Reduced Atmospheric Methane Consumption by Temperate Forest Soils Under Elevated CO_2: Causative Factors

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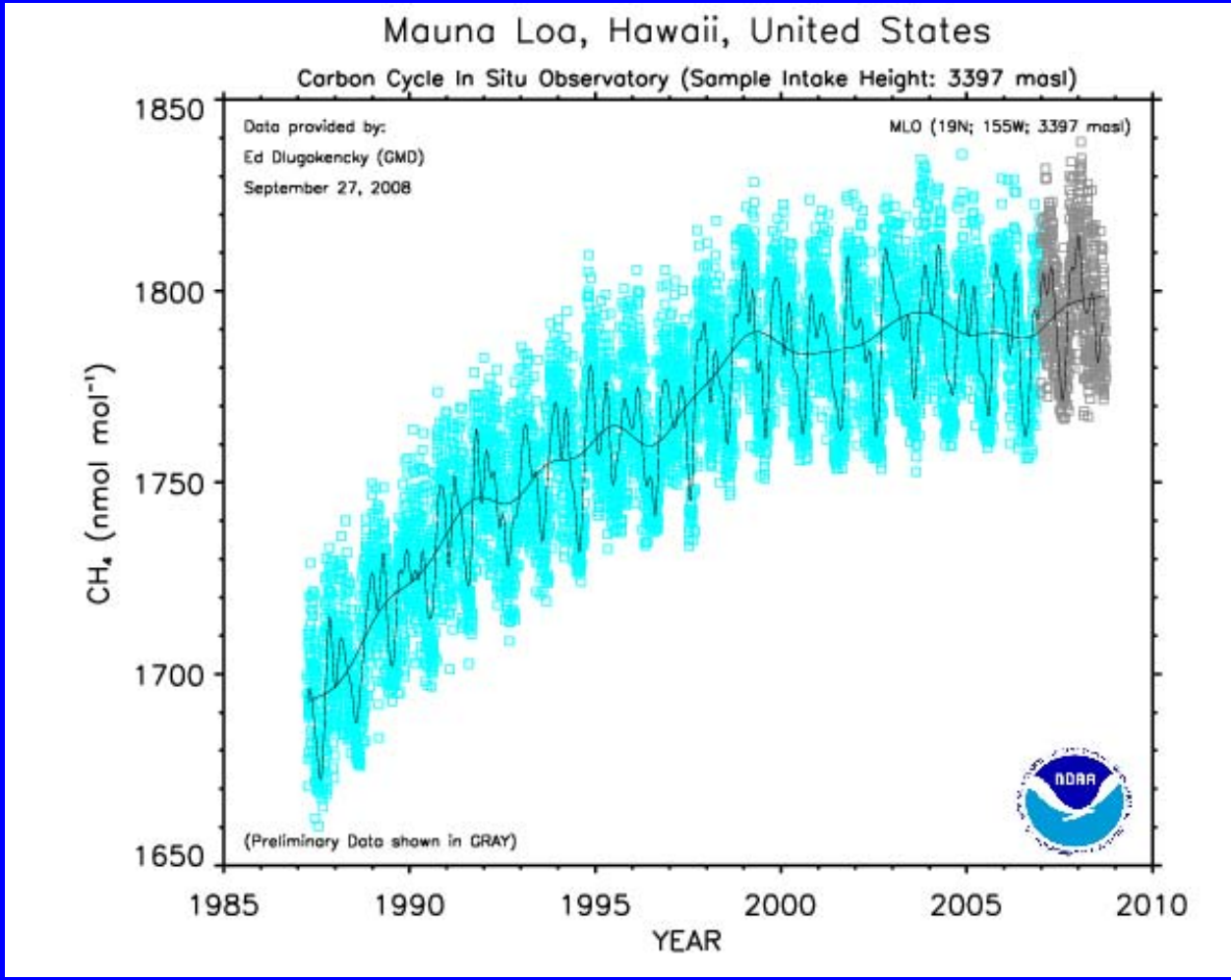
Background – Atmospheric CH_4

- Preindustrial mixing ratio: ~700 nmol mol^{-1}
- Current mixing ratio: 1780 nmol mol^{-1}



Source: http://www.esrl.noaa.gov/gmd/ccgg/iadv/

Background – Atmospheric CH_4

Radiatively active

- Accounts for 20% of radiative forcing over past 200 yr
- GWP = 62 X CO_2 on 20 yr time horizon

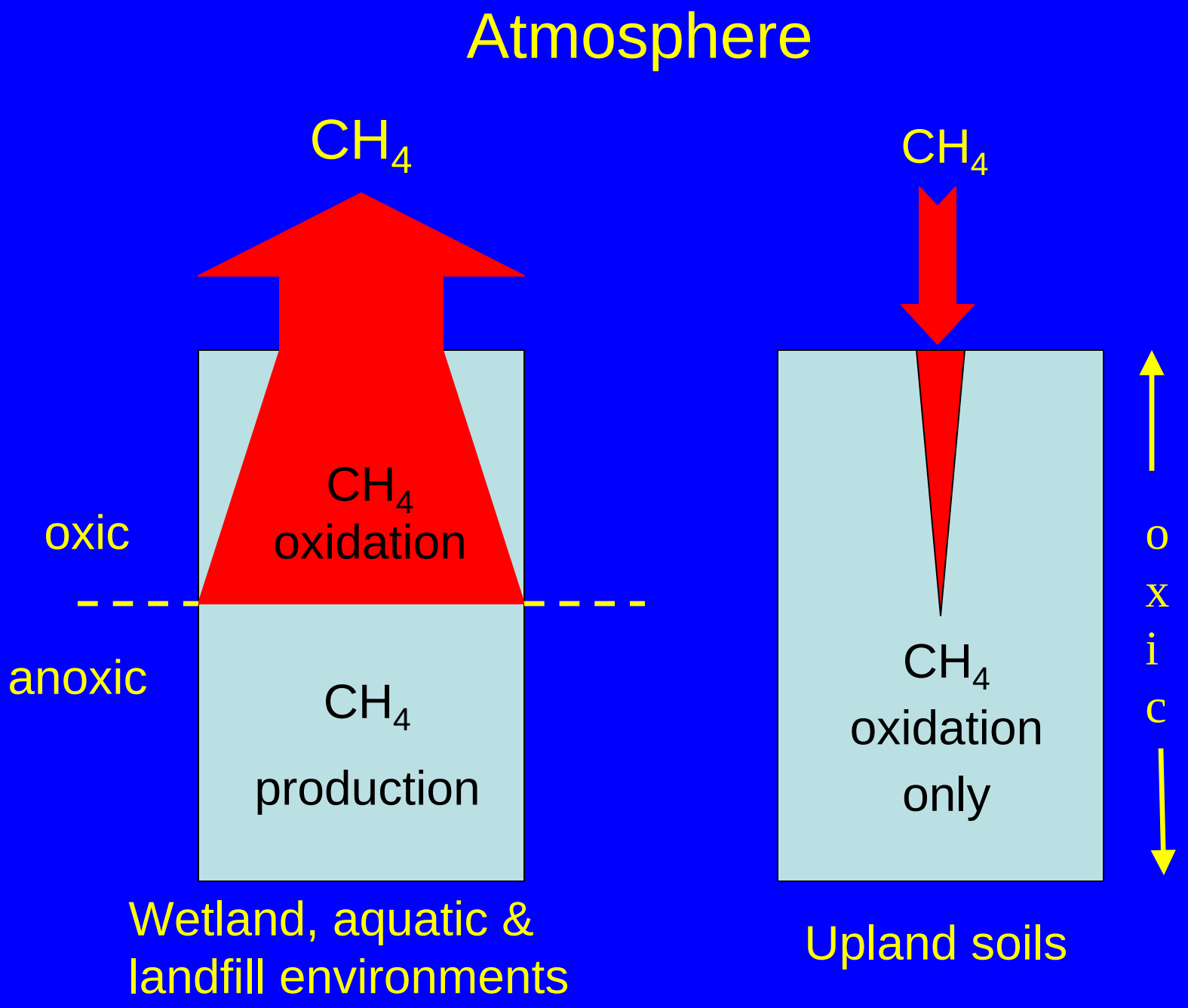
Photochemically active

- Oxidized by OH
- Intermediate product = CO (sink for OH)
- Low $NO_x \rightarrow O_3$
- Involved in stratospheric chemistry

Atmospheric CH_4 Budget

Sources	Tg CH_4 yr^{-1}
Wetlands	145
Rice	80
Oceans, freshwater	20
Termites	20
Ruminants	115
Landfills	40
Wastewater treatment	25
Biomass burning	40
Energy-related	110
	Σ = 600
Sinks	
Tropospheric OH	510
Stratospheric loss	40
Soils	**30**
	Σ = 580

Source: Lelieveld et al. (1998)

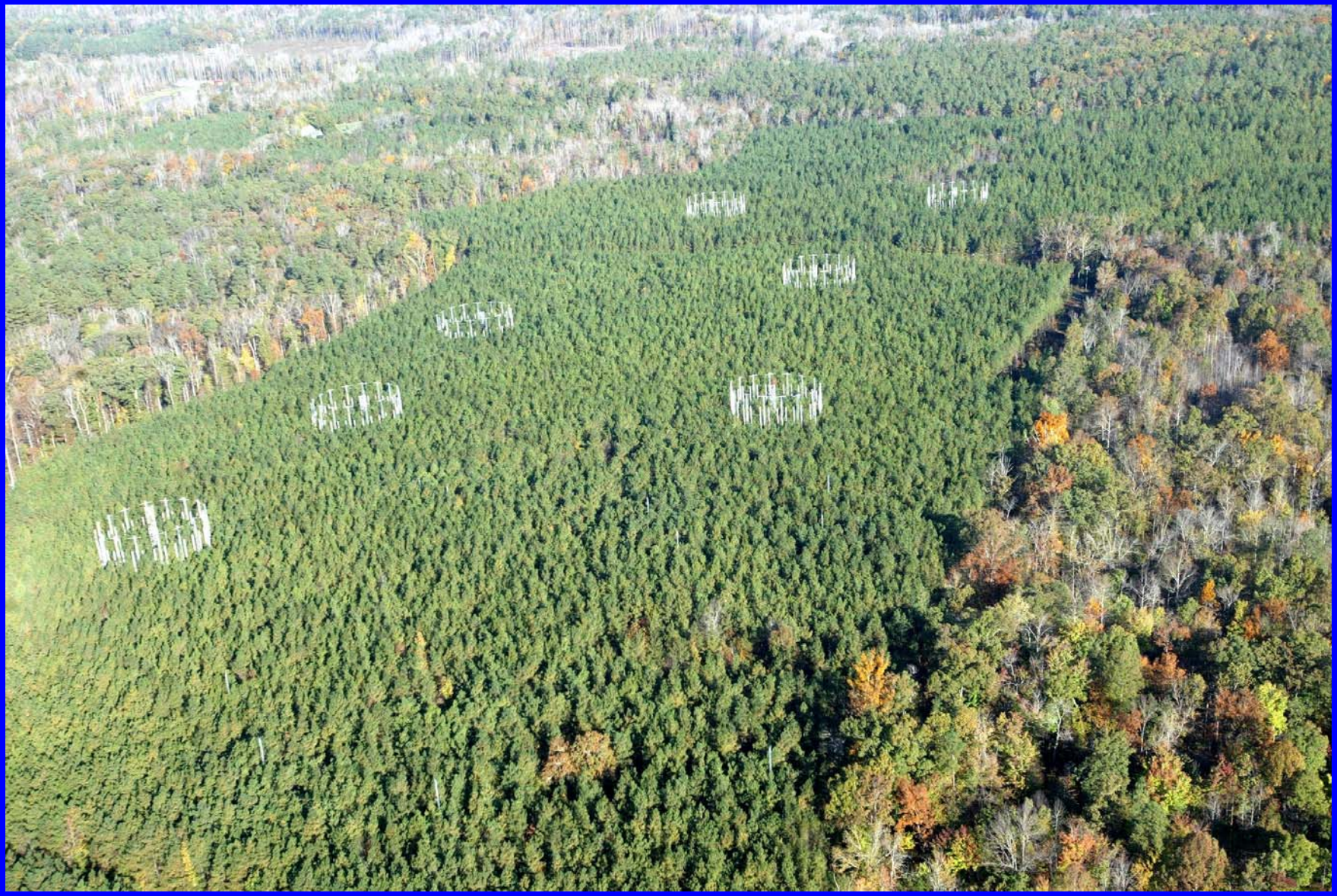

Atmosphere
CH_4
CH_4
oxic
anoxic
CH_4 oxidation
CH_4 production
CH_4 oxidation only
oxic
Wetland, aquatic & landfill environments
Upland soils

Forest response to elevated CO_2 that could impact rates of atmospheric CH_4 consumption

Response	CH_4 oxidation rate
Increased water use efficiency	decrease
Increased root mass, fine root production	decrease
Increased N use efficiency	increase
Δ Microbial community composition	?
Increased rhizodeposition, belowground C allocation	?
Increased belowground release secondary metabolites	?
Δ chemistry of root exudates, throughfall, stemflow	?

Duke Forest Free-Air CO_2 Enrichment (FACE) Site

- Direct CO_2 enrichment of intact ecosystem
- ~25 yr old loblolly pine forest in Durham, NC
- Operational since August 1996
- Realistic evaluation of feedbacks/interactions between atmosphere and plant/soil systems under projected future climates
- Design
    1. 6 x 30 m diameter rings
    2. Each ring consists of 4 quadrants = 24 total quadrants
    3. 3 rings at ambient CO_2 (~380 µL L^{-1}) = control
    4. 3 rings at elevated CO_2 (~580 µL L^{-1})



Previous Research – Soil CH_4 oxidation at Duke Forest FACE site (design)

Field

- 24 flux collars located at FACE site
- One collar permanently emplaced per quadrant
- = 12 collars at ambient CO_2, 12 collars at elevated CO_2
- CH_4 flux determinations at 2 week intervals
  1. Calendar years 1998, 1999
  2. April 2001 through March 2002

Laboratory

- Influence of N salts on CH_4 consumption

Previous Research – Soil CH_4 oxidation at Duke Forest FACE site (results)

Field (Phillips et al. 2001a, Whalen, unpublished)

- No difference in soil moisture or pH between treatments
- 16% (1998), 30% (1999) and 13% (4/01 – 3/02) reduction in soil CH_4 consumption in CO_2-fertilized rings

Laboratory (Phillips et al. 2001b)

- No difference in sensitivity between treatments to addition of N salts

Significance:

- A 25% reduction in the 30 Tg yr^{-1} upland soil CH_4 sink (7.5 Tg) ≈ 50% of annual increase in atmospheric burden (14 Tg yr^{-1})
- If response is sustained → increased atmospheric [CH_4]

STAR Research (1/04-present) Overall Questions

Relative to decreased soil atmospheric CH_4 consumption under elevated CO_2:

1. Is this a sustained response?
2. What are the physicochemical and/or biological factors responsible?

Hypotheses

H_1: Reduced soil CH_4 consumption is sustained response of forests to elevated atmospheric CO_2

H_2: Differences in throughfall chemistry between elevated and ambient CO_2 sites do not impact rates of CH_4 oxidation

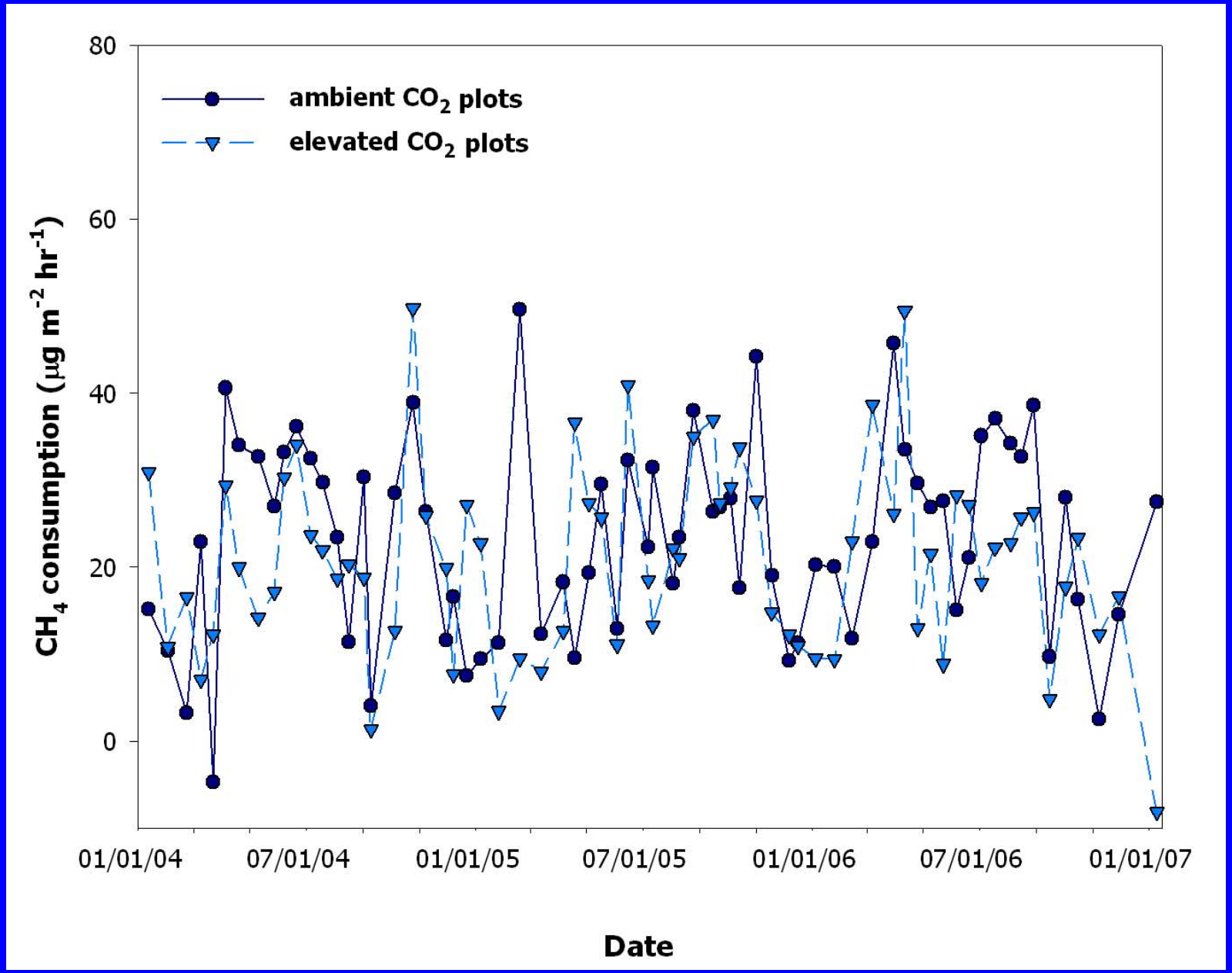
H_3: Rates of CH_4 oxidation are decreased by chemical compounds released to soils by plants growing under elevated CO_2

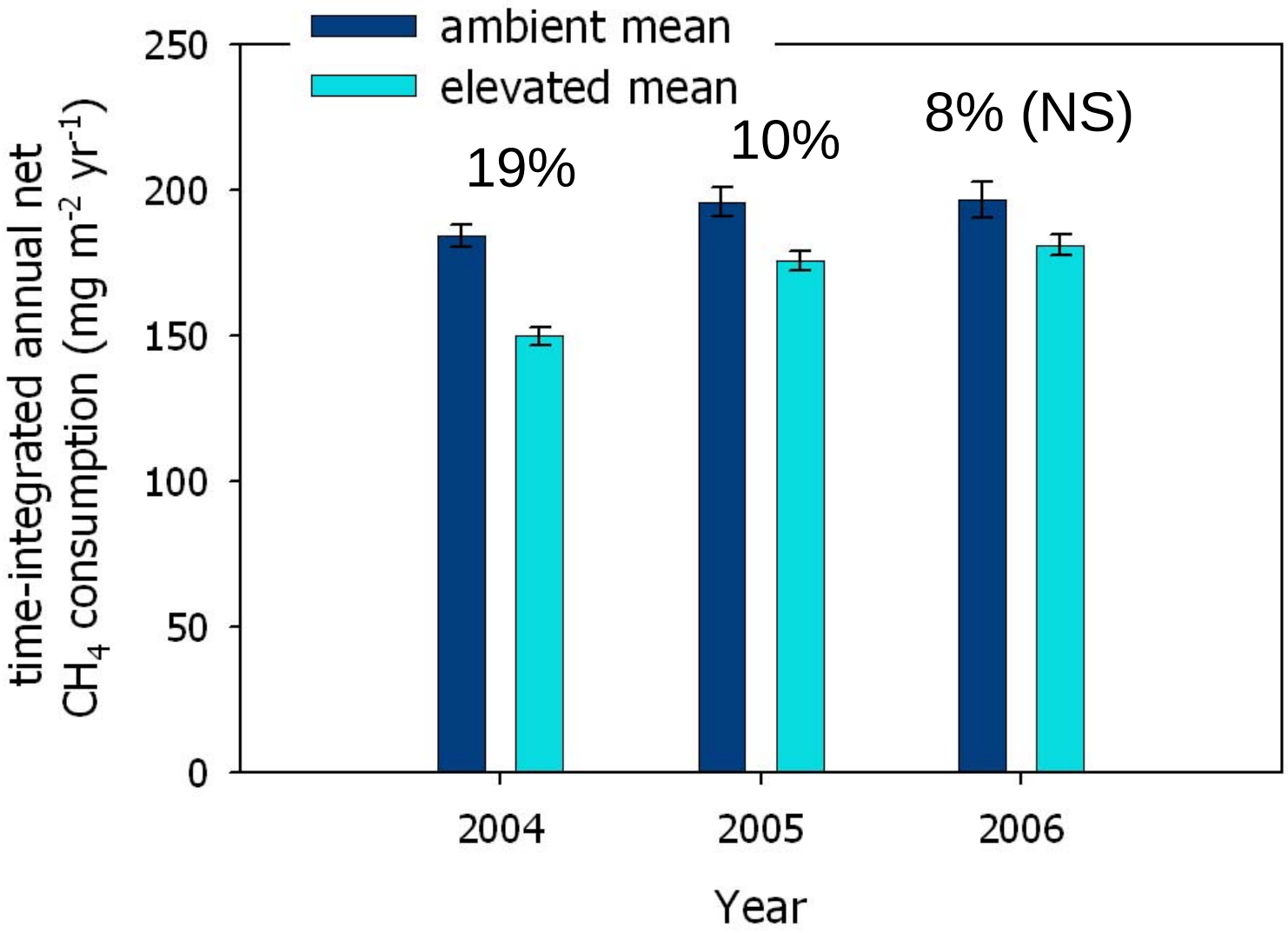
H_4: Reduced atmospheric CH_4 consumption by soil microbes under elevated CO_2 is related to rate of CH_4 supply to or structure of the CH_4-oxidizing community

STAR Research (1/04-present)
Hypotheses/Approaches

H_1: Reduced soil CH_4 consumption is sustained response of forest to elevated atmospheric CO_2

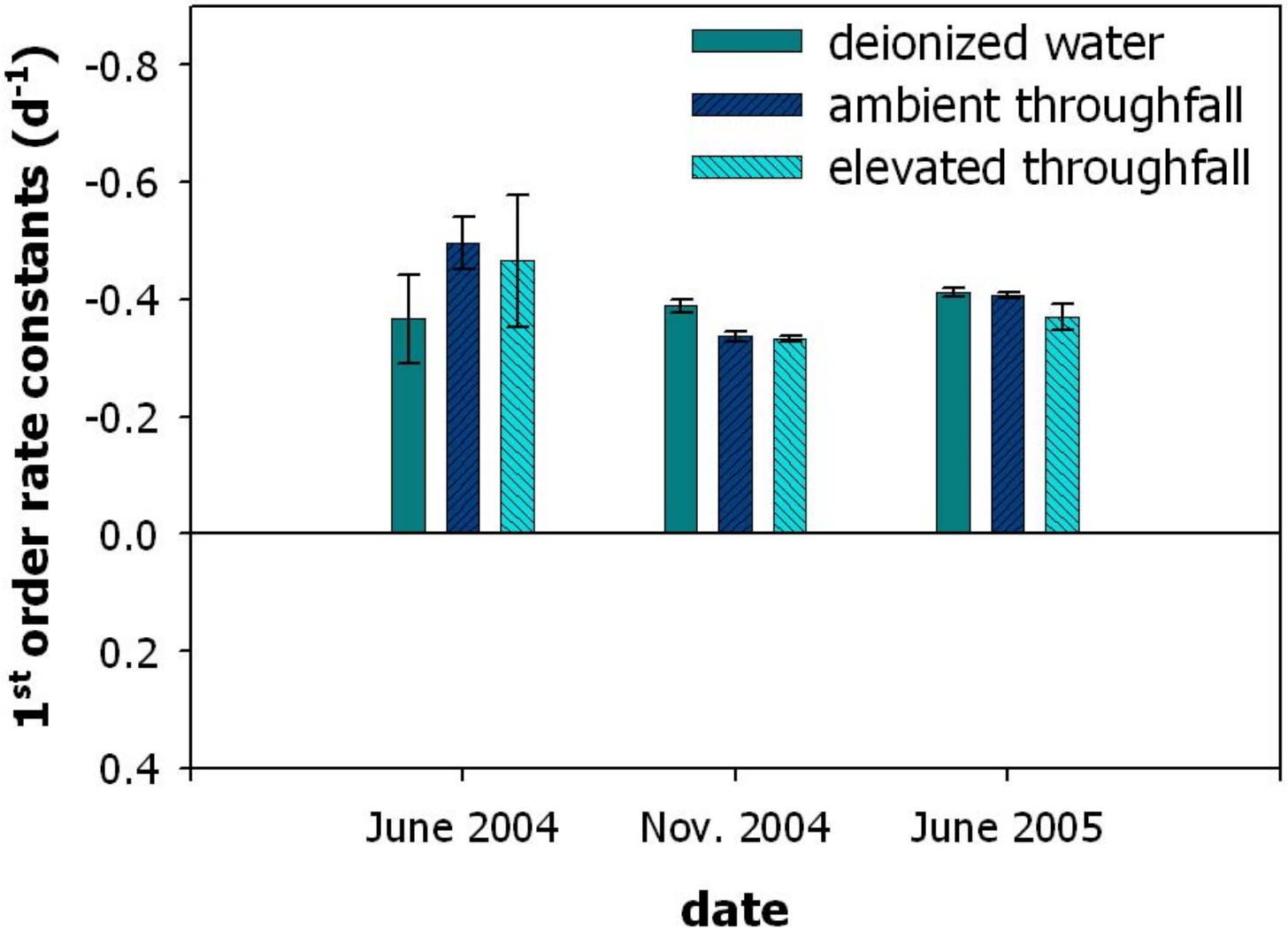
Approach: Biweekly CH_4 flux determinations at previously established fixed sites


ambient CO_2 plots
elevated CO_2 plots
CH_4 consumption ($\mu g\ m^{-2}\ hr^{-1}$)
80
60
40
20
0
01/01/04
07/01/04
01/01/05
07/01/05
01/01/06
07/01/06
01/01/07
Date


ambient mean
elevated mean
19%
10%
8% (NS)
250
200
150
100
50
0
2004
2005
2006
Year
time-integrated annual net
CH4 consumption (mg m-2 yr-1)

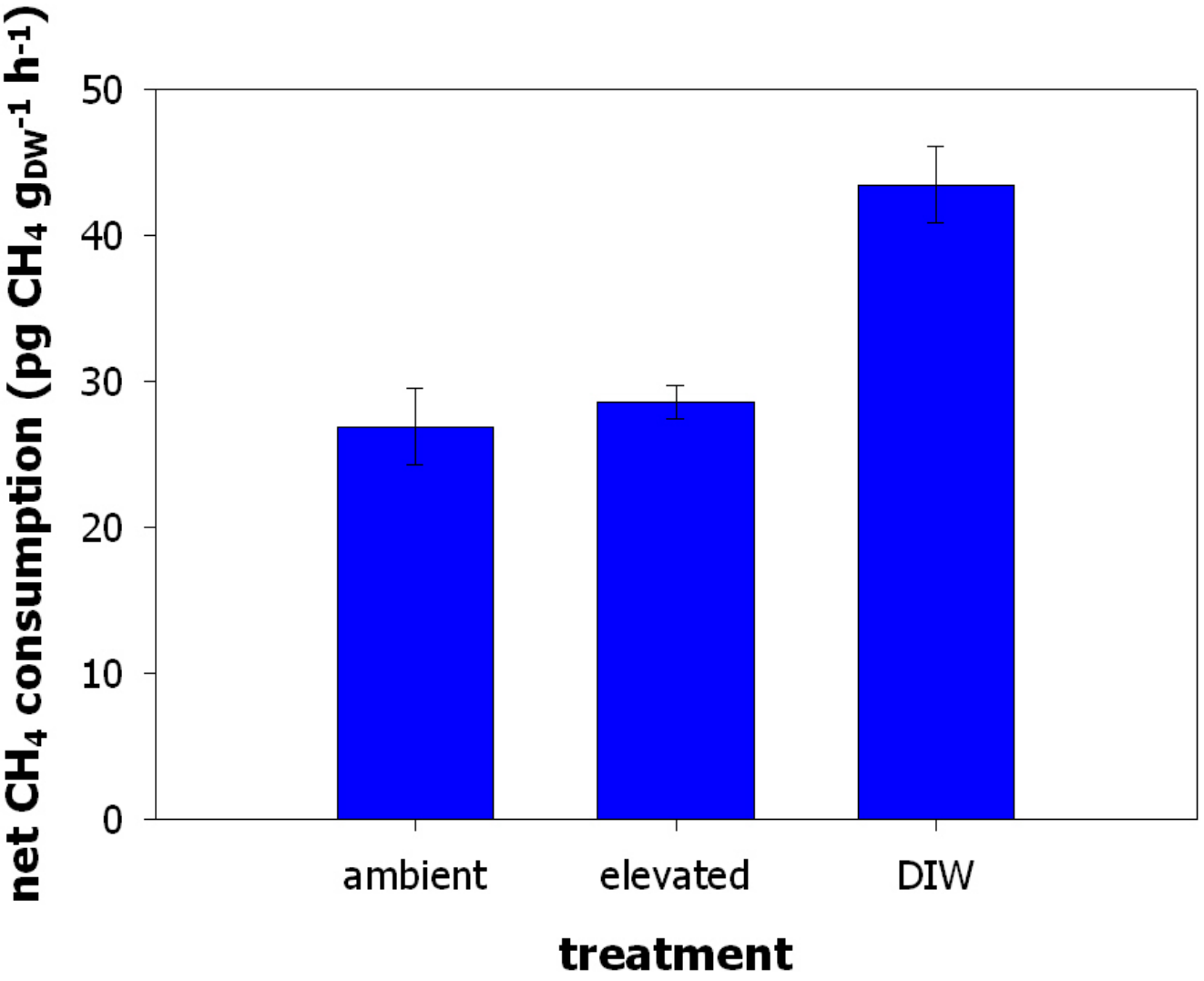
$\underline{H_2}$: Differences in throughfall chemistry between elevated and ambient CO_2 sites do not impact rates of CH_4 oxidation.

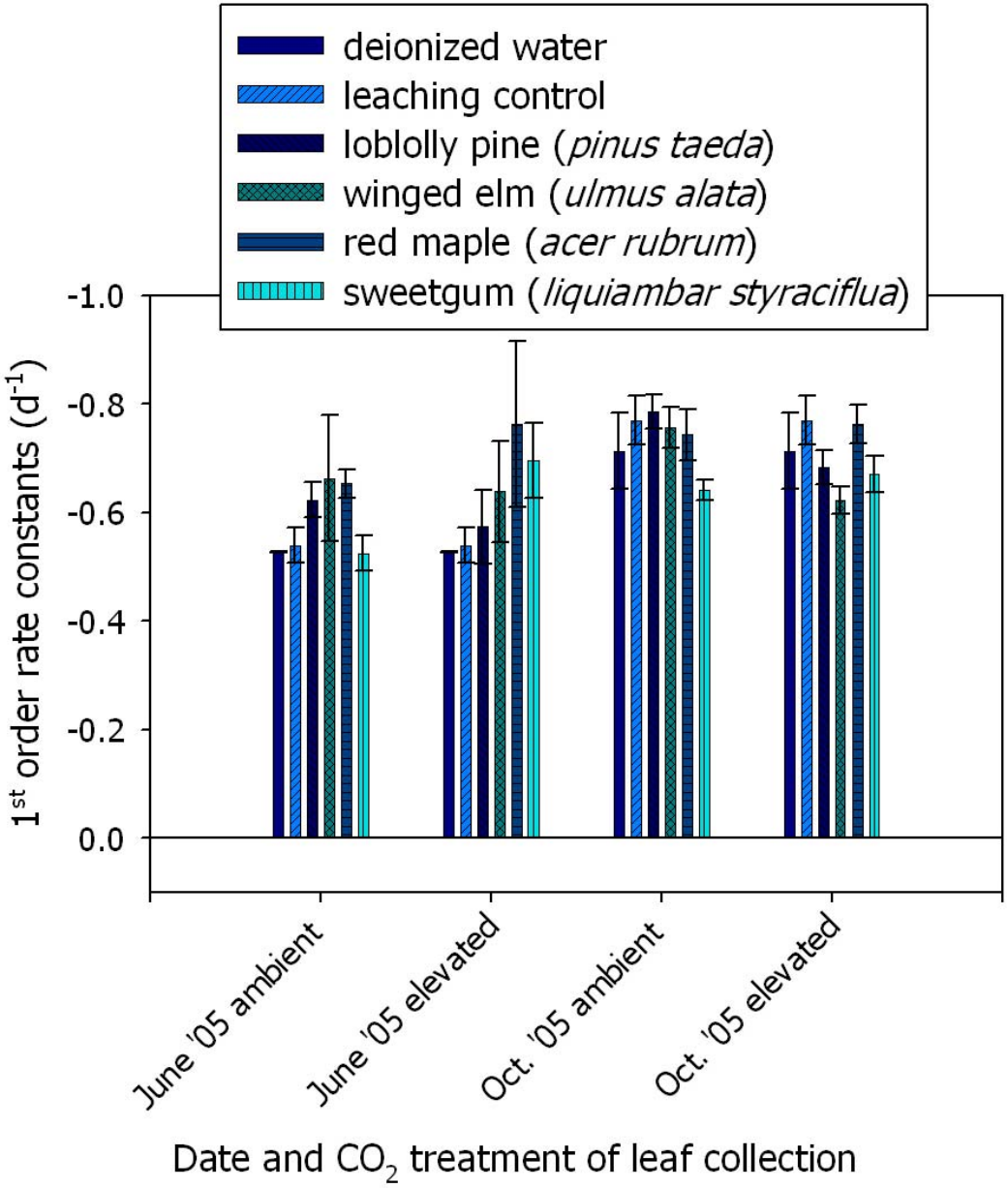
<u>Approach:</u> Jar experiments; Compare rates of CH_4 oxidation in soils amended with throughfall or deionized water.

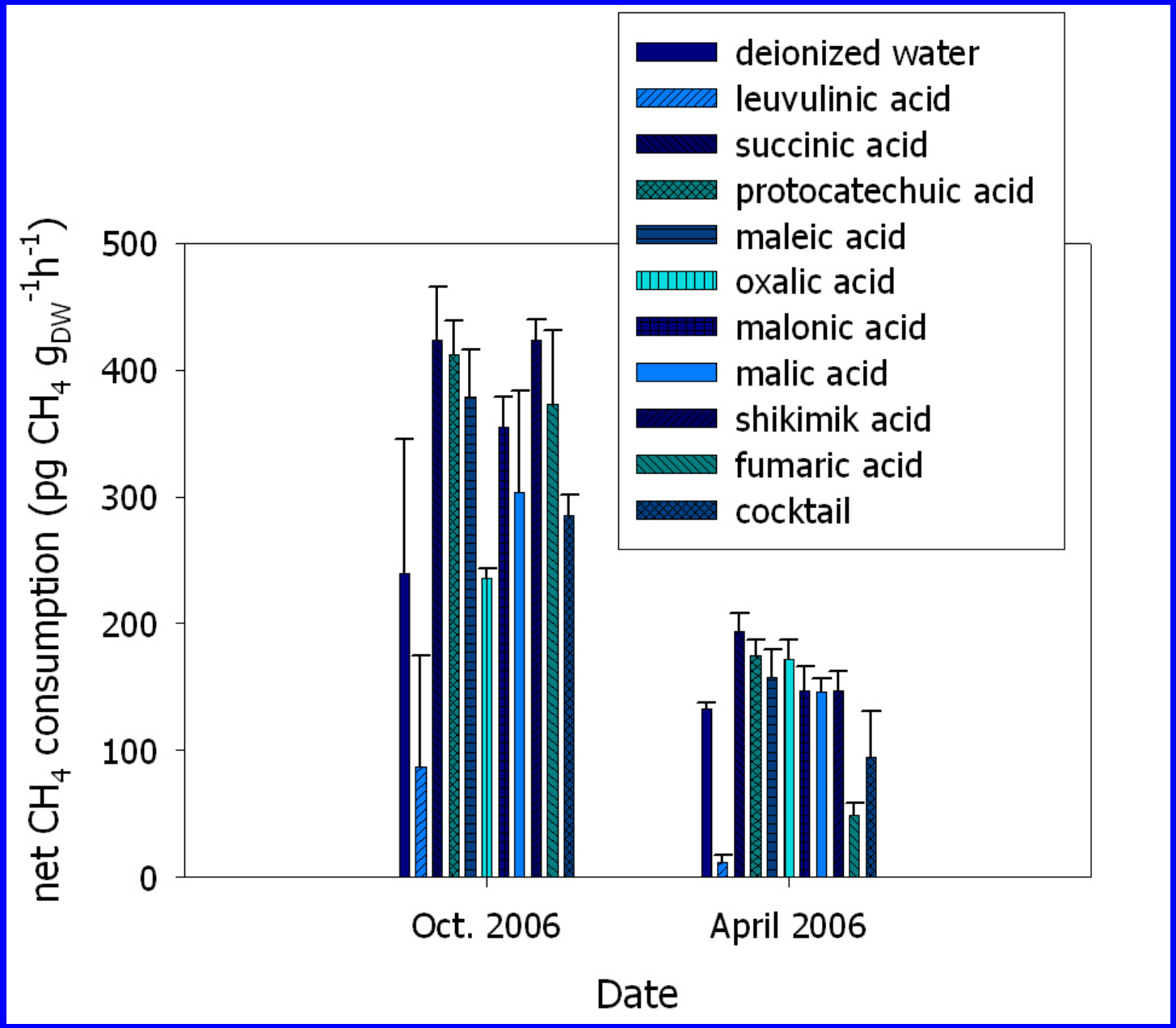

deionized water
ambient throughfall
elevated throughfall
1st order rate constants (d-1)
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
June 2004
Nov. 2004
June 2005
date

$\underline{H_3}$: Rates of CH_4 oxidation are decreased by chemical compounds released to soils by plants growing under elevated CO_2

Approach: Jar experiments; Amend homogenized soil samples with duff leachate or chemical compounds known or predicted to to be released by plants under elevated CO_2


net CH_4 consumption (pg CH_4 g_{DW}^{-1} h^{-1})
50
40
30
20
10
0
ambient
elevated
DIW
treatment

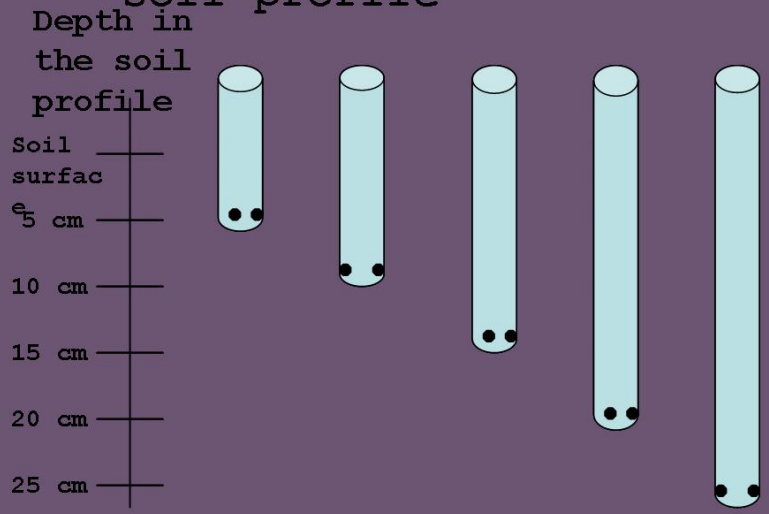

deionized water
leaching control
loblolly pine (*pinus taeda*)
winged elm (*ulmus alata*)
red maple (*acer rubrum*)
sweetgum (*liquiambar styraciflua*)
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
1st order rate constants (d-1)
June '05 ambient
June '05 elevated
Oct. '05 ambient
Oct. '05 elevated
Date and CO2 treatment of leaf collection

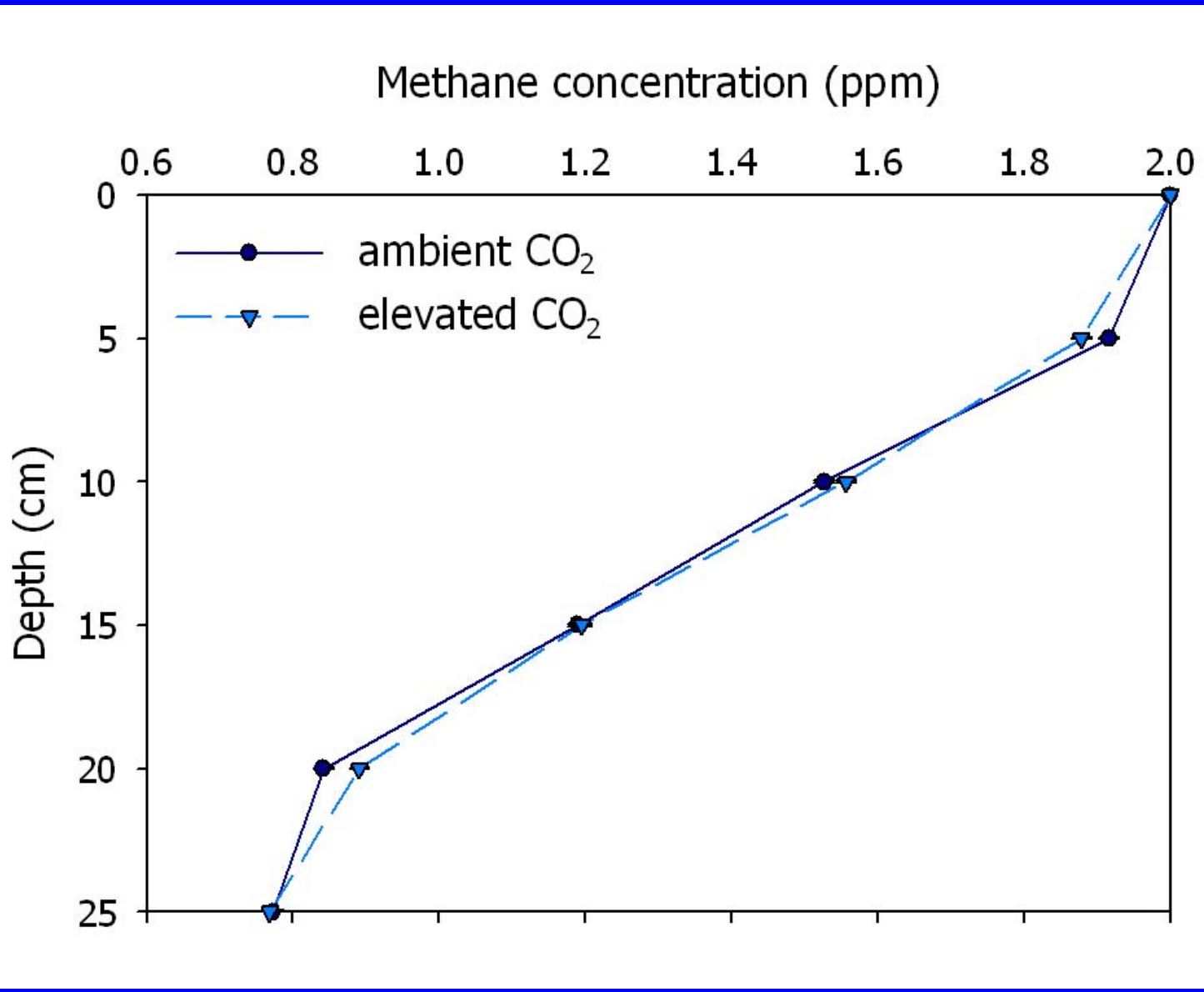

deionized water
leuvulinic acid
succinic acid
protocatechuic acid
maleic acid
oxalic acid
malonic acid
malic acid
shikimik acid
fumaric acid
cocktail
net CH4 consumption (pg CH4 gDW-1h-1)
500
400
300
200
100
0
Oct. 2006
April 2006
Date

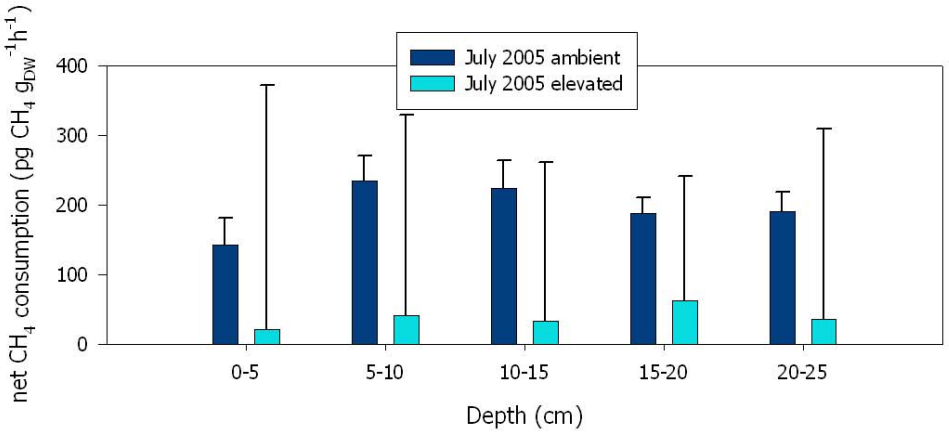
H_4: Reduced atmospheric CH_4 consumption by soil microbes under elevated CO_2 is related to rate of CH_4 supply to or structure of the CH_4-oxidizing community

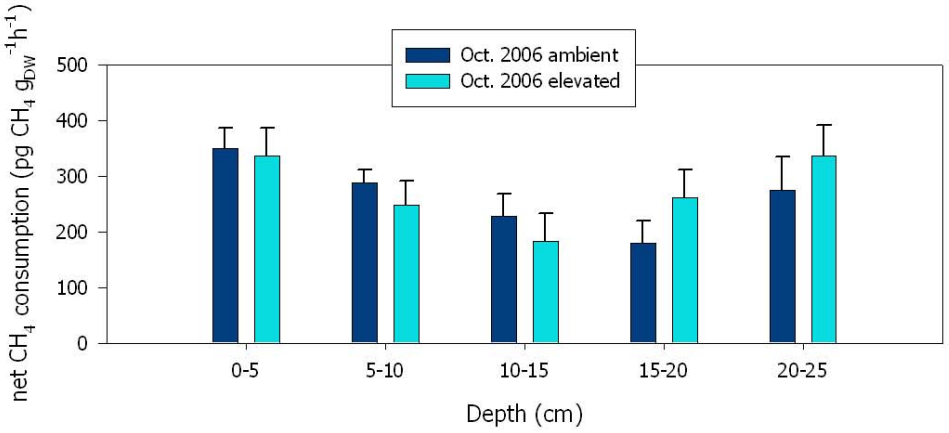
Approaches: Field and jar experiments; (a) homogenized soils in 5 cm increments analyzed for CH_4 oxidation, NH_4^+ oxidation and methangenic potentials; (b) determine profiles of soil CH_4; (c) assess relationship between soil moisture and CH_4 oxidation; (d) determine ^{222}Rn-based effective soil diffusivity

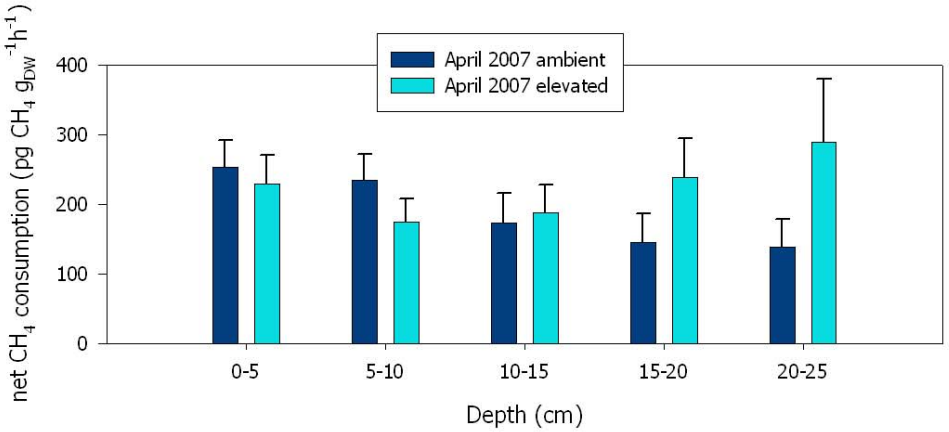
Gas sampling wells at different depths in the soil profile

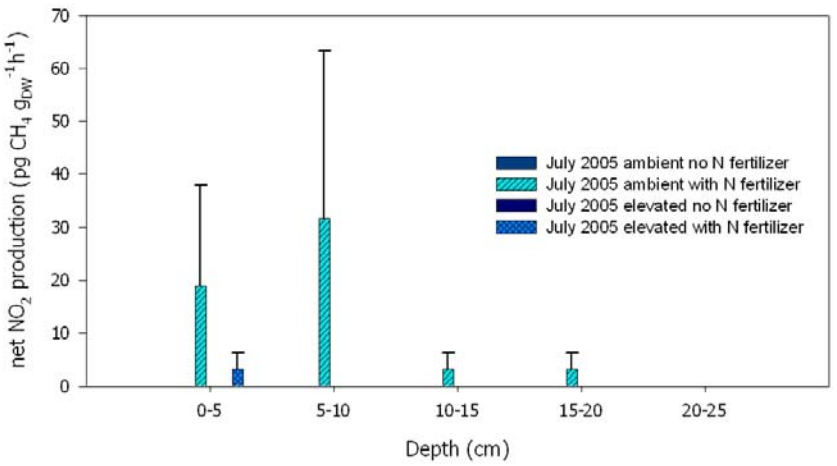


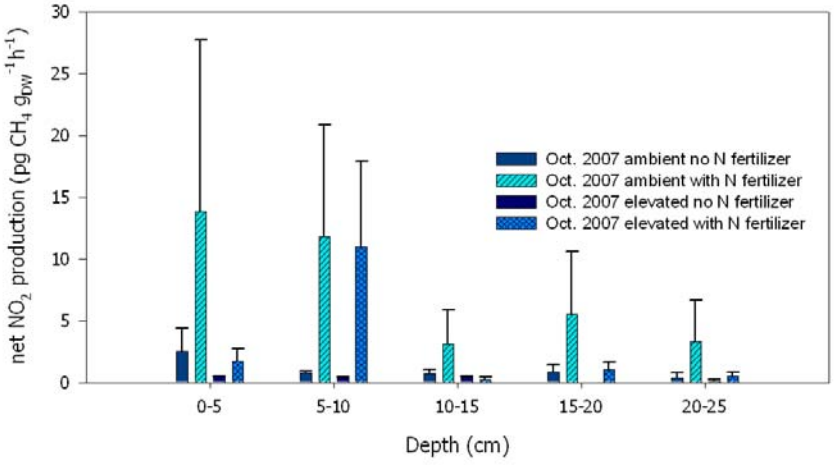

Methane concentration (ppm)
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0
5
10
15
20
25
Depth (cm)
ambient CO_2
elevated CO_2

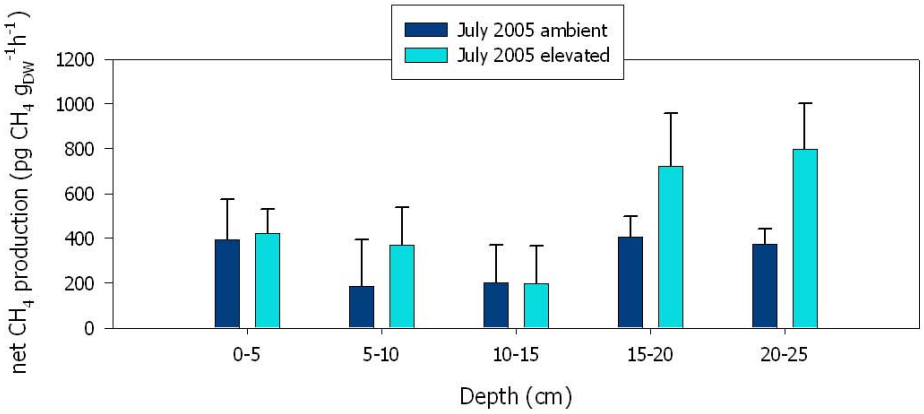

July 2005 ambient
July 2005 elevated
net CH4 consumption (pg CH4 gDW-1h-1)
400
300
200
100
0
0-5
5-10
10-15
15-20
20-25
Depth (cm)

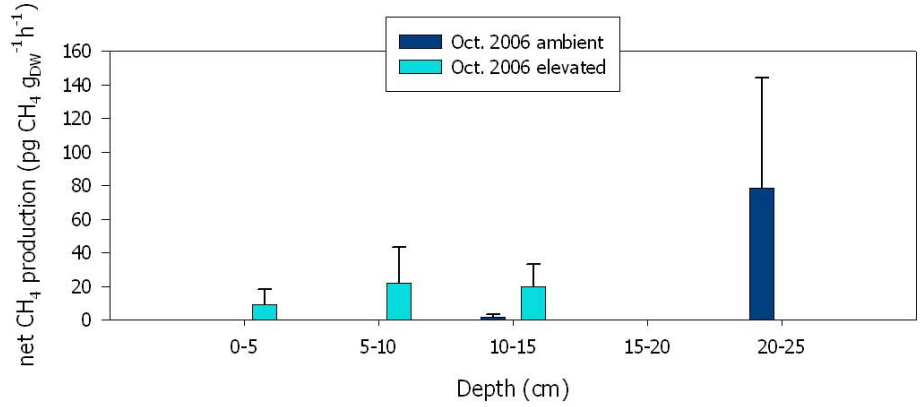

Oct. 2006 ambient
Oct. 2006 elevated
net CH4 consumption (pg CH4 gDW-1h-1)
500
400
300
200
100
0
0-5
5-10
10-15
15-20
20-25
Depth (cm)

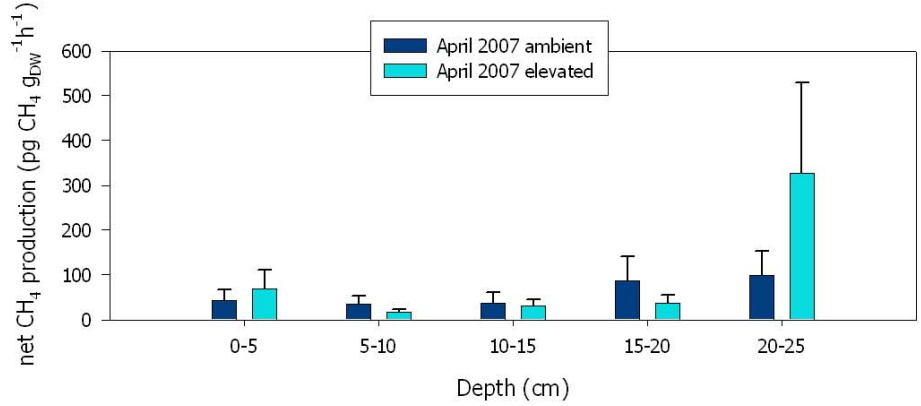

April 2007 ambient
April 2007 elevated
net CH4 consumption (pg CH4 gDW-1h-1)
400
300
200
100
0
0-5
5-10
10-15
15-20
20-25
Depth (cm)

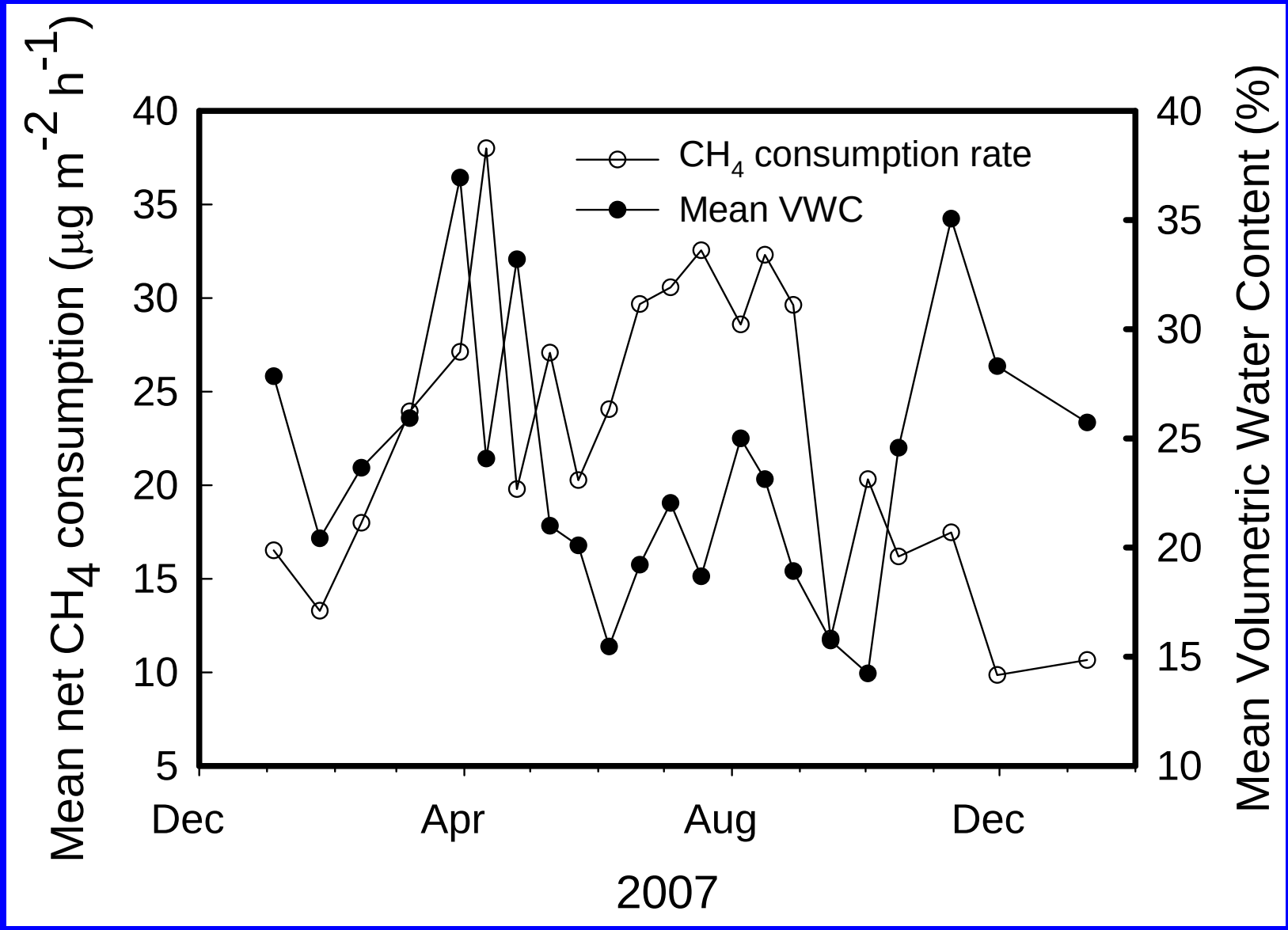

net NO_2 production (pg CH_4 $g_{DW}^{-1}h^{-1}$)
70
60
50
40
30
20
10
0
July 2005 ambient no N fertilizer
July 2005 ambient with N fertilizer
July 2005 elevated no N fertilizer
July 2005 elevated with N fertilizer
0-5
5-10
10-15
15-20
20-25
Depth (cm)

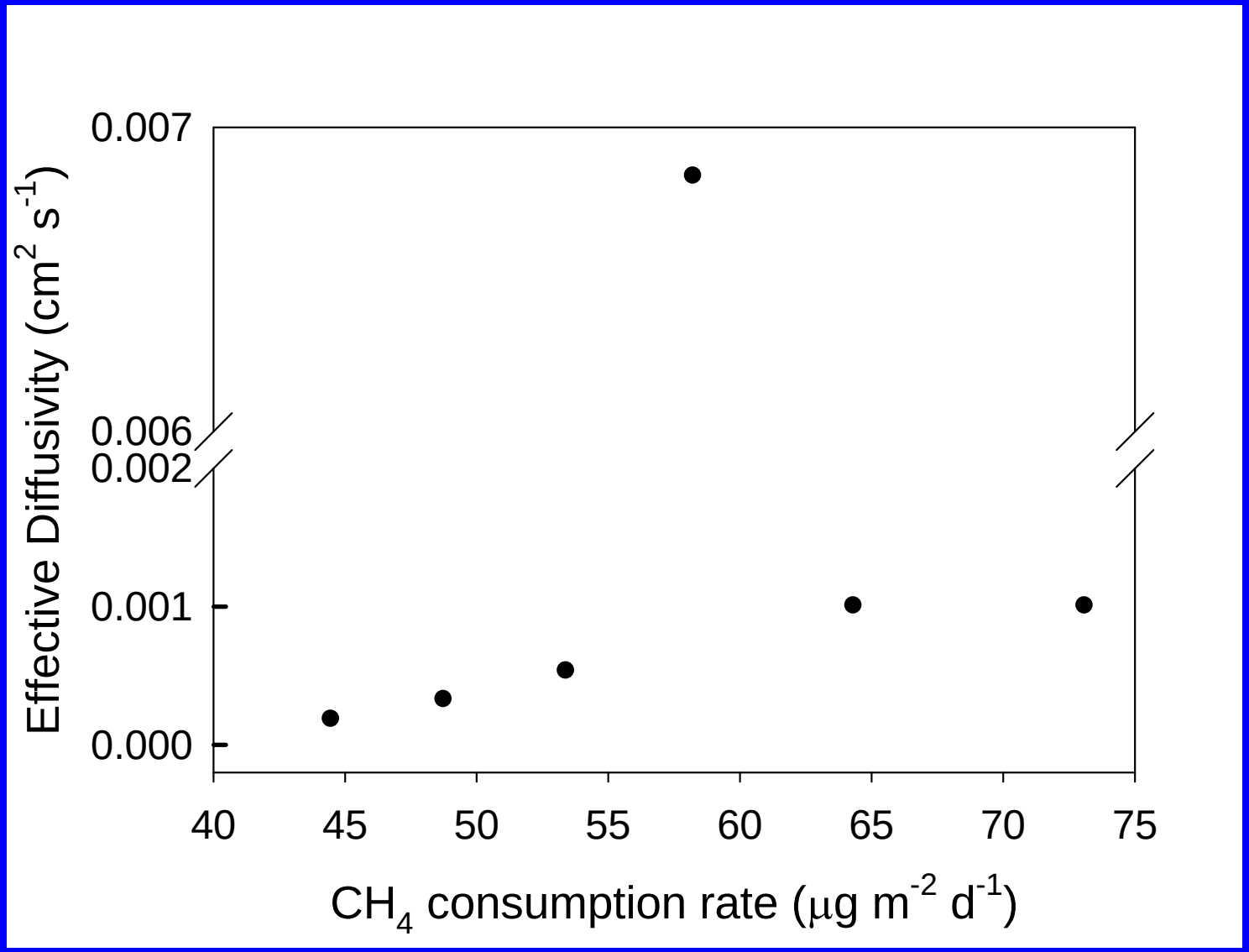

net NO_2 production (pg CH_4 $g_{DW}^{-1}h^{-1}$)
30
25
20
15
10
5
0
Oct. 2007 ambient no N fertilizer
Oct. 2007 ambient with N fertilizer
Oct. 2007 elevated no N fertilizer
Oct. 2007 elevated with N fertilizer
0-5
5-10
10-15
15-20
20-25
Depth (cm)


July 2005 ambient
July 2005 elevated
net CH4 production (pg CH4 gDW-1h-1)
1200
1000
800
600
400
200
0
0-5
5-10
10-15
15-20
20-25
Depth (cm)


Oct. 2006 ambient
Oct. 2006 elevated
net CH4 production (pg CH4 gDW-1h-1)
160
140
120
100
80
60
40
20
0
0-5
5-10
10-15
15-20
20-25
Depth (cm)


April 2007 ambient
April 2007 elevated
net CH4 production (pg CH4 gDW-1h-1)
600
500
400
300
200
100
0
0-5
5-10
10-15
15-20
20-25
Depth (cm)


Mean net CH4 consumption (μg m-2 h-1)
Mean Volumetric Water Content (%)
CH4 consumption rate
Mean VWC
40
35
30
25
20
15
10
5
Dec
Apr
Aug
Dec
2007


0.007
0.006
0.002
0.001
0.000
Effective Diffusivity (cm2 s-1)
40
45
50
55
60
65
70
75
CH4 consumption rate (μg m-2 d-1)

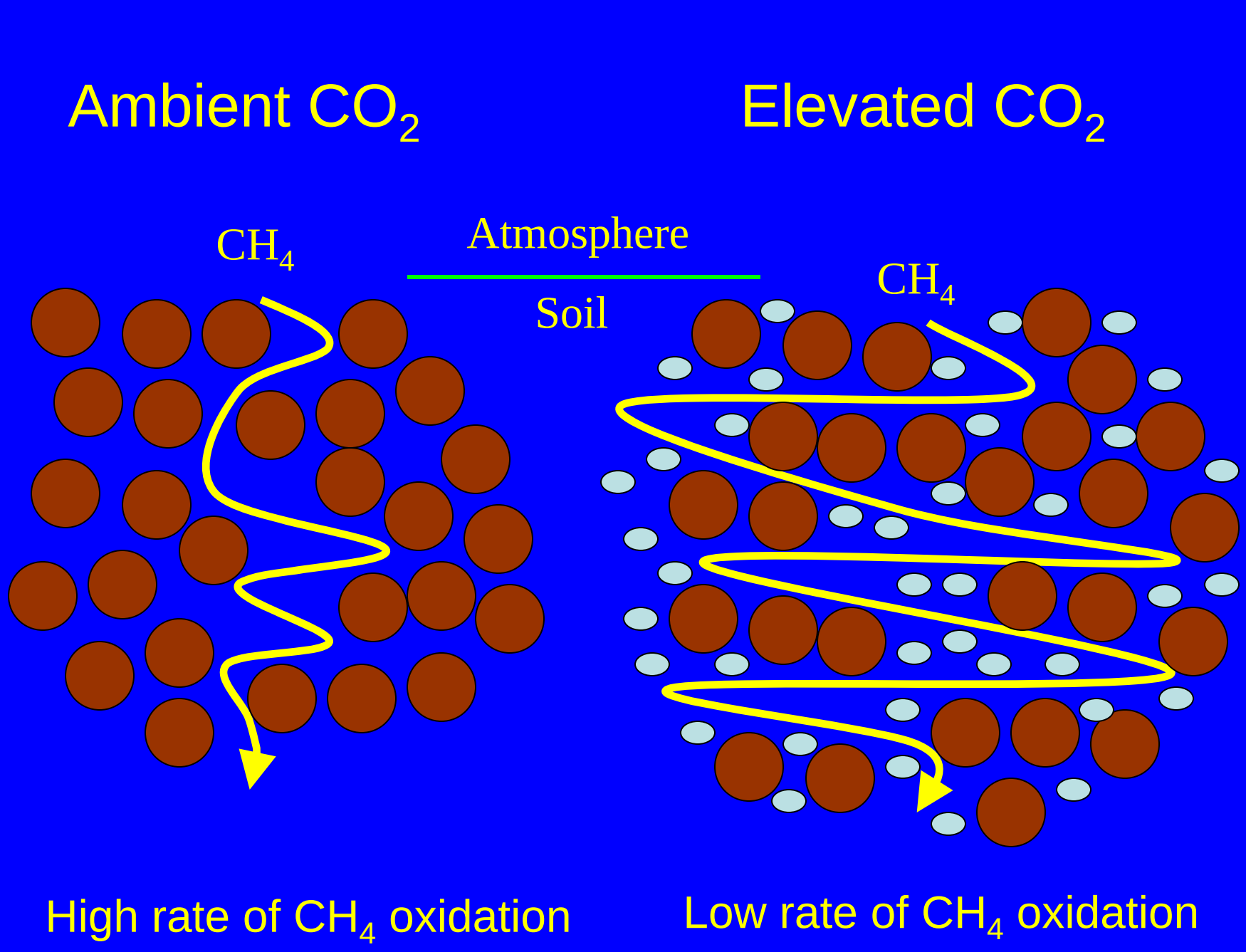
Conclusions

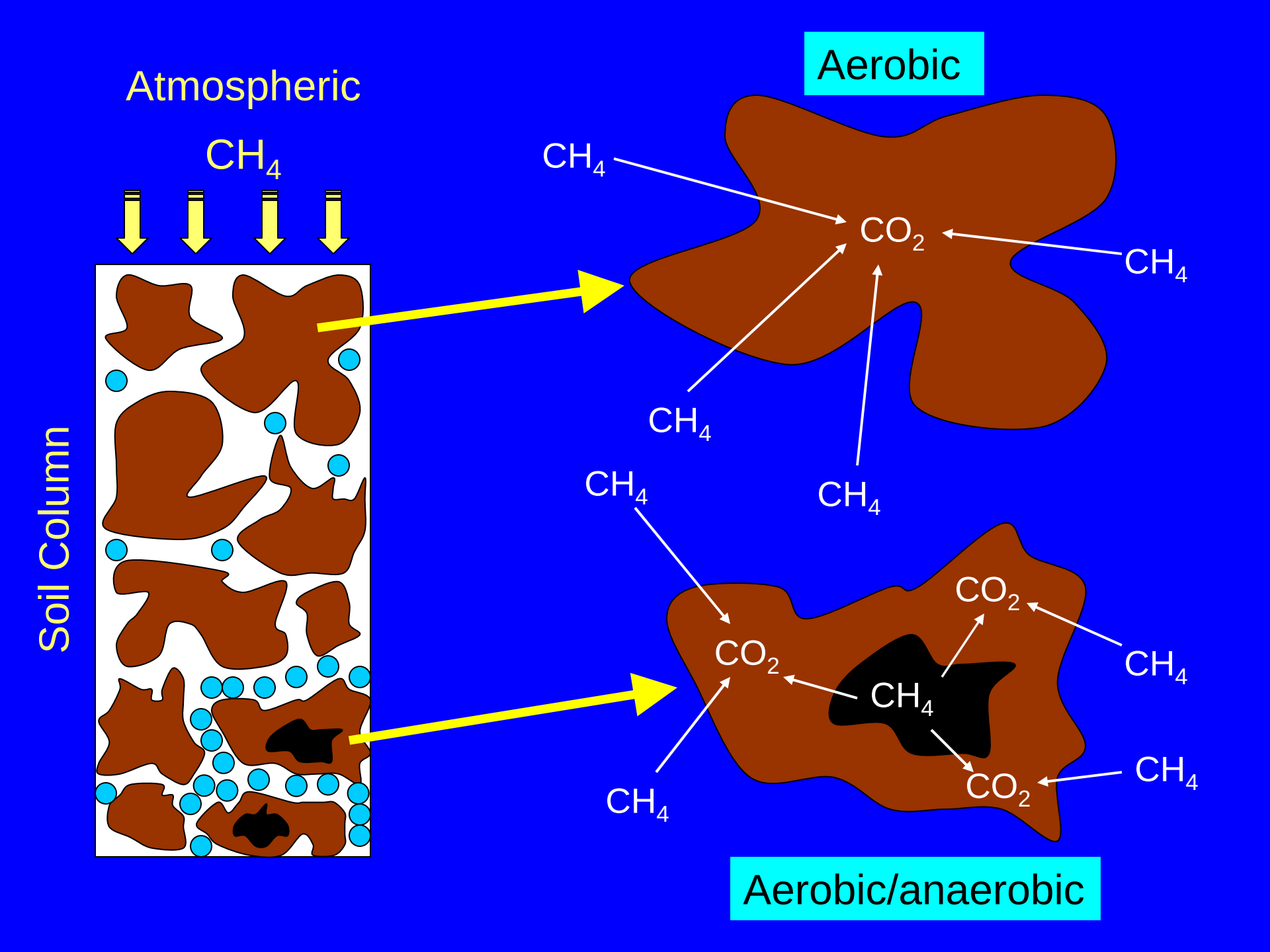
1) Reduced atmospheric CH_4 consumption under elevated CO_2 is a sustained response.

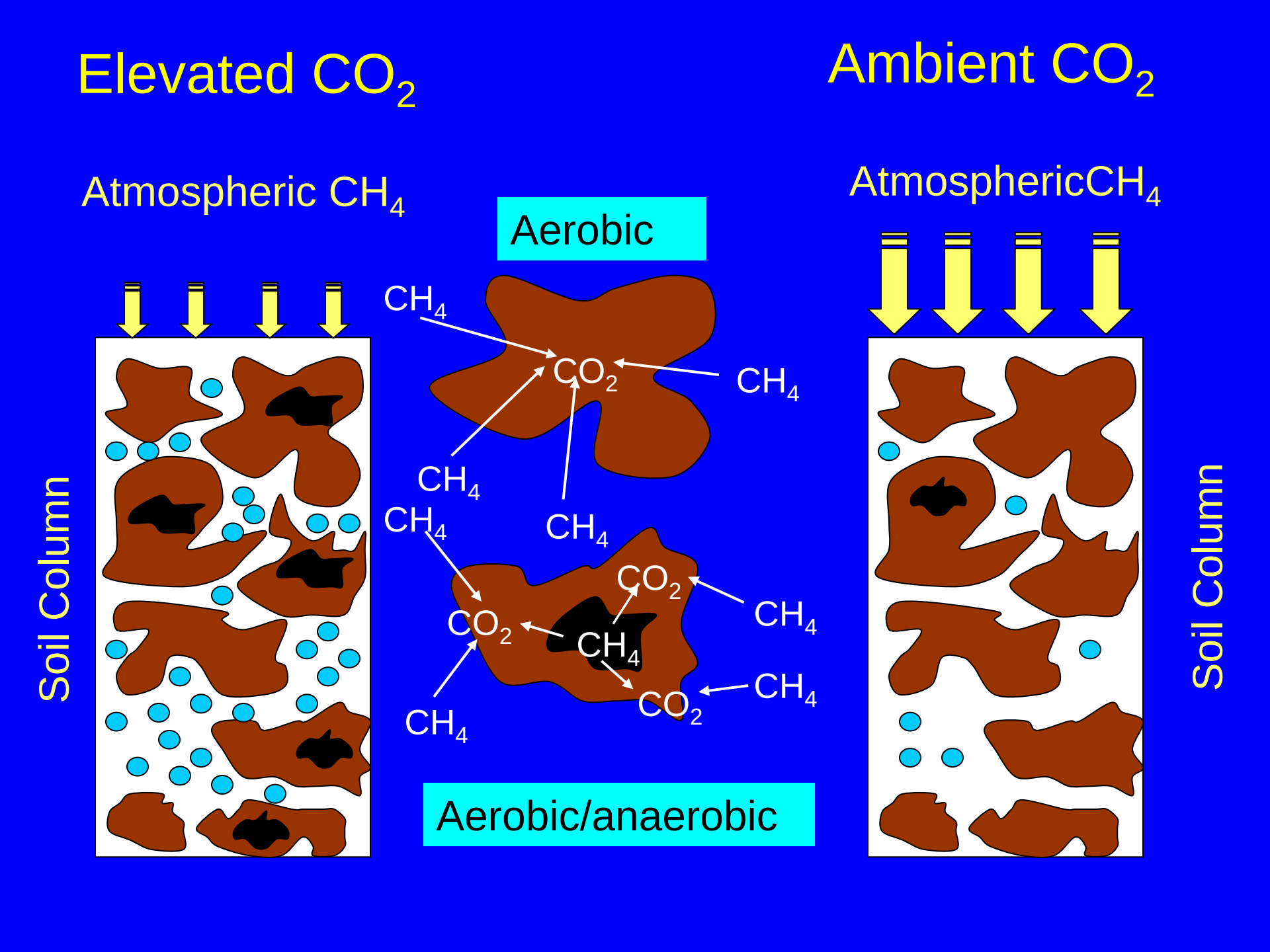
2) Causes remain difficult to identify
   a) Limits of detection approached wrt instrumentation
   b) Limited destructive sampling
      - Few lab studies can be performed
      - Few treatment reps

3) Probably not due to:
   a) Δ structure or locus of CH_4-oxidizing community
   b) Inhibitory chemicals

4) Likely due to combination of:
   a) Reduced rates of CH_4 diffusion into soil
   b) Localized zones of CH_4 production in soil


Ambient CO_2
Elevated CO_2
CH_4
Atmosphere
Soil
CH_4
High rate of CH_4 oxidation
Low rate of CH_4 oxidation


Atmospheric
CH_4
Soil Column
Aerobic
CH_4
CO_2
CH_4
CH_4
CH_4
CH_4
CO_2
CO_2
CH_4
CH_4
CH_4
CO_2
Aerobic/anaerobic


Elevated CO_2
Ambient CO_2
Atmospheric CH_4
AtmosphericCH$_4$
Aerobic
CH_4
CO_2
CH_4
CH_4
CH_4
CH_4
CO_2
CO_2
CH_4
CH_4
CH_4
CO_2
Aerobic/anaerobic
Soil Column
Soil Column

Ongoing and Planned Work

- Seasonal comparison of ^{222}Rn-based effective diffusivities vs. rates of atmospehric CH_4 consumption
- SF_6-based rates of effective diffusivity

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