Soil organic carbon management for global benefits : a discussion paper

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Four themes

- Spatial and temporal dimensions of Soil Organic Carbon (SOC)
- Major issues of potential relevance to the GEF
- Linkages to GEF areas
- How SOC management may deliver multiple benefits

This presentation

- Some important principles and numbers
- Some ideas/visions on SOC management and SOC research
  - Maybe somewhat provocative from time to time
  - Open for discussion

Spatial and temporal dimensions

How much SOC is there ?

Source	0-1 m	0-2 m
Batjes (1996)	1462-1548	2376-2456
Kasting (1998)	1580	
Robert (2001)	1500	2456
Jobbagy and Jackson (2000)	1502	1993
Post *et al.* (1982)	1395	
Hiederer and Köchyl (2012)	1417	

- Topsoils contain 1400-1500 Pg (or Gt, billions of tonnes) of SOC
- There is an additional 1000 Pg stored in deeper soil layers

That is very considerable

- 1Pg=1Gt=1 billion tonnes
- Three times the amount that is present in the atmosphere (ca. 800 Pg) or vegetation
- 200 times the amount that is annually emitted by human activities into the atmosphere (ca. 9 Pg)
- But much less than C stored in the ocean, or in carbohydrates
- SOC management is therefore of obvious importance

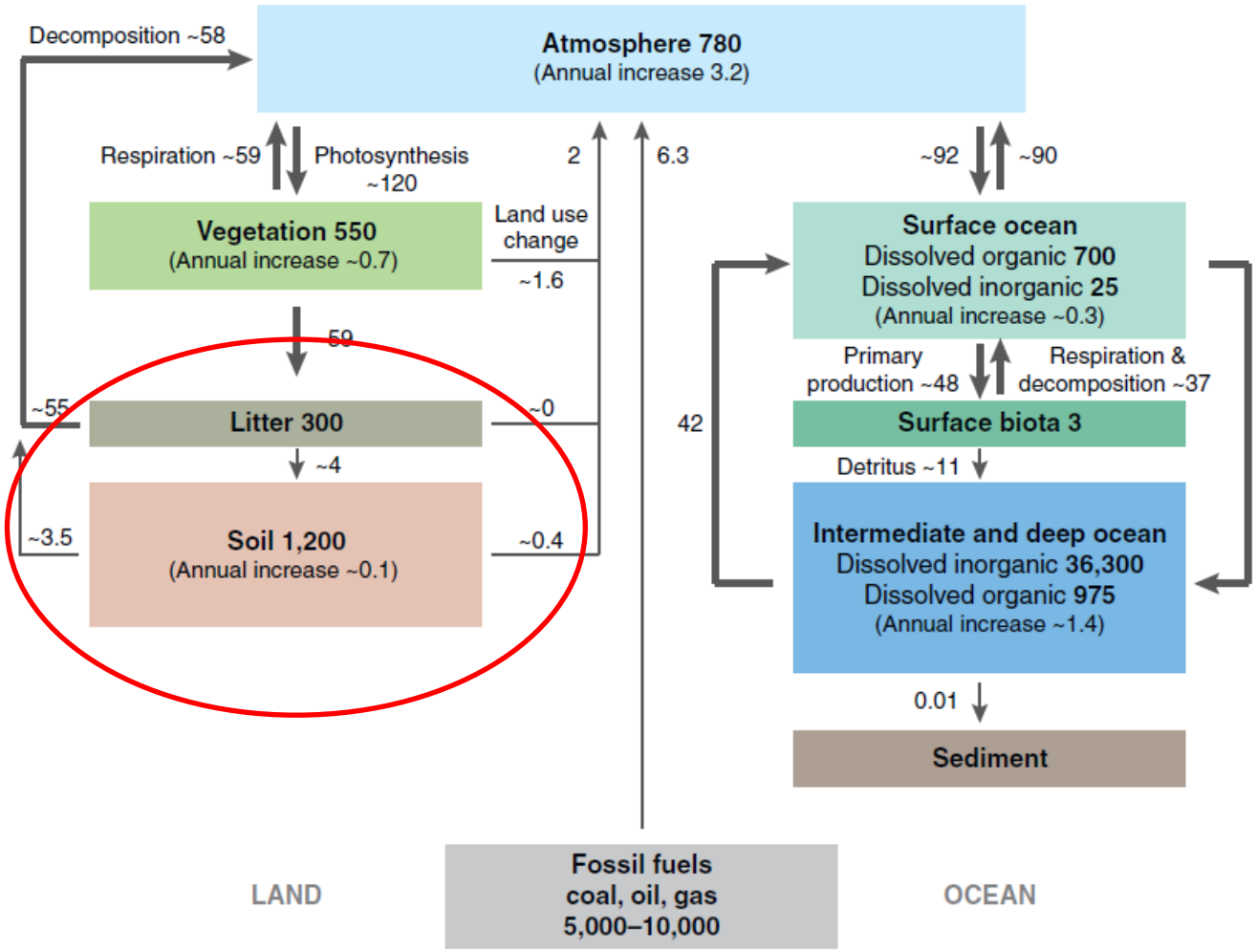


Figure 1

The global carbon cycle in the 1990s. Units are PgC or PgC year^{-1}.

C cycle: exchange between reservoirs

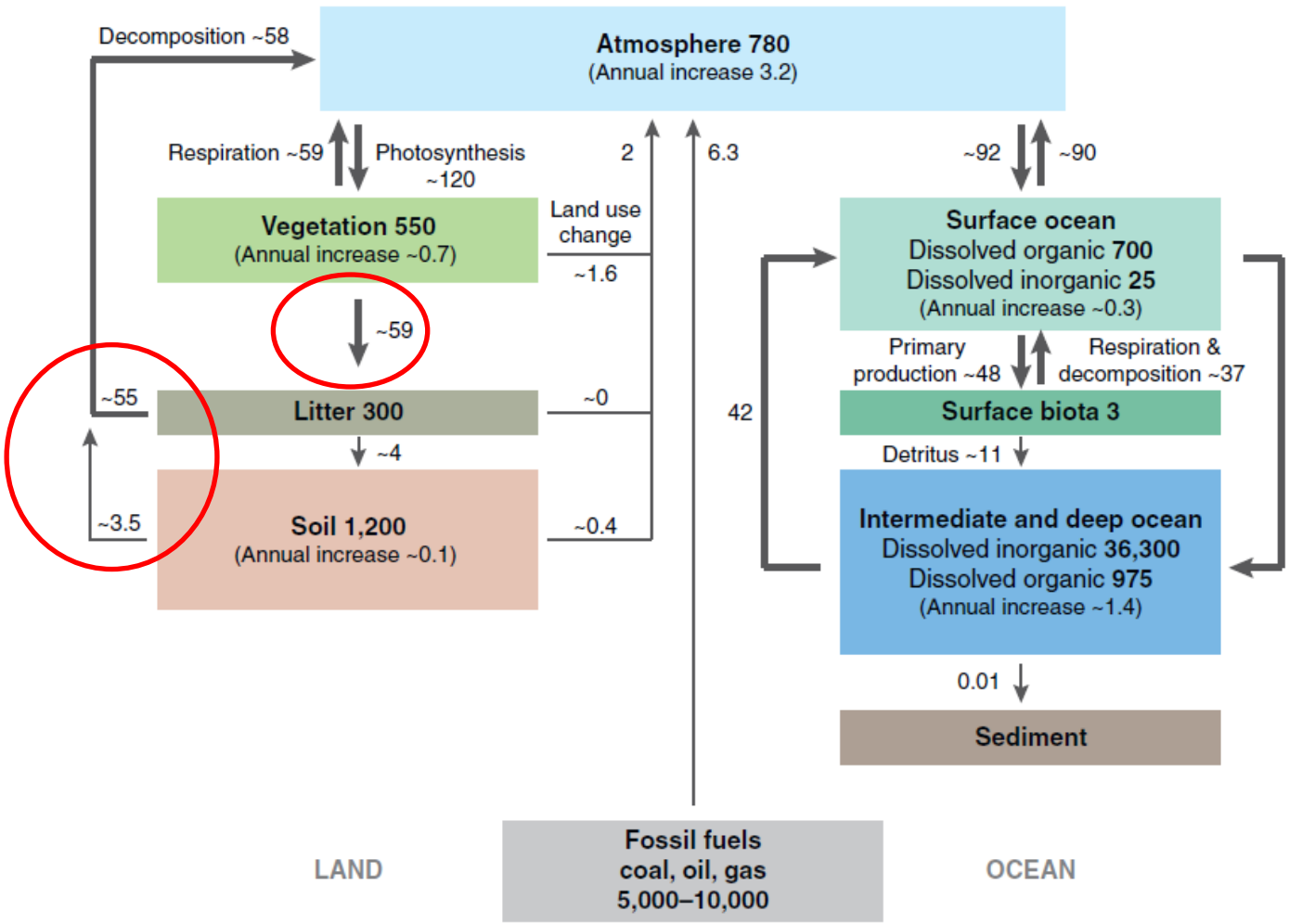


Figure 1

The global carbon cycle in the 1990s. Units are PgC or PgC year^{-1}.

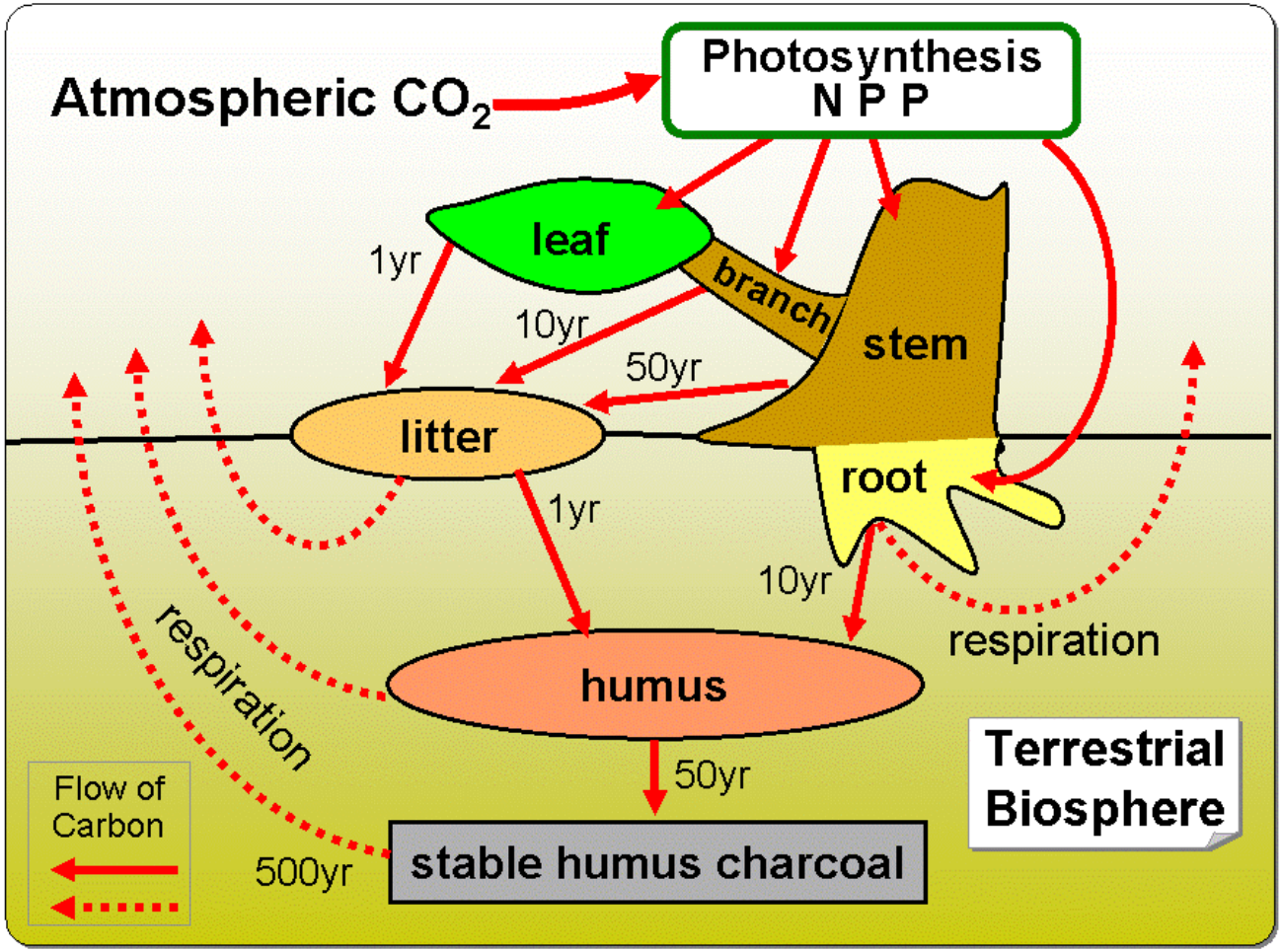
Input into the soil : dead plant material (litter, roots, branches)

http://www.flickr.com/photos/myshots_gallery/6685364153/sizes/z/in/photostream/

Output: autotrophic and heterotrophic respiration

- Autotrophic: root respiration
- Heterotrophic: CO_2 respiration of soil organisms (funghi, bacteria, soil animals…) that use dead plant matter as a food source.

So, all toghether it looks like this:

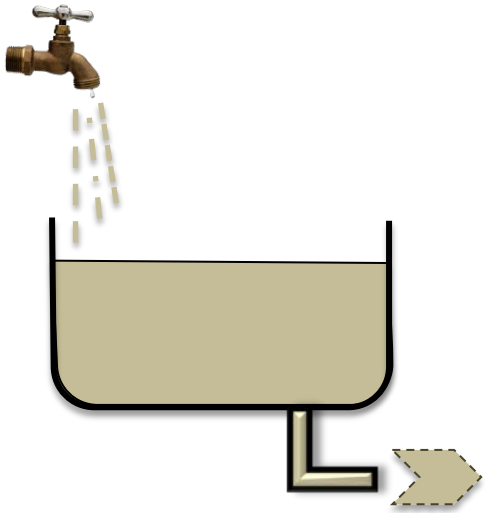


http://www.mri-jma.go.jp/Project/1-21/1-21-1/carbon_land_e.gif

What determines the amount of SOC in a soil : the kitchen sink analogy

http://hotfile.wordpress.com/2008/10/09/mccain-and-palin-launch-kitchen-sink-strategy/

What happens if we vary (i) water input through the tap and/or water evacuation (by opening or closing the drain) ?



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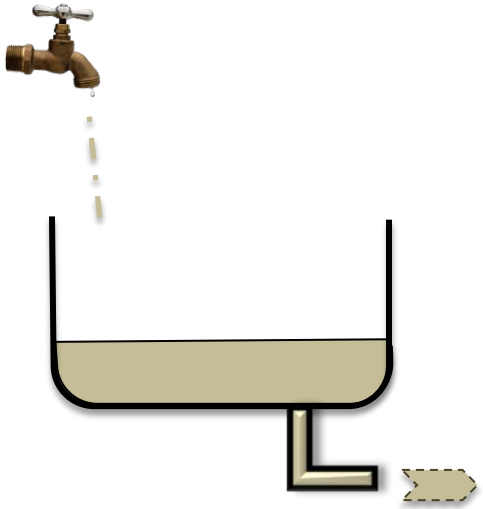

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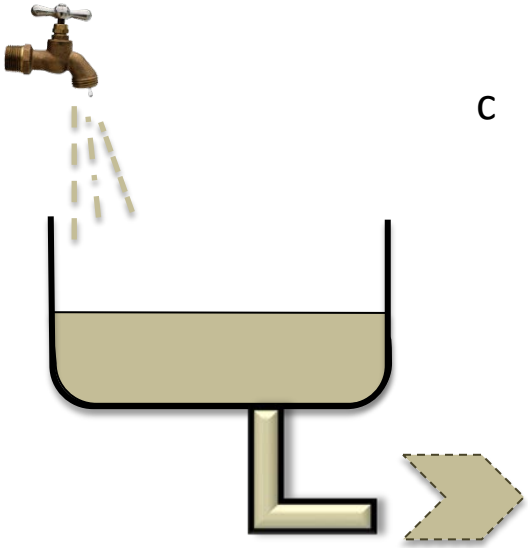
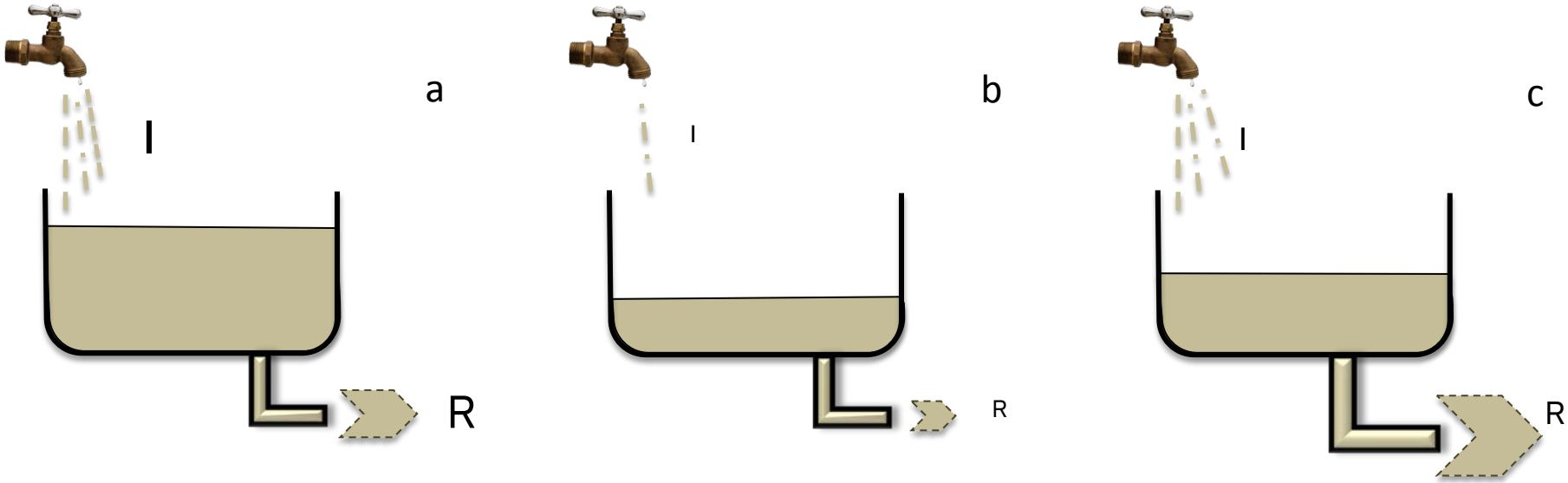


c

Soil organic carbon is basically the same thing: just think of the tap discharge by C input rate and think of the drain discharge as the respiration rate i.e the rate at which it is consumed and converted to CO_2



How is an equilibrium reached ?

- Input (tap rate) is more or less independent of the SOC stock
- Output (drain discharge) *is proportional to the magnitude of the stock*
- Equilibrium means that input=output
- If the input rate is changed the SOC stock will go up or down until the respiration rate is again in equilibrium with the new input rate
- If, on the other hand, the respiration rate is changed, the SOC stock will change until a new respiration rate is established in equilibrium with the input rate

How does this looks in equations

At equilibrium:

$I=O$

But also:

$O= k\ SOC$ *(k=decomposition rate)*

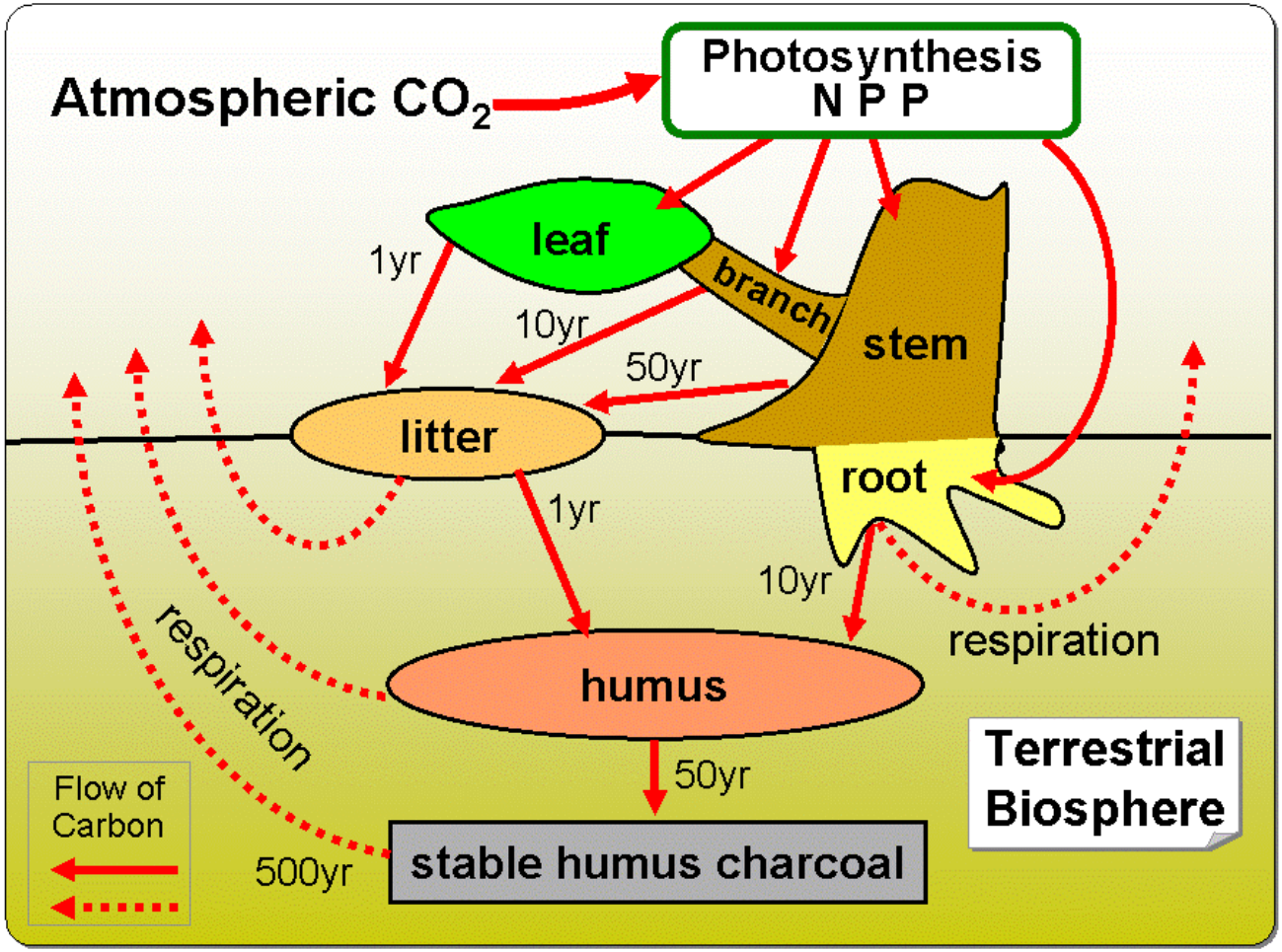
Thus

$I=k\ SOC,$

Or

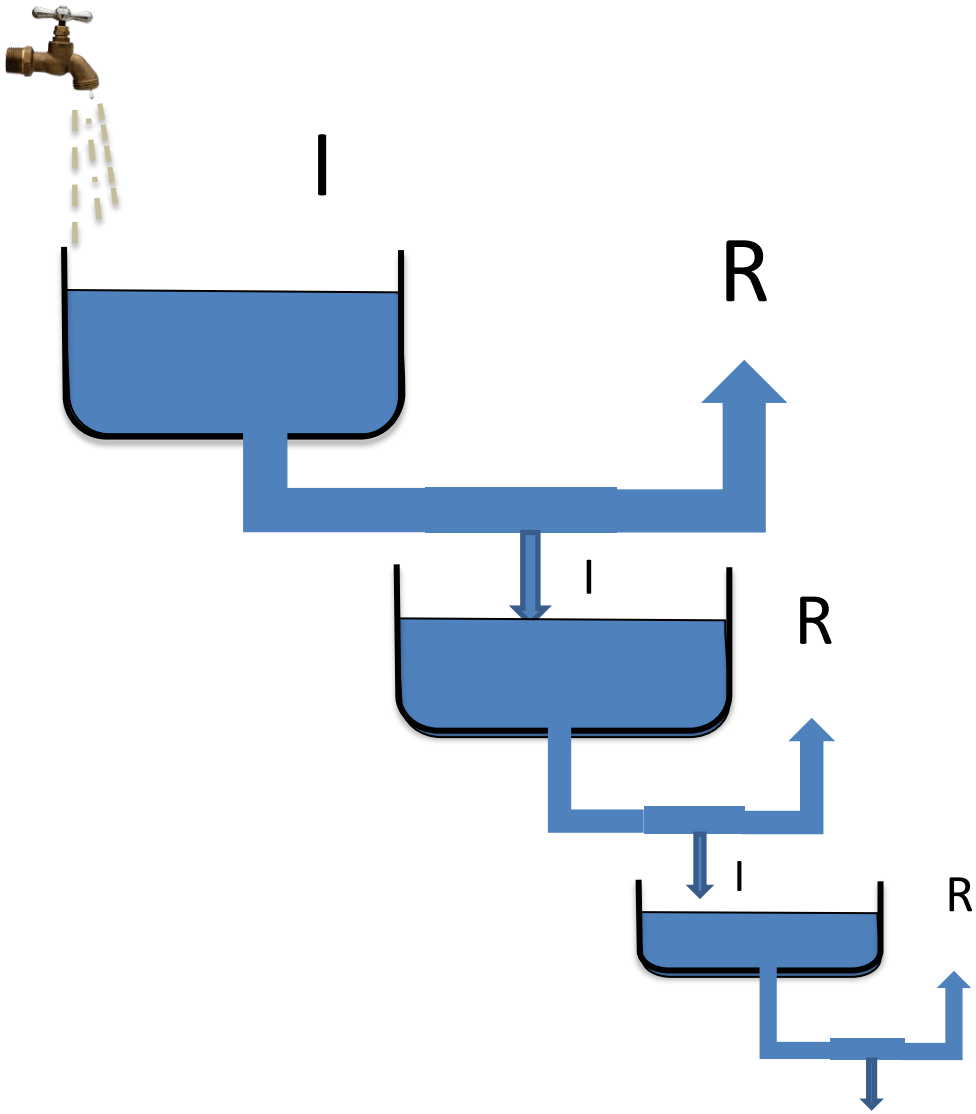
$SOC=I/k=I*MRT$ *(MRT=mean residence time)*

Things are more complicated as MRT's vary strongly between different types of SOC



http://www.mri-jma.go.jp/Project/1-21/1-21-1/carbon_land_e.gif

Or,using the kitchen sink analogy



Nevertheless:

Increasing SOC stocks through the increase of inputs and/or decreasing C decomposion is at the heart of SOC sequestration

M. Stocking, 2012

How realistic is it to expect benefits from SOC management ?

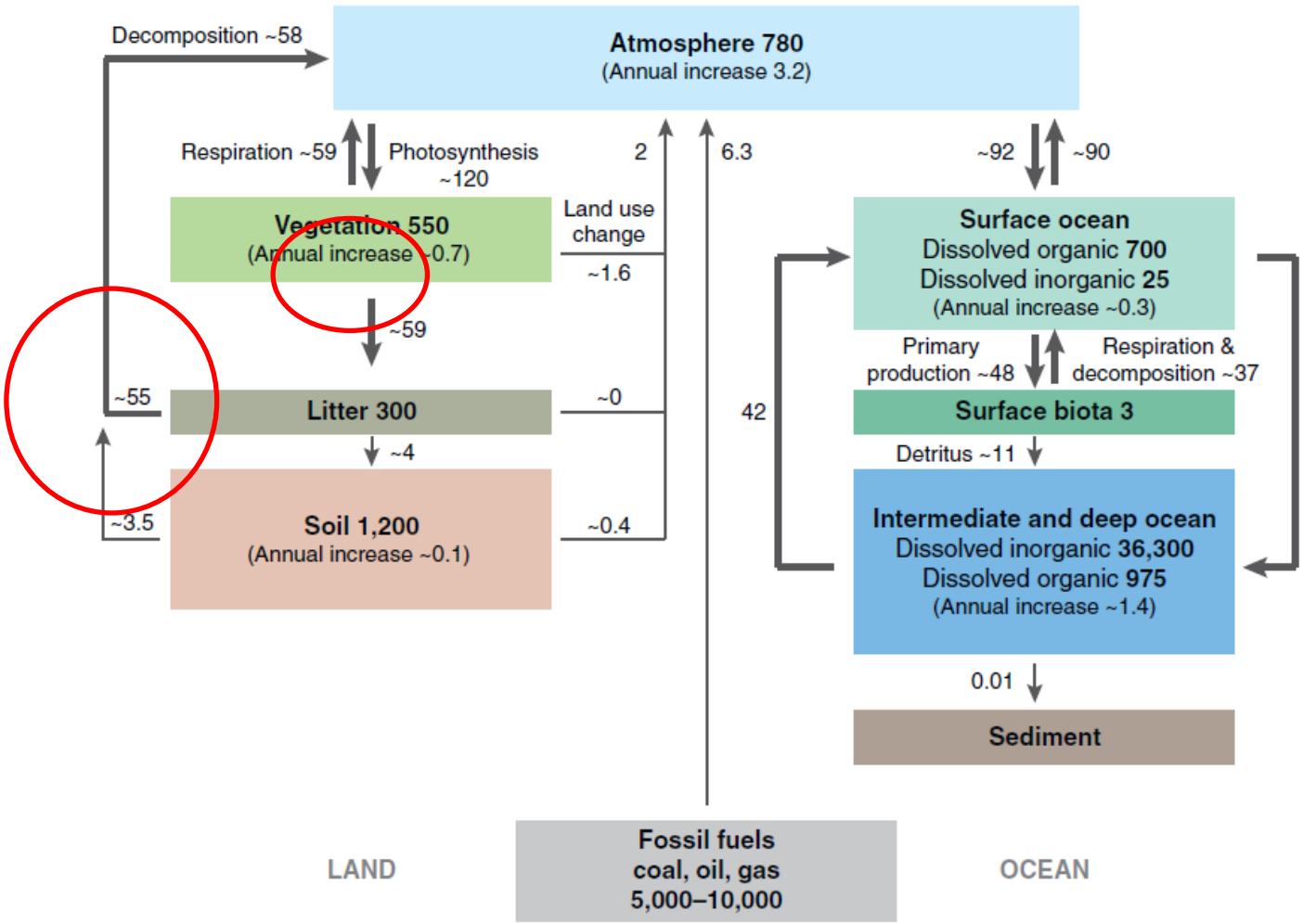


Figure 1

The global carbon cycle in the 1990s. Units are PgC or PgC year^{-1}.

How realistic is it to expect benefits from SOC management ?

- *k* = 60/1500 and MRT=1500/60=30 yrs
- SOC reservoir is therefore quite responsive to perturbance /management *over timescales of decennia*

Disturbances may be natural of human-induced

- Climate change:
  - warming increases respiration rates: SOC ↘
  - Warming and atmosphering CO_2 stimulate plant growth : SOC ↗
- Disturbance by tillage: increases respiration rates: SOC ↘
- Harvesting: reduces input: SOC ↘
- Land use change: SOC ↘ or SOC ↗

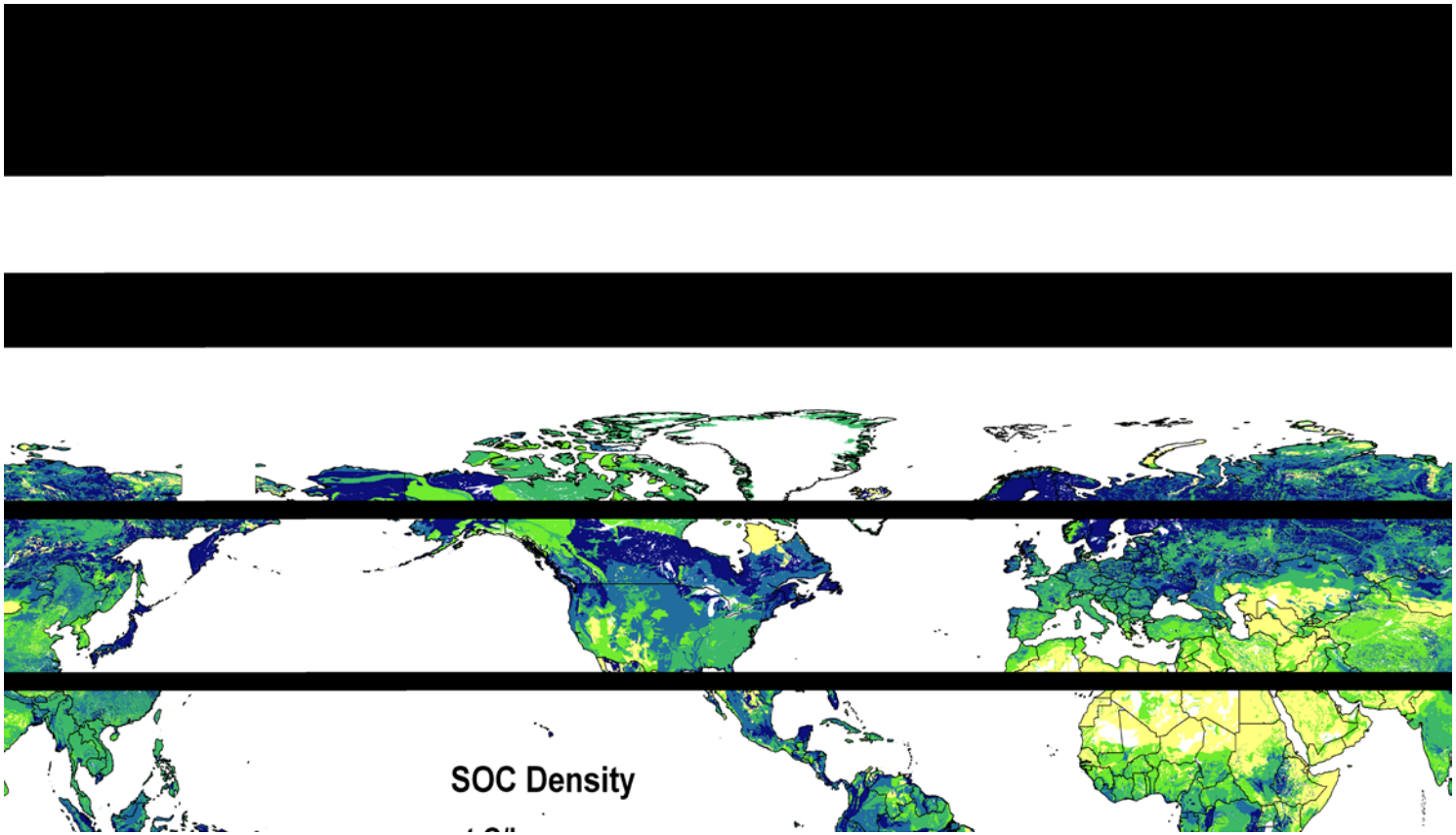
What would happen if we would be able to increase inputs by 1 % ?

- *We know that SOC=I/k*
- *Thus new equilibrium would mean that 1% more SOC would be stored*
- *That would be ca. 15 Pg*
- *Response time = 30 yrs, therefore 0.5 Pg/y for 30 yrs*

It now become easy to predict where we will find large SOC stocks

- Largest stocks where either (i) mineralization rates are very low (cold, moist climates) or input rates are very high (warm, wet climates)

Thus high stocks in tropics and in the arctic



Global variation in C density (Mg C ha^{-1}), own processing based on data from (Hiederer and Köchyl, 2012) and (Panagos et al., 2012)

Distribution over major biomes

	Area (10^{12} m^2)	SOC content (Mg C ha^{-1}) 0-1m	SOC content (Mg C ha^{-1}) 0-3m	SOC storage (Pg) 0-1 m	SOC storage (Pg) 0-3 m	Uncertainty +
Boreal Forest	12	93	125	112	150	
Crops	14	112	177	157	248	
Deserts	18	62	115	112	208	
Sclerophyllous shrubs	8,5	89	146	76	124	U
Temperate deciduous forest	7	174	228	122	160	
Temperate Evergreen forest	5	145	204	73	102	
Temperate Grassland	9	117	191	105	172	
Tropical Deciduous forest	7,5	158	291	119	218	U
Tropical evergreen forest	17	186	279	316	474	U
Tropical savanna/grasslands	15	132	230	198	345	U
Tundra	8	142	180	114	144	U
Total	121			1502	2345	
Peatland	3,5				400-500	U
Permafrost*	18,8				1024	U

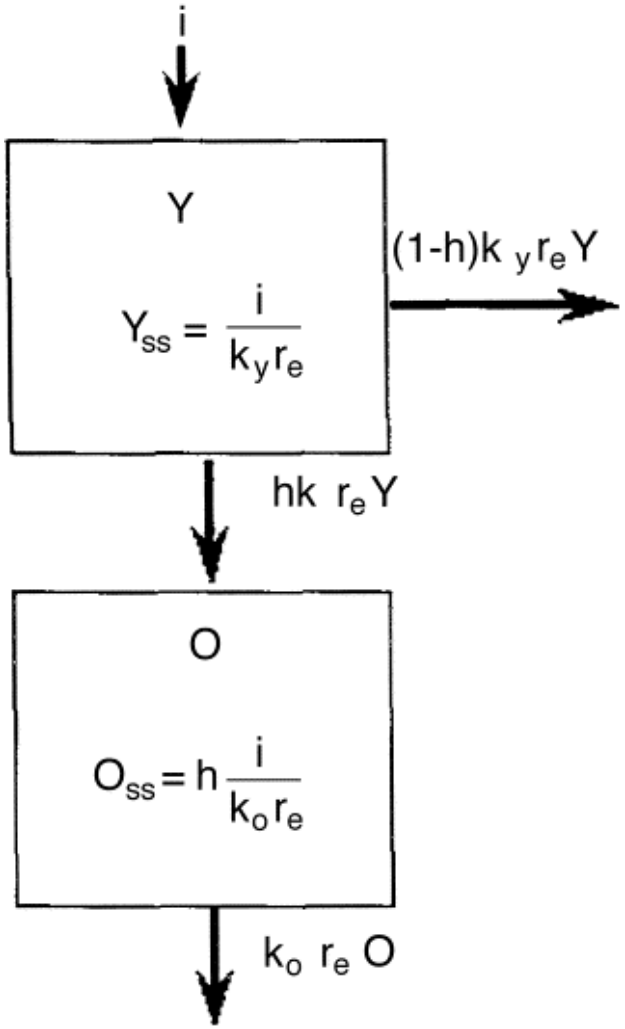
Major issues of relevance

- Over recent decennia we have gained much more insight in SOC dynamics

SOC pools

- SOC pools are reservoirs of SOC that have distinct physico-chemical characteristics
- Literature has convincingly shown that understanding and describing SOC dynamics is far more efficient when different SOC pools are considered

Most simple possible model: 2 pools (Andren and Katterer)



In some cases: clear implications for management

Chivenge et al., 2007, long-term study on sandy and clayey soils

- management should try to increase SOC input on sandy soils (coarse sand SOC most responsive and important pool)
- management should try to reduce soil disturbance on clayey soils to preserve fine sand (fine sand SOC in aggregates is most important pool)

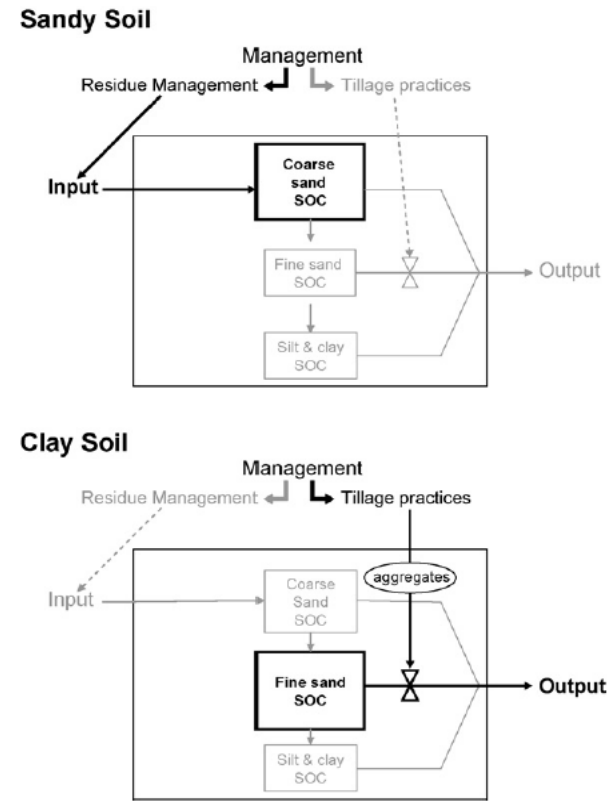


Fig. 1. Conceptual representation of the interactive effects between management and soil texture on soil organic C (SOC) stabilization. (a) In sandy soils organic matter inputs improve SOC contents and especially increase SOC in the coarse sand fraction. (b) Tillage plays a lesser role in controlling SOC content in coarse textured soils. In clay soils soil disturbance regulates SOC storage where high tillage intensity results in greater losses of SOM. This occurs mainly in the fine sand and coarse silt fractions, which are strongly affected by aggregate turnover that tends to be faster in heavily tilled systems.

However, in general…

- Yet, while scientifically extremely rewarding, it remains unlikely that increased understanding will in the short run lead to a drastically improved predictive capacity or improved policy guidelines, reaching beyond what already can be achieved with the semi-empirical approach taken based on size and density separates in combination with SOM models *en vogue*. The enhanced understanding, resulting from a much better explanation of the true nature behind the speciation of organic matter components in soil aggregates of diverse sizes will nevertheless be essential in providing the mechanistic rationale behind the hitherto mainly conceptual approaches (R. Merckx, 2012)

Why is that ?

- The curse of environmental sciences:
  - Systems that are studied are intrinsically complicated, controlled by many factors and coupling is often non-linear and affected by feedbacks
  - Such systems may be better described with more complex models, but that does not lead to better predictions

GEF focal areas

- Biodiversity
- Climate change
- Land degradation
- International waters
- Persistent organic pollutants

Biodiversity

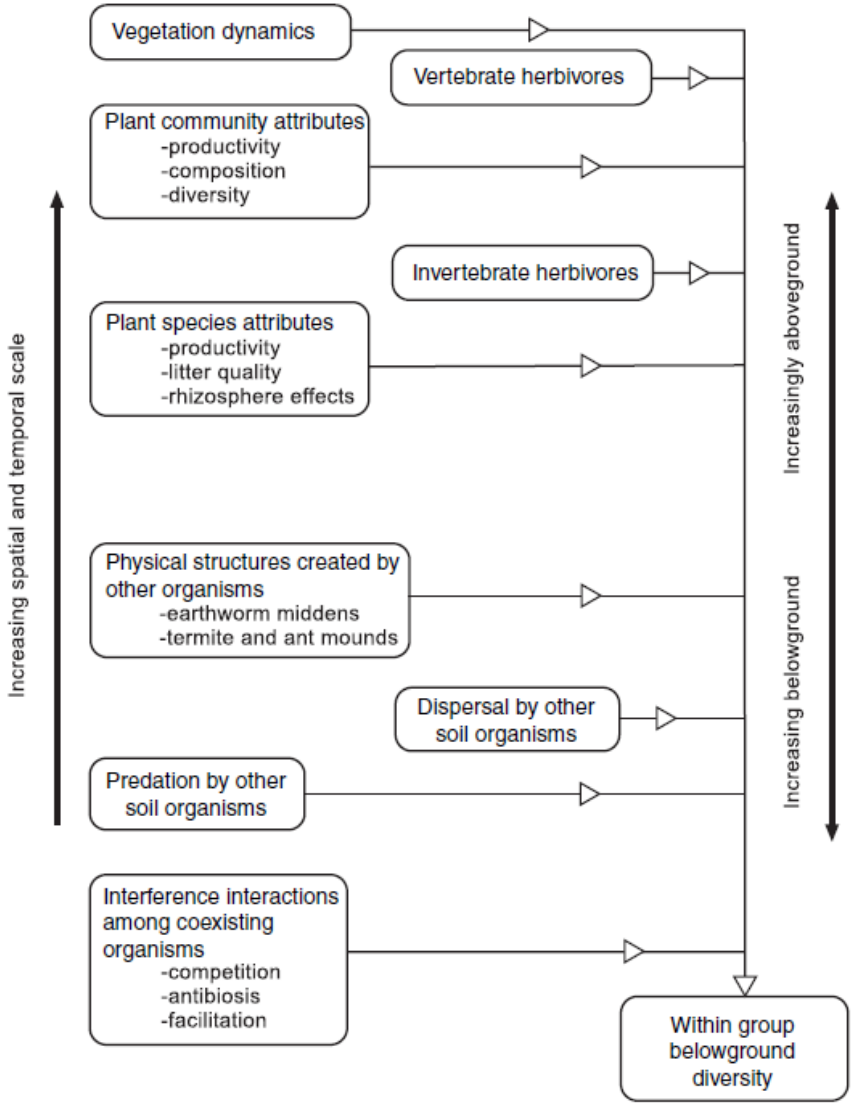
Soil biodiversity

General biodiversity

Soil biodiversity

- May be more important (in terms of species diversity) than aboveground biodiversity
  - > 1 million species
  - Interacts with aboveground vegetation composition and density
  - May have beneficial effects for agricultural production and resilience of soils

Soil biodiversity



Wardle, 2006

Treatment-fauna interaction

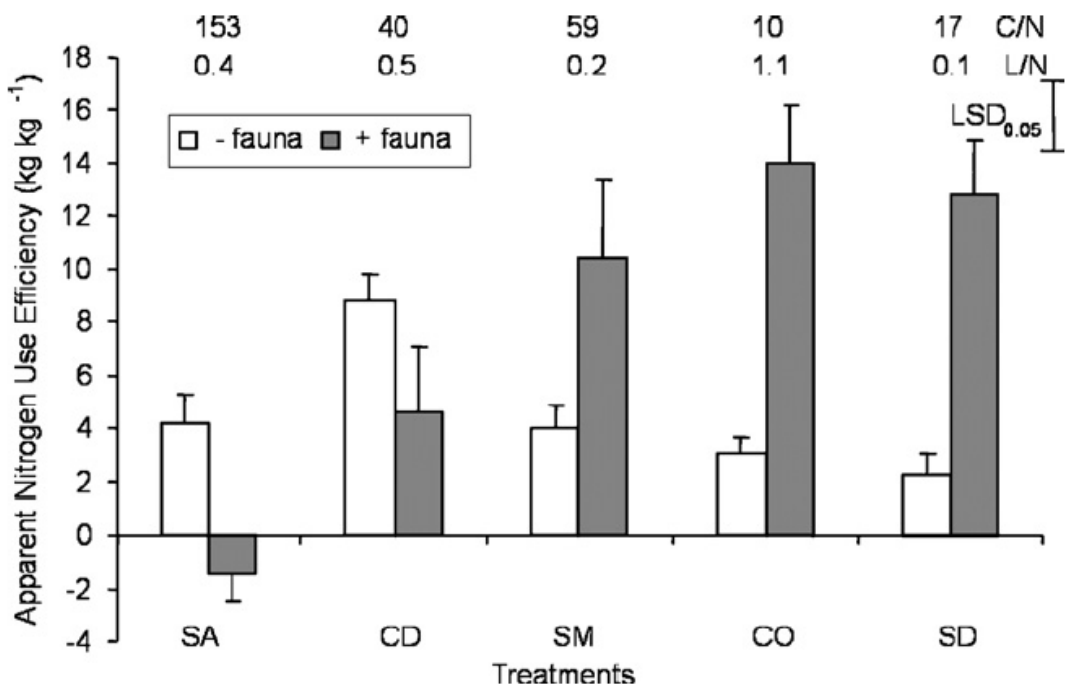


Fig. 4. Sorghum apparent N use efficiency in fauna and no-fauna plots at Kaibo, Burkina Faso, after application of organic resources of different qualities. SA: *Andropogon* straw, CD: cattle dung, SM: maize straw, CO: compost, SD: sheep dung. Bars represent standard deviations. LSD: Least Significant difference at $P = 0.05$. C/N: carbon–nitrogen ratio, L/N: lignin–nitrogen ratio. From: Ouédraogo et al. (2006).

Brussaard, 2007

Overall

- Management techniques have been shown to affect biodiversity of agricultural soils (less disturbance=more diversity)
- Role of SOC is less clear

Aboveground biodiversity: sparing or sharing ?

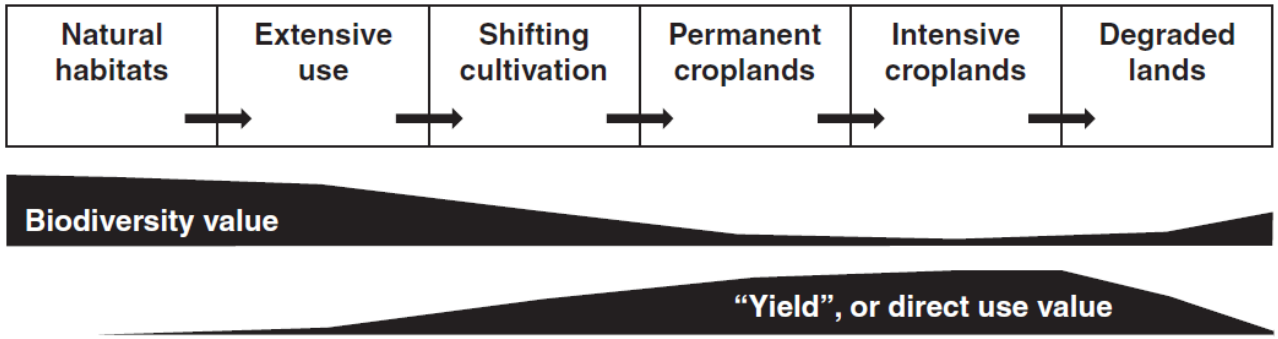
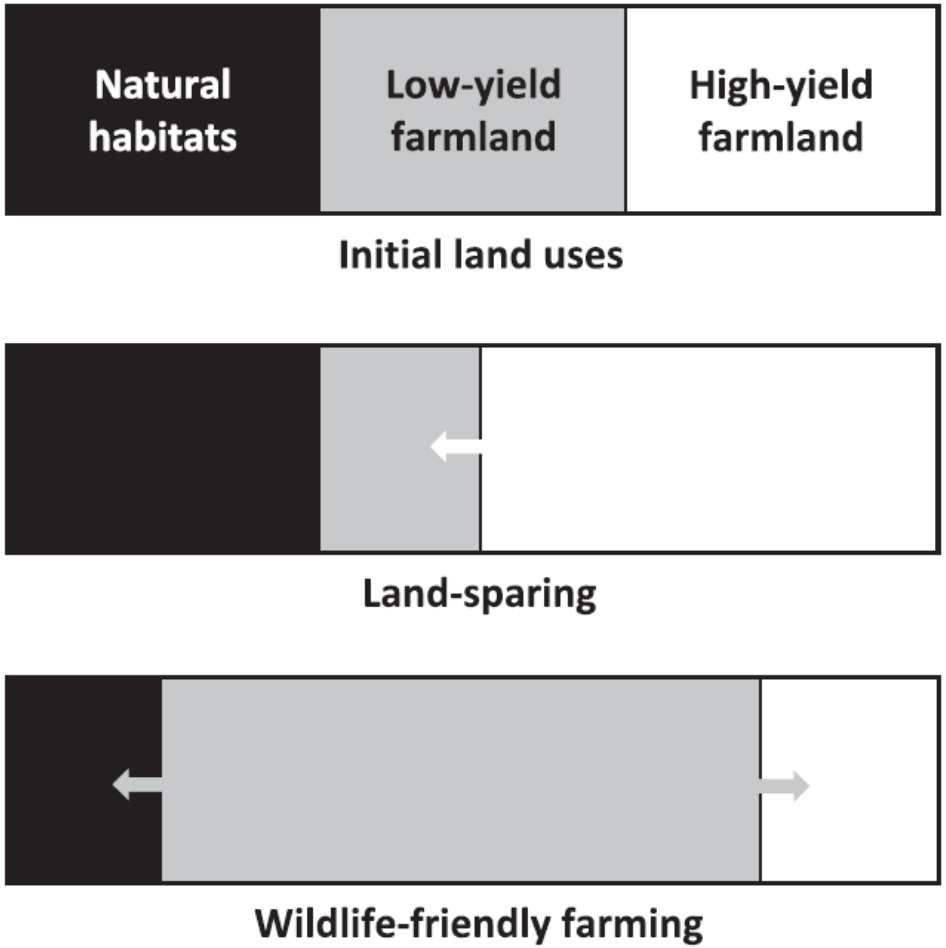


Fig. 1. Simplified diagram of the land-use cascade. Over time, people tend to intensify land use and land management, generating increasing yields and other direct benefits, while reducing populations of many wild species and often reducing indirect ecosystem benefits such as carbon storage. Unsustainably exploited land is eventually abandoned as degraded land, which has the potential to revert to some sort of natural habitat, but with the consequence that land elsewhere will have to move along the land-use cascade. Figure based loosely on Fig. 2.5 of Terborgh and Van Schaik (1996) and Fig. 1 of Grainger (2009).

Phalan et al., 2011

Sparing vs. sharing



What about SOC ?

- Sparing may be advantageous:
  - Non-disturbed biomes are high in SOC
  - Intensive agriculture can provide more C input into the soil, thereby maintaining SOC stocks (if properly managed)
  - Benefits of sparing will depend on species dynamics and type of wildlife-friendly farming adapted
  - Care should be taken in evaluating low-input agricultural systems: effects on yields should be accounted for

In mathematical terms:

$$C_D = C_{D,f}\left(1 - D_{ar} A_{ar}\right)$$

C_D=carbon density

D_{ar} = carbon reduction factor on arabe land

A_{ar}=fraction of land converted, as a fraction

Climate change

- Human impact = undeniable
- Historical release of SOC due to land use change has strongly contributed to warming
- Future of SOC stocks is unclear
  - Increased productivity of the biosphere may increase them: tap discharge increases
  - Increased temperature and reduction of soil moisture may decrease them: drain discharge increases

Final result

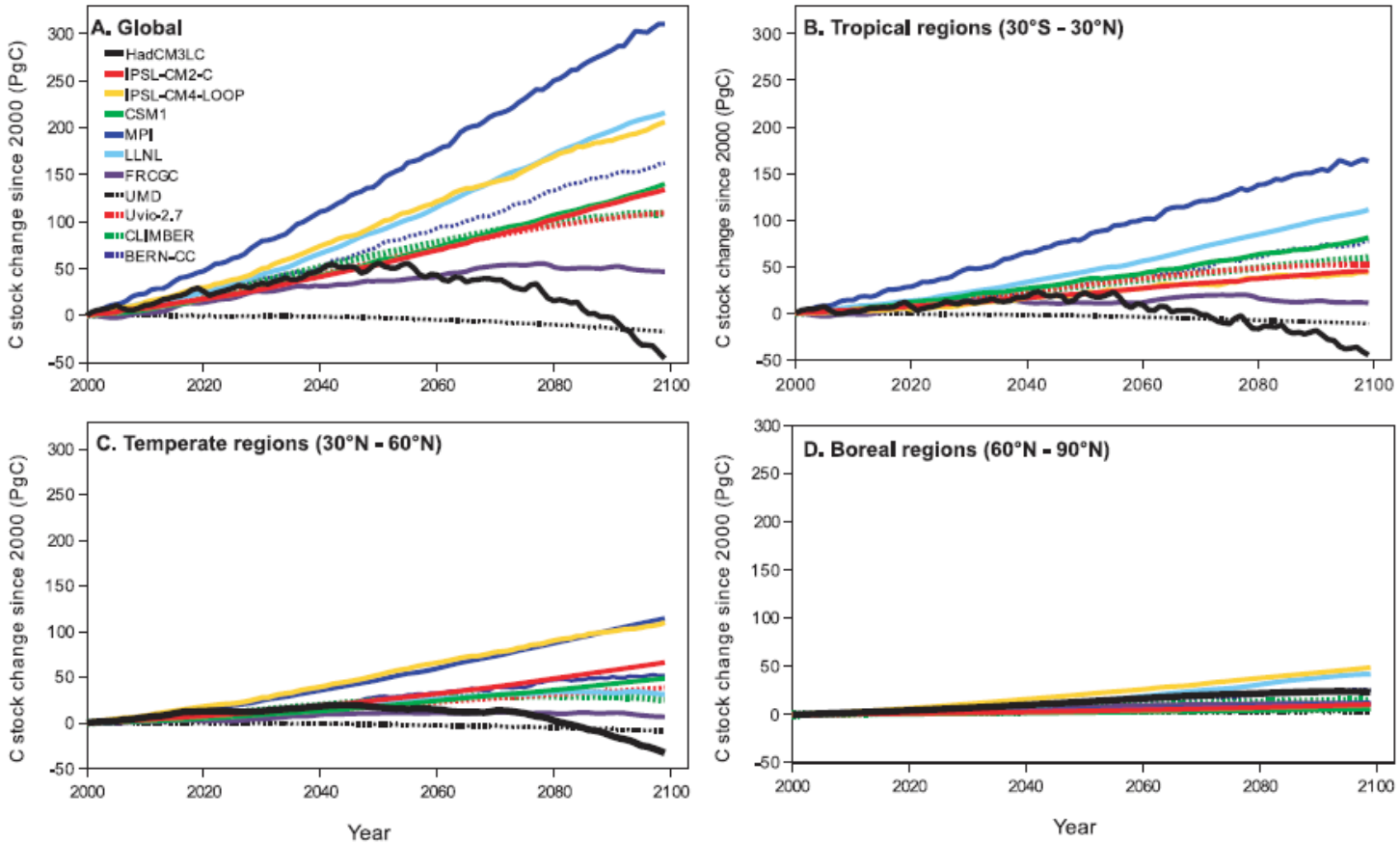


Fig. 6. Future evolution of global and regional soil organic carbon (SOC) stocks from 2000 to 2099 simulated by the 11 C4MIP model (Friedlingstein et al., 2006).

Things may even be worse

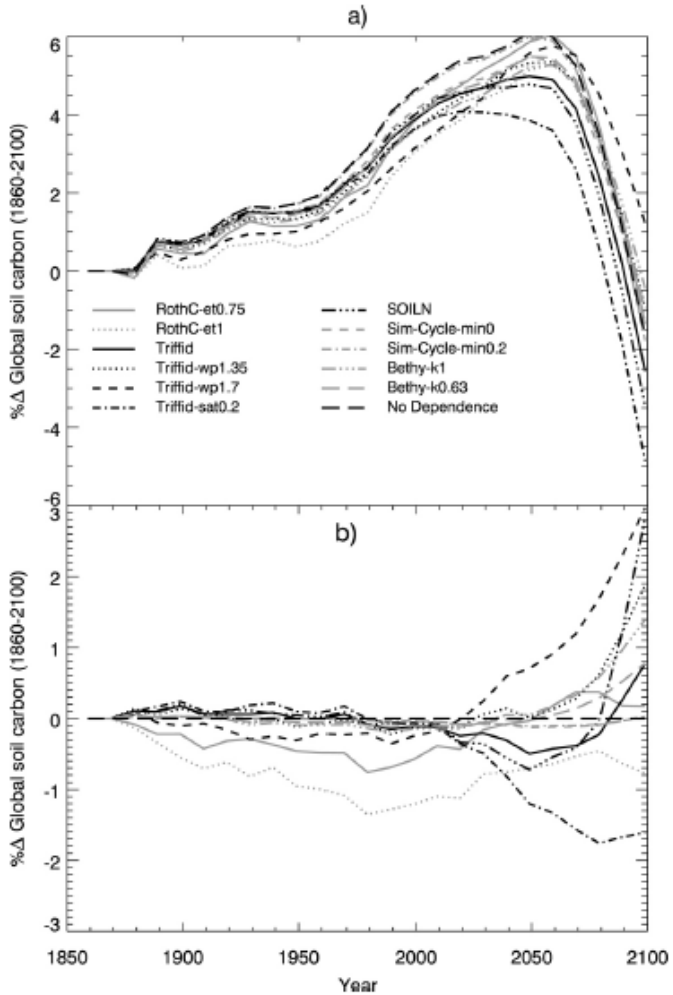


Figure 3. Changes in global total soil carbon from 1860 values (as a % of 1860 values) using the RothC model and different soil moisture–respiration functions driven by HadCM3LC outputs changing (a) all forcings (soil temperature, moisture and plant carbon inputs) and (b) soil moisture only.

Falloon, 2011

Can management, within a given land use, make a difference ?

- Initial estimates: up to 1Pg C/y may be stored by implementing adequate land management

Is this a lot ?

- Yes, it is : if you would like to store that on cropland alone you can calculate the equivalent C sequestration rate.
  - We have about 15 million km^2 or 1.5 billion ha of cropland globally
  - Thus, you would need to sequester ca. 0.6 Mg C/(ha y)

What do numbers tell us ?

- Conversion to no-tillage
- Agroforestry
- Grassland
- Forests
- Organic agriculture

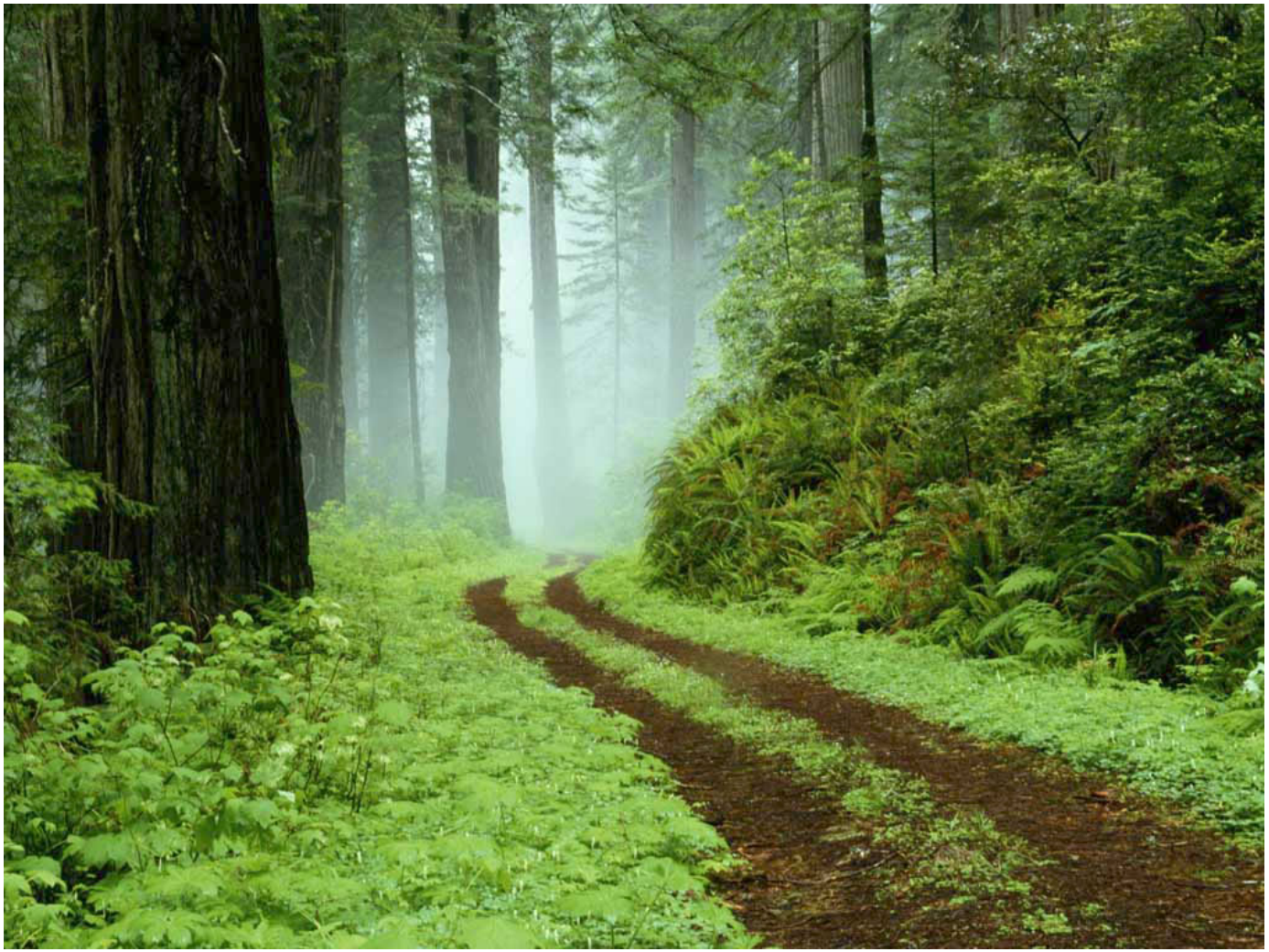
No-tillage

- Temperate arable land: 0-1 Mg C/(ha yr), generally < 0.3 Mg C/(ha yr) but recent regional study found no significant effects
- Tropical arable land: less data, 0.3-0.8 Mg C/(ha yr)

Agroforestry

0-1 Mg C/(ha yr), but many studies did not find significant effects, effects sometimes overstated in literature, no accounting for land use effects

Forests



Management may make a difference: potential effect is largely unknown

Grasslands

Ca. 0.3 Mg C/(ha yr), but very variable

Organic agriculture

•Reduces, on average yields (and therefore inputs)
•Significant gains in SOC are therefore unlikely, unless respiration rates are decreased

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- Forests
  - Management may make a difference: potential effect is largely unknown
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  - Reduces, on average yields (and therefore inputs)
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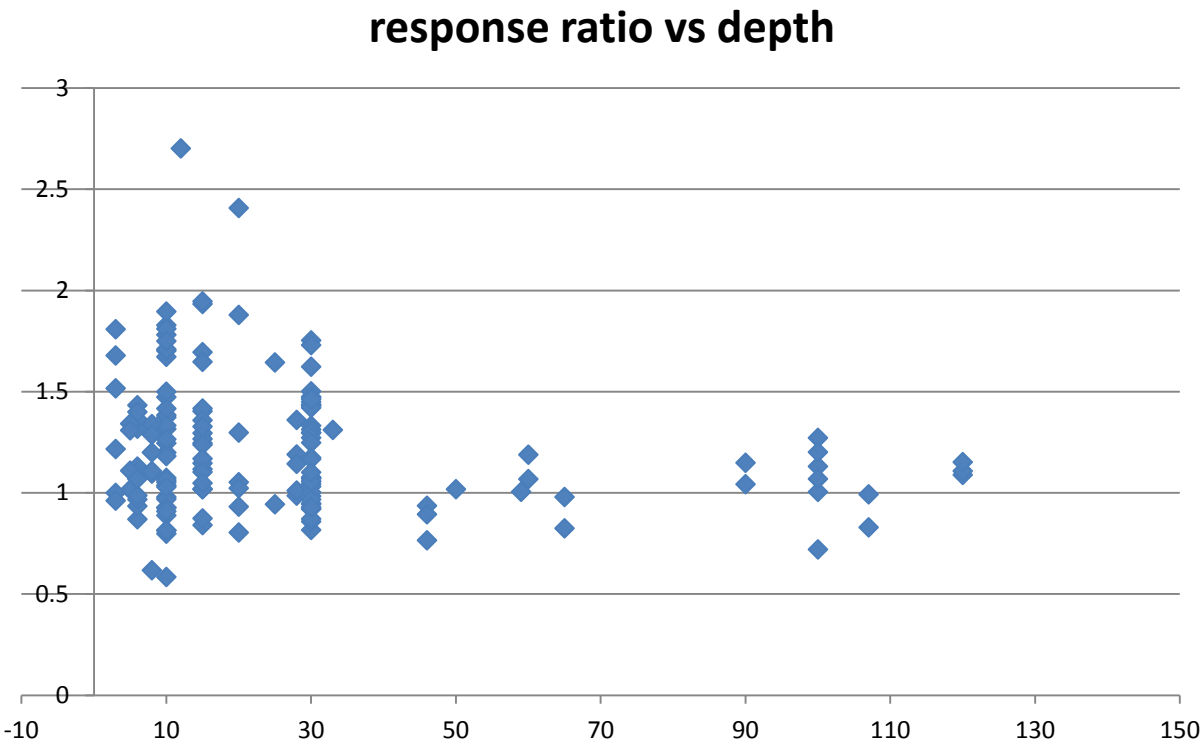
Also, we should be cautious with the data we have

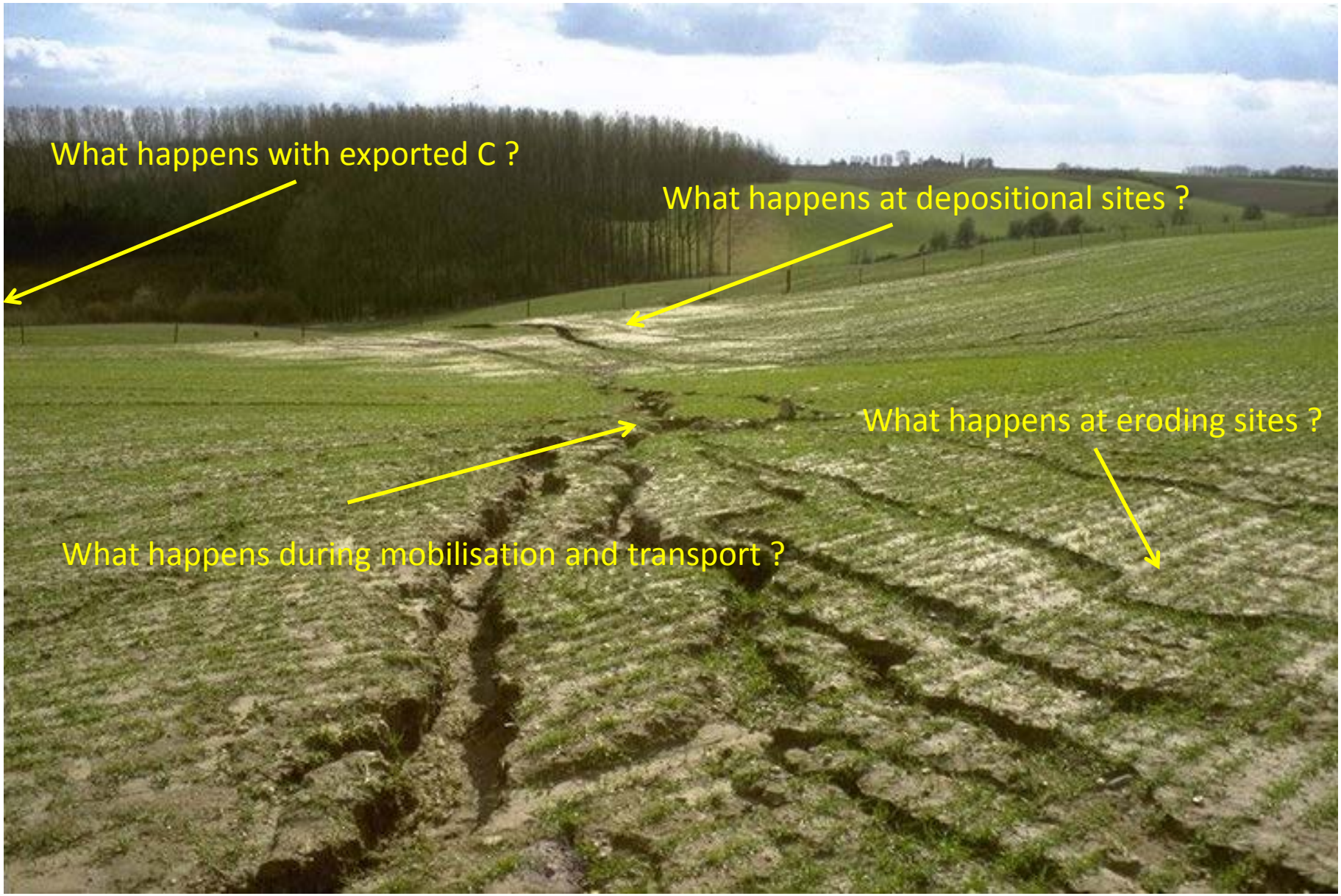


Response ratio (depth integrated SOC stock in alternatively managed or converted grassland vs. tradionally managed grassland) vs. sampling depth as calculated from the data compiled by (Conant et al., 2001). Note that the response ratio generally decreases with increasing sampling depth, an observation also made by (Manley et al., 2005)

Land degradation

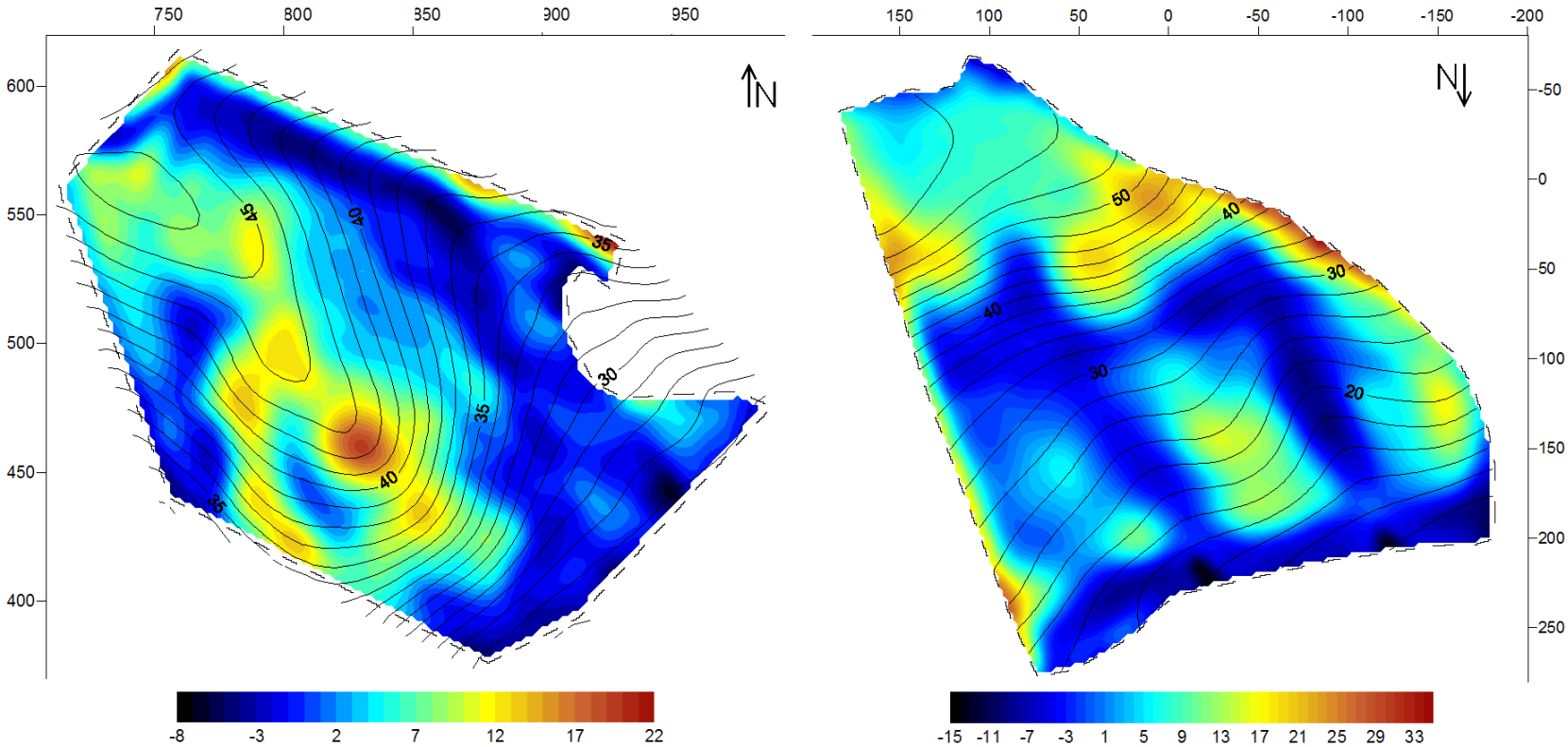
- Consists of a complex interplay of different processes
  - Wind and water erosion
  - Compaction
  - Salinisation

Erosion : 4 subprocesses



Detailed information comes from field observations (Van Hemelryck et al., 2010)

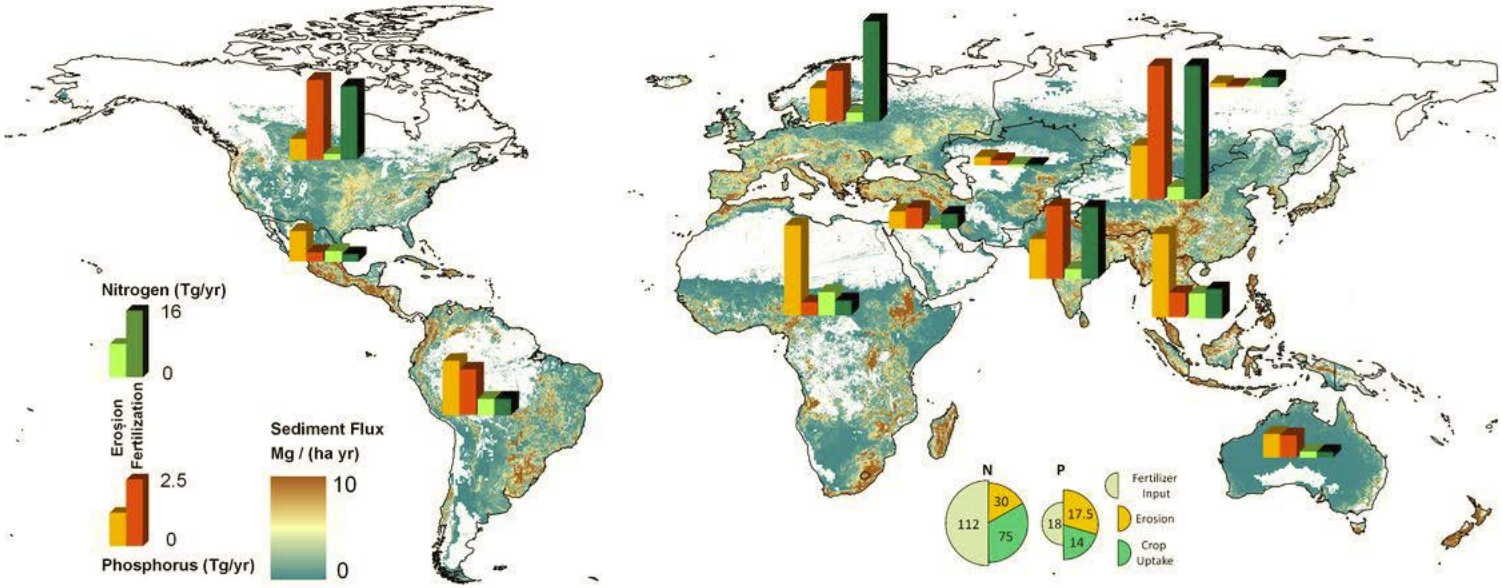
Deposition leads to carbon burial, erosion to dynamic replacement (Van Oost et al., 2005)



Erosion is a small source of C for the soil (sink for the atmosphere, Van Oost et al., Science, 2007): why is that ?

- SOC is dynamically replaced at eroding sites
- Most of the SOC that is eroded is stored for longer time spans in depositional environments

Furthermore, erosion causes detrimental nutrient losses, especially in low input agricultural areas



Quinton et al., 2010

Other soil degradation processes

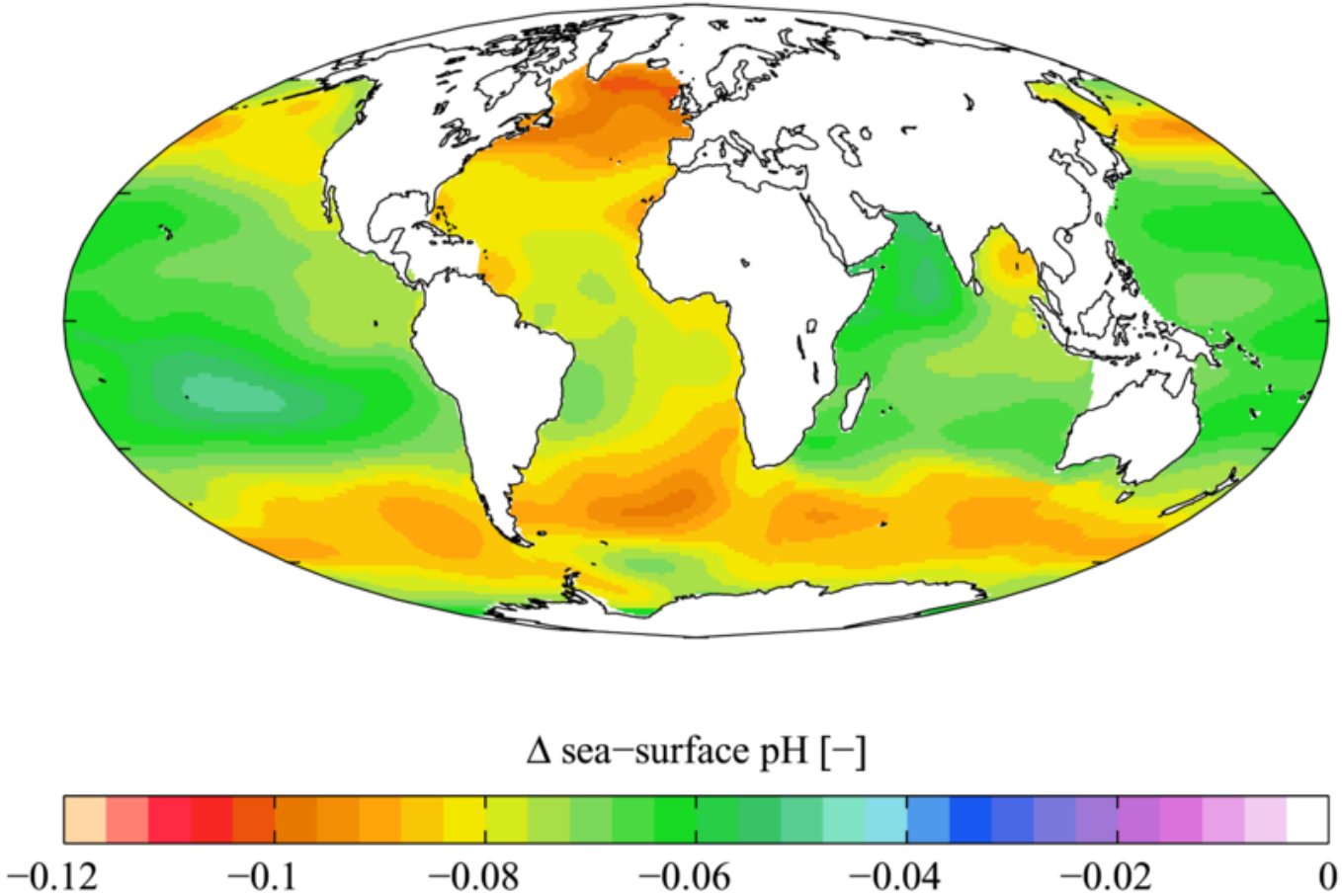
- General principle: if degration decreases primary productivity (plant growth) it will lead to a SOC loss

However, reclamation of degraded land is still (very) beneficial

- On degraded land, dynamic replacement is less important or even non-existing
- In strongly degraded environments erosion may therefore indeed be a source of C to the atmosphere, not a sink

International waters

- Links is (evidently) indirect : SOC sequestration will reduce ocean acidification



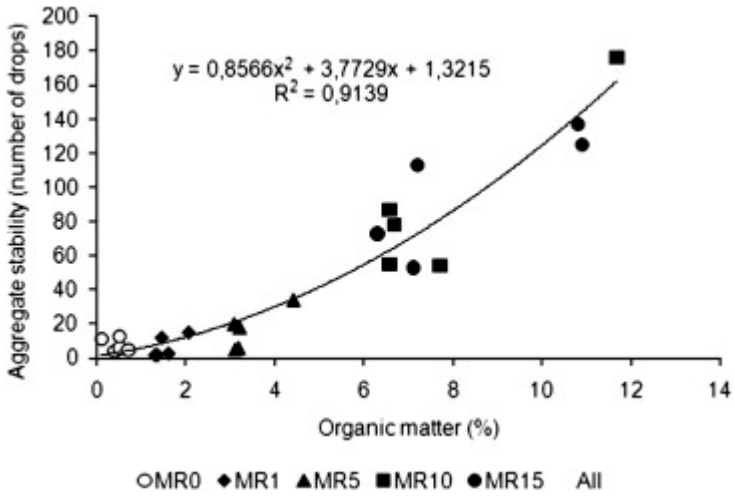
POP’s

- POP’s stored in SOC may be released if the SOC stock is disturbed
- Relation between SOC stock and the capacity of the soil to degrade POP’s is unclear
  - Increase of SOC may protect POP’s from chemical attach
  - Increase of SOC will also increase microbial activity in general

SOC and multiple benefits

- Biodiversity: already discussed
- Soil quality
- Soil productivity

Soil quality: soil structure



Jordan et al., 2010

Soil quality: erosion

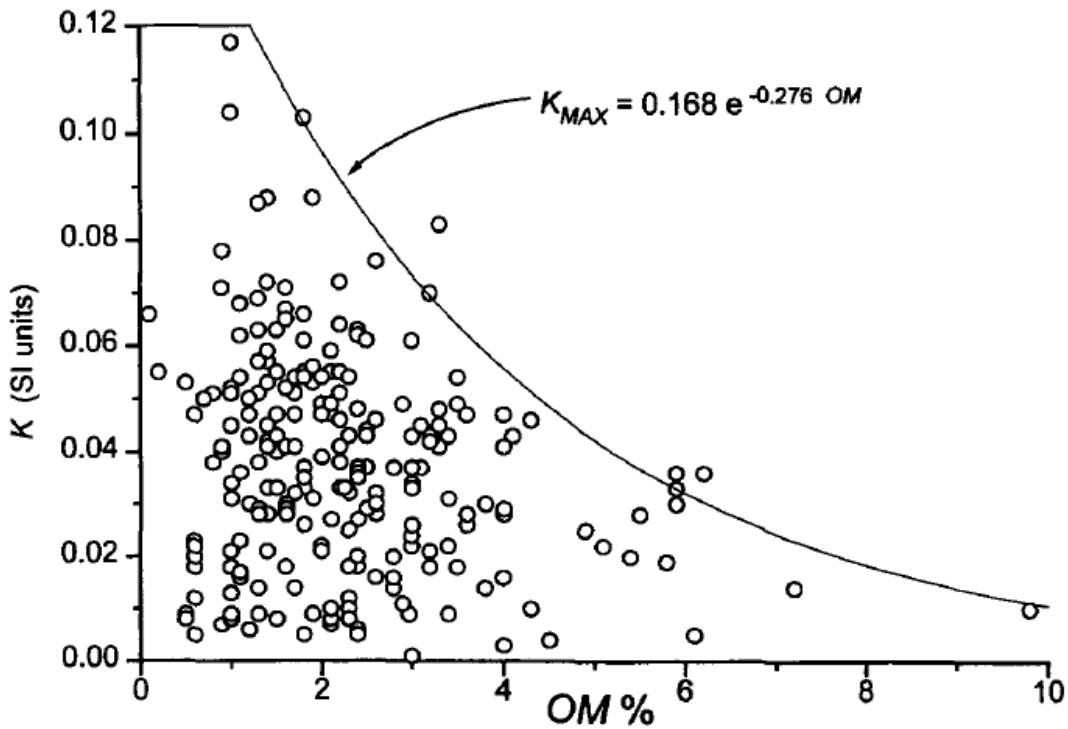
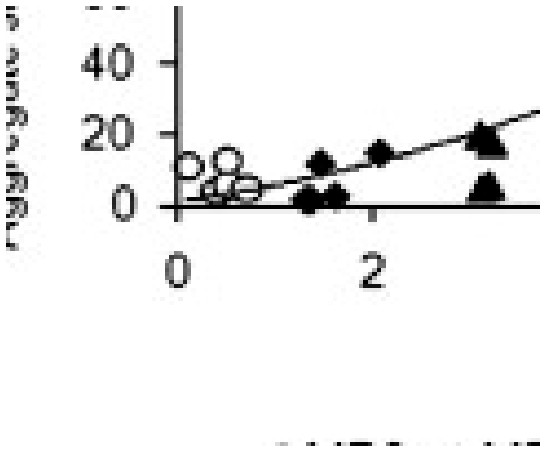


Fig. 1. Soil erodibility factor values K vs. organic matter content (OM). The K_{MAX} line indicates maximum observed K value for a given OM value.

Poesen and Torri, 1997

However….



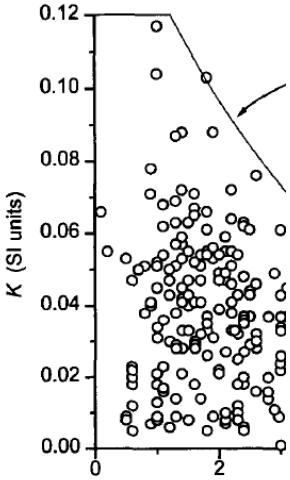
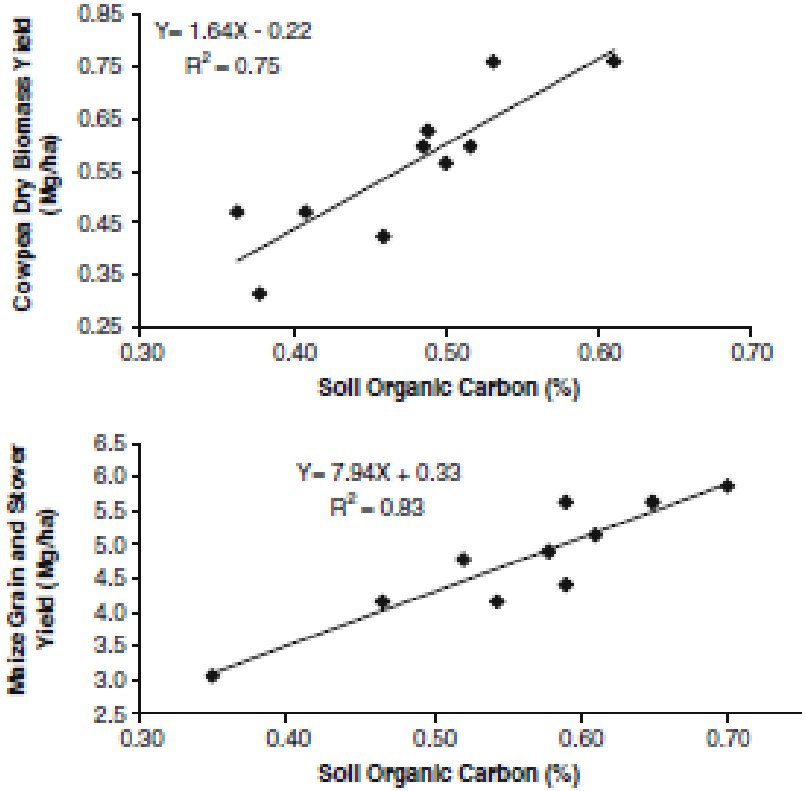


Fig. 1. Soil erodibility factor values K vs. o
observed K value for a given OM value.

Effects within normal ranges for arable soils (where this is most important) are not so clear

Crop yields: often a positive relationship betweeen SOC and yield is found



Lal, 2010

However….

- Relationship is not always causal: increased yield is often due to co-variation in nutrients available to plants

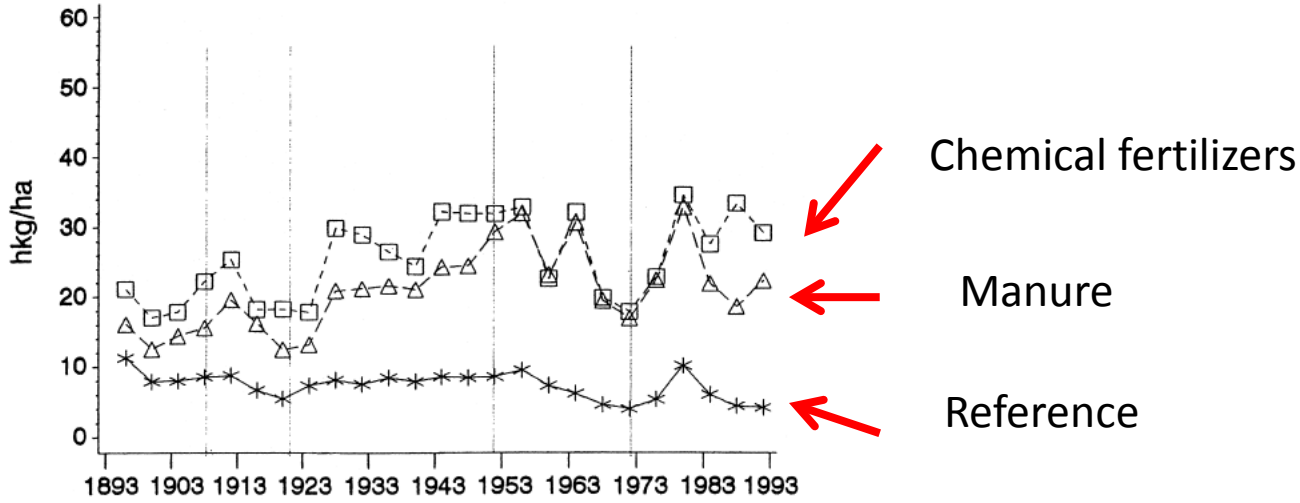


Figure 4. Effect of manure (triangles) and fertiliser (squares), relative to no treatment (stars), on the long-term yields of spring cereals grown at Askov. (Top) Sandmarken; (bottom) Lermarken (from Christensen et al. 1994).

Edmeades, 2003

Kukal et al., 2009

- Studied maize-wheat and rice-wheat system in India
- Treatment applied for >30 yrs

SOC stocks (Mg C/ha)

Treatments	Soil depth (cm)				
	0–15	15–30	30–45	45–60	Total
Rice–wheat					
Control	7.35	6.04	4.99	2.89	21.4
FYM1	2.1	8.31	6.44	4.59	31.4
N_{120}	9.65	6.80	5.68	3.37	25.5
$N_{120}P_{30}$	10.7	7.26	5.61	3.87	27.4
$N_{120}P_{30}K_{30}$	11.8	7.67	6.05	4.10	29.6
Mean	10.3	7.22	5.75	3.76	
LSD (0.05)					
Fertilization = 4.3					
Soil depth = 2.1					
Fertilization × soil depth = NS					
Maize–wheat					
Control	6.84	4.36	4.13	3.37	18.7
FYM	9.18	5.28	5.10	3.69	23.3
N_{100}	7.31	4.82	4.08	3.59	19.8
$N_{100}P_{50}$	7.38	4.73	4.53	3.31	20.0
$N_{100}P_{50}K_{50}$	8.11	5.07	4.64	3.49	21.3
Mean	7.76	4.85	4.50	3.49	
LSD (0.05)					
Fertilization = 2.1					
Soil depth = 2.5					
Fertilization × soil depth = NS					

Table 4
Grain and straw yield and total above-ground biomass production (Mg ha^{-1}) of rice–wheat and maize–wheat cropping systems in relation to FYM and inorganic fertilization

Treatments	Rice–wheat			Maize–wheat		
	Grain	Straw	Total	Grain	Straw	Total
Control	7.36 a	19.8 a	27.2 a	4.21 a	7.41 a	13.6 a
FYM	12.7 b	35.7 b	48.4 b	10.1 b	20.4 b	30.5 b
N_{100}	9.84 c	26.6 c	36.4 c	8.66 c	12.6 c	21.3 c
$N_{100}P_{50}$	11.5 b	32.7 b	44.2 b	9.55 b	13.5 c	23.0 c
$N_{100}P_{50}K_{50}$	12.1 b	35.1 b	47.2 b	9.78 b	14.8 d	24.6 d

Similar letters in the columns indicate non-significant whereas dissimilar letters indicate significant differences among the treatments.

” Improved SOC content enhances soil quality,reduces soil erosion and degradation, and increases soil. The soils under rice–wheat sequestered 55% higher SOC in FYM plots and 70% higher in NPK plots than in maize–wheat. These results document thecapacity of optimally fertilized rice–wheat system to sequester higher C as compared to maize–wheatsystem.”, Kukal et al., 2009

Overall

- Conclusive evidence regarding positive causal effect of SOC on soil structure, soil life, soil erodibility
- Effects on yields is inconclusive: reported relationships are often to a large extent explainable by co-variations and causal effect may even be inverse

Where does all this this leave us ? Towards a vision on SOC management within the GEF context

SOC management requires an integrated, landscape scale approach

- Opting for low-intensity land use should account for disturbance of ‘virgin’ SOC stocks over larger areas (that does not mean that it always has to be negative !)
- Same holds for FYM-based systems: manure has to come from somewhere
- Other landscape functions (water provision, tourism, biodiversity) need to be accounted for

It is easier (and probably cheaper) to preserve than to restore.

- Preserving a stock has immediate benefits
- Managed systems only rarely meet SOC stocks found under undisturbed natural vegetation (exception: specific cases of grassland afforestation)

Improving crop yields and restoring soil fertility is a key component of SOC management

- Higher yields means that less land is necessary (although true sparing may demand further encouragement)
- Higher yields have a positive effect on SOC stocks on cropland

Target soils and environments correctly

What was happening ?

Paramo afforestation dramatically reduces water yield

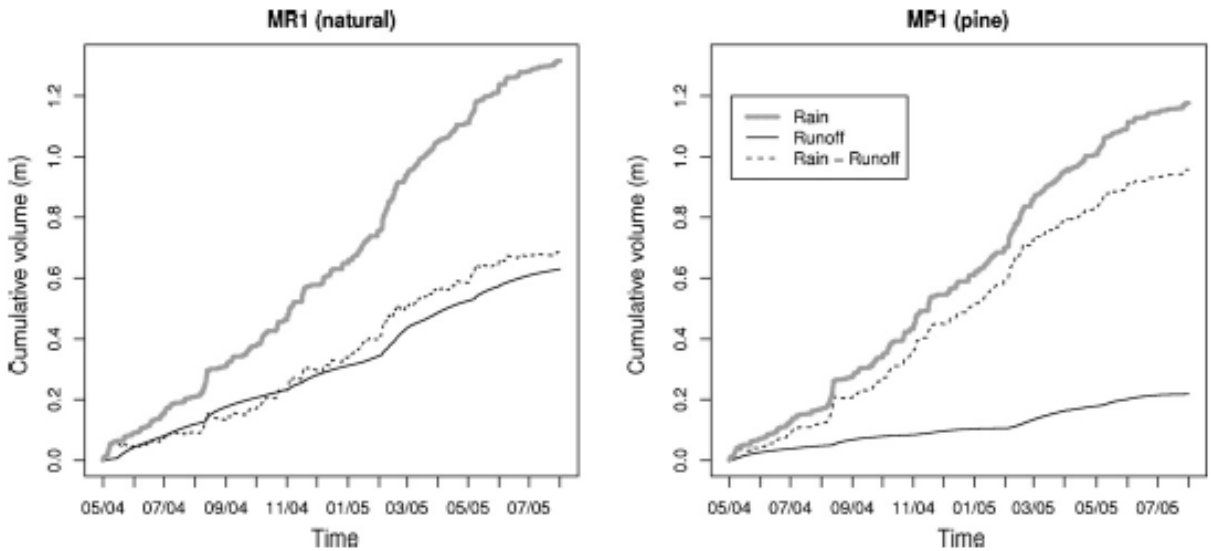
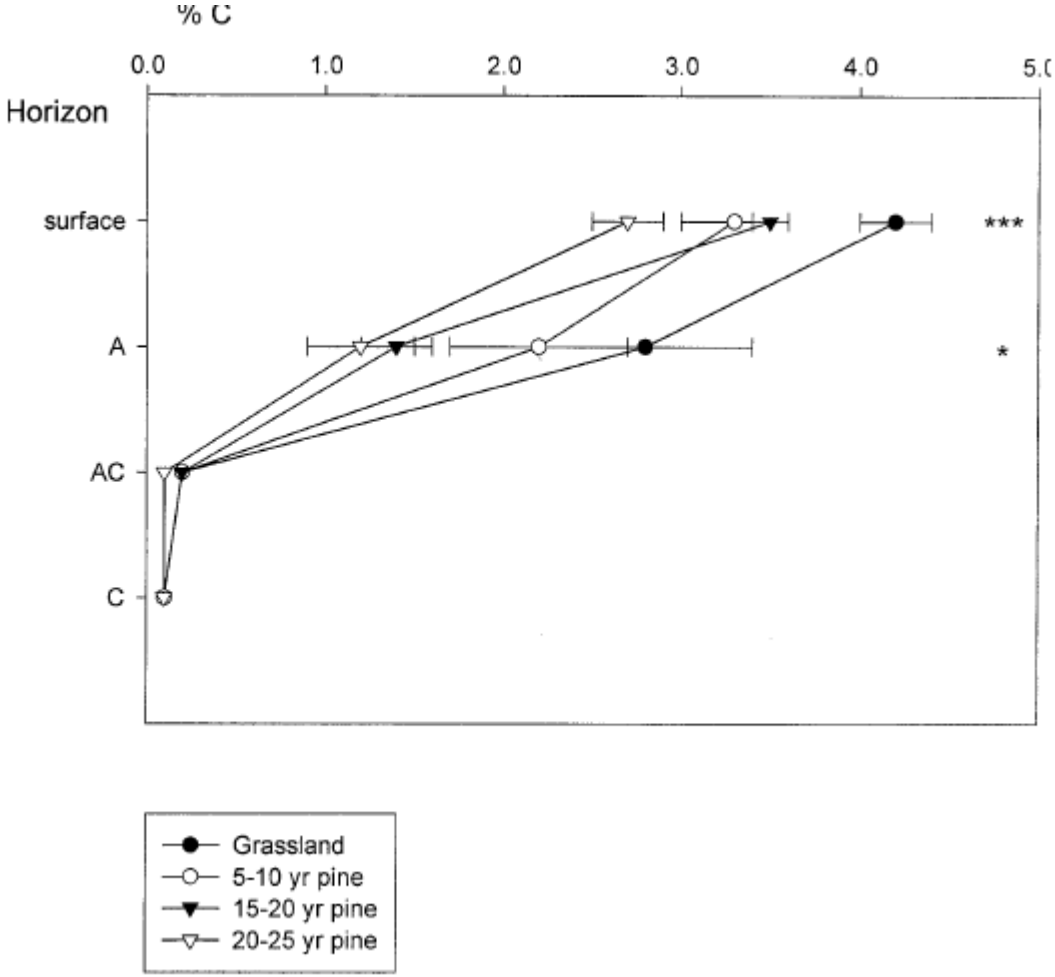


Fig. 6. Cumulative water balance of the catchments MR1 and MP1. The strong linearity of the curves are indicative for the lack of seasonality in the páramo climate and thus a small impact of internal catchment storage on the water balance over time.

Paramo afforestation *reduces* SOC stocks (Farley et al., 2004)



These results are not unique, Berthrong et al., 2012, Rio de la Plata

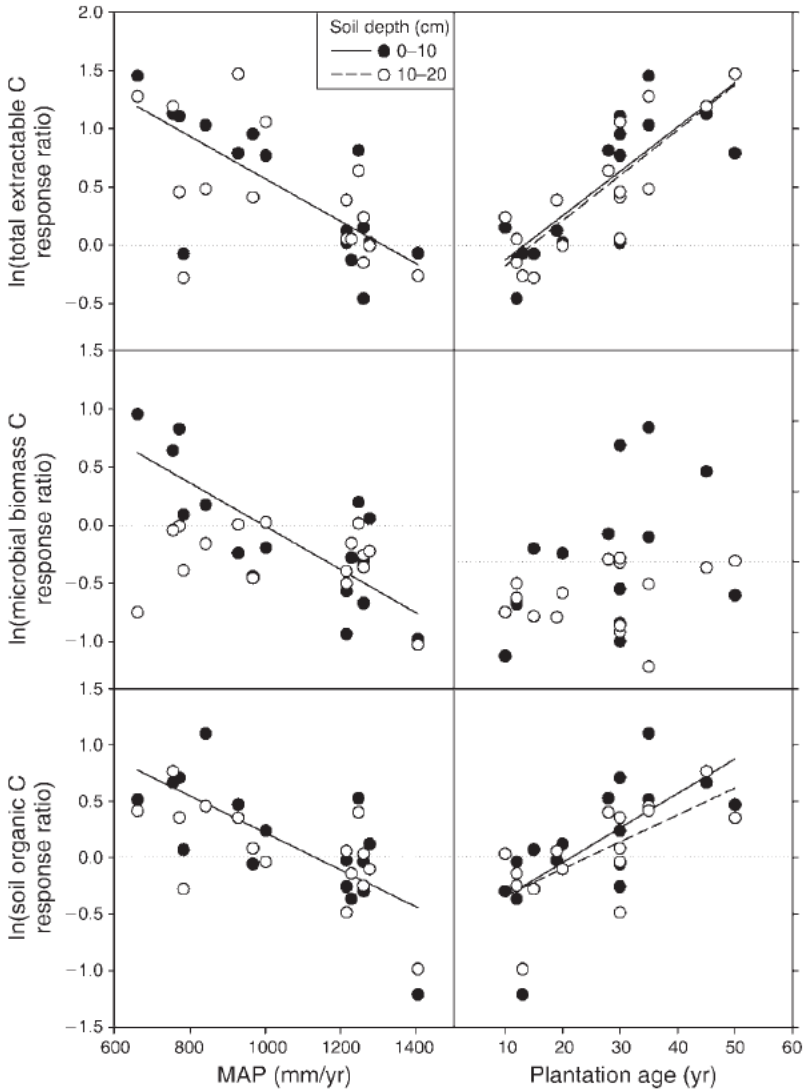


FIG. 2. Association of soil carbon pools with mean annual precipitation (MAP) and plantation age. The *y*-axis gives the ln-ransformed response ratio, ln(value for *Eucalyptus*: value for grassland); positive values indicate an increase in the pool due to fforestation, and negative values indicate a decrease. Regressions were conducted separately for different soil depths, and only ignificant regression models are displayed. Regression parameter estimates are listed in Table 1.

The general picture (Berthrong et al., 2011)

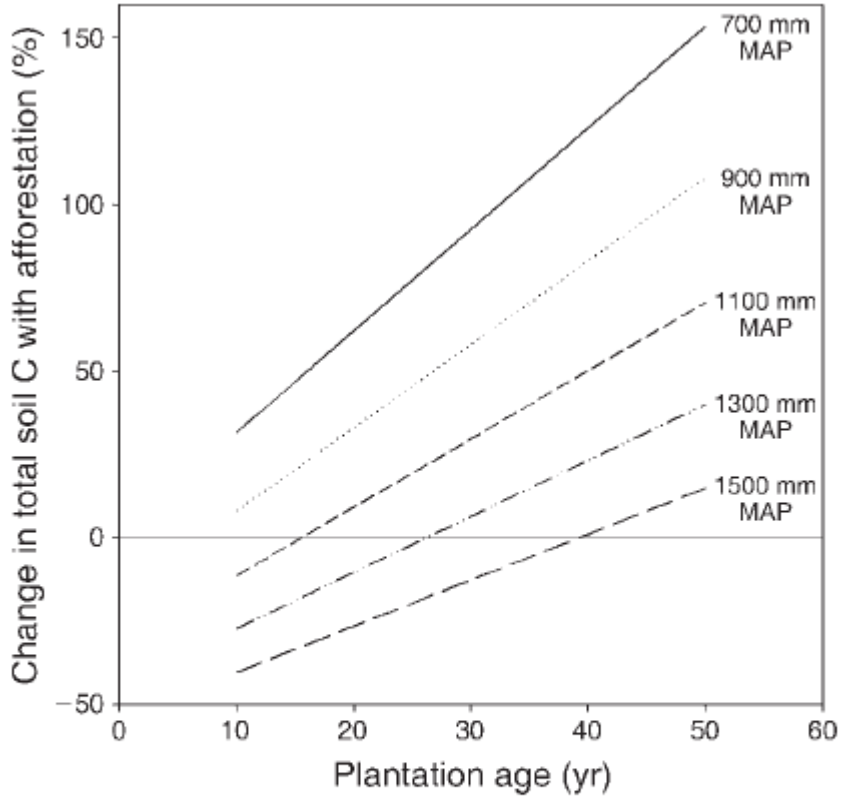
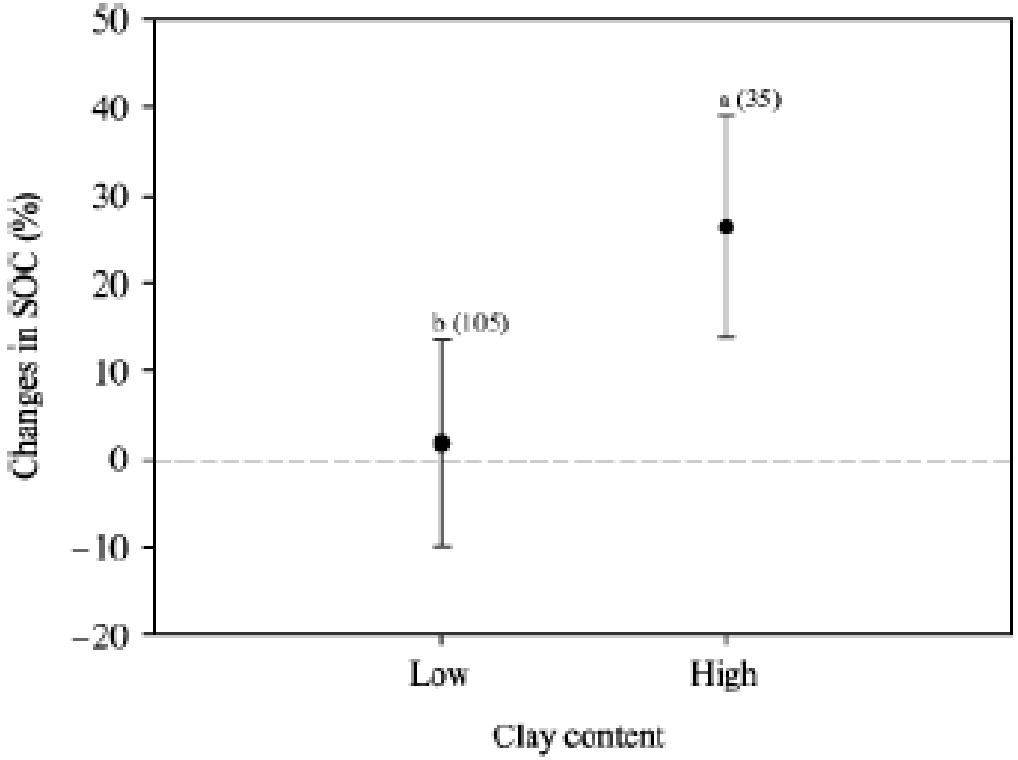


FIG. 5. Family of linear regression models representing the relationship between the effect of afforestation and plantation age at different mean annual precipitation (MAP) levels. Regression parameters were estimated by ridge regression of 0–10 cm soil samples.

Target the best soil type (grain size, level of C saturation), Laganière et al., 2010



More gain is to be expected from the afforestation of cropland (SOC stocks are low), Laganière et al., 2010

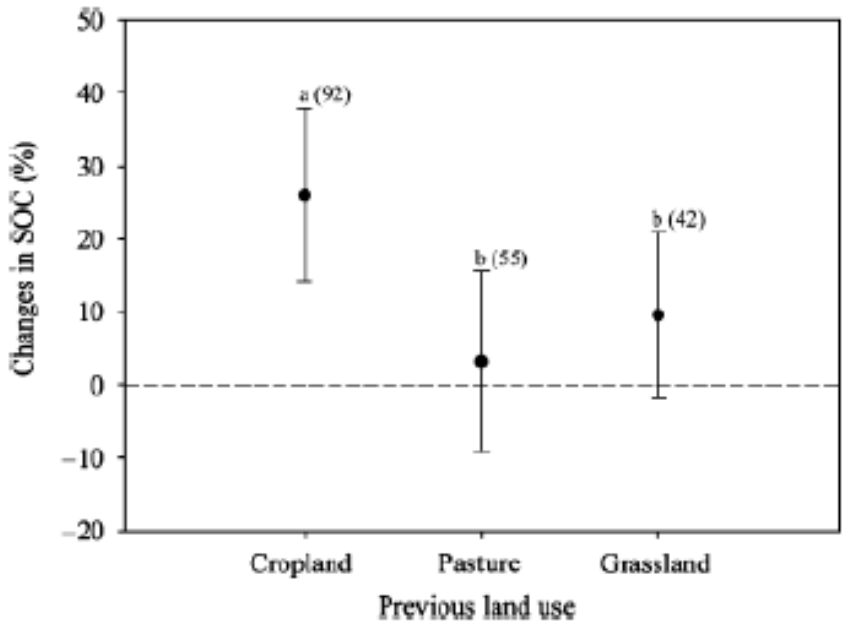


Fig. 1 Influence of previous land use on changes in SOC stocks after afforestation. The error bars are the standard errors of the mean. A different letter means a difference significant at $P<0.05$. The number of observations is indicated in parentheses. The mean age of plantation is 23.3 years and the mean depth of sampling is 34.2 cm. SOC, soil organic carbon.

Afforesting, degraded, dry lands will have undoubtedly positive effects

Afforesting, degraded, dry lands will have undoubtedly positive effects

Set goals realistically

- The response time of SOC=decades
- The sequestration rates possible under alternative management systems may be lower than initially proposed
- Account for negative externalities when they are likely to occur (water yield, land use, biodiversity…)

Generate co-benefits

- SOC sequestration is not a commercially viable operation at present (one would need prices of ca. $ 100 USD/(ton C) for the conversion of cropland in developing countries to see significant effects.
- Co-benefits may be reduced labour, increased yields, biodiversity preservation, increased soil quality

Why is this important ?

- Ask the following question: how much do you need to pay a farmer for each ton of sequestered SOC in order for him to switch his management system to a more C-friendly one

Grace et al., 2012: study in Indo-Gangetic plain

Table 6
Proportion (%) of potential net C sequestration achieved after 20 years over a range of carbon prices (USD) when implementing no-tillage practices in wheat based cropping systems of the Indo-Gangetic Plain.

State	Rotation	Carbon price (USD $Mg\,C^{-1}$)			
		25	50	100	200
Bihar	Rice–wheat	7.4	18.9	56.9	96.5
Haryana	Rice–wheat	26.4	49.8	84	100
Punjab	Rice–wheat	10.7	25.9	55.8	91.7
Uttar Pradesh	Rice–wheat	3.4	8	23.8	62.2
West Bengal	Rice–wheat	4.5	17.3	66.4	97.5
Total	Rice–wheat	7	16.5	42	78.6
Uttar Pradesh	Maize–wheat	4.9	13.6	35	77.8
Haryana	Cotton–wheat	1.9	4.2	12.2	31.6
Punjab	Cotton–wheat	5.1	11.9	33.1	78
Total	Cotton–wheat	2.8	6.3	17.7	43.8

Assess the socio-economic implications (see also Stringer et al., 2012)

- What is the effect of pine forests on local communities in the Paramo ?
  - Where does the income generated by the wood go ?
  - Are they able to deal with reduced water yields ?
  - What is replacing their traditional activities in the Paramo ?
  - What will be the effect on the gender distribution of the workload ?
  - How will the arrival of the Iphone 12 in 2020 affect these results ?

Assess socio-economic conditions that may affect potential success of SOC management projects

- Do the farmers-land managers have access to all relevant information ?
- Are the relevant skills present ?

Conclusions

(almost) None !

This is all discussion material and we should do that now to try to arrive at a common view

Nevertheless…

Where do we need scientific progress the most ?

- Concept of SOC saturation appears critical
- When talking about improving SOC stocks, we need to be able to assess them adequately: how do we monitor them ? How do we improve our models (e.g. GEFCarbon approach) to aid in assessment ?
- Can we apply recently developed high-througput measurement techniques (Vis-NIR etc..) to arrive at more accurate and more rapid assessments ?

Concept of soil saturation appears to be critical

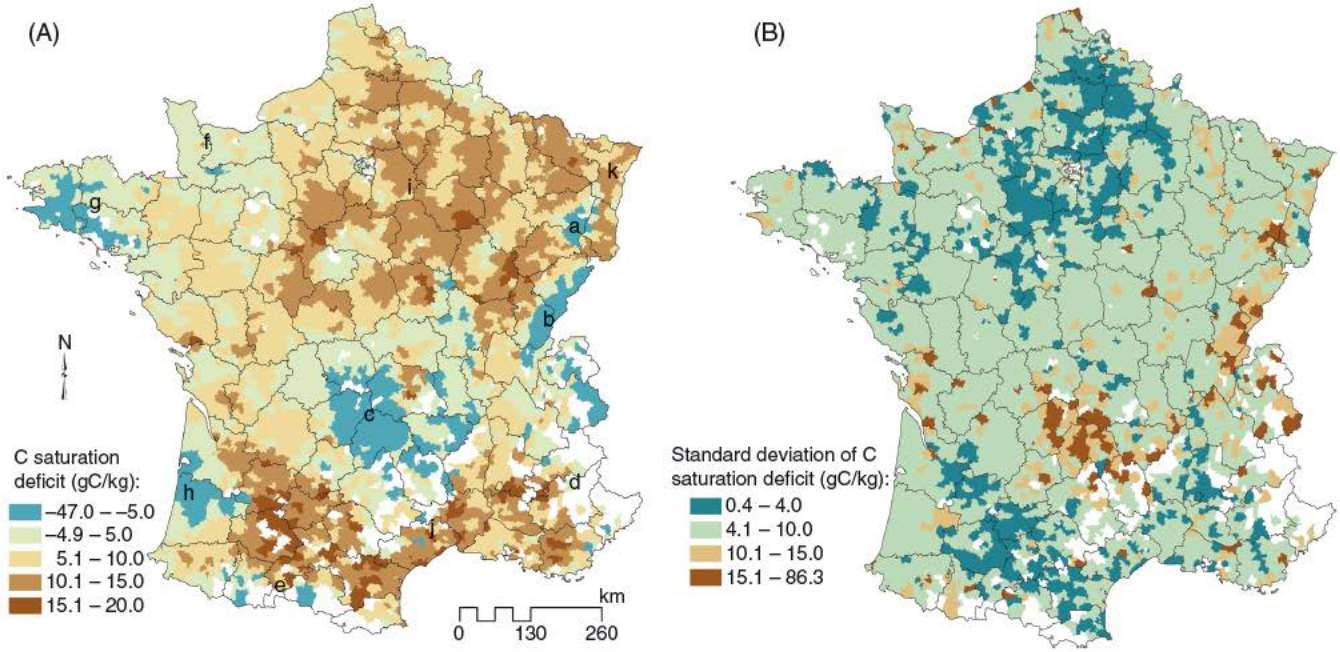


Figure 4 Maps of carbon saturation deficit per canton: (A) mean estimate and (B) standard deviation from 100 Monte Carlo estimations of C saturation deficit. Letters refer to broad regional physiographic units: (a) Vosges; (b) Jura; (c) Massif Central; (d) Alpes; (e) Pyrenees; (f) Normandy; (g) Brittany; (h) Landes of Gascony; (i) Paris Basin; (j) Languedoc-Roussillon; (k) Alsace.

The theoretical value of C saturation (C_{sat}) was calculated according to the equation proposed by Hassink (1997):

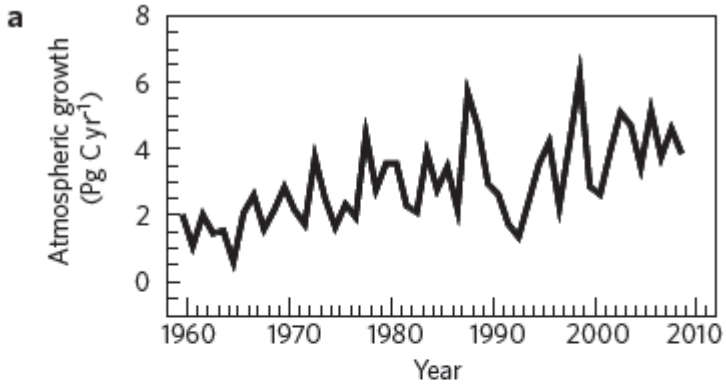
$$C_{sat} = 4.09 + 0.37(\text{Clay} + \text{fSilt}) \qquad (1)$$

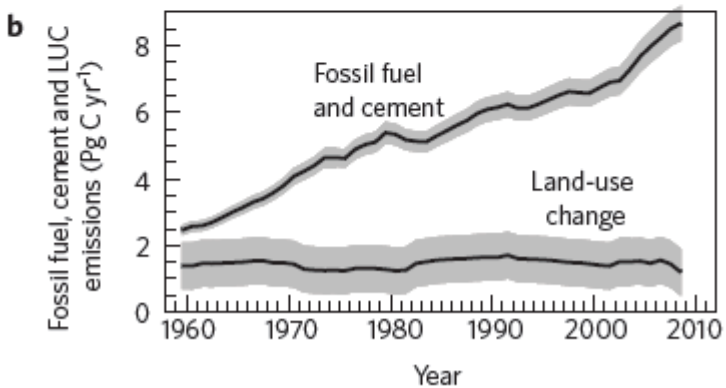
Angers et al., 2011

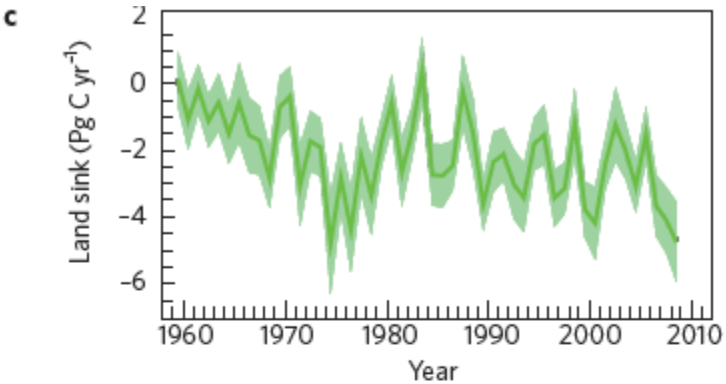
Climatic effects on SOC stocks are still very uncertain

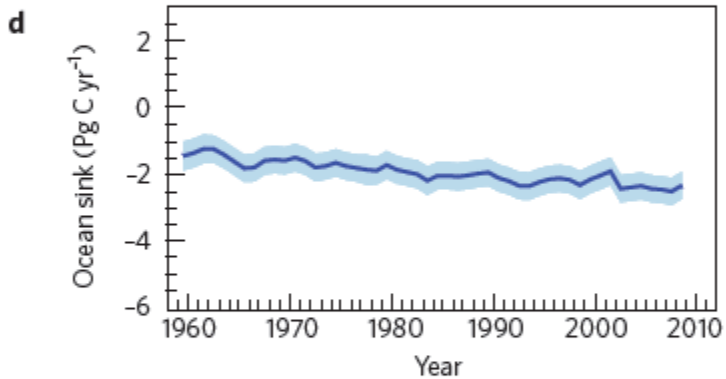
- Makes it very difficult to assess future stocks
- Correctly understanding climate effects is also important if we want to disentangle effects of different drivers (climate (temperature, moisture, CO2) from management effects

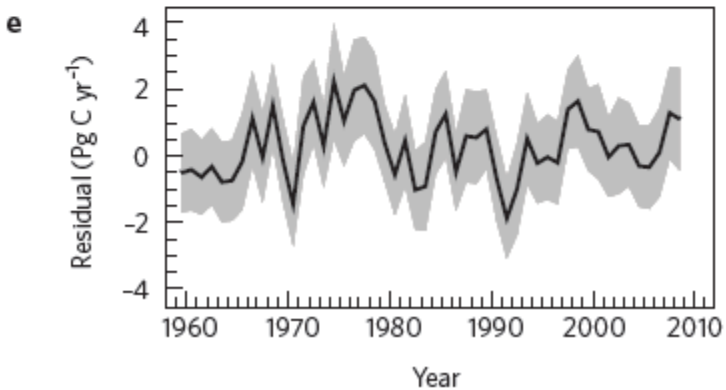
The land is at present a strong sink (Le Quéré et al., 2009)











How to assess SOC stocks ?

- Role of monitoring vs. modelling
- Role of high-throughput measurement techniques

0.1% of C = ca. 4 Mg C/ha

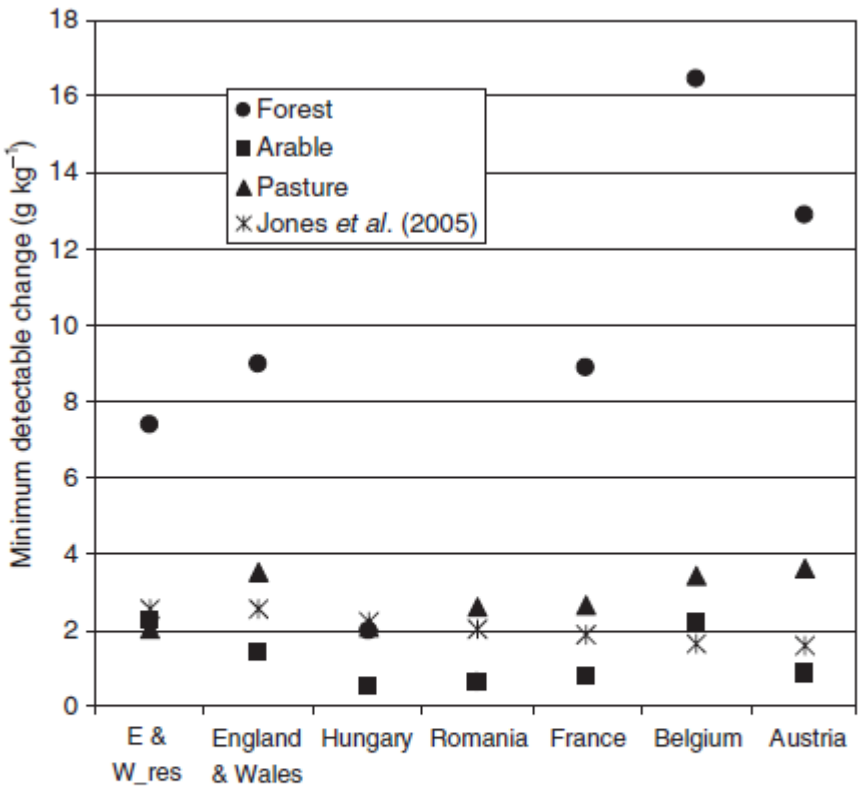


Fig. 1 Minimum detectable changes in SOC concentrations estimated using summary statistics from National monitoring networks (solid symbols), and European topsoil SOC map (Jones *et al.*, 2005) (stars) for six European countries and also using actual resampled data for England and Wales (E & W_res).

Saby et al., 2008