Soil carbon loss and sequestration – myths and reality

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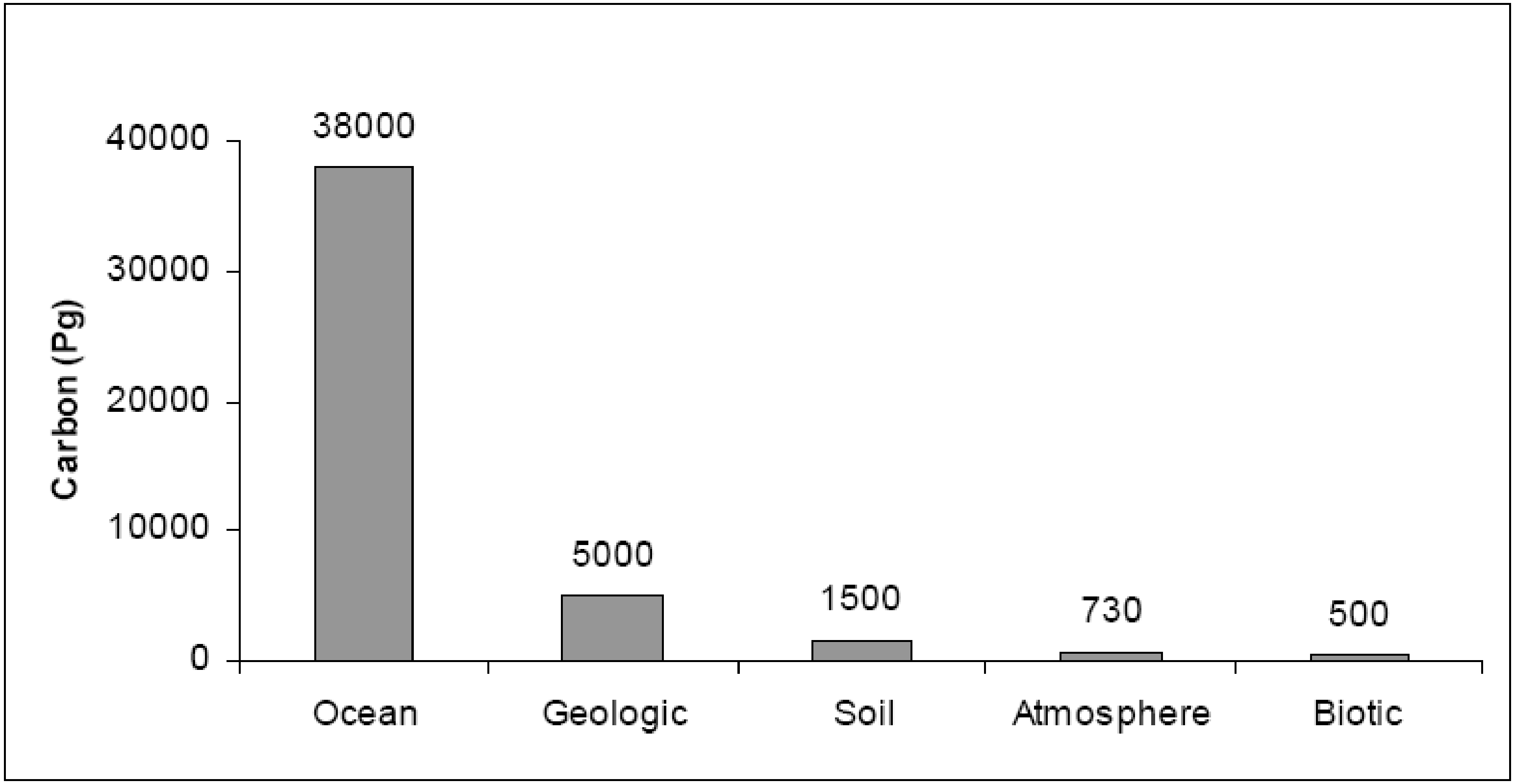
Introduction
Aims and objectives

- Introduction
- Responses of soil carbon to environmental change
- SOC stocks and responses to management
- Evaluation of measures

Global carbon pools and fluxes

Schils et al. (2008)

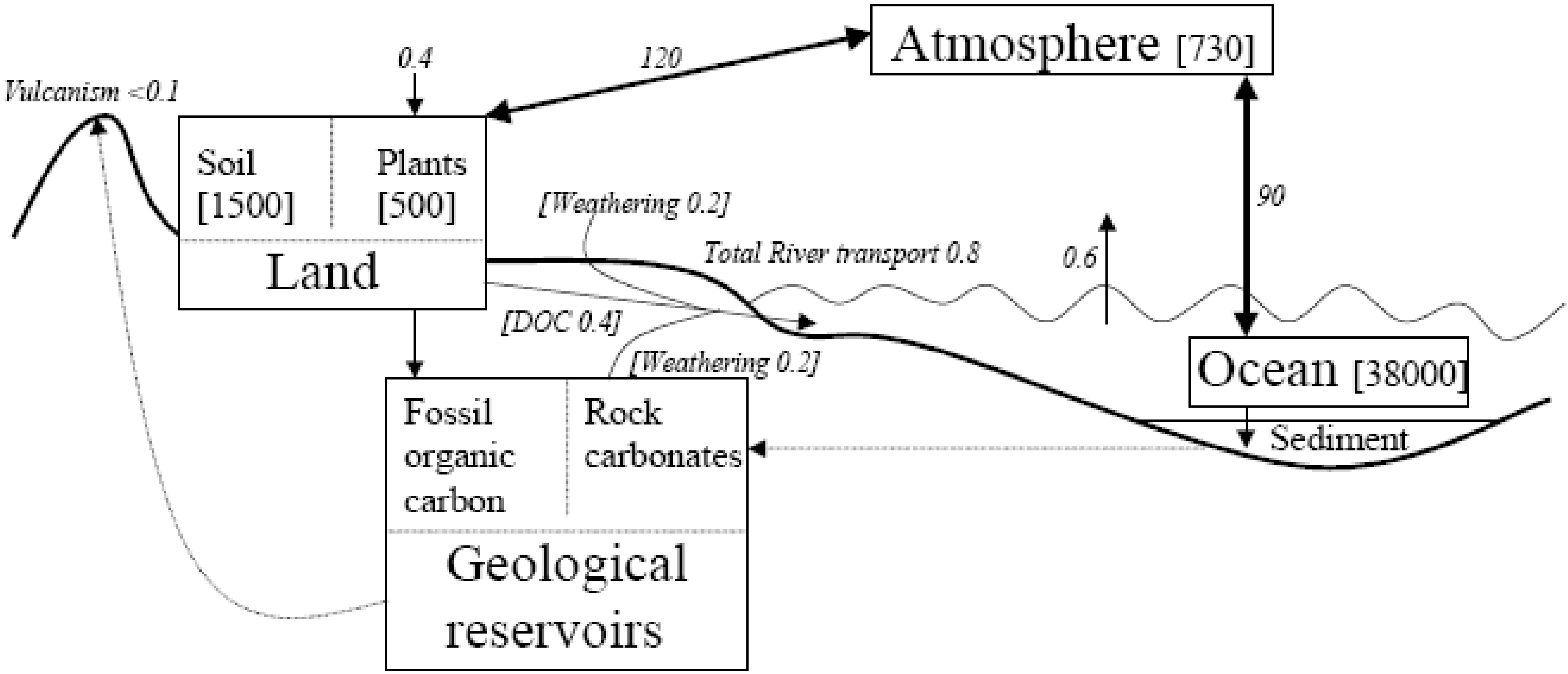
Principal global carbon pools in Pg (1 Pg = 1 Gt = 1015 g).



Global carbon pools and fluxes

Schematic diagram of carbon cycle, with main pools and flows of the natural global C cycle (in Pg) between the pools.

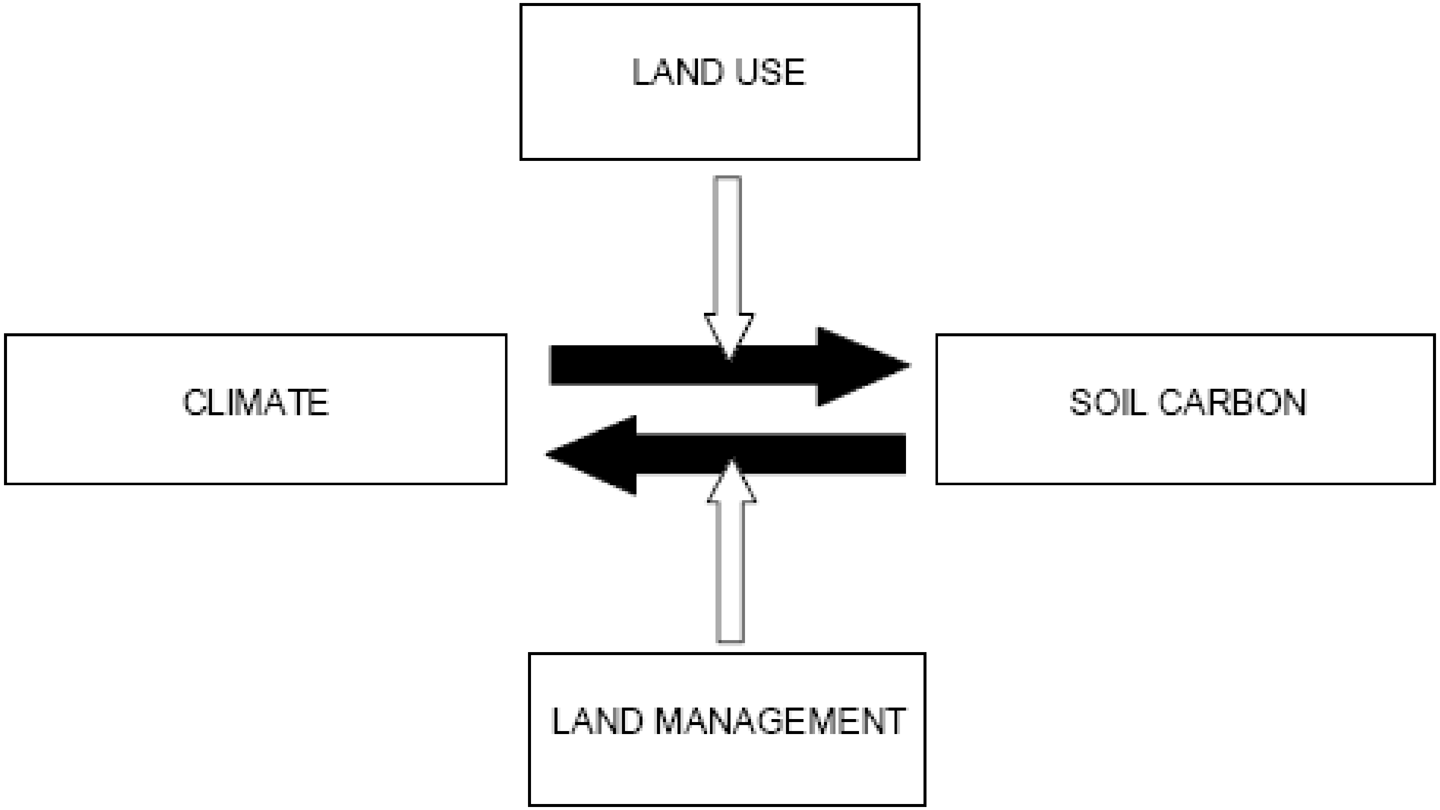
Schils et al. (2008)



Global carbon pools and fluxes

Climate change affects the soil carbon pool and vice versa changes in soil carbon affect the climate. For these relationships, land use and land management are major factors.

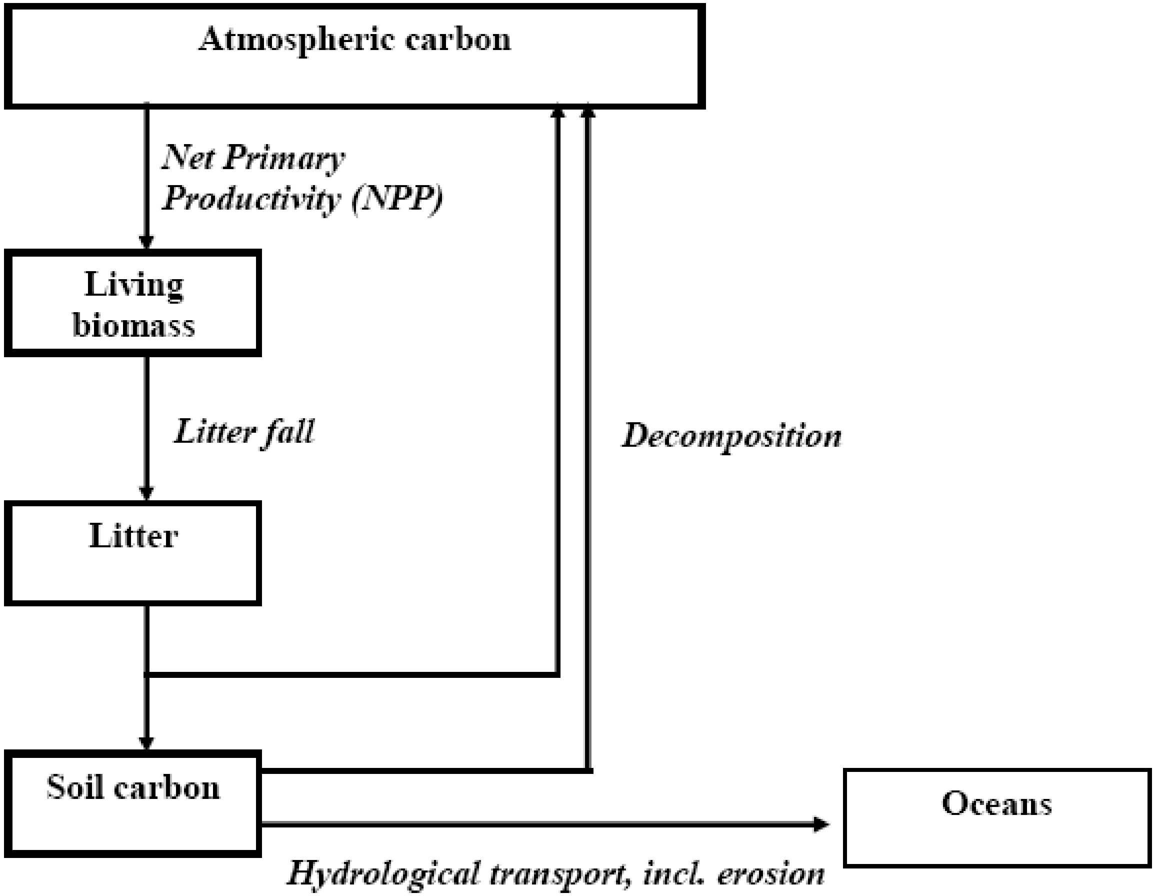
Schils et al. (2008)



Global carbon pools and fluxes

Processes leading to formation and loss of soil carbon

Schils et al. (2008)



Responses of soil carbon to environmental change

Schils et al. (2008)

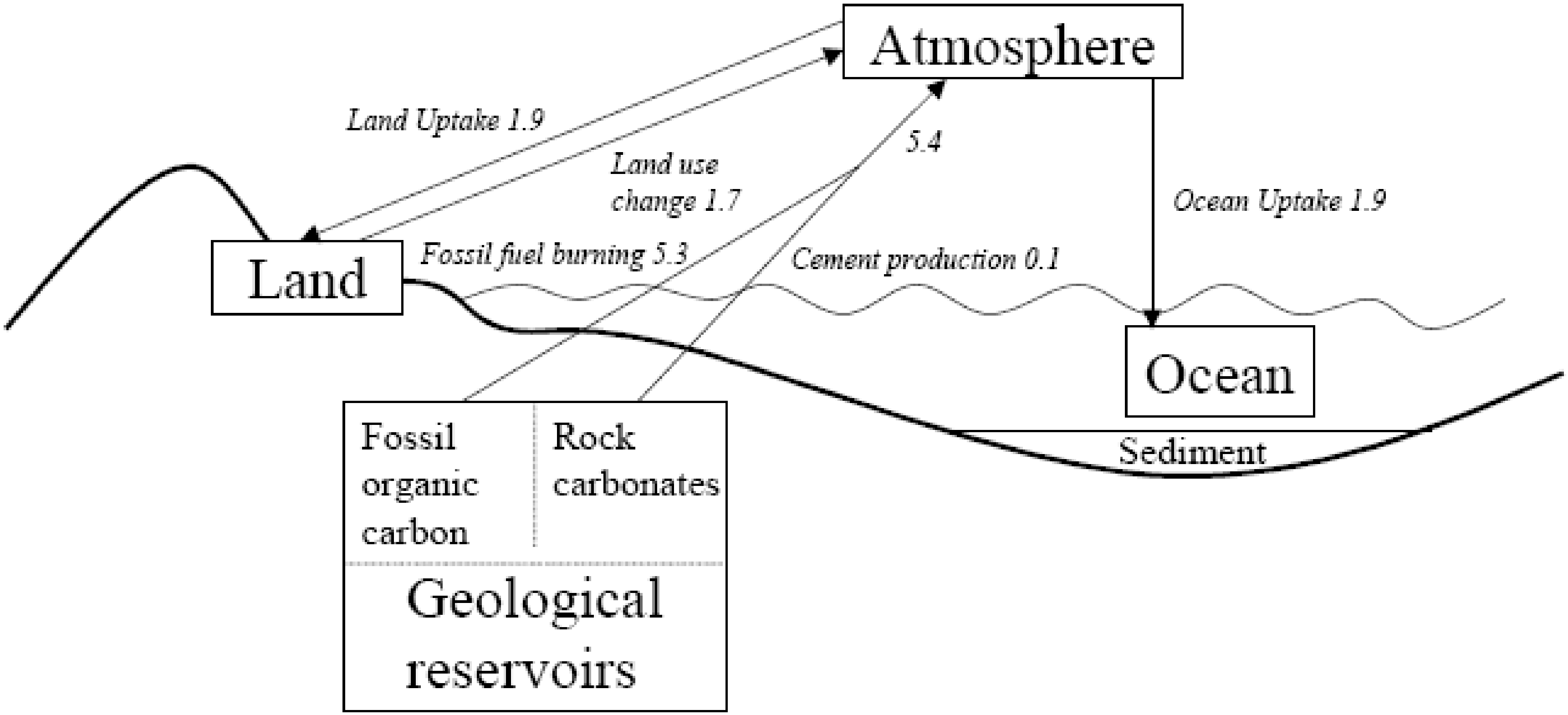
		Process response			Soil carbon response	
		Plant and litter production	Decomposition	Erosion	Soil carbon	Uncertainty
Environmental change	Increased CO_2	↗	↕	–	↗	Medium
	Increased temperature	↕	↗	–	↕	High
	Dry spells on mineral soils	↘	↘	–	↕	High
	Dry spells on organic soils	–	↗	↗	↘	Medium
	Heavy rain events	–	–	↗	↘	Medium
	Increased nutrient availability	↗	↕	–	↗	Low

Expected responses of soil carbon and the underlying processes to key environmental change factors. (Note: "Uncertainty" refers to the direction of the soil carbon response: uncertainties about magnitudes of change are high throughout.)

Responses of soil carbon to environmental change

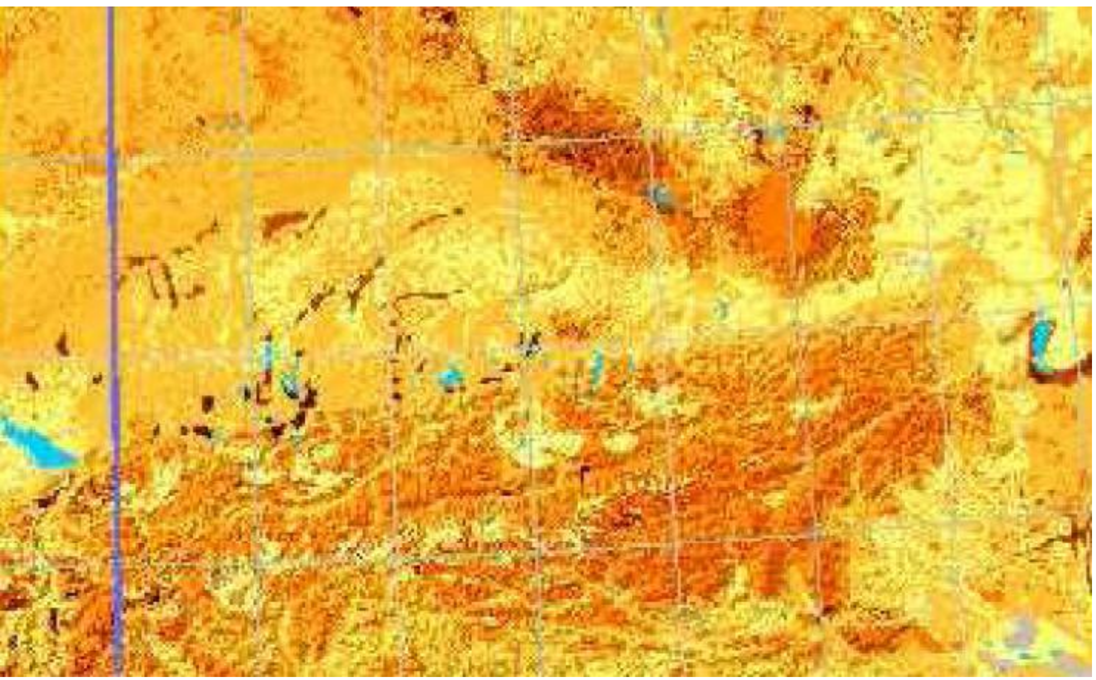
Schematic diagram of carbon cycle, showing the human perturbation to the flows of C (in Pg) between the pools.

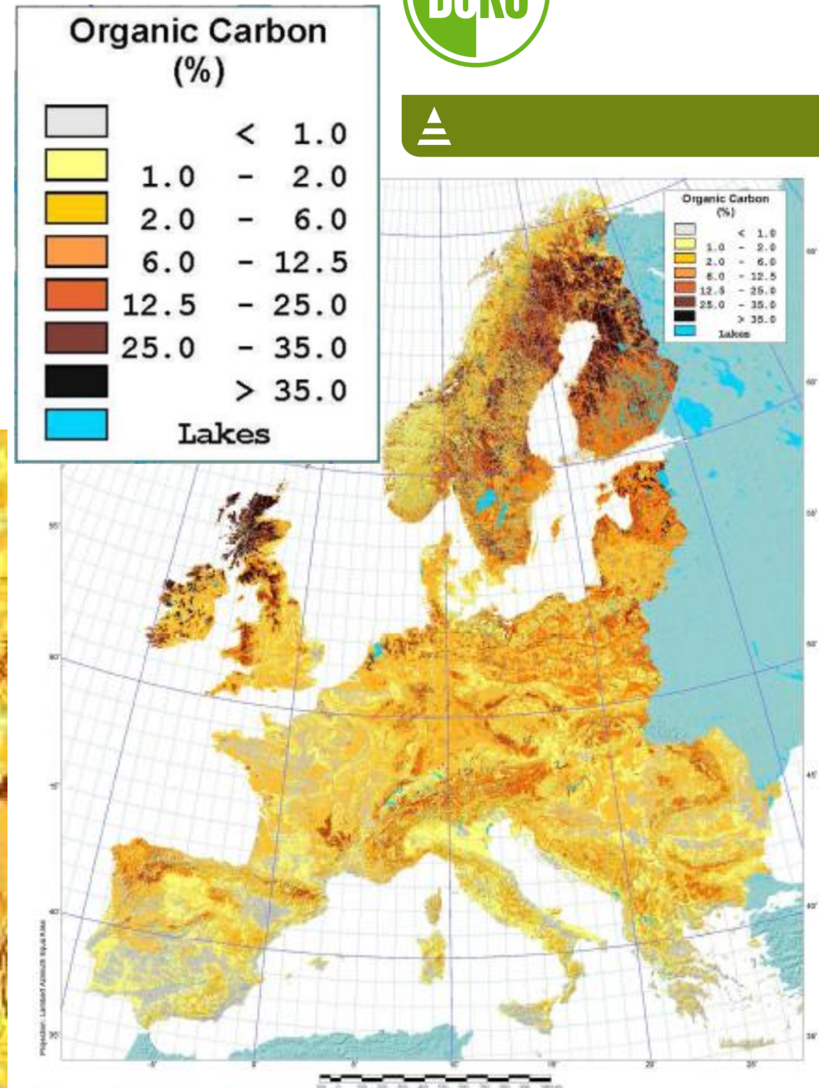
Schils et al. (2008)



SOC stocks and responses

Carbon stocks:
Austria: 1.2-1.4 Pg (1.5%)
Europe: 75.3-79.7 Pg
(Schils et al., 2008)

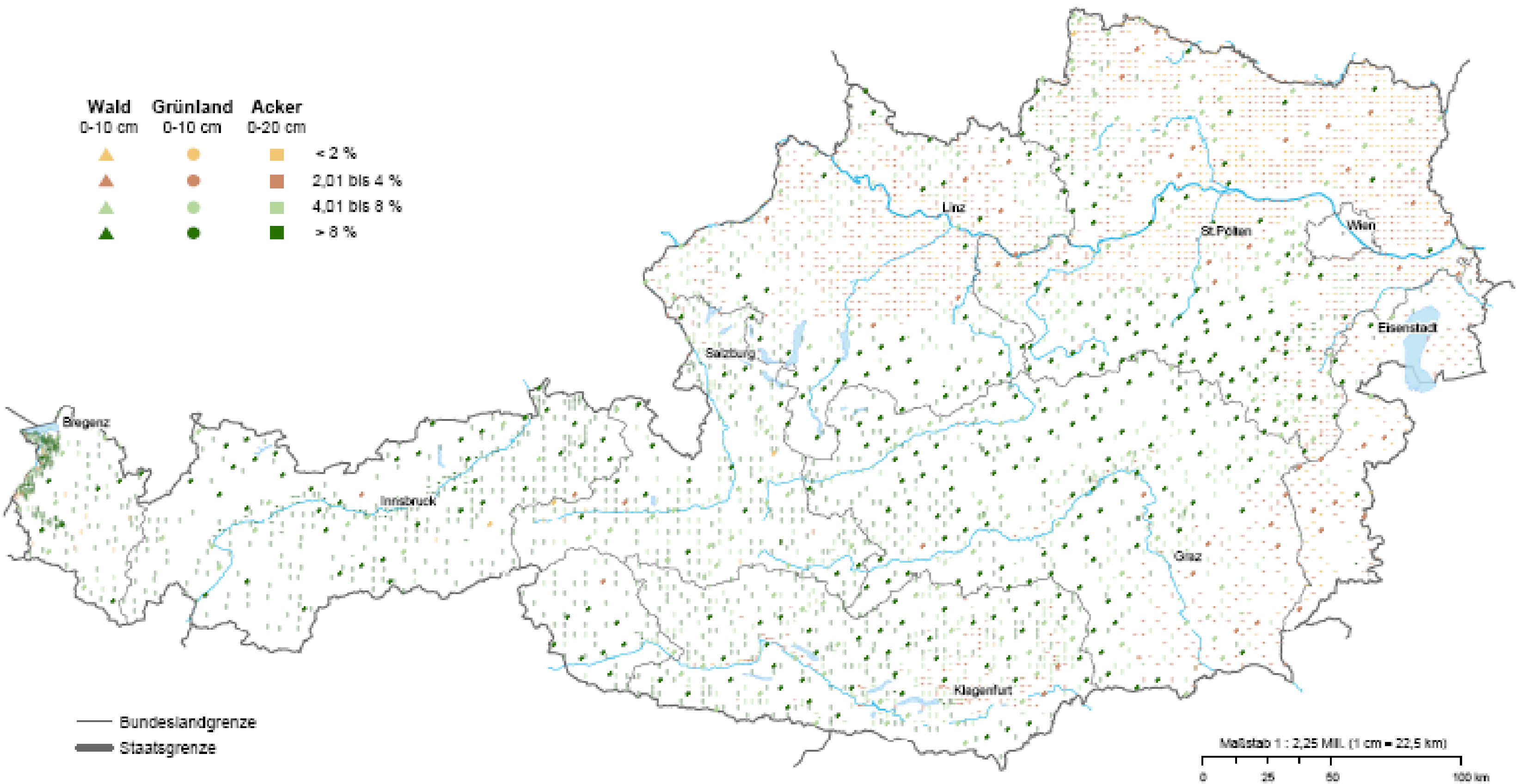




SOC stocks and responses

Soil organic carbon (SOC) contents in Austria

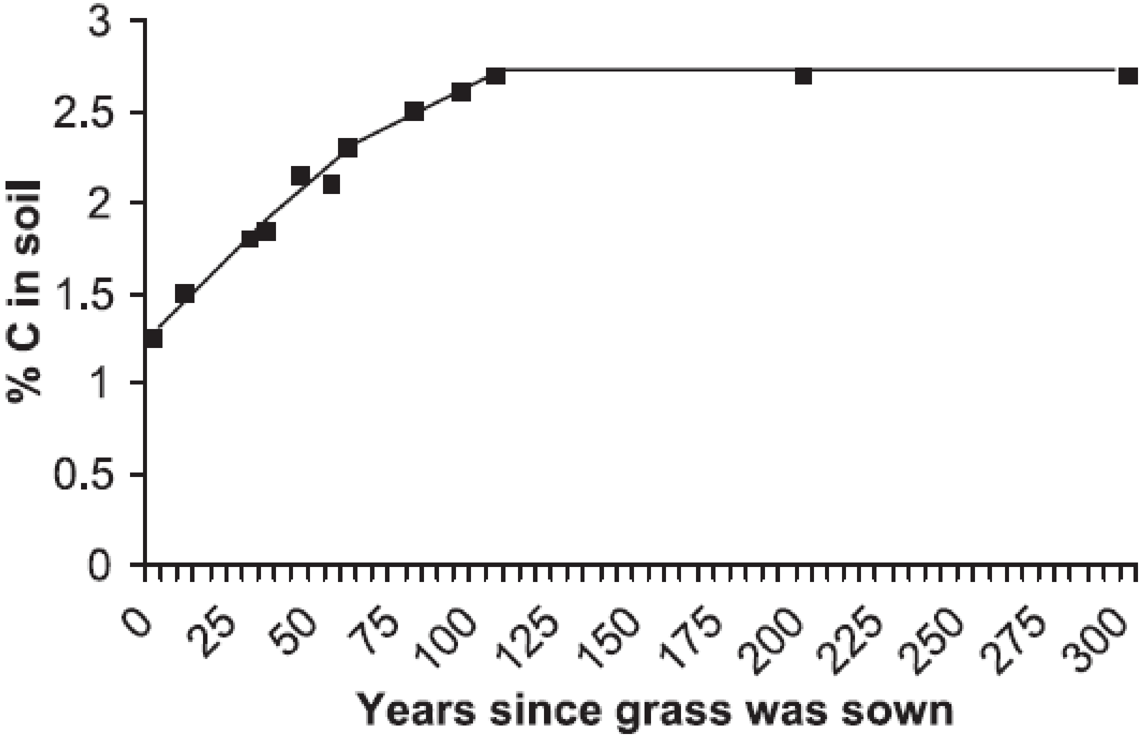
UBA (2003)



Carbon stocks and responses

Carbon accumulation in a silty clay loam soil at Rothamsted (U.K.) after conversion of arable to permanent grassland

Freibauer et al. (2004)
Jenkinson (1988)



Carbon stocks and repsonses

- Carbon stocks: grasslands > arable land (Soussana et al., 2004), e.g. 1.6 times (4% vs. 2.5%) greater in permanent pasture compared to cereal cultivation in a Swedish farm system (no changes of cultivation since 1880) (Katterer et al., 2008)
- Conversion from grassland to arable land lowers C stock; conversion back to grassland increases C stock, e.g. by 0.6% C in 32 years in the Swedish study (Katterer et al., 2008)
- Change from arable to cropping may increase C stock by 33 g m^{-2} y^{-1} (estimate based on a literature review by Post and Kwon, 2000)
- Soils with initially high C content are more susceptible to loss upon land use change or certain management practices than low C soils (Katterer et al., 2004)

Carbon stocks and responses

- Complex crop rotations maintain higher C stocks than monocultures (Morari et al., 2006) but not in every case (Persson et al., 2008)
- Enhancing crop rotation complexity (monoculture to continuous rotation; crop fallow to rotation; increasing the number of crops in a rotation system) may increase C stocks by 20±12 g C m^{-2} y^{-1} (comprehensive literature data analysis of 67 long-term experiments by West and Post, 2002)
- Changing from conventional to no tillage may sequester 57±14 g C m^{-2} y^{-1} (except wheat – fallow systems: no change) (West and Post, 2002)
- Carbon peaks are encountered after 5-10 years, new equilibrium is typically approached after 15-20 (100) years (Smith et al., 1997a,b)

SOC stocks and responses

- Arable soils
  - European scale estimate suggests arable soils to be a net source of 92 g C m^{-2} y^{-1} (Janssens et al., 2003)
  - The complexity of interacting factors makes it difficult to obtain reliable estimates of carbon fluxes from / to arable soils
- Grassland soils
  - Under current management conditions, grasslands are considered net sinks of C (Jones and Donelly, 2004)
  - Measurements suggest sequestration rates of 45-80 g C m^{-2} y^{-1} with an estimate for Europe of 76 g C m^{-2} y^{-1} (Janssens et al., 2003)

SOC stocks and responses

- Grassland soils (continued)
  - Appropriate management (irrigation, organic and mineral fertilisers, grazing) may increase C stocks by 30-35 g C m^{-2} y^{-1} (Conant et al., 2001)
- Forst soils
  - Forest biomass inventories combined with modelling suggests carbon sequestration in the range of 7-12 g C m^{-2} y^{-1} by Swedish and Finnish forest soils (de Wit et al., 2006; Liski et al., 2006; Agren et al., 2007)
  - Soil monitoring in three Swedish forest systems suggested C sequestration of 18 g C m^{-2} y^{-1} (Berg et al., 2007)

SOC stocks and responses

Schils et al. (2008)

Estimated changes in soil carbon pool under different land uses in Europe. Positive figures mean increase in the pool, negative ones decrease; sd stands for standard deviation

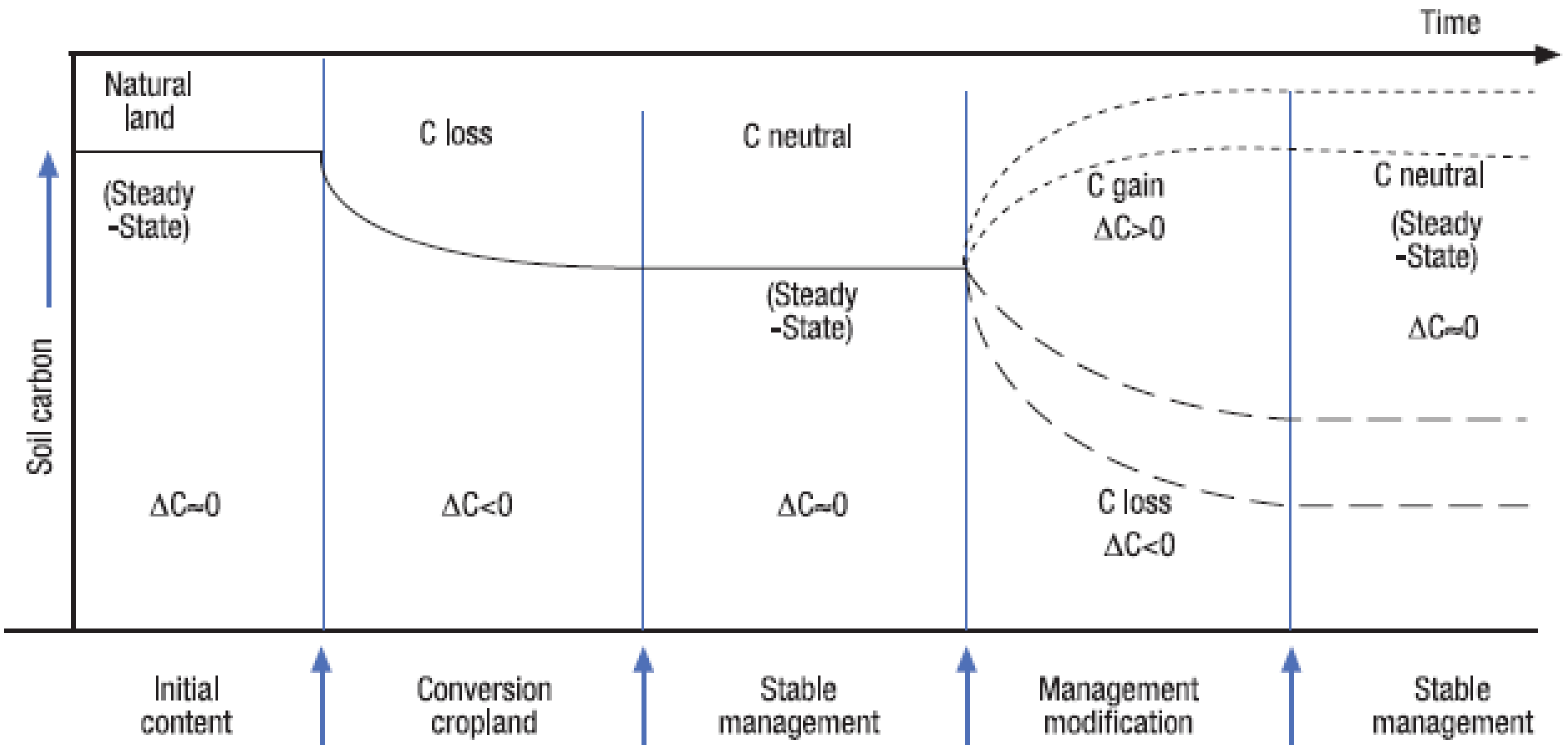
Land use	Change in soil carbon pool (Tg year^{-1})	Source
Grasslands	+1 to +45	Smith *et al.*, 2005
	+101 (sd 133)	Janssens *et al.*, 2003
Croplands	-39 to +10	Smith *et al.*, 2005
	-300 (sd 186)	Janssens *et al.*, 2003
Forest	+17 to +39	Liski *et al.*, 2002

European soils are estimated to be a sink for 1-100 million tons of CO_2 per year

SOC stocks and responses

Conceptual model of soil organic carbon (SOC) changes due to cultivation and land use modifications in agricultural soils

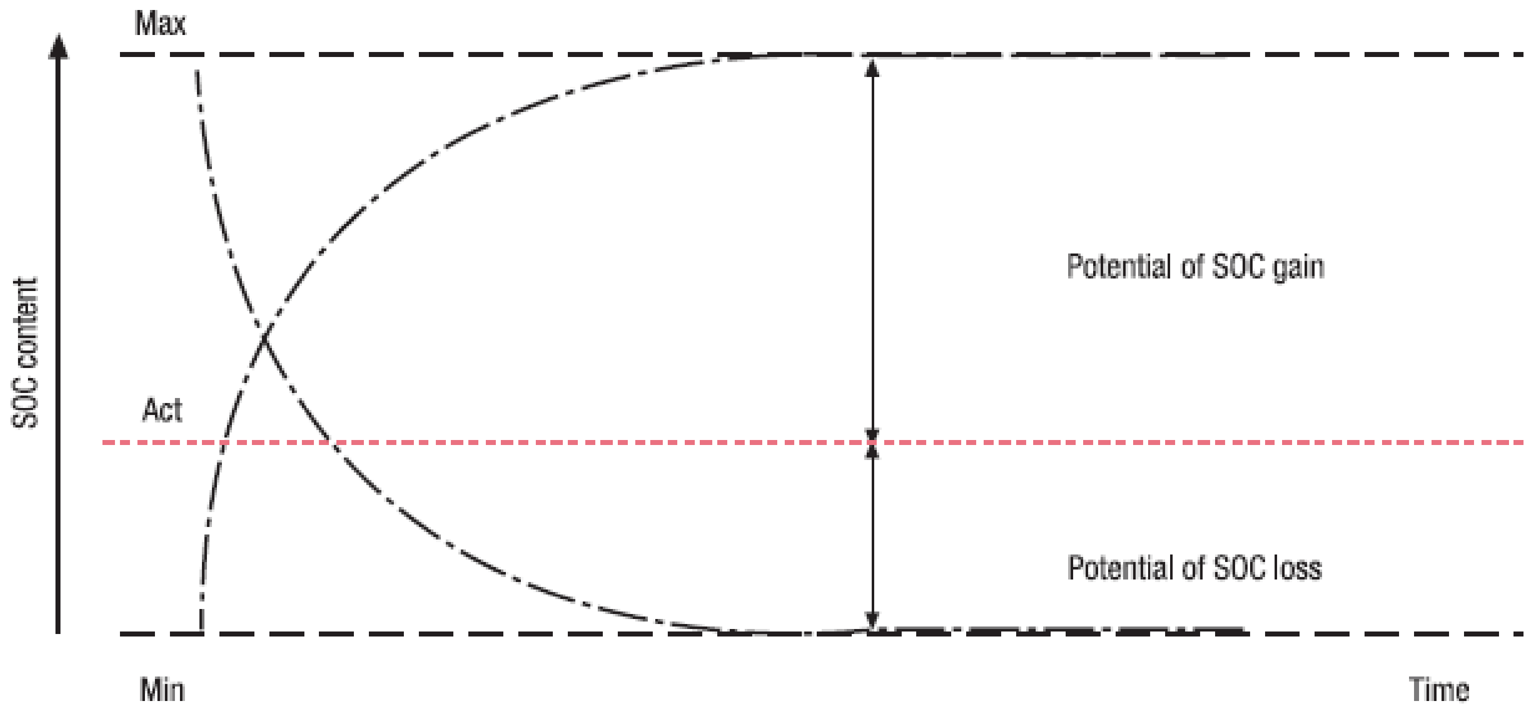
Louwagie et al. (2009)



SOC stocks and responses

Critical threshold values for soil organic carbon (SOC)

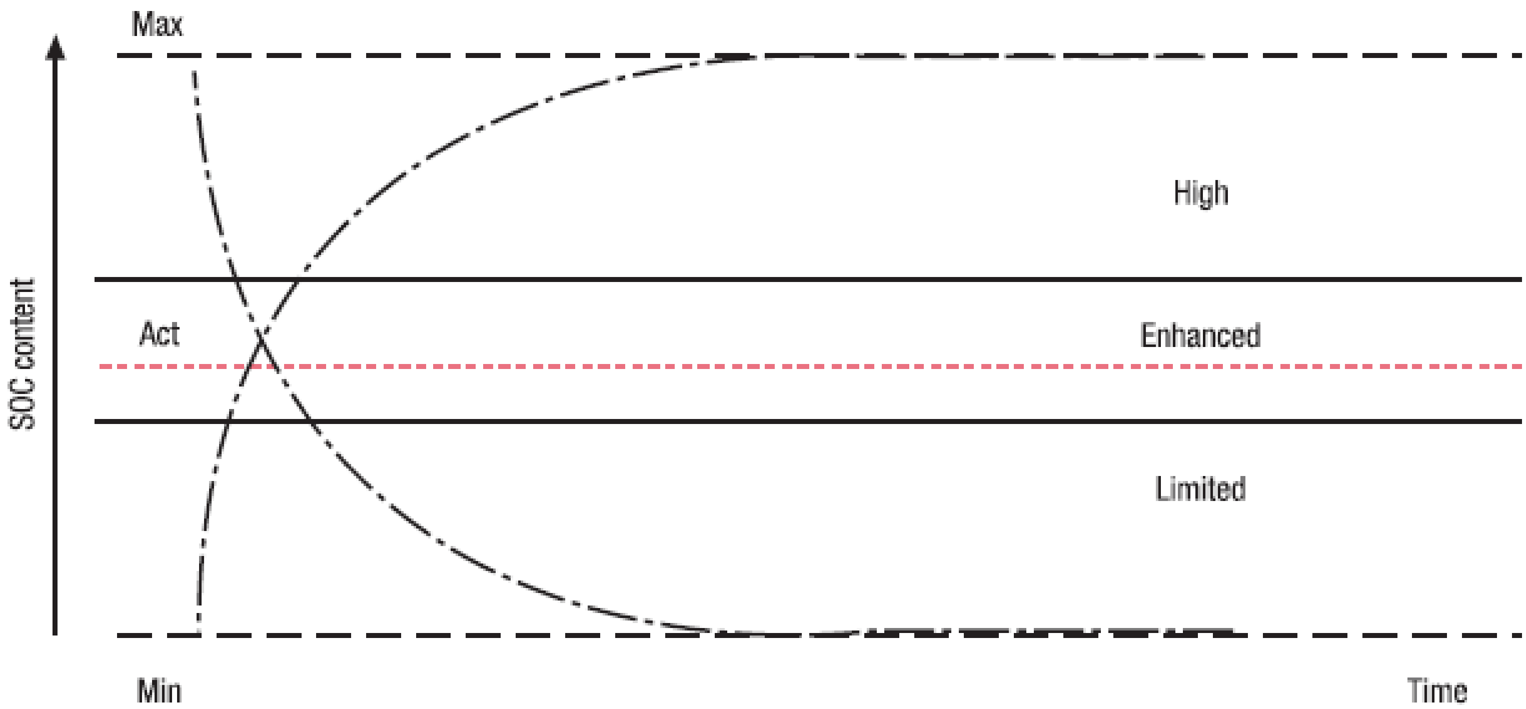
Louwagie et al. (2009)



SOC stocks and responses

Risk and probability zones for soil organic carbon (SOC) loss (indicated by horizontal lines)

Louwagie et al. (2009)



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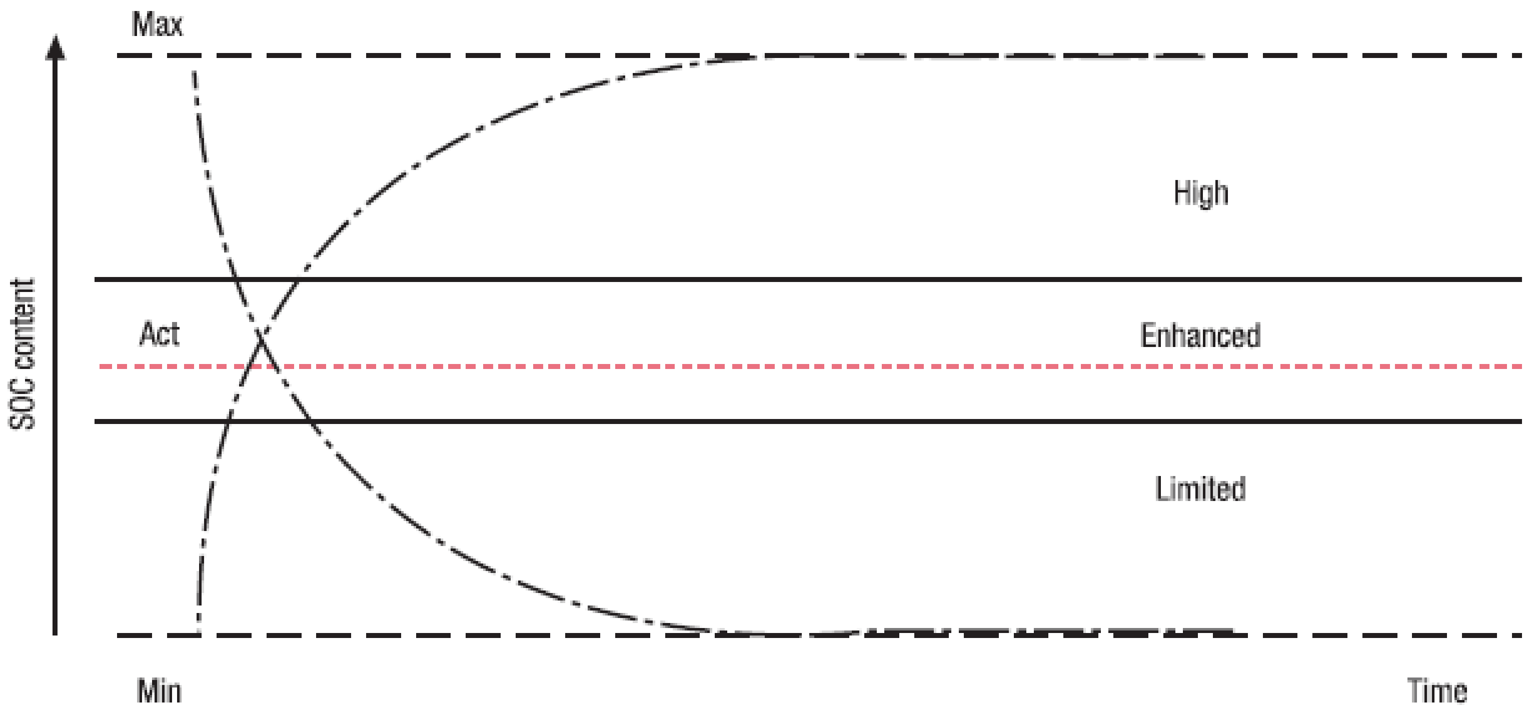
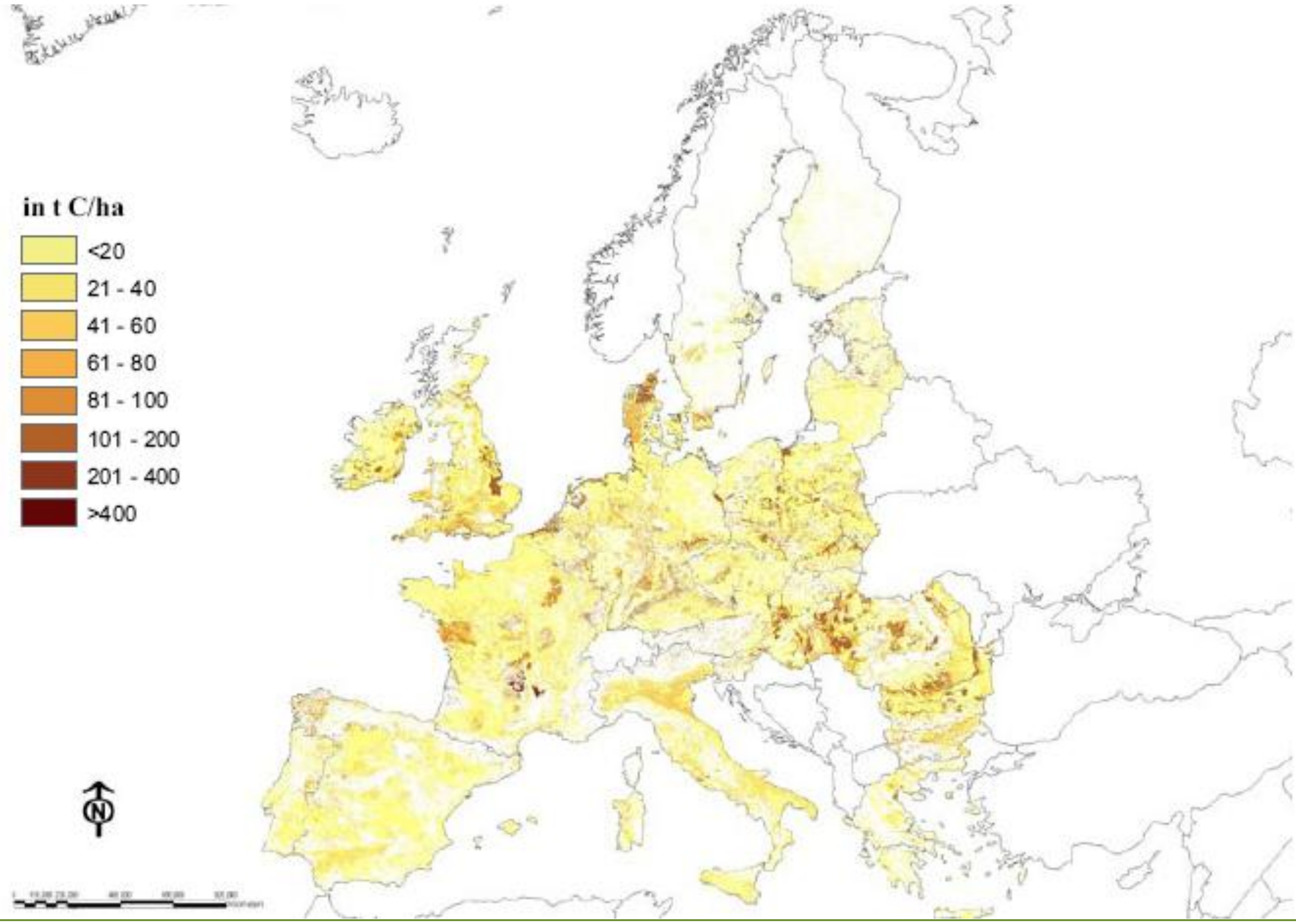


Soil threats and state
SOC stocks and responses

Minimum soil organic carbon (SOC) contents in Europe

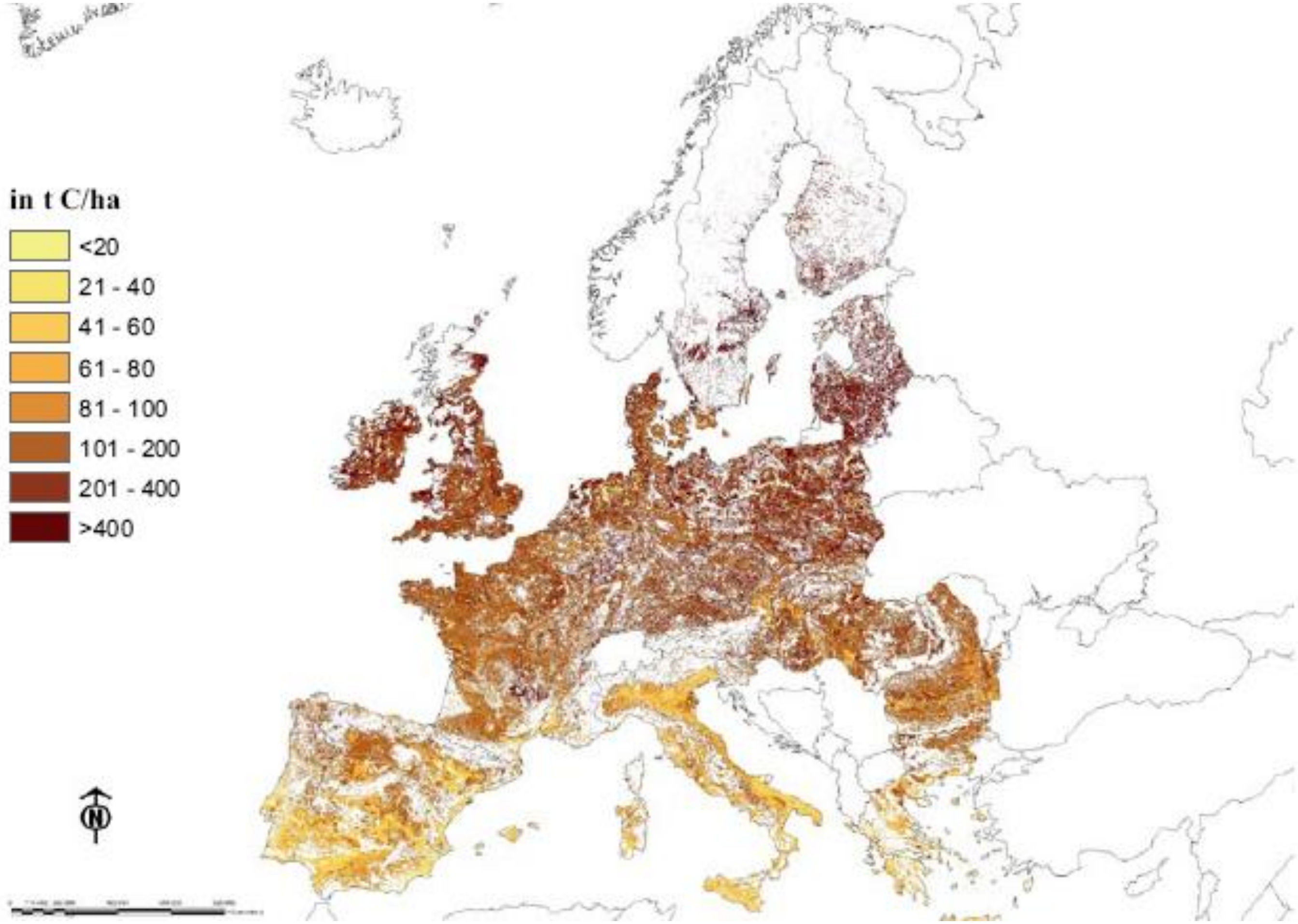
Louwagie et al. (2009)



SOC stocks and responses

Maximum soil organic carbon (SOC) contents in Europe

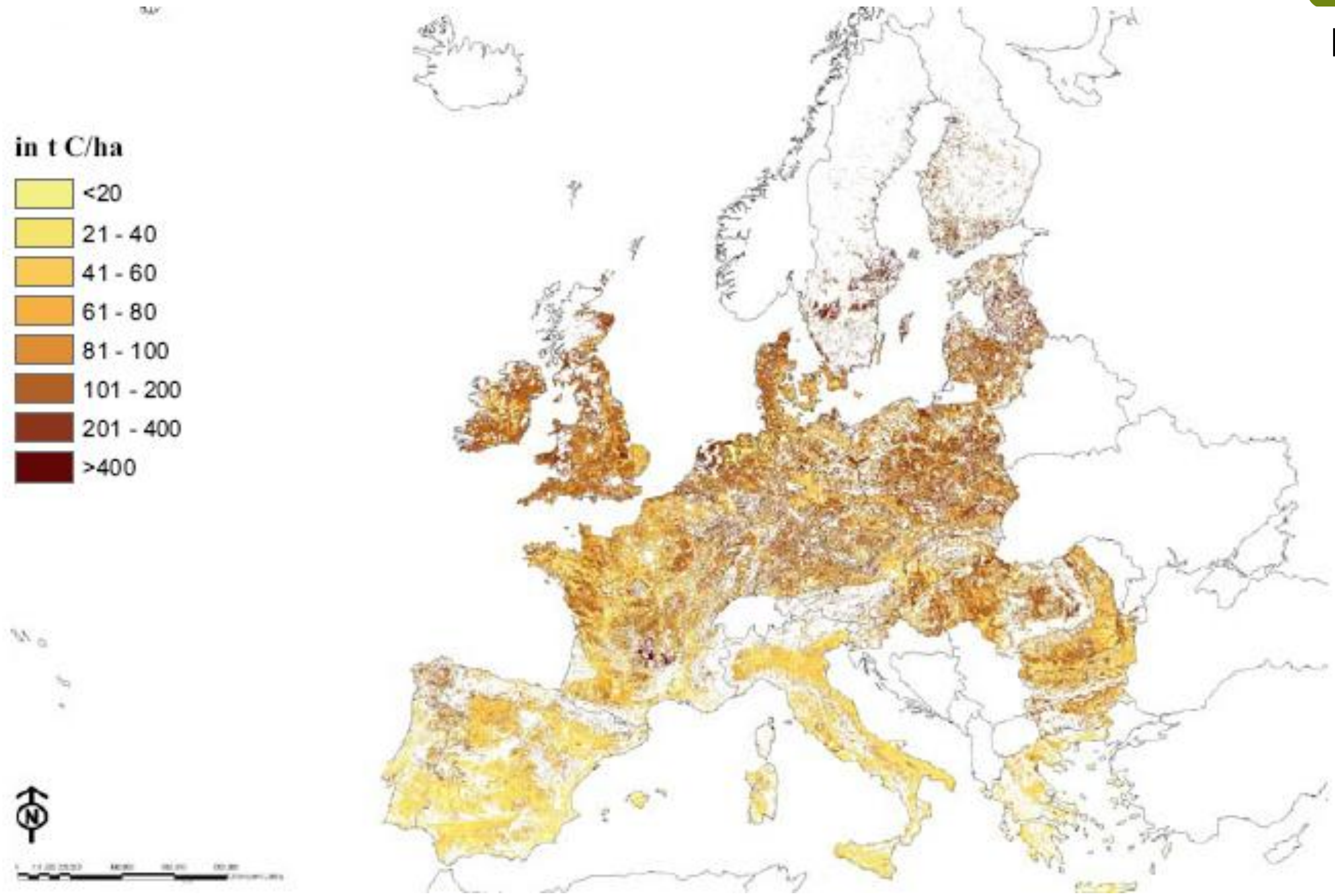
Louwagie et al. (2009)



SOC stocks and responses

Actual soil organic carbon (SOC) contents in Europe

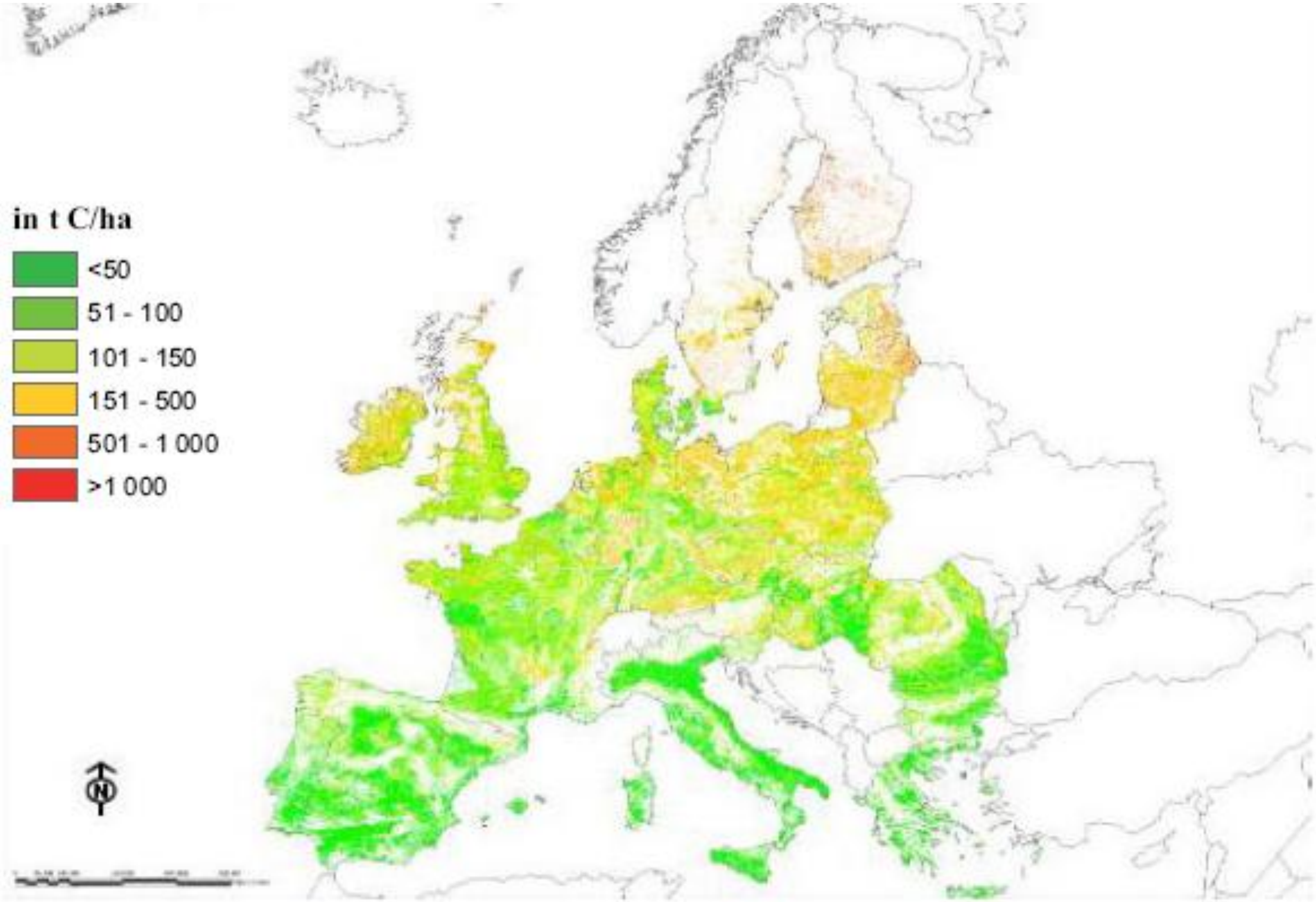
Louwagie et al. (2009)



SOC stocks and reponses

Potential loss of soil organic carbon (SOC) in Europe

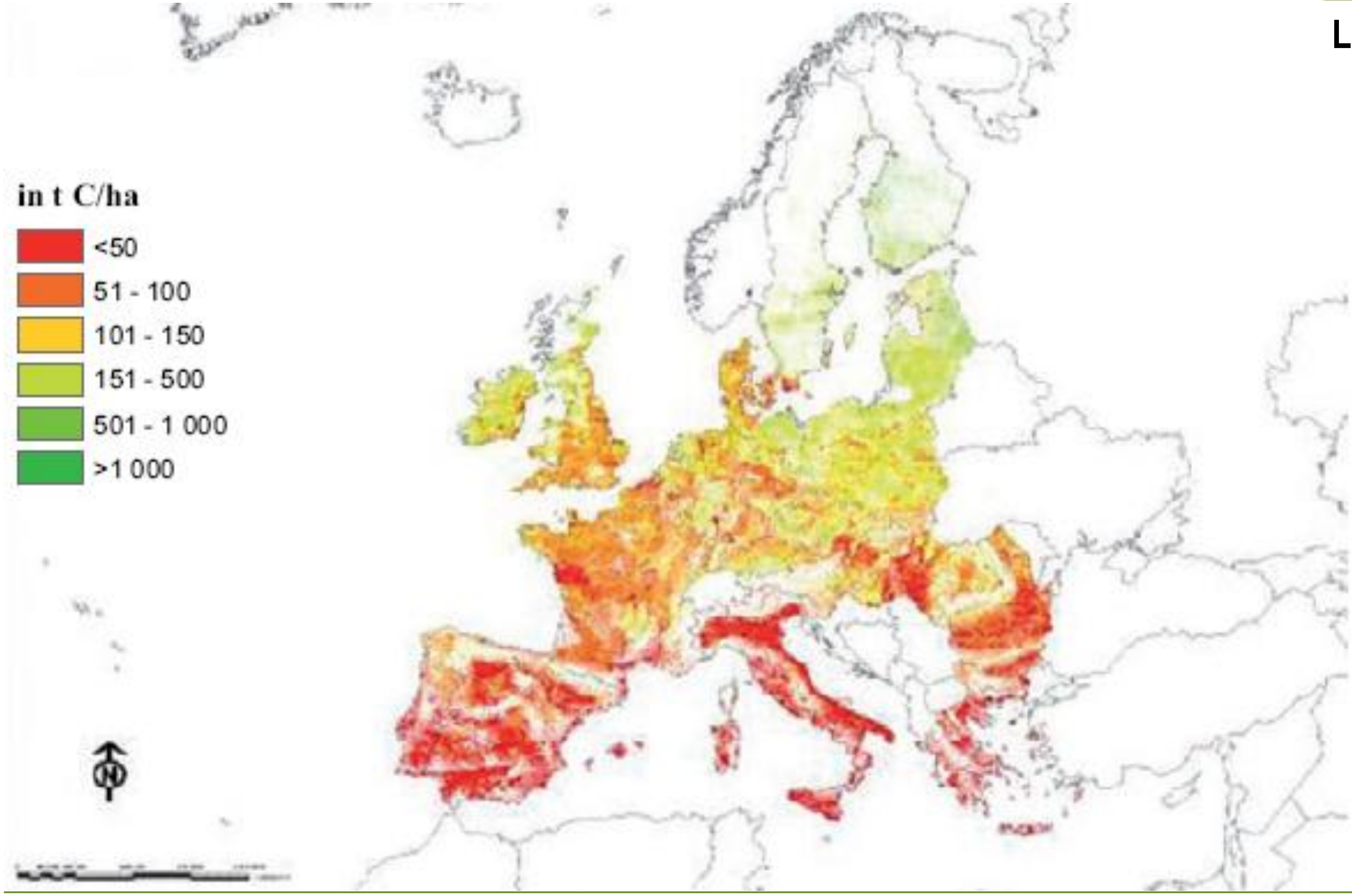
Louwagie et al. (2009)



SOC stocks and responses

Potential gain of soil organic carbon (SOC) in Europe

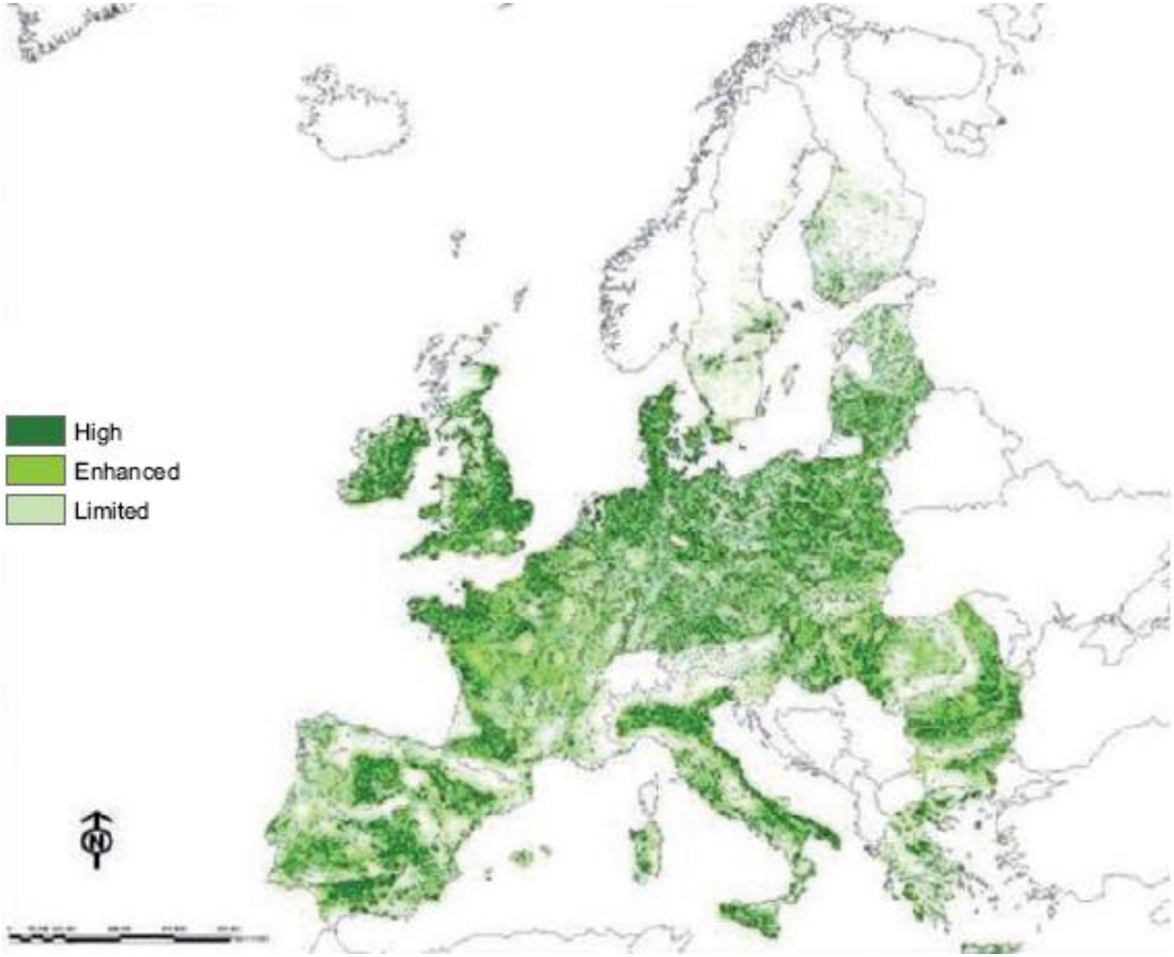
Louwagie et al. (2009)



SOC stocks and responses

Probability zones of soil organic carbon (SOC) gain in Europe

Louwagie et al. (2009)

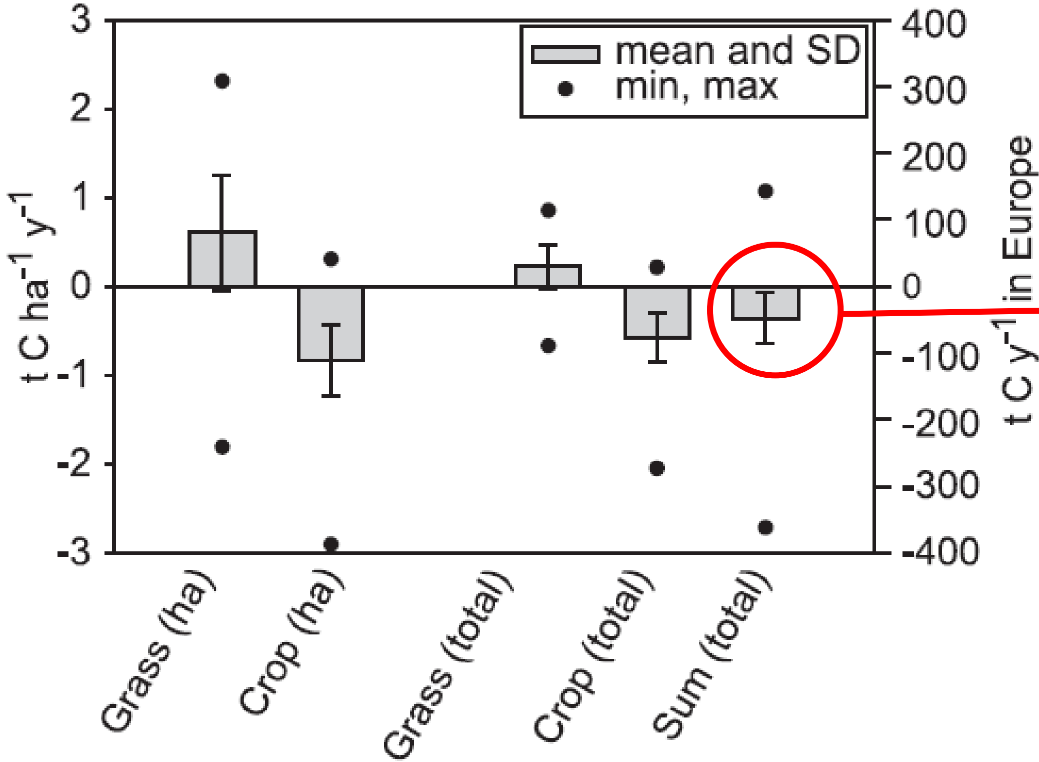


SOC stocks and responses

Estimated annual carbon fluxes from/to managed soils in EU-15 in the first Kyoto commitment period 2008-2012 for the business-as-usual scenario.

Positive signs refer to soil as carbon sink, negative signs to soil as carbon

Vleeshouwers & Verhagen (2002)
Freibauer et al. (2004)



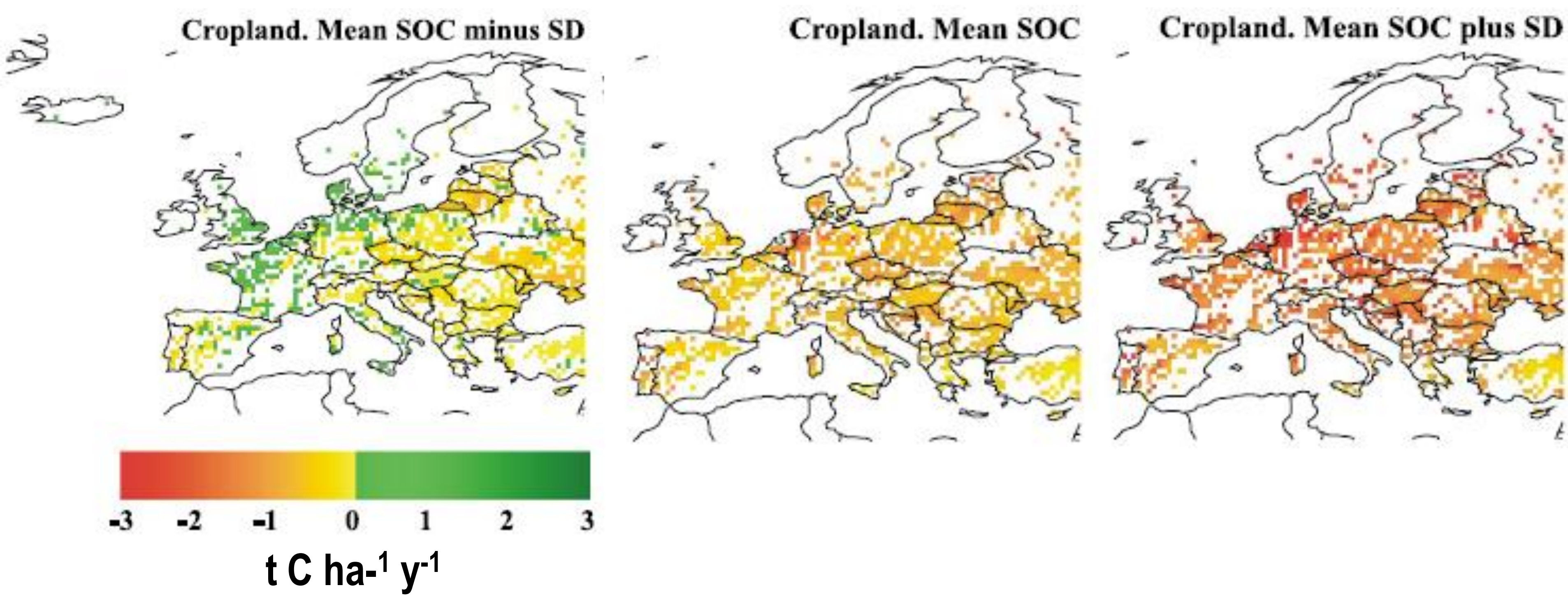
Overall, European soils are estimated to be a source for millions of tons of CO_2 per year

Note: Uncertainty estimates include only uncertainty of soil carbon stocks but not those of inputs

SOC stocks and responses

Simulated carbon fluxes to European cropland soils in the commitment period 2008-2012 of the Kyoto Protocol

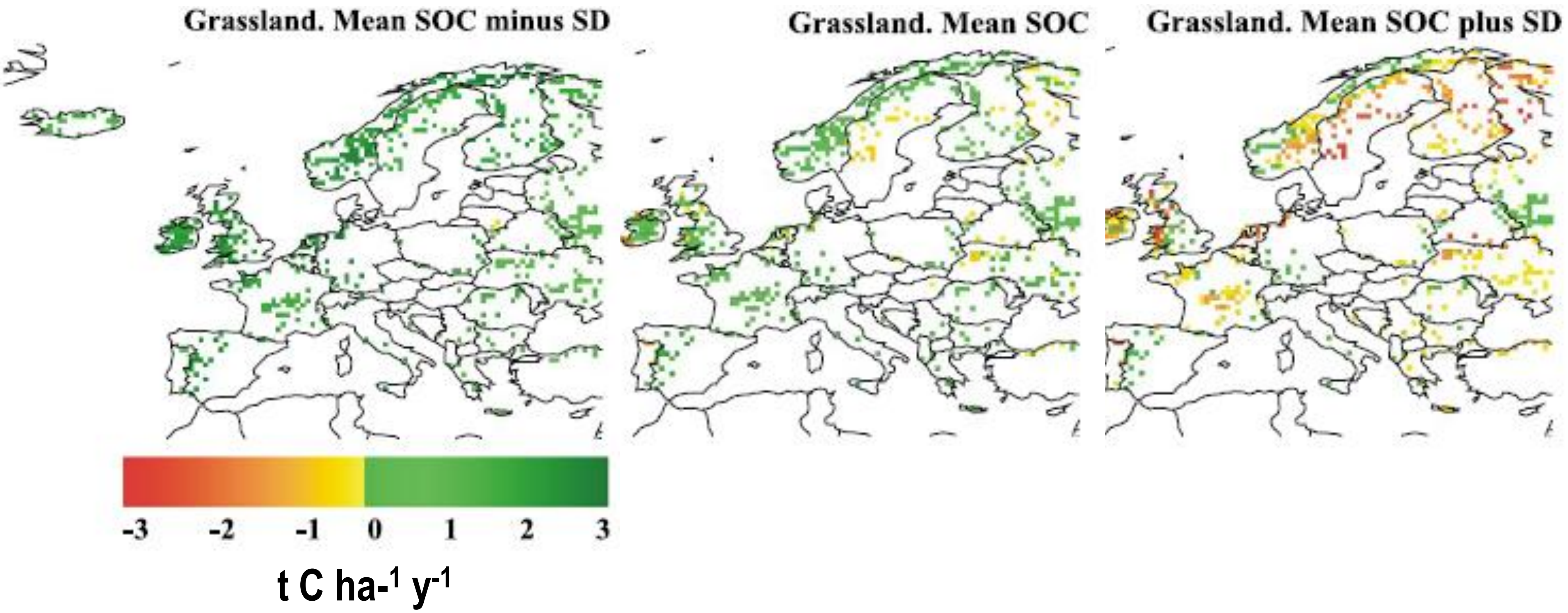
Vleeshouwers & Verhagen (2002)
Freibauer et al. (2004)



SOC stocks and responses

Simulated soil carbon fluxes to European grassland soils in the commitment period 2008-2012 of the Kyoto Protocol

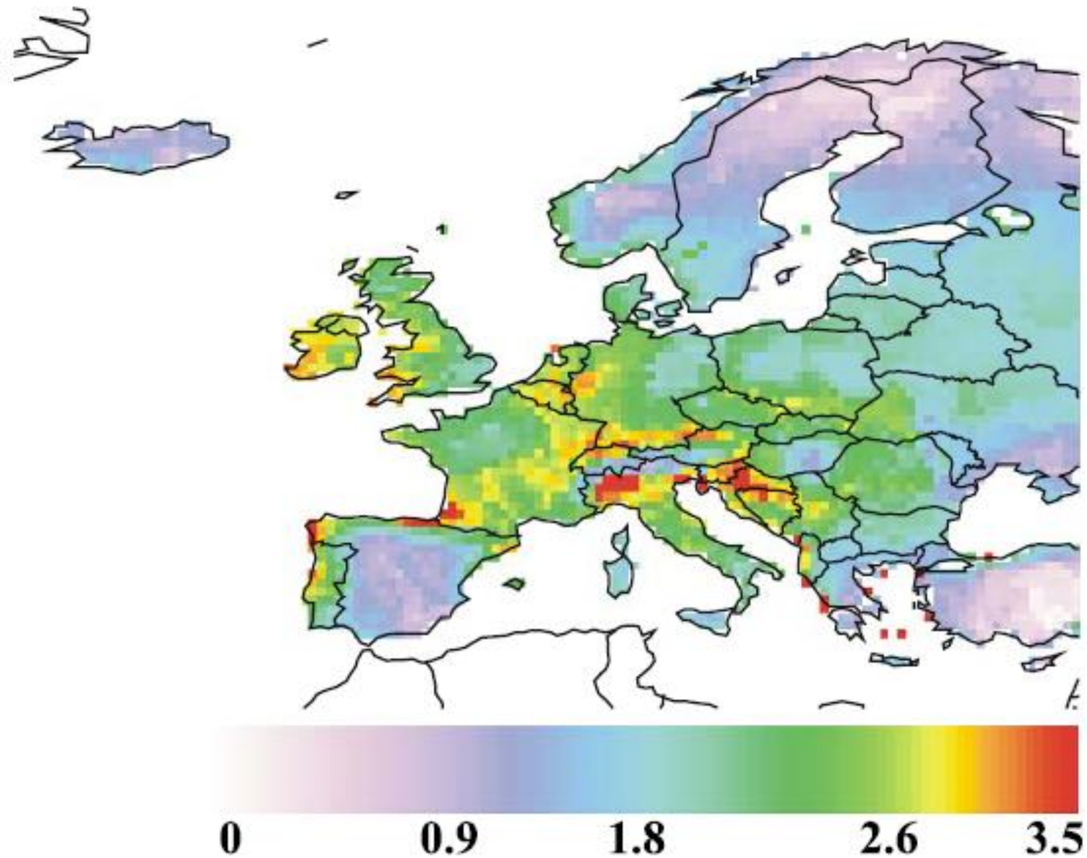
Vleeshouwers & Verhagen (2002)
Freibauer et al. (2004)



SOC stocks and responses

Annual relative decomposition rates of organic matter in European soils

Vleeshouwers & Verhagen (2002)
Freibauer et al. (2004)



% y^{-1} of total organic matter

- High decomposition in regions where high temperatures coincide with moist conditions in summer
- Low decomposition in cold and wet climatic conditions

Evaluation of measures

Promising measures for enhancing soil carbon sequestration

Weiseke et al. (2007)

Measure	Sequestration potential per unit area [t CO_2-eq. ha^{-1} a^{-1}]	Emission reduction potential during first commitment period (EU15) [Mt CO_2-eq. a^{-1}]
Promotion of organic input	1-3	20
Permanent revegetation of set-aside (increased soil carbon; part of afforestation)	2-7	15
Biofuel production on set-aside (increased soil carbon)	2-7	15
Promotion of organic farming	>0-2	14
Promotion of permanently shallow water table on peatland	5-15	15
Zero and/or conservation tillage	>0-3	<9

Conversion factor CO_2 : C = 3.67

Evaluation of measures

Promising measures for enhancing soil carbon sequestration

Realistic C sequestration potential in EU-15 during first commitment period (Mt C y^{-1}) Freibauer et al. (2004)

Cropland management

- 5.5 — Promote organic inputs (crop residues, cover crops, FYM, compost, sewage sludge)
- 3.8 — Organic farming
- <2.5 — Conservation / zero tillage

Grassland management

- 4.1 — Maintain permanent shallow water table and rewett peat soils

Permanent vegetation cover on set-aside land

- 4.1 — Perennial grasses
- 4.1 — Woody bio-energy crops (afforestation, short rotation coppice plantations)

Total: 16-19 Mt C y^{-1}

Evaluation of measures

Potential pitfalls of carbon sequestration policies

Freibauer et al. (2004)
Weiske (2007)

Cropland management

More N inputs – more N_2O emissions

Organic farming

Poorer aeration – more N_2O emissions
(1.46 kg N ha y-1 – wives out 50-60% of C sequestration)

Grassland management

Reduced conditions – more CH_4 emissions

Permanent vegetation cover on set-aside land

More animals – more CH_4 emissions

Woody bio-energy crops
(afforestation, short rotation coppice plantations)

Return to previous management (quick loss of C)

Evaluation of measures

Dersch & Böhm (2001)

Effects of N fertilization on organic carbon stocks (t ha^{-1}) in topsoil (0–25 cm) after a period of 36 years at the experimental sites (27 replicates)

Sites⇒ Treatments ⇓	Alpenvorland	Waldviertel	Marchfeld
No N	59.3	37.7	49.3
Medium N	60.3	37.1	50.3
Optimal N	61.3	38.3	53.1*
Excessive N	60.1	38.0	50.4
LSD ($P<0.05$)	3.7	2.6	3.7

Evaluation of measures

Dersch & Böhm (2001)

Influence of increasing NPK-fertilization on crop yields (t ha^{-1}) of selected years at the experimental sites (3 replicates)

Sites ⇒	Waldviertel			Marchfeld			Alpenvorland		
Treatments⇒ ⇓	Barley	Rye	Oats	Maize	Wheat	Rye	Rape	Wheat	Rye
No NPK	2.56	2.90	4.68	5.62	1.46	1.59	0.85	2.74	2.18
Medium NPK	3.25	4.07	5.96	8.41	3.58	2.83	2.22	4.37	3.68
Optimal NPK	3.84	5.43	6.27	9.73	5.17	3.61	2.52	5.09	4.73
Excessive NPK	3.83	5.57	6.54	8.64	6.08	4.13	3.12	5.93	4.89
LSD ($P<0.05$)	1.21	1.21	1.01	1.27	0.98	0.80	0.71	0.61	0.45

Evaluation of measures

Dersch & Böhm (2001)

Effects of additional farm yard manure application (10 t ha^{-1} y^{-1}) combined with increased N fertilization on increase of SOC content (t ha^{-1}) and on absolute SOC level (t ha^{-1}) in topsoil (0–25 cm) after a period of 21 years

Sites⇒	Alpenvorland		Waldviertel	
Treatments⇒ ⇓	Increase due to FYM	SOC-level absolute	Increase due to FYM	SOC-level absolute
No N	+3.7	63.0	+ 8.0	45.7
Medium N	+3.4	65.1	+ 8.1	45.2
Optimal N	+3.3	64.6	+ 7.7	46.0
Excessive N	+3.1	63.2	+ 7.8	45.8
LSD (P<0,05)	3.7		2.6	

Evaluation of measures

Dersch & Böhm (2001)

Influence of additional FYM-application (10 t ha^{-1} y^{-1}) combined with increased NPK fertilization on yield increase (t ha^{-1}) (3 replicates).

Sites⇒	Waldviertel			Alpenvorland		
Treatments⇒ ⇓	Barley	Rye	Oats	Rape	Wheat	Rye
No NPK	+ 0.29	+ 0.66	+ 0.93	+ 0.69	+ 0.60	+ 0.58
Medium NPK	+ 0.46	+ 0.30	+ 0.45	+ 0.11	+ 0.31	+ 0.32
Optimal NPK	+ 0.23	+ 0.32	+ 0.30	+ 0.29	+ 0.32	+ 0.16
Excessive NPK	+ 0.36	+ 0.06	+ 0.03	+ 0.14	+ 0.26	+ 0.14
LSD ($P<0.05$)	*1.21*	*1.21*	*1.01*	*0.71*	*0.61*	*0.45*

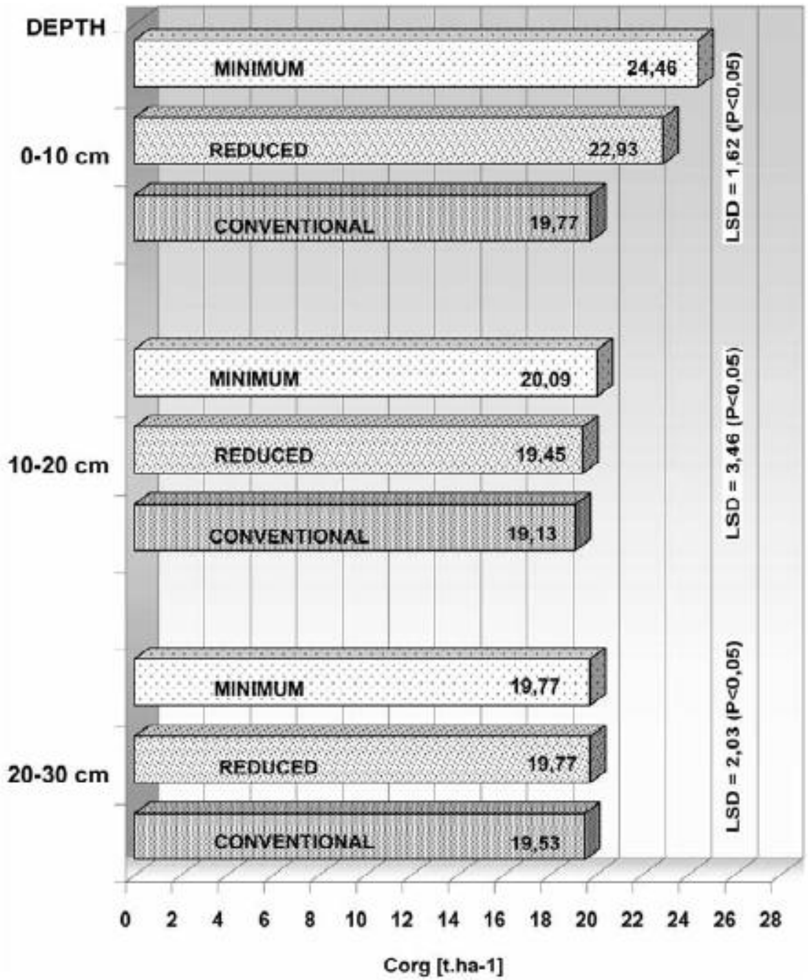
Evaluation of measures

Dersch & Böhm (2001)

Effect of incorporation or removal of crop residues on SOC stock (t ha^{-1}) after a period of 17 years (16 replicates).

Treatments ⇓ Sites⇒	Marchfeld	Waldviertel
Removal of crop residues	58.0	34.1
Incorporation of crop residues	63.2	37.5
LSD (P<0,05)	*2.9*	*4.1*

Evaluation of measures



Dersch & Böhm (2001)

Effects of different tillage treatment on SOC-stock (t ha^{-1}) in topsoil layers at Marchfeld after a period of 10 years (3 replicates).

Evaluation of measures

Freibauer et al. (2004)
Weiske (2007)

- Implementing carbon sequestration in agricultural policy
  - Stability of agricultural policy / incentives for long periods (>20 years)
  - Permanency of measures (otherwise quick release of CO_2 and N_2O)
  - Efficiency of carbon sequestration depends on soil (texture, initial C level) and climatic conditions (e.g., almost no C sequestration in sandy soils after 100 y)
  - Attention must be paid to unwanted environmental side effects such as the potential of enhanced N_2O or CH_4 emissions (net accounting required)
  - Measures should consider existing practices and incentive systems (e.g. CAP, ÖPUL) and build on them rather than take independent approaches
  - High uncertainties of potential C sequestration estimates
  - "Saturation" of carbon pools limits efficient sequestration to about 20 years
  - No tools to measure and monitor stock changes at short time scales (e.g. first commitment period of Kyoto protocol)

Evaluation of measures

Weiske (2007)
Schils et al. (2008)
Dersch & Böhm (2001)

- Implementing carbon sequestration in agricultural policy
  - Current CAP and ÖPUL likely help to maintain carbon pools
  - Legislation and incentives to promote production of feed stocks for bio-energy in arable systems are the most likely to counteract carbon sequestration and other soil protection (e.g. erosion) policies
  - It may be worth to check those measures of ÖPUL that are likely to support carbon sequestration policy in term of acceptance and actual implementation by farmers and to put efforts into increased participation in these measures
    - Information / education
    - Direct the measures to situations where they are most effective
    - Increase incentives for specific, effective, yet only little implemented measures (maybe compensate costs by reducing other incentives)
  - Measures already widely practiced (e.g. manure application, incorporation of crop residues) have little potential to further enhance carbon sequestration