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Effects of Elevated CO_2 on Soil Processes

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Papers of our group (free download)
wwwuser.gwdg.de/~kuzyakov/papers.htm

Slides copy
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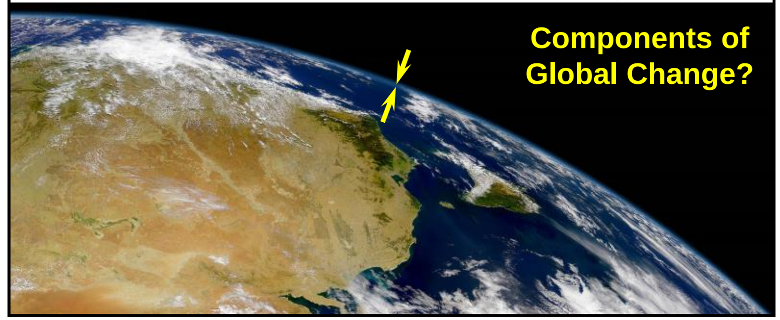
Global Change

- Global change encompasses the full range of natural and human-induced changes in the Earth's environment
- Changes in the global environment (climate, land productivity, water resources, atmospheric chemistry, and ecosystems) that may alter the capacity of the Earth to sustain life

U.S. Global Change Research Act 1990



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Components of Global Change

1. **Climate**
   a. Temperature and precipitation
   b. Extreme events (droughts, floods, heat waves, …)
   c. O_3 and UV radiation
   d. Composition of the atmosphere: CO_2, CH_4, N_2O
2. **Land cover, Land use and erosion**
   a. Soil fertility
   b. Nutrient losses
3. **Element's cycling**: N, P, S, Ca, …
4. **Population growth**: Urbanization, Migration
5. **Resource depletion**
   a. Agricultural land
   b. Fresh water
   c. Nonrenewable resources
6. **Chemical Pollution**
   a. Organics, Pesticides
   b. Heavy metals, Radionuclides
   c. Acid deposition
7. **Biodiversity**: Decrease of genetic heterogeneity

direct effects on soil processes

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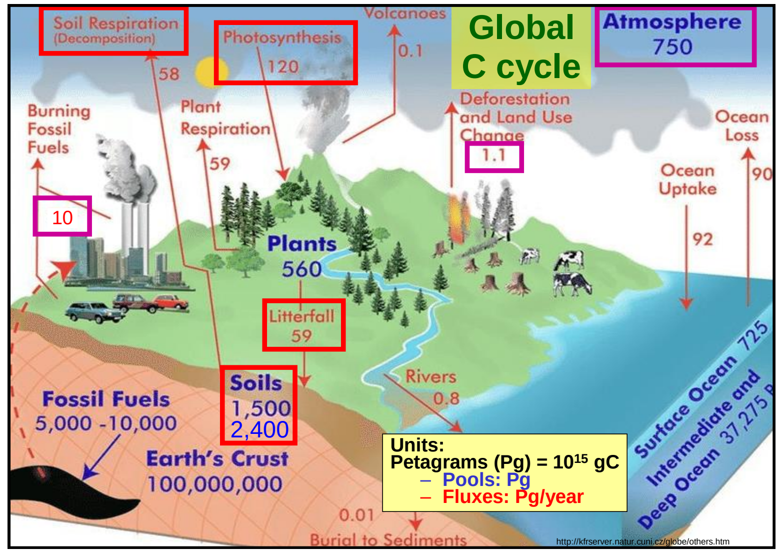

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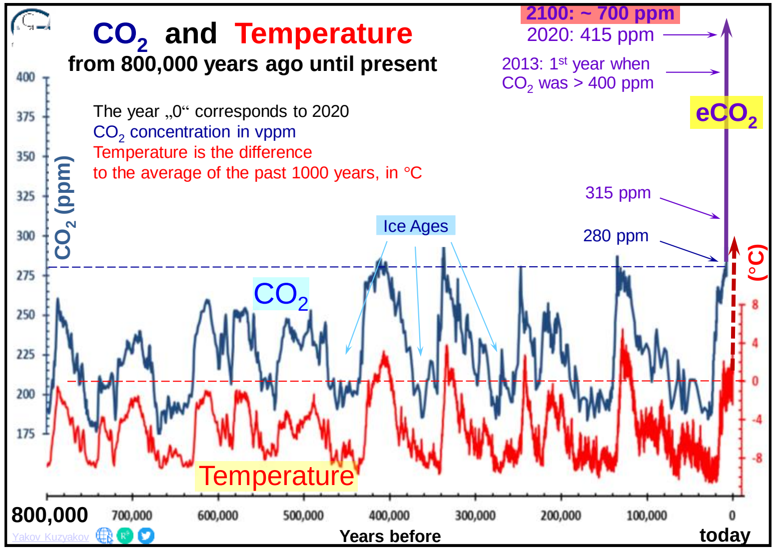

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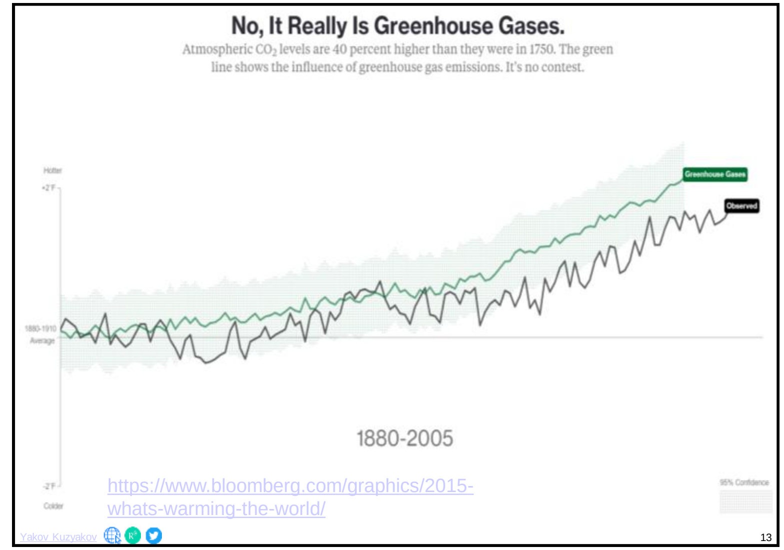

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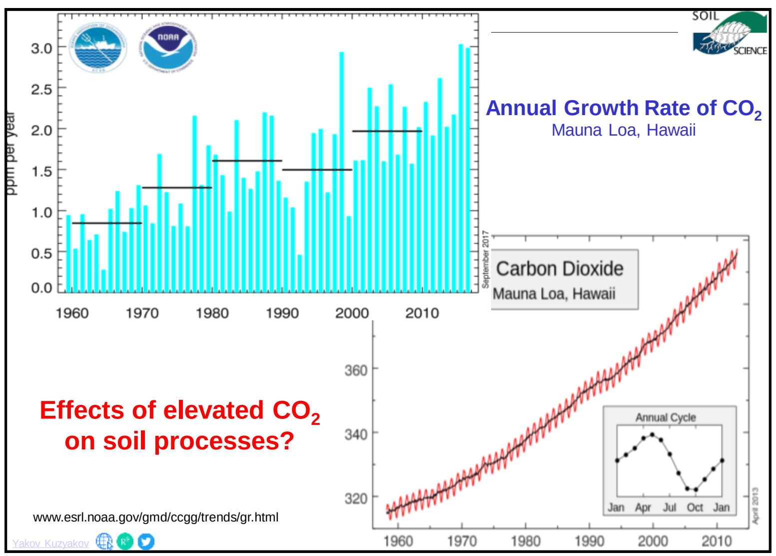

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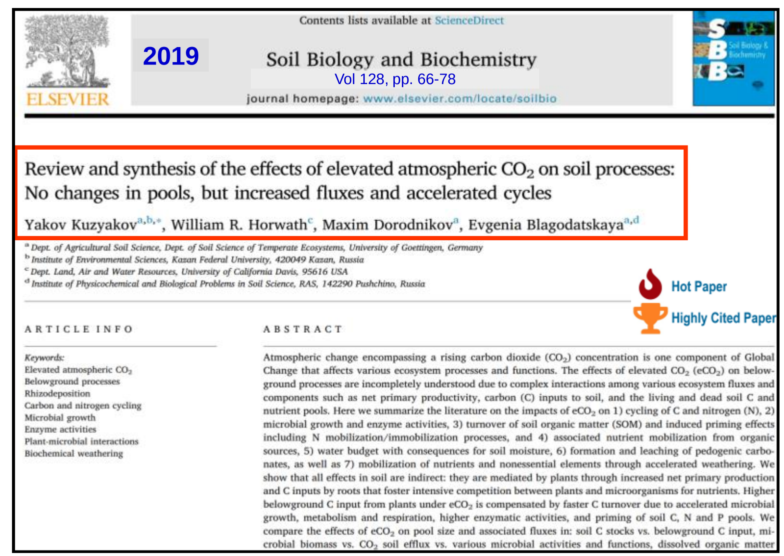

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ELSEVIER

Review and synthesis of the effects of elevated atmospheric CO_2 on soil processes: No changes in pools, but increased fluxes and accelerated cycles

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Hot Paper

Highly Cited Paper

ARTICLE INFO

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Belowground processes
Rhizodeposition
Carbon and nitrogen cycling
Microbial growth
Enzyme activities
Plant-microbial interactions
Biochemical weathering

ABSTRACT

Atmospheric change encompassing a rising carbon dioxide (CO_2) concentration is one component of Global Change that affects various ecosystem processes and functions. The effects of elevated CO_2 (eCO_2) on below-ground processes are incompletely understood due to complex interactions among various ecosystem fluxes and components such as net primary productivity, carbon (C) inputs to soil, and the living and dead soil C and nutrient pools. Here we summarize the literature on the impacts of eCO_2 on 1) cycling of C and nitrogen (N), 2) microbial growth and enzyme activities, 3) turnover of soil organic matter (SOM) and induced priming effects including N mobilization/immobilization processes, and 4) associated nutrient mobilization from organic sources, 5) water budget with consequences for soil moisture, 6) formation and leaching of pedogenic carbo-nates, as well as 7) mobilization of nutrients and nonessential elements through accelerated weathering. We show that all effects in soil are indirect: they are mediated by plants through increased net primary production and C inputs by roots that foster intensive competition between plants and microorganisms for nutrients. Higher belowground C input from plants under eCO_2 is compensated by faster C turnover due to accelerated microbial growth, metabolism and respiration, higher enzymatic activities, and priming of soil C, N and P pools. We compare the effects of eCO_2 on pool size and associated fluxes in: soil C stocks vs. belowground C input, mi-crobial biomass vs. CO_2 soil efflux vs. various microbial activities and functions, dissolved organic matter

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CO_2 Concentration in Soil Air

- 1-2 orders of magnitude higher than in the atmosphere
- Very high variations

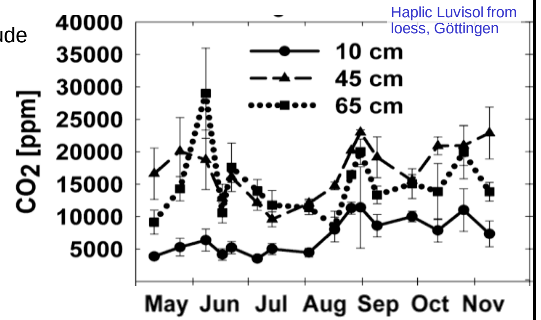
↓

No direct effects of elevated CO_2 on soil processes

↓

Effects through plants?

Indirect effects?



Pausch & Kuzyakov 2012 Soil Biol Biochem

More difficult to study, because indirect effects are based on interactions

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Approaches to Study Effects of eCO_2

Controlled conditions
- Leaf chambers
- Climate chambers

Mechanisms at plant level

Field
- CO_2 springs
- Solardomes
- Open Top Chambers (OTC)
- Free Air Carbon dioxide Enrichment (FACE)

Relevance at ecosystem level

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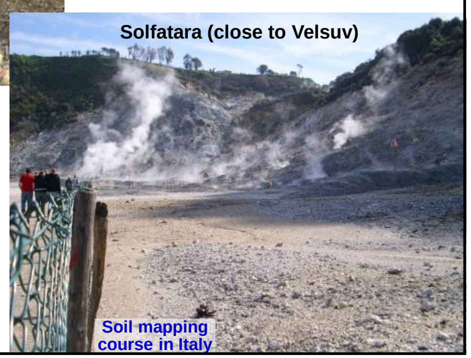
CO_2 springs

Advantages
- Natural CO_2 source
- No costs



Shortcomings
- Few places
- Not zonal vegetation
- Very fast CO_2 dilution
- Toxic gases
- Extreme soil conditions
  - High soil temperature
  - High salinization
- ... ...

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Solardome

Advantages
- High CO_2 enrichment is possible
- CO_2 with shifted $\delta^{13}C$

Shortcomings
- Small scale (no upscaling)
- No ecosystem processes
- Mainly short term studies
- Higher temperature
- Higher humidity

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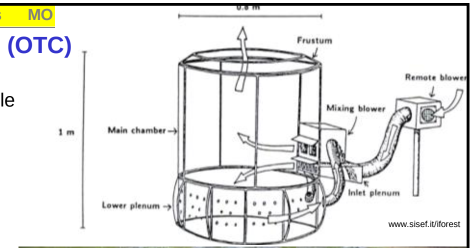
Open Top Chambers (OTC)

Advantages
- High CO_2 enrichment is possible
- „Low“ costs
- CO_2 with shifted $\delta^{13}C$

Shortcomings
- Small scale (no upscaling)
- No ecosystem processes
- Mainly short term studies
- Higher temperature
- Higher humidity



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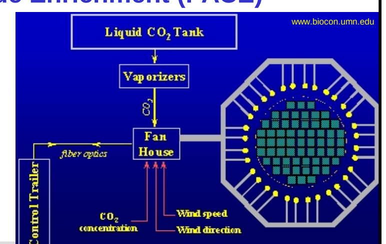
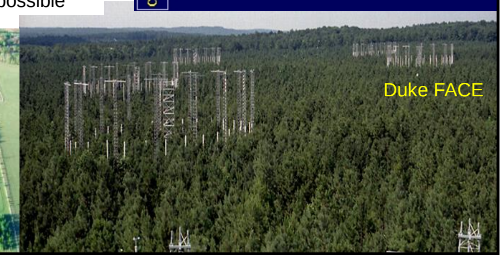
Free Air Carbon dioxide Enrichment (FACE)

Advantages
- Ecosystem processes
- Long term studies
- Medium scale
- Energy balance and gas exchange
- CO_2 with shifted $\delta^{13}C$

Shortcomings
- High costs of CO_2 maintenance
- High CO_2 enrichment is impossible





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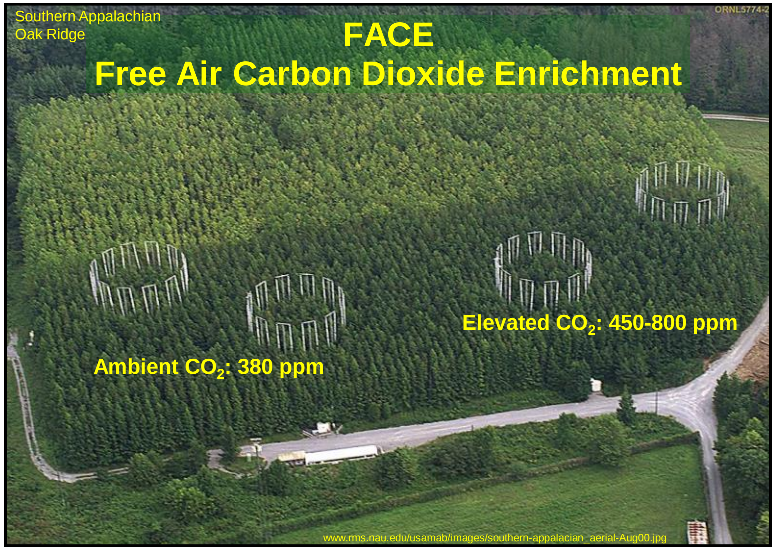

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Intro | Approaches | Roots | MO | Pool | Activity | Functions | SOM

Known effects of elevated CO_2

(from FACE studies)

Above ground

- Increase of:
  - Photosynthesis ~ 10%
  - Plant biomass ~ 10%
    - if N is available
  - Yield of agricultural crops ~ 13%
    - if N is available
  - Temperature of the canopy
- Decrease of
  - Stomatal conductance
  - Quality of plant residues:
    - C/N ratio ↑
    - Lignin content ↑

Below ground

- Water use efficiency increase
- N use efficiency increase

→ **Results mainly for above ground**

→ **Few info about below ground**

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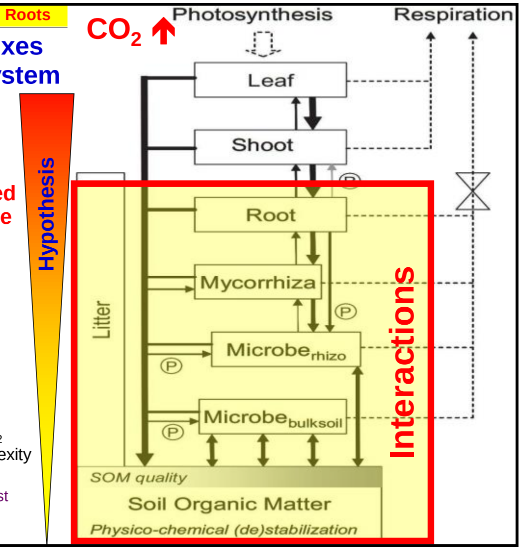
Belowground Processes

- **Roots** (and plant residues)
  - Growth rates & production → Increase
  - Morphology → Fine roots increase
  - Rhizodeposition (+ exudation) → Increase
  - Respiration
  - Quality
  - Decomposition
- **Microorganisms**
  - Compositions
    - Bacteria
    - Fungi, Mycorrhiza
    - … …
  - Activity
    - Growth rates
    - Enzyme activities
    - … …
  - Functions
- **Soil organic matter**
  - Content
  - Composition
  - Turnover

Unknown ?

Pools and Fluxes in Plant-Soil System

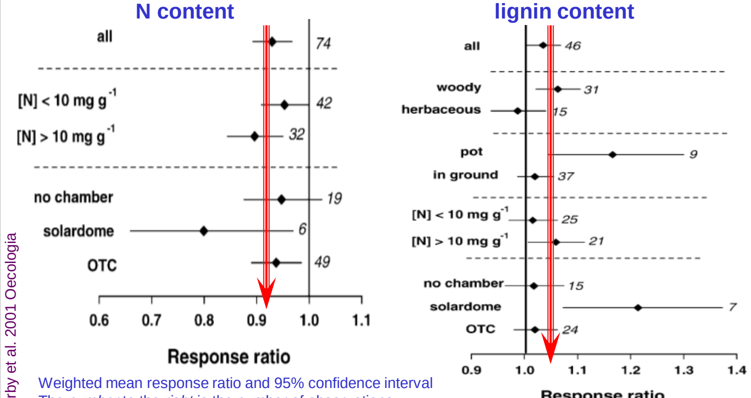


Expected increase

- - - gaseous fluxes
P potential priming effects
R transport of refixed root-CO_2
SOM shades: gradient of complexity

Bahn et al. 2010 New Phytologist

Effect of elevated CO_2 on leaf litter quality

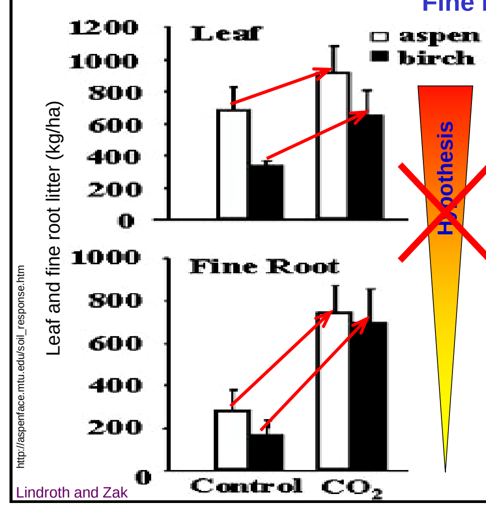


Norby et al. 2001 Oecologia

Weighted mean response ratio and 95% confidence interval
The *number* to the *right* is the number of observations.
If the confidence interval includes a response ratio of 1, the effect is not significant

→ Decrease of litter quality → decrease of decomposition rates in soil

Fine root production



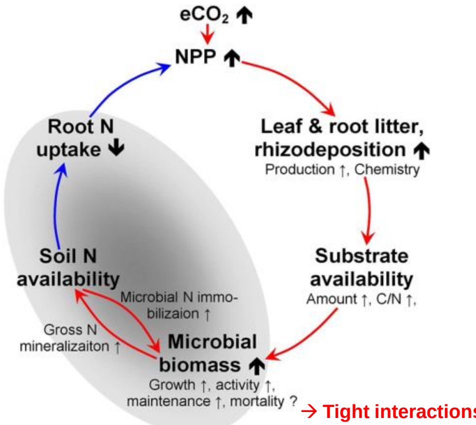
Root with root hairs surrounded by bacteria in the pore space

Increase of:
→ Roots > leafs

→ fine roots
→ exudation
→ C availability

Lindroth and Zak

Interactions between plant and microbial activity, and N availability by elevated CO_2



Plant production is limited by N made available during litter decomposition

But, microbial growth is controlled by C from litter and root exudation

Litter compounds that fuel microbial growth also fuel N demand to build microbial cells

Elevated CO_2 increases the amount of C for microbial growth, alters microbial demand for N and decreases N available for plants

→ Tight interactions: roots ←→ microorganisms

→ Competition for N

Zak et al. 2000 New Phytologist, modified

Kuzyakov & Xu 2013 New Phytologist

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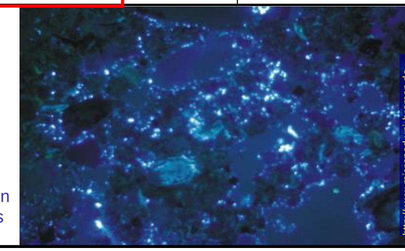
Change of Microbial Biomass under Elevated CO_2

Plants	Relative to ambient CO_2	± SD	No of studies
Graminoid	**+ 17**	± 86	19
Herbaceous	**+ 29**	± 29	11
Woody	**+ 19**	± 46	17

Zak et al. 2000 New Phytologist

→ Increase of microbial biomass

but very high variation



Bacteria in pores on aggregate surfaces

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Response of microbial functions to elevated CO_2

Pool or process	Mean response (%)	Coefficient of variation (%)	Significant responses/ total observations	Percentage of Increase	Percentage of Decrease
Soil respiration	+45	80	12/41	96	4
Microbial respiration	+28	96	3/20	95	5
Microbial biomass	+19	326	8/45	62	18
Gross N mineralization	−3	800	0/10	40	40
Microbial immobilization	+93	231	3/24	50	42
Net N mineralization	+44	285	2/19	68	11

Changes in soil respiration, microbial respiration, microbial biomass, gross N mineralization, microbial immobilization and net N mineralization are presented, because they are key pools and fluxes controlling the cycling of C and N.
Responses have been averaged across graminoid, herbaceous and woody plants grown under ambient and elevated CO_2 in soil.
Positive values () represent an increase and negative values (-) represent a decrease under elevated CO_2.

→ The intensity of most soil processes increases under elevated CO_2

→ Very high uncertainties belowground

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Zak et al. 2000 New Phytologist 35

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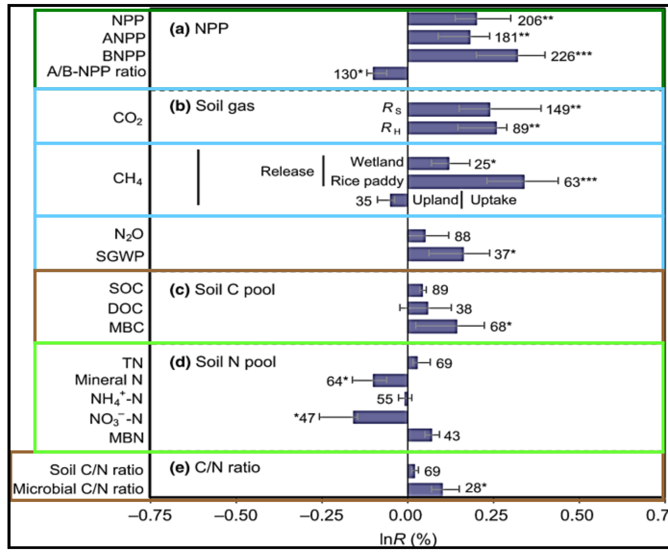

Above & Below Ground Pools & Fluxes

Liu et al. 2018 Ecology Letters

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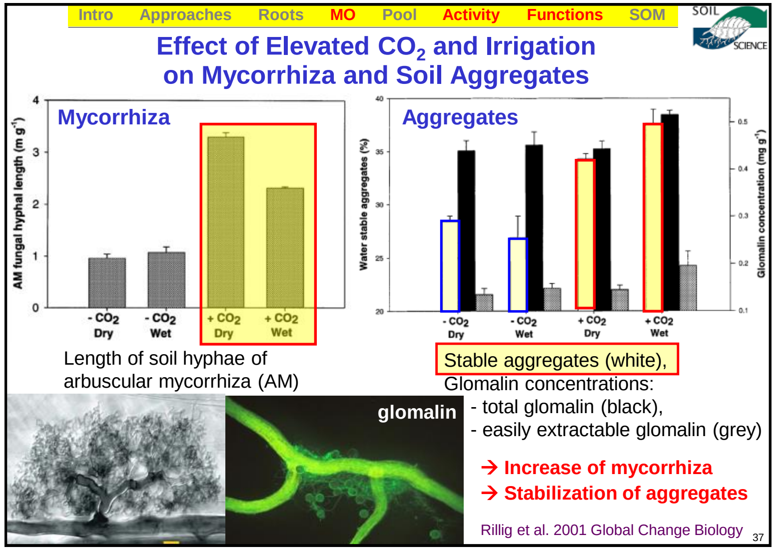
Intro Approaches Roots MO Pool Activity Functions SOM
Effect of Elevated CO2 and Irrigation on Mycorrhiza and Soil Aggregates
Mycorrhiza
AM fungal hyphal length (m g-1)
- CO2 Dry
- CO2 Wet
+ CO2 Dry
+ CO2 Wet
Length of soil hyphae of arbuscular mycorrhiza (AM)
Aggregates
Water stable aggregates (%)
Glomalin concentration (mg g-1)
Stable aggregates (white),
Glomalin concentrations:
- total glomalin (black),
- easily extractable glomalin (grey)
glomalin
→ Increase of mycorrhiza
→ Stabilization of aggregates
Rillig et al. 2001 Global Change Biology
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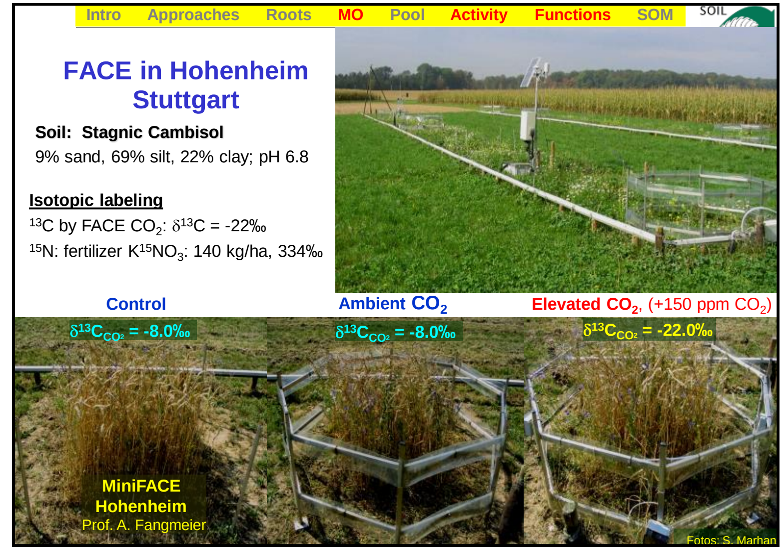
Intro Approaches Roots MO Pool Activity Functions SOM
FACE in Hohenheim Stuttgart
Soil: Stagnic Cambisol
9% sand, 69% silt, 22% clay; pH 6.8
Isotopic labeling
13C by FACE CO2: δ13C = -22‰
15N: fertilizer K15NO3: 140 kg/ha, 334‰
Control
Ambient CO2
Elevated CO2, (+150 ppm CO2)
δ13CCO2 = -8.0‰
δ13CCO2 = -8.0‰
δ13CCO2 = -22.0‰
MiniFACE
Hohenheim
Prof. A. Fangmeier
Fotos: S. Marhan

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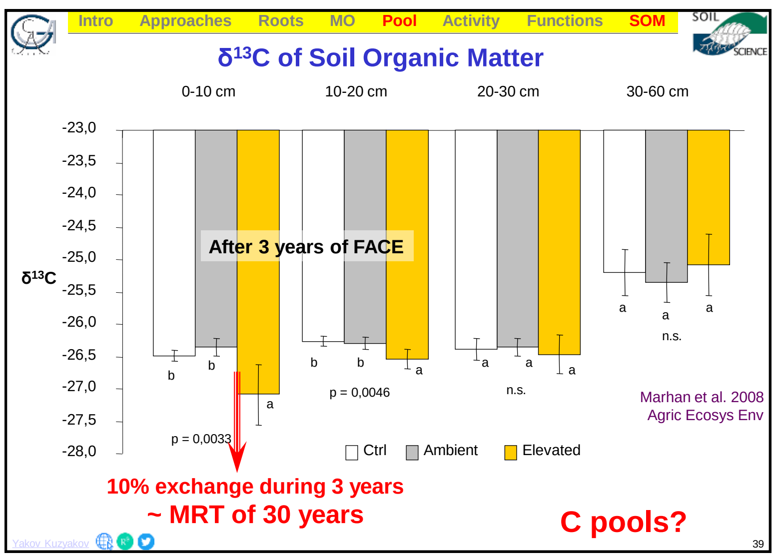
Intro Approaches Roots MO Pool Activity Functions SOM
δ13C of Soil Organic Matter
0-10 cm
10-20 cm
20-30 cm
30-60 cm
δ13C
After 3 years of FACE
p = 0,0033
p = 0,0046
n.s.
n.s.
Ctrl
Ambient
Elevated
Marhan et al. 2008
Agric Ecosys Env
10% exchange during 3 years
~ MRT of 30 years
C pools?
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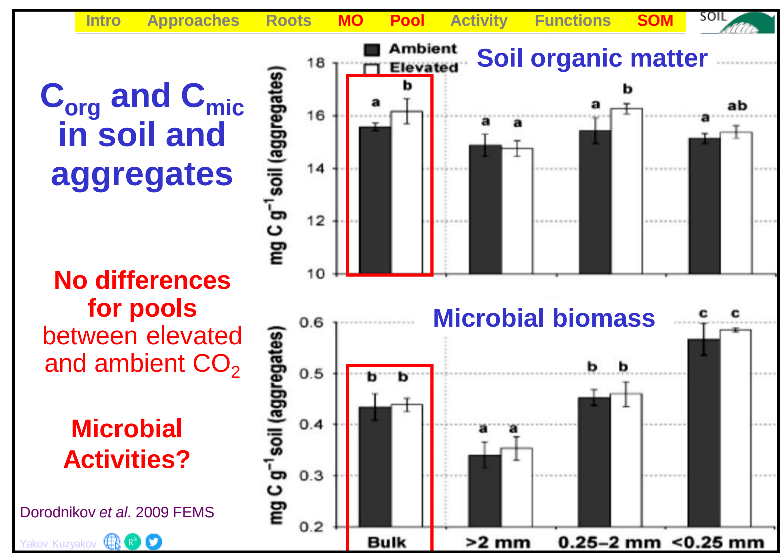
Intro Approaches Roots MO Pool Activity Functions SOM
Corg and Cmic in soil and aggregates
No differences for pools between elevated and ambient CO2
Microbial Activities?
Dorodnikov et al. 2009 FEMS
Ambient
Elevated
Soil organic matter
Microbial biomass
mg C g-1 soil (aggregates)
Bulk
>2 mm
0.25–2 mm
<0.25 mm

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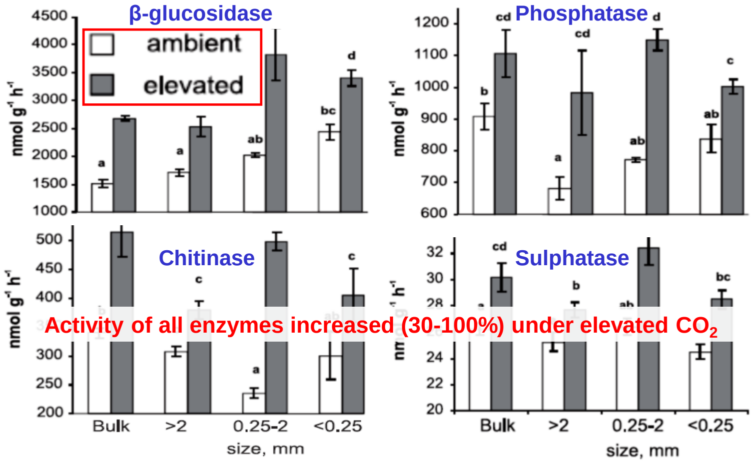
Effect of Elevated CO_2 on Enzyme Activities



Activity of all enzymes increased (30-100%) under elevated CO_2

Dorodnikov *et al.* 2009 Global Change Biology

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Growth Rates of Microorganisms

- fast: organisms with r strategy
- slow: organisms with K strategy

Kinetic approach:

CO_2 evolution rate (V) after substrate addition:

$V(t) = A + B * \exp(\mu_m t)$

A – initial rate of uncoupled (non-growth) respiration

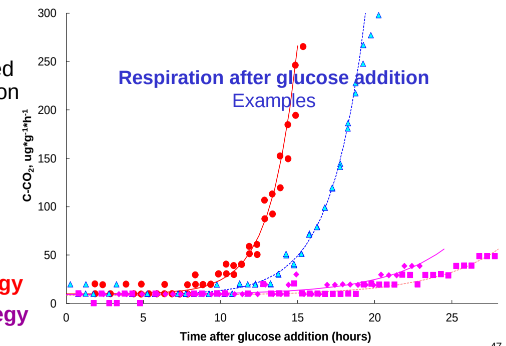
B – initial rate of coupled (growth) respiration

t – time

μ_m – maximal specific growth rate

- μ_m increase → r strategy
- μ_m decrease → K strategy

Principle of substrate induced growth respiration (Panikov, 1995)



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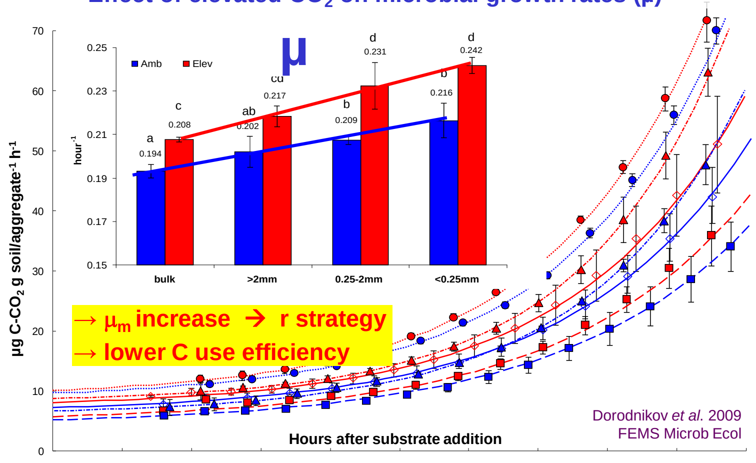
Effect of elevated CO_2 on microbial growth rates (μ)



→ μ_m increase → r strategy

→ lower C use efficiency

Dorodnikov *et al.* 2009 FEMS Microb Ecol

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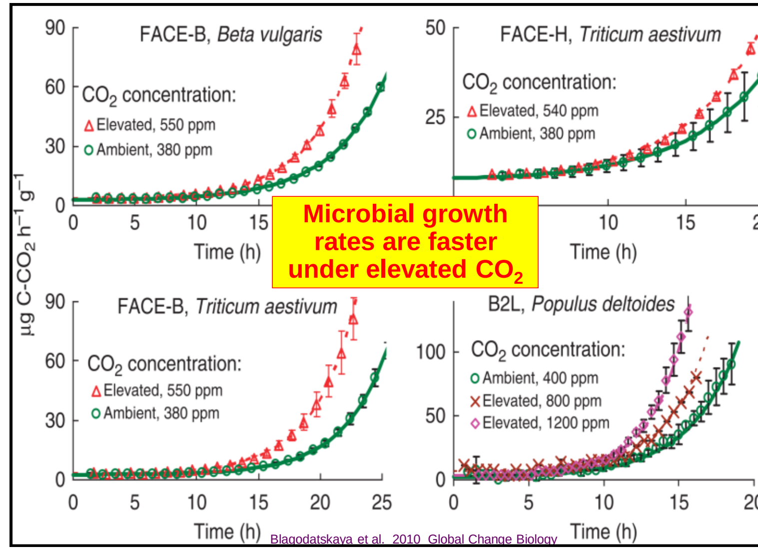

Microbial growth rates are faster under elevated CO_2

Blagodatskaya et al. 2010 Global Change Biology

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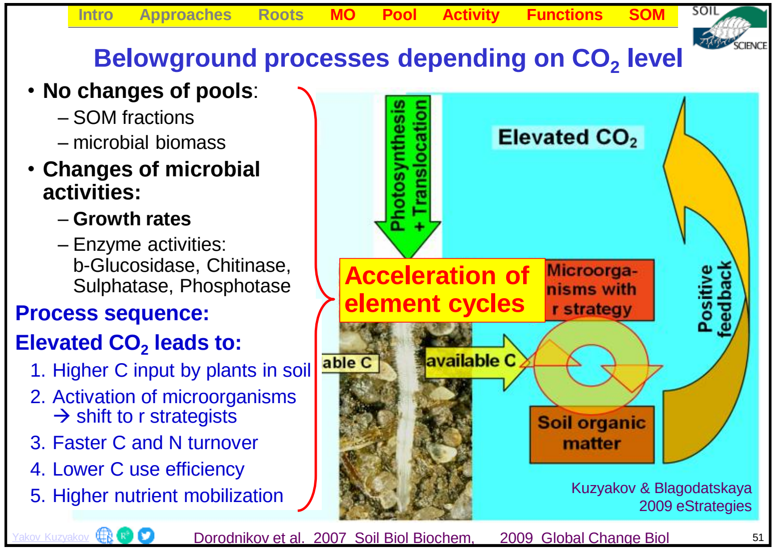
Intro Approaches Roots MO Pool Activity Functions SOM
Belowground processes depending on CO2 level
• No changes of pools:
– SOM fractions
– microbial biomass
• Changes of microbial activities:
– Growth rates
– Enzyme activities: b-Glucosidase, Chitinase, Sulphatase, Phosphotase
Process sequence:
Elevated CO2 leads to:
1. Higher C input by plants in soil
2. Activation of microorganisms → shift to r strategists
3. Faster C and N turnover
4. Lower C use efficiency
5. Higher nutrient mobilization
Photosynthesis + Translocation
Elevated CO2
Acceleration of element cycles
Microorganisms with r strategy
Positive feedback
able C
available C
Soil organic matter
Kuzyakov & Blagodatskaya 2009 eStrategies
Dorodnikov et al. 2007 Soil Biol Biochem, 2009 Global Change Biol
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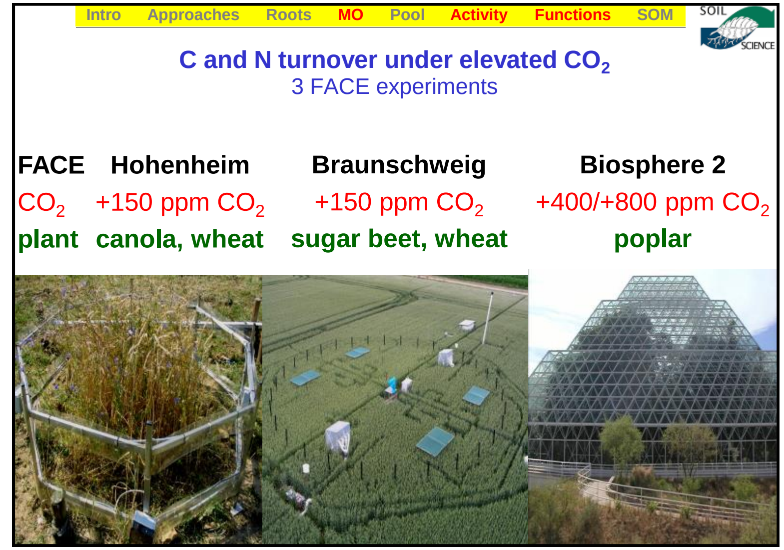
Intro Approaches Roots MO Pool Activity Functions SOM
C and N turnover under elevated CO2
3 FACE experiments
FACE Hohenheim Braunschweig Biosphere 2
CO2 +150 ppm CO2 +150 ppm CO2 +400/+800 ppm CO2
plant canola, wheat sugar beet, wheat poplar

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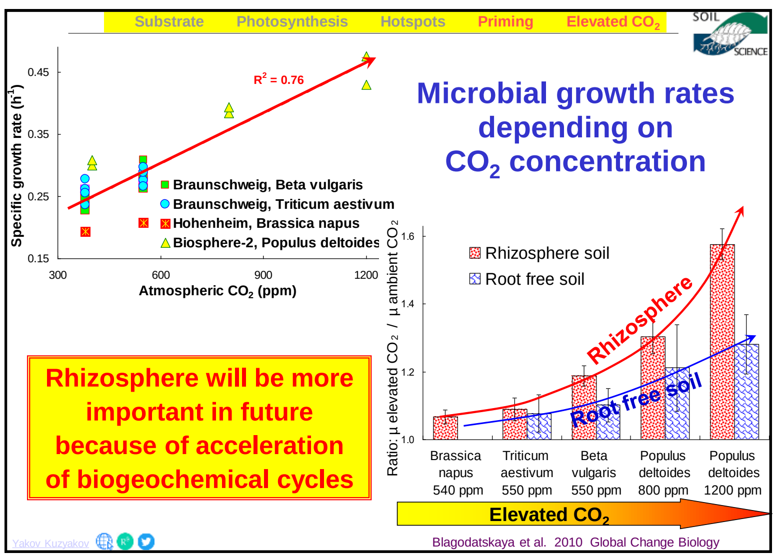
Substrate Photosynthesis Hotspots Priming Elevated CO2
Microbial growth rates depending on CO2 concentration
R² = 0.76
Specific growth rate (h⁻¹)
0.45
0.35
0.25
0.15
300 600 900 1200
Atmospheric CO2 (ppm)
Braunschweig, Beta vulgaris
Braunschweig, Triticum aestivum
Hohenheim, Brassica napus
Biosphere-2, Populus deltoides
Ratio: µ elevated CO2 / µ ambient CO2
1.6
1.4
1.2
1.0
Rhizosphere soil
Root free soil
Rhizosphere
Root free soil
Brassica napus 540 ppm
Triticum aestivum 550 ppm
Beta vulgaris 550 ppm
Populus deltoides 800 ppm
Populus deltoides 1200 ppm
Elevated CO2
Rhizosphere will be more important in future because of acceleration of biogeochemical cycles
Blagodatskaya et al. 2010 Global Change Biology

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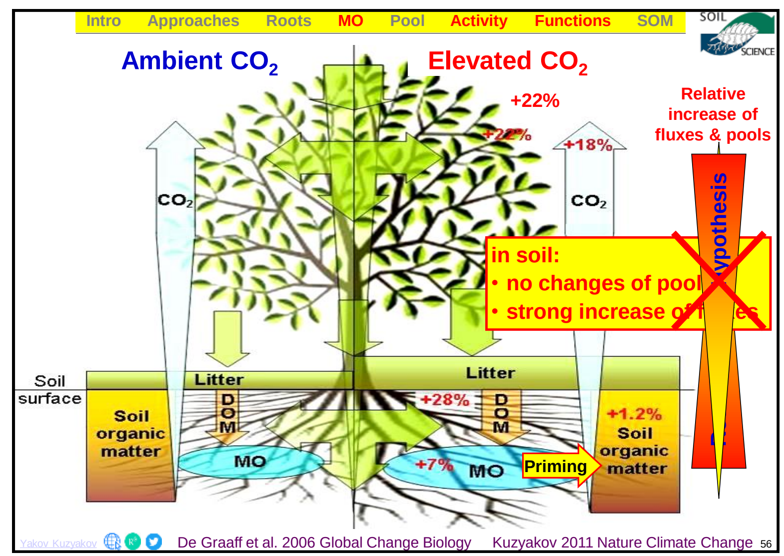
Intro Approaches Roots MO Pool Activity Functions SOM
Ambient CO2
Elevated CO2
+22%
+22%
+18%
Relative increase of fluxes & pools
CO2
CO2
Hypothesis
in soil:
• no changes of pool
• strong increase of f es
Soil surface
Litter
Litter
Soil organic matter
DOM
DOM
+28%
MO
+7%
MO
Priming
+1.2%
Soil organic matter
De Graaff et al. 2006 Global Change Biology
Kuzyakov 2011 Nature Climate Change
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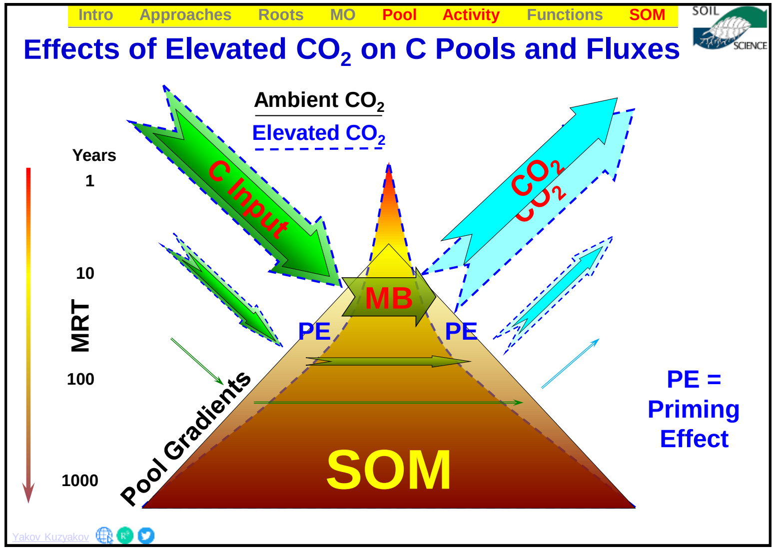
Intro Approaches Roots MO Pool Activity Functions SOM
SOIL SCIENCE
Effects of Elevated CO_2 on C Pools and Fluxes
Ambient CO_2
Elevated CO_2
Years
1
10
100
1000
MRT
C Input
CO_2
CO_2
MB
PE
PE
Pool Gradients
SOM
PE = Priming Effect
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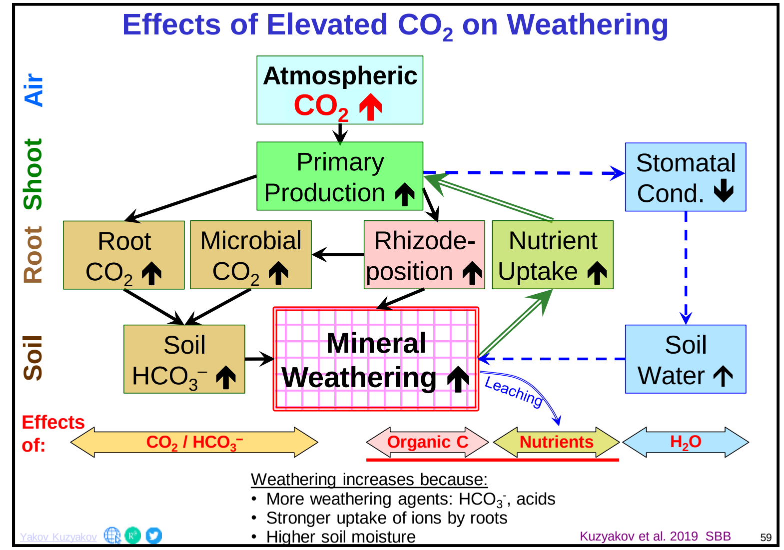
Effects of Elevated CO_2 on Weathering
Air
Shoot
Root
Soil
Atmospheric CO_2 ↑
Primary Production ↑
Stomatal Cond. ↓
Root CO_2 ↑
Microbial CO_2 ↑
Rhizode-position ↑
Nutrient Uptake ↑
Soil HCO_3^- ↑
Mineral Weathering ↑
Soil Water ↑
Leaching
Effects of:
CO_2 / HCO_3^-
Organic C
Nutrients
H_2O
Weathering increases because:
• More weathering agents: HCO_3^-, acids
• Stronger uptake of ions by roots
• Higher soil moisture
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Kuzyakov et al. 2019 SBB
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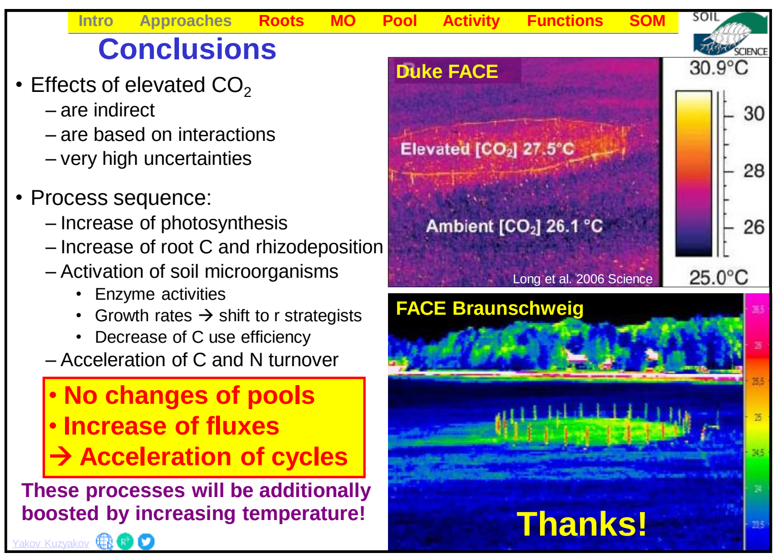
Intro Approaches Roots MO Pool Activity Functions SOM
SOIL SCIENCE
Conclusions
• Effects of elevated CO_2
– are indirect
– are based on interactions
– very high uncertainties
• Process sequence:
– Increase of photosynthesis
– Increase of root C and rhizodeposition
– Activation of soil microorganisms
• Enzyme activities
• Growth rates → shift to r strategists
• Decrease of C use efficiency
– Acceleration of C and N turnover
• No changes of pools
• Increase of fluxes
→ Acceleration of cycles
These processes will be additionally boosted by increasing temperature!
Duke FACE
30.9°C
30
28
26
25.0°C
Elevated [CO_2] 27.5°C
Ambient [CO_2] 26.1 °C
Long et al. 2006 Science
FACE Braunschweig
Thanks!
Yakov Kuzyakov

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