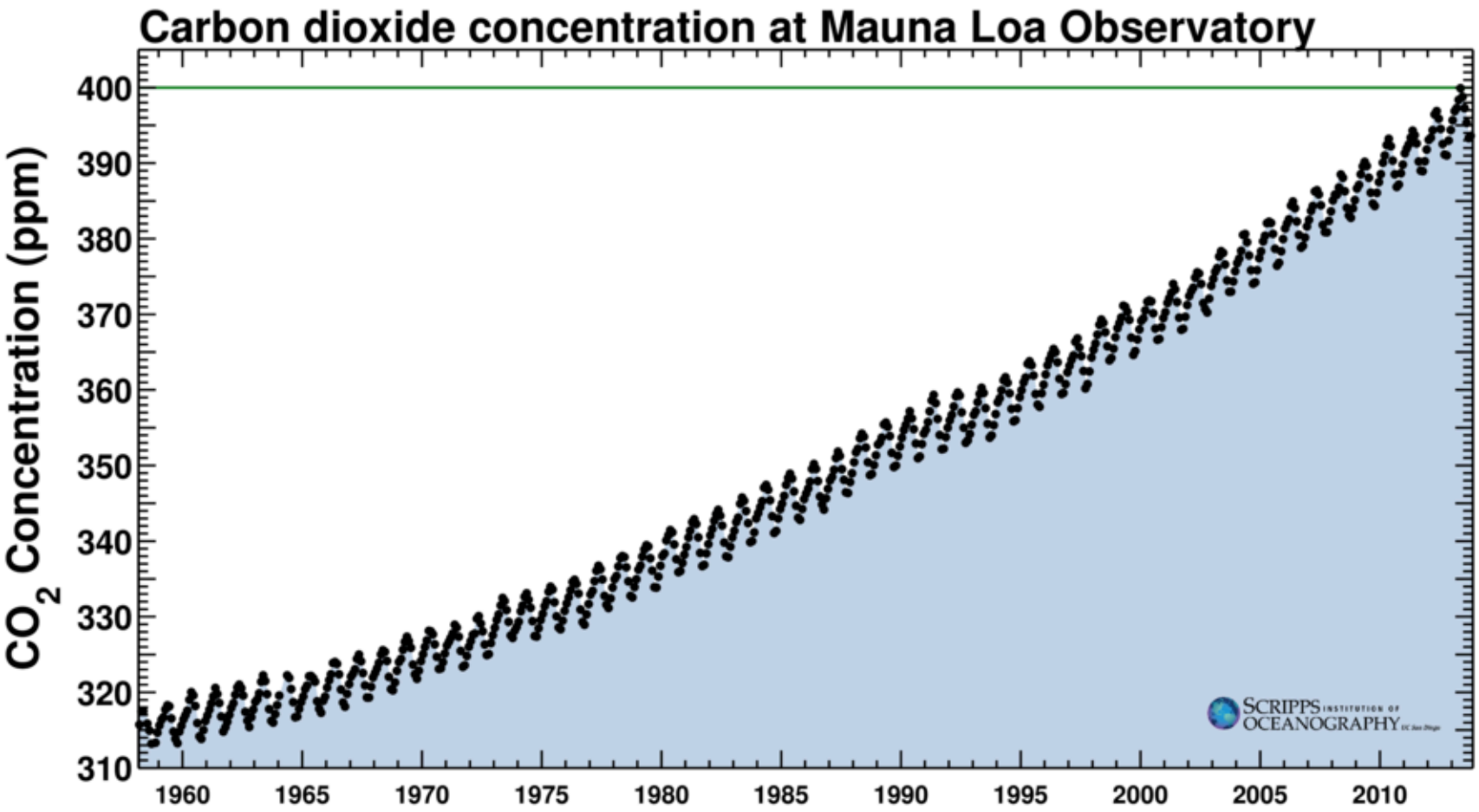
Plant root contributions to the carbon balance of a changing Midwest

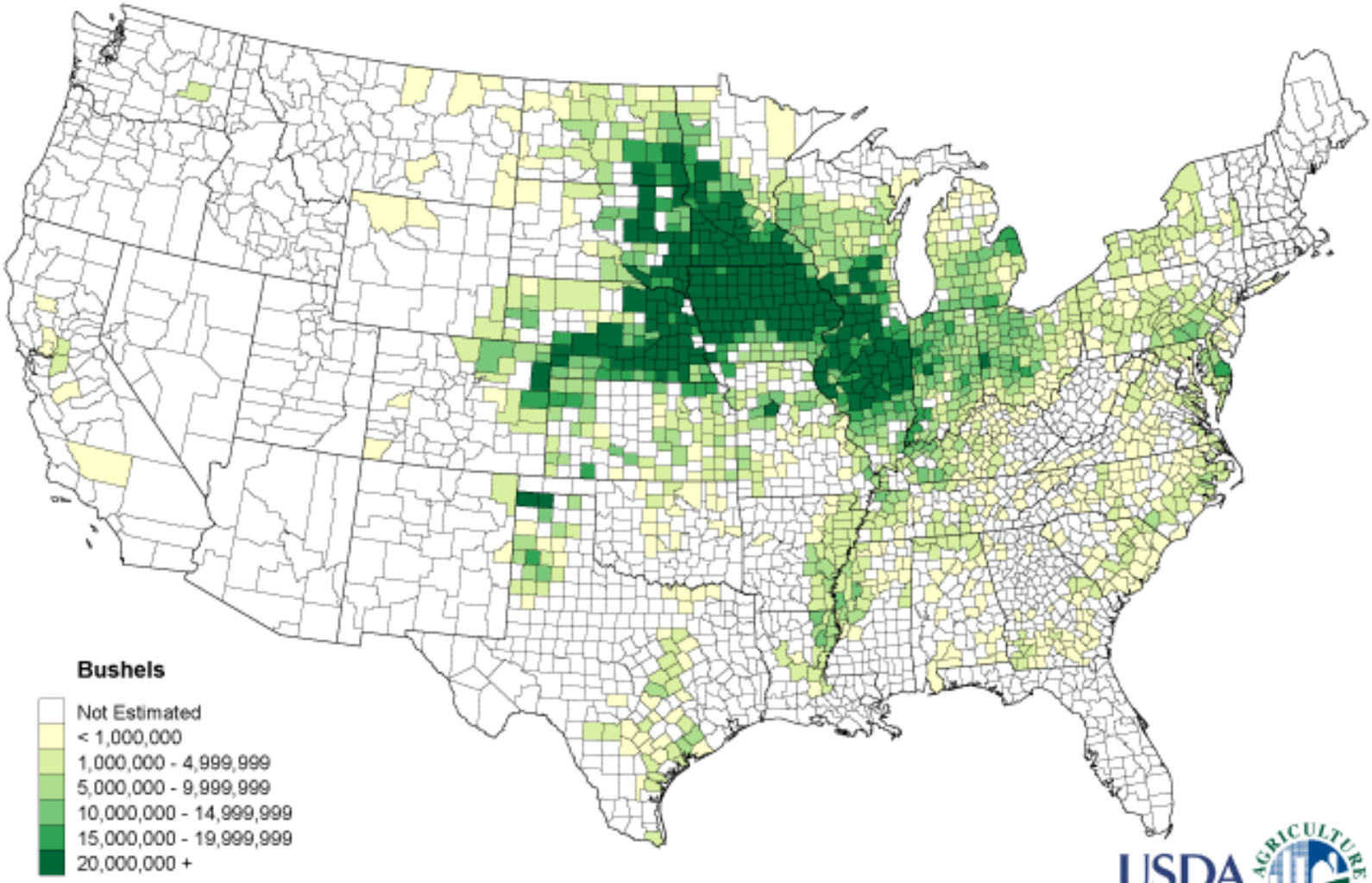
Christopher K Black

PhD Defense

October 31, 2016


Carbon dioxide concentration at Mauna Loa Observatory
CO_2 Concentration (ppm)
400
390
380
370
360
350
340
330
320
310
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
SCRIPPS INSTITUTION OF OCEANOGRAPHY

Corn for Grain 2015
Production by County
for Selected States



U.S. Department of Agriculture, National Agricultural Statistics Service

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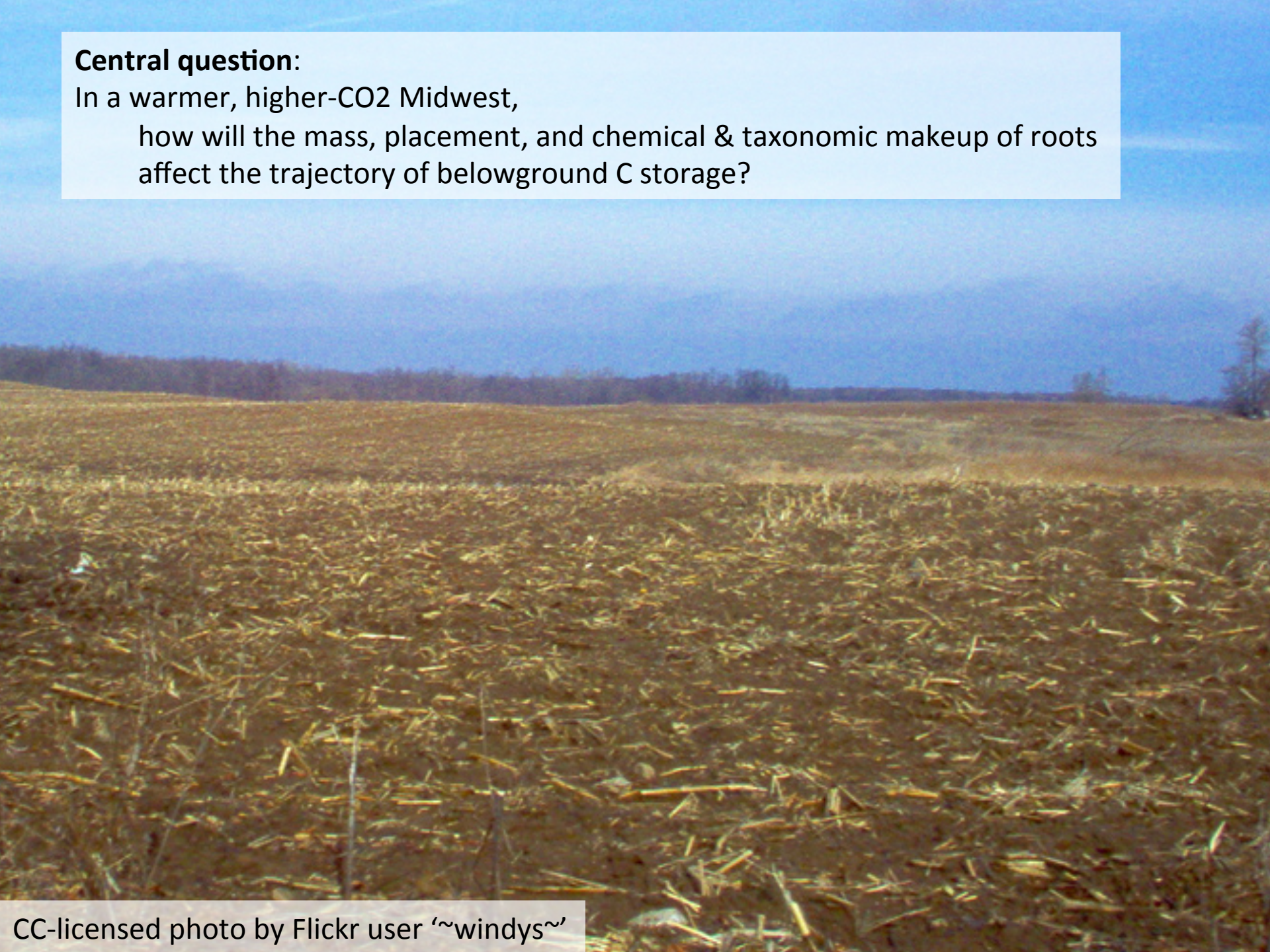
Central question:
In a warmer, higher-CO2 Midwest,
how will the mass, placement, and chemical & taxonomic makeup of roots affect the trajectory of belowground C storage?



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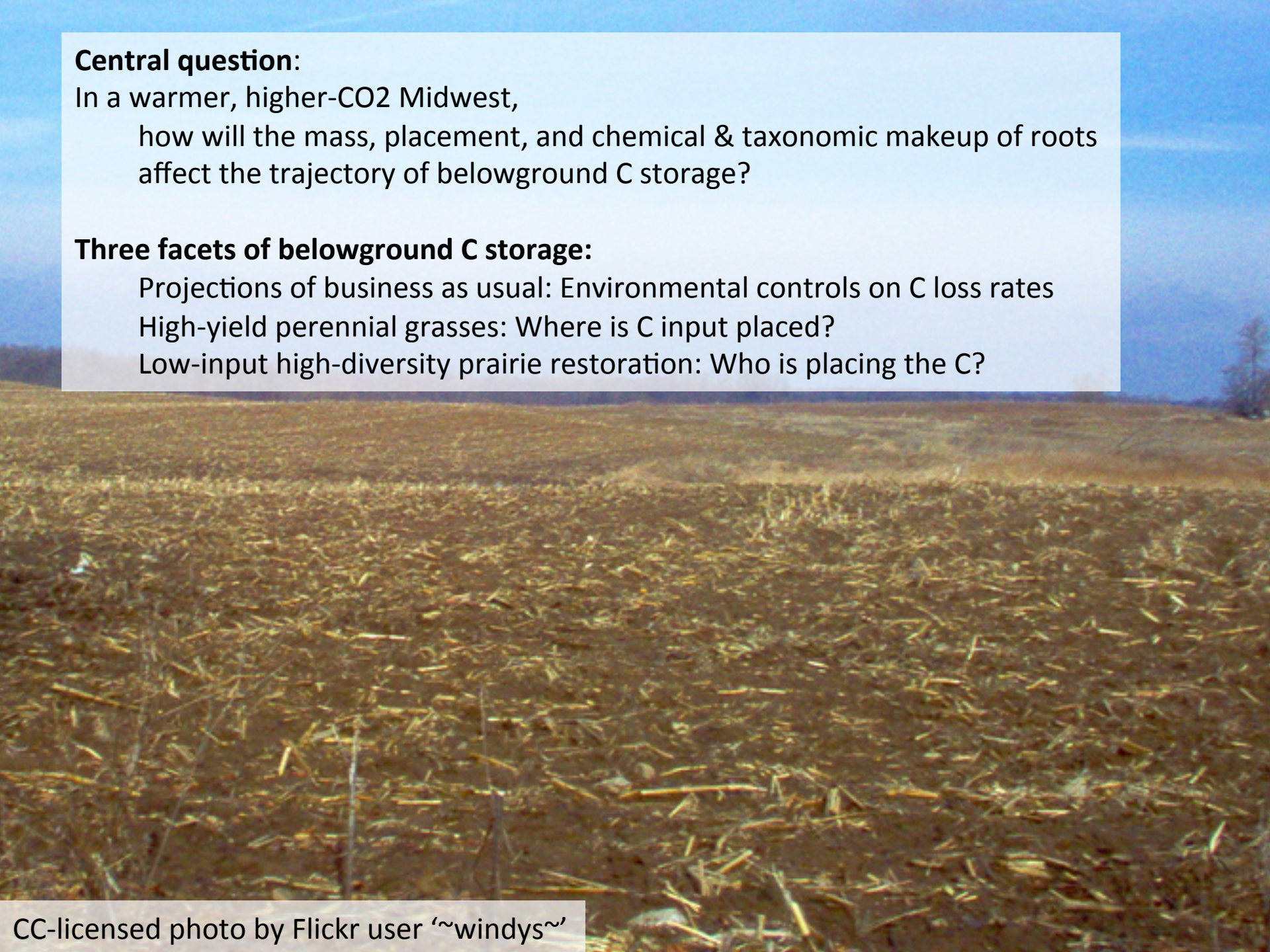
Three facets of belowground C storage:
Projections of business as usual: Environmental controls on C loss rates
High-yield perennial grasses: Where is C input placed?
Low-input high-diversity prairie restoration: Who is placing the C?



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Common challenge:
Measurements are "easy" on small scales too small to matter
Measurements are hard or impossible at the scale of the questions

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Measurements are hard or impossible at the scale of the questions

Approach:
Measure what I can, scale up in time and space to match the scale of the question
AKA *model-data fusion*
…but always with the simplest model I can get away with.
(Sometimes this is still pretty complex)

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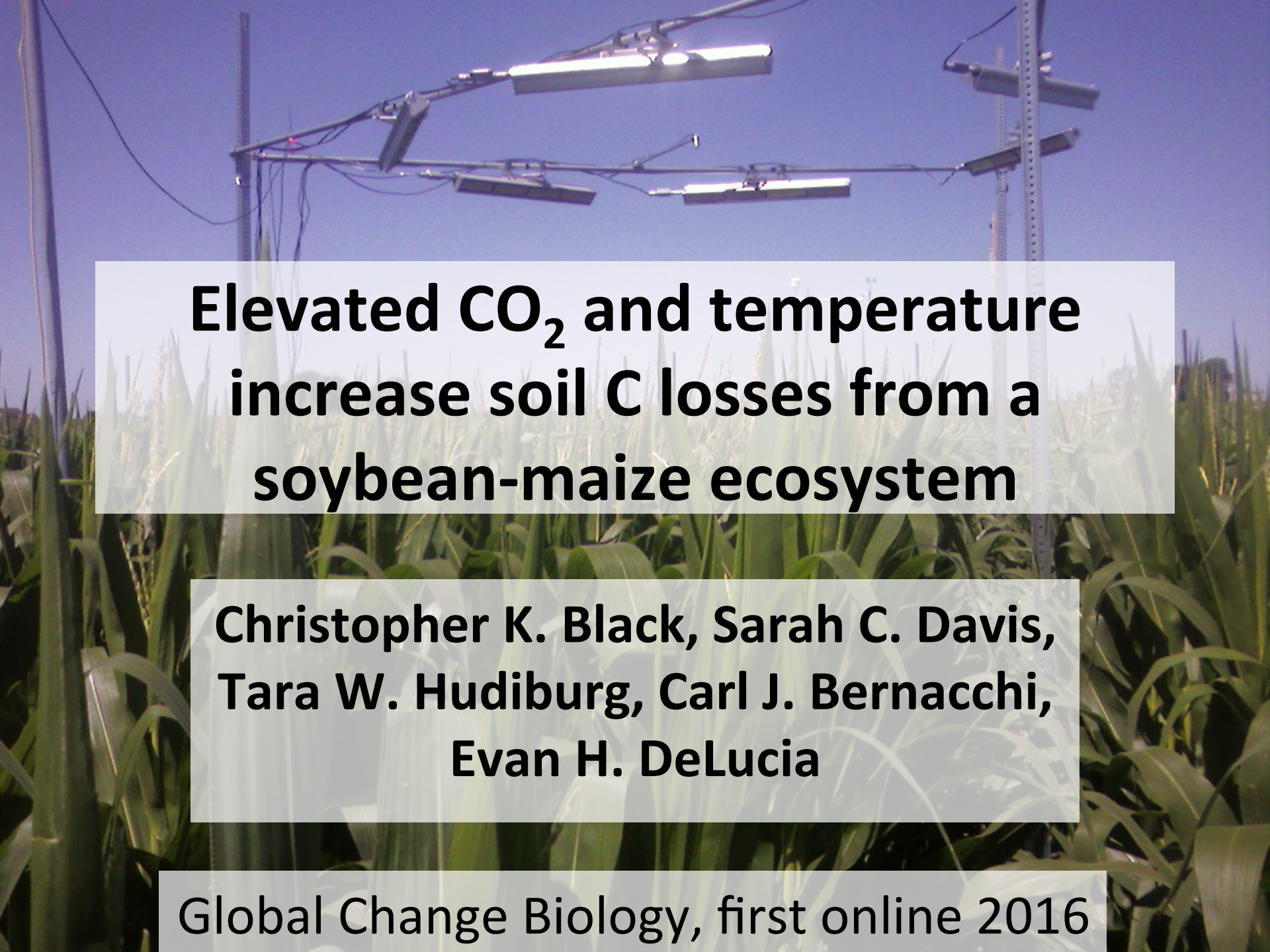
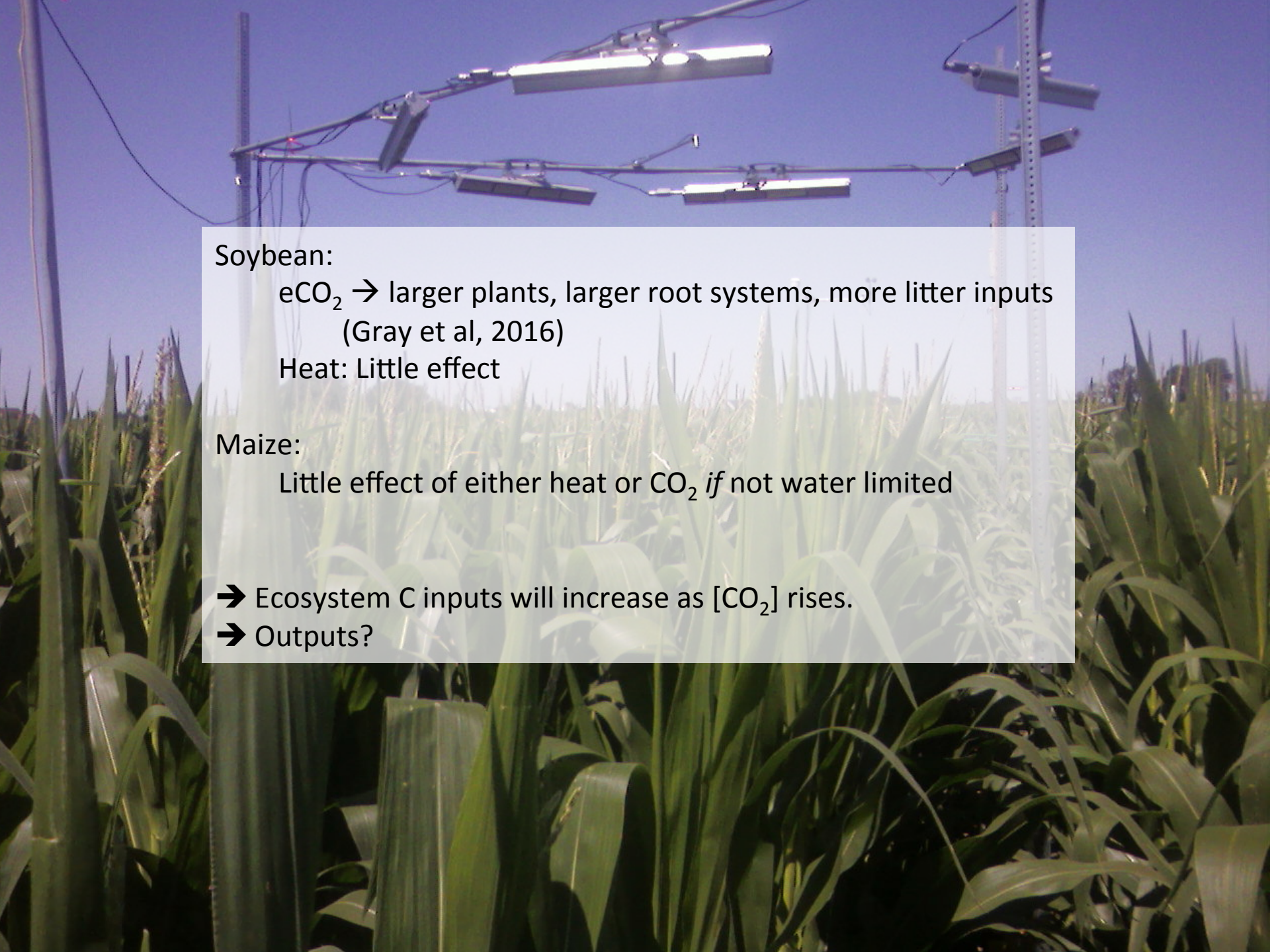


Elevated CO_2 and temperature increase soil C losses from a soybean-maize ecosystem

Christopher K. Black, Sarah C. Davis, Tara W. Hudiburg, Carl J. Bernacchi, Evan H. DeLucia

Global Change Biology, first online 2016



Soybean:

eCO_2 → larger plants, larger root systems, more litter inputs (Gray et al, 2016)

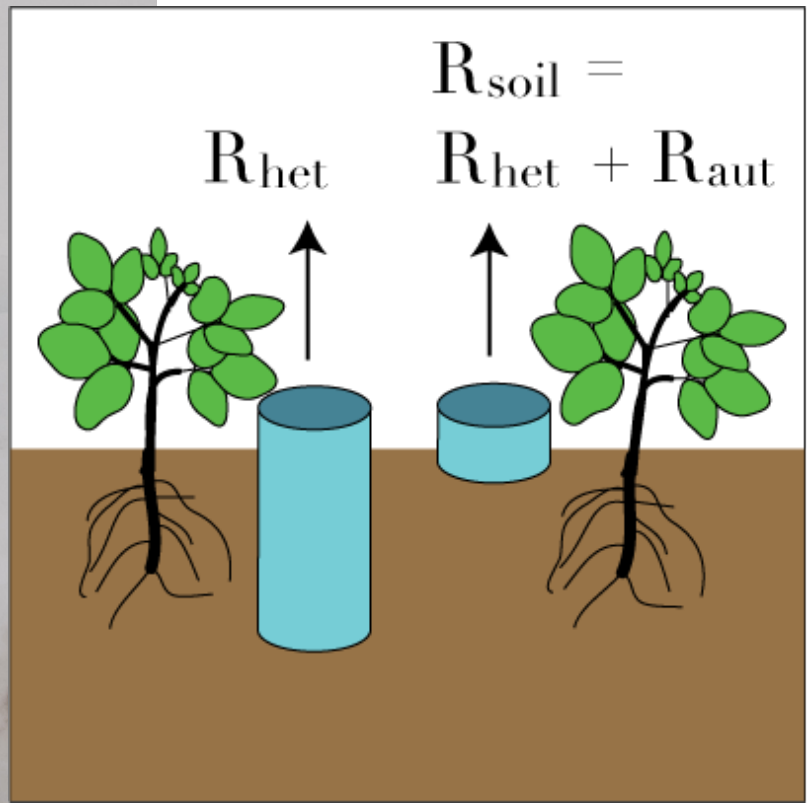
Heat: Little effect

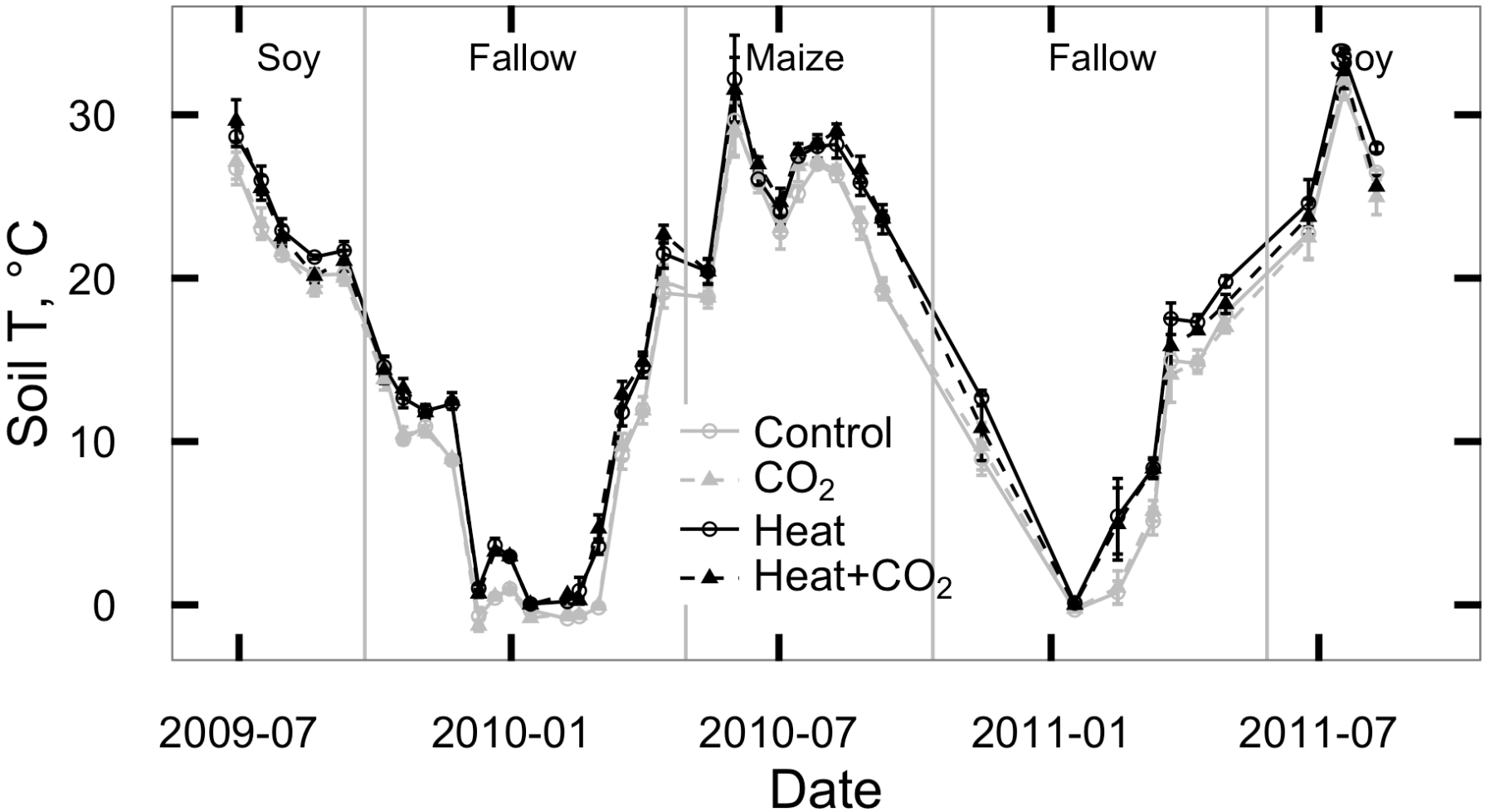
Maize:

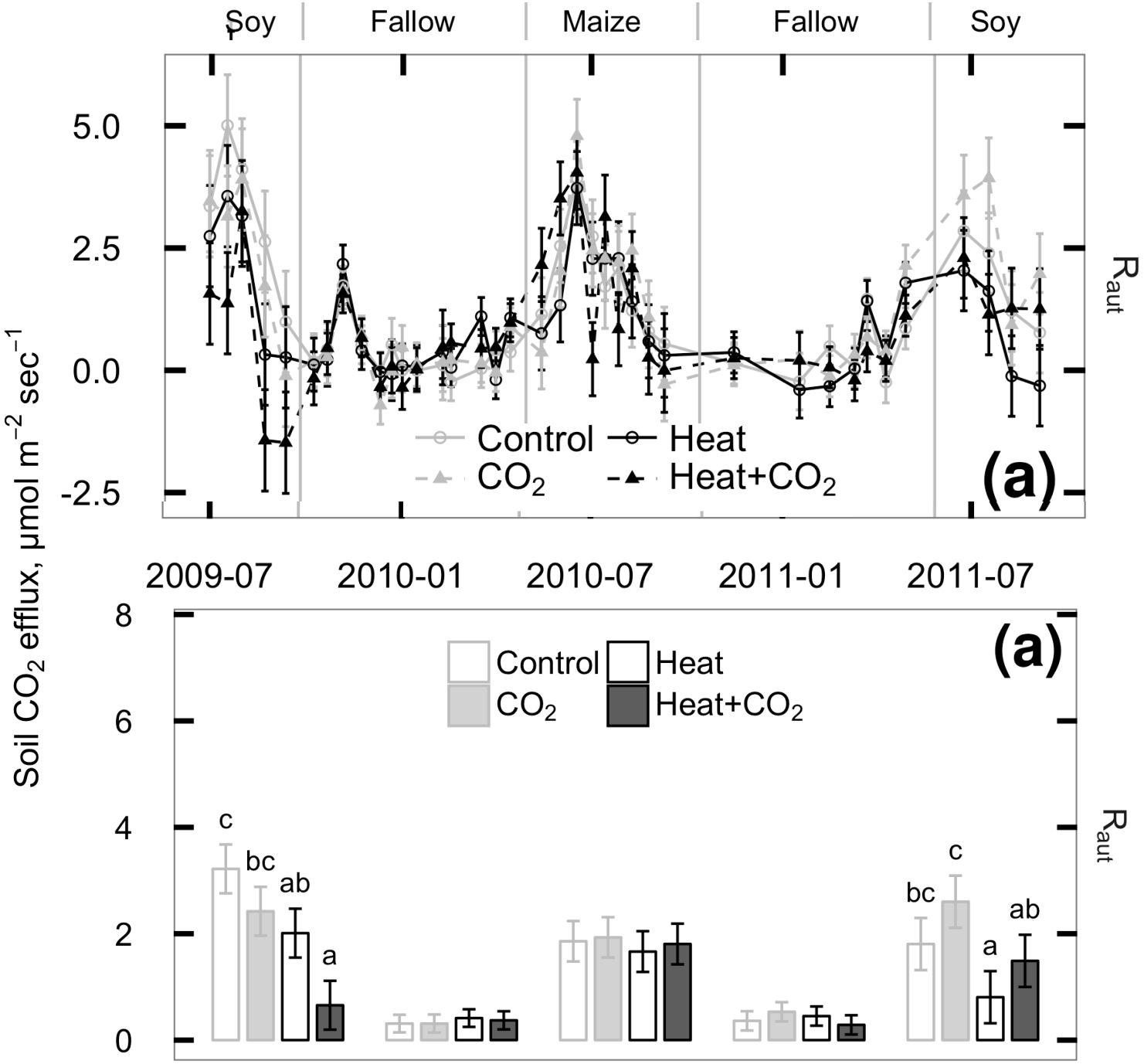
Little effect of either heat or CO_2 *if* not water limited

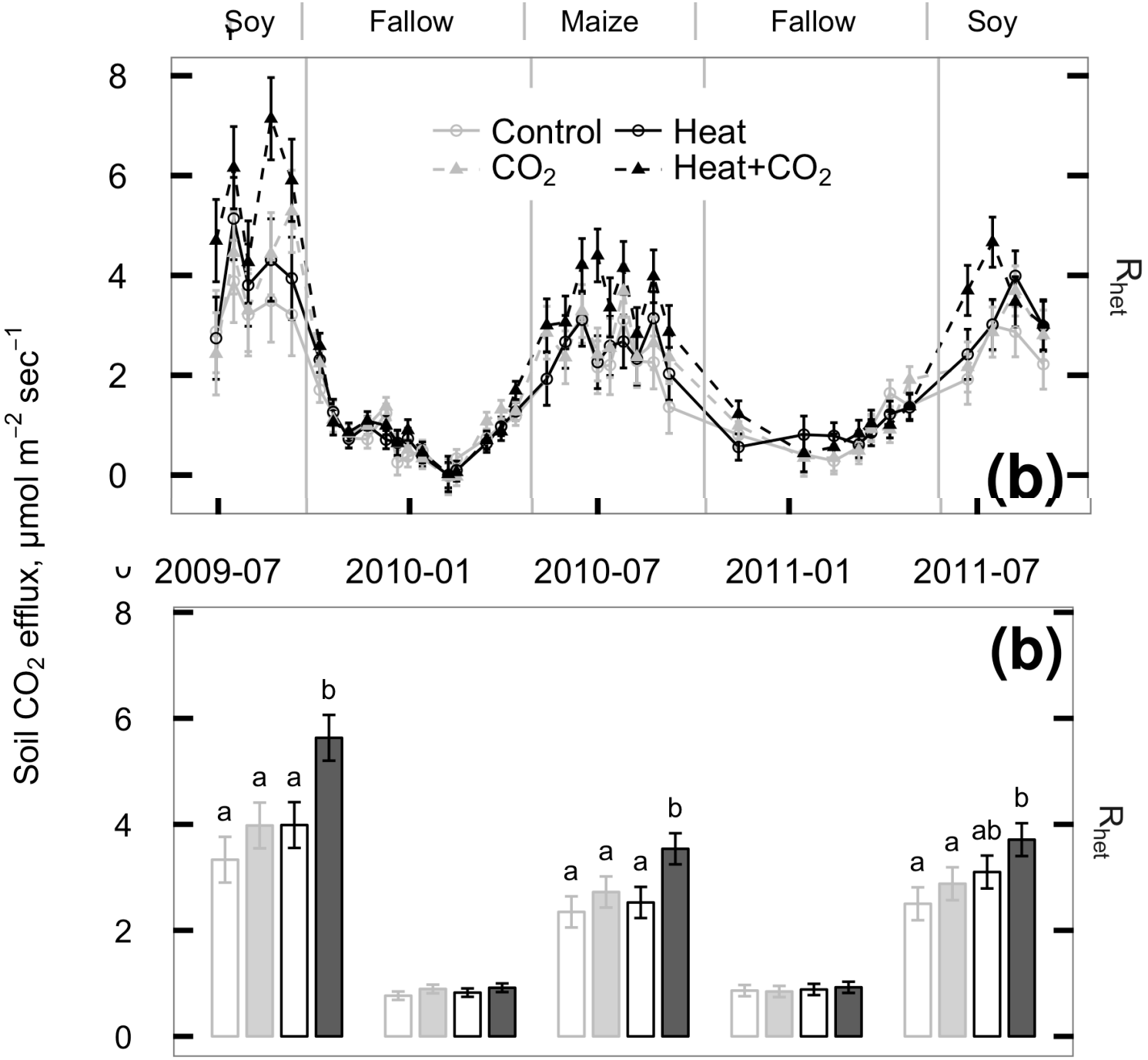
➔ Ecosystem C inputs will increase as [CO_2] rises.

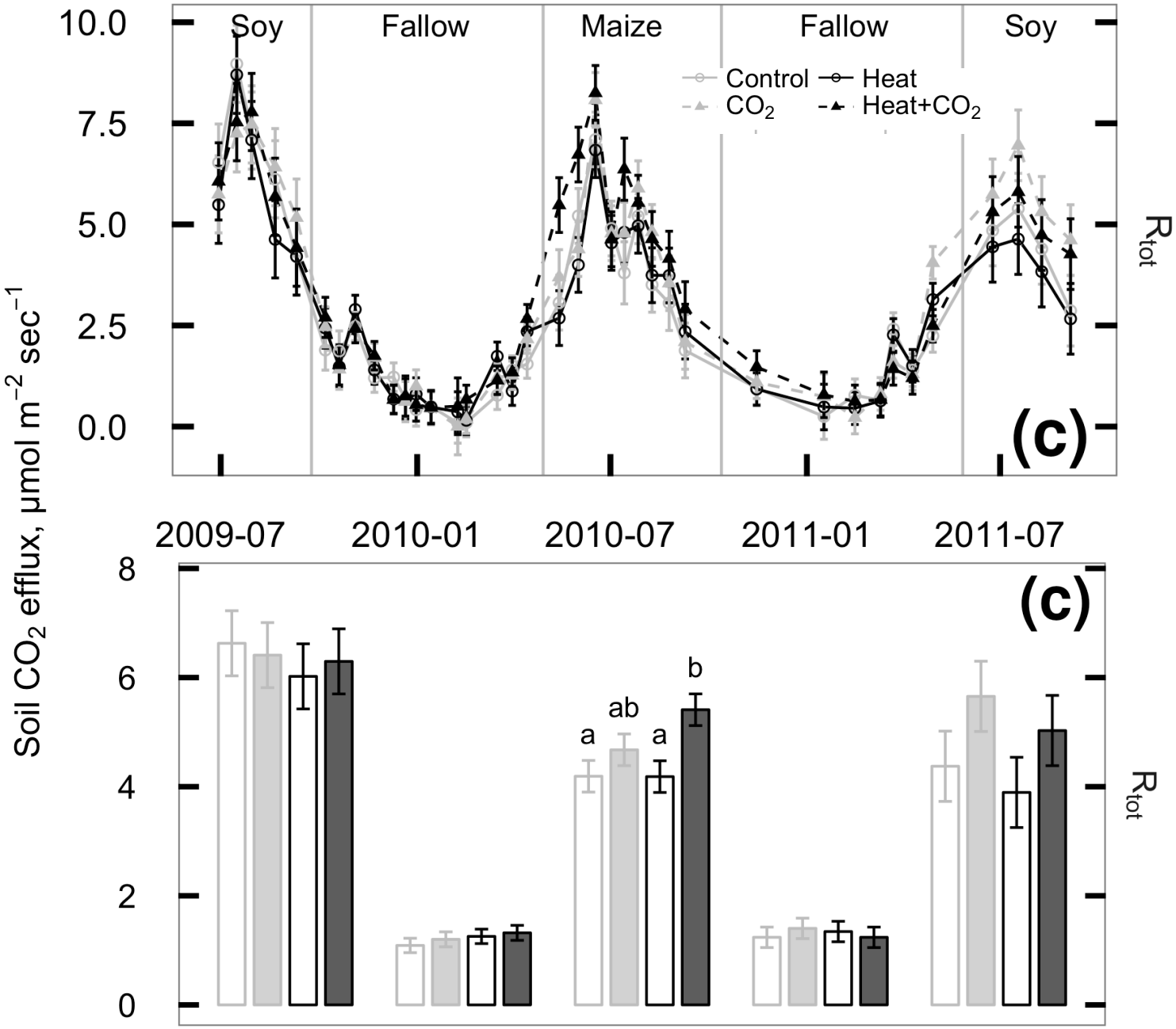
➔ Outputs?

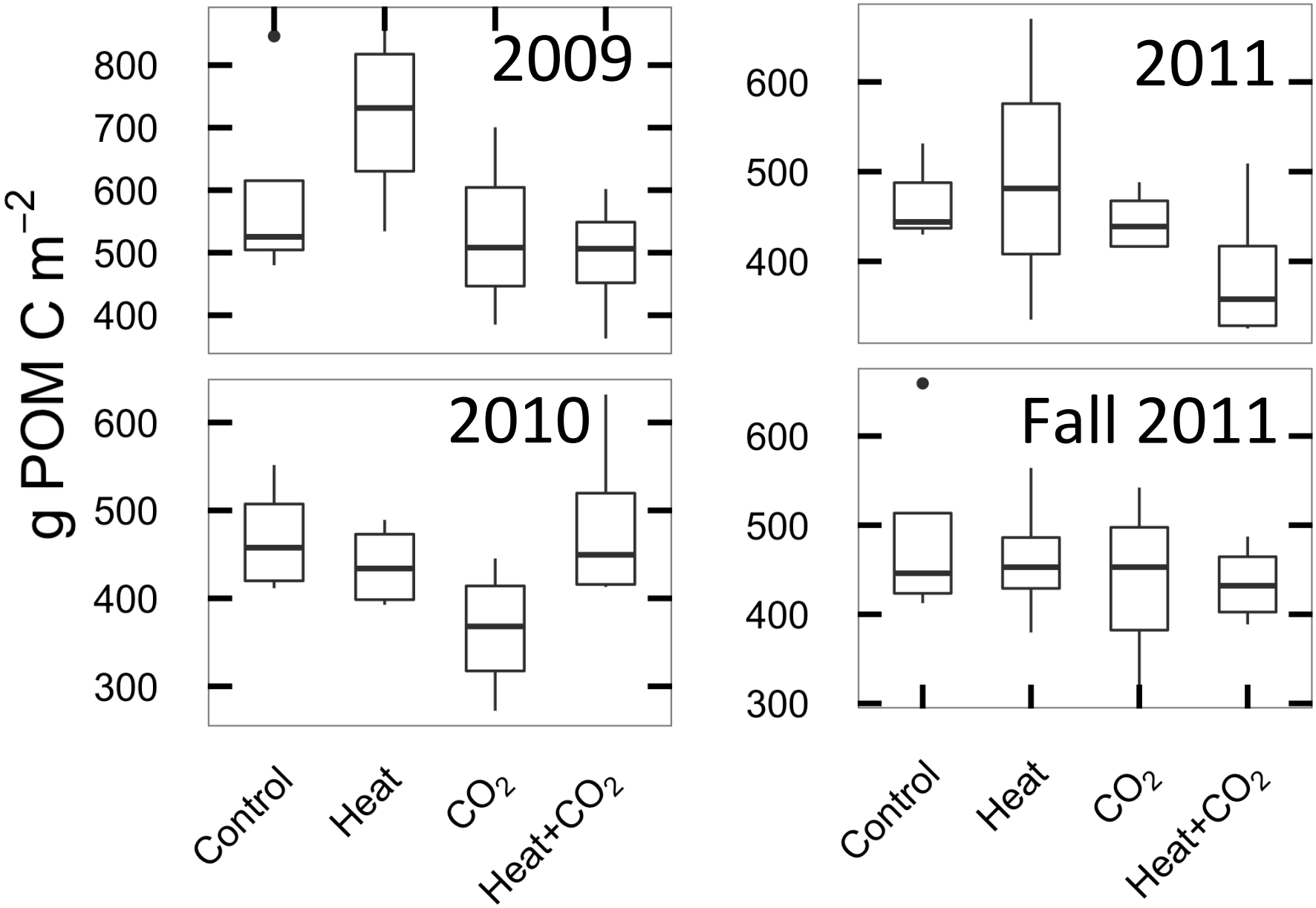

R_{soil} =
R_{het}
R_{het} + R_{aut}


Soy
Fallow
Maize
Fallow
Soy
30
20
10
0
Soil T, °C
Control
CO2
Heat
Heat+CO2
2009-07
2010-01
2010-07
2011-01
2011-07
Date


Soy
Fallow
Maize
Fallow
Soy
5.0
2.5
0.0
-2.5
Control
Heat
CO2
Heat+CO2
(a)
2009-07
2010-01
2010-07
2011-01
2011-07
Raut
Soil CO2 efflux, µmol m−2 sec−1
8
6
4
2
0
Control
Heat
CO2
Heat+CO2
(a)
c
bc
ab
a
bc
c
a
ab
Raut


Soy
Fallow
Maize
Fallow
Soy
Control
Heat
CO2
Heat+CO2
(b)
2009-07
2010-01
2010-07
2011-01
2011-07
Soil CO2 efflux, µmol m−2 sec−1
Rhet
(b)
Rhet


Soy
Fallow
Maize
Fallow
Soy
Control
Heat
CO2
Heat+CO2
(c)
Rtot
Soil CO2 efflux, µmol m−2 sec−1
10.0
7.5
5.0
2.5
0.0
2009-07
2010-01
2010-07
2011-01
2011-07
8
6
4
2
0
a
ab
a
b

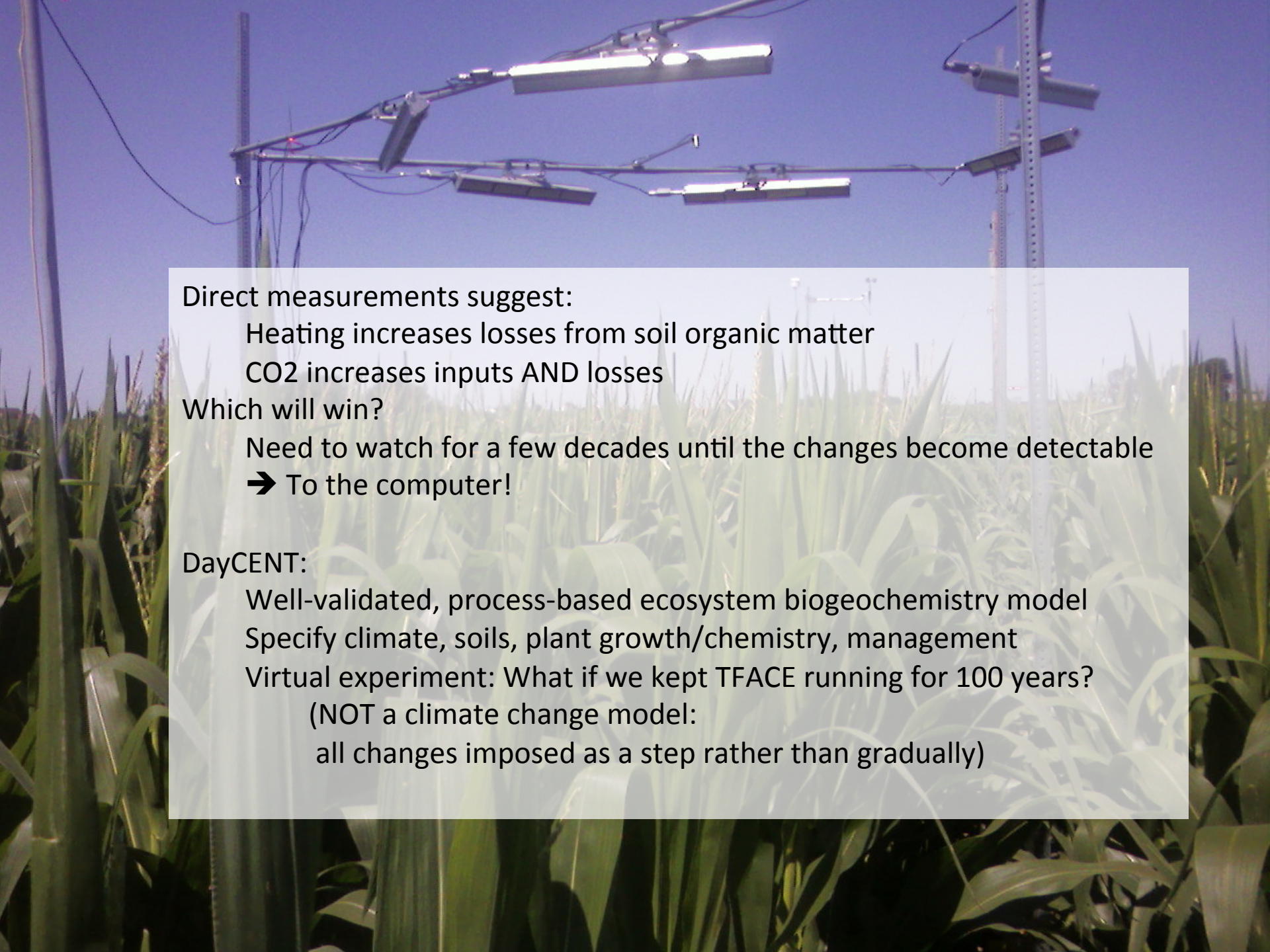

g POM C m^{-2}
2009
2011
2010
Fall 2011
800
700
600
500
400
300
Control
Heat
CO_2
Heat+CO_2

Direct measurements suggest:

- Heating increases losses from soil organic matter
- CO_2 increases inputs AND losses

Which will win?

- Need to watch for a few decades until the changes become detectable
- ➔ To the computer!



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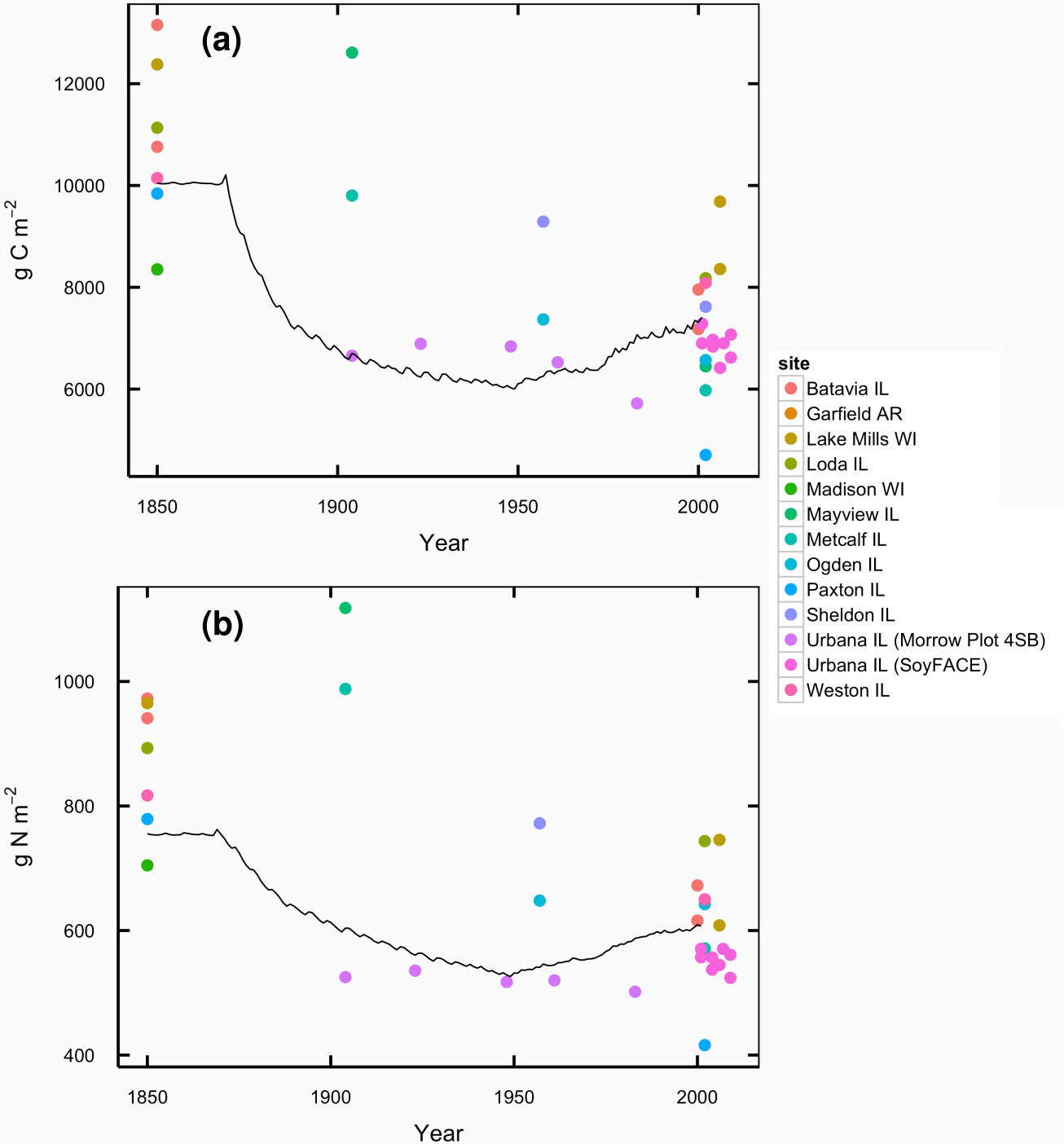
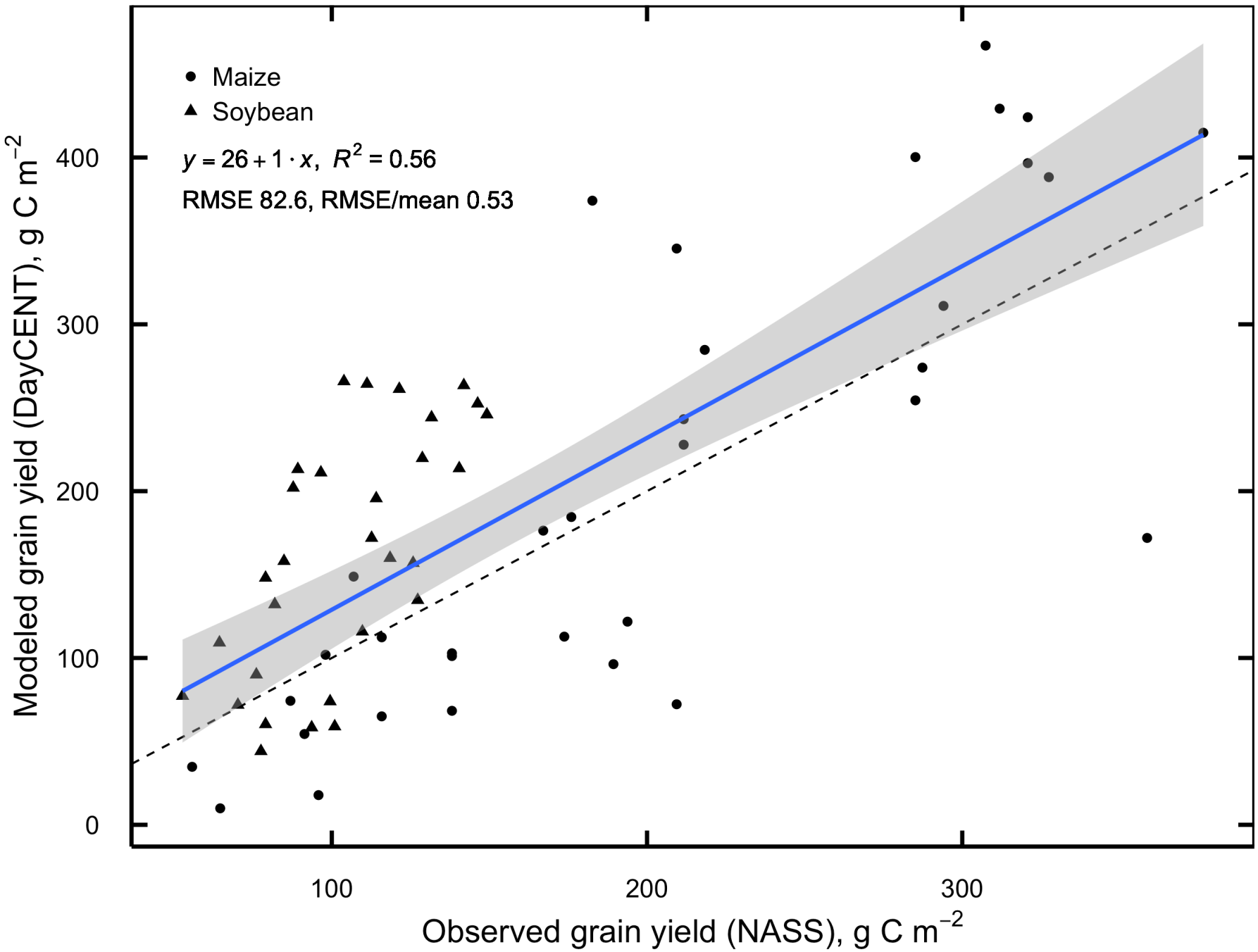
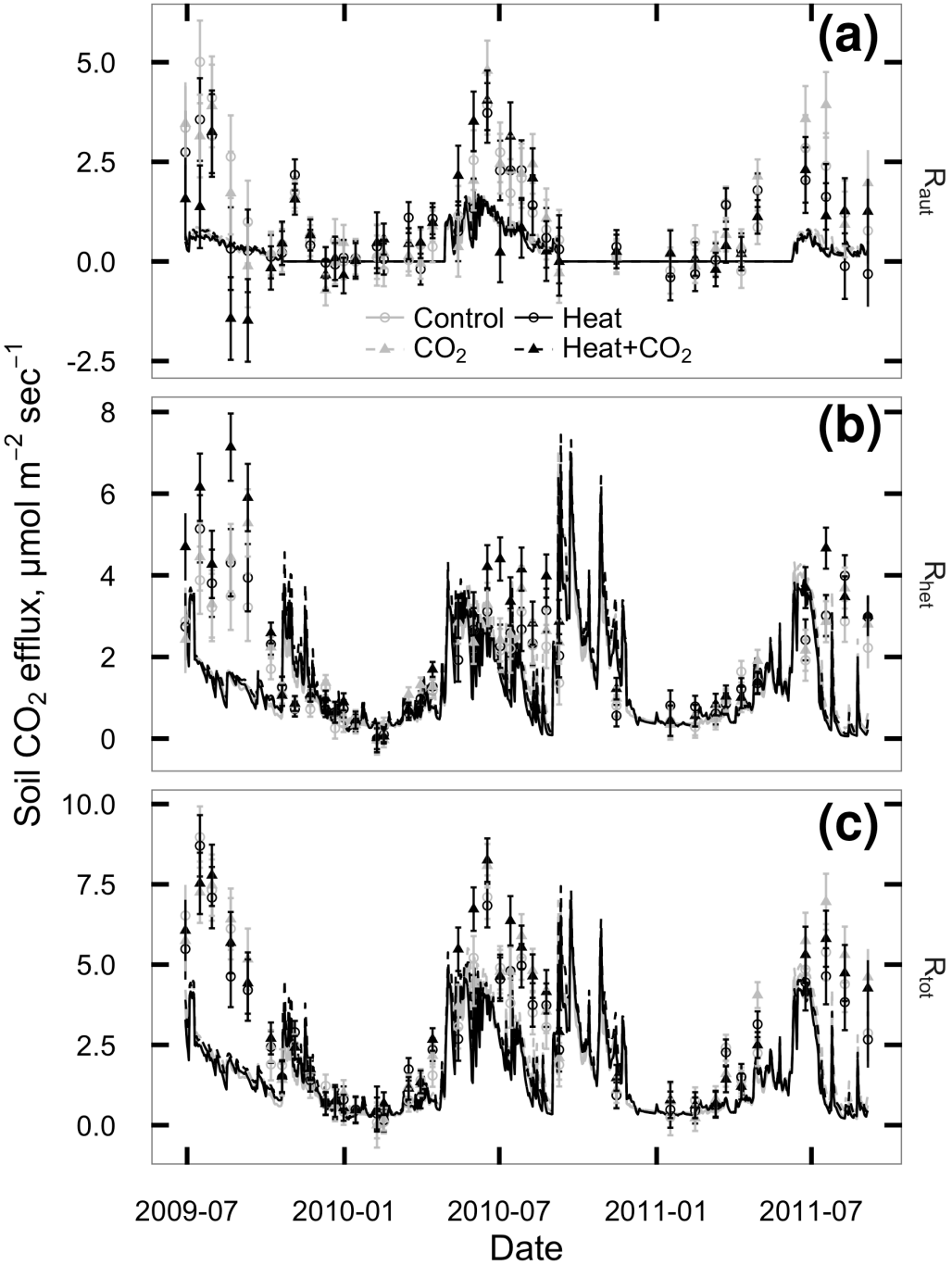
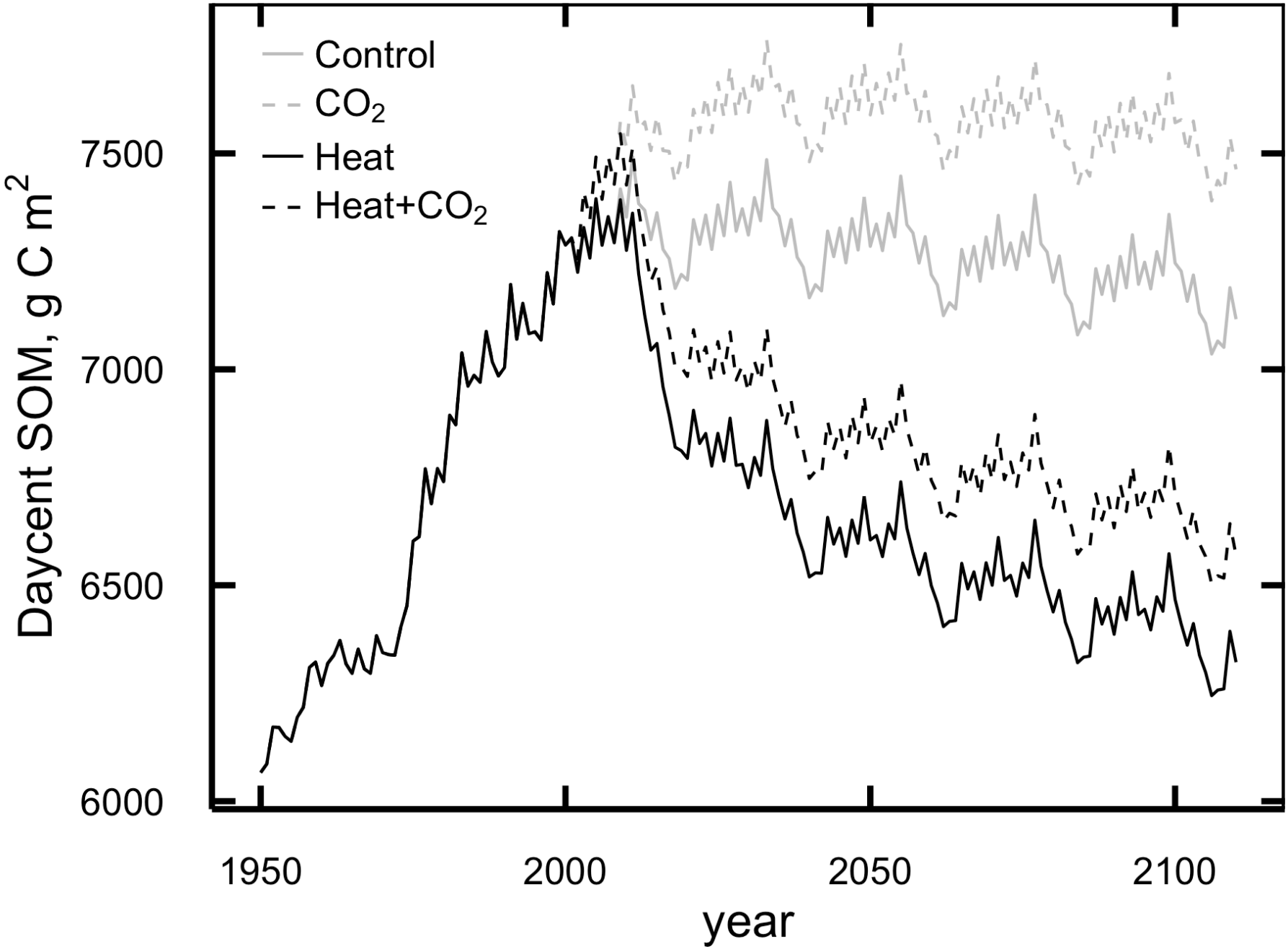
DayCENT:

- Well-validated, process-based ecosystem biogeochemistry model
- Specify climate, soils, plant growth/chemistry, management
- Virtual experiment: What if we kept TFACE running for 100 years?
  - (NOT a climate change model:
    all changes imposed as a step rather than gradually)


(a)
12000
10000
8000
6000
g C m^{-2}
1850
1900
1950
2000
Year
(b)
1000
800
600
400
g N m^{-2}
1850
1900
1950
2000
Year
site
Batavia IL
Garfield AR
Lake Mills WI
Loda IL
Madison WI
Mayview IL
Metcalf IL
Ogden IL
Paxton IL
Sheldon IL
Urbana IL (Morrow Plot 4SB)
Urbana IL (SoyFACE)
Weston IL


Maize
Soybean
$y = 26 + 1 \cdot x$, $R^2 = 0.56$
RMSE 82.6, RMSE/mean 0.53
Modeled grain yield (DayCENT), g C m^{-2}
Observed grain yield (NASS), g C m^{-2}
0
100
200
300
400
100
200
300


(a)
(b)
(c)
Control
Heat
CO2
Heat+CO2
Raut
Rhet
Rtot
Soil CO2 efflux, µmol m−2 sec−1
5.0
2.5
0.0
-2.5
8
6
4
2
0
10.0
7.5
5.0
2.5
0.0
2009-07
2010-01
2010-07
2011-01
2011-07
Date


Control
CO2
Heat
Heat+CO2
7500
7000
6500
6000
Daycent SOM, g C m2
1950
2000
2050
2100
year

How to store soil carbon:

[ ] High inputs

[ ] Physical protection

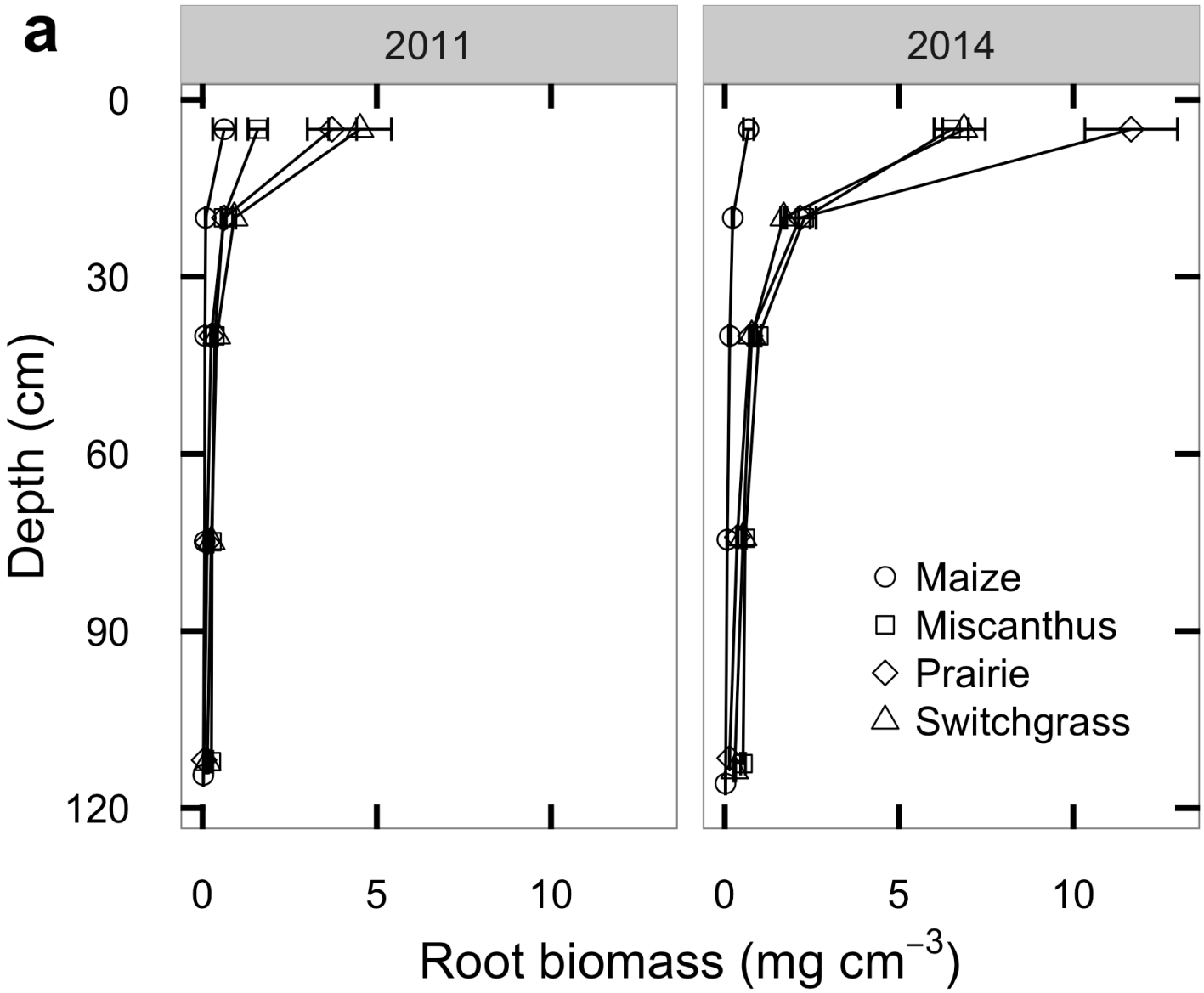
[ ] Low disturbance

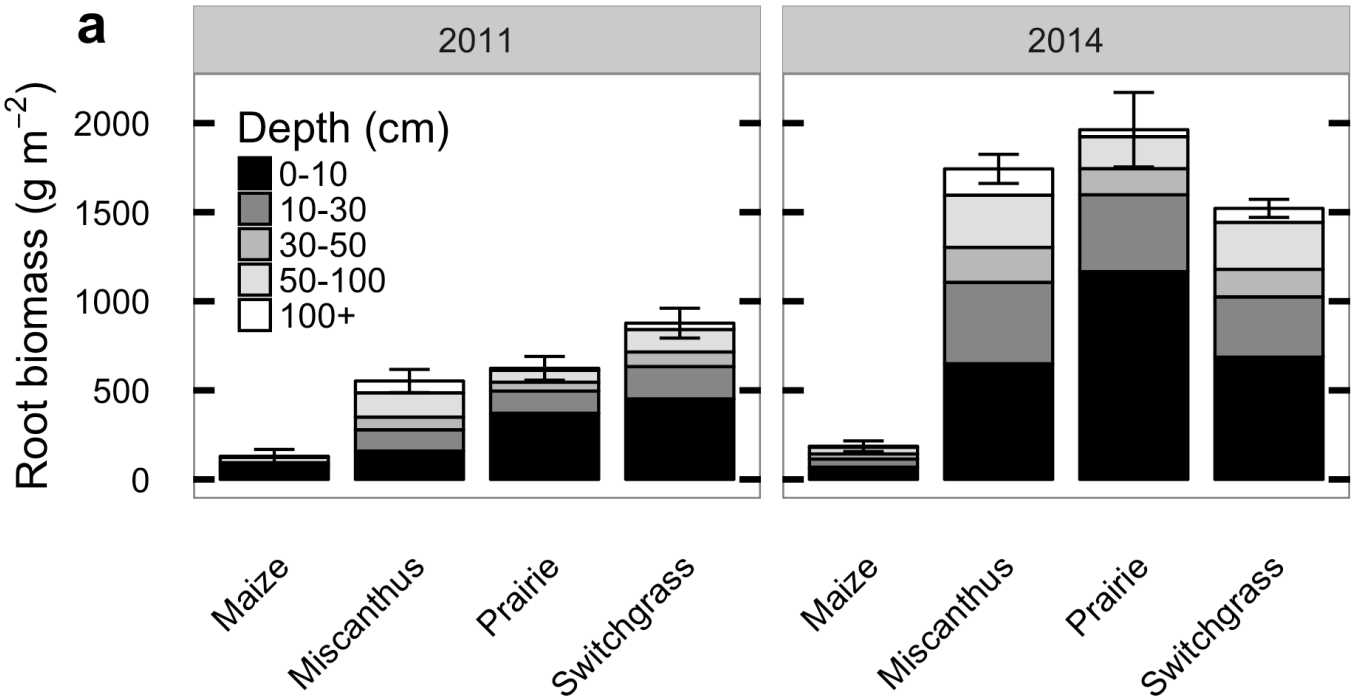
Steve Renich, Wikimedia

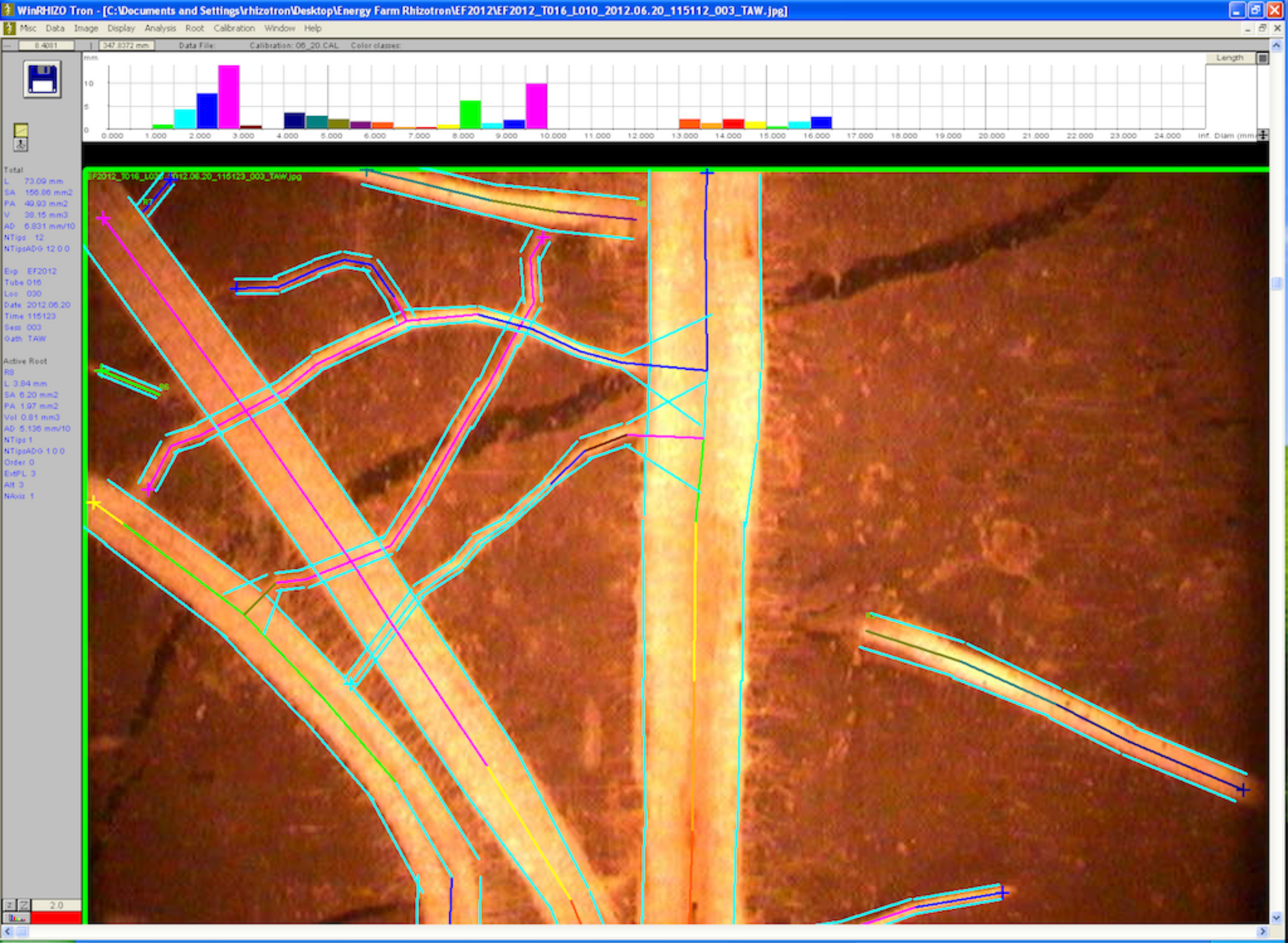
Joel McKinney, The Noun Project

Root volume distribution of maturing perennial grasses revealed by correcting for minirhizotron surface effects

Christopher K. Black, Michael D. Masters, Kristina J. Anderson-Teixeira, David S. LeBauer, Evan H. DeLucia


a
2011
2014
Depth (cm)
0
30
60
90
120
0
5
10
0
5
10
Root biomass (mg cm^{-3})
Maize
Miscanthus
Prairie
Switchgrass


a
2011
2014
Root biomass (g m^{-2})
2000
1500
1000
500
0
Depth (cm)
0-10
10-30
30-50
50-100
100+
Maize
Miscanthus
Prairie
Switchgrass
Maize
Miscanthus
Prairie
Switchgrass


WinRHIZO Tron - [C:\Documents and Settings\rhizotron\Desktop\Energy Farm Rhizotron\EF2012\EF2012_T016_L010_2012.06.20_115112_003_TAW.jpg]
Misc Data Image Display Analysis Root Calibration Window Help
Data File:
Calibration: 06_20.CAL
Color classes:
Length
mm
10
5
0
0.000 1.000 2.000 3.000 4.000 5.000 6.000 7.000 8.000 9.000 10.000 11.000 12.000 13.000 14.000 15.000 16.000 17.000 18.000 19.000 20.000 21.000 22.000 23.000 24.000 Inf. Diam (mm)
Total
L 73.09 mm
SA 156.86 mm2
PA 49.93 mm2
V 38.15 mm3
AD 6.831 mm/10
NTips 12
NTipsAD-0 12 0 0
Exp EF2012
Tube 016
Loc 030
Date 2012.06.20
Time 115123
Seq 003
Path TAW
Active Root
R8
L 3.84 mm
SA 6.20 mm2
PA 1.97 mm2
Vol 0.81 mm3
AD 5.136 mm/10
NTips 1
NTipsAD-0 1 0 0
Order 0
EstPL 3
Alt 3
NAxis 1
2.0

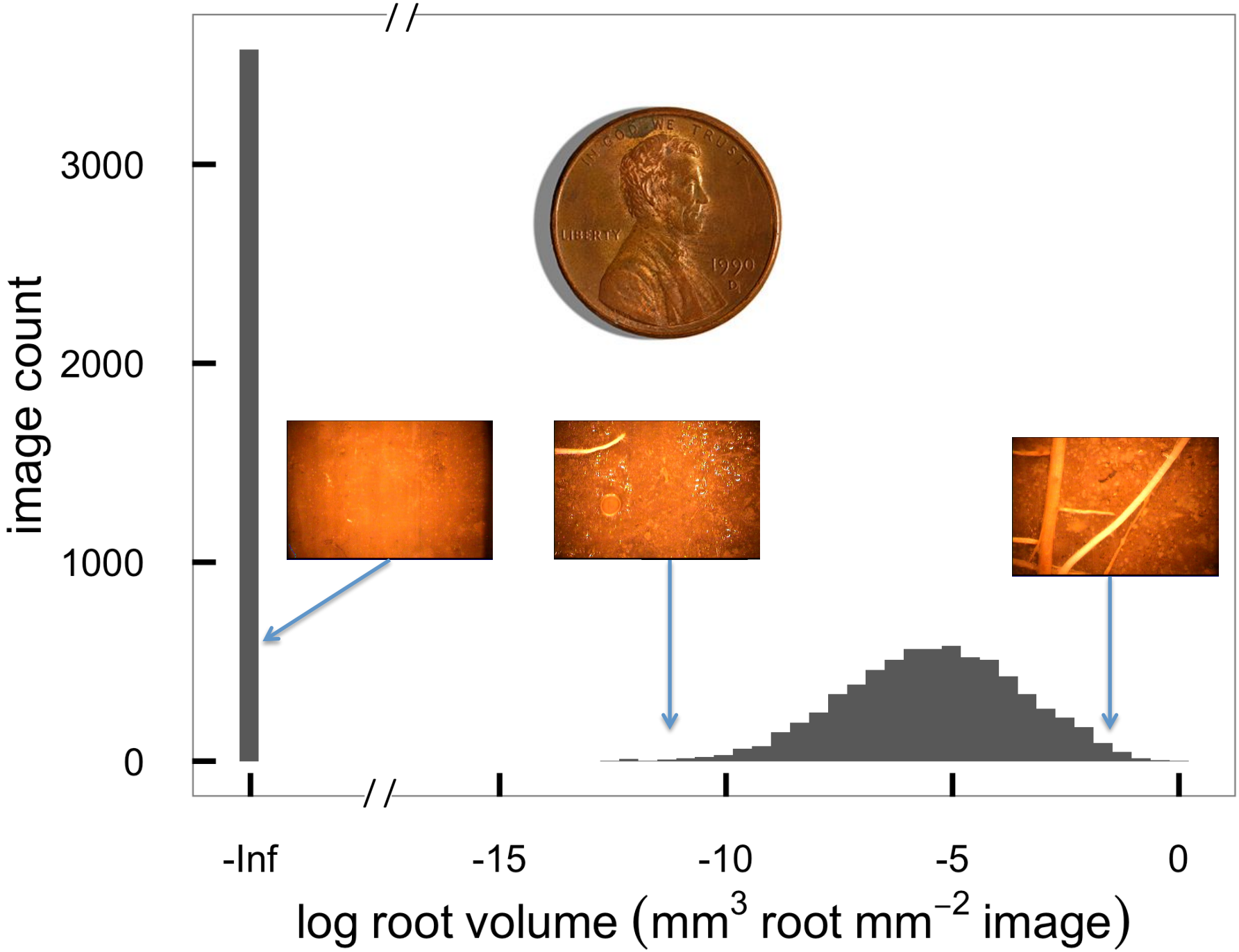


image count
3000
2000
1000
0
-Inf
-15
-10
-5
0
log root volume (mm^3 root mm^{-2} image)
IN GOD WE TRUST
LIBERTY
1990
D

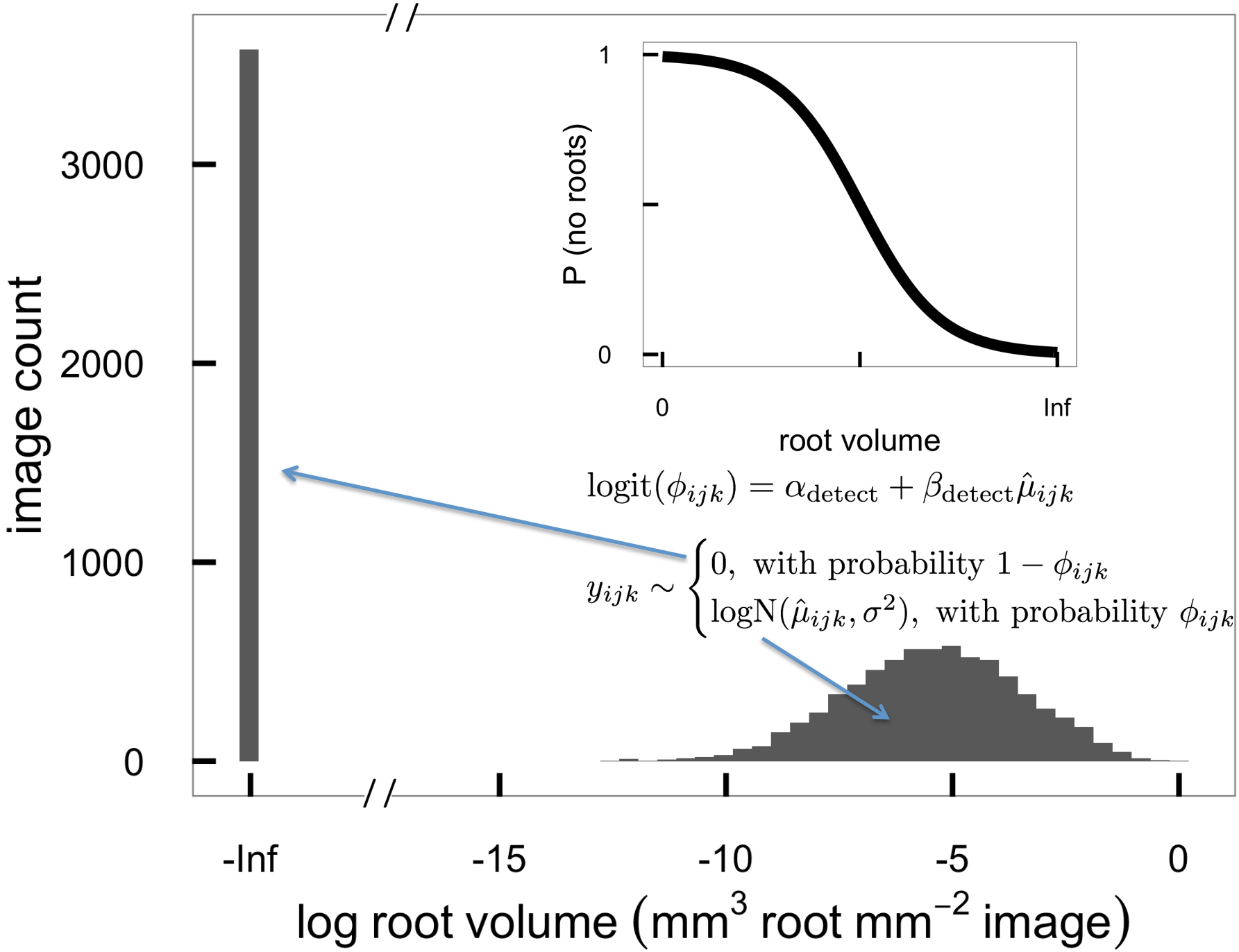
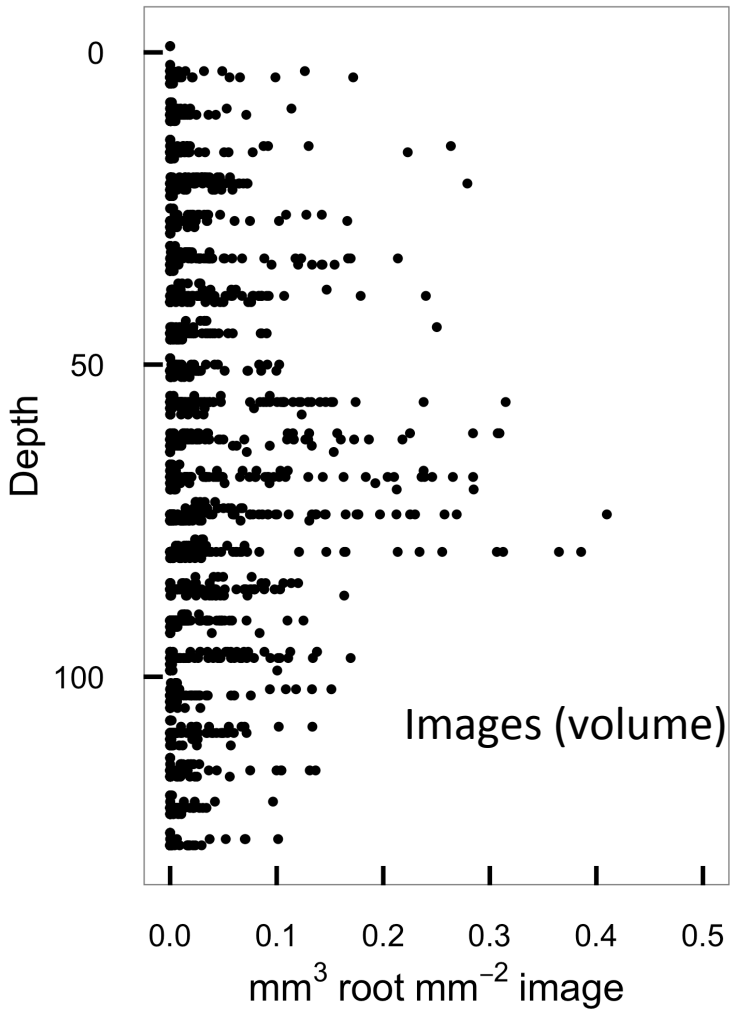
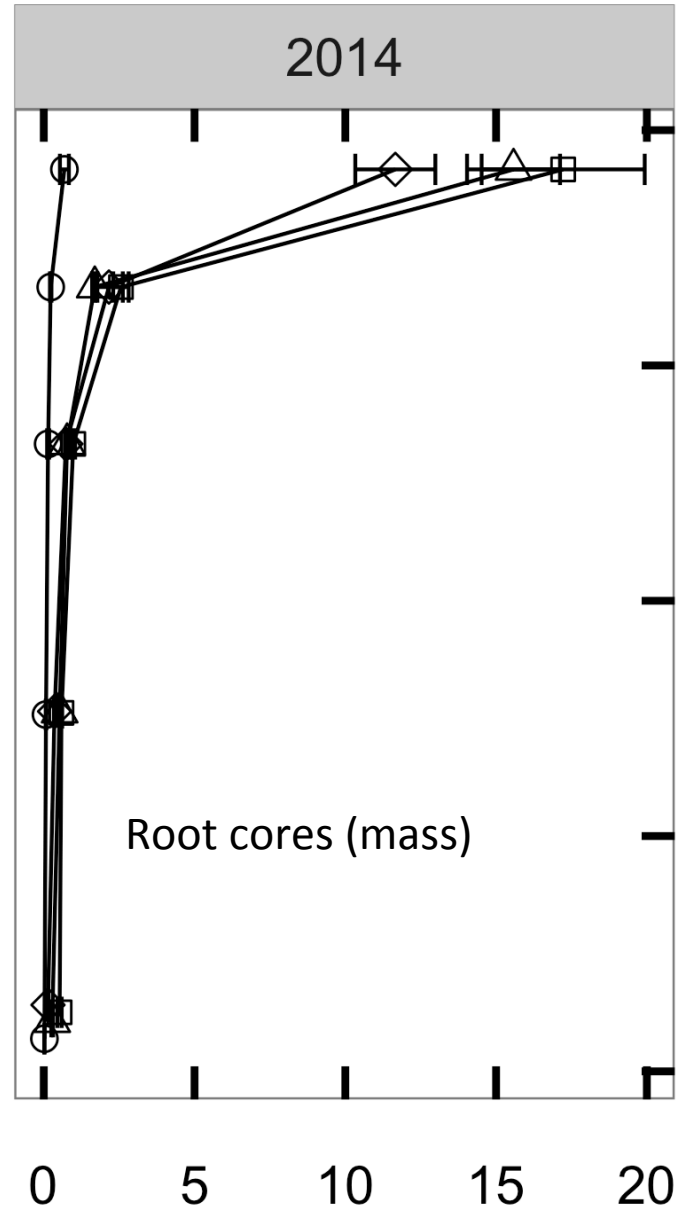


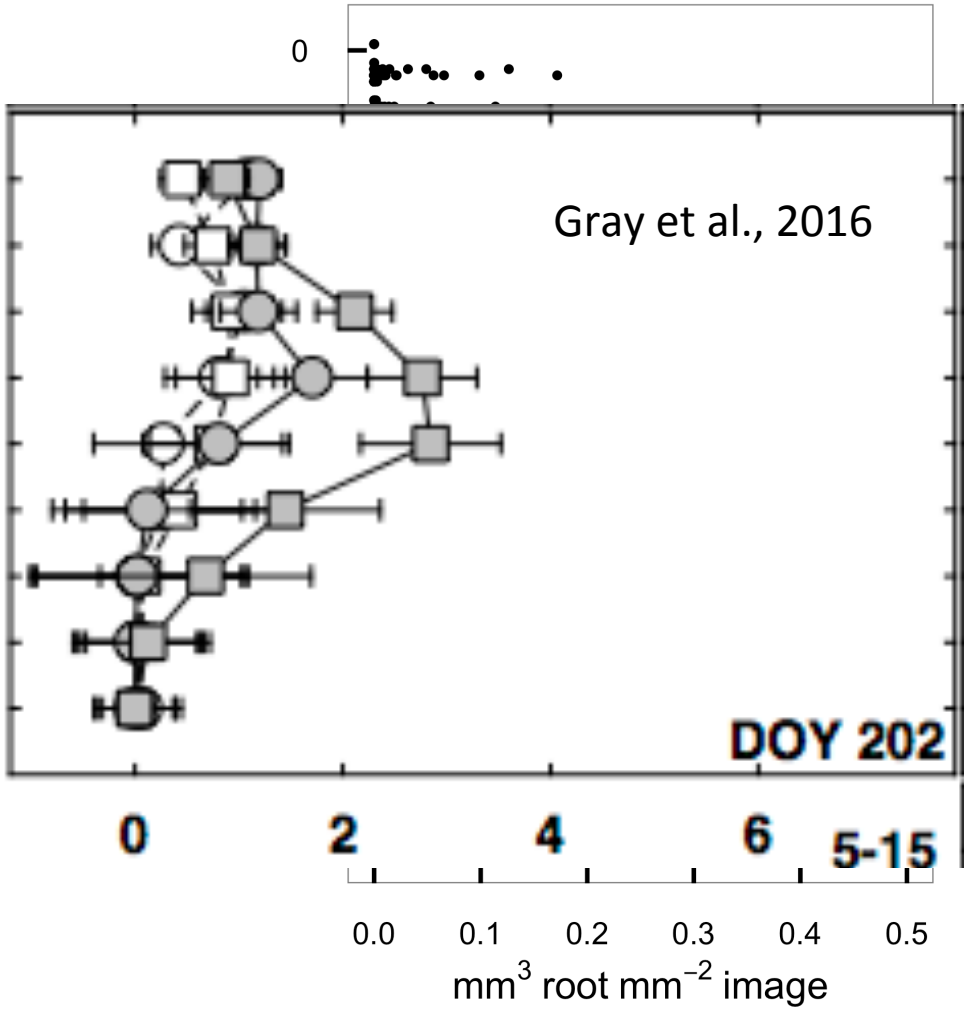
image count
3000
2000
1000
0
-Inf
-15
-10
-5
0
log root volume (mm^3 root mm^{-2} image)
P (no roots)
1
0
0
Inf
root volume
$\text{logit}(\phi_{ijk}) = \alpha_{\text{detect}} + \beta_{\text{detect}}\hat{\mu}_{ijk}$
$y_{ijk} \sim \begin{cases} 0, \text{ with probability } 1 - \phi_{ijk} \\ \text{logN}(\hat{\mu}_{ijk}, \sigma^2), \text{ with probability } \phi_{ijk} \end{cases}$

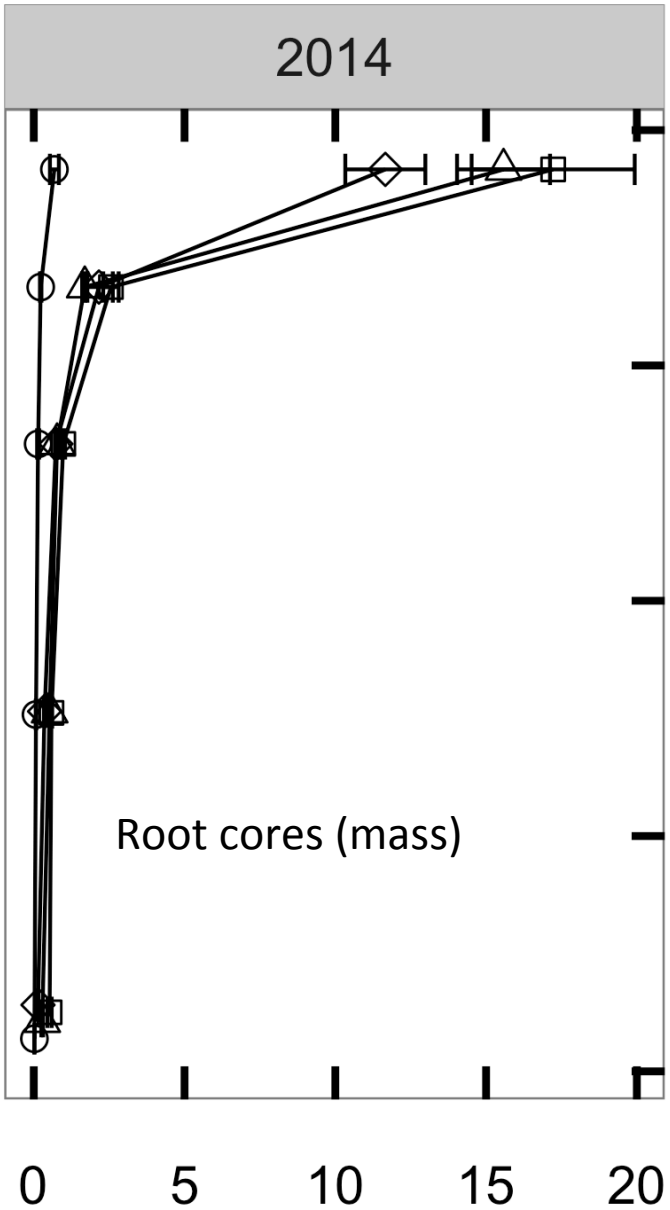
Detection is low near surface



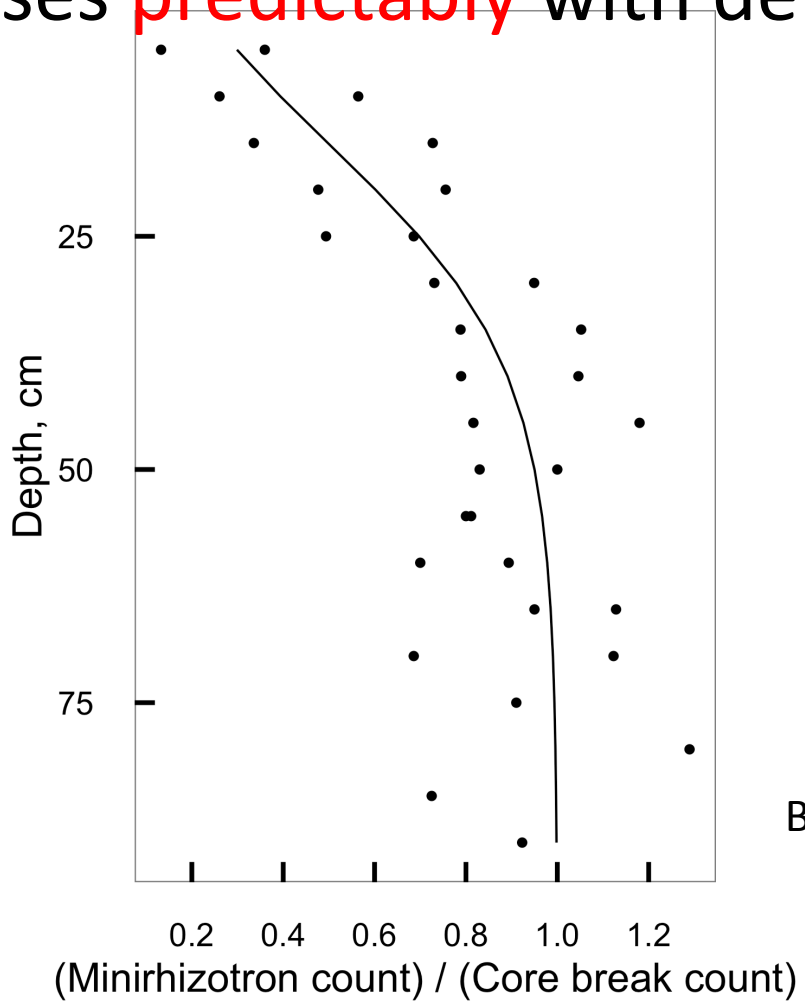


Detection is low near surface





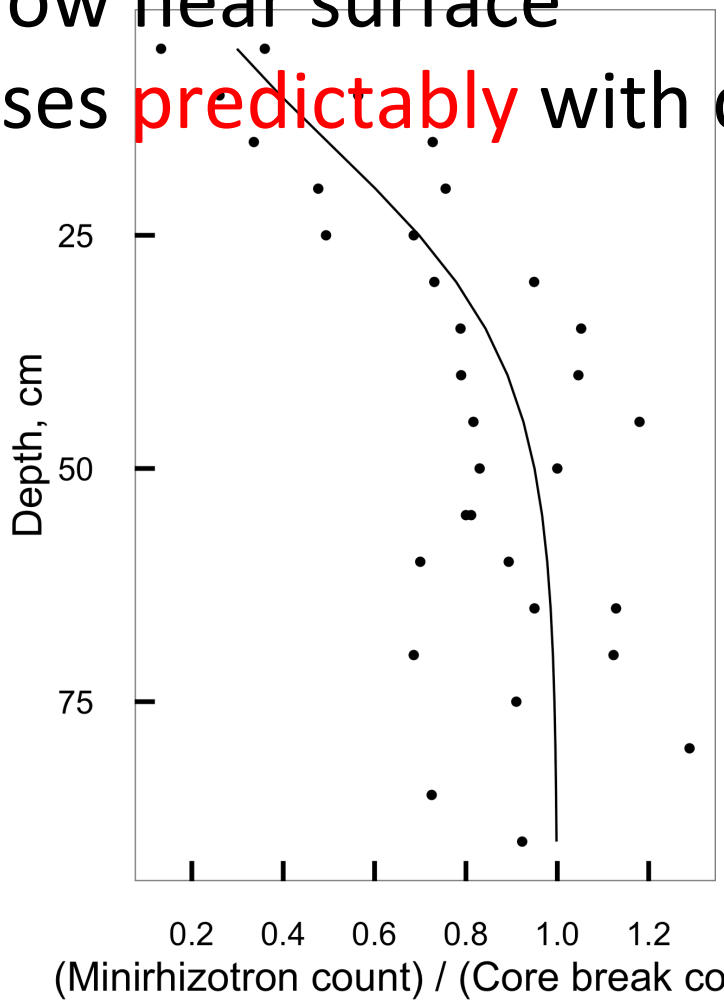
Detection is low near surface
…and decreases predictably with depth



Bragg et al., 1983

$$\hat{\mu}_{ijk} = \mu_{ijk} \cdot \mathrm{logistic}(\alpha_{\mathrm{surf}i} + \beta_{\mathrm{surf}i}\mathrm{depth}_k)$$

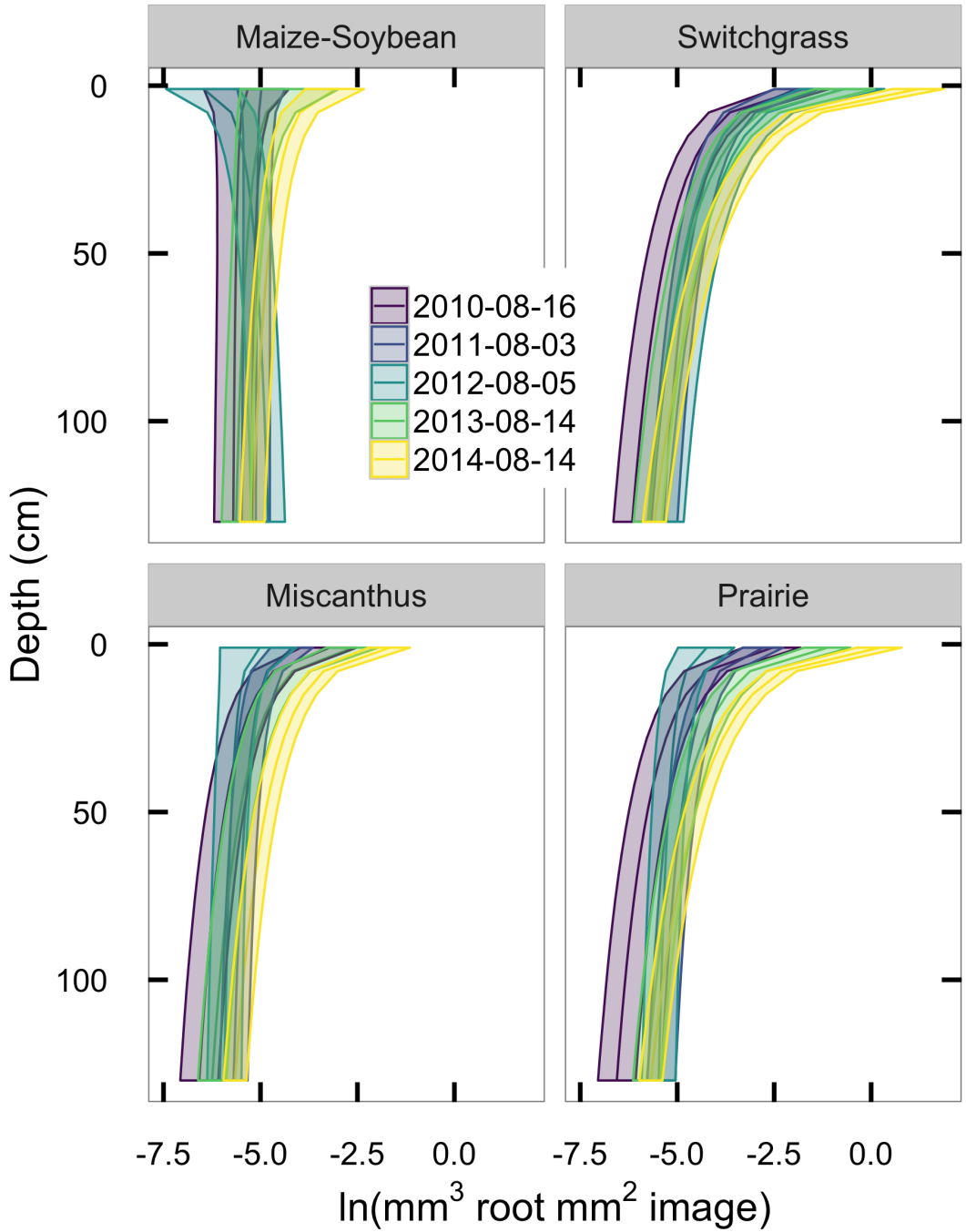
Detection is low near surface
…and decreases predictably with depth

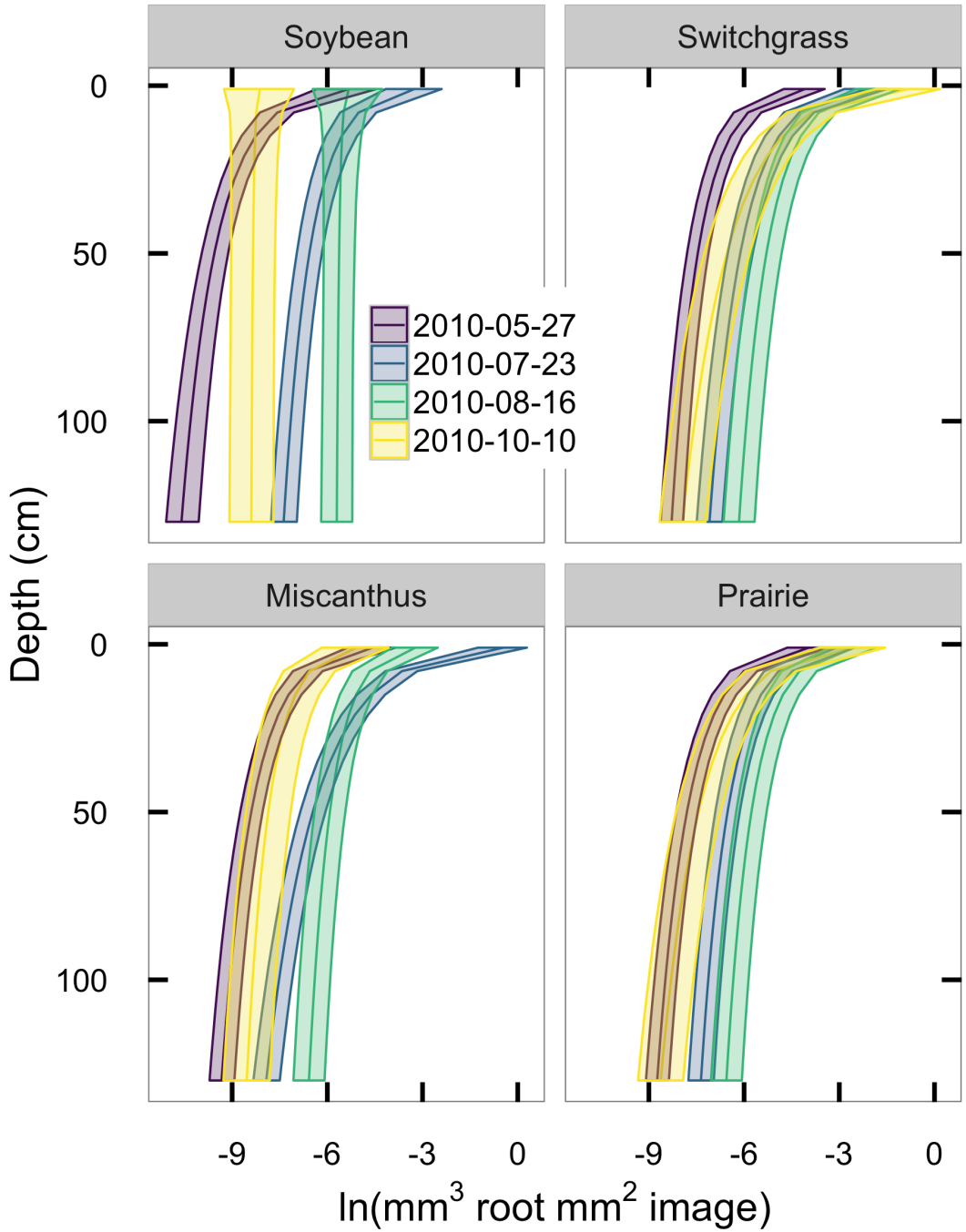


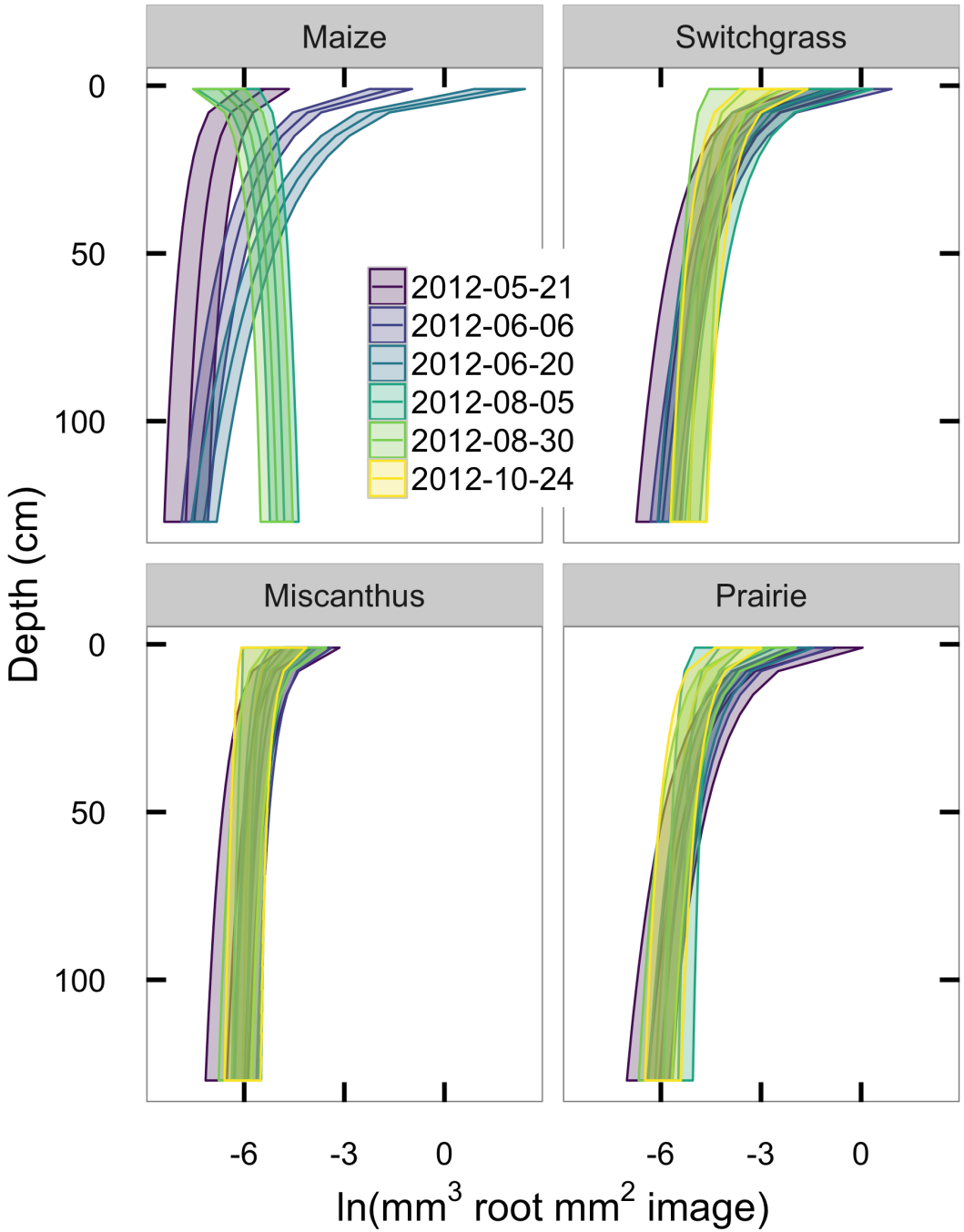
Bragg et al., 1983

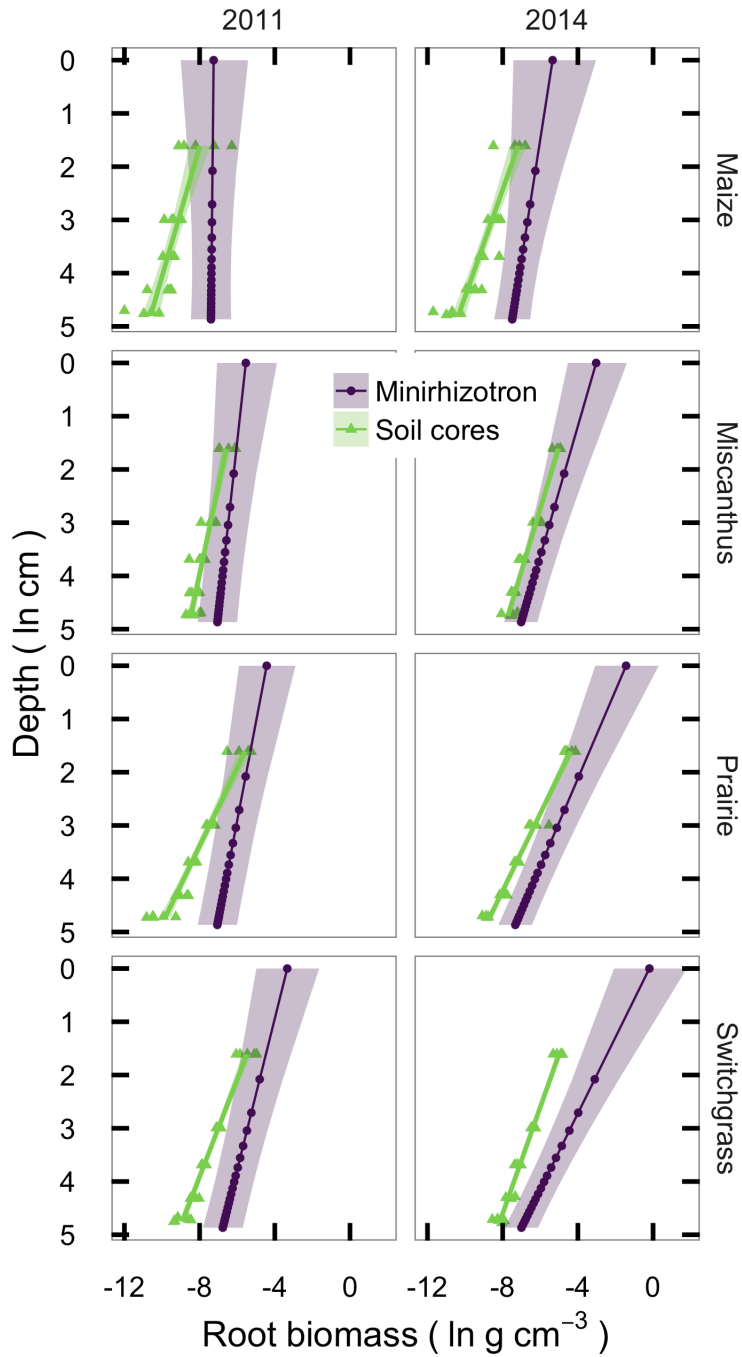
$$\hat{\mu}_{ijk} = \mu_{ijk} \cdot \mathrm{logistic}(\alpha_{\mathrm{surf}i} + \beta_{\mathrm{surf}i}\mathrm{depth}_k)$$

$$\mu_{ijk} = \alpha_i + \gamma_j + \beta_i \ln(\mathrm{depth}_k) + \epsilon_i, \quad \begin{array}{l} \gamma_j \sim N(0,\ \sigma_{\mathrm{tube}}) \\ \epsilon \sim N(0,\ \sigma) \end{array}$$


Maize-Soybean
Switchgrass
Miscanthus
Prairie
2010-08-16
2011-08-03
2012-08-05
2013-08-14
2014-08-14
Depth (cm)
0
50
100
-7.5
-5.0
-2.5
0.0
ln(mm3 root mm2 image)


Soybean
Switchgrass
Miscanthus
Prairie
2010-05-27
2010-07-23
2010-08-16
2010-10-10
Depth (cm)
0
50
100
-9
-6
-3
0
ln(mm3 root mm2 image)


Maize
Switchgrass
Miscanthus
Prairie
2012-05-21
2012-06-06
2012-06-20
2012-08-05
2012-08-30
2012-10-24
Depth (cm)
0
50
100
-6
-3
0
ln(mm3 root mm2 image)


2011
2014
Maize
Miscanthus
Prairie
Switchgrass
Minirhizotron
Soil cores
Depth (ln cm)
Root biomass (ln g cm^{-3})
0
1
2
3
4
5
-12
-8
-4
0

- Statistical model reconciles rhizotron and core data
- Non-destructive sampling
  - allows monitoring of detailed temporal dynamics
- Defensible mass estimates from 2D images!
- Opens door to automation of the imaging process

How to store soil carbon:

[✓] High inputs

Perennials >4x more root than corn

Standing root stock still increasing in year 6

[✓] Physical protection

~25% of roots are in deep soil layers

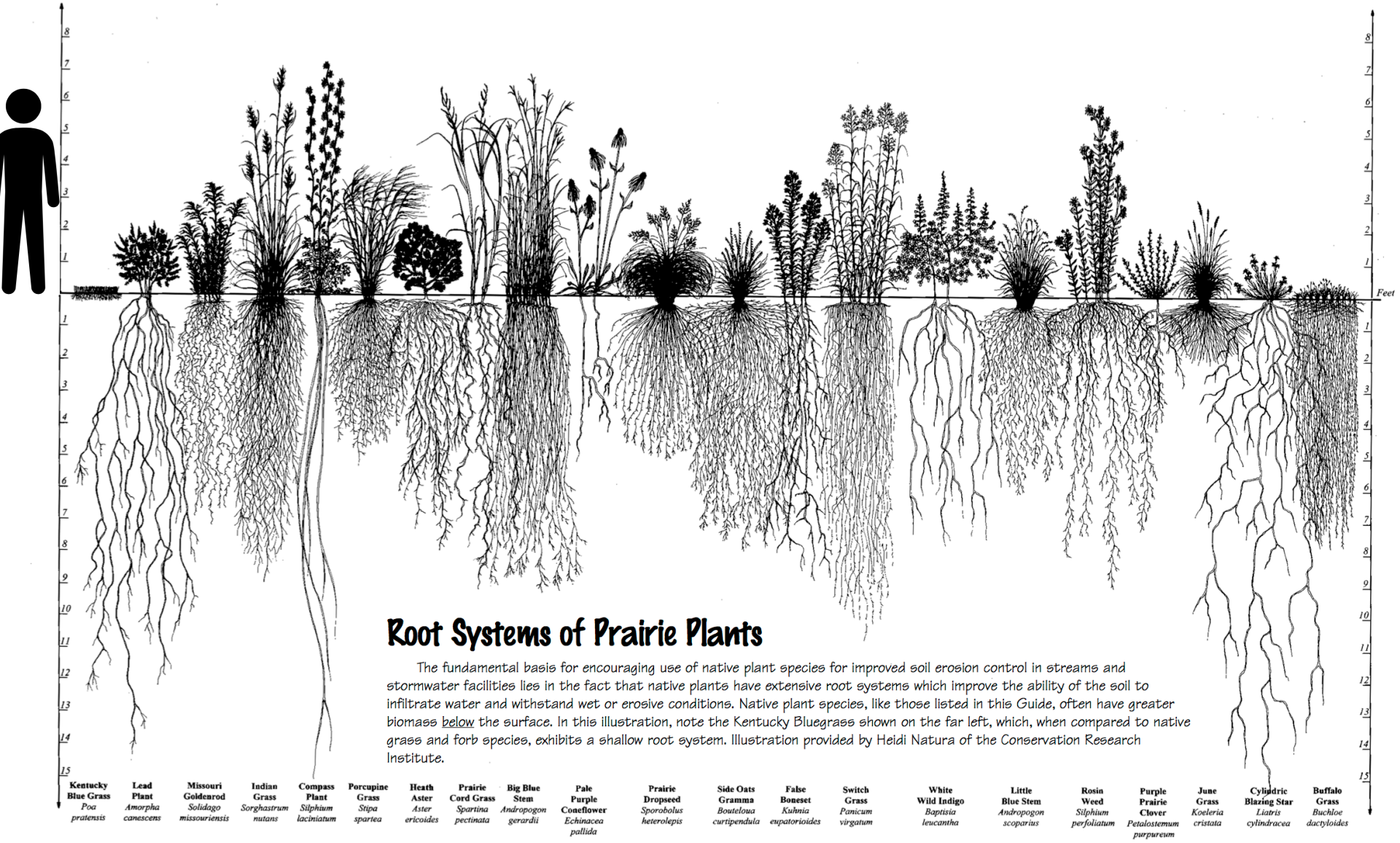
[✓] Low disturbance

No annual tillage

Resilient to a historic drought

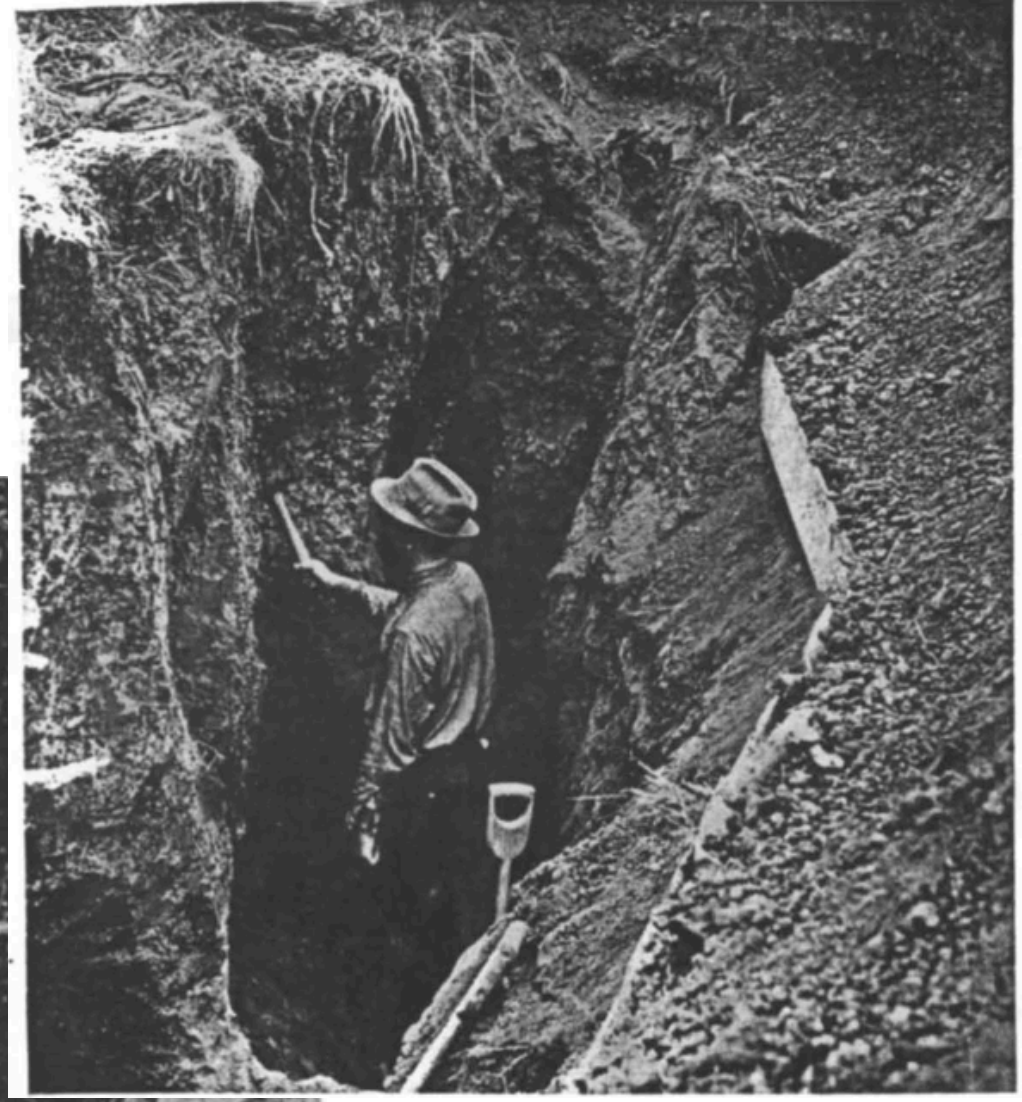
Molecular analysis shows taxonomic partitioning of root placement by depth in a prairie plant community

Christopher K. Black, Scott A. Woolbright, Taylor L. Pederson, Christopher R. Sligar, Evan H. DeLucia

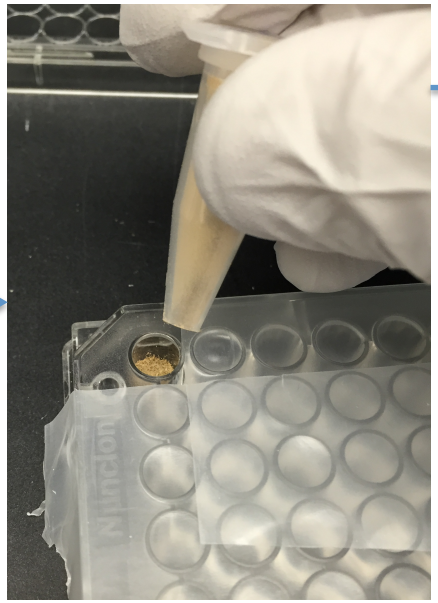


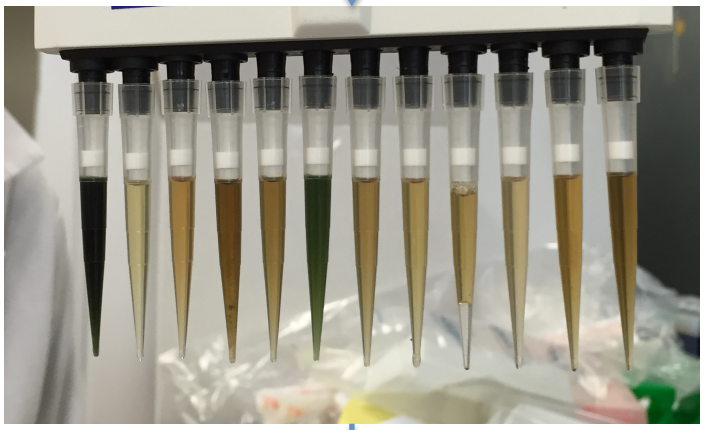
Root Systems of Prairie Plants

The fundamental basis for encouraging use of native plant species for improved soil erosion control in streams and stormwater facilities lies in the fact that native plants have extensive root systems which improve the ability of the soil to infiltrate water and withstand wet or erosive conditions. Native plant species, like those listed in this Guide, often have greater biomass below the surface. In this illustration, note the Kentucky Bluegrass shown on the far left, which, when compared to native grass and forb species, exhibits a shallow root system. Illustration provided by Heidi Natura of the Conservation Research Institute.



J.E. Weaver, 1919





High-throughput sequencing
(Illumina; MiSeq 2x300)
Alvaro Hernandez, W.M. Keck Center

Microfluidic PCR targeting ITS region
(Fluidigm; Access Array)
Mark Band, Carver Center

Filtering & chimera removal

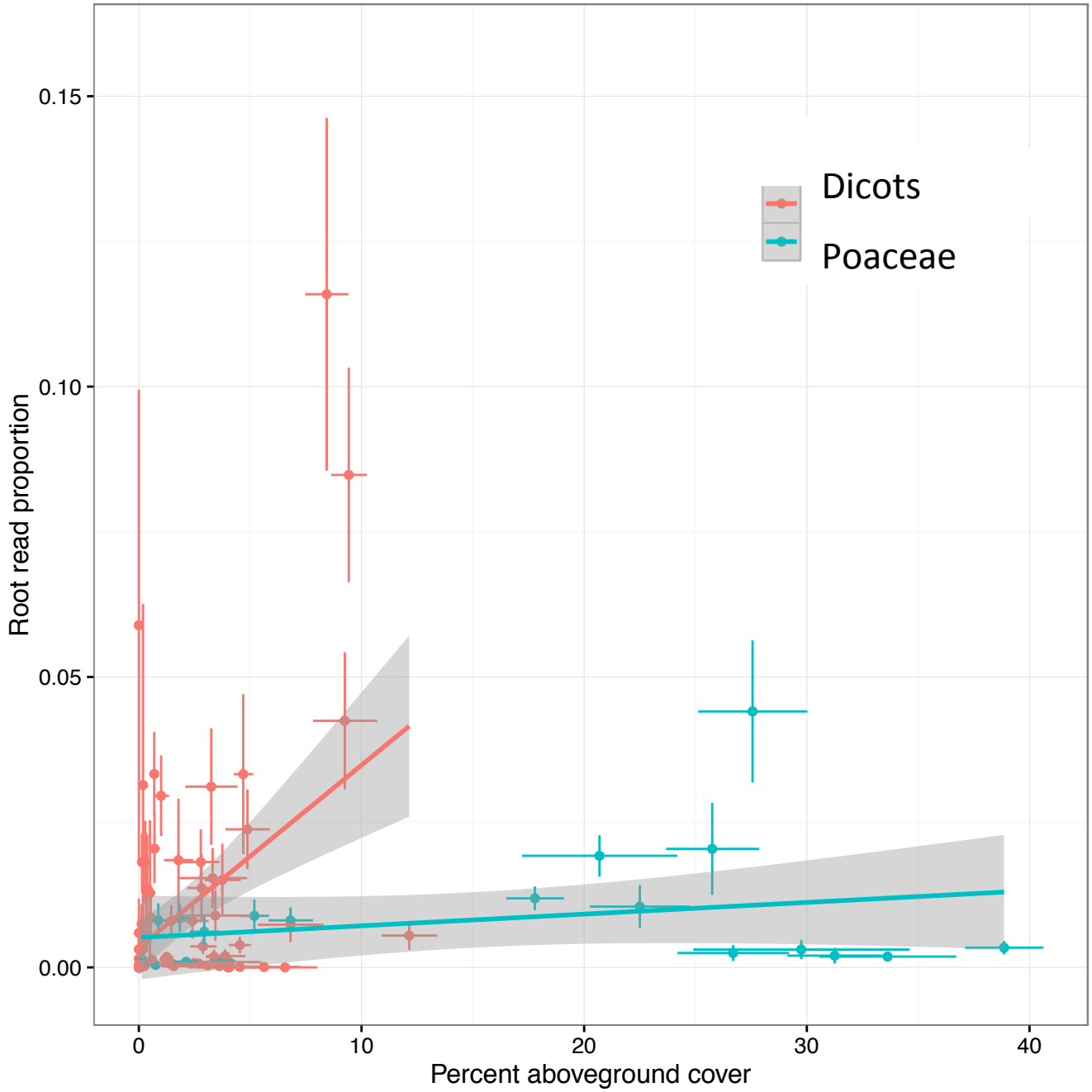
Extract ITS2 variable region

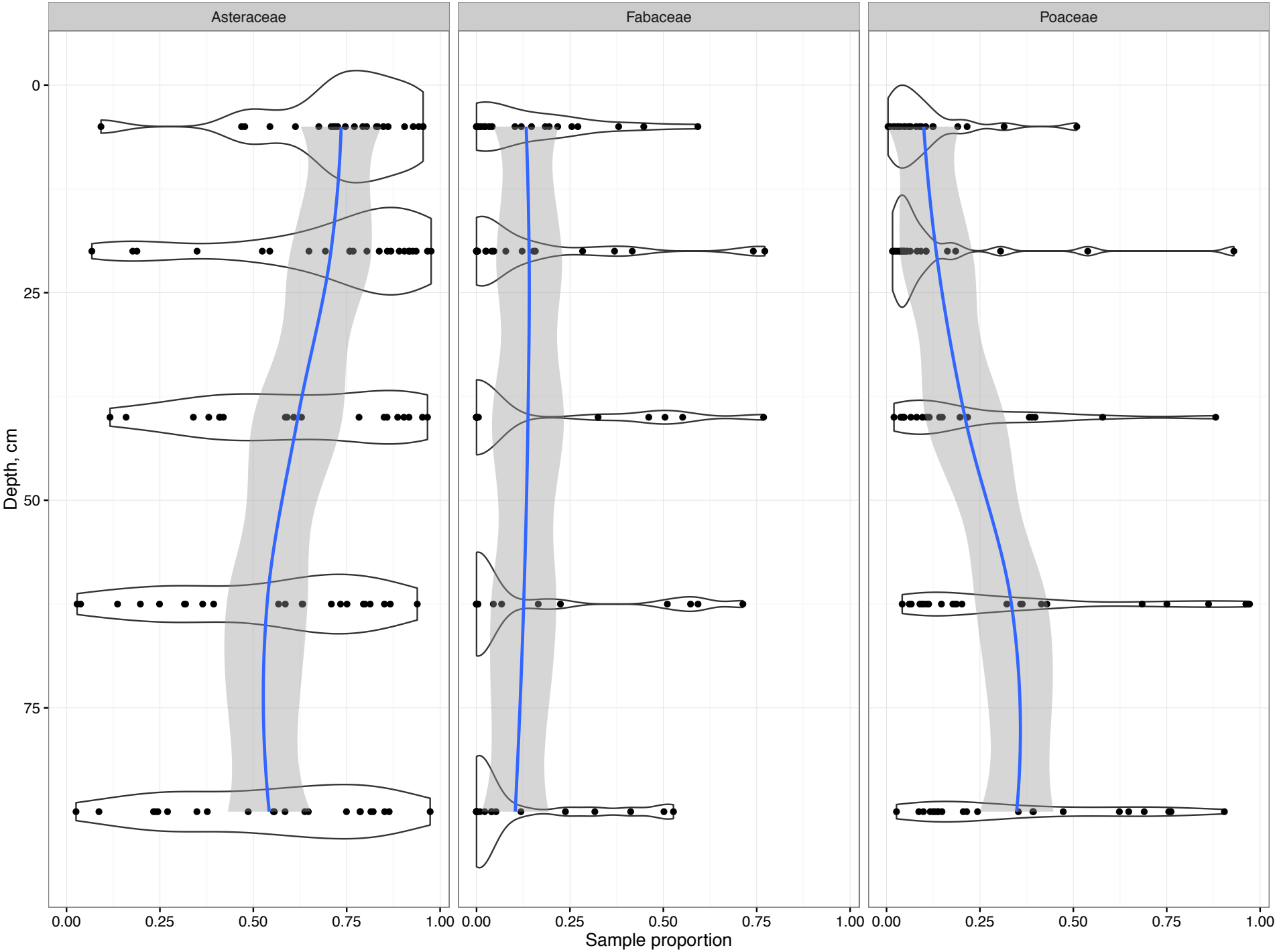
Match sequences against full nt database
(BLAST, full nt database)

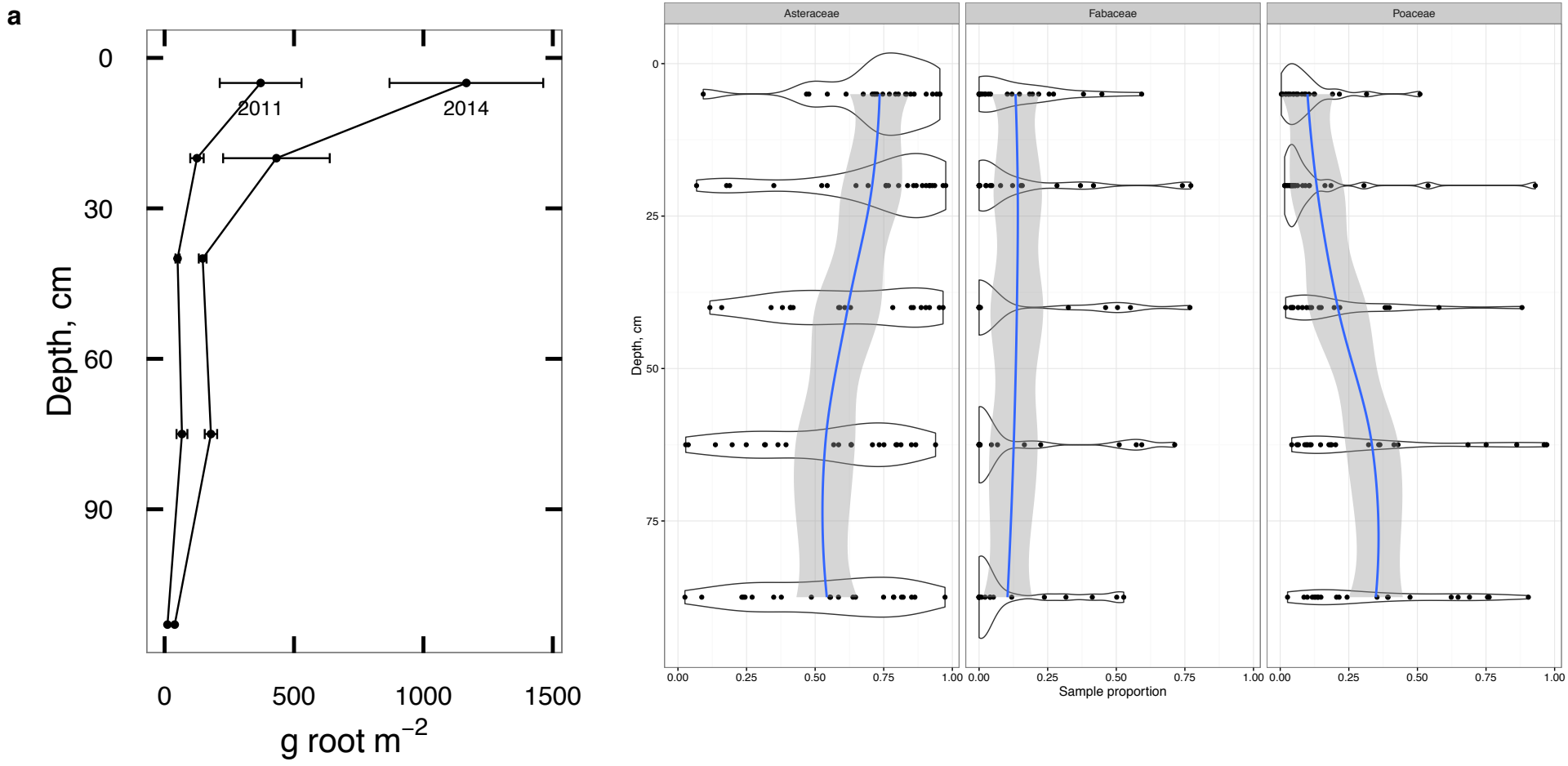
Collapse by taxon

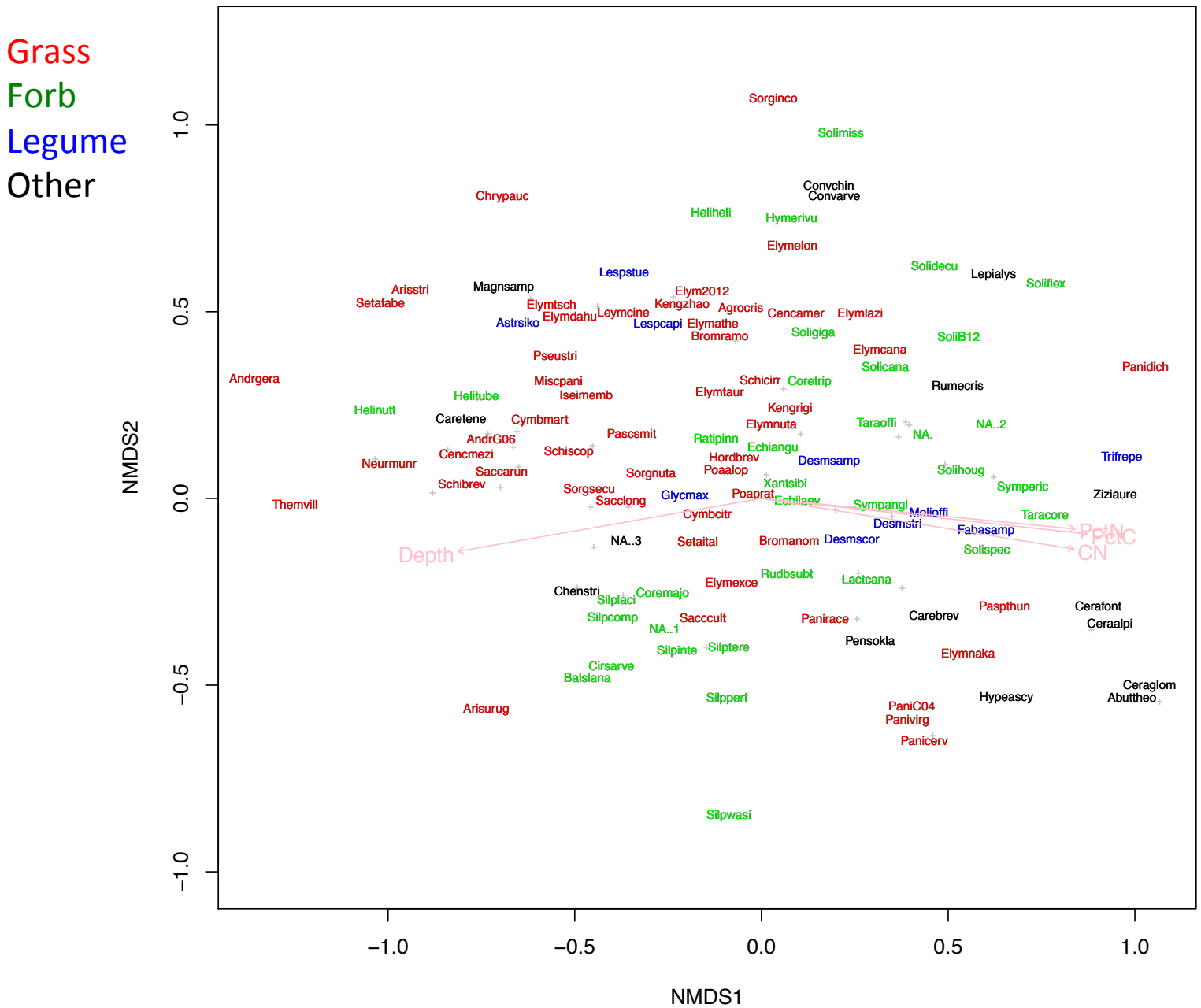
Normalize read counts

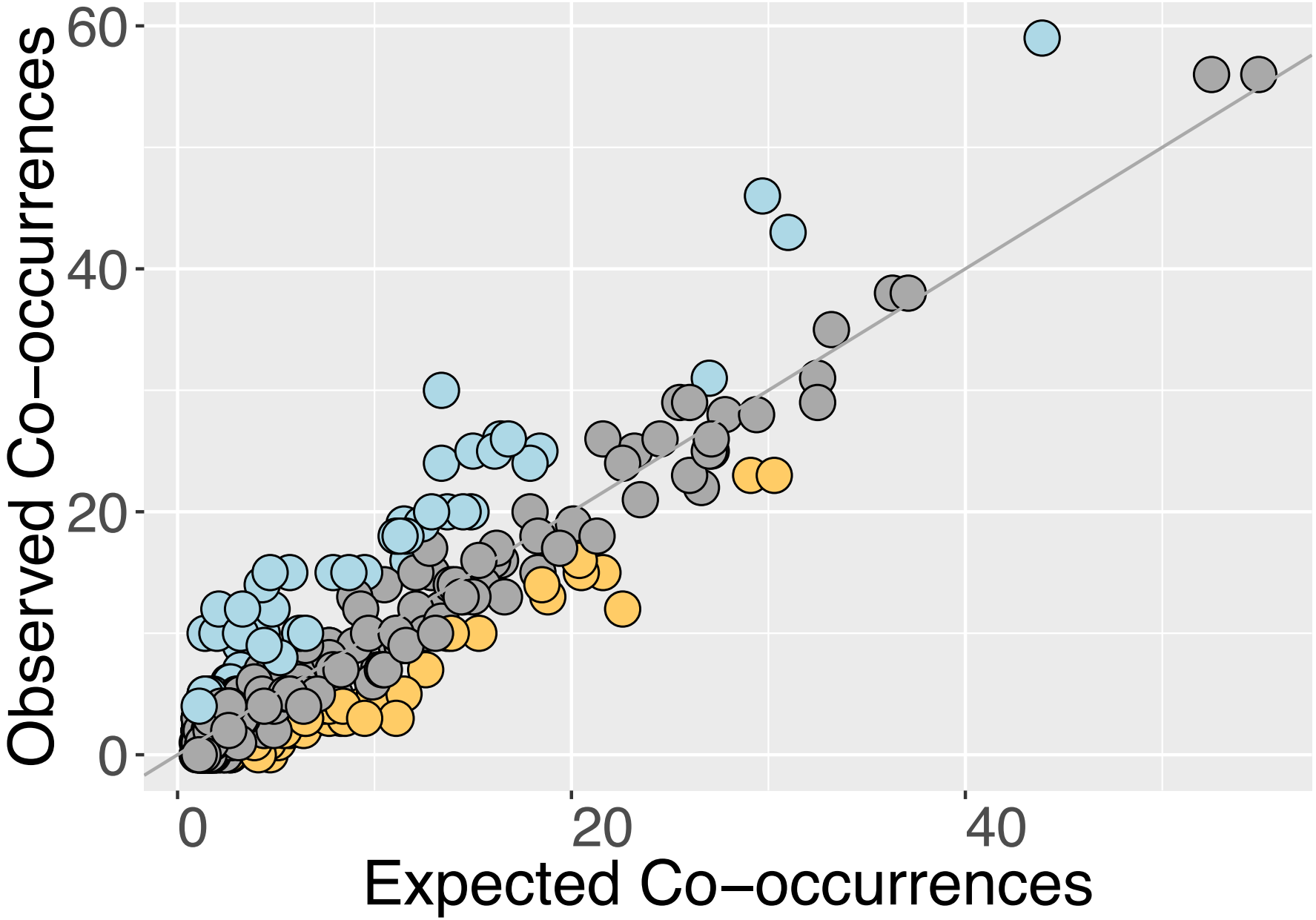
taxa-by-sample matrix

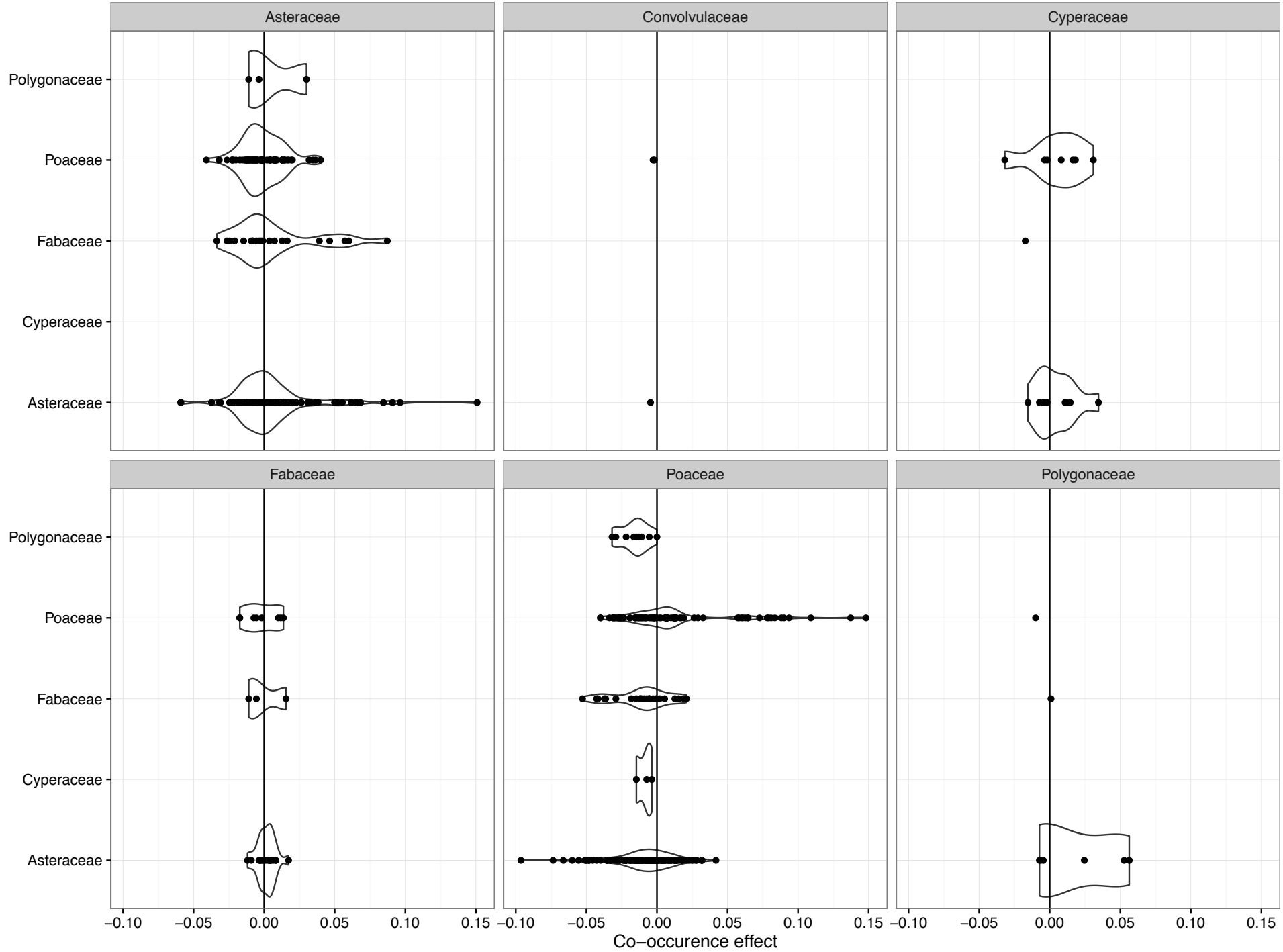

Dicots
Poaceae
Root read proportion
0.15
0.10
0.05
0.00
0
10
20
30
40
Percent aboveground cover


Asteraceae
Fabaceae
Poaceae
Depth, cm
0
25
50
75
0.00
0.25
0.50
0.75
1.00
Sample proportion


a
Depth, cm
0
30
60
90
2011
2014
0
500
1000
1500
g root m^{-2}
Asteraceae
Fabaceae
Poaceae
Depth, cm
0
25
50
75
0.00
0.25
0.50
0.75
1.00
Sample proportion


Grass
Forb
Legume
Other
NMDS2
NMDS1
1.0
0.5
0.0
−0.5
−1.0
Sorginco
Solimiss
Convchin
Convarve
Chrypauc
Heliheli
Hymerivu
Elymelon
Lespstue
Solidecu
Lepialys
Soliflex
Arisstri
Magnsamp
Setafabe
Elym2012
Elymtsch
Kengzhao
Agrocris
Cencamer
Elymlazi
Astrsiko
Elymdahu
Leymcine
Lespcapi
Elymathe
Bromramo
Soligiga
SoliB12
Elymcana
Pseustri
Solicana
Panidich
Andrgera
Miscpani
Schicirr
Coretrip
Rumecris
Helitube
Iseimemb
Elymtaur
Helinutt
Kengrigi
Caretene
Cymbmart
Elymnuta
Taraoffi
NA..2
Pascsmit
Ratipinn
NA.
AndrG06
Echiangu
Cencmezi
Schiscop
Hordbrev
Desmsamp
Trifrepe
Neurmunr
Saccarun
Sorgnuta
Poaalop
Solihoug
Schibrev
Xantsibi
Symperic
Sorgsecu
Ziziaure
Themvill
Sacclong
Glycmax
Poaprat
Echilaev
Sympangl
Melioffi
Taracore
Cymbcitr
Desmstri
Fabasamp
PctN
PctC
CN
Depth
NA..3
Setaital
Bromanom
Desmscor
Solispec
Rudbsubt
Elymexce
Lactcana
Chenstri
Silplaci
Coremajo
Paspthun
Cerafont
Silpcomp
Sacccult
Panirace
Carebrev
Ceraalpi
NA..1
Pensokla
Silpinte
Silptere
Elymnaka
Cirsarve
Balslana
Ceraglom
Abuttheo
Silpperf
Hypeascy
Arisurug
PaniC04
Panivirg
Panicerv
Silpwasi


Observed Co−occurrences
60
40
20
0
0
20
40
Expected Co−occurrences


Asteraceae
Convolvulaceae
Cyperaceae
Fabaceae
Poaceae
Polygonaceae
Polygonaceae
Poaceae
Fabaceae
Cyperaceae
Asteraceae
−0.10
−0.05
0.00
0.05
0.10
0.15
Co−occurence effect

- Highly parallel PCR + sequencing = easy root ID
  - Taxonomic resolution of *ITS2* not a big limitation for this system, but could probably be improved with a localized database.
- Grass roots probably contribute less *mass* to total than expected
  - But need species-specific yields to quantify this
- Grasses appear to have distinct ecological role & occupy different spatial niche
  - Deeper rooting = more reliable water access, but probably less N access
  - If grass roots decompose slower, deep placement good for stable C storage
- Most other functional types co-occur randomly or overdispersed
  - Reasonable? System was planted homogeneously on a rich, even soil

Climate change + current ag practice = bad news
Perennial grasses appear to have potential to build soil C

Open questions:

- Turnover time?
- Grass responses to climate change

POLICY:

- Perennials have long establishment lag
- ➔ Land managers need stable, long-term policy/conditions.

Thanks!

Committee
Evan DeLucia
Carl Bernacchi
Sarah Davis
Andrew Leakey

Committee Emeritus
Mark David

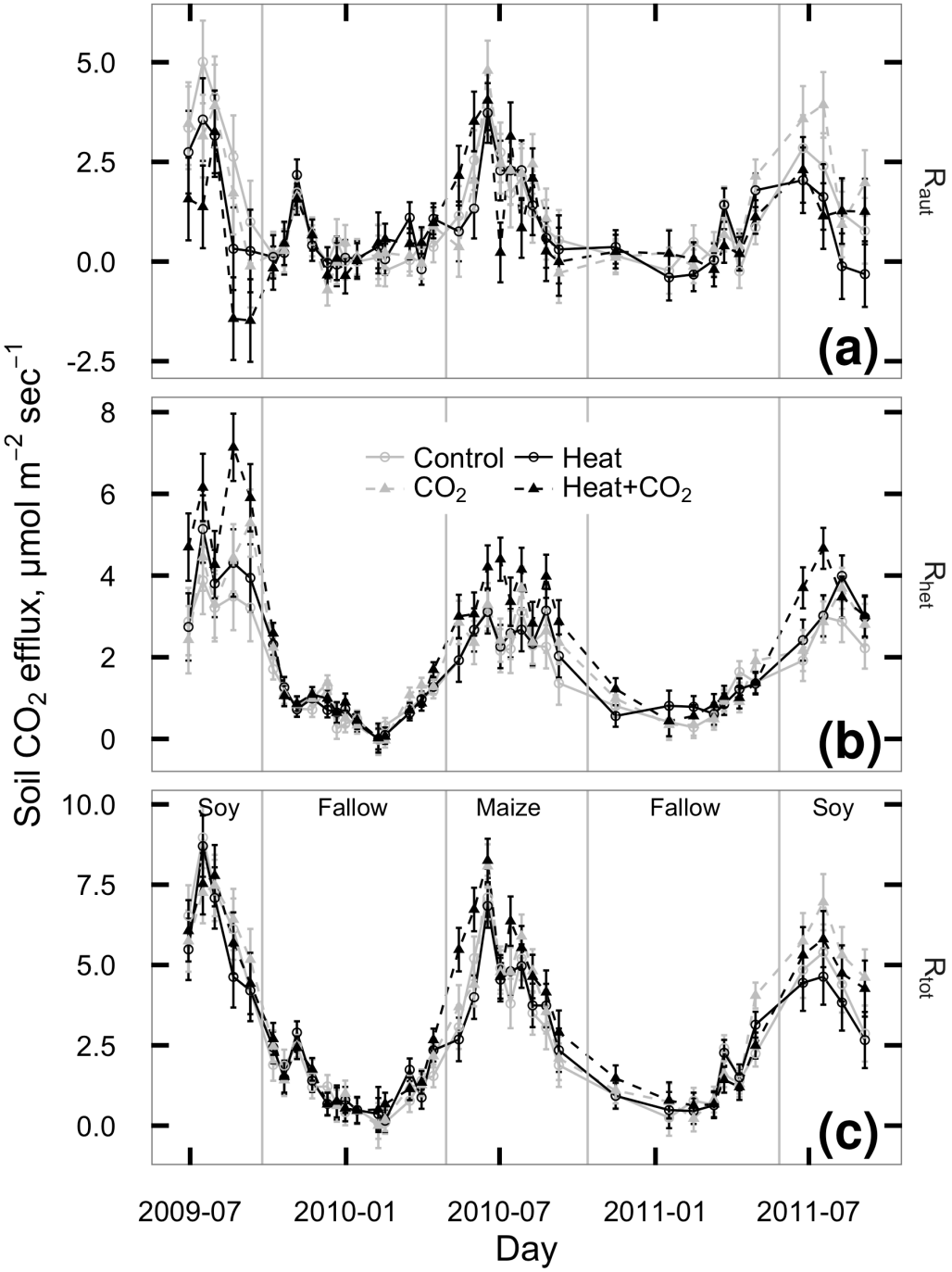
Sanity preservation
The entire DeLucia lab
Anna Locke
Cody Markelz
Jesse Miller
Liz Olney
Matt & Angie Isaacs
Flying Machine Coffee

Funding
Energy Biosciences Institute
DOE/NICCR
Laughnan award
IGB Fellows fund (Woolbright)

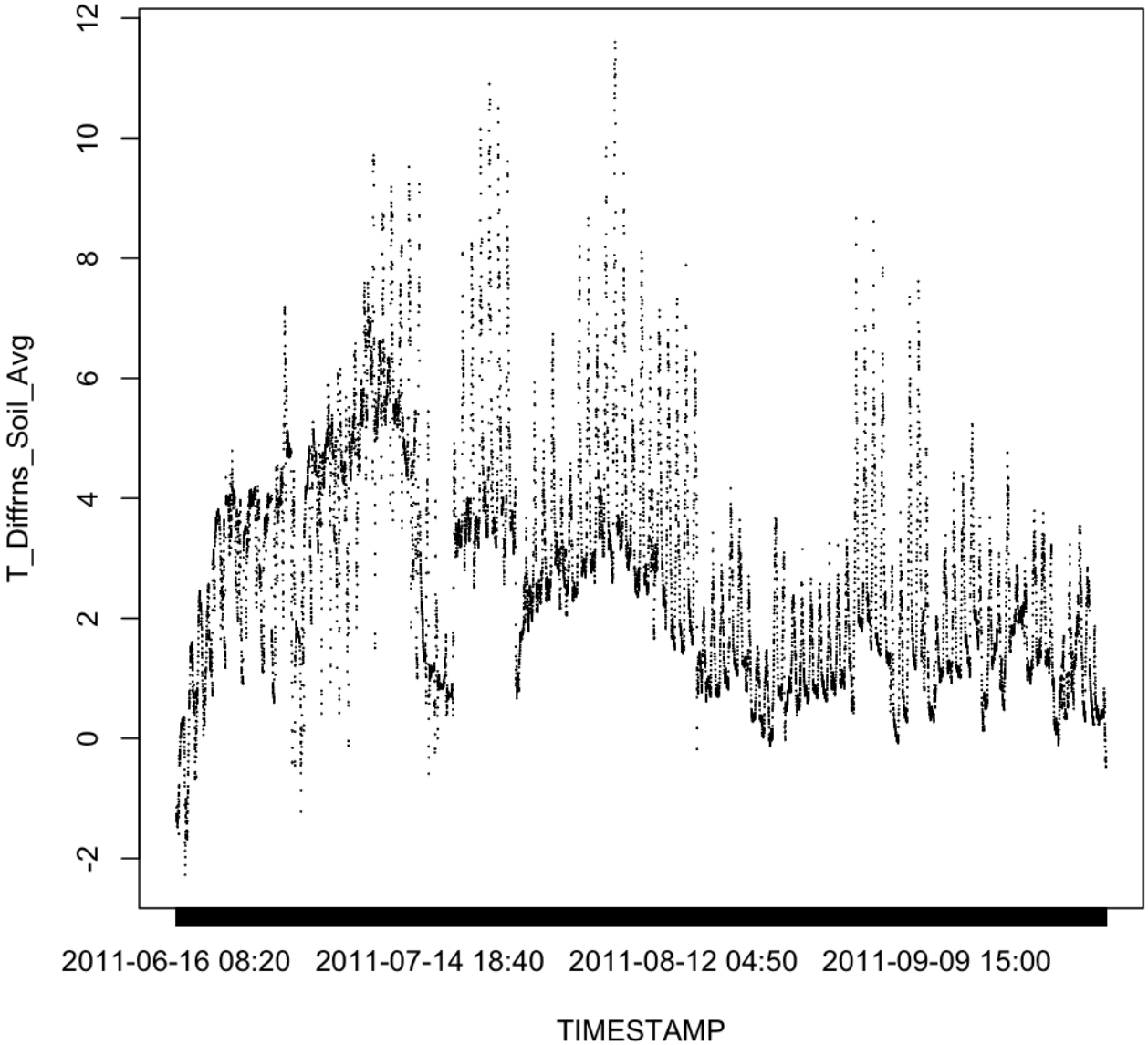
All credit not otherwise assigned
Laurel Brehm

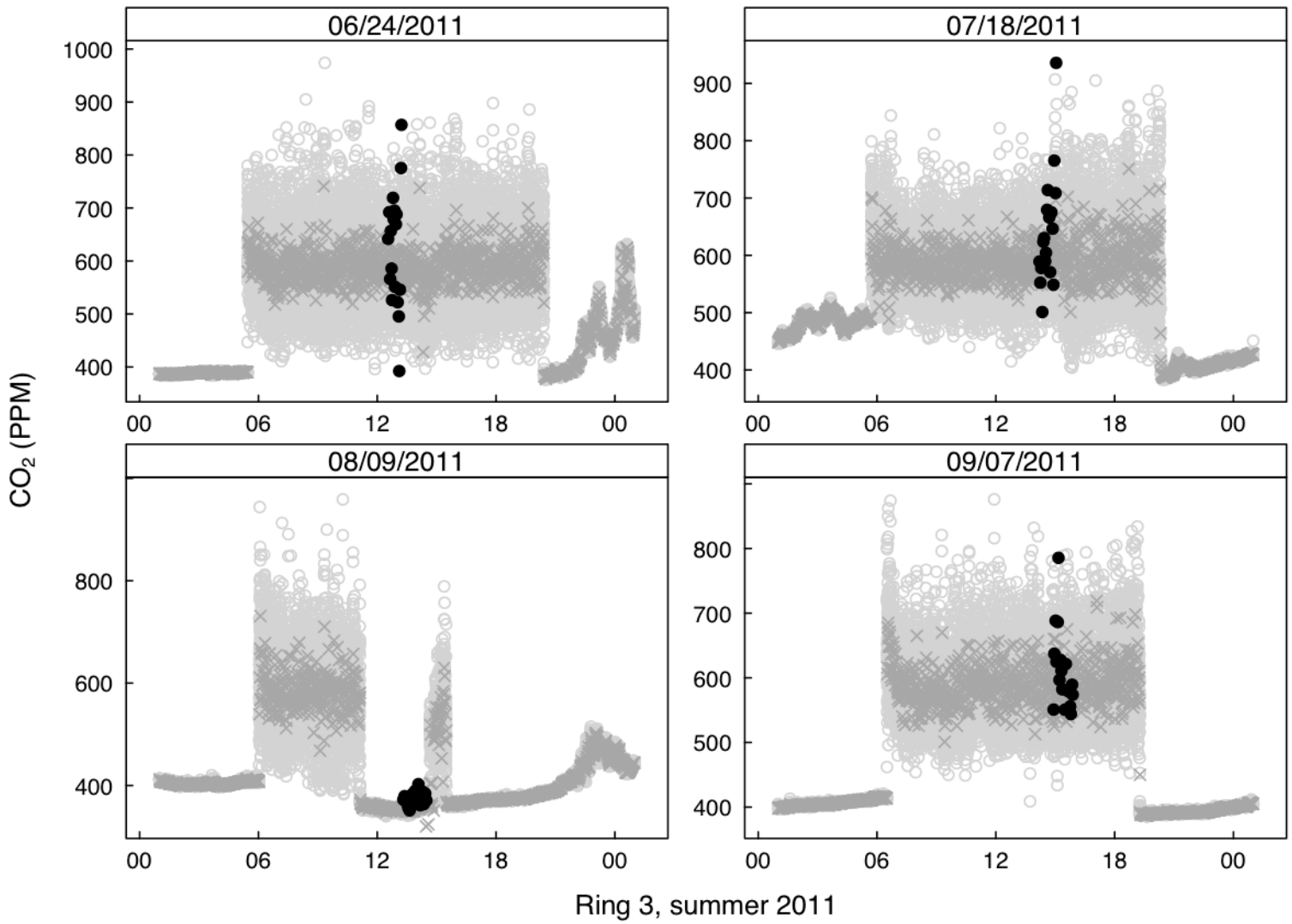
TRACED BY
Chris Sligar
ANY ROOTS?
no
NOTES
Ornithorhynchus xylocopa

tface


Soil CO_2 efflux, µmol m^{-2} sec^{-1}
5.0
2.5
0.0
-2.5
(a)
R_{aut}
8
6
4
2
0
Control
Heat
CO_2
Heat+CO_2
(b)
R_{het}
10.0
7.5
5.0
2.5
0.0
Soy
Fallow
Maize
Fallow
Soy
(c)
R_{tot}
2009-07
2010-01
2010-07
2011-01
2011-07
Day

Plot 1 thermocouples, summer 2011




06/24/2011
07/18/2011
08/09/2011
09/07/2011
CO_2 (PPM)
1000
900
800
700
600
500
400
00
06
12
18
00
Ring 3, summer 2011

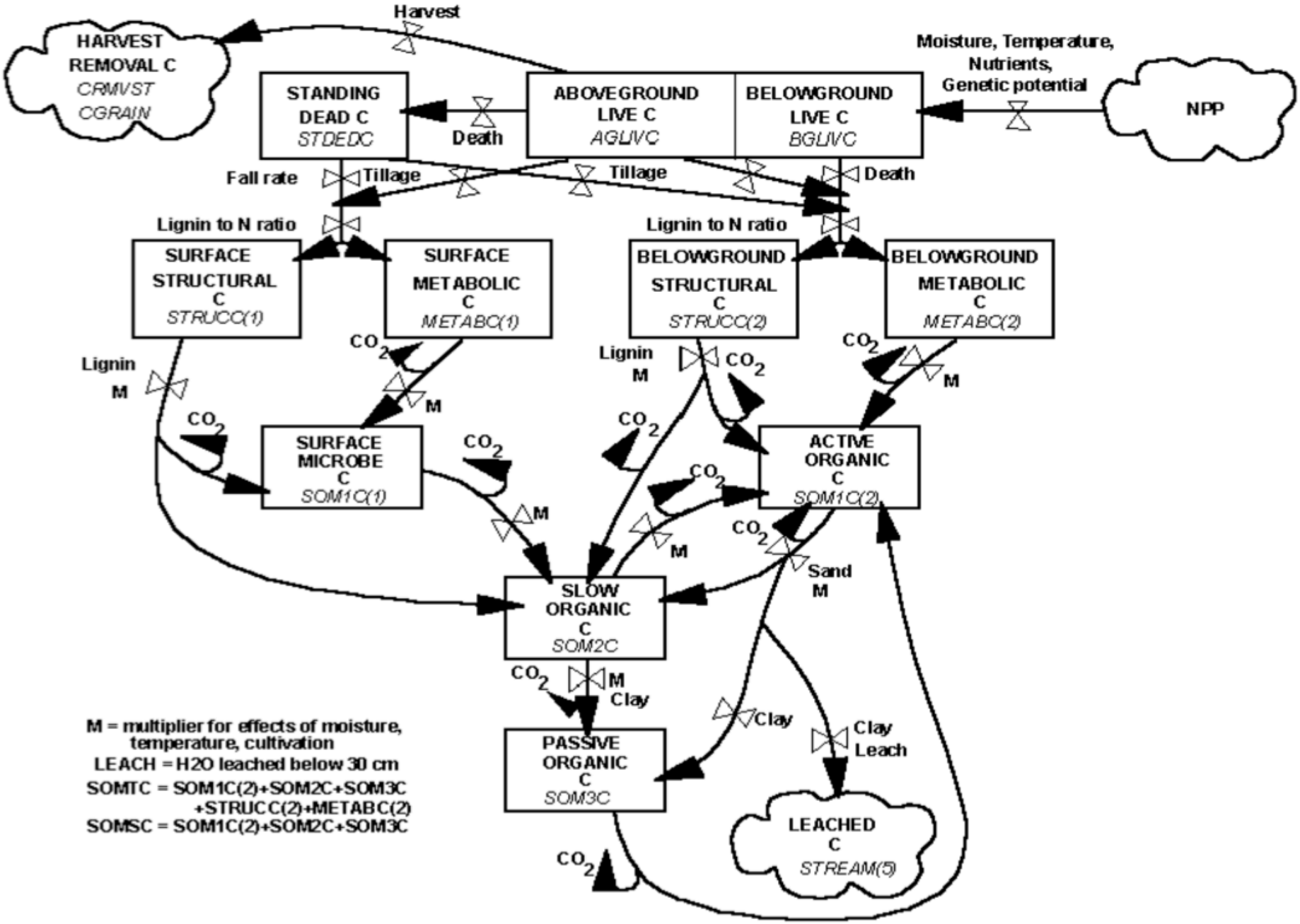
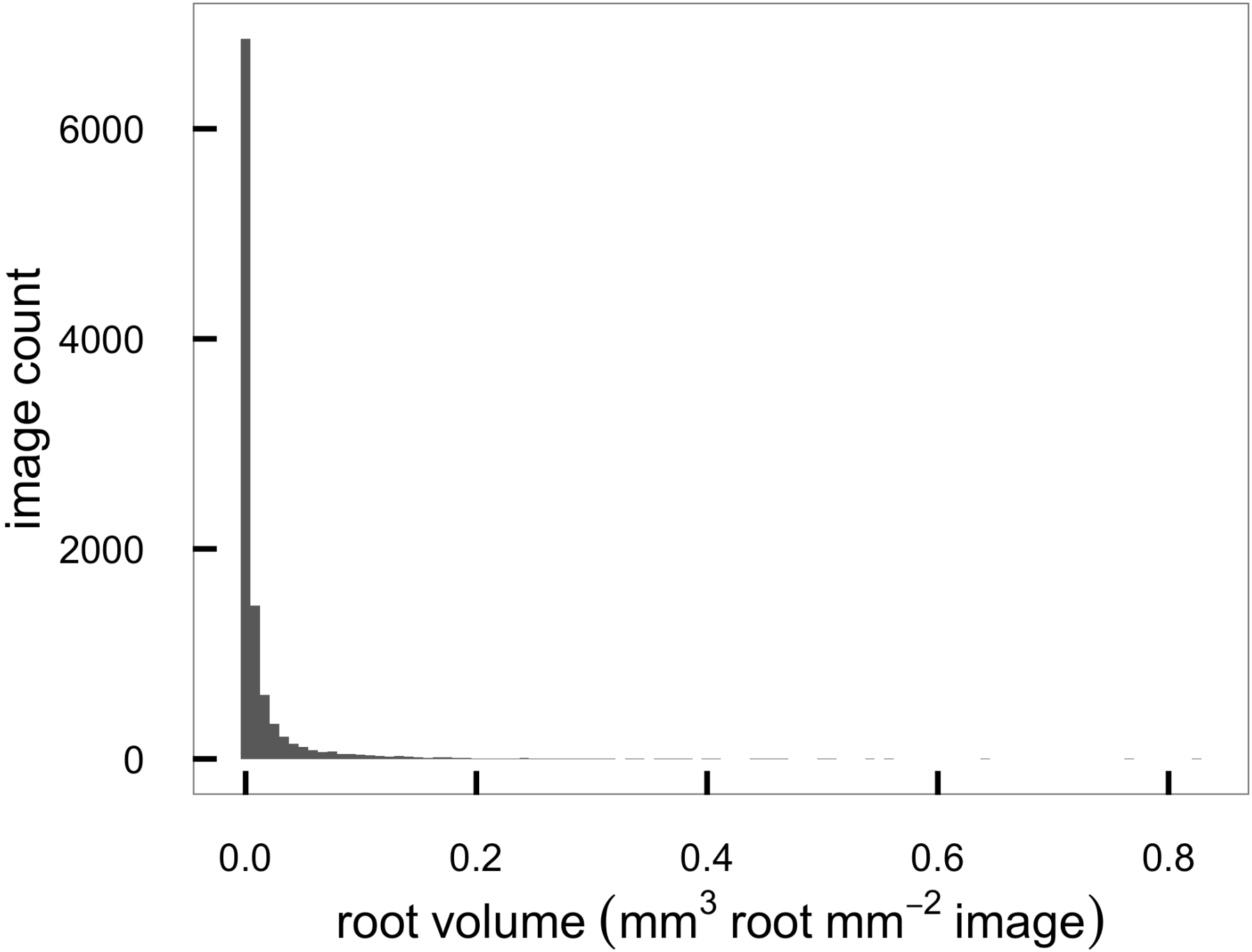


Figure 3-1: The pools and flows of carbon in the CENTURY model. The diagram shows the major factors which control the flows.

Rhizo


6000
4000
2000
0
image count
0.0
0.2
0.4
0.6
0.8
root volume (mm3 root mm−2 image)

Full model

$$y_{ijk} \sim \begin{cases} 0, \text{ with probability } 1 - \phi_{ijk} \\ \text{logN}(\hat{\mu}_{ijk}, \sigma^2), \text{ with probability } \phi_{ijk} \end{cases}$$

$$\text{logit}(\phi_{ijk}) = \alpha_{\text{detect}} + \beta_{\text{detect}} \hat{\mu}_{ijk}$$

$$\hat{\mu}_{ijk} = \mu_{ijk} \cdot \text{logistic}(\alpha_{\text{surf}i} + \beta_{\text{surf}i} \text{depth}_k)$$

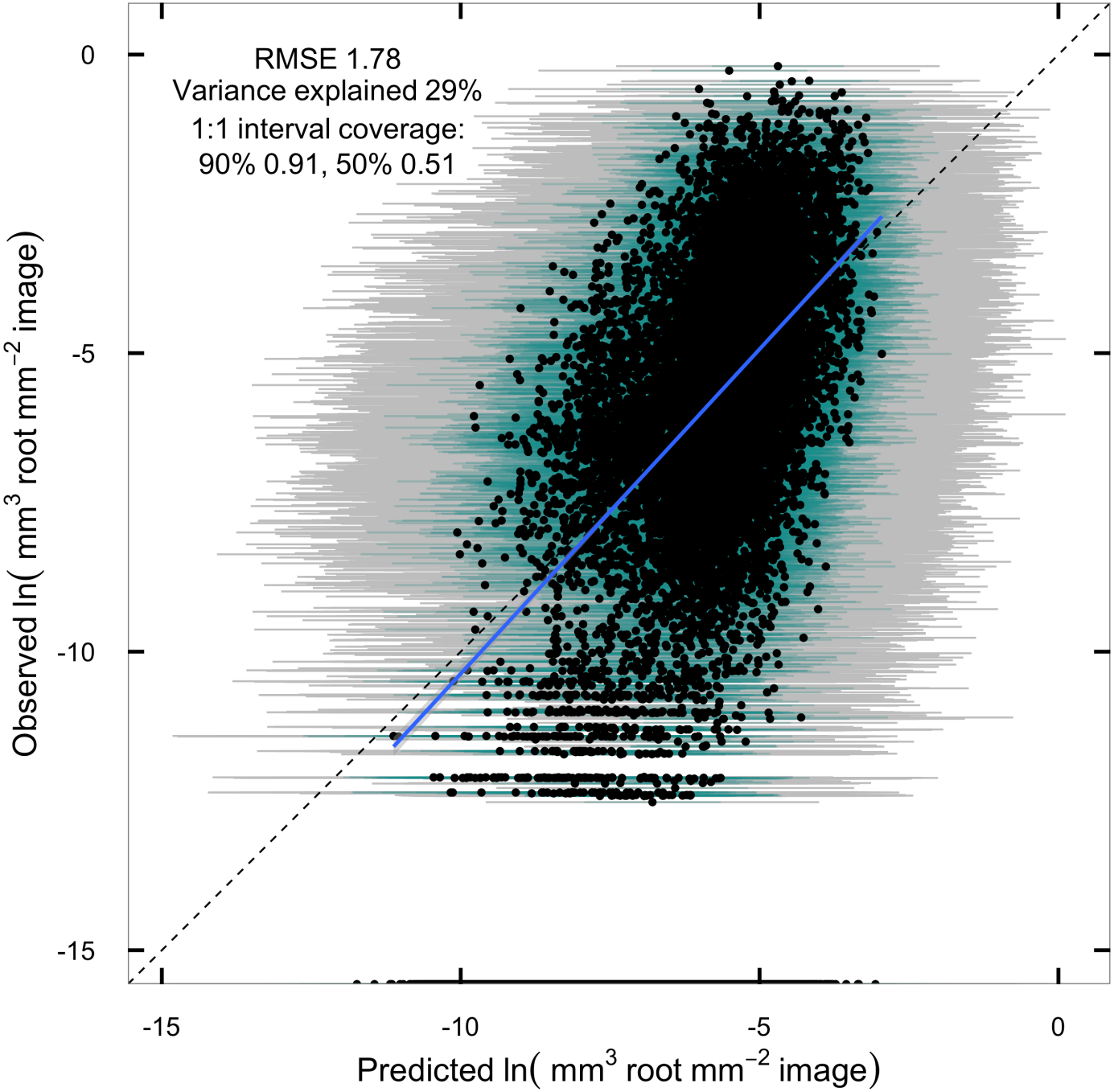
$$\mu_{ijk} = \alpha_i + \gamma_j + \beta_i \ln(\text{depth}_k) + \epsilon_i$$

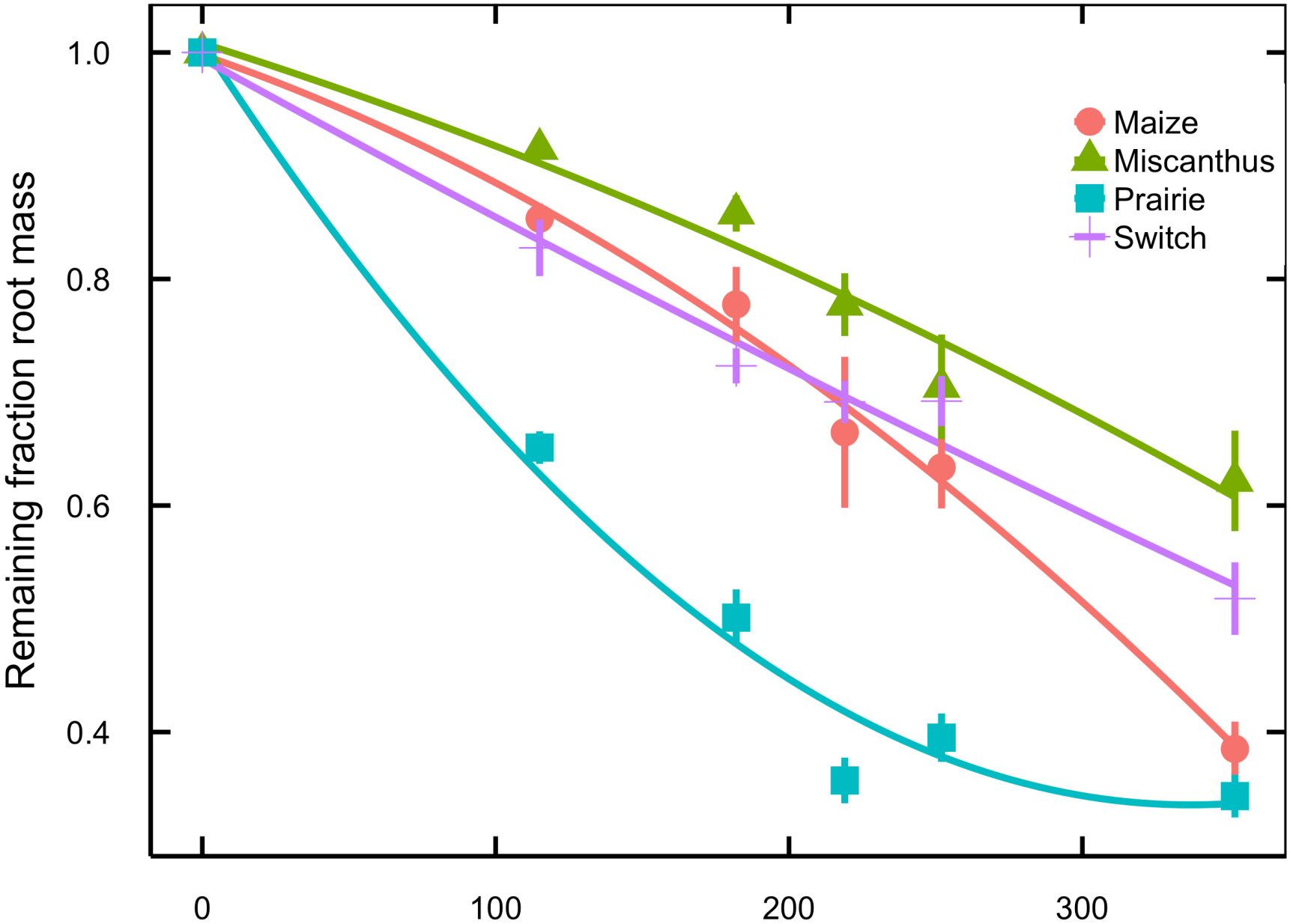
$$\gamma_j \sim N(0, \ \sigma_{\text{tube}})$$

$$\epsilon \sim N(0, \ \sigma)$$

Photos: Mike Masters

Photo: Mike Masters

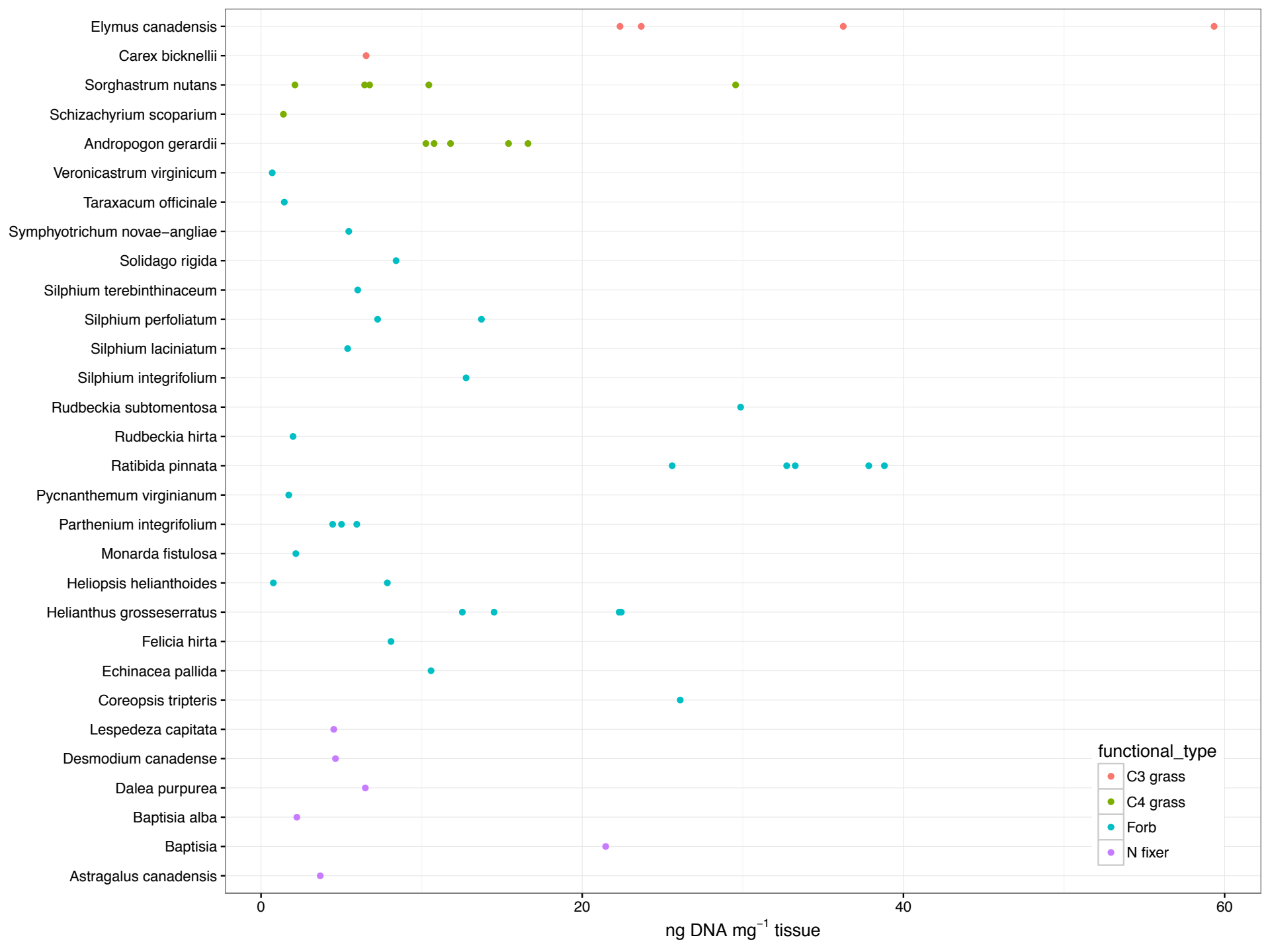

RMSE 1.78
Variance explained 29%
1:1 interval coverage:
90% 0.91, 50% 0.51
0
-5
-10
-15
-15
-10
-5
0
Observed ln(mm^3 root mm^{-2} image)
Predicted ln(mm^3 root mm^{-2} image)

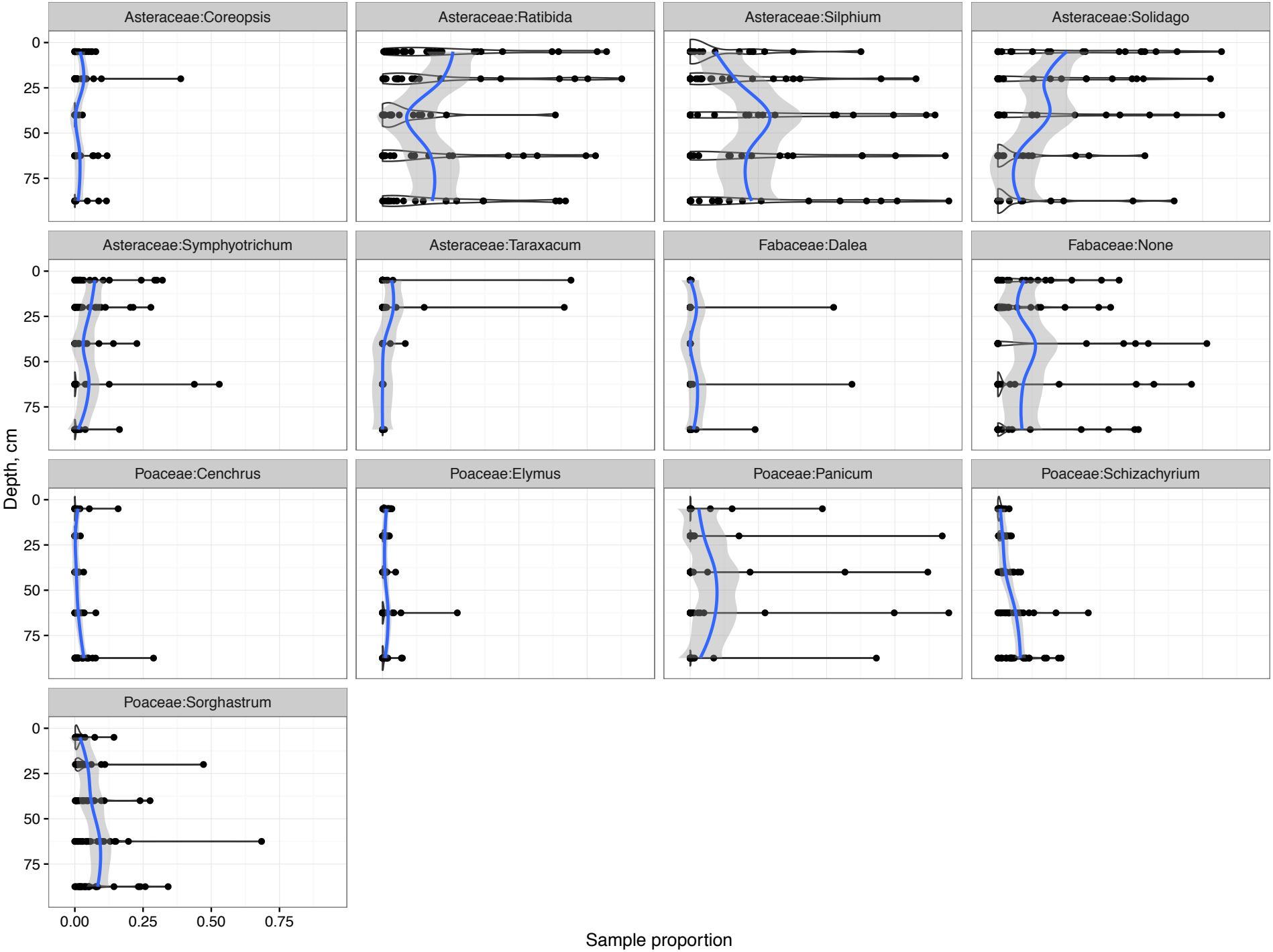


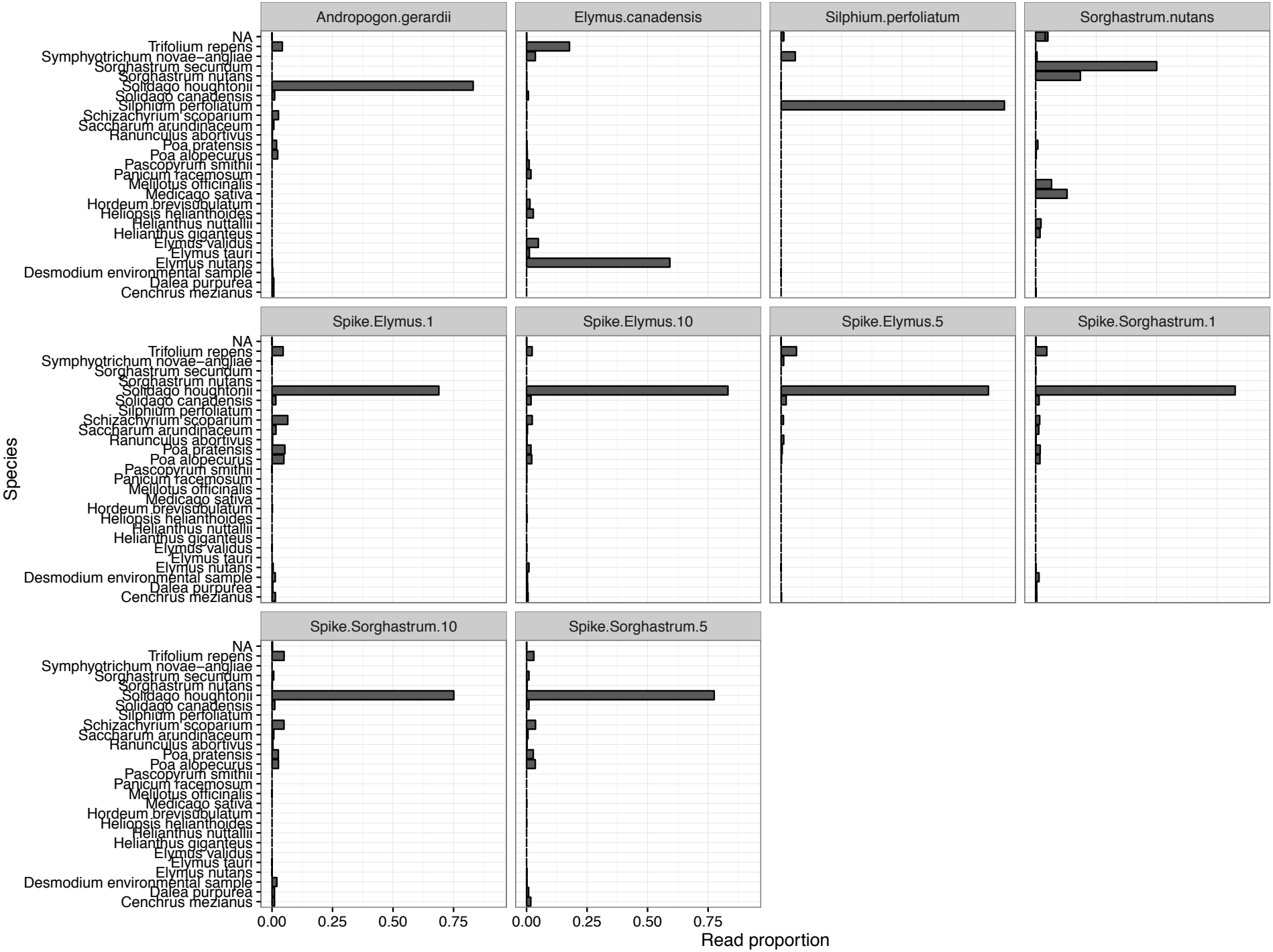
Eoghan Smythe, in prep

prairie

Voucher.mix.A
Voucher.mix.B
Voucher.mix.C
Proportion of sample
0.00
0.05
0.10
0.15
0.20
expected proportion
Genus
Andropogon
Astragalus
Baptisia
Bromus
Carex
Cenchrus
Coreopsis
Dalea
Desmodium
Echinacea
Elymus
Felicia
Helianthus
Heliopsis
Lespedeza
Medicago
Melilotus
Monarda
None
Panicum
Parthenium
Poa
Pycnanthemum
Ratibida
Rudbeckia
Rumex
Schizachyrium
Silphium
Solidago
Sorghastrum
Symphyotrichum
Taraxacum
Trifolium
Veronicastrum
Xanthium


Elymus canadensis
Carex bicknellii
Sorghastrum nutans
Schizachyrium scoparium
Andropogon gerardii
Veronicastrum virginicum
Taraxacum officinale
Symphyotrichum novae−angliae
Solidago rigida
Silphium terebinthinaceum
Silphium perfoliatum
Silphium laciniatum
Silphium integrifolium
Rudbeckia subtomentosa
Rudbeckia hirta
Ratibida pinnata
Pycnanthemum virginianum
Parthenium integrifolium
Monarda fistulosa
Heliopsis helianthoides
Helianthus grosseserratus
Felicia hirta
Echinacea pallida
Coreopsis tripteris
Lespedeza capitata
Desmodium canadense
Dalea purpurea
Baptisia alba
Baptisia
Astragalus canadensis
0
20
40
60
ng DNA mg^{-1} tissue
functional_type
C3 grass
C4 grass
Forb
N fixer


Asteraceae:Coreopsis
Asteraceae:Ratibida
Asteraceae:Silphium
Asteraceae:Solidago
Asteraceae:Symphyotrichum
Asteraceae:Taraxacum
Fabaceae:Dalea
Fabaceae:None
Poaceae:Cenchrus
Poaceae:Elymus
Poaceae:Panicum
Poaceae:Schizachyrium
Poaceae:Sorghastrum
Depth, cm
0
25
50
75
0.00
0.25
0.50
0.75
Sample proportion


Andropogon.gerardii
Elymus.canadensis
Silphium.perfoliatum
Sorghastrum.nutans
Spike.Elymus.1
Spike.Elymus.10
Spike.Elymus.5
Spike.Sorghastrum.1
Spike.Sorghastrum.10
Spike.Sorghastrum.5
Species
NA
Trifolium repens
Symphyotrichum novae−angliae
Sorghastrum secundum
Sorghastrum nutans
Solidago houghtonii
Solidago canadensis
Silphium perfoliatum
Schizachyrium scoparium
Saccharum arundinaceum
Ranunculus abortivus
Poa pratensis
Poa alopecurus
Pascopyrum smithii
Panicum racemosum
Melilotus officinalis
Medicago sativa
Hordeum brevisubulatum
Heliopsis helianthoides
Helianthus nuttallii
Helianthus giganteus
Elymus validus
Elymus tauri
Elymus nutans
Desmodium environmental sample
Dalea purpurea
Cenchrus mezianus
0.00
0.25
0.50
0.75
Read proportion