Soil carbon sequestration for climate change adaptation and mitigation

Keynote 10 Dec 2025

Thomas Kätterer

Swedish University of Agricultural Sciences

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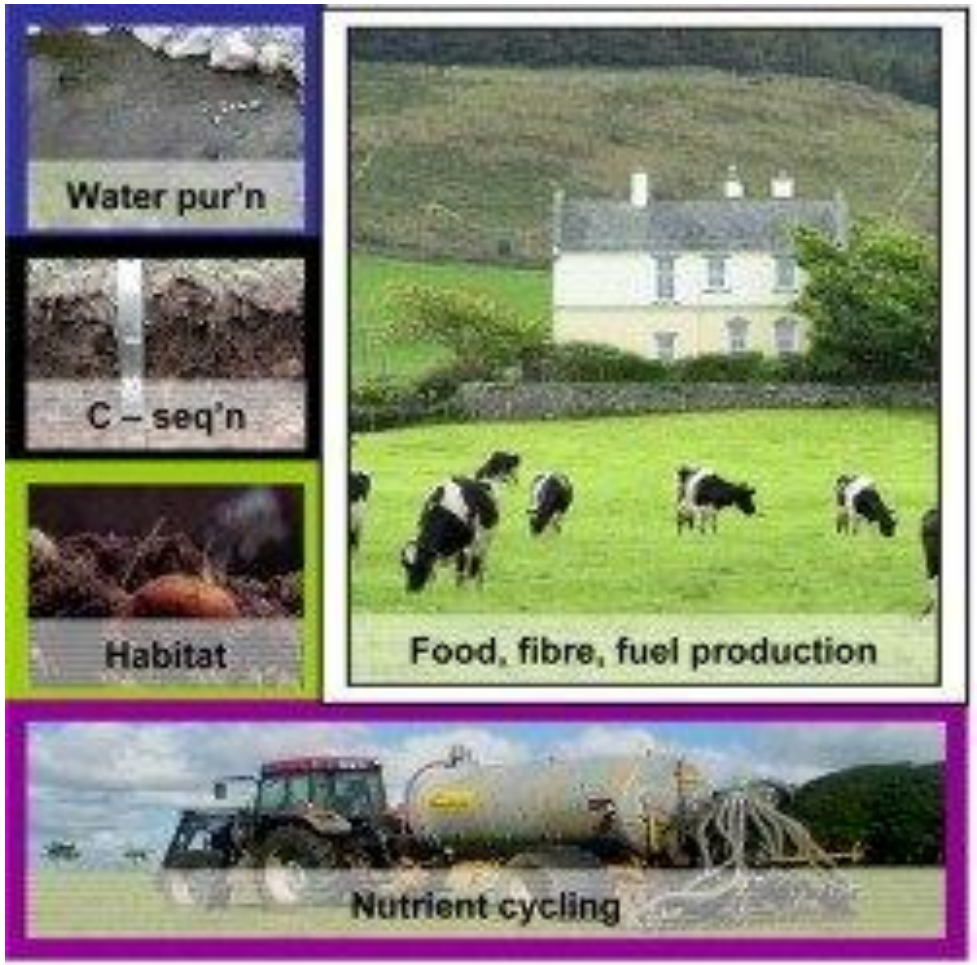
Soil organic matter/carbon content relates to all **soil functions**

that link directly to policy frameworks and concepts, such as **Ecosystem Services and Sustainable Development Goals** (zero hunger, good health, clean water, climate, life on land)

Source: FAO



Schulte et al., 2014, LANMARK project

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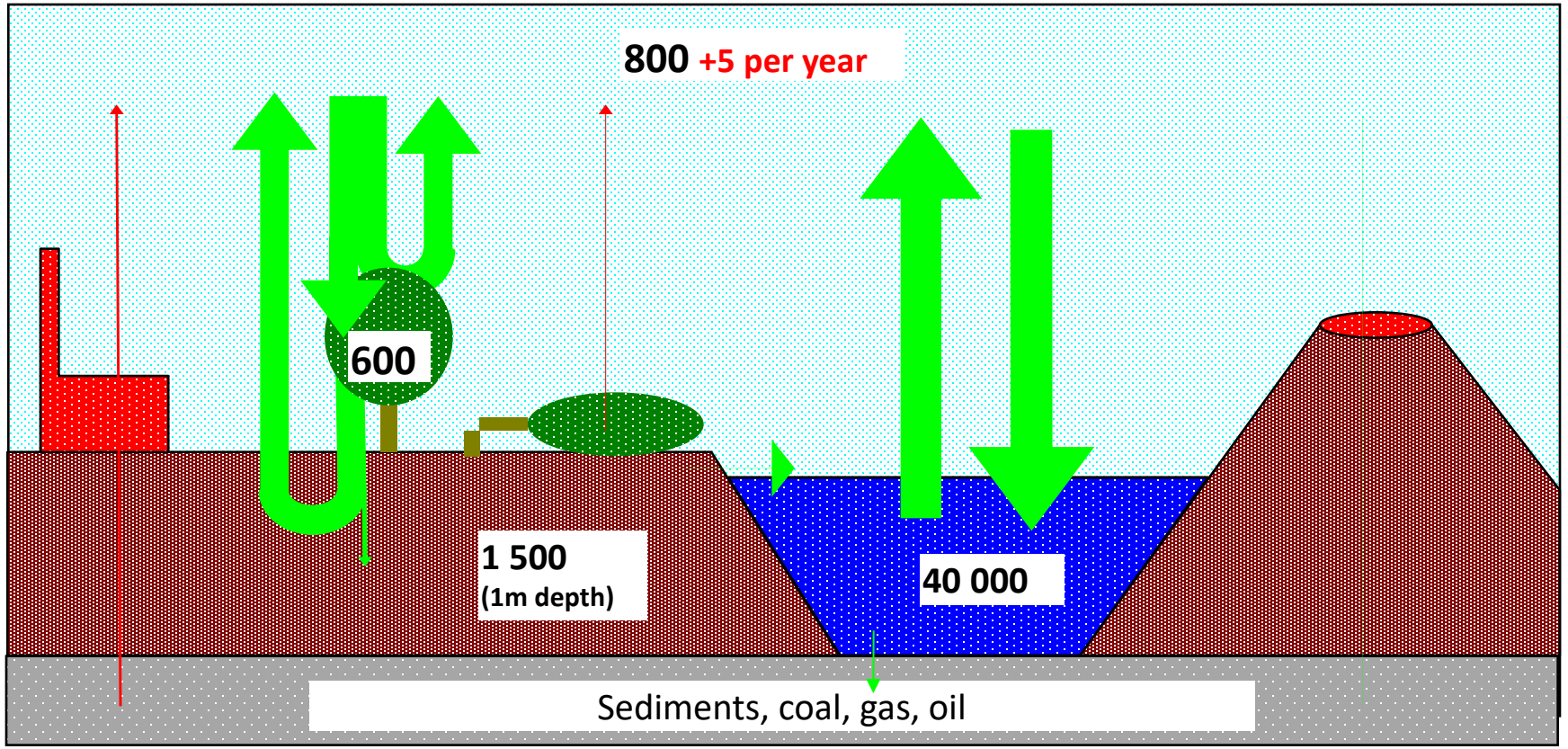
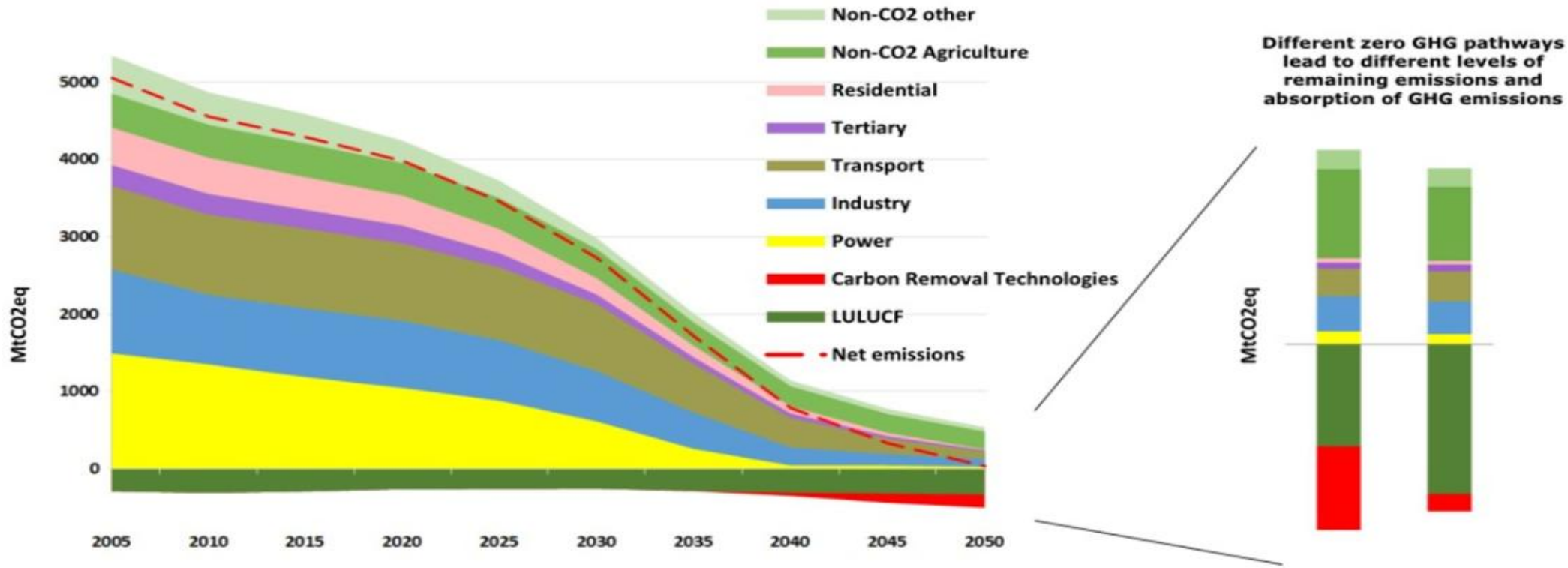
Soils play a major role in the global C cycle

(units in Pg C; Billion tons)



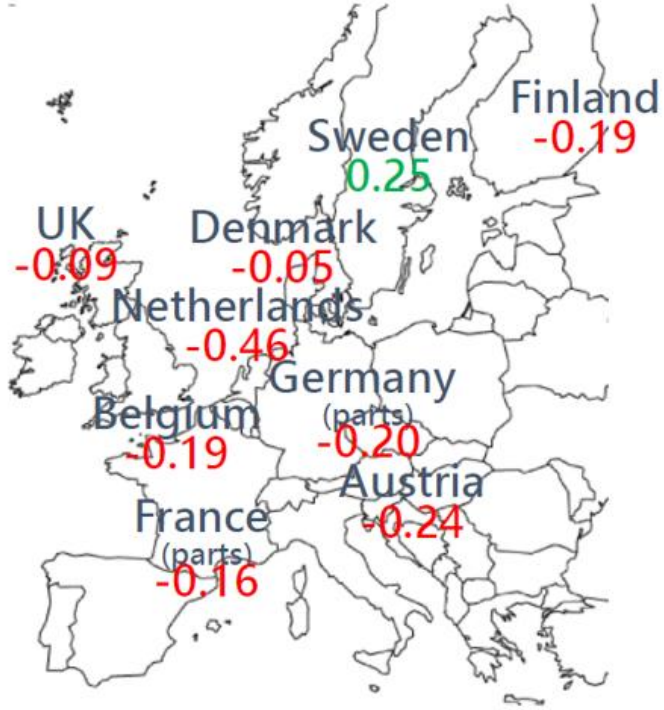
Vision for a Clean Planet by 2050

Several pathways for a climate neutral Europe, challenging but feasible from technological, economic, environmental and social perspectives



In Europe, we have to focus on C loss mitigation rather than SOC sequestration

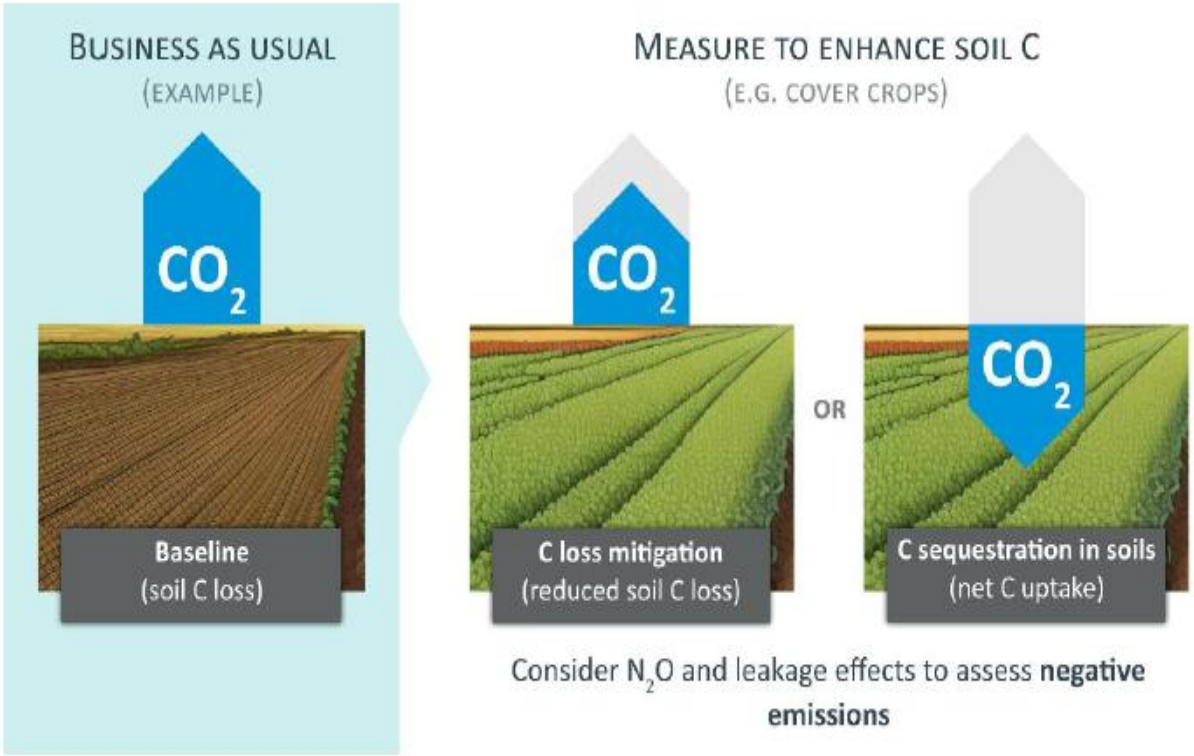
Recent soil carbon stock changes in croplands



In t C/ha/yr and based on repeated soil inventories

Sources: Heikkinen et al. 2013, Poeplau et al. 2015, Taghizadeh-Toosi et al. 2014, Lettens et al. 2005, Knotters et al. 2022, Dersch and Böhm 1997, Höper 2021, Antoni et al., 2008

Slide from Axel Don



Don et al., 2024 Global Change Biology

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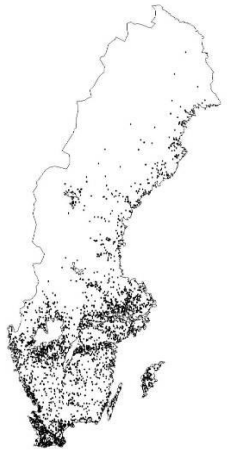
Increasing soil carbon content in Swedish mineral soils

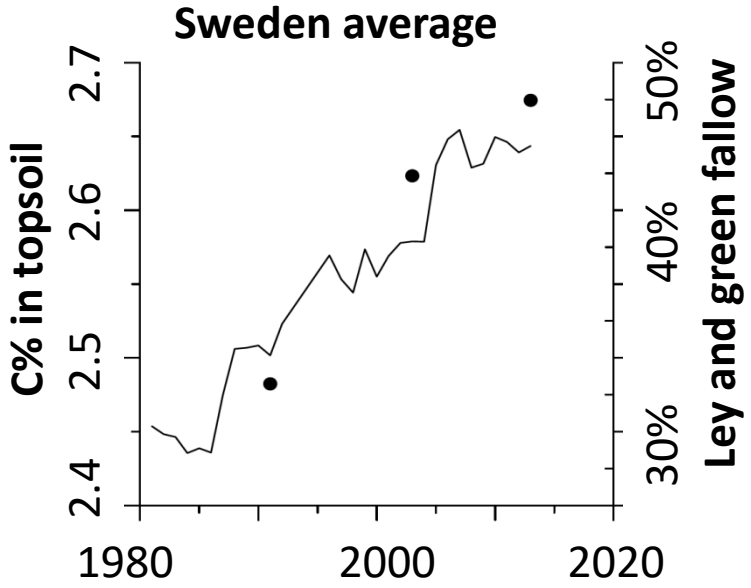


Soil inventories
I (1988-97),
II (2001-07),
III (2011-17)
IV (2021-27) ongoing

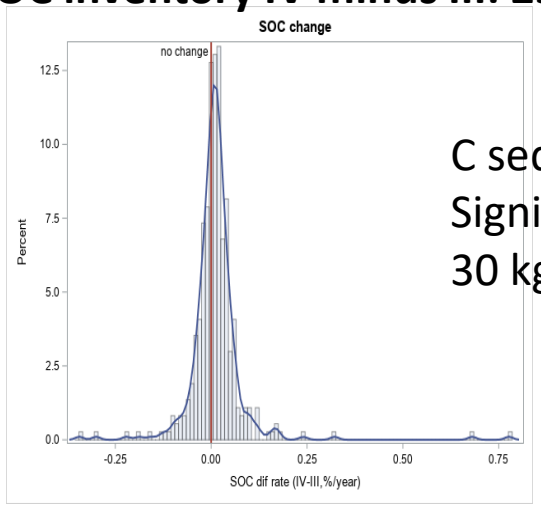
Reasons for SOC increase

- More ley (grass/clover forage)
- More winter-crops, less spring crops

Losses of SOC from organic soils are higher than sequestration in mineral soils



SOC inventory IV minus III: 25% completed



C sequestration continues.
Significant increase,
30 kg C ha^{-1} $year^{-1}$ on average

Poeplau et al. 2015 Biogeosciences 12: 3241–3251
Lang et al. 2025 Eurosoil

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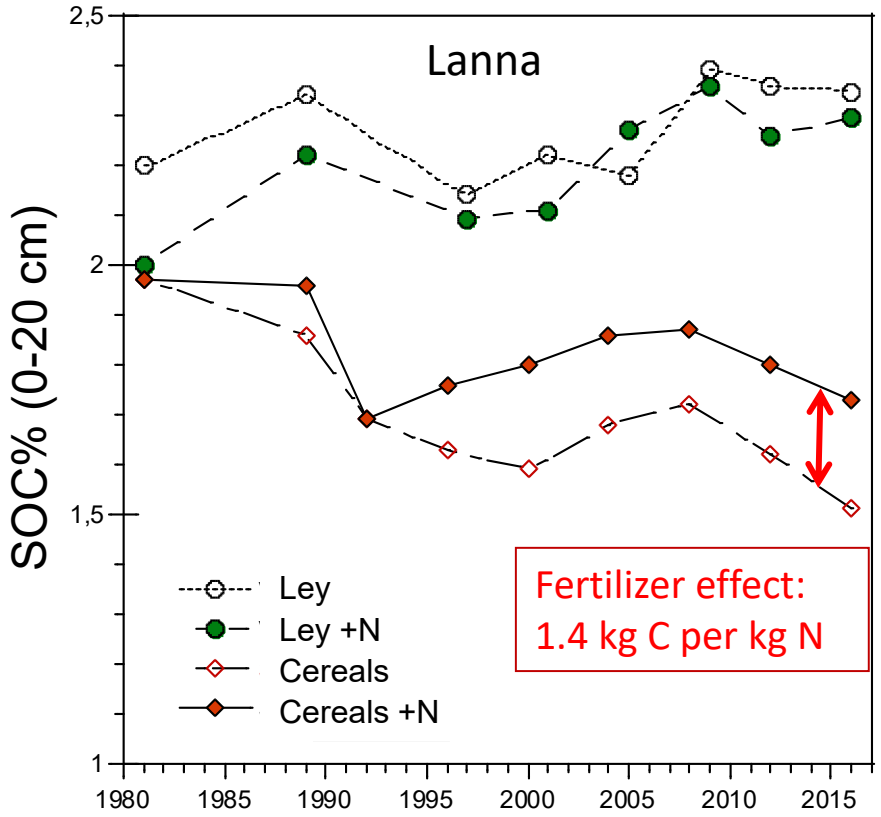
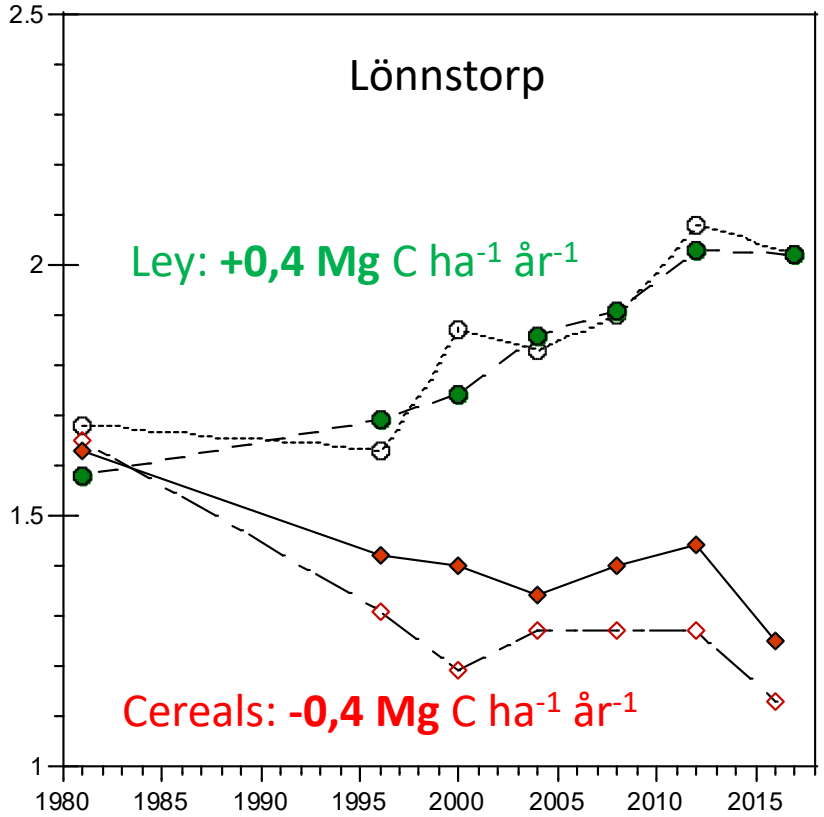
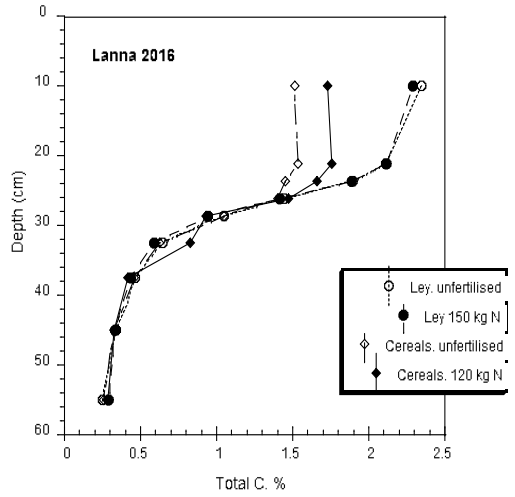
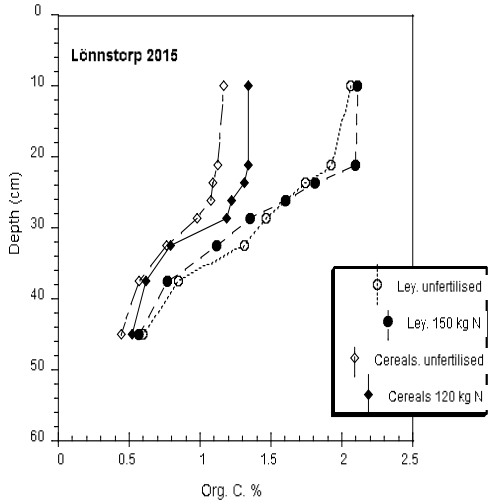
SOC increases in ley-dominated rotations (spring barley, 3 years ley) and decreases in cereal monocultures

2 Swedish sites since 1981









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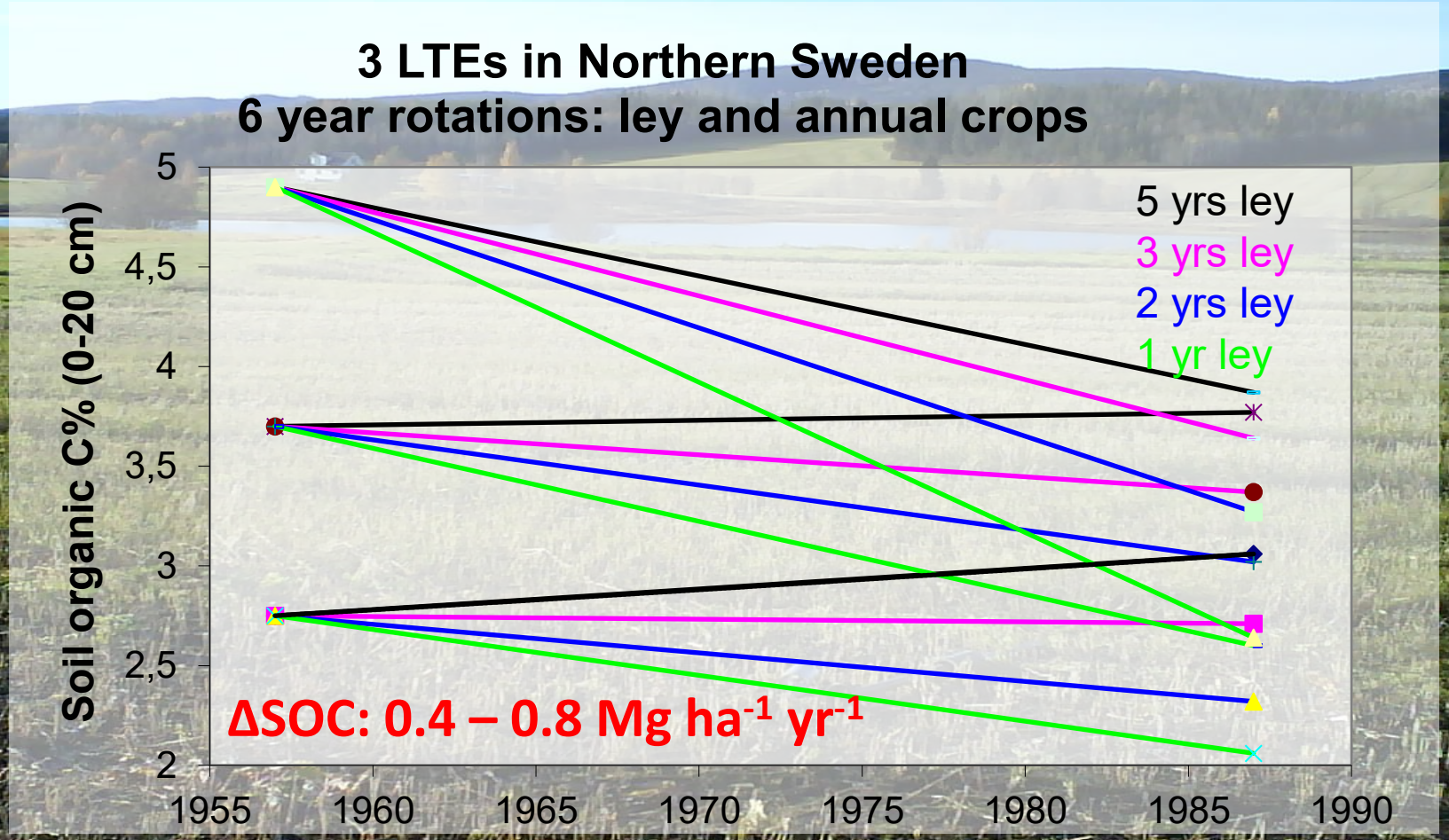
Börjesson et al. 2018 Biol Fert Soils

Frequency of perennial leys vs. annual crops affecting SOC

(Bolinder et al. 2010, AGEE 38: 335–342; Bolinder et al., 2012, Can J. Soil Sci. 92: 821-833)



Absolute changes in SOC are governed by field history

Perennial vs. annual plants

Kernza (wheatgrass)

Wheat

Photo by Jim Richardson, Land Institute, Salina, Kansas

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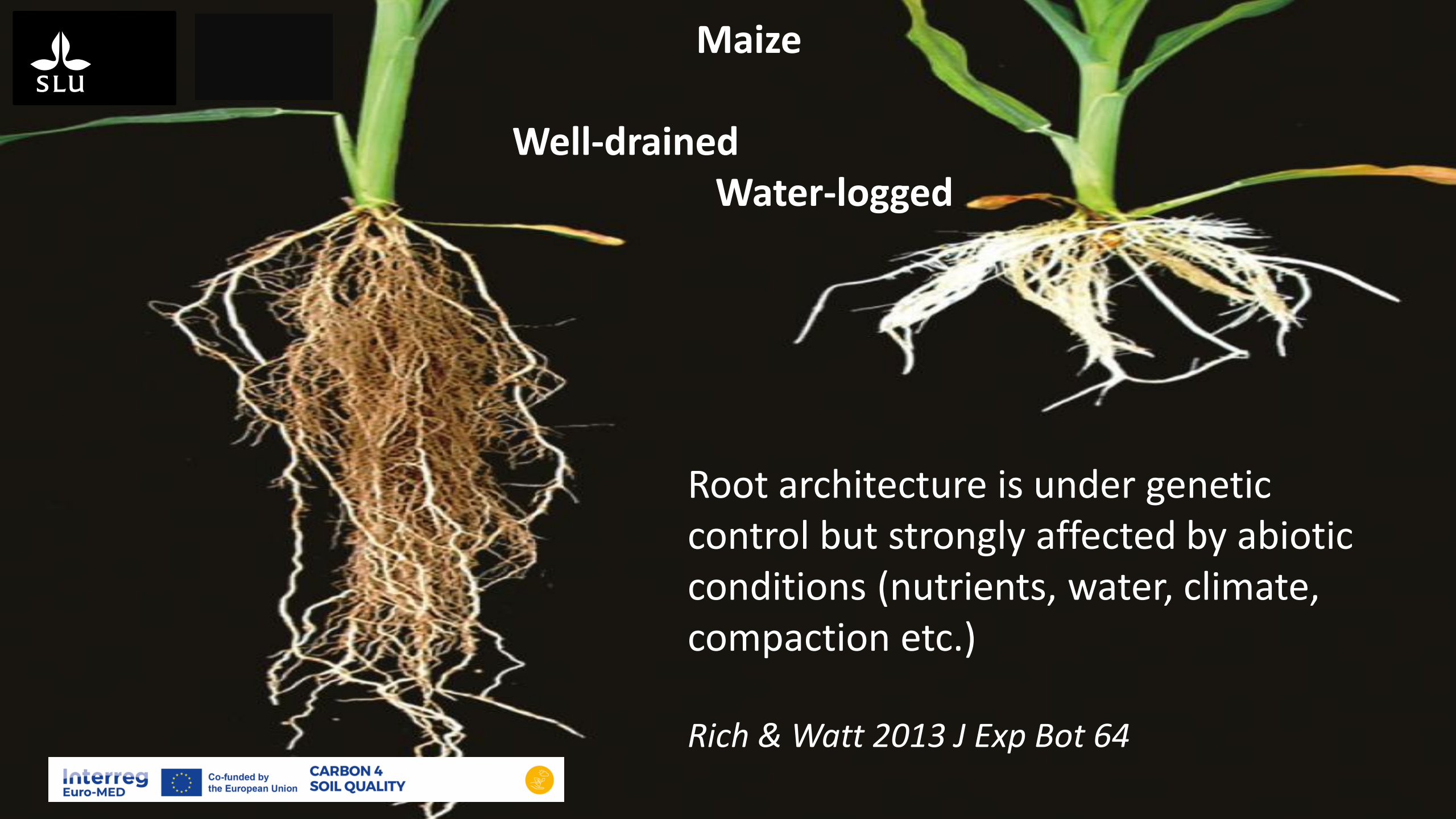

Root architecture is under genetic control but strongly affected by abiotic conditions (nutrients, water, climate, compaction etc.)

Rich & Watt 2013 J Exp Bot 64

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Plant breeding for phenotypes with improved root traits

Cajsa Lithell, SLU_220615_0001_cll

- More efficient crops, tolerant to stress
- Perennial crops
- Site-adapted cover crops
- Deeper roots
- Modified rhizodeposition favoring mycorrhiza och other beneficial organisms, decreasing N2O and CH4 emission
- Etc.

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Avoid bare soil!

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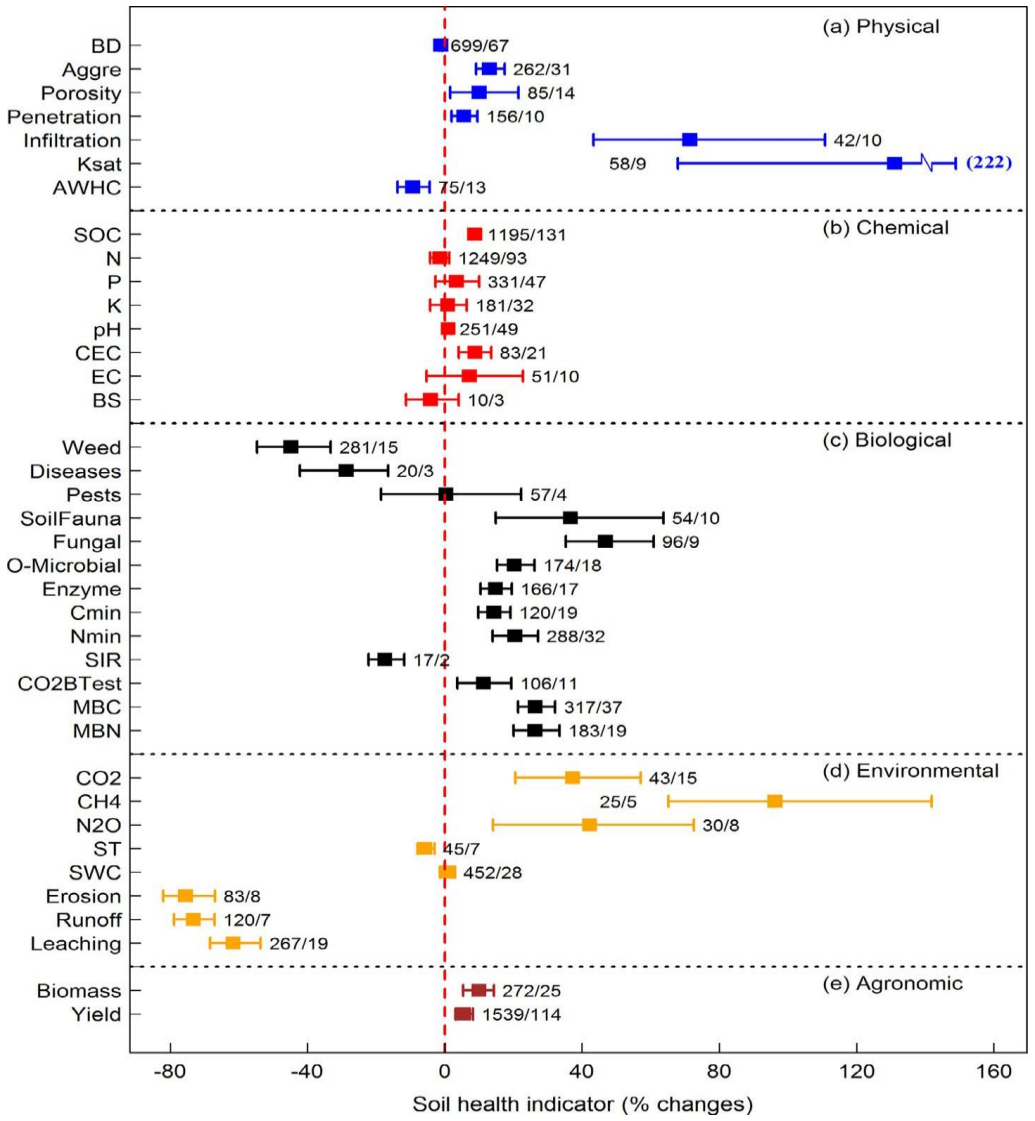
Cover crops affecting soil health and productivity

Meta-analysis including 281 studies (mostly from Nordamerika)



- Improved soil structure and infiltration
- SOC accrual (0.56 Mg C ha-1 yr-1; 543 studies *Jian et al. 2020 SBB 143,107735*
- Less weeds
- Less pests
- More soil animals and higher biological activity
- Higher emissions of N2O and CH4
- Less erosion
- Less surface runoff
- Less leaching
- Higher yields of main crops

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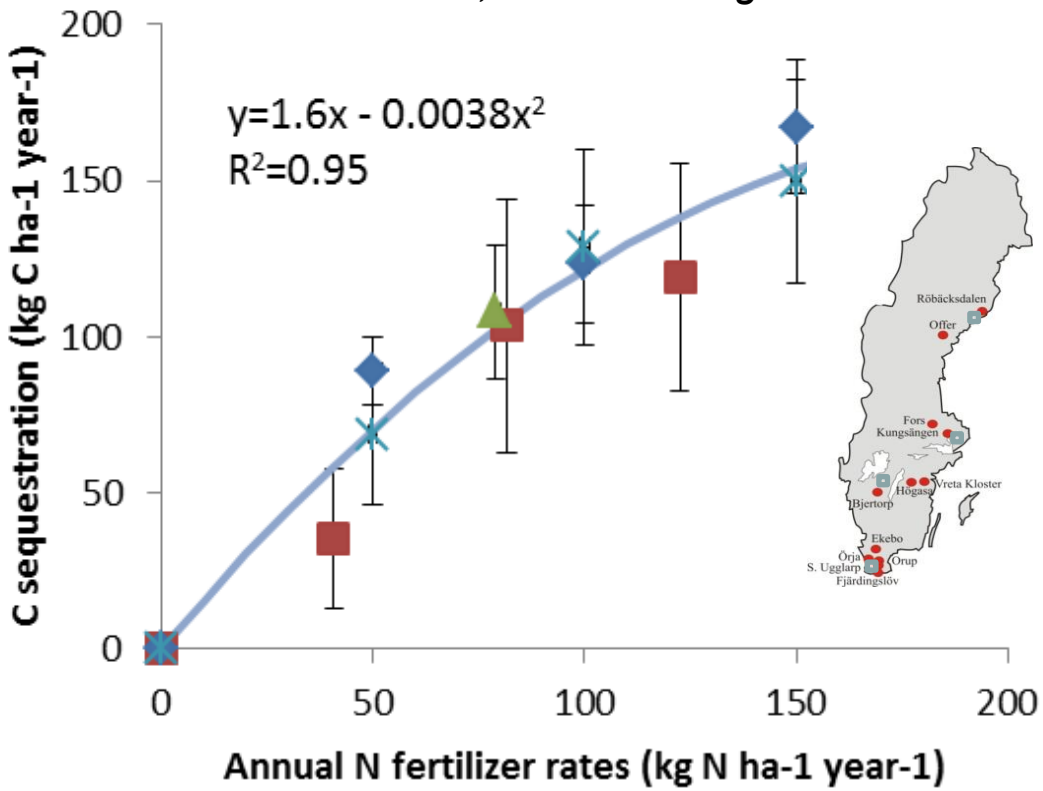
J. Jian, X. Du and R.D. Stewart / Data in Brief 29 (2020) 105376

N fertilization increases C stocks

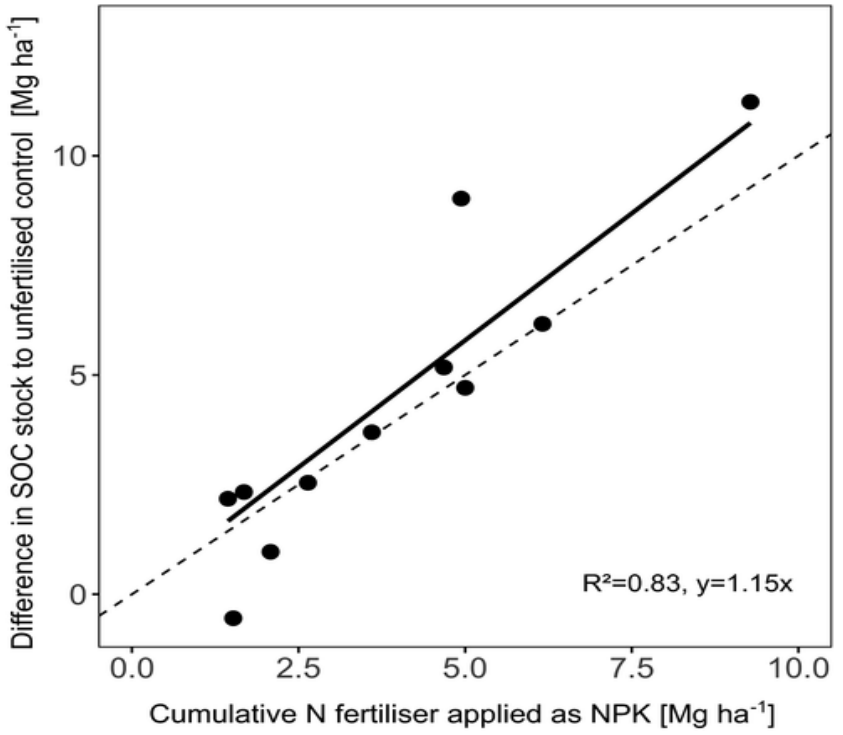
Results from 16 experiments with annual crops

Kätterer et al., 2012 Acta Agric. Scand.



European grasslands

Poeplau 2021 Grass and Forage Science 76, 186-195



Rule of thumb: Each kilo N applied increases SOC stock by about 1 kg in both annual and perennial systems

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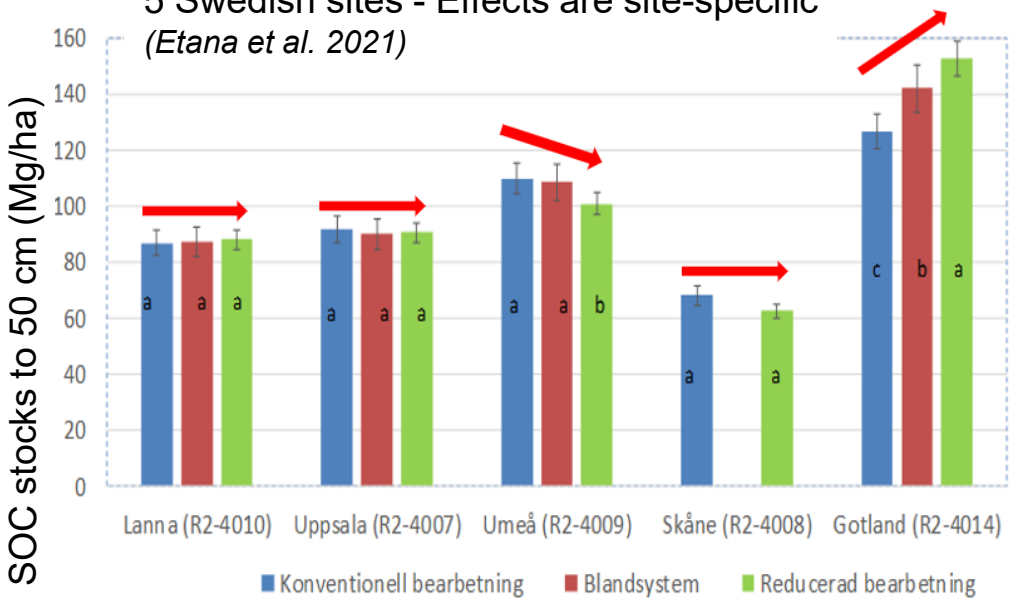
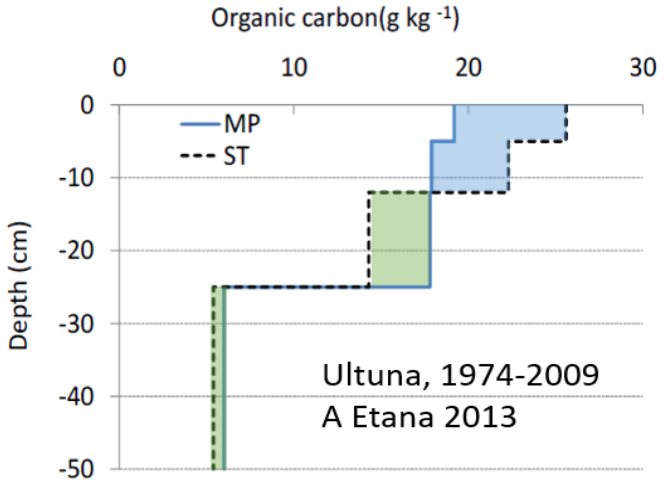
Tillage effects on SOC

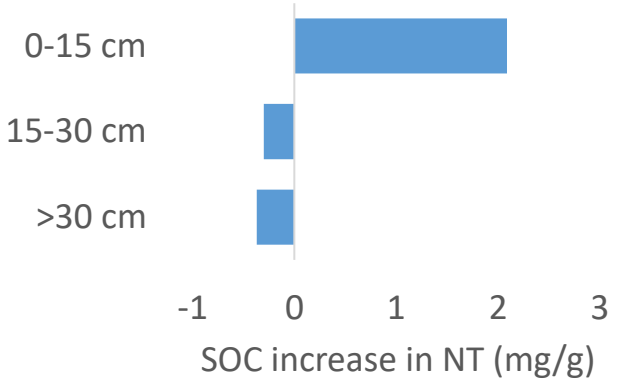
5 Swedish sites - Effects are site-specific
(Etana et al. 2021)



Typical pattern – redistribution of SOC



Meta-analyses including 351 LTEs
Haddaway et al. 2017 Environ. Evid. 30



Reduced tillage leads to

- Higher albedo (0.1 Mg CO2 ha^{-1} yr^{-1}; Desmet et al. 2025)
- Less soil erosion
- Less energy use (diesel)
- Less working hours

Net effects on SOC stocks are smaller (when accounting for changes in bulk density, 101 LTEs)
Meurer et al 2018. Earth Sci Rev 177

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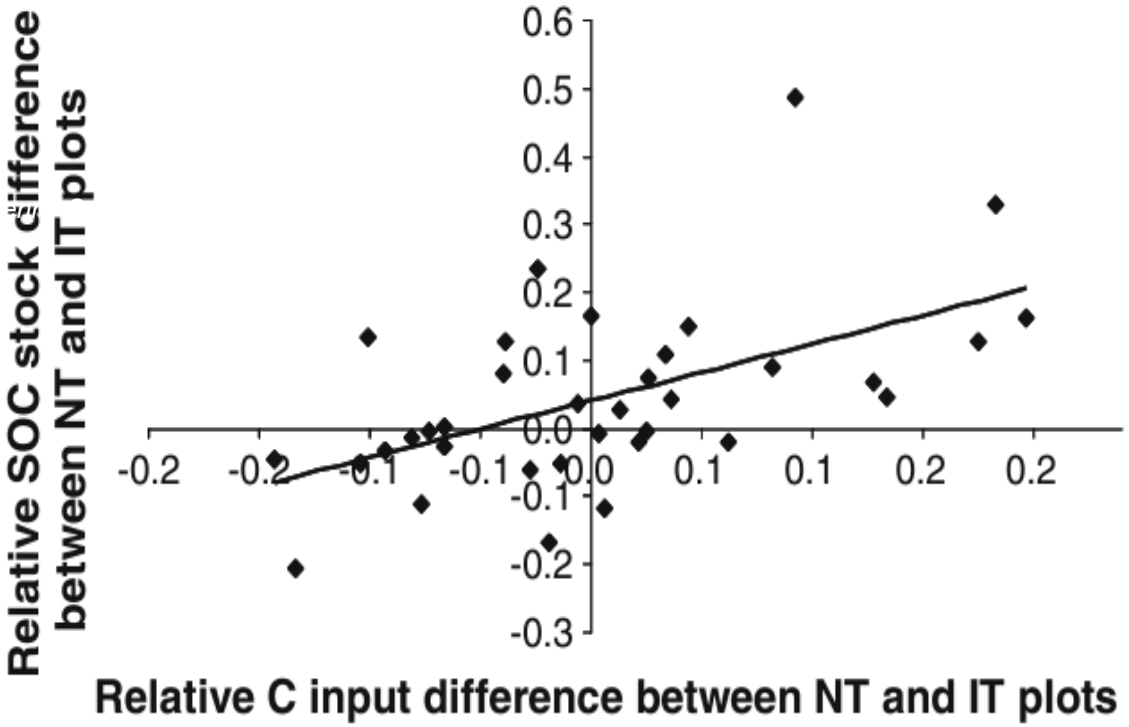
Tillage effects on SOC depend on their impact on crop productivity

Effects are greater under drier than under humid conditions

Anger 2025 Soil Sci Plant Nutr

Positive correlation between SOC and crop yield responses to no-till



IT=inversion tillage (plöjning)
NT=no till (plöjningsfri)

Virto et al. 2012 Biogeochemistry 108:17–26

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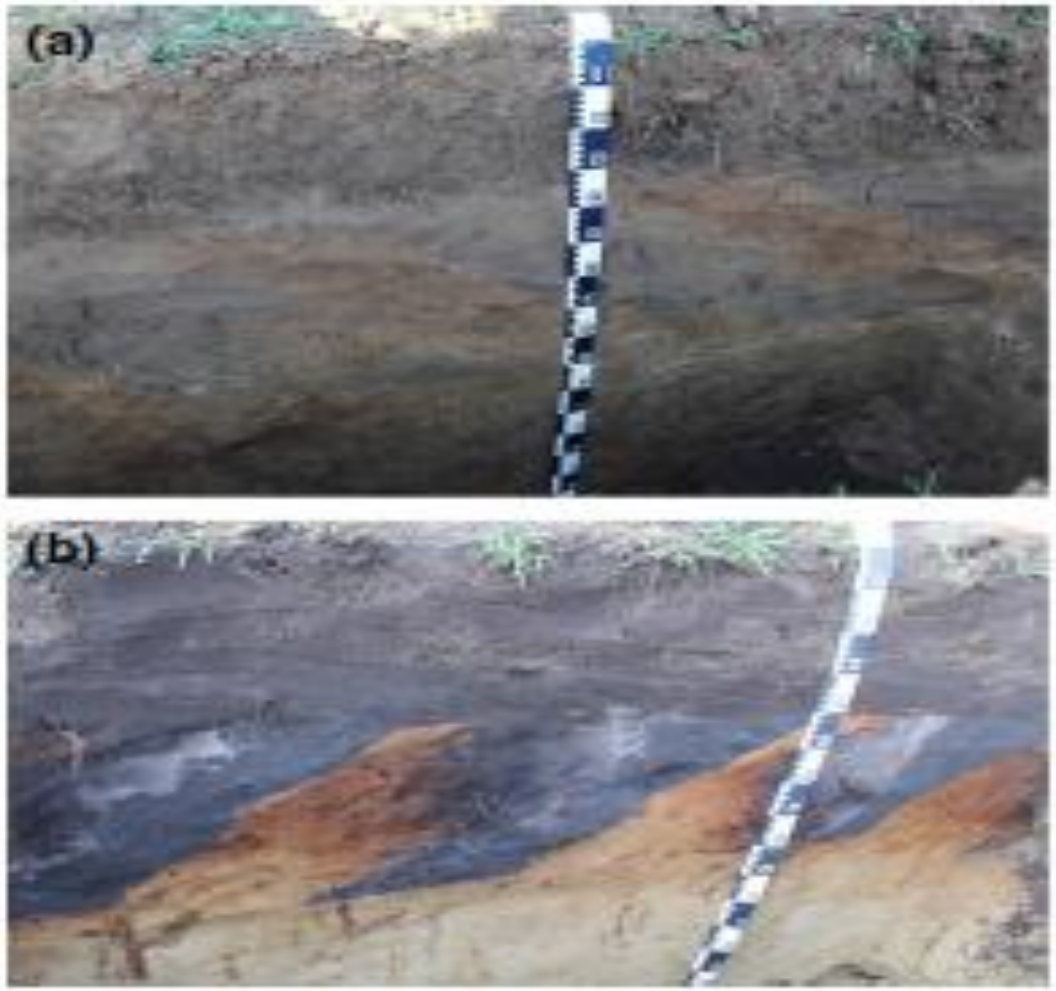
Deep ploughing to 1 meter at 10 sites in Germany



15% lower SOC in topsoil, but
42% increases in the whole soil profile after 45 years

Alcantara et al., GCB 2016

Similar results from Nya Zealand (*Schiedung et al., GCB 2019*)
No effect in a Finnish trial (*Hyväluoma et al., Soil Till Res 2025*)

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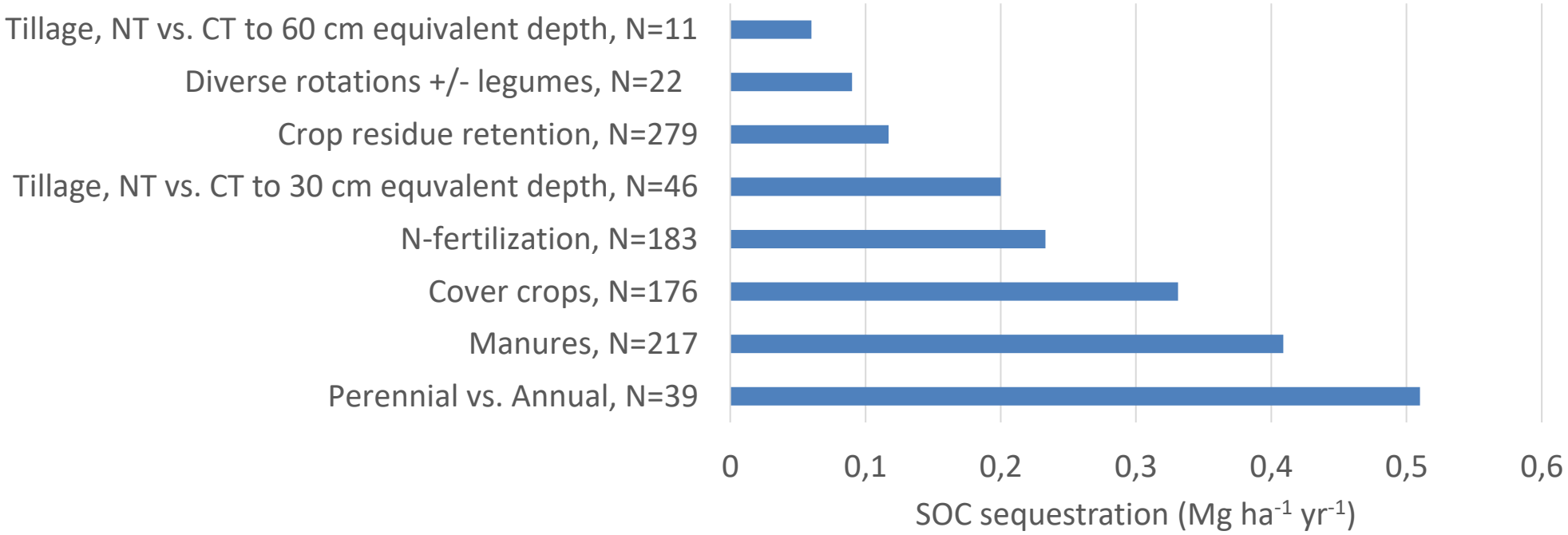
C sequestration practices – synthesis of literature



OBS! Huge variation between individual studies

More research is needed to identify site-specific drivers

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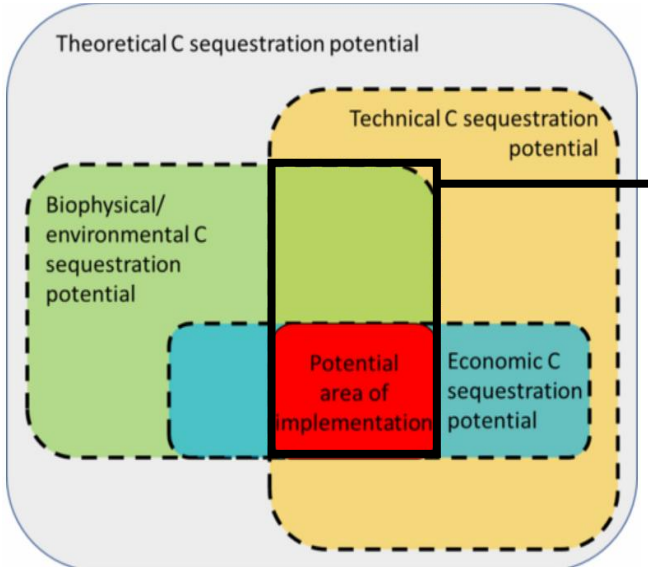
Kätterer and Bolinder, 2022, Burleigh Dodds Science Publishing

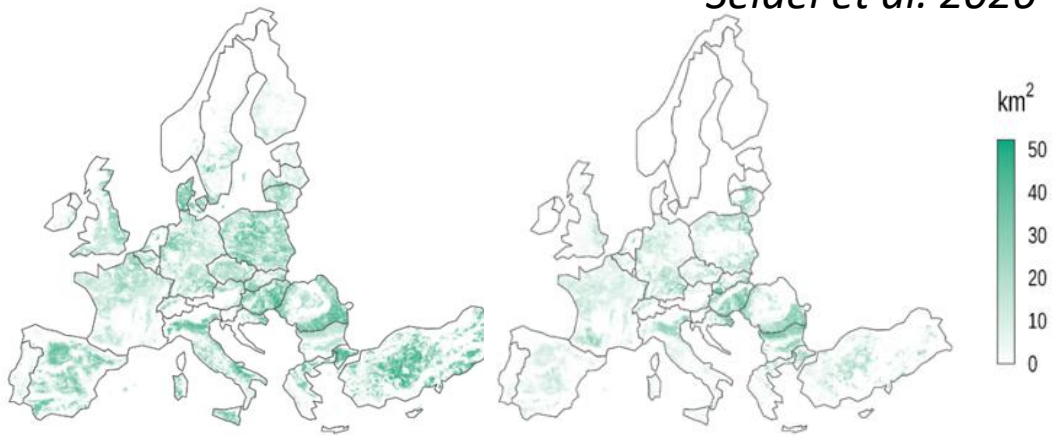
The potential of C sequestration in Europe



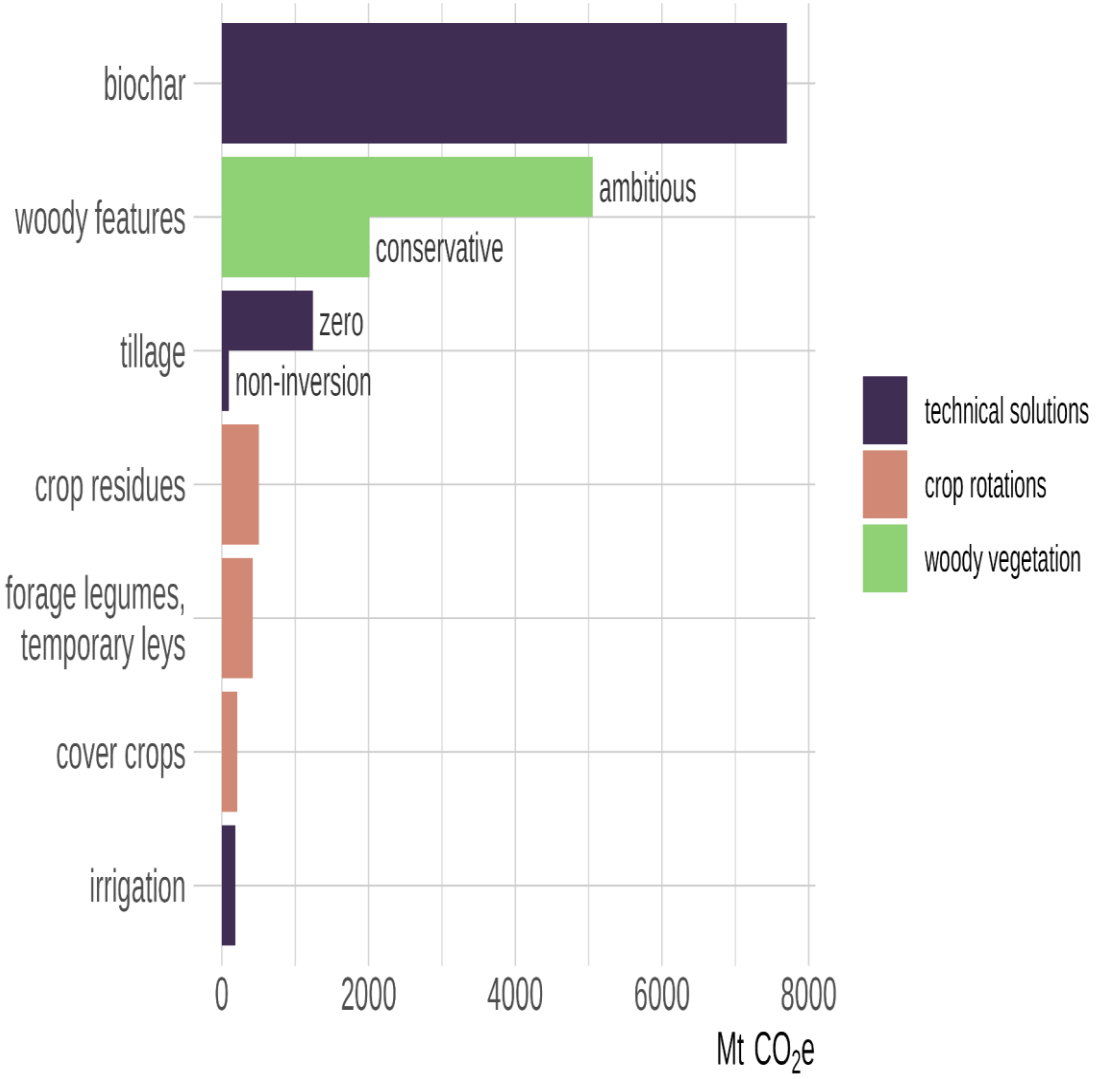
145-229 Mt CO_2e a^{-1}, i.e., 21-33% of current EU agricultural GHG emissions (sector agriculture and LULUCF)

Only a fraction is economically feasible with current CO2 pricing

Seidel et al. 2026



(a) Non-inversion tillag (f) Cover crops



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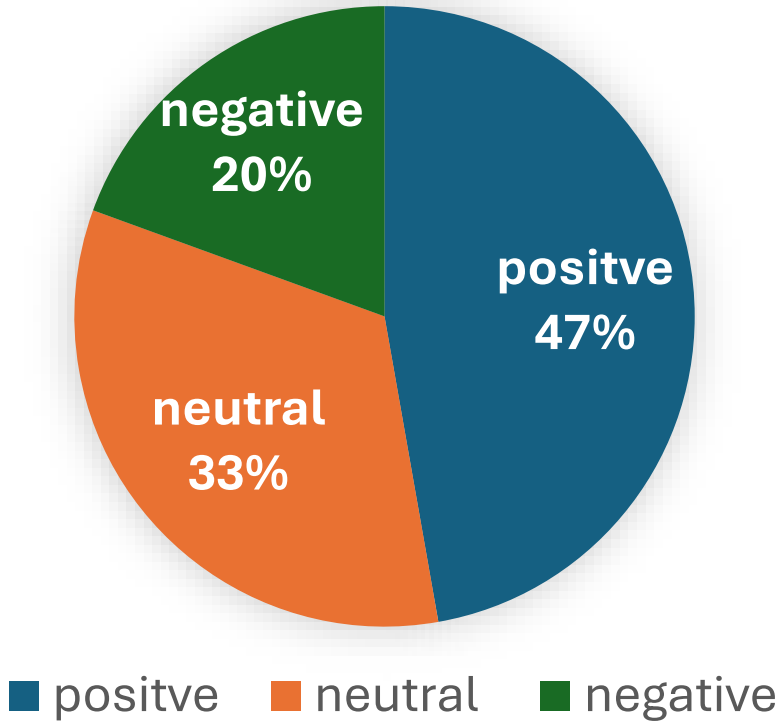
Does soil organic carbon (SOC) accrual boost crop yield?

Scientific evidence is not clear

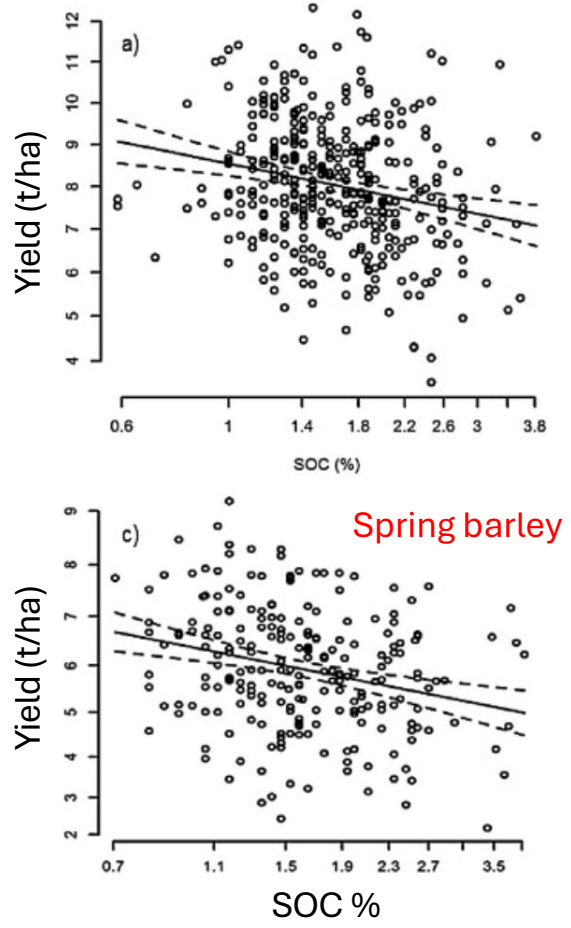
Moinet et al. 2023 GCB
36 meta-analyses from four continents

- Mechanisms are complex
- Responses are context-specific
- Spatial variability is a major limitation
- Confounding factors



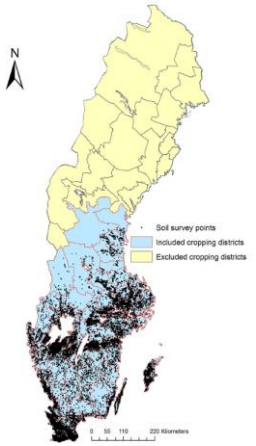
Negative correlation between crop yield and SOC at national scales

Danish fertilization trials

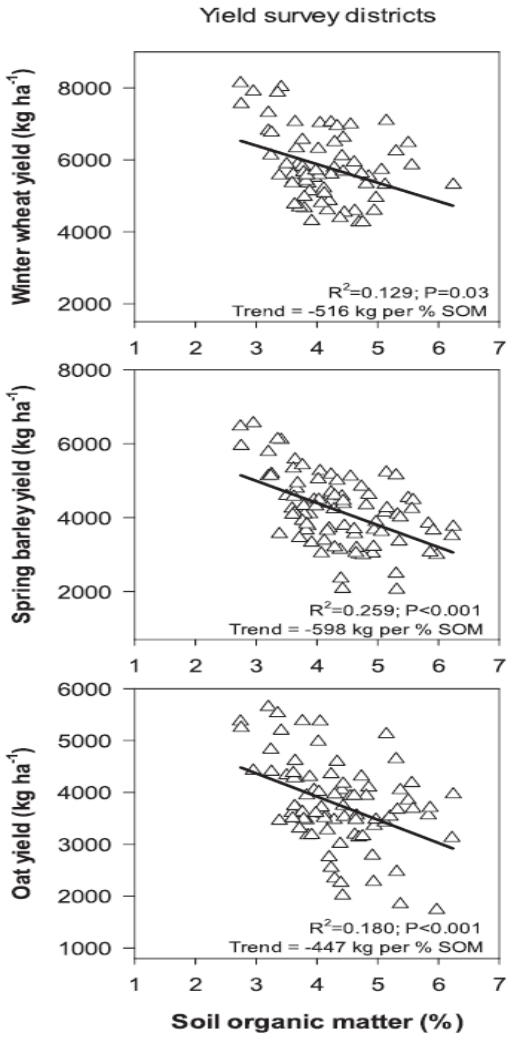


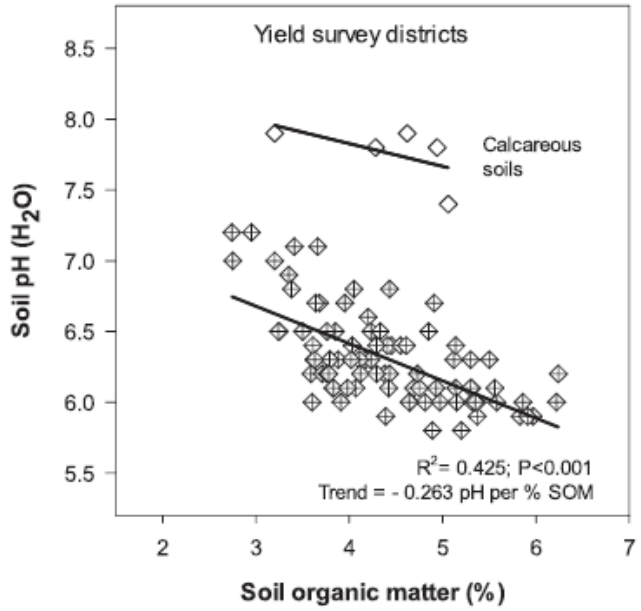
Oelofse et al. 2015 Europ J Agron 66, 62-73

Sweden: Yields in 90 districts vs. SOC (2000-2015 National statistics)



Soil inventory
11,419 samples





The negative correlations between yield and SOC were not causative, but due to confounding factors (pH, farm type, legacy effects etc.).

Kirchmann et al. 2020 Europ J Agron 120, 126132

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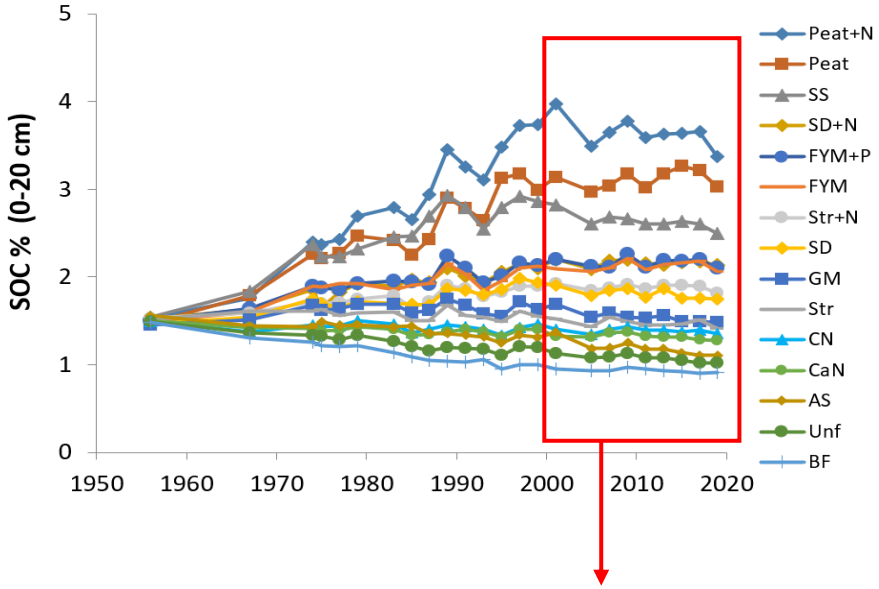
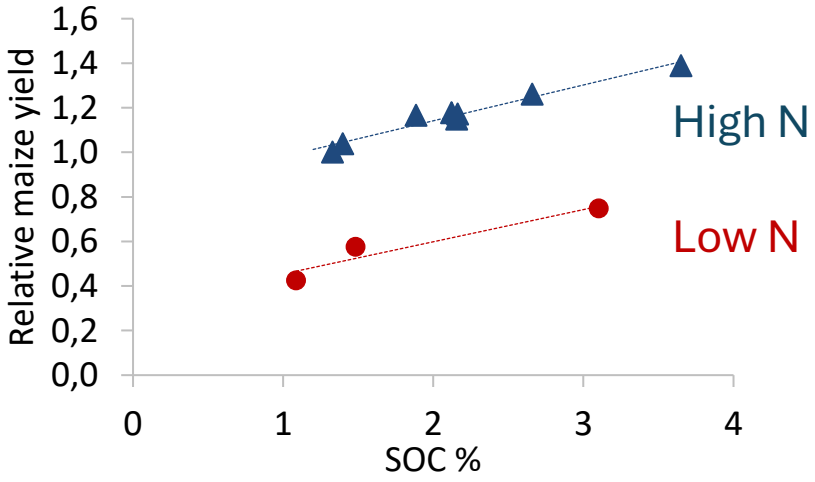
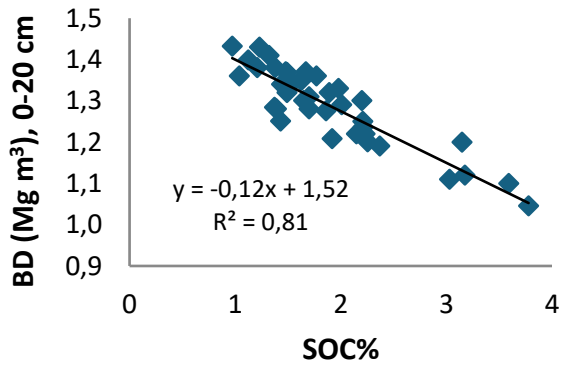
Crop yields increase with SOC in the Ultuna long-term trial - since 1956



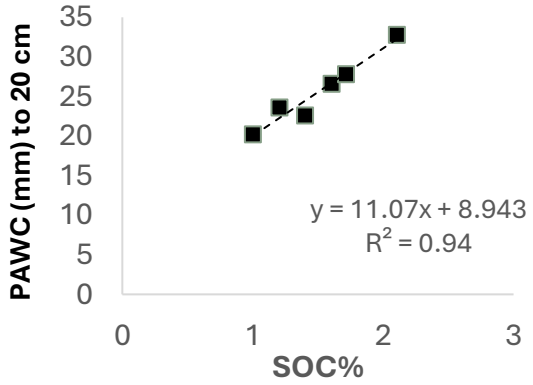
- Maize yields (2000-2019) increased with SOC
- 95% of the variation in crop yield could be explained by nitrogen availability, pH and bulk density
- Two-thirds of the effect was explained by improved soil physical properties affecting water availability



Soil dry bulk density



Plant available water capacity



Kätterer & Bolinder 2024 Eur J Soil Sci. 75:e13482

Carbon Farming

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Carbon Farming: Harnessing Agricultural Practices for Carbon...

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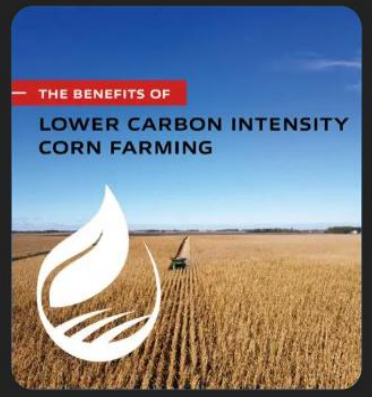
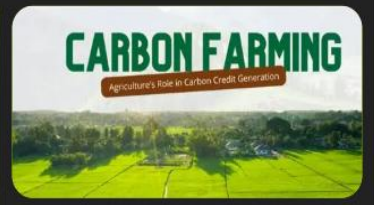


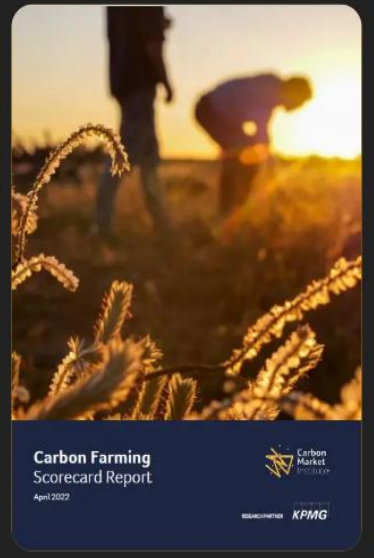
The Benefits of Lower Carbon Intensity (CI) Corn Farming |...

Farming and the carbon economy - Irrigation Today



Carbon Farming - Vajirao IAS

Carbon Farming · UPSCprep.com



Reports - Carbon Market Institute

Carbon Farming: Agriculture's Role in Carbon Credits

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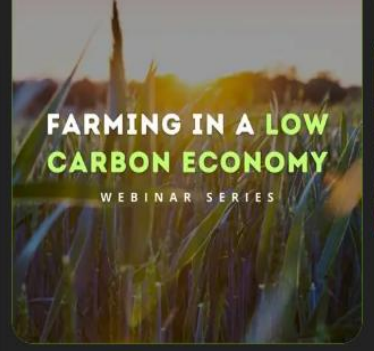
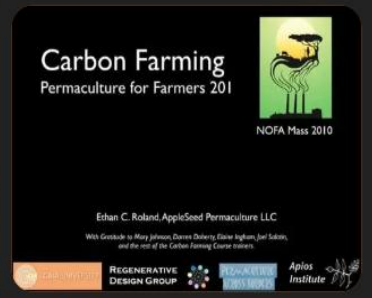


New series of webinars coming: Farming in a low carbon econom...

Flonja Drenofci on LinkedIn: #psggcoalition4soilhealth...

Understanding Carbon Farming - YouTube



Carbon Farming: Concepts, Tools & Markets | PDF | Agriculture |

Voluntary carbon market programmes

Carbon farming programme	Reduced till	Cover crops	Nutrient management	Crop rotation	Grazing management	Agroforestry and hedges	Incorporation of compost and plant residues	Reduced fuel use
Bayer Carbon Program								
Agoro carbon alliance								
RegenConnect (Cargill)								
Corteva's Carbon Initiative								
Nutrien's Carbon Program								
CarbonNOW (LocusAg)								
Truterra								
SWOF								
ESMC								
Carbon by Indigo								
AgreenaCarbon								
Farmers edge								
CIBO								
ORMEX								
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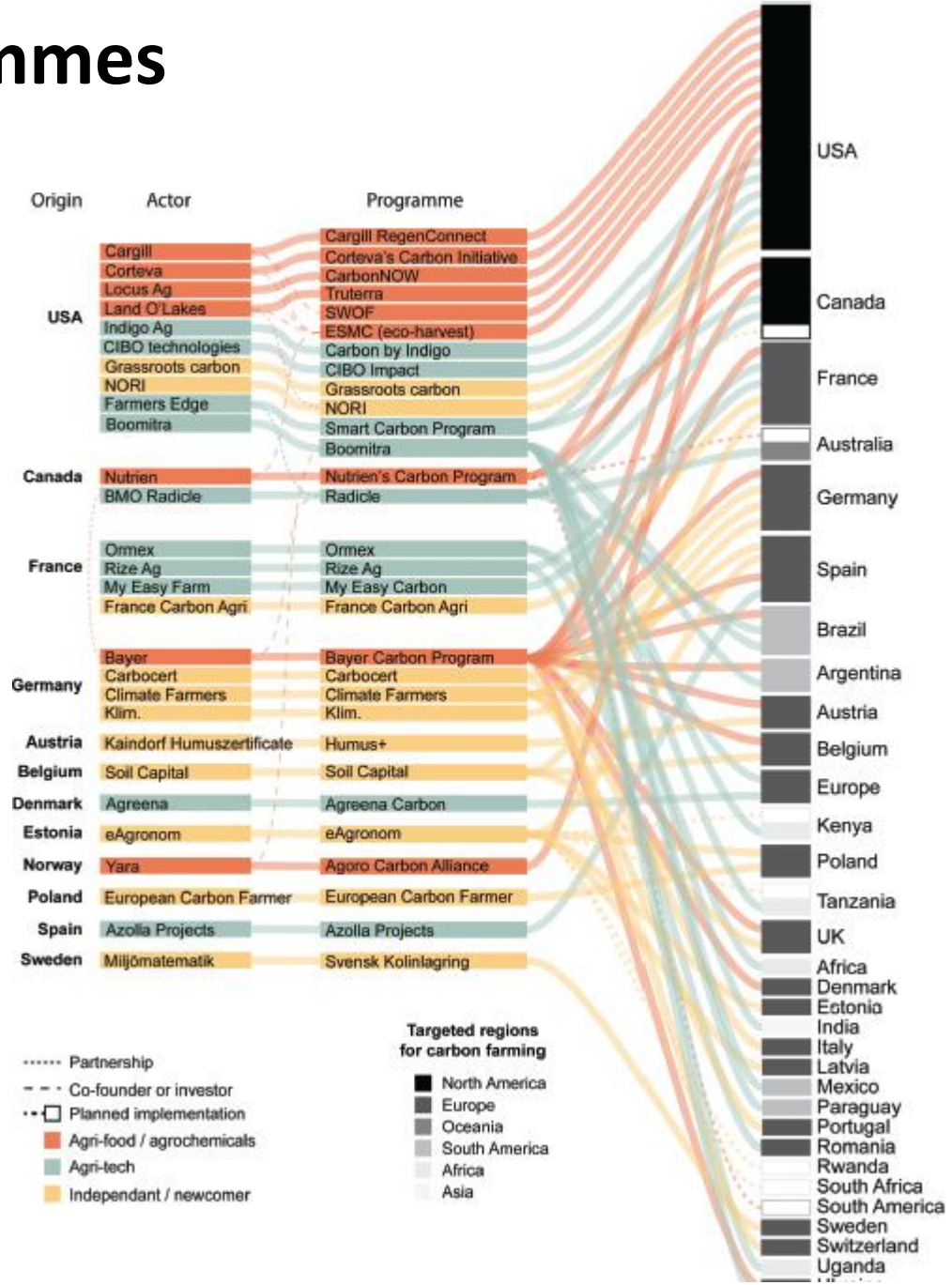
Soil Capital								
Carbocert								
Humus+								



Johansson et al., 2025 https://doi.org/10.1080/13504509.2025.2561262

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Challanges for carbon market programs

- **Verification** - problematic at farm scale due to high spatial variation
- **Permanence** – how long will the carbon stay in soil?
- **Trade-offs** – increased N2O-emission, N leaching etc.
- **Additionality** – measures may have been implemented anyhow
- **Leakage** – increased emissions at another location – e.g. deforestation due to lower yields

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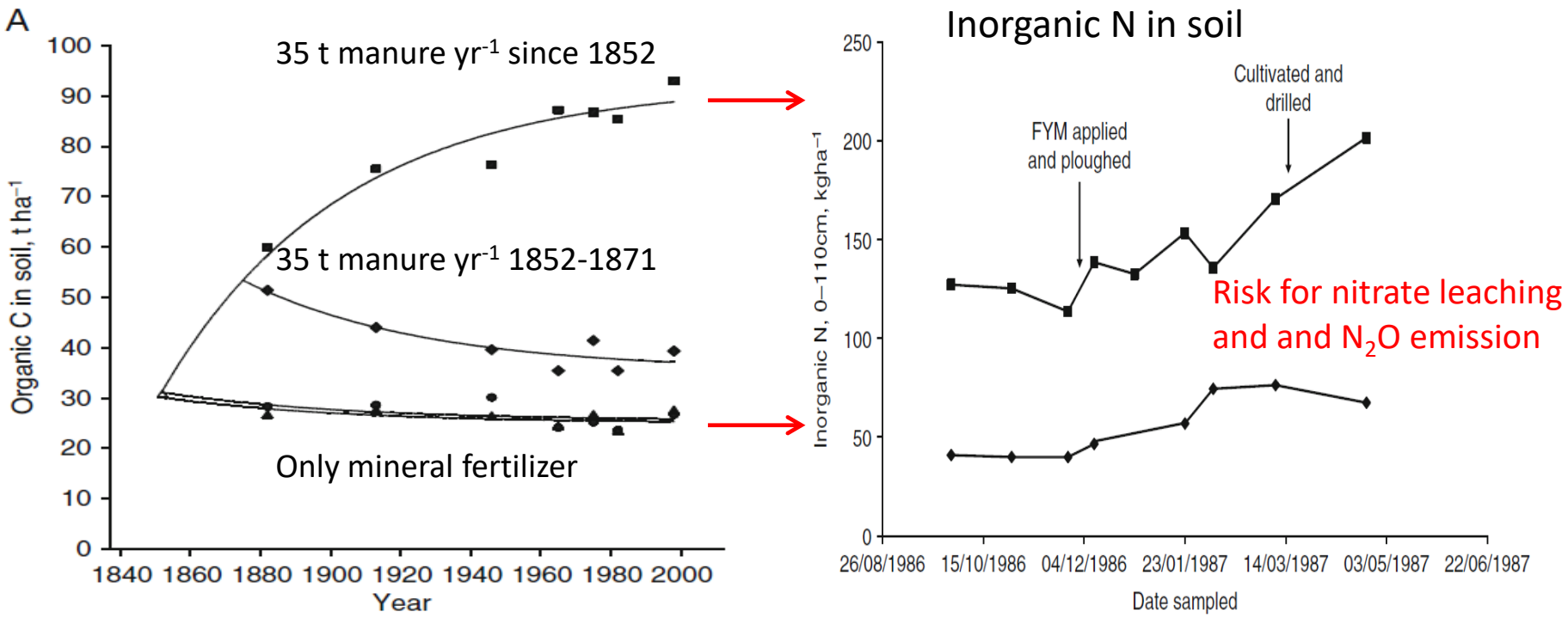
Trade-offs

Hoosfield Continuous Barley, Rothamsted



- Risk for N loss to air and water may increase with SOC and has to be counteracted by management (cover crops etc.)
- C sequestration rates decrease with time

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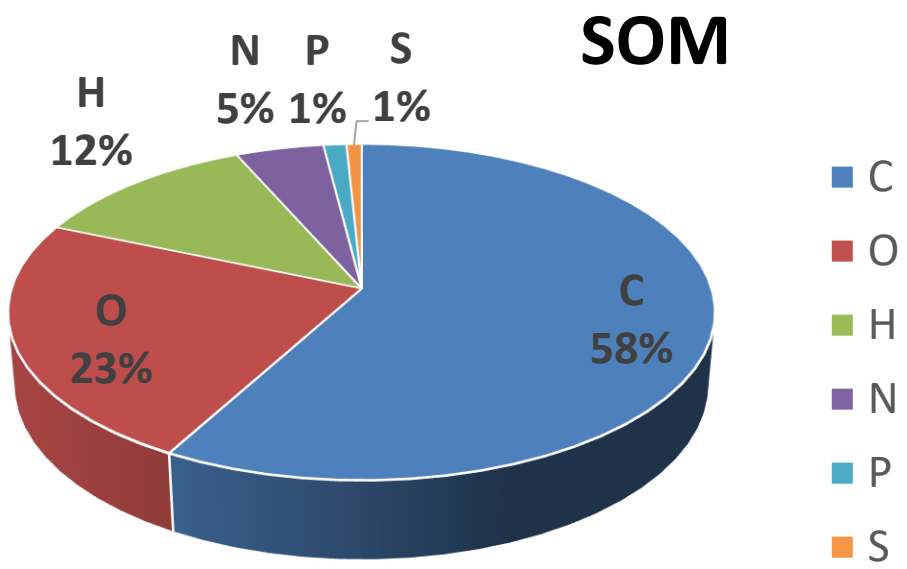
Johnston m.fl., 2009; Powlson et al, 1989

Nutrients are needed for sequestering carbon

Nutrients* needed for sequestering 1 ton C
80 kg N
20 kg P
14 kg S



The crucial question is: How much of N, P and S can be captured by reducing losses – or must be added with fertilizer

*Global average
(Kirby et al. 2011 Geoderma, 163, 197-208)

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Take home messages

- Land use and management are affecting soil carbon stocks
- C sequestration is possible (Sweden), but SOC accrual on European cropland generally leads to C loss mitigation rather than C sequestration
- Synergies and trade-offs (N_2O, N leaching) have to be considered
- Verification of SOC changes at the field/farm scale is challenging.
- Crop yields and yield stability increase with SOC
- Thus, SOC accrual is a promising mitigation and adaptation strategy

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Thanks for your attention!

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