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

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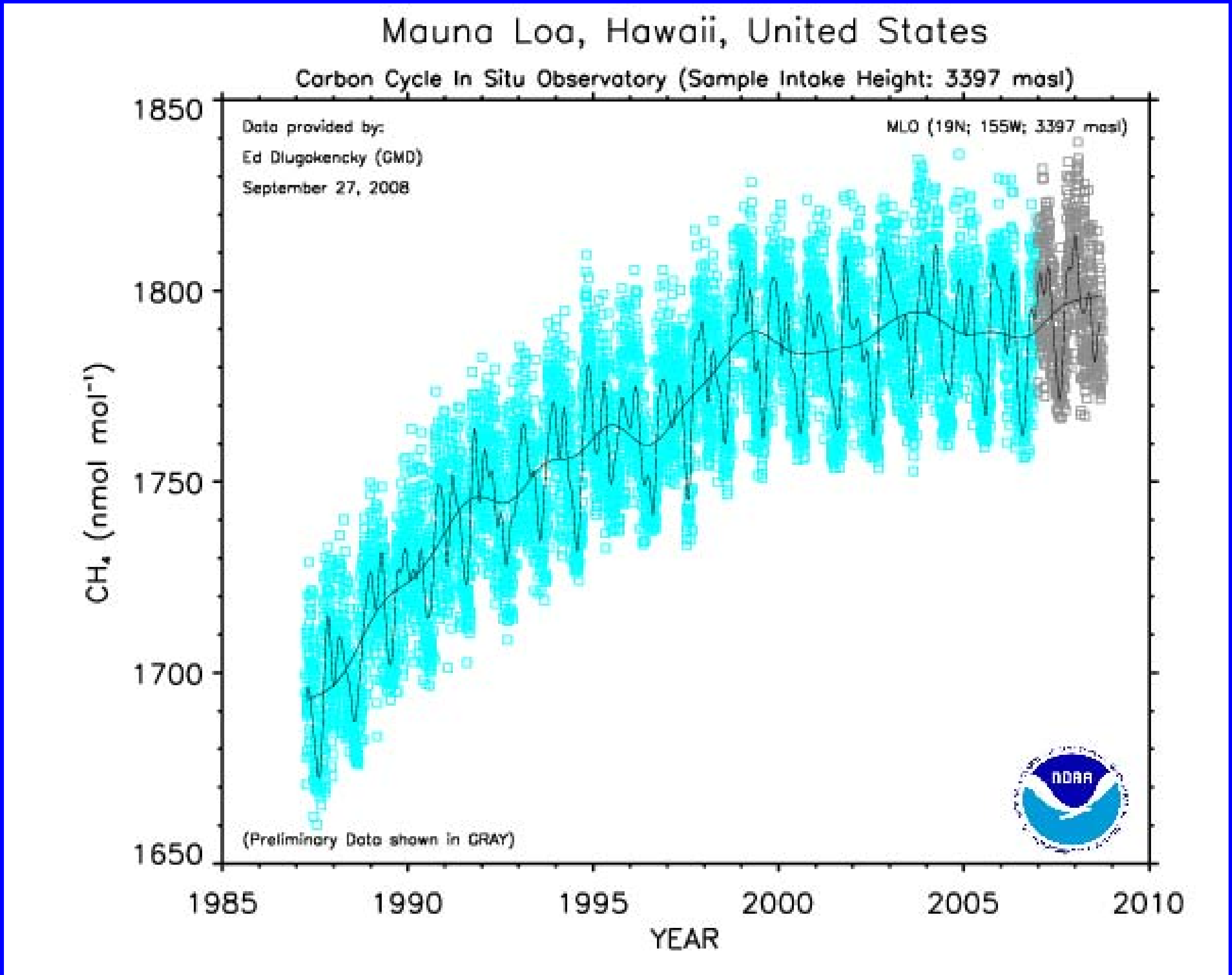
Background – Atmospheric CH_4

- 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

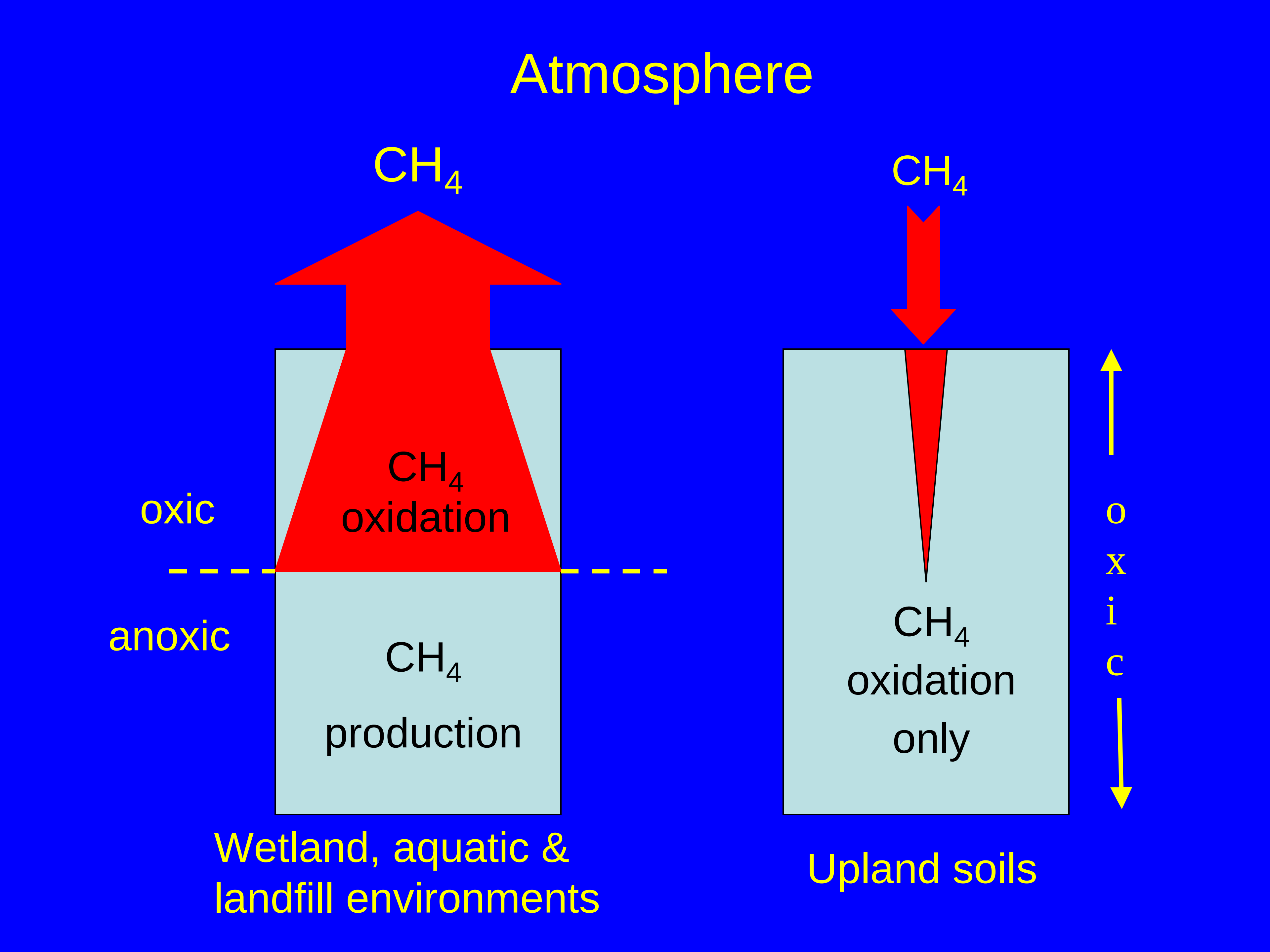
Photochemically active

- 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
	$\Sigma = 600$
Sinks	
Tropospheric OH	510
Stratospheric loss	40
Soils	**30**
	$\Sigma = 580$

Source: Lelieveld et al. (1998)



Atmosphere
CH_4
CH_4
CH_4 oxidation
oxic
anoxic
CH_4 production
CH_4 oxidation only
o x i c
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)

<u>Field (Phillips et al. 2001a, Whalen, unpublished)</u>

- 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

<u>Laboratory (Phillips et al. 2001b)</u>

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

<u>Significance:</u>

- 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

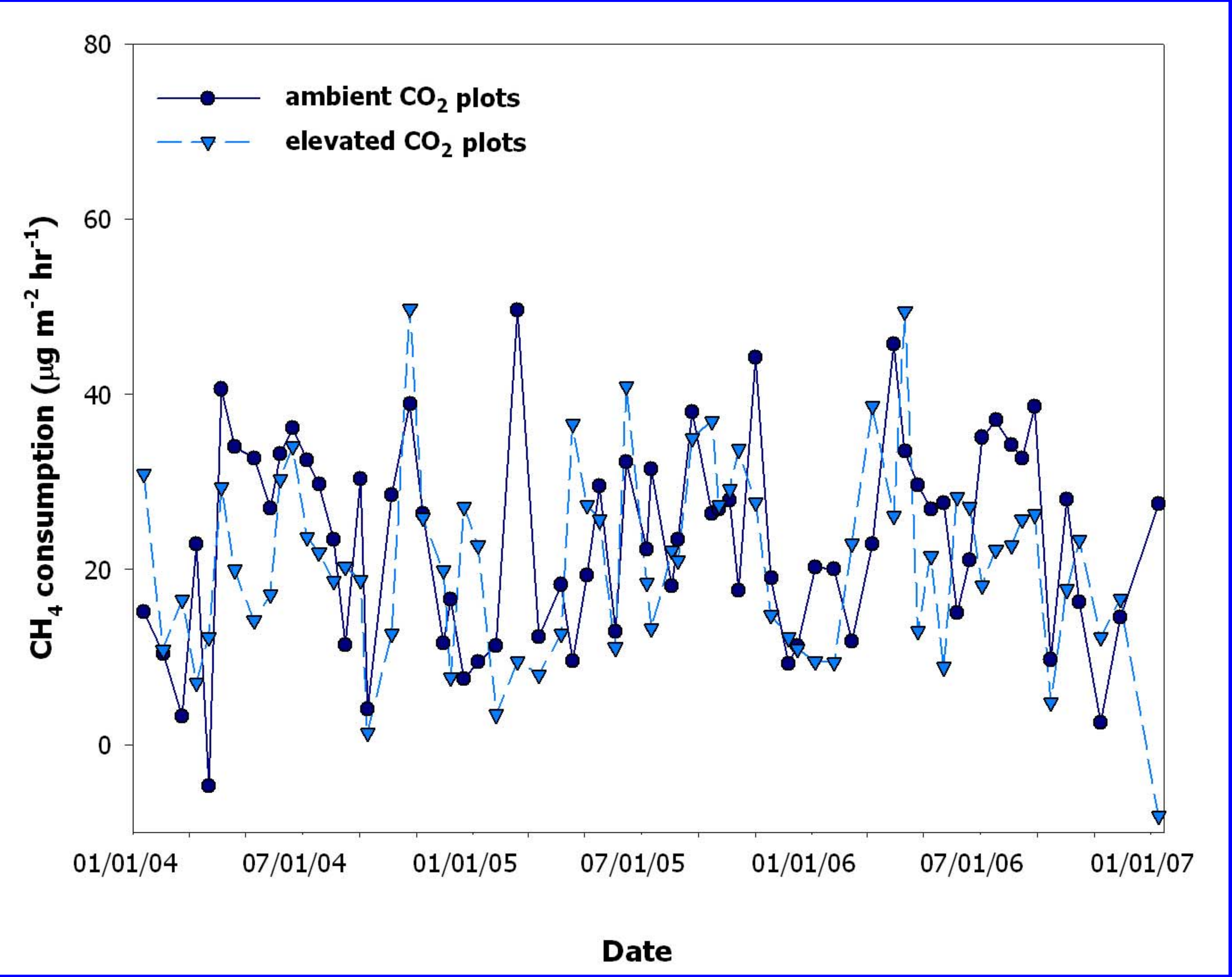
H$_3$: Rates of CH_4 oxidation are decreased by chemical compounds released to soils by plants growing under elevated CO_2

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

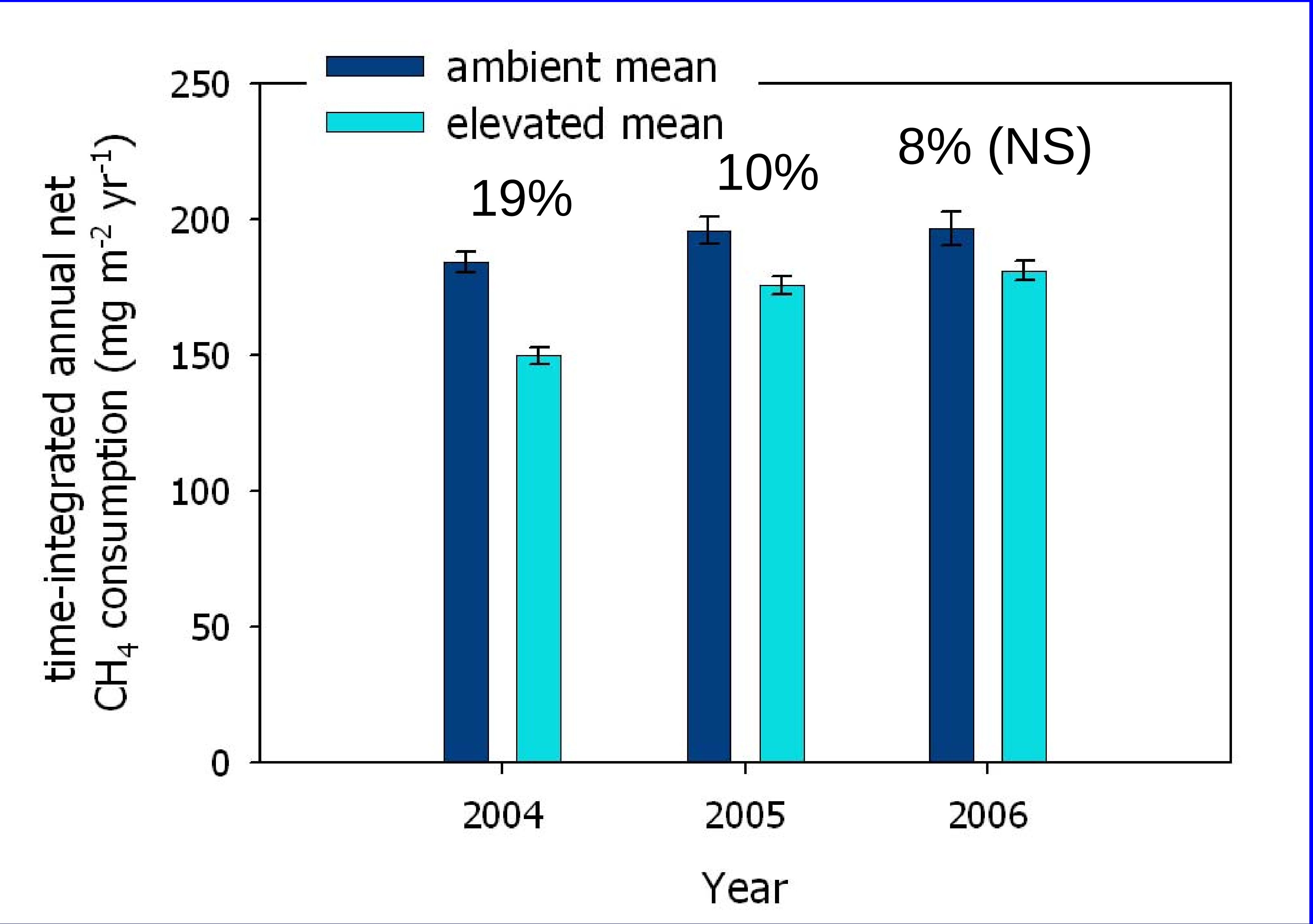
STAR Research (1/04-present)
Hypotheses/Approaches

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



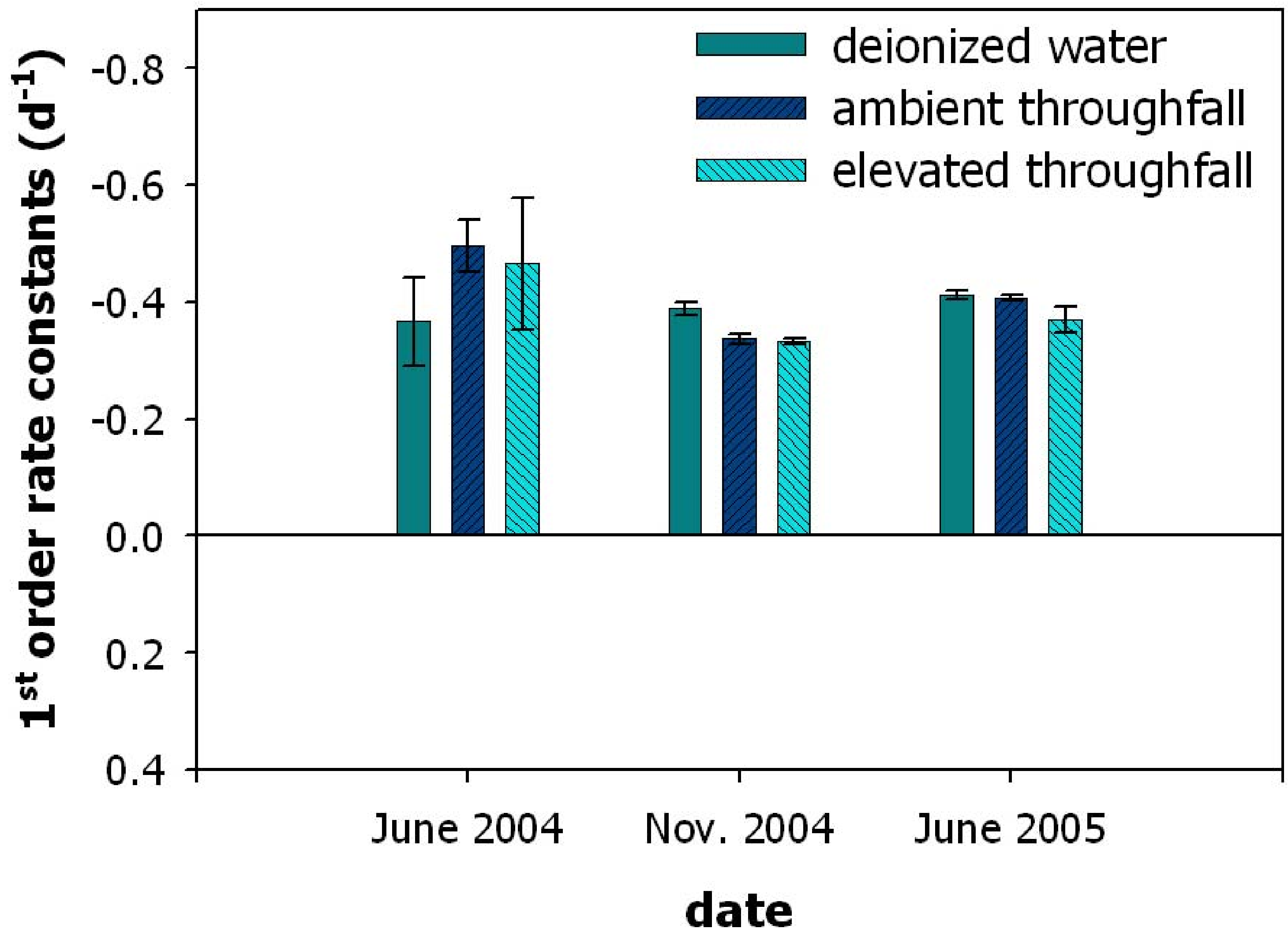
ambient CO_2 plots
elevated CO_2 plots
CH_4 consumption ($\mu g\ m^{-2}\ hr^{-1}$)
80
60
40
20
0
01/01/04
07/01/04
01/01/05
07/01/05
01/01/06
07/01/06
01/01/07
Date



ambient mean
elevated mean
19%
10%
8% (NS)
time-integrated annual net
CH_4 consumption (mg m^{-2} yr^{-1})
250
200
150
100
50
0
2004
2005
2006
Year

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

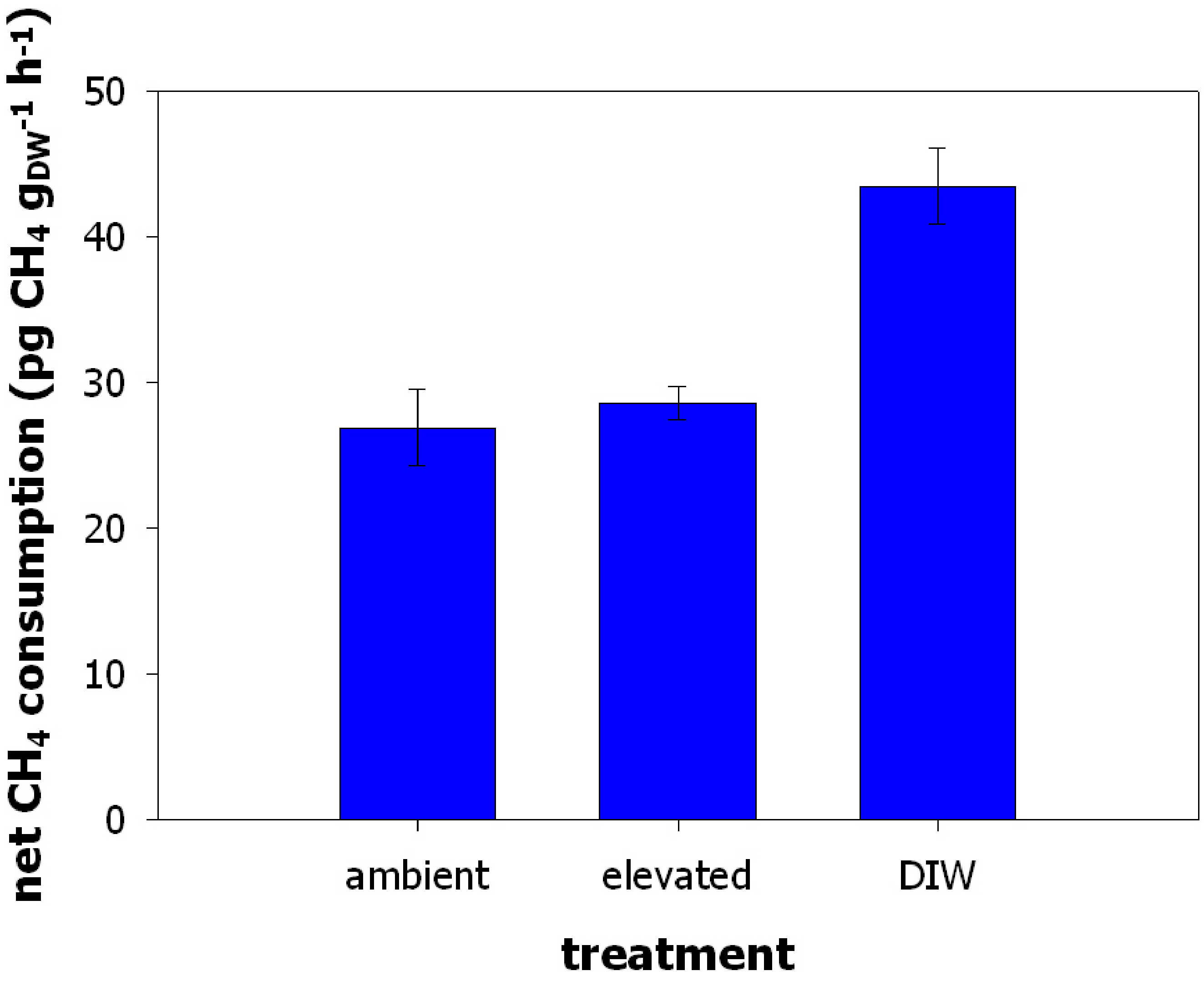
Approach: Jar experiments; Compare rates of CH_4 oxidation in soils amended with throughfall or deionized water.



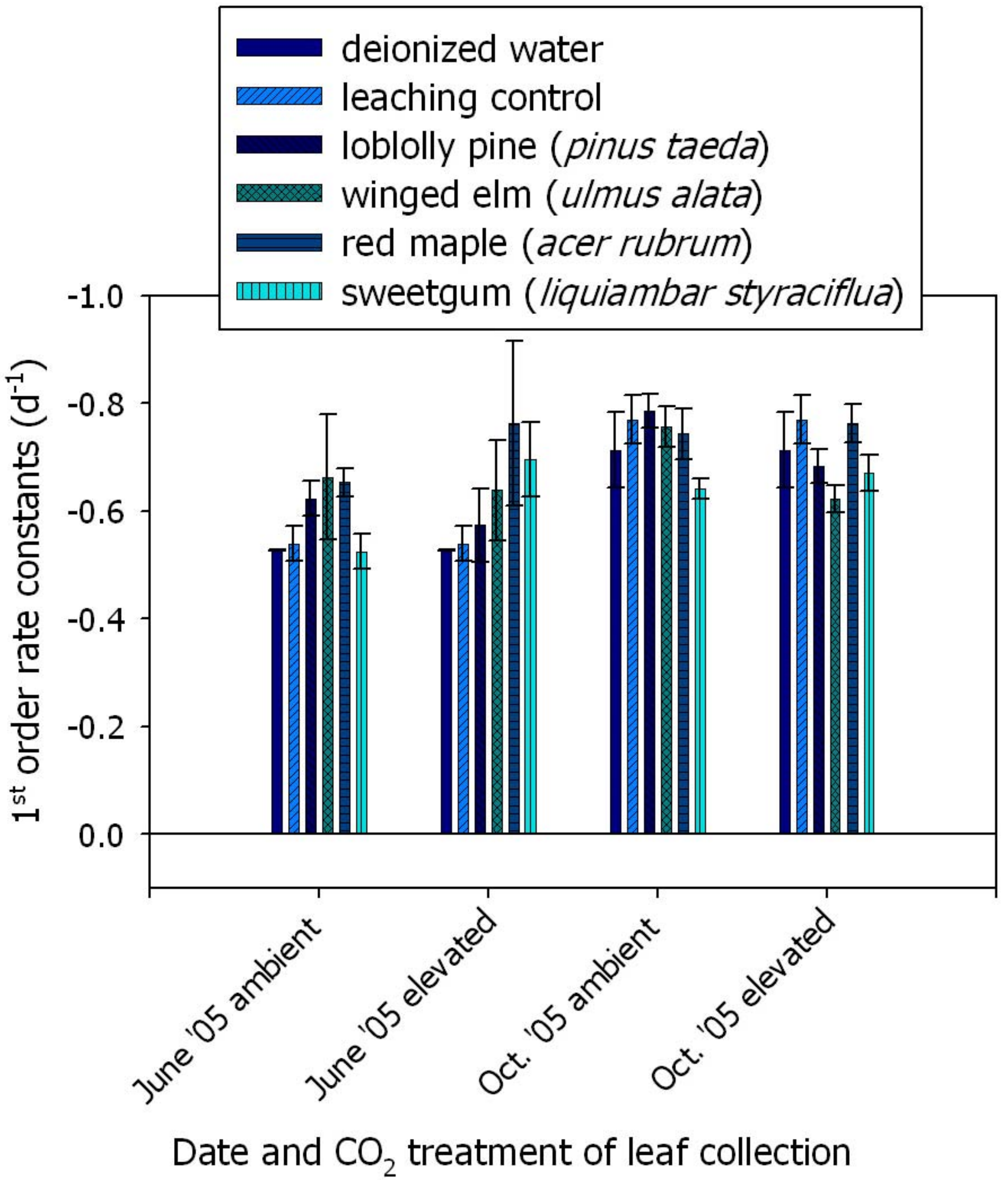
deionized water
ambient throughfall
elevated throughfall
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
1st order rate constants (d-1)
June 2004
Nov. 2004
June 2005
date

$\underline{H}_3$: Rates of CH_4 oxidation are decreased by chemical compounds released to soils by plants growing under elevated CO_2

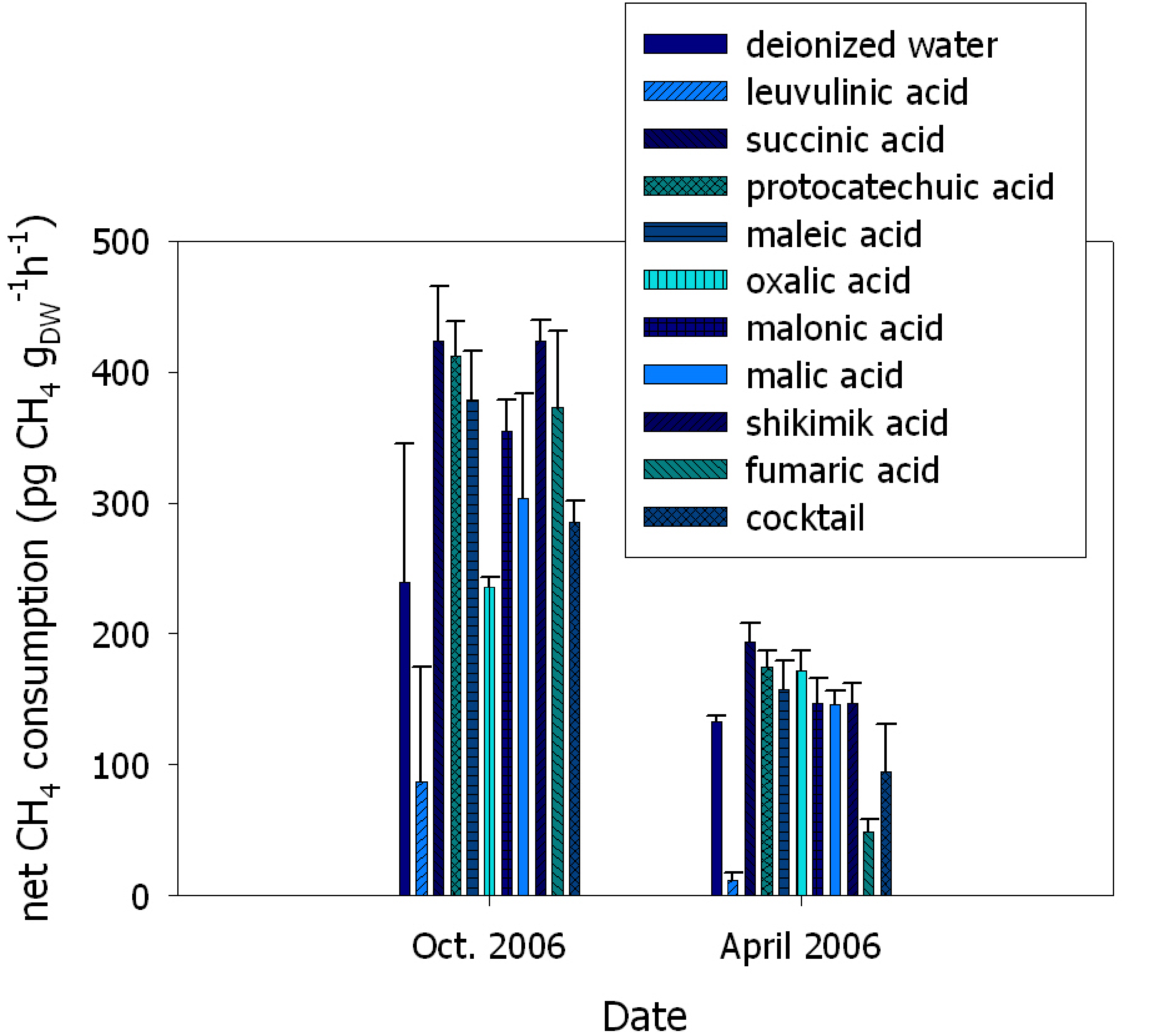
Approach: Jar experiments; Amend homogenized soil samples with duff leachate or chemical compounds known or predicted to to be released by plants under elevated CO_2



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



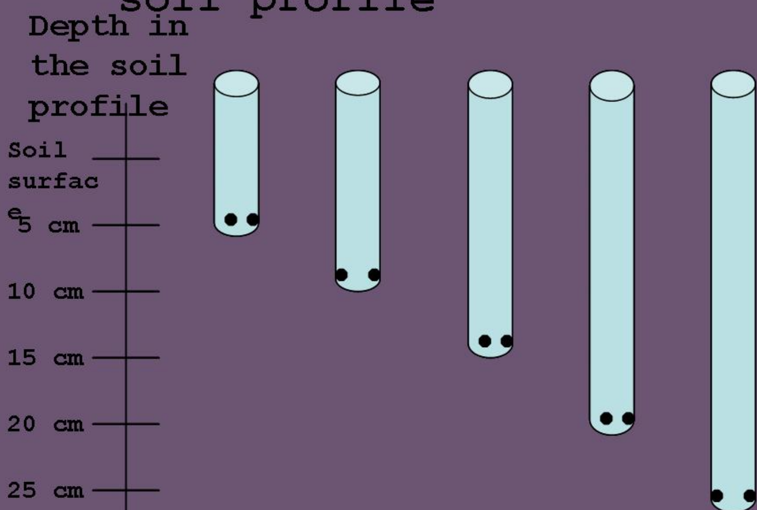
deionized water
leaching control
loblolly pine (*pinus taeda*)
winged elm (*ulmus alata*)
red maple (*acer rubrum*)
sweetgum (*liquiambar styraciflua*)
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
1st order rate constants (d^{-1})
June '05 ambient
June '05 elevated
Oct. '05 ambient
Oct. '05 elevated
Date and CO_2 treatment of leaf collection

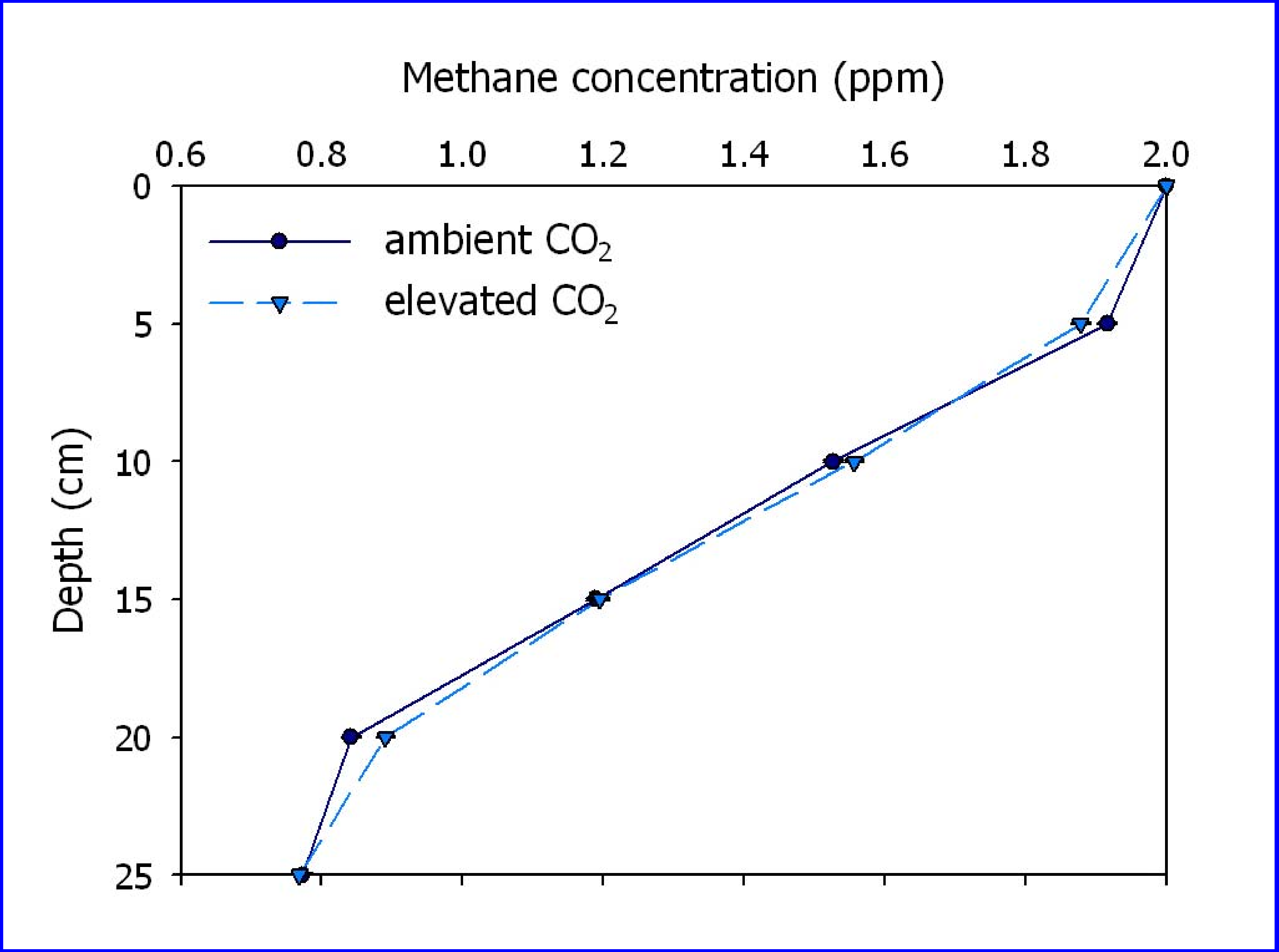

deionized water
leuvulinic acid
succinic acid
protocatechuic acid
maleic acid
oxalic acid
malonic acid
malic acid
shikimik acid
fumaric acid
cocktail
net CH_4 consumption (pg CH_4 $g_{DW}^{-1}h^{-1}$)
500
400
300
200
100
0
Oct. 2006
April 2006
Date

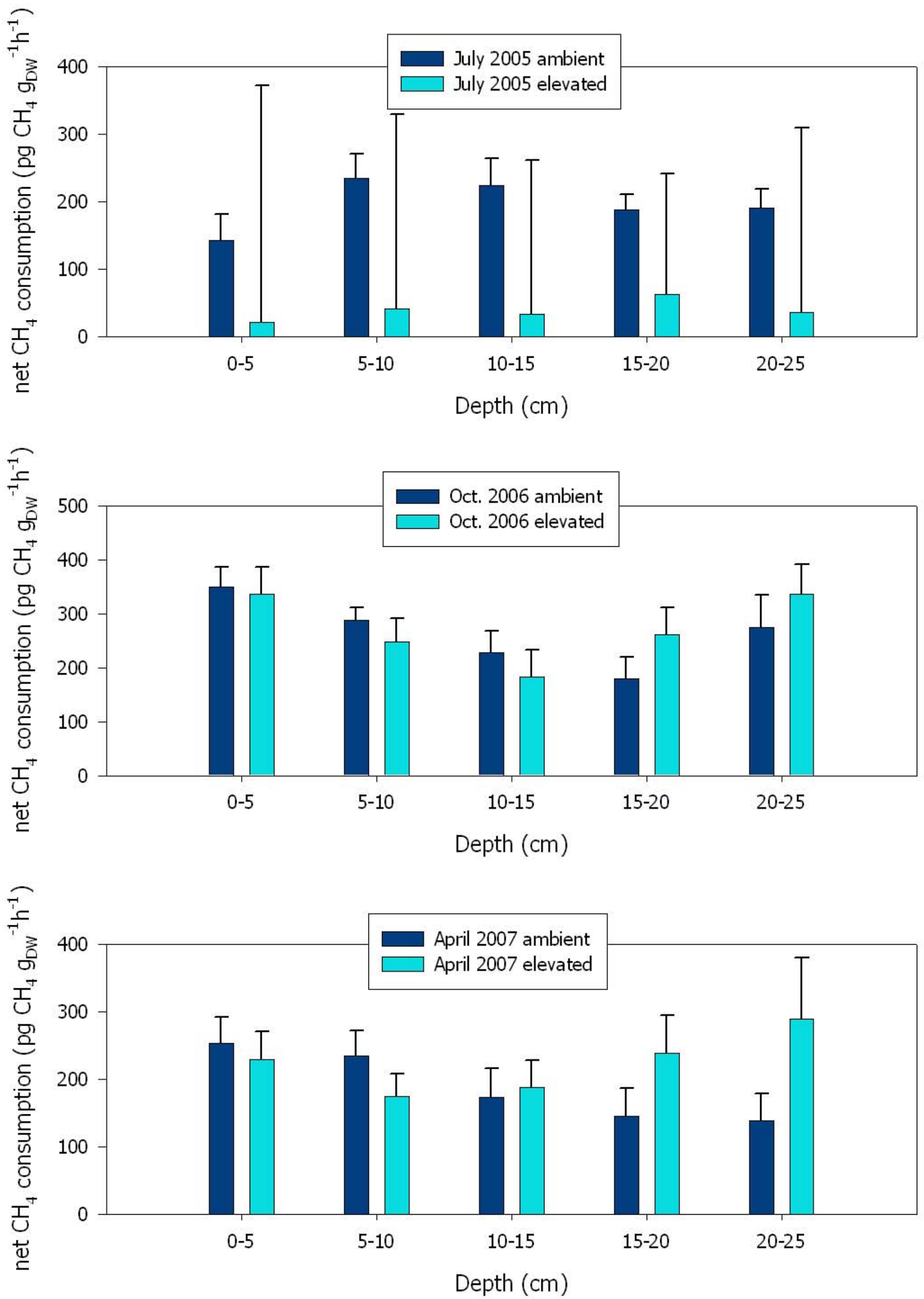
H$_4$: Reduced atmospheric CH_4 consumption by soil microbes under elevated CO_2 is related to rate of CH_4 supply to or structure of the CH_4-oxidizing community

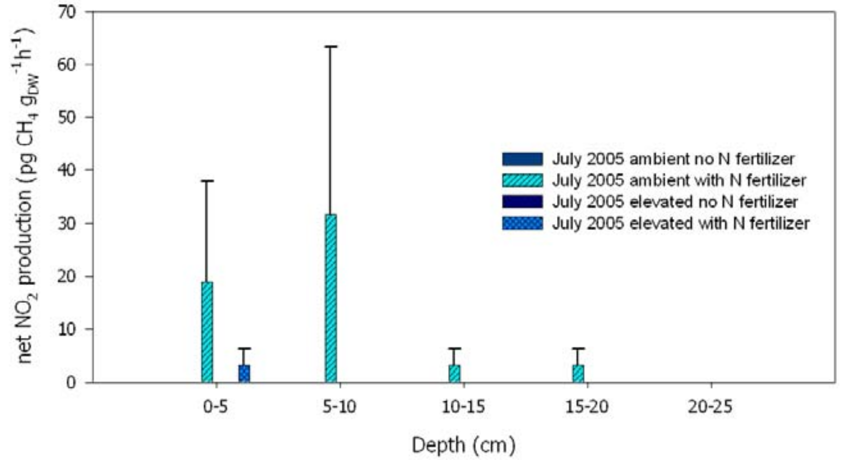
Approaches: Field and jar experiments; (a) homogenized soils in 5 cm increments analyzed for CH_4 oxidation, NH_4^+ oxidation and methangenic potentials; (b) determine profiles of soil CH_4; (c) assess relationship between soil moisture and CH_4 oxidation; (d) determine ^{222}Rn-based effective soil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

Gas sampling wells at different depths in the soil profile

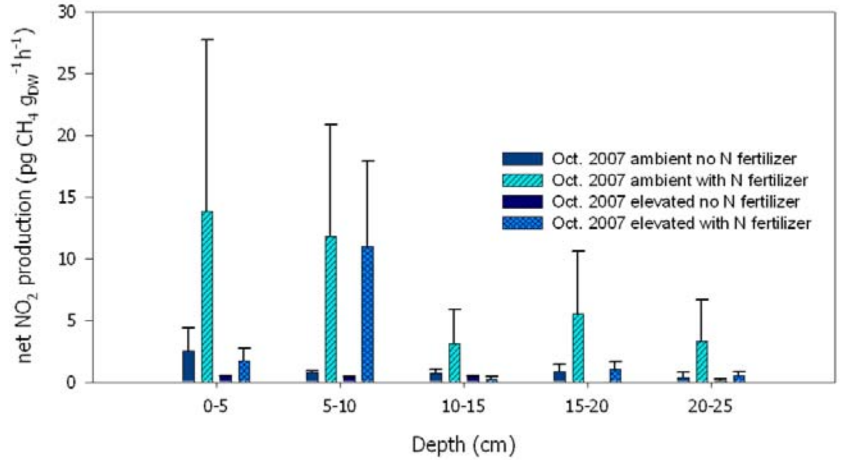



Methane concentration (ppm)
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0
5
10
15
20
25
Depth (cm)
ambient CO_2
elevated CO_2

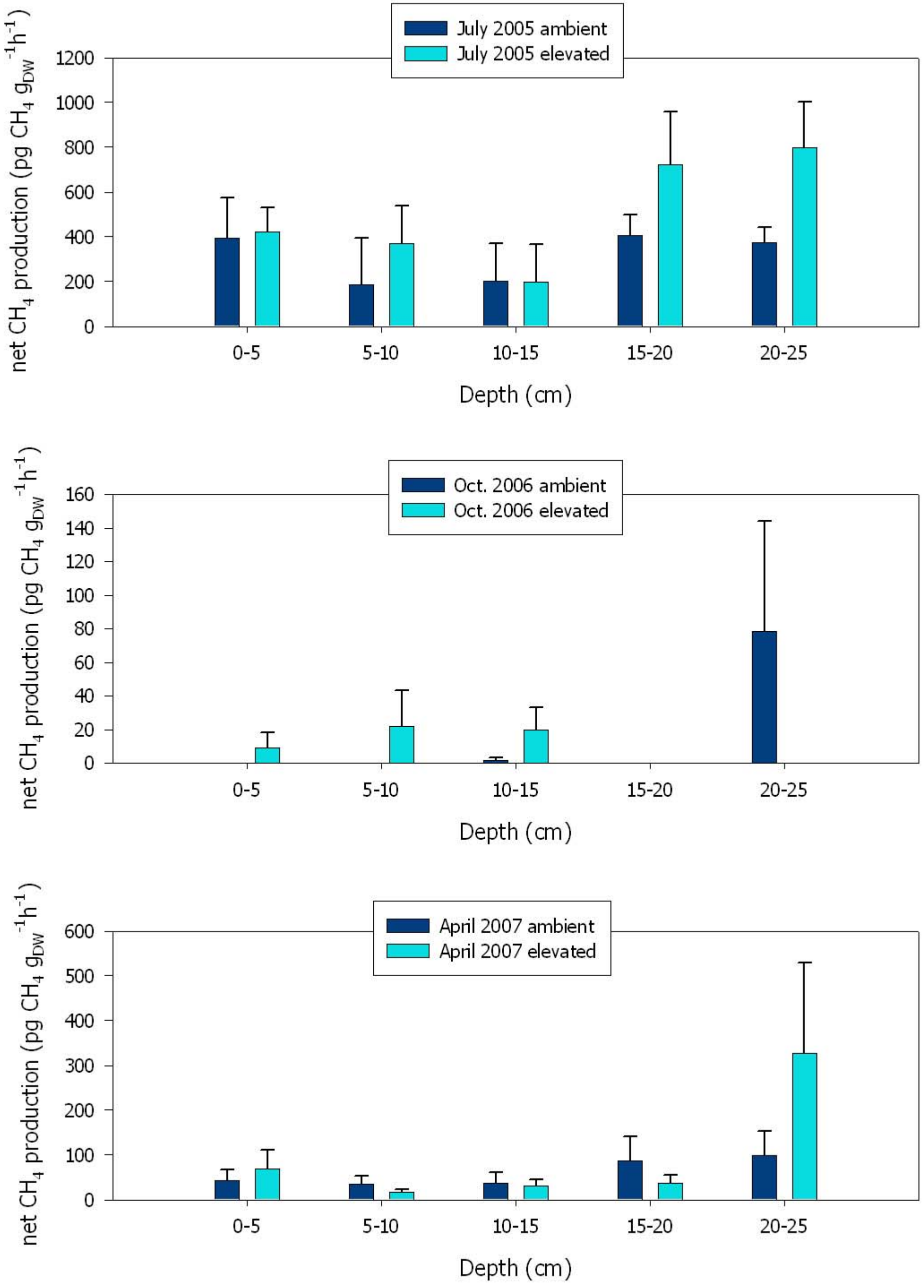

July 2005 ambient
July 2005 elevated
net CH4 consumption (pg CH4 gDW-1h-1)
Depth (cm)
0-5
5-10
10-15
15-20
20-25
Oct. 2006 ambient
Oct. 2006 elevated
April 2007 ambient
April 2007 elevated



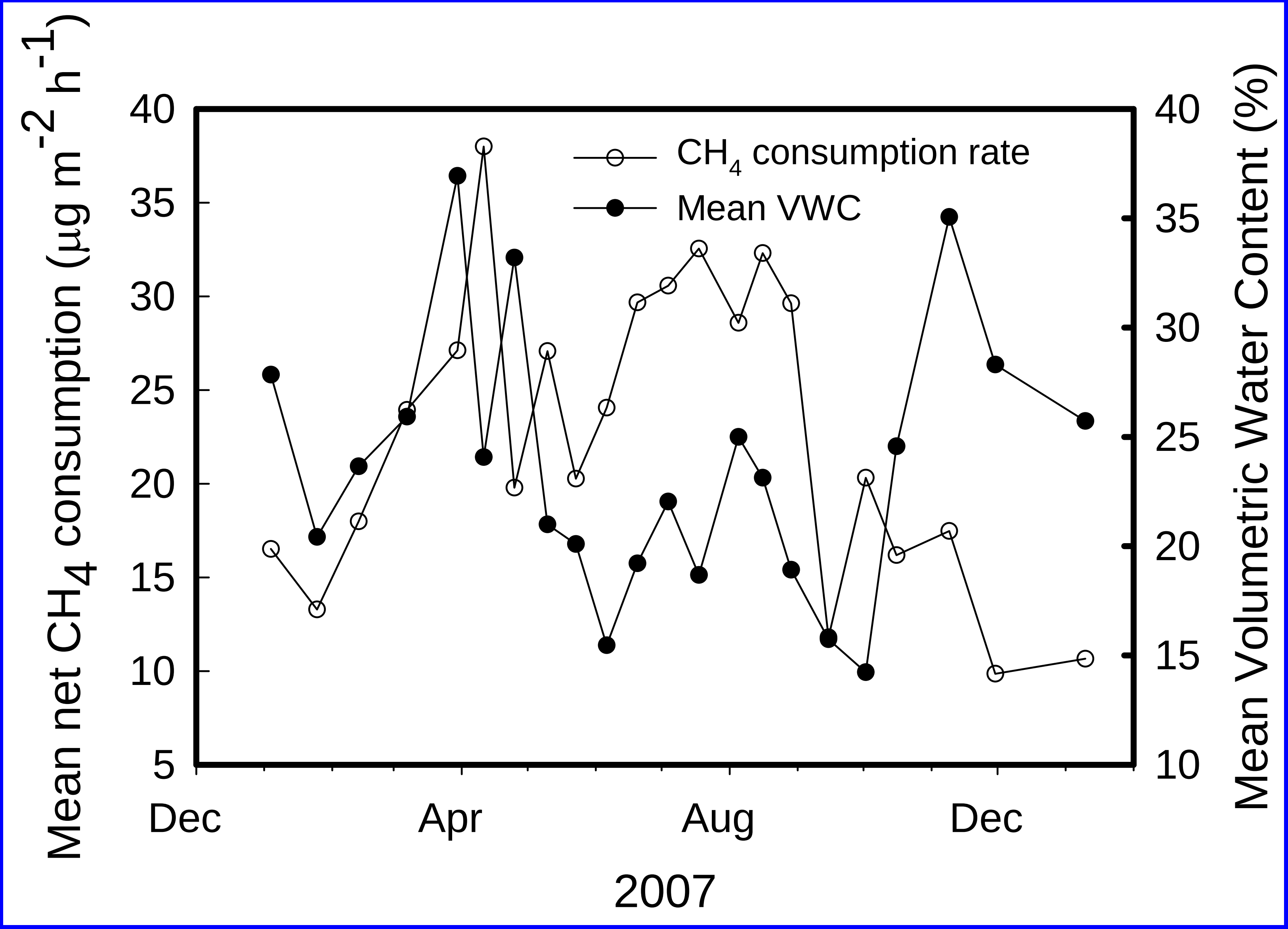
net NO2 production (pg CH4 gDW-1 h-1)
70
60
50
40
30
20
10
0
0-5
5-10
10-15
15-20
20-25
Depth (cm)
July 2005 ambient no N fertilizer
July 2005 ambient with N fertilizer
July 2005 elevated no N fertilizer
July 2005 elevated with N fertilizer



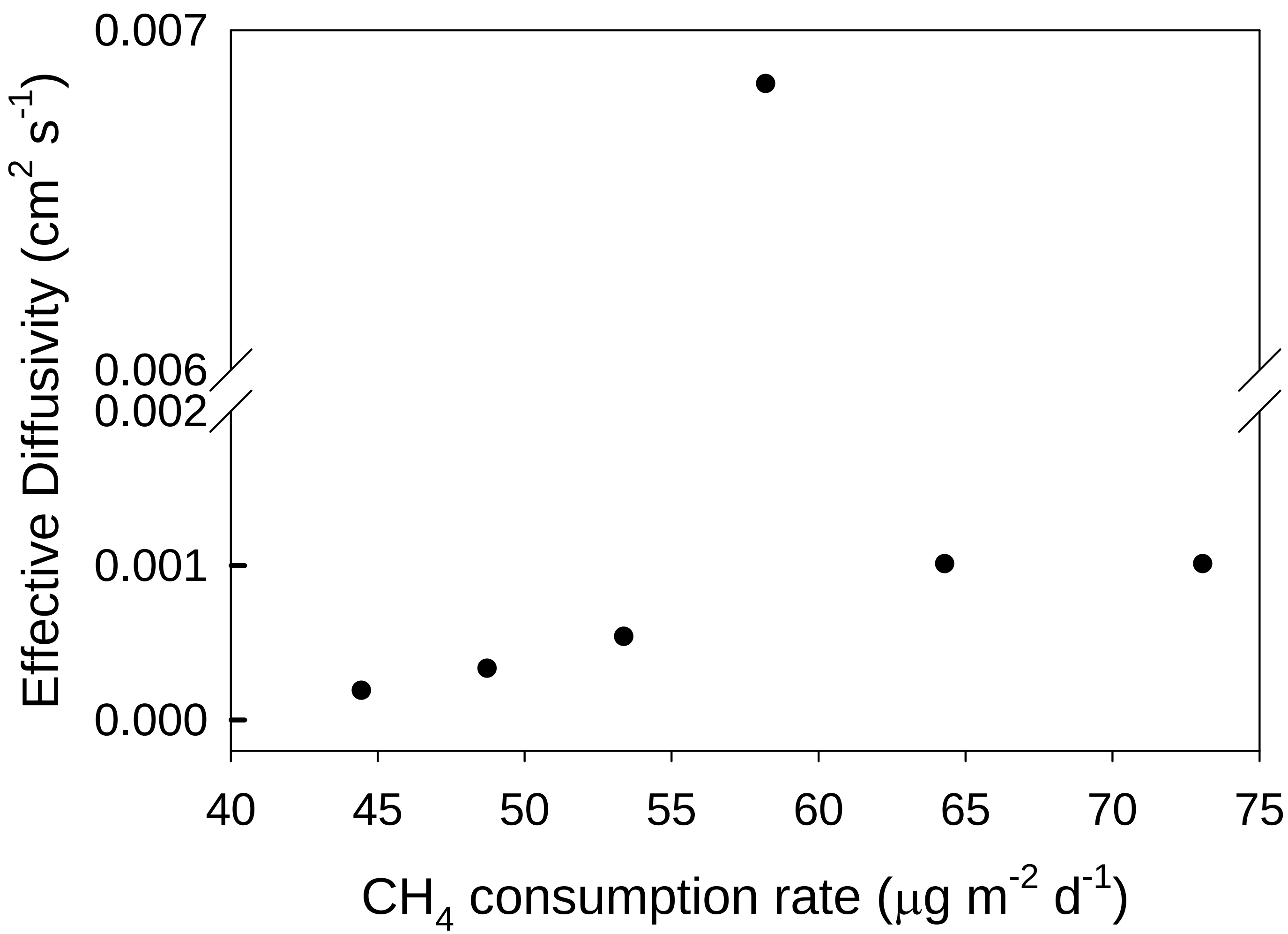
net NO2 production (pg CH4 gDW-1 h-1)
30
25
20
15
10
5
0
0-5
5-10
10-15
15-20
20-25
Depth (cm)
Oct. 2007 ambient no N fertilizer
Oct. 2007 ambient with N fertilizer
Oct. 2007 elevated no N fertilizer
Oct. 2007 elevated with N fertilizer



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 CH_4 consumption ($\mu g\ m^{-2}\ h^{-1}$)
Mean Volumetric Water Content (%)
CH_4 consumption rate
Mean VWC
40
35
30
25
20
15
10
5
40
35
30
25
20
15
10
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

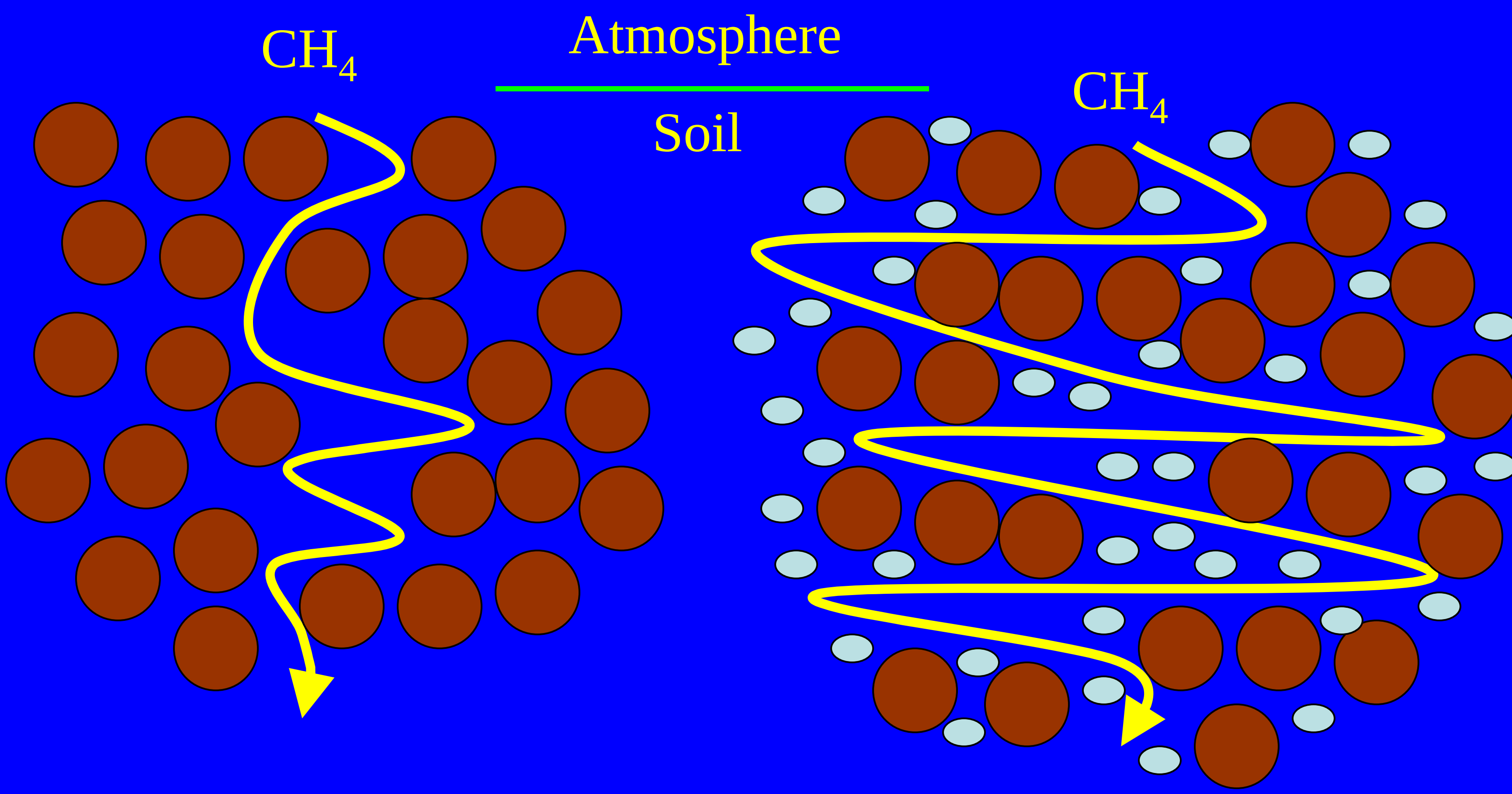
1) Reduced atmospheric CH_4 consumption under elevated CO_2 is a sustained response.

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

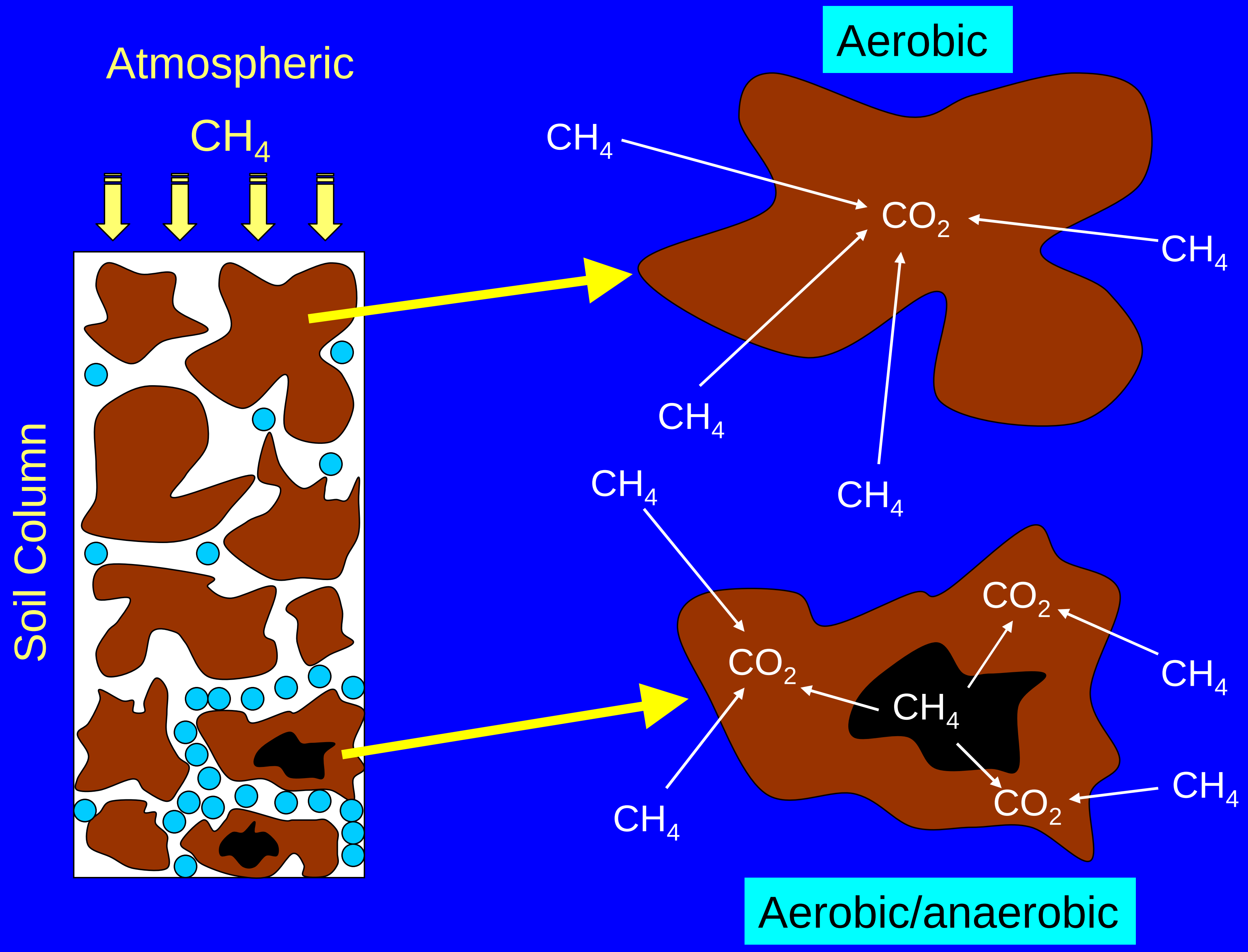
3) Probably not due to:
   a) Δ structure or locus of CH_4-oxidizing community
   b) Inhibitory chemicals

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

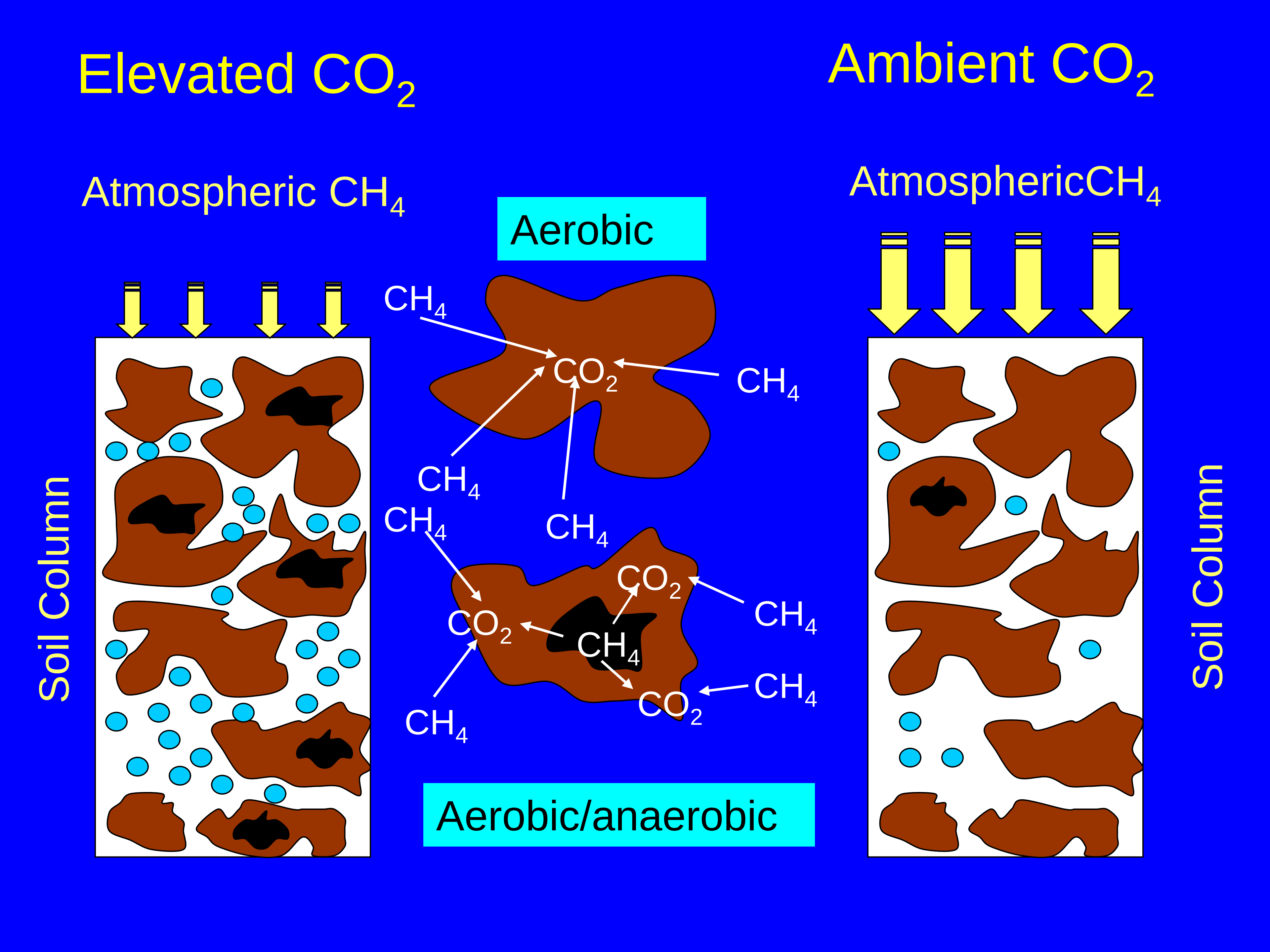
Ambient CO_2 | Elevated CO_2



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
CO_2
CH_4
CH_4
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
CH_4
CO_2
CH_4
CO_2
CH_4
CH_4
CO_2
CH_4
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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