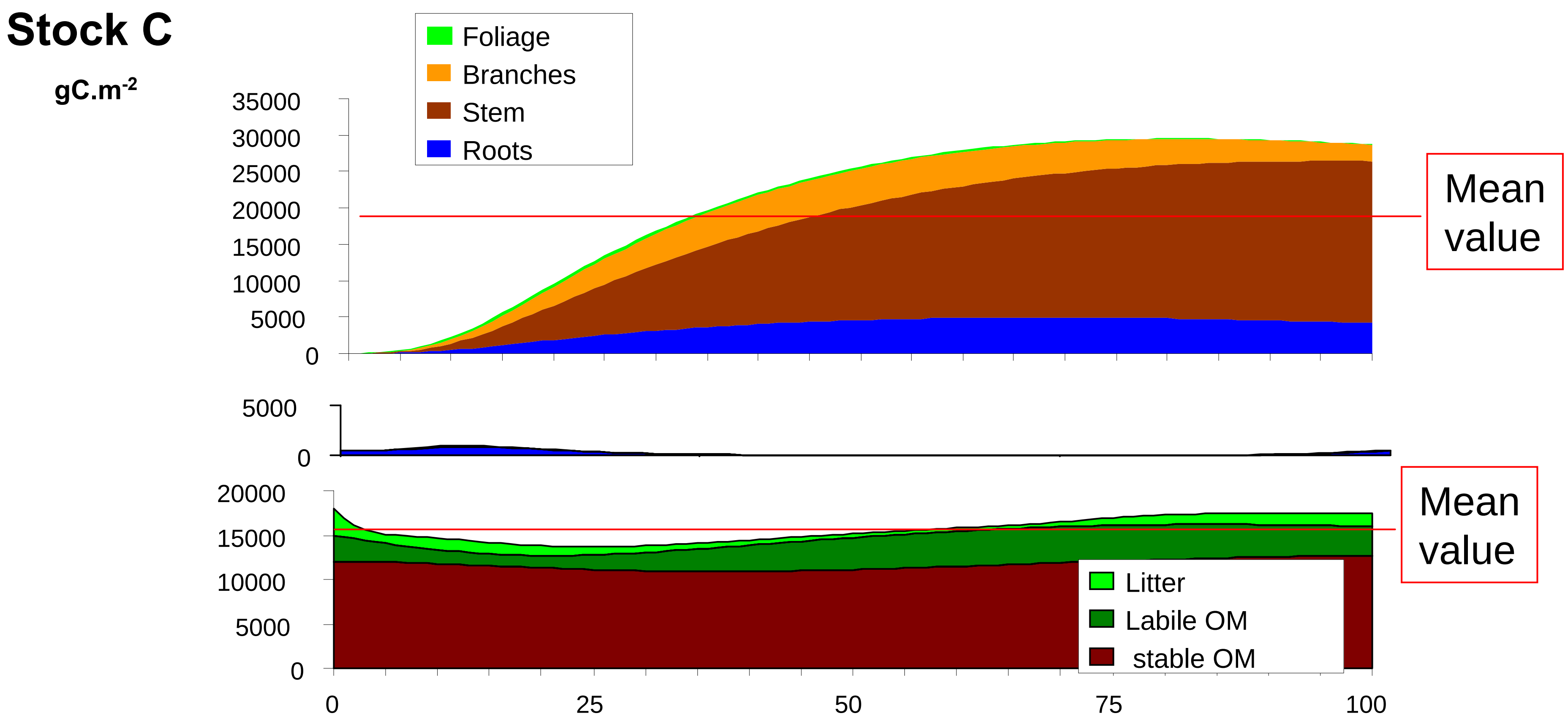
Annual balance of production forests in France (gC m^{-2} an^{-1})





Estimated annual total carbon stocks and flows for three representative forest stands in the tropical, temperate, and boreal regions. Stocks in bold italics are in tons of carbon per hectare (t C ha^{-1}). Flows are in t C ha^{-1} yr^{-1}. (a) Tropical rain forest near Manaus, Amazonia, Brazil; (b) temperate deciduous oak-hickory forest, near Oak Ridge, Tennessee, USA; and (c) boreal evergreen black spruce forest, near Prince Albert, Saskatchewan, Canada.

Temporal changes along the lifetime of an ecosystem



Biomass and labile organic matter stocks are changing from zero to their maximum along the lifecycle.

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How much carbon can we sequester in forest and natural ecosystems ?

Carbon removed by forestry practices: global estimates

Tableau 2. Estimations mondiales de la quantité potentielle de C stockée et conservée grâce aux pratiques de gestion forestière entre 1995 et 2050 (tiré de Brown *et al.* 1996).

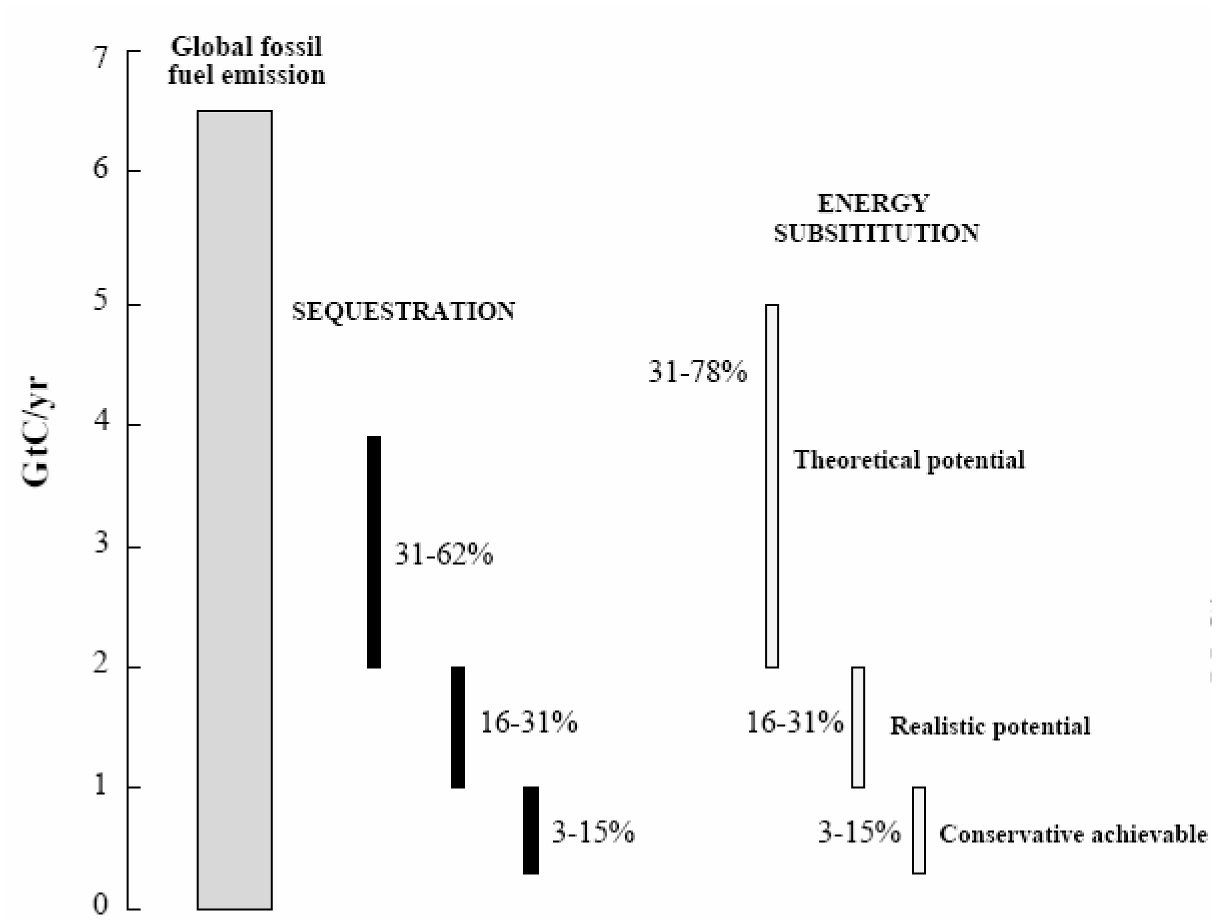
Latitudes	Pratique	Superficie *(Mha)*	C stocké et conservé *(Pg)*
Hautes	Afforestation	95,2[1]	2,4
Moyennes	Afforestation	113	11,8
	Agroforestry	6,5	0,7
Basses	Afforestation	66,9	16,4
	Agroforestry	63,2	6,3
	Reforestation	217	11,5-28,7
	Avoided deforestation	138	10,8-20,8
	Total	**700**	**60-87**

[1] Comprend les forêt insuffisamment reboisées du Canada

[2] Comprend 25% additionnels de C dans la biomasse aérienne pour tenir compte de la biomasse souterraine (racines, litière et sol) (d'après les données de Nilsson et Schopfhauser, 1995 et Brown *et al.*,1993b); la fourchette des valeurs est le résultat de l'emploi d'estimations faibles et élevées de la densité de carbone dans la biomasse dû à l'incertitude des estimations.

~Approximately 12% of fossil fuel emissions

Carbon removal potential of continental ecosystems



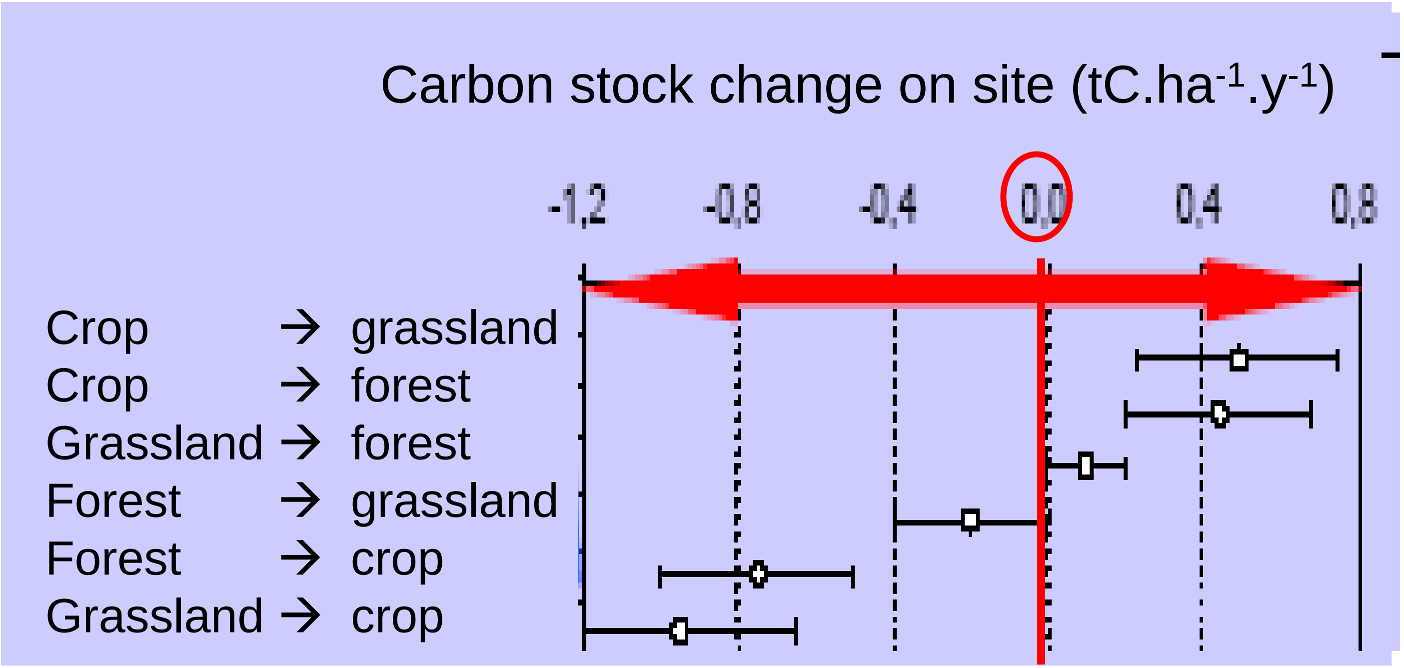
Energy production and carbon sequestration by continental ecosystems can offset 30- 60% of the global emissions (derived from Cannell, 2003).

How to proceed ?

→ land use changes

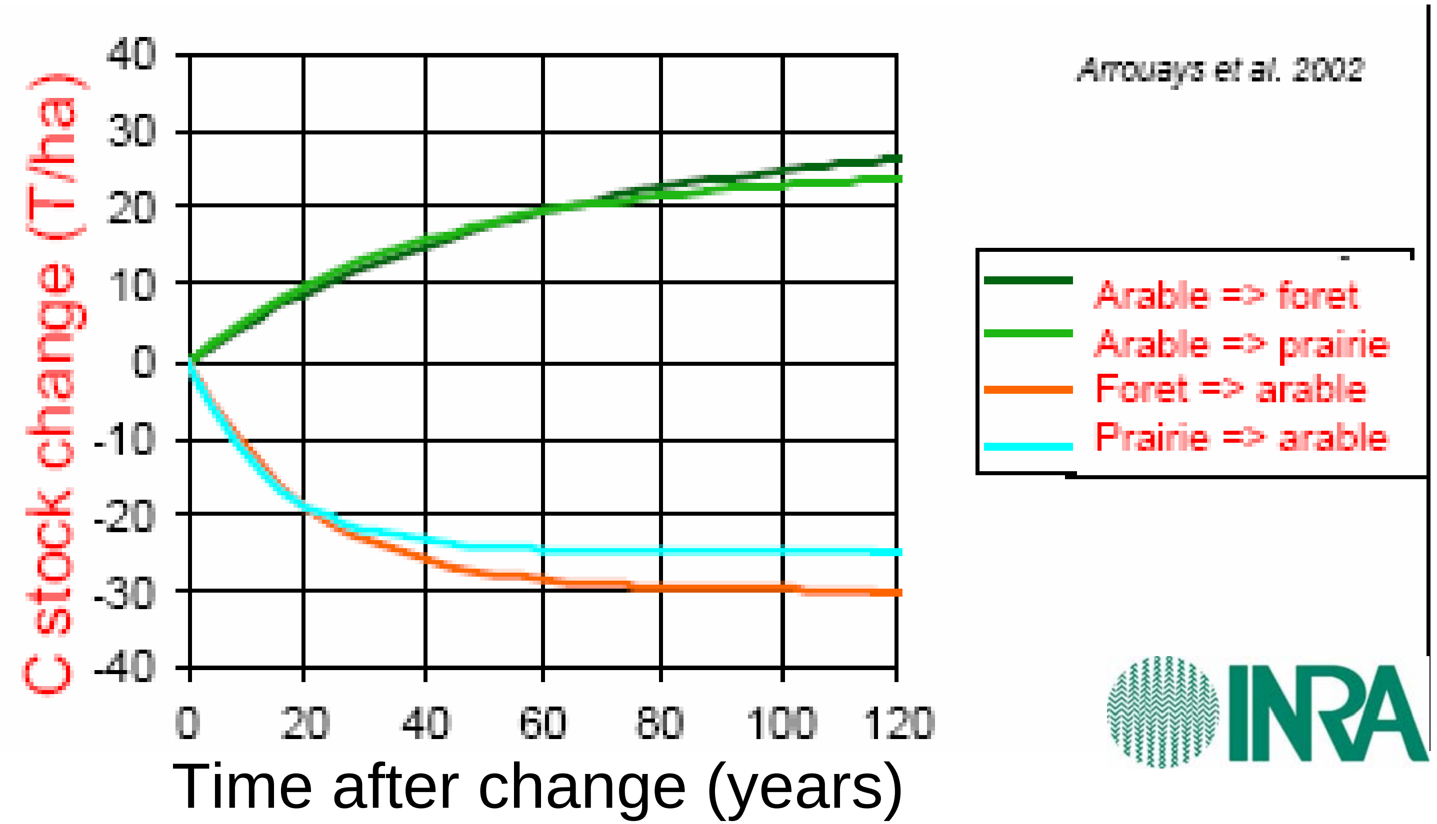
→forest management for carbon sequestration

Conversion of crops, abandoned lands, …into forests



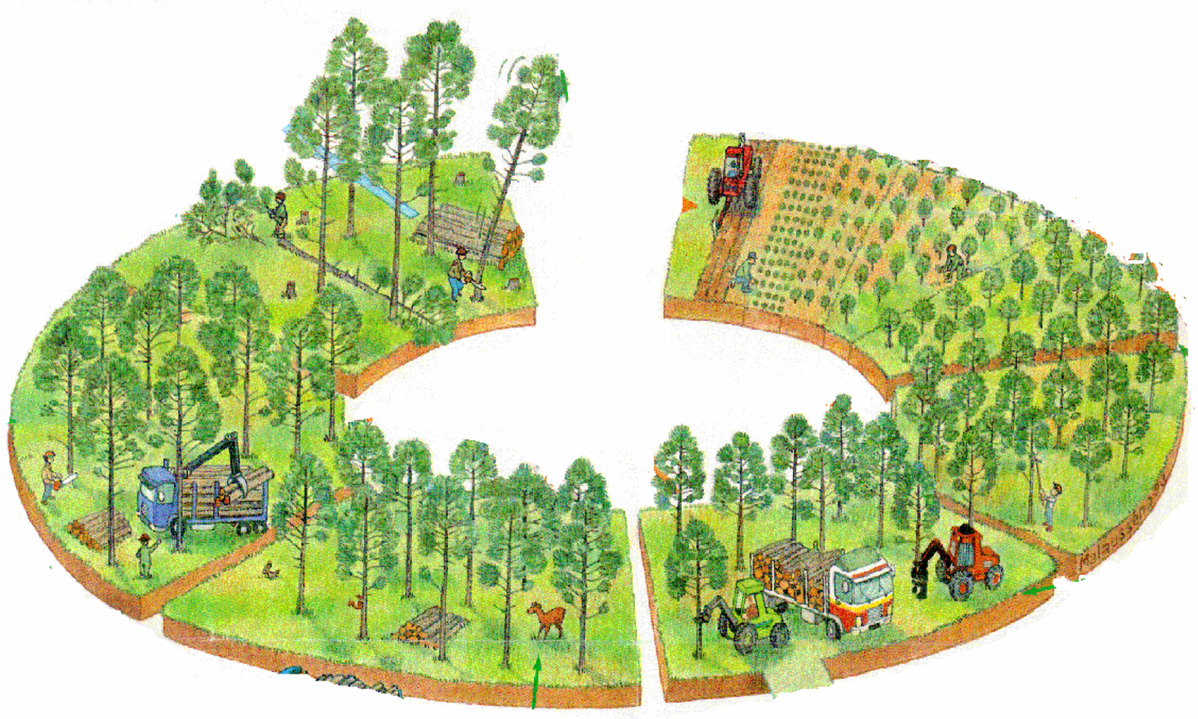
(Values averaged over 20 years. Arrouays et al. INRA)

Land use change: effects on carbon stocks.



- hysteresis: carbon is lost faster than it is gained
- slow: steady values take a century to be reached
- Reforesting renders many additional services: soil protection, water quality, air quality, local climate

Forest management for carbon sequestration

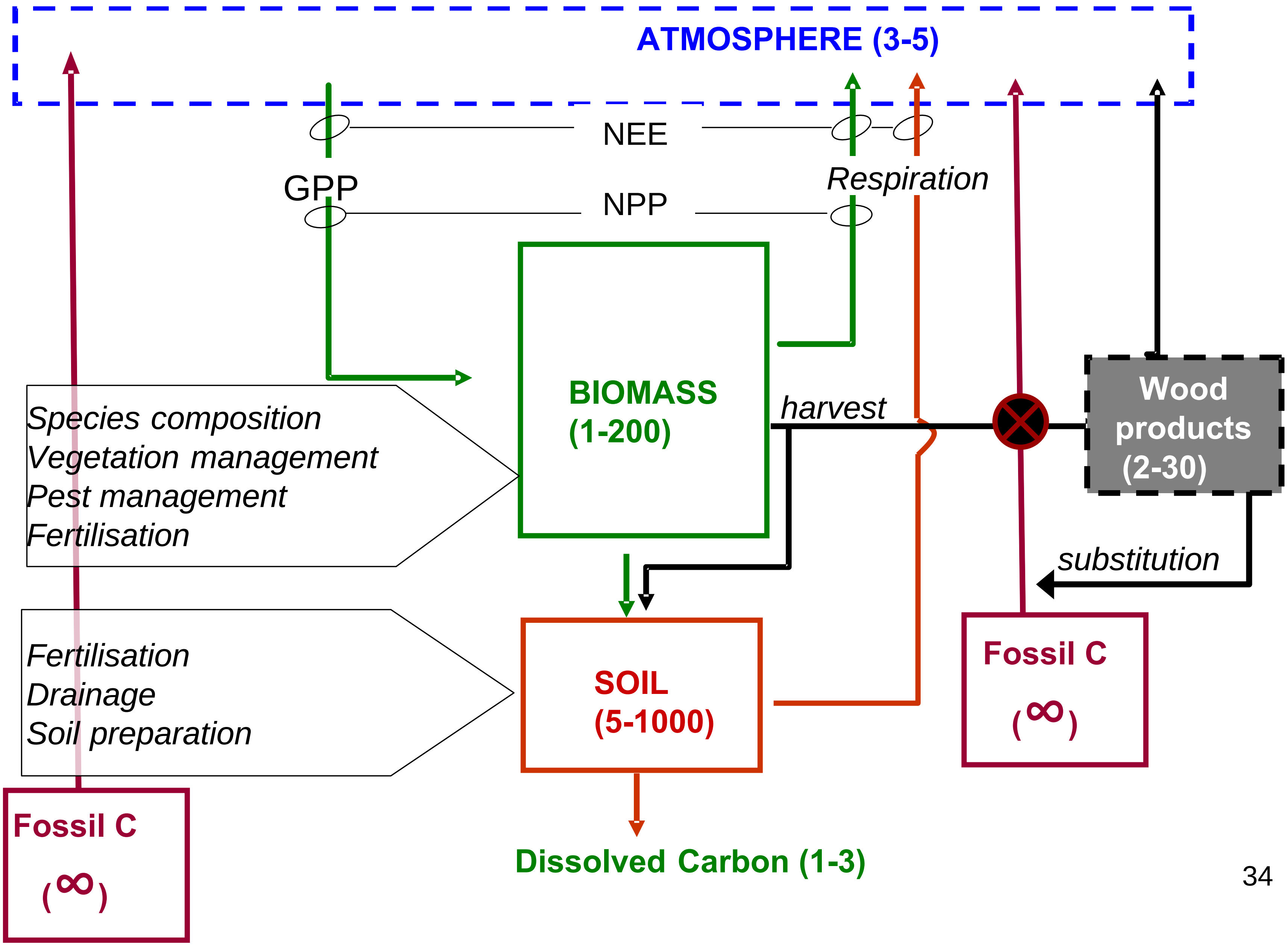


Assessment of impacts of forest management on carbon cycle: tentative framework

- Time scale: the entire life cycle including harvest
- Reference state: definition of a reference state: b.a.u., “nature”, state at a reference date (1990 for the Kyoto protocol)…
- Assessment of the only relative impact, i.e. stock change
- Completeness: Include additional carbon costs of forest operation, seedling, logging, drainage, transportation, transformation, product use and products replaced (concrete, steel, fossil fuel, others…)
- Consistent basis for calculation: unit land area (ha), unit production (ton biomass, cubic meter of roundwood,…)

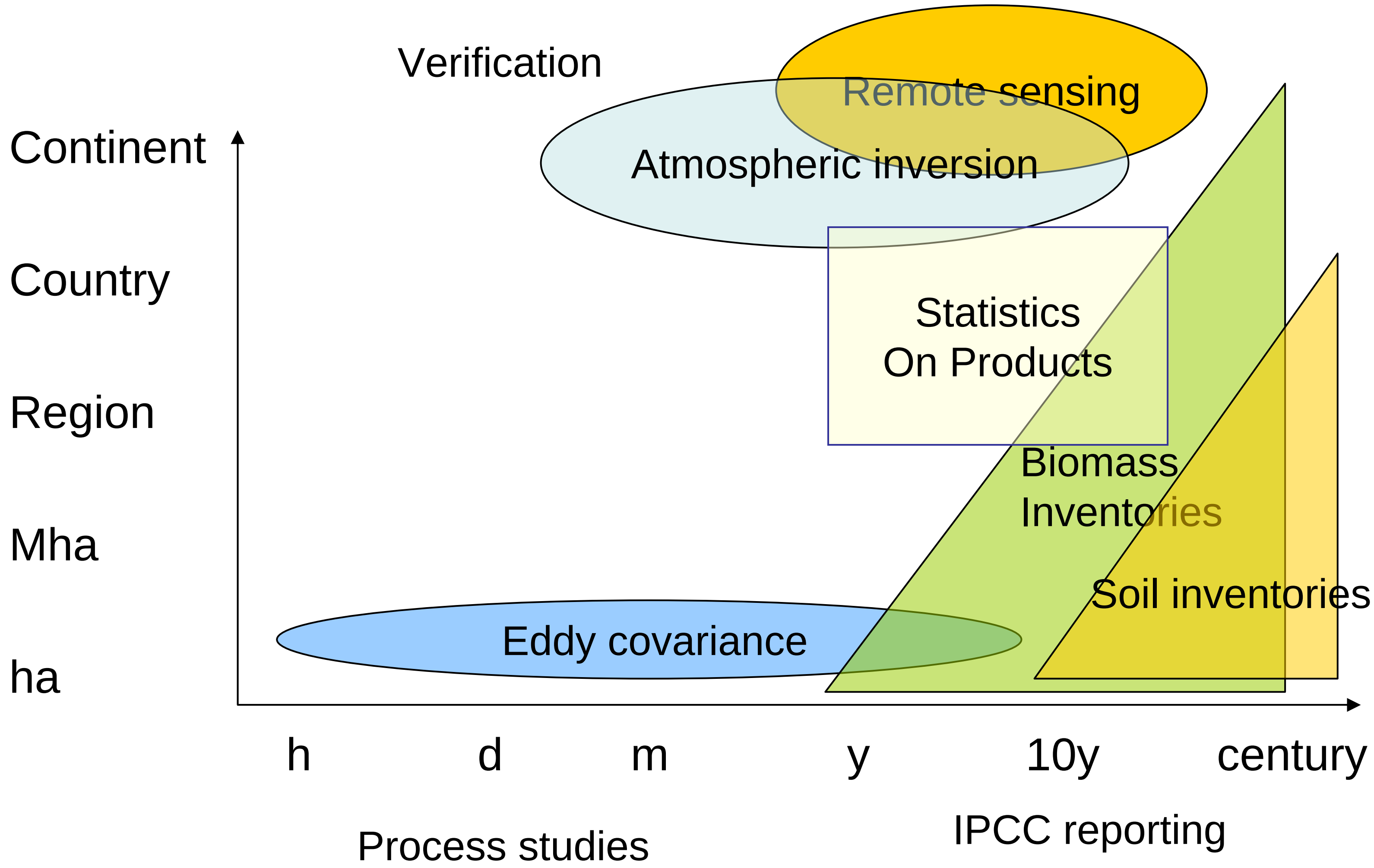
Default simplified method: Good Practice Guidance for Land Use and-Use Change and Forestry, IPCC 2003.

System boundary

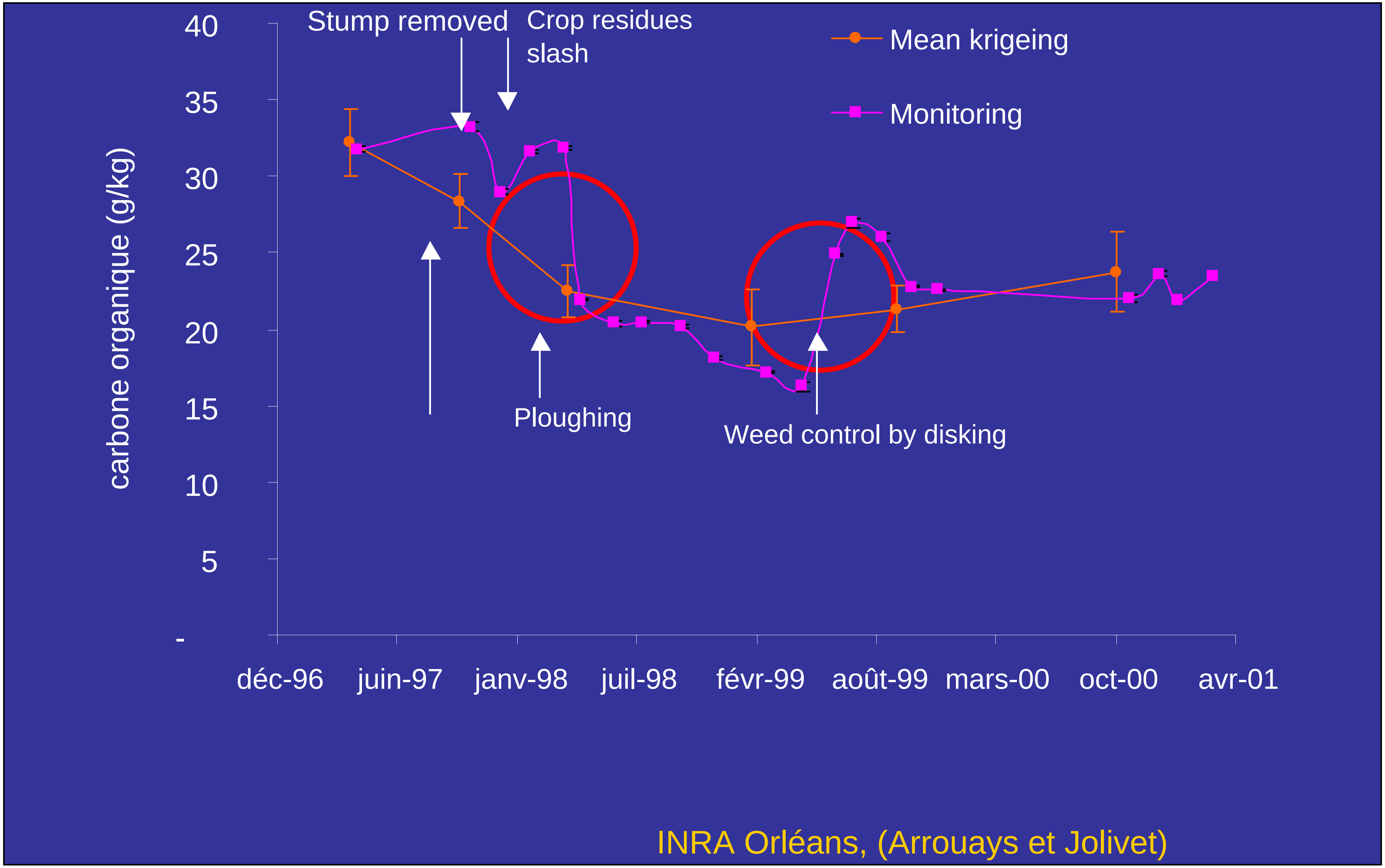


Accounting and verifying:

space and time resolution of C flux measurement methods



Forest operations example: soil carbon stock is primarily affected by mechanical disturbances (ploughing).



Forest operation impacts: qualitative assessment

(Hyvonen et al. 2007 New Phytol.)

Table 2 Qualitative effects on average carbon stocks of management operation in managed forests over a rotation period compared with the rotation period prior to management (modified from Freeman *et al.*, 2005)

Management measure	Soil C stock	Biomass C stock	Ecosystem C stock
Stand initiation phase			
Prescribed burning*	Decreasing	Decreasing, neutral or increasing	Decreasing, neutral or increasing
Drainage of peatlands†	Decreasing	Increasing	Decreasing, neutral or increasing
Site preparation method‡			
Low–intensive	Neutral	Increasing	Increasing
Intensive	Decreasing	Increasing	Decreasing, neutral or increasing
Tree species change§			
To conifers from broadleaves	Increasing	Increasing	Increasing
To broadleaves from conifers	Decreasing	Decreasing	Decreasing
To mixed conifers and broadleaves from mono-specific coniferous	Neutral or decreasing	Neutral or decreasing	Neutral or decreasing
Stem exclusion phase			
Thinning method¶	Neutral or decreasing	Decreasing	Decreasing
Fertilization**	Increasing	Increasing	Increasing
Increased rotation length††	Decreasing, neutral or increasing	Increasing	Increasing
Harvesting method‡‡	Decreasing, neutral or increasing	Decreasing, neutral or increasing	Decreasing, neutral or increasing

The carbon cost of forest operations : E. Sonne 2006, *J of Environm. Quality*

- Life cycle analysis
- CO_2, CH_4, N_2O accounted
- “Upstream” and on site costs accounted
- 408 management alternatives analysed
- Douglas fir, Washington and Oregon.

- “Downstream” costs not accounted
- Units: land are (ha) and wood volume (m3), time frame 50yr, units a CO_2 eq.

Estimate of carbon cost of management operations

Table 8. Contribution of each unit process to greenhouse gas (GHG) emissions.

	GHG emissions	Percent contribution†
	Mg CO_2e‡ ha^{-1}, except where specified	%
P + 1§	0.022	<1
1 + 1	0.027	<1
Large plug	0.01	<1
Pile and burn	4.0	32
Chemical site preparation	0.12	1
Transportation: 1 + 1, P + 1	0.05	<1
Transportation: large plug	0.15	1
Fertilization	1.9	15
Herbicide treatment	0.15	1
Harvesting (including CT and PCT)¶	5.9	51

† Based on P + 1, pile and burn, fertilization, herbicide, and harvesting 747 m^3 timber.
‡ Carbon dioxide equivalents.
§ Seedling emissions are based on 1236 seedlings ha^{-1}.
¶ Emissions are based on 700 m^3 harvested timber. CT, commercial thinning; PCT, pre-commercial thinning.

Estimate of carbon cost of scenario alternatives

Table 6. Direct emissions contribution to global warming impact (normalized to 50 yr). **And distribution among main GHG**

Rotation age†	carbon dioxide equivalents (CO_2e) ha^{-1}	CO_2	N_2O	CH_4
yr			%	
30	11.1	57	31	12
40	10.9	66	24	10
50	9.9	72	19	8
60	8.9	73	19	8

Shorter rotations emit more carbon per unit area

N fertilisation is a major source of global warming through N_2O (Crutzen P.J. et al., 2007)

Table 9. Greenhouse gas (GHG) emissions per 100 m^3 harvested timber by rotation age.

Scenario	Rotation age (yr)			
	30	40	50	60
	Mg CO_2e† 100 m^{-3}			
865_CT‡_fert	2.47	1.59	1.59	1.34
865_NA§	1.59	1.24	1.31	1.24
865_PCT¶_CT_fert	2.58	1.59	1.59	1.34
865_PCT_CT_herb_fert	2.54	1.59	1.55	1.38
1235_CT_fert	2.08	1.52	1.48	1.31
1235_CT_herb_fert	2.05	1.52	1.48	1.31
1235_NA	1.45	1.24	1.27	1.24
1235_PCT_CT_fert	2.61	1.55	1.59	1.38
1235_PCT_CT_herb_fert	2.68	1.59	1.59	1.38
1235_PCT_CT	1.94	1.27	1.34	1.16
1235_PCT	1.87	1.27	1.38	1.24
1729_CT_fert	1.91	1.45	1.45	1.27
1729_CT_herb_fert	1.87	1.45	1.45	1.27
1729_PCT_CT_fert	2.72	1.55	1.62	1.41
1729_PCT_CT_herb_fert	2.75	1.55	1.62	1.41
1729_PCT_CT	1.98	1.27	1.34	1.20
1729_PCT	1.91	1.27	1.38	1.27
Average of management intensities	2.19	1.45	1.48	1.31

† Carbon dioxide equivalents.
‡ Commercial thinning.
§ No treatment.
¶ Pre-commercial thinning.

Estimate of carbon cost of forest operations

Table 12. Percent of greenhouse gas (GHG) emissions to average carbon storage by rotation age (normalized to a 50-yr rotation).

Rotation age†	GHG emissions as percent of average carbon storage	GHG emissions with transportation as percent average carbon storage
yr	%	
30	6.8	12.5
40	4.7	10.6
50	3.8	8.6
60	2.5	6.0

† Average of all 102 management intensities in the 30-, 40-, 50-, and 60-yr rotations, respectively.

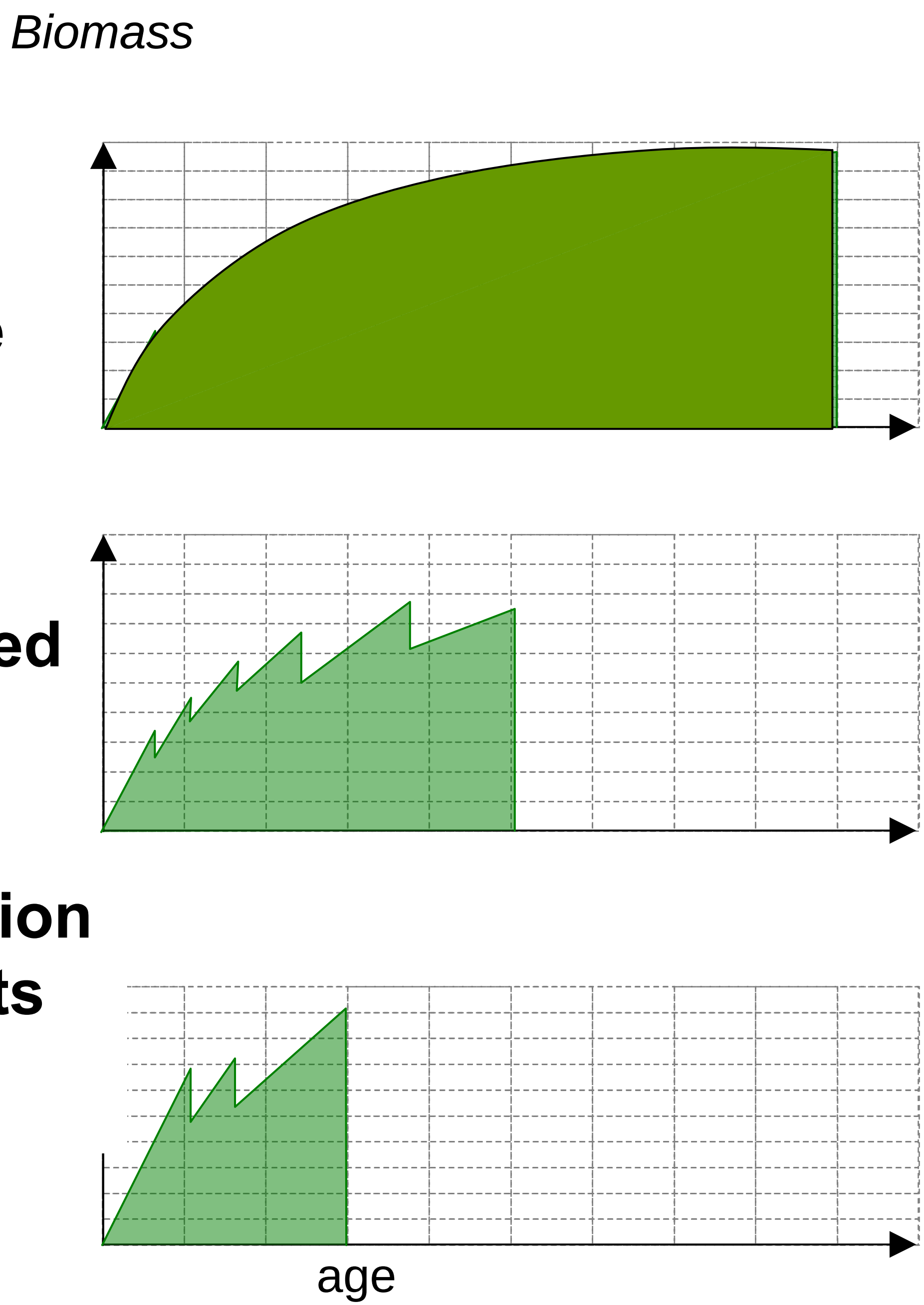
The cost of forest operations (upstream and on site) is 6.0 to 12.5% of the average carbon storage.

Forest management alternatives

Close from nature (UM)

Managed (M)

Plantation forests (FI)



Regeneration assisted

Thinnings

Clearcut

Timber logging

Soil preparation

Plantation / seeding

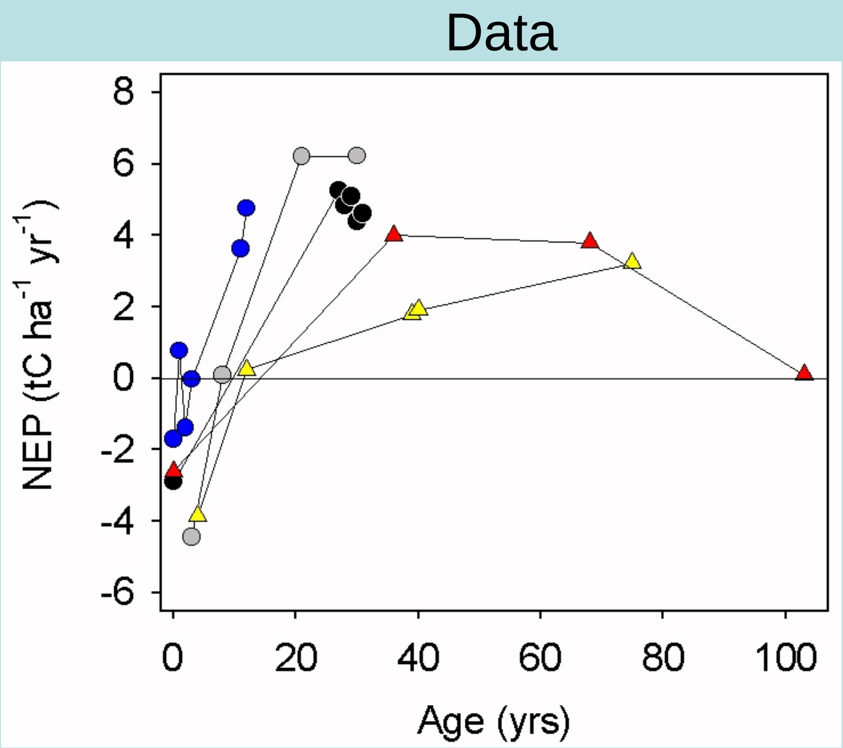
Fertilisation, drainage

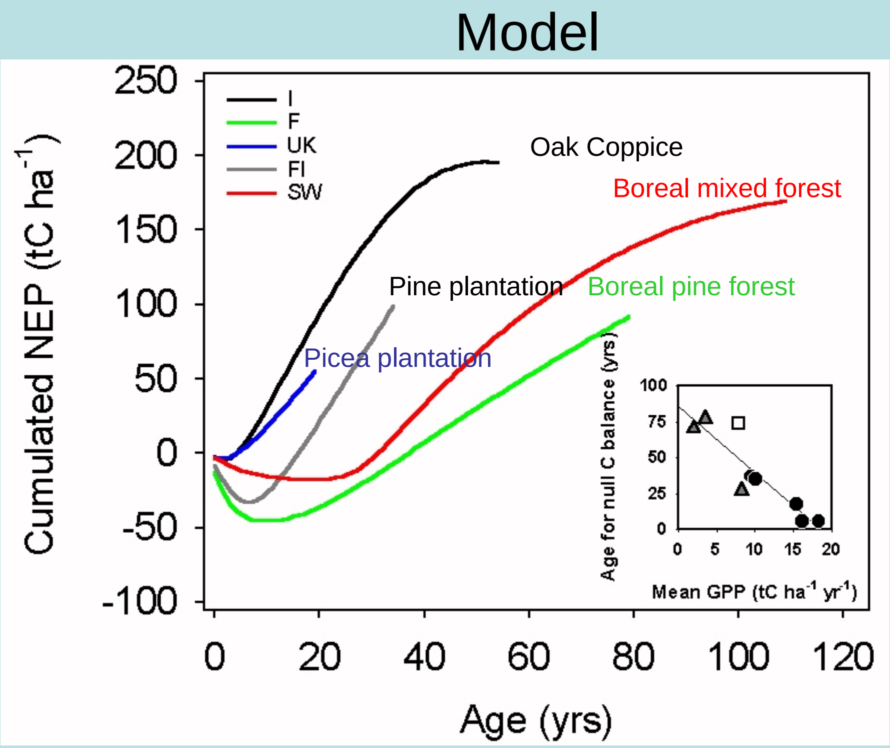
Weed control

Pest control

Whole tree harvesting

Age effect on forest carbon balance





Disturbance → Forest = C Source

Earlier recovery in intensive management alternative

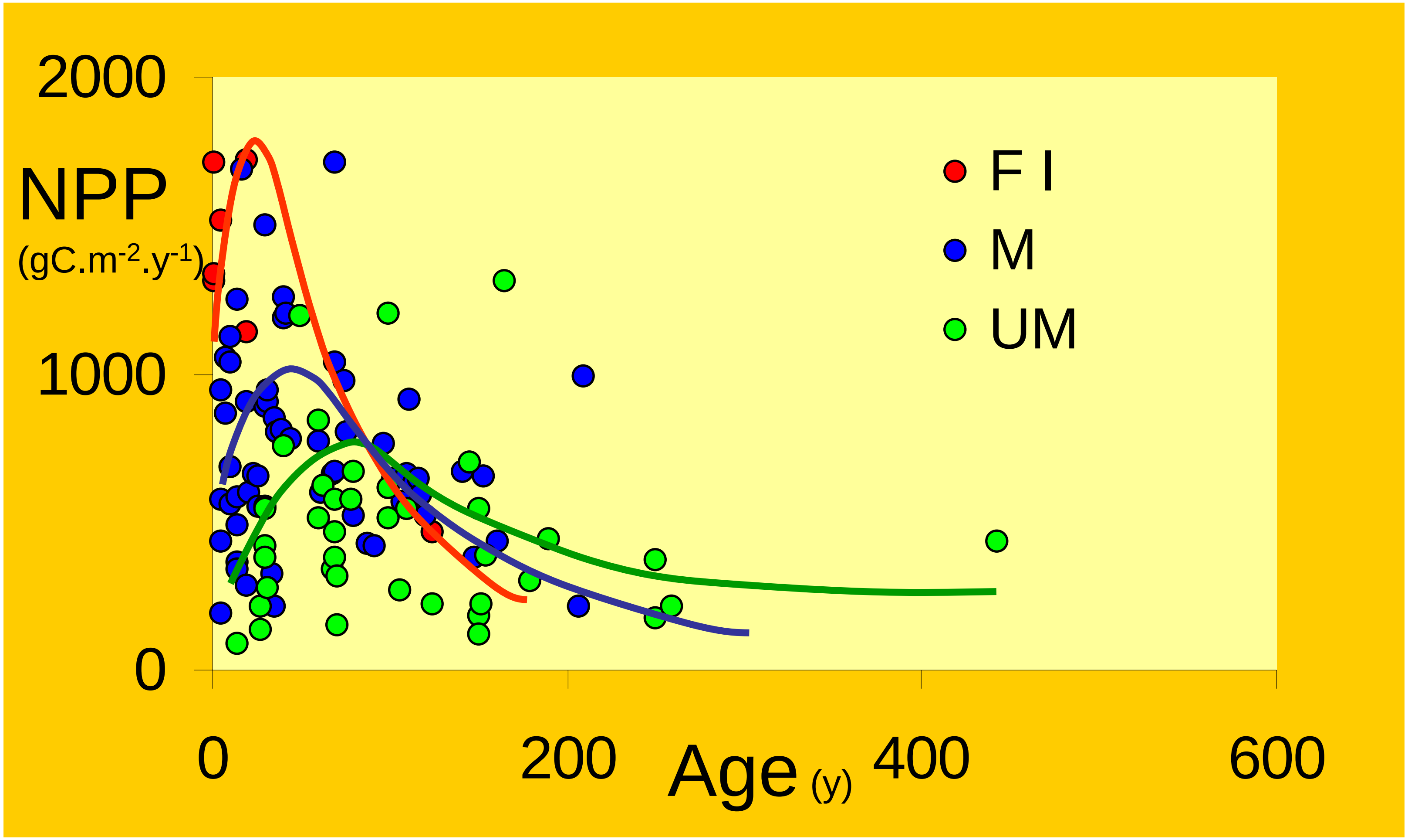
Magnani et al., *Nature*, (2007).

C stocks (e.g. temperate coniferous)

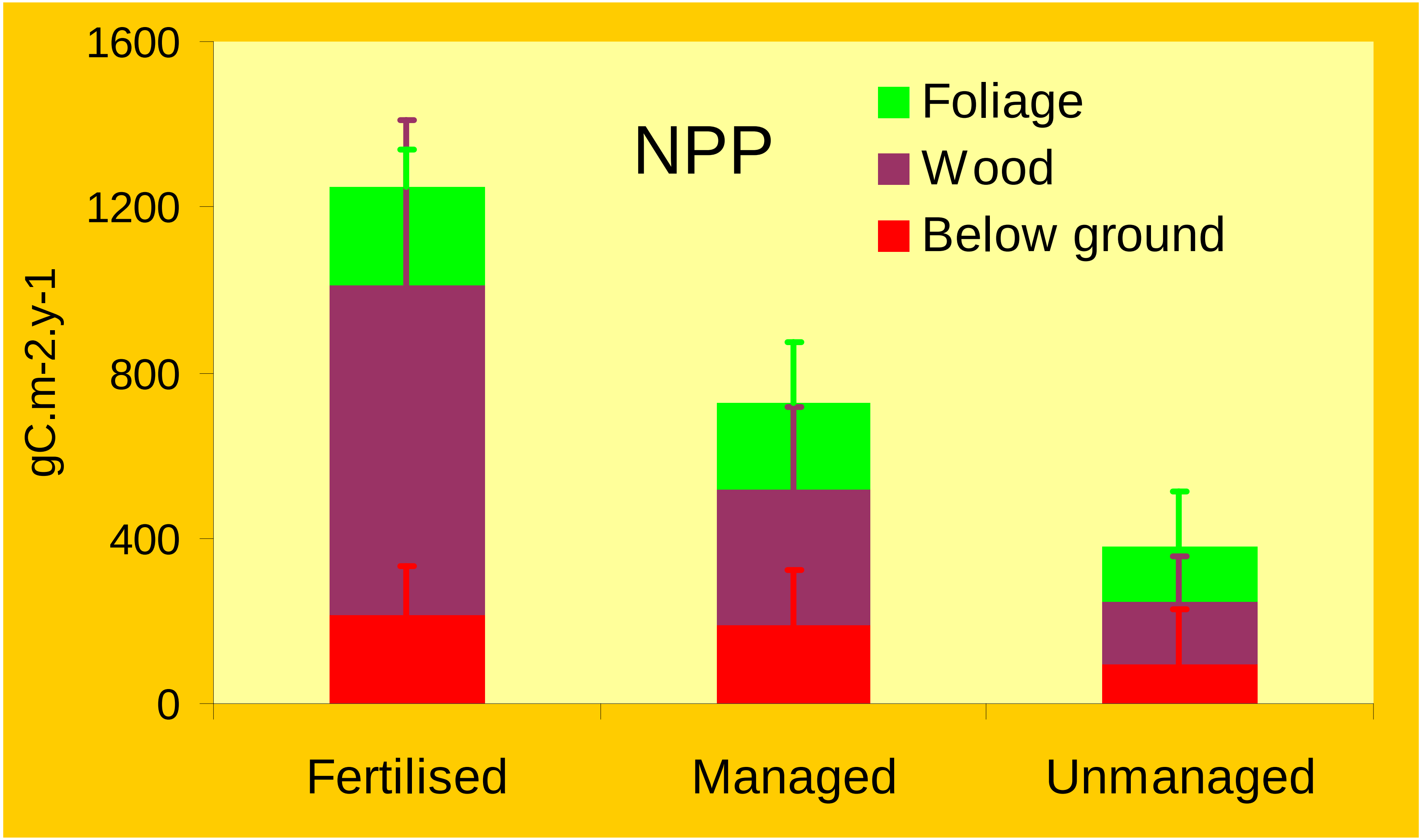
OPTIONS	C stock *in situ* ($tC.ha^{-1}$) Biomass: trees	C stock *in situ* Biomass: others	C stock *in situ*: soil	Mean annual production ($m^3.ha^{-1}.an^{-1}$)	fossil C substituted ($tC.ha^{-1}.an^{-1}$)
UM	57.5	7.5	100	6	1.3
M	27.7	5.0	80	12	2.6
FI	14.2	0	40	18	3.9

Faster growth and shorter rotation = smaller carbon stock on site

C flux (database from Luyssaert et al. 2007)

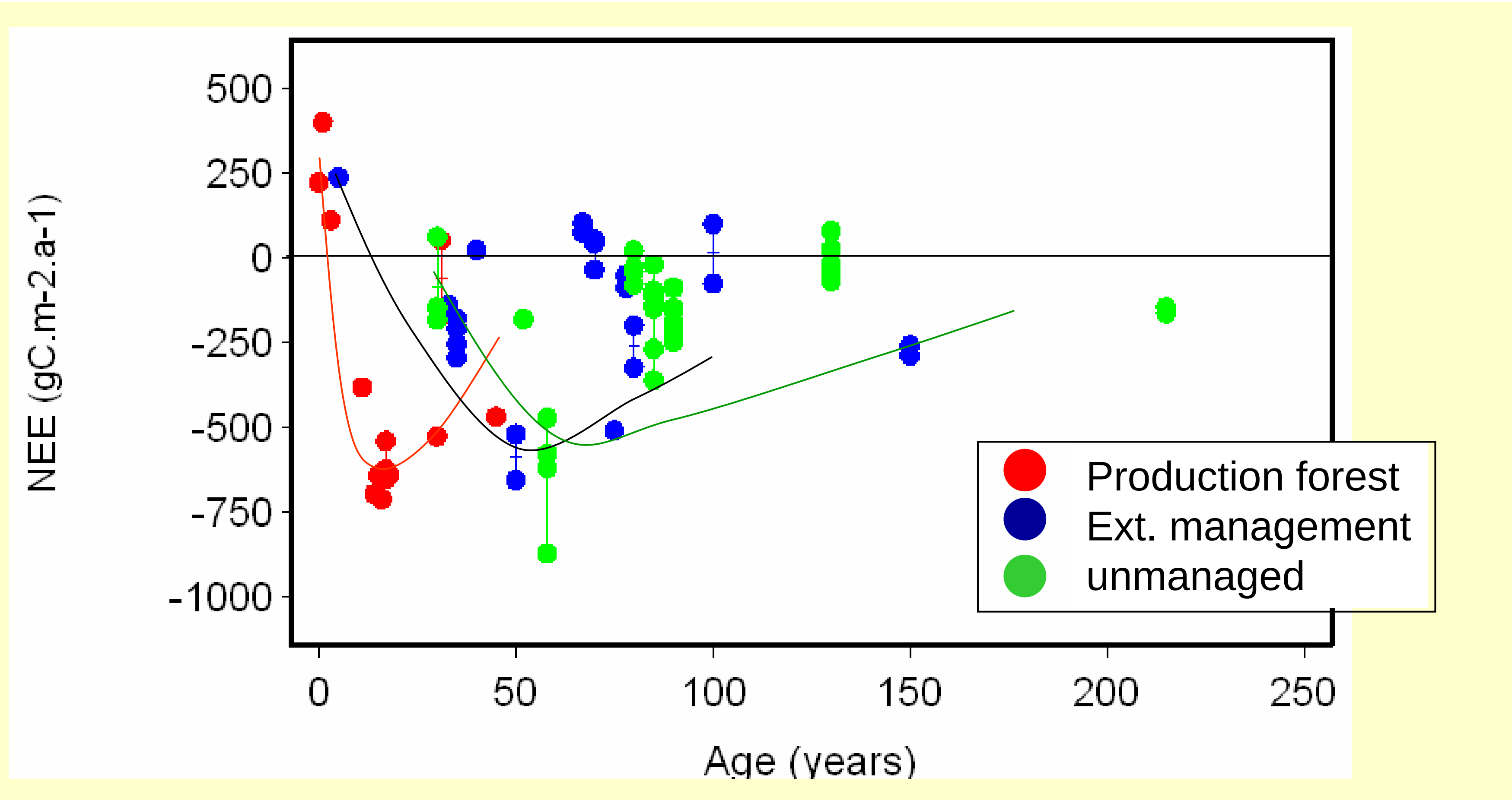


C allocation (database from Luyssaert et al. 2007)

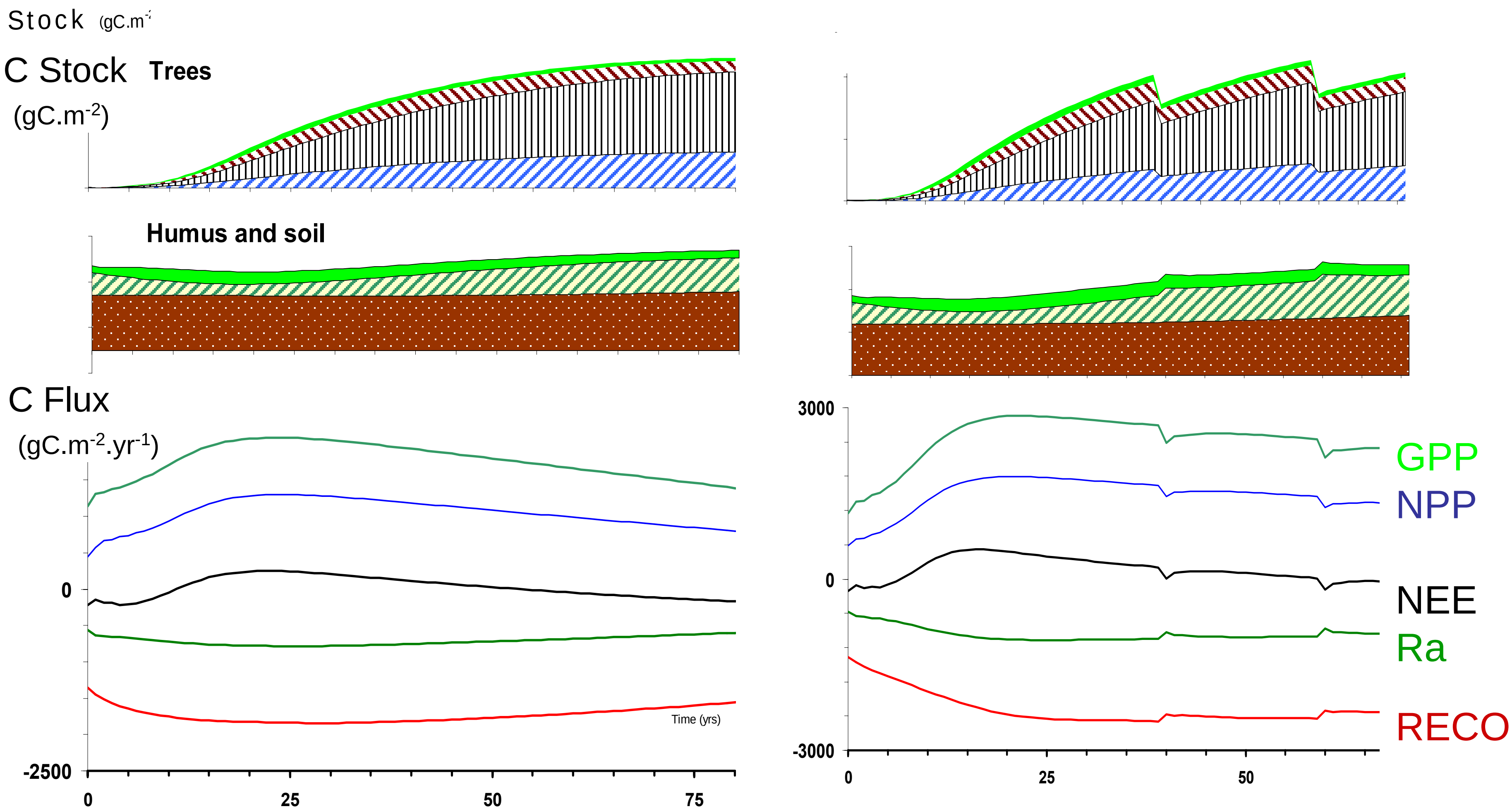


Management increases the NPP share to the wood

C balance over the rotation



(Data fom Black *et al.* 2005 & Hyvonen et al., New Phytol. 2007)



- shortens life cycle
- amplifies NEP and NPP
- increase the fraction of harvest biomass (timber)
- but depletes carbon stock in soil and biomass

Summary: management keeps forest younger

- shortens life cycle

- amplifies NEP and NPP

- increase the fraction of harvest biomass (timber)

- but depletes carbon stock in soil and biomass

- has a higher cost in carbon for forest operation (up to 12.5%)

(Pine plantation, SW Fance)

(Rimu Forest SW NZ)

Should we produce…………..or store carbon ?

- The carbon cycle updated 2007, natural and human- disturbed.

- Its terrestrial component
  - Generic scheme and important definitions
  - Land use types
  - Geographical distribution

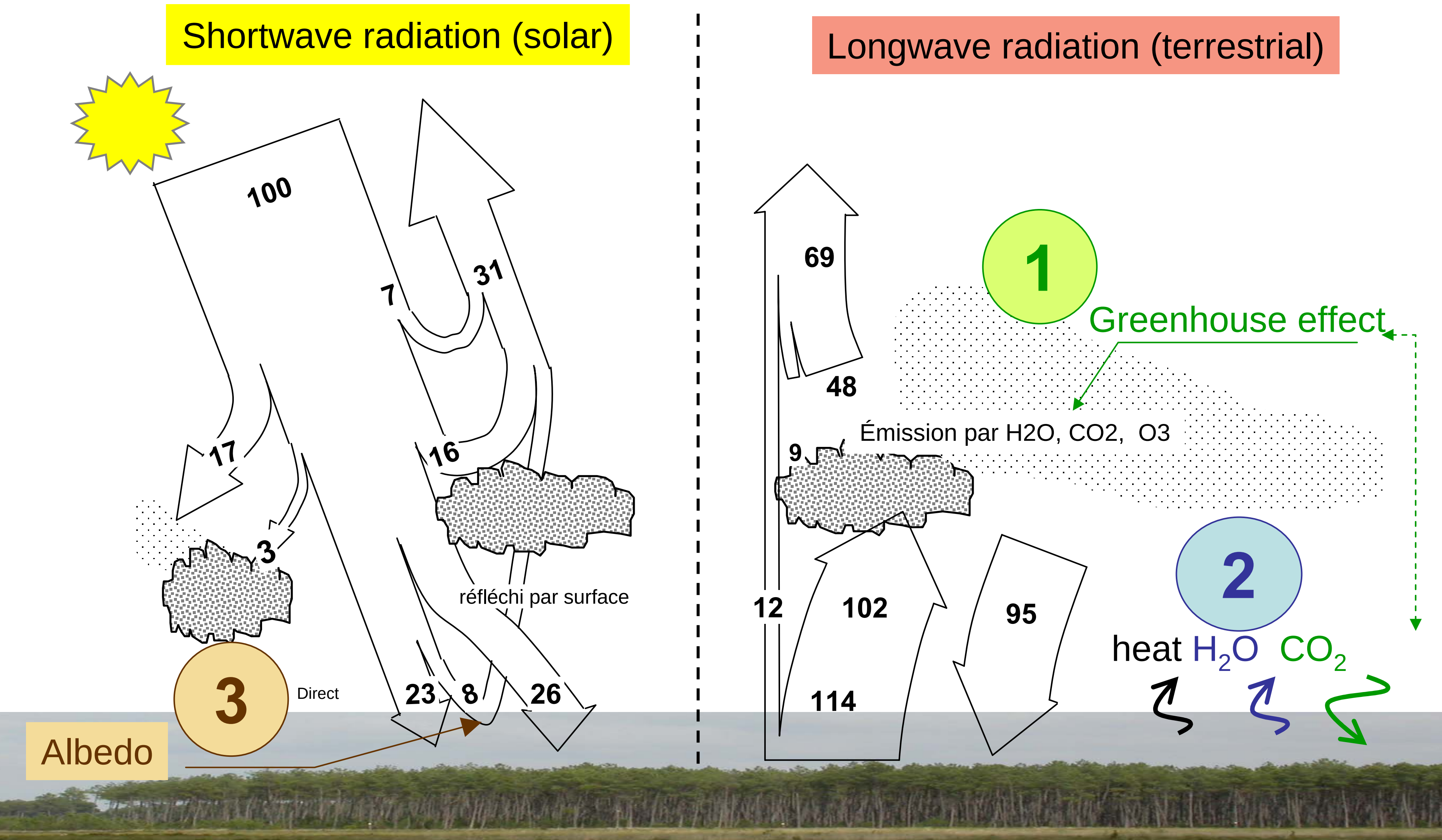
- Managing carbon in "natural" ecosystems
  - Land use changes
  - Forest operations
  - Forest scenario alternatives

- Beyond carbon, managing the overall climate impacts
  - Carbon free greenhouse gases (N_2O, O_3)
  - Energy Balance: heat flux, evaporation
  - Global warming potential

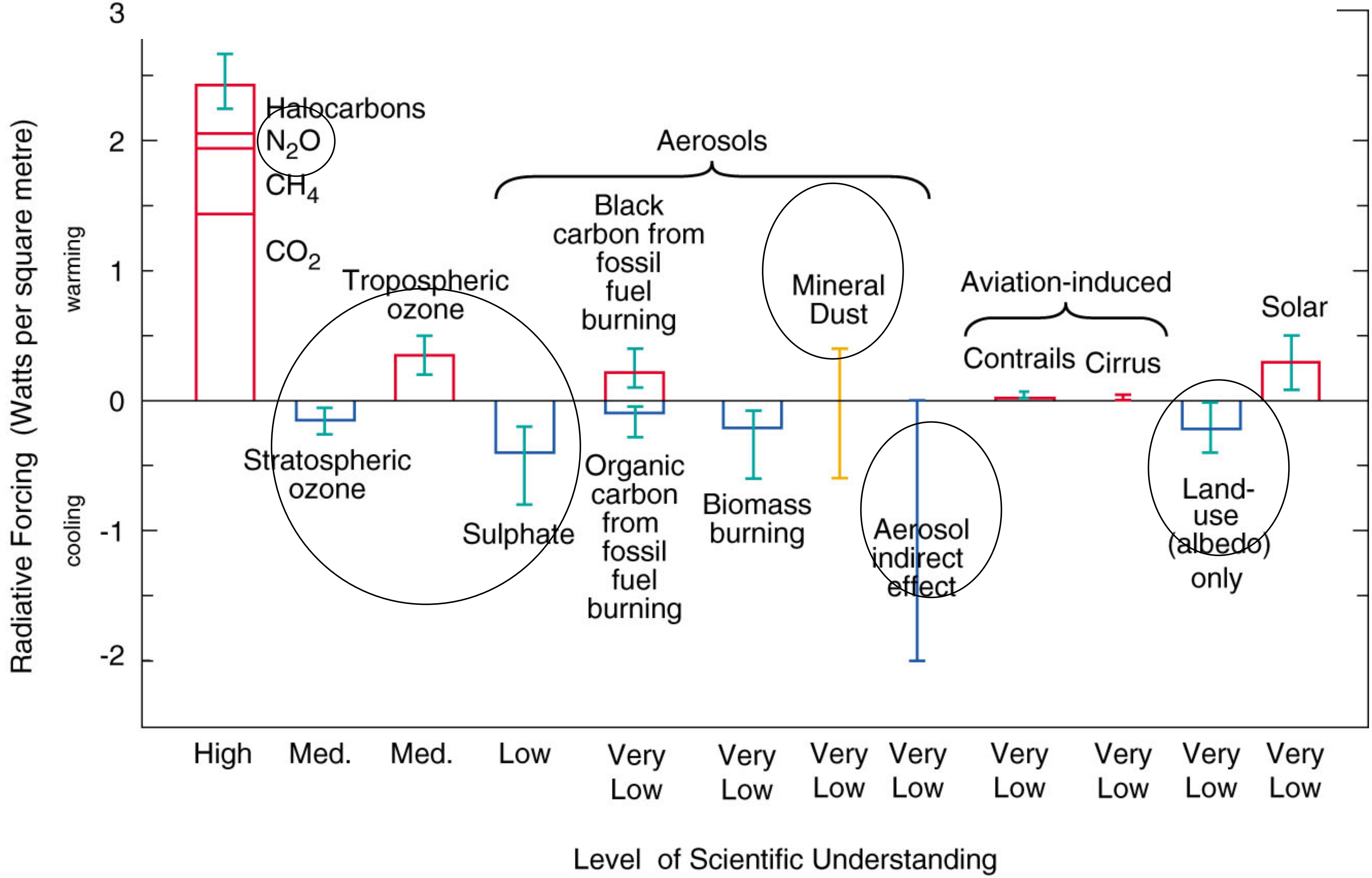
- Diversity

- Conclusion

Accounting for all atmospheric impacts: GHG, energy balance,



Carbon is only a (large) part of the story :



GLOBAL WARMING POTENTIAL

- A measure of how the energy balance of the earth-atmosphere system is influenced when factors such as GHG concentration, surface albedo or heat flux emitted by vegetation are altered.

- Unit $W.m^{-2}$

- Allows to compare different alternatives and should be used for estimating climate impacts of terrestrial ecosystems

Other greenhouse gases involved in forestry

	Estimated lifetime in the atmosphere (years)	Global Warming potential relative to CO_2 integration time (years)		
		20	100	500
CO_2		1	1	1
CH_4	10	63	21	9
N_2O	150	270	290	190

Accounting for GHG and energy balance (albedo only !)
Change in the global warming index as compared with standard management scenario (M)

	total C. stock	Fossil C. saved	Albedo	**Total**
20 y				
FI	0.24	-0.11	-0.01	**+0.12**
UM	-0.22	0.11	0.01	**-0.10**
50 y				
FI	0.24	-0.27	-0.01	**-0.04**
UM	-0.22	0.27	0.01	**+0.06**

- Importance of the time scale
- « ghg » effect > albedo
- Production is better in fertile sites

- The carbon cycle updated 2007, natural and human- disturbed.

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Species composition: single or multiple species stands ?

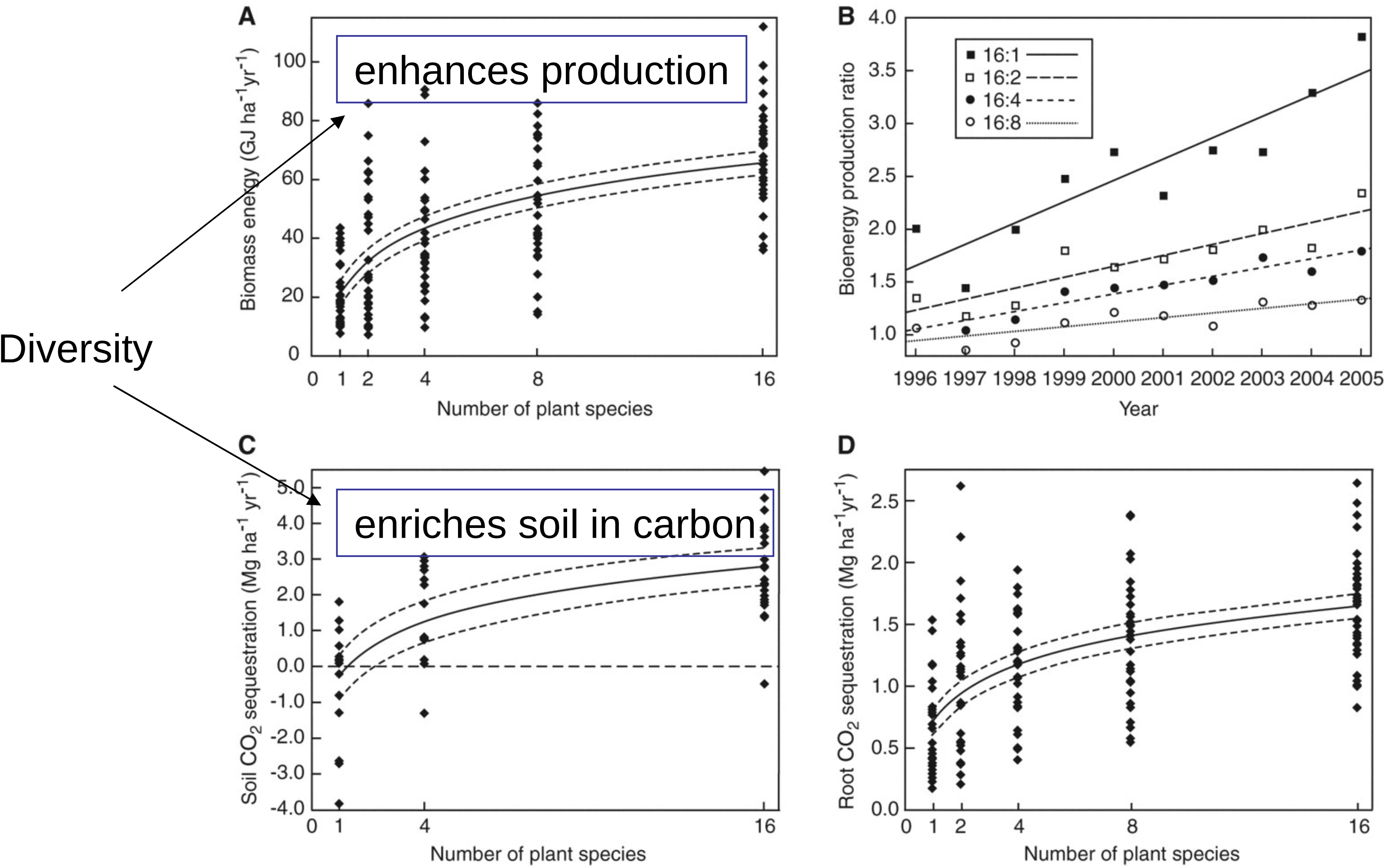
Not so much literature on forest

→Answers from grasslands

D. Tilman et al., Science 314, 1598 -1600 (2006)

Species composition: single or multiple species stands ?

Effects of plant diversity on biomass energy yield and CO2 sequestration for low-input perennial grasslands

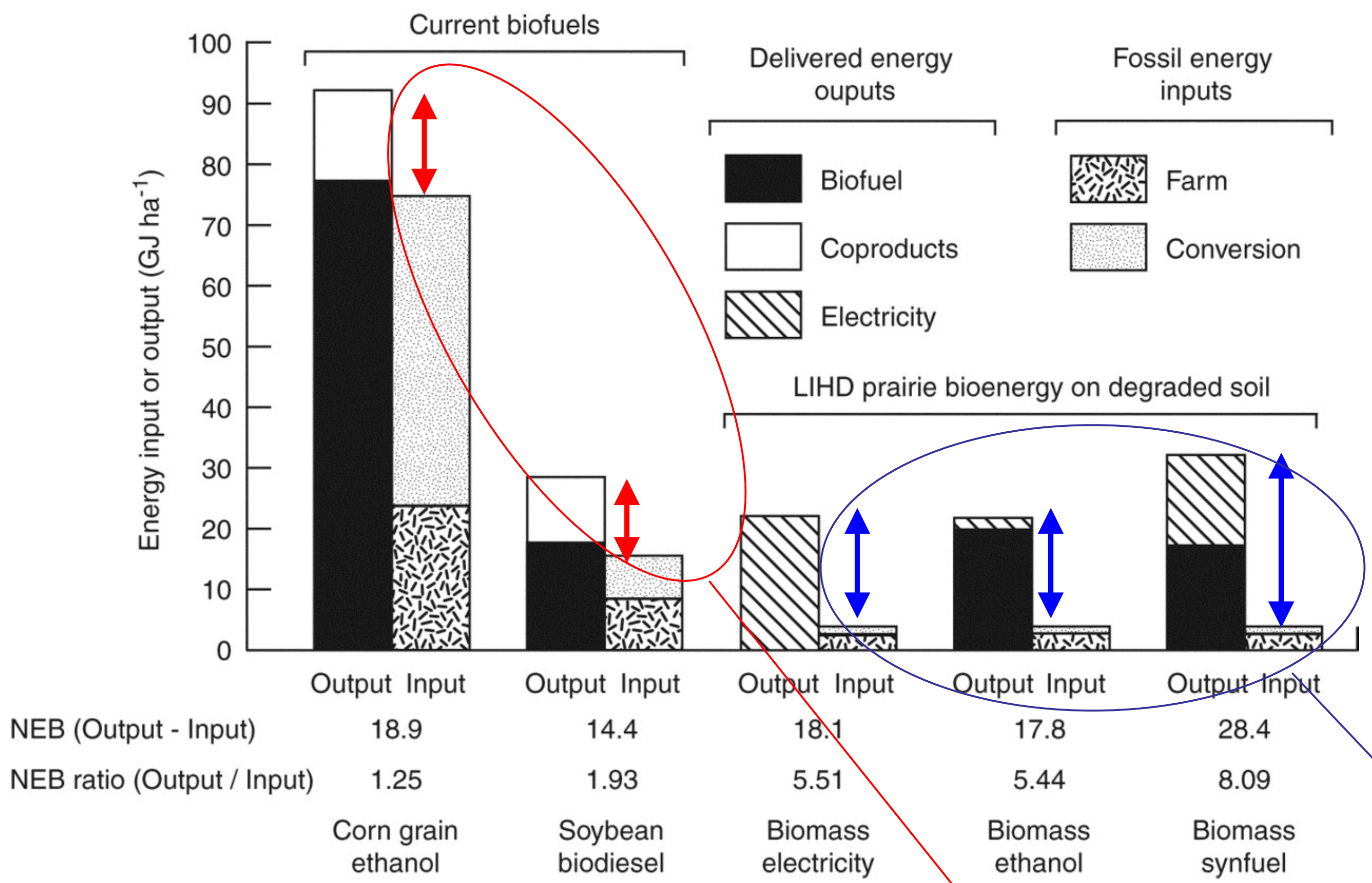


D. Tilman et al., Science 314, 1598 -1600 (2006)

Published by AAAS

Species composition: single or multiple species stands ?

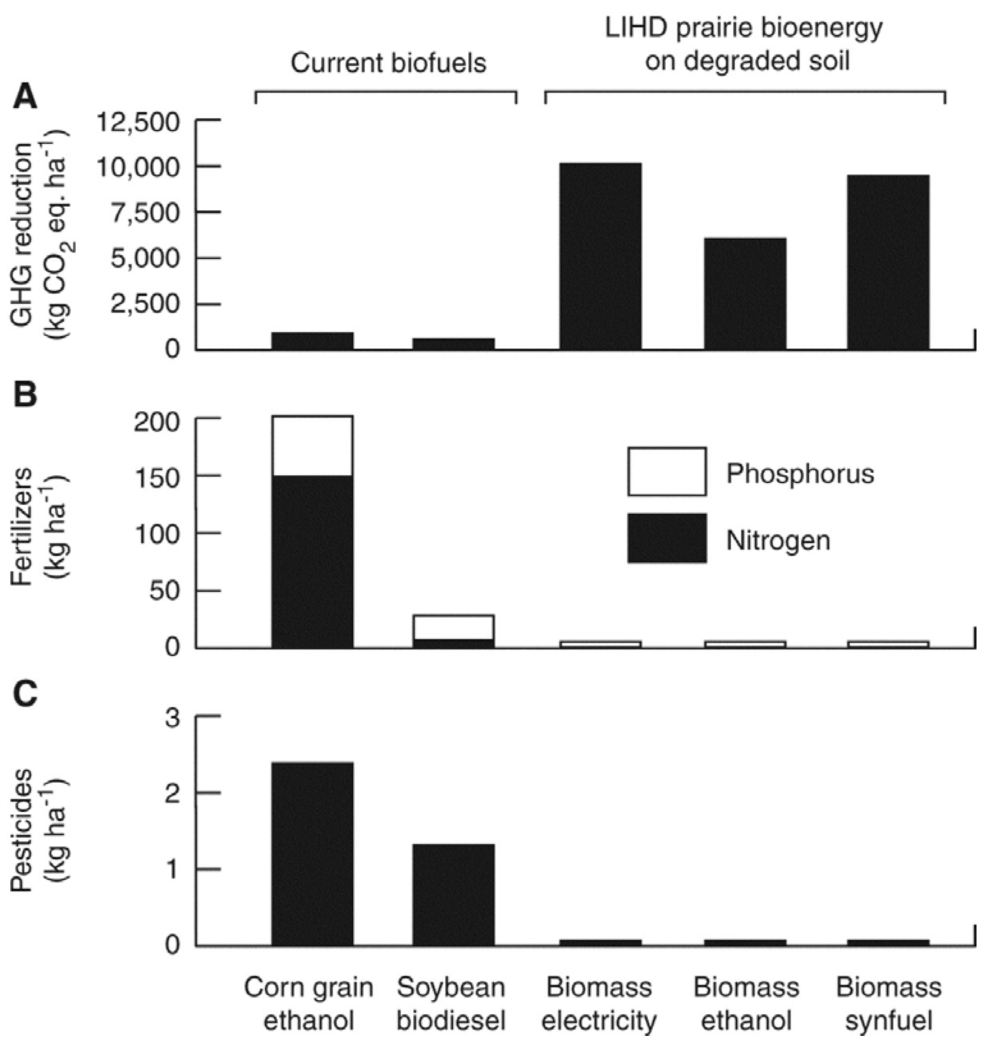
Net Energy Balance for two food-based biofuels (current biofuels) grown on fertile soils and for LIHD biofuels from agriculturally degraded soil



The net energy balance of “natural” biodiverse grasslands overtakes the maïze and soybean crops.

Published by AAAS

Environmental effects of bioenergy sources



Highest GHG reduction

low cost in fertilisers

and phytocides

D. Tilman et al., Science 314, 1598 -1600 (2006)

Published by AAAS

Environmental effects of bioenergy sources

Tilman's study puts forward the hypothesis that, from the atmospheric point of view, low input high diversity alternatives may overcompete monospecific crops wih high input

The question is open and Tilman's work has been discussed.

Using natural ecosystem functions for increasing resource capture (N, light, CO2, water) at the expense of fossil carbon expensive fertilisers and phytocide must be considered.

Diversity may also enhance ecosystem resilience and adaptative capacity, a major issue for forest managers in a rapidly changing world.

D. Tilman et al., Science 314, 1598 -1600 (2006)

Published by AAAS

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- Summary

Summary : a forest ideotype for climate

1. Site

- No tillage, minimize soil work
- Increase productivity (NPP): site remediation, soil improvement

2. Stand

- permanent cover (albedo)
- uneven aged stands
- Mitigate climate impacts: LAI control, understorey control,
- target the adaptative potential to changing climate , 2 options:
  - intra- and inter-species diversity, multi-aged canopy
  - short rotation

Summary: a forest ideotype for climate

3. Regional management

•Mitigate the impact of climate change: ex. continuous forest cover, increases species diversity, ..

•Allocate forest functions according to site conditions:

rich and deep soils → high production with low input
poor soil … → conservation / protection and carbon storage *in situ*.

•Lengthen the residence time of carbon : promote long lived wood products (house, furniture, …)

•Maximise fossil fuel substitution

Conclusions