Greenhouse gas footprint of shale gas obtained by hydraulic fracturing

Robert Howarth, Renee Santoro, Anthony Ingraffea
(Cornell University)

and Nathan Phillips
(Boston University)

BOSTON UNIVERSITY

Cornell University
College of Agriculture and Life Sciences

The technology to obtain shale gas is new! Combination of high-volume hydraulic fracturing with precision directional drilling.

Half of all shale gas ever developed has occurred in just the last 3 years.

So of course the science is also new…. First peer-reviewed papers only since April 2011.

What is the greenhouse gas footprint of shale gas?

How does it compare with conventional natural gas and other fossil fuels?

(and therefore how suitable is shale gas as a bridge fuel over the coming few decades?)

For just the release of carbon dioxide during combustion…..

	g C of CO_2 MJ^{-1} of energy
Natural gas	15
Diesel oil	20
Coal	25

(Hayhoe et al. 2002)

Howarth, Santoro, and Ingraffea began researching shale gas footprint in a more comprehensive way (indirect CO_2 emissions, methane) in late 2009…

…. At the time, no prior papers on the topic (and only a few papers on conventional gas, in 2002, 2005, and 2007).

….. EPA national greenhouse gas inventory based solely on (highly optimistic) data from 1996 (assuming shale gas the same as conventional natural gas).

Posted brief progress reports on the web 4 times, with first in March 2010.

….. incredibly helpful feedback (data sources, possible errors).

…… amazing pushback by industry (ANGA, Energy in Depth, API) and some NGO's funded by industry.

….. immediate interest from White House, which started a lot of new activity at DOE and EPA.

Update by US EPA on methane emissions from gas (Nov. 30, 2010):

Table 1: Comparison of Emissions Factors from Four Updated Emissions Sources

Emissions Source Name	EPA/GRI Emissions Factor	Revised Emissions Factor	Units
1) Well venting for liquids unloading	1.02	11	CH_4 – metric tons/year-well
2) Gas well venting during completions			
Conventional well completions	0.02	0.71	CH_4 – metric tons/year-completion
Unconventional well completions	0.02	177	CH_4 – metric tons/year-completion
3) Gas well venting during well workovers			
Conventional well workovers	0.05	0.05	CH_4 – metric tons/year-workover
Unconventional well workovers	0.05	177	CH_4 – metric tons/year-workover
4) Centrifugal compressor wet seal degassing venting	0	233	CH_4 – metric tons/year-compressor

1. Conversion factor: 0.01926 metric tons = 1 Mcf

1996 **Nov. 2010**

[4] EPA did consider the data available from two new studies, TCEQ (2009) and TERC (2009). However, it was found that the data available from the two studies raise several questions regarding the magnitude of emissions

Climatic Change
DOI 10.1007/s10584-011-0061-5

LETTER

Methane and the greenhouse-gas footprint of natural gas from shale formations

A letter

Robert W. Howarth · Renee Santoro · Anthony Ingraffea

Received: 12 November 2010 / Accepted: 13 March 2011

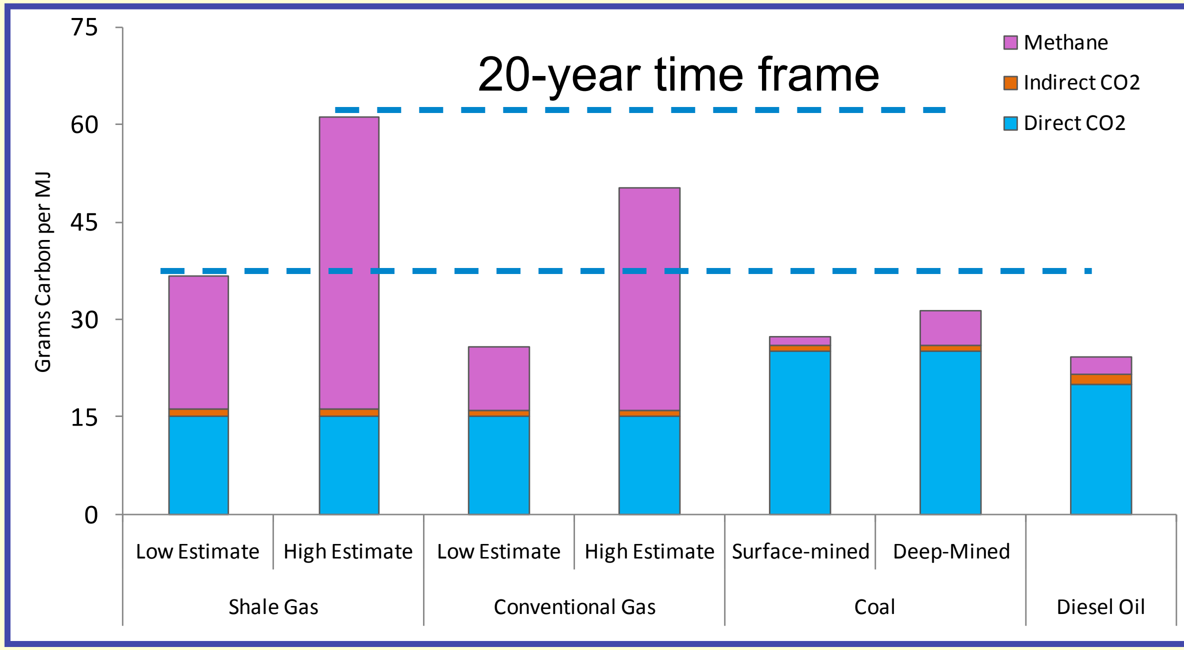
Abstract We evaluate the greenhouse gas footprint of natural gas obtained by high-volume hydraulic fracturing from shale formations, focusing on methane emissions. Natural gas is composed largely of methane, and 3.6% to 7.9% of the methane from shale-gas production escapes to the atmosphere in venting and leaks over the life-time of a well. These methane emissions are at least 30% more than and perhaps more than twice as great as those from conventional gas. The higher emissions from shale gas occur at the time wells are hydraulically fractured—as methane escapes from flow-back return fluids—and during drill out following the fracturing. Methane is a powerful greenhouse gas, with a global warming potential that is far greater than that of carbon dioxide, particularly over the time horizon of the first few decades following emission. Methane contributes substantially to the greenhouse gas footprint of shale gas on shorter time scales, dominating it on a 20-year time horizon. The footprint for shale gas is greater than that for conventional gas or oil when viewed on any time horizon, but particularly so over 20 years. Compared to coal, the footprint of shale gas is at least 20% greater and perhaps more than twice as great on the 20-year horizon and is comparable when compared over 100 years.

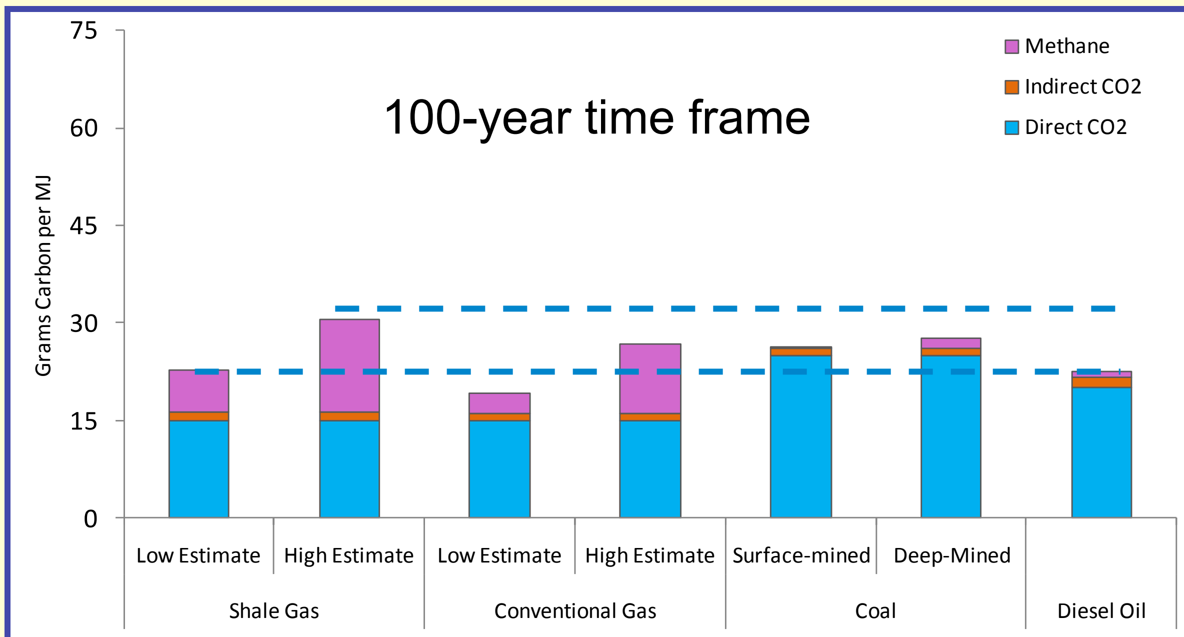
Keywords Methane · Greenhouse gases · Global warming · Natural gas · Shale gas · Unconventional gas · Fugitive emissions · Lifecycle analysis · LCA · Bridge fuel · Transitional fuel · Global warming potential · GWP

n of this article
ary material, which is available

ornell University, Ithaca, NY 14853, USA

nell University, Ithaca, NY 14853, USA





Published in April 2011

Full Life-cycle, Peer-Reviewed Estimates for Methane Emissions

(Percent of life-time production of a well; listed by date of publication)

	Conventional gas	Shale gas
Hayhoe et al. (2002)	3.8	*
Jamarillo et al. (2007)	1.0	*
Howarth et al. (2011)	1.6 – 6.0	3.6 – 7.9

* Estimates not provided in these papers and reports.

Full Life-cycle, Peer-Reviewed Estimates for Methane Emissions
(Percent of life-time production of a well; listed by date of publication)

	Conventional gas	Shale gas
Hayhoe et al. (2002)	3.8	*
Jamarillo et al. (2007)	1.0	*
Howarth et al. (2011)	1.6 – 6.0	3.6 – 7.9

Very good agreement

* Estimates not provided in these papers and reports.

Full Life-cycle, Peer-Reviewed Estimates for Methane Emissions

(Percent of life-time production of a well; listed by date of publication)

	Conventional gas	Shale gas
Hayhoe et al. (2002)	3.8	*
Jamarillo et al. (2007)	1.0	*
Howarth et al. (2011)	1.6 – 6.0	3.6 – 7.9

Low, since based entirely on old and low emissions factors from EPA 1996

* Estimates not provided in these papers and reports.

Full Life-cycle, Peer-Reviewed Estimates for Methane Emissions
(Percent of life-time production of a well; listed by date of publication)

	Conventional gas	Shale gas
Hayhoe et al. (2002)	3.8	*
Jamarillo et al. (2007)	1.0	*
Howarth et al. (2011)	1.6 – 6.0 →	3.6 – 7.9

Roughly 40% more methane

* Estimates not provided in these papers and reports.

Marcellus Well Being "Finished"
Outside Dimock, PA, June 2011

Photo and FLIR Methane-Tuned Video Courtesy Frank Finan

Papers and reports since April 2011:

- Howarth et al. (2011)
- EPA (2011-a)
- Hughes (2011a, 2011b)
- Venkatesh et al. (2011)
- Jiang et al. (2011)
- Wigley (2011)
- EPA (2011-b)
- Fulton et al. (2011)
- Stephenson et al. (2011)
- Hultman et al. (2011)
- Skone et al. (2011)
- Burnham et al. (2011)
- Cathles et al. (2012)
- Howarth et al. (2012-a)
- Howarth et al. (2012-b)
- Petron et al. (2012)
- Alvarez et al. (2012)
- API/ANGA (2012)

Blue indicates peer-reviewed publication

Full Life-cycle, Peer-Reviewed Estimates for Methane Emissions

(Percent of life-time production of a well; listed by date of publication)

	Conventional gas	Shale gas
Hayhoe et al. (2002)	3.8	*
Jamarillo et al. (2007)	1.0	*
Howarth et al. (2011)	1.6 – 6.0	3.6 – 7.9
EPA (2011a) *	2.5	3.9
Venkatesh et al. (2011)	2.2	*
Jiang et al. (2011)	*	2.0
Stephenson et al. (2011)	0.5	0.7
Hultman et al. (2011)	2.3	3.8
Burnham et al. (2011)	2.6	1.9
Cathles et al. (2012)	0.9 - 2.4	0.9 - 2.4

* Not peer reviewed

Conventional natural gas, upstream and midstream emissions (well site plus processing)

(Howarth et al. 2012, background paper, National Climate Assessment)

Hayhoe et al. (2002)	1.2 %	("best estimate")
Howarth et al. (2011)	1.4 %	(mean; range = 0.2% to 2.4%)
EPA (2011)*	1.6 %	
Hultman et al. (2011)	1.3 %	
Venkatesh et al. (2011)	1.8 %	
Burnham et al. (2011)	2.0 %	
Stephenson et al. (2011)	0.4 %	
Cathles et al. (2012)	0.9 %	

* The EPA (2011) estimate is as calculated in Howarth et al. (2012), using national emissions from EPA reports and national gas production data from US Department of Energy reports.

Shale gas and tight-sands unconventional natural gas, upstream and midstream emissions

(Howarth et al. 2012, background paper, National Climate Assessment)

Howarth et al. (2011)	3.3 %	(mean; range = 2.2% to 4.3%)
EPA (2011)*	3.0 %	
Jiang et al. (2011)	2.0 %	
Hultman et al. (2011)	2.8 %	
Burnham et al. (2011)	1.3 %	
Stephenson et al. (2011)	0.6 %	
Cathles et al. (2012)	0.9 %	
Petron et al. (2012)	4.0 %	("best estimate;" range = 2.3 to 7.7%)

* The EPA (2011) estimate is as calculated in Howarth et al. (2012), using national emissions from EPA reports and national gas production data from US Department of Energy reports.

Shale gas and tight-sands unconventional natural gas, upstream and midstream emissions

(Howarth et al. 2012, background paper, National Climate Assessment)

Howarth et al. (2011)	3.3 %	(mean; range = 2.2% to 4.3%)
EPA (2011)*	3.0 %	
Jiang et al. (2011)	2.0 %	
Hultman et al. (2011)	2.8 %	
Burnham et al. (2011)	1.3 %	
Stephenson et al. (2011)	0.6 %	
Cathles et al. (2012)	0.9 %	
Petron et al. (2012)	4.0 %	("best estimate;" range = 2.3 to 7.7%)

Direct, landscape scale measurements!!

* The EPA (2011) estimate is as calculated in Howarth et al. (2012), using national emissions from EPA reports and national gas production data from US Department of Energy reports.

Downstream emissions (all natural gas: storage, transmission pipelines, distribution systems)

(Howarth et al. 2012, background paper, National Climate Assessment)

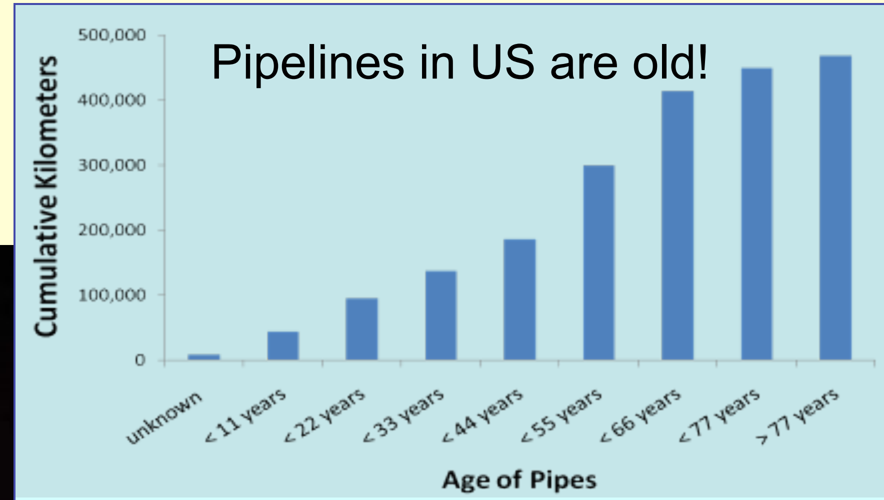
Hayhoe et al. (2002)	2.5 %	("best estimate;" range = 0.2% – 10%)
Lelieveld et al. (2005)	1.4 %	("best estimate;" range = 1.0% – 2.5%)
Howarth et al. (2011)	2.5 %	(mean; range = 1.4% – 3.6%)
EPA (2011)*	0.9 %	
Jiang et al. (2011)	0.4 %	
Hultman et al. (2011)	0.9 %	
Ventakesh et al. (2011)	0.4 %	
Burnham et al. (2011)	0.6 %	
Stephenson et al. (2011)	0.07 %	
Cathles et al. (2012)	0.7 %	

* The EPA (2011) estimate is as calculated in Howarth et al. (2012), using national emissions from EPA reports and national gas production data from US Department of Energy reports.

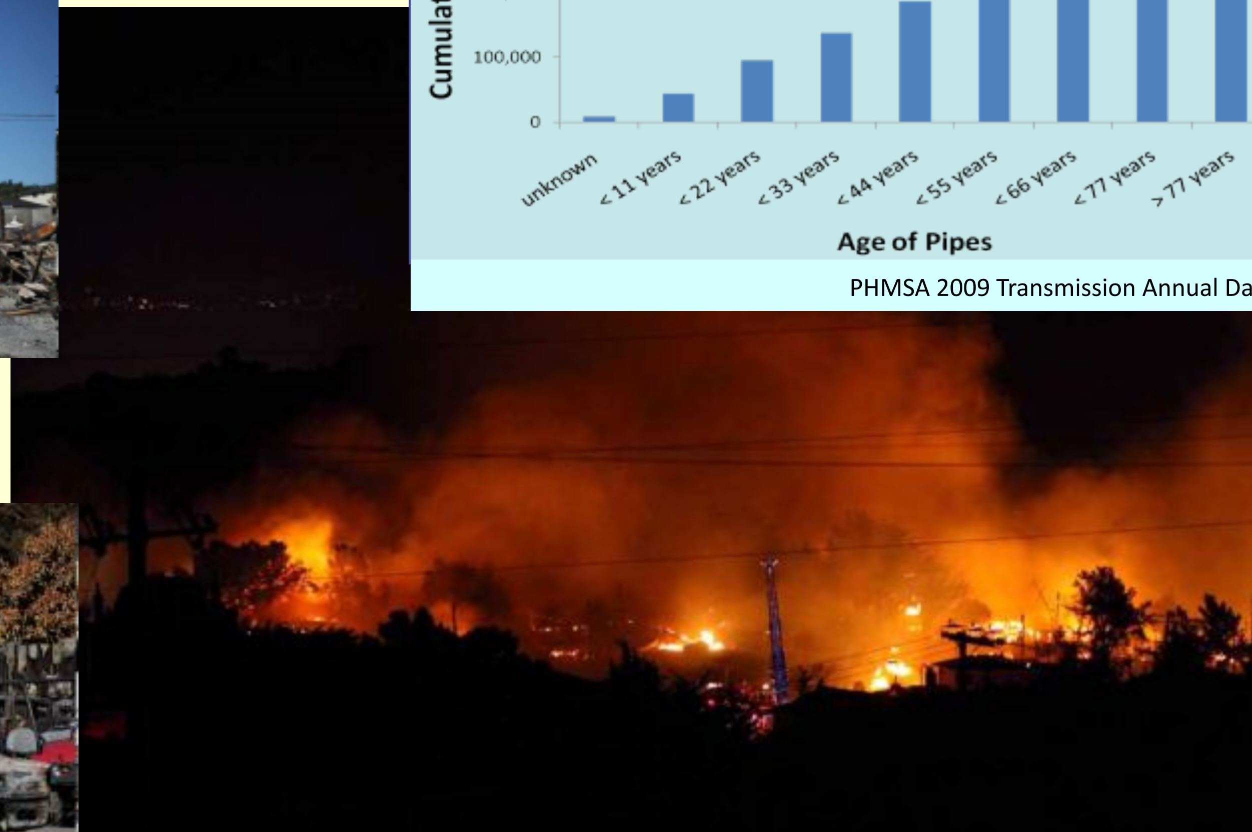
Bruce Gellerman, “Living on Earth,” Jan. 13, 2012, based on work of Nathan Phillips

http://www.loe.org/shows/segments.html?programID=12-P13-00002&segmentID=3

Pipeline accidents and explosions happen, due to large leaks….
….. small leaks are ubiquitous.



PHMSA 2009 Transmission Annual Data



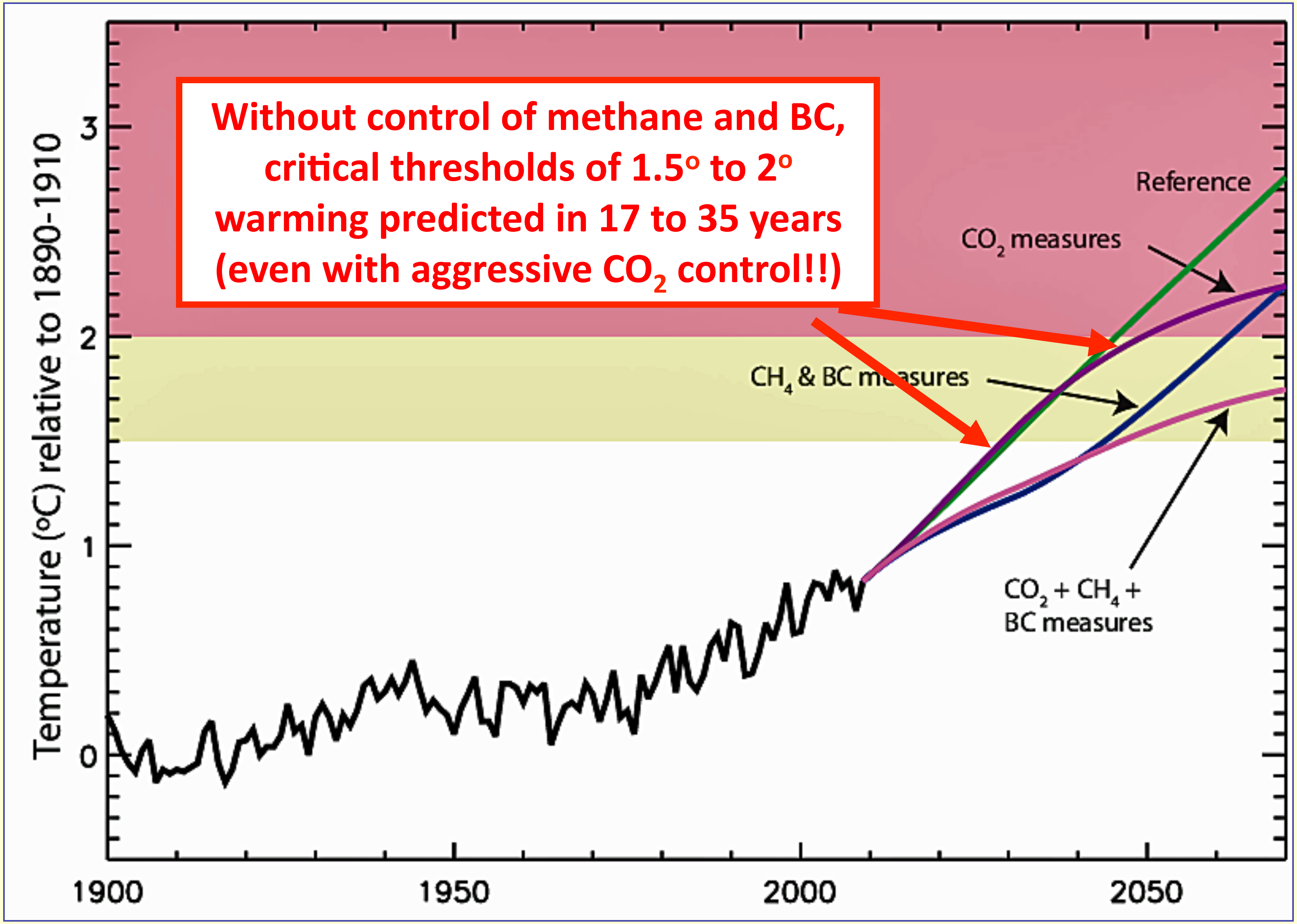
Flames consume homes during a massive fire in a residential neighborhood September 9, 2010 in San Bruno, California. (Photo by Ezra Shaw/Getty Images)

With time and with more scientists making integrated measurements of methane emissions from gas fields, from cities, etc., the emissions debate will be greatly clarified.

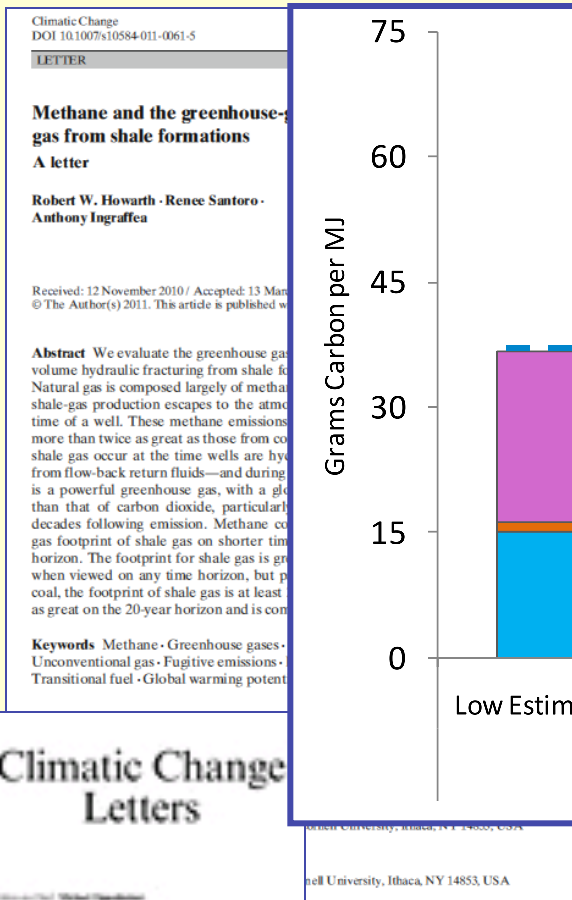
In the meanwhile, we feel our estimates are as strong as any, far better documented than most, and most in agreement with the first of the integrated measurements.

Time frame for comparing methane and carbon dioxide:

• Hayhoe et al. (2002)	0 to 100 years
• Lelieveld et al. (2005)	20 & 100 years
• Jamarillo et al. (2007)	100 years
• Howarth et al. (2011)	20 & 100 years
• Hughes (2011)	20 & 100 years
• Venkatesh et al. (2011)	100 years
• Jiang et al. (2011)	100 years
• Wigley (2011)	0 to 100 years
• Fulton et al. (2011)	100 years
• Stephenson et al. (2011)	100 years
• Hultman et al. (2011)	100 years
• Skone et al. (2011)	100 years
• Burnham et al. (2011)	100 years
• Cathles et al. (2012)	100 years
• Alvarez et al. (2012)	0 to 100 years



Shindell et al. 2012 *Science*


Climatic Change
DOI 10.1007/s10584-011-0061-5

LETTER

Methane and the greenhouse-
gas from shale formations
A letter

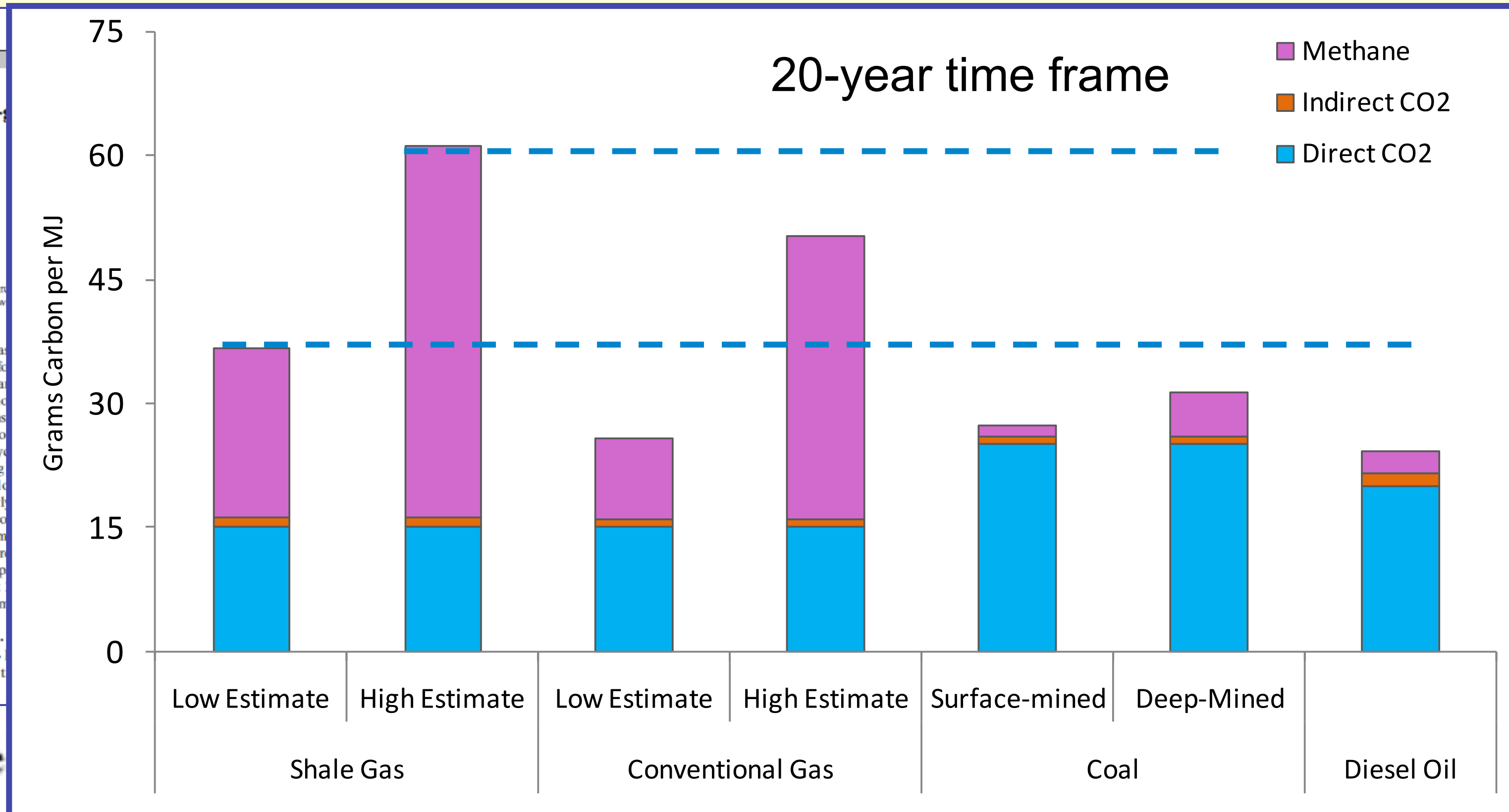
Robert W. Howarth · Renee Santoro ·
Anthony Ingraffea

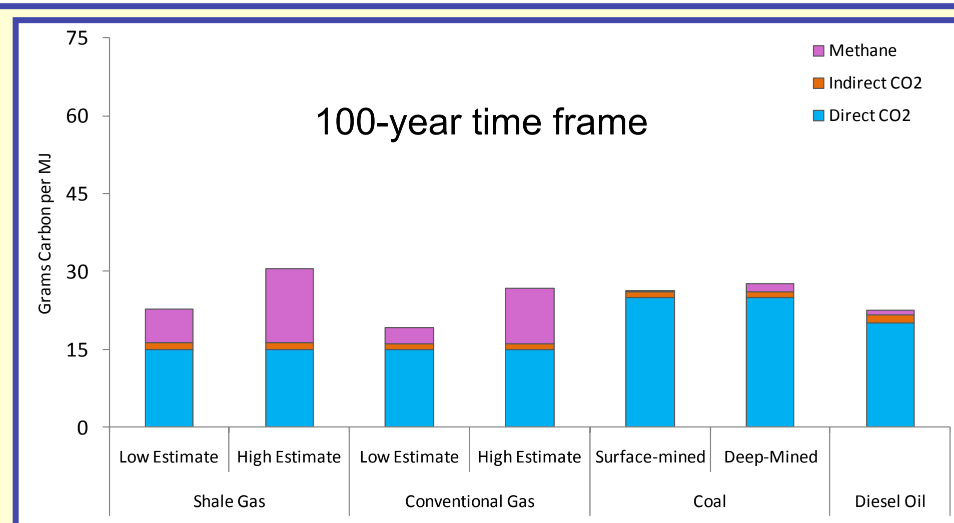
Received: 12 November 2010 / Accepted: 13 Mar
© The Author(s) 2011. This article is published w

Abstract We evaluate the greenhouse ga
volume hydraulic fracturing from shale f
Natural gas is composed largely of metha
shale-gas production escapes to the atmo
time of a well. These methane emissions
more than twice as great as those from co
shale gas occur at the time wells are hy
from flow-back return fluids—and during
is a powerful greenhouse gas, with a gl
than that of carbon dioxide, particularl
decades following emission. Methane co
gas footprint of shale gas on shorter tim
horizon. The footprint for shale gas is gr
when viewed on any time horizon, but p
coal, the footprint of shale gas is at least
as great on the 20-year horizon and is com

Keywords Methane · Greenhouse gases ·
Unconventional gas · Fugitive emissions ·
Transitional fuel · Global warming potent

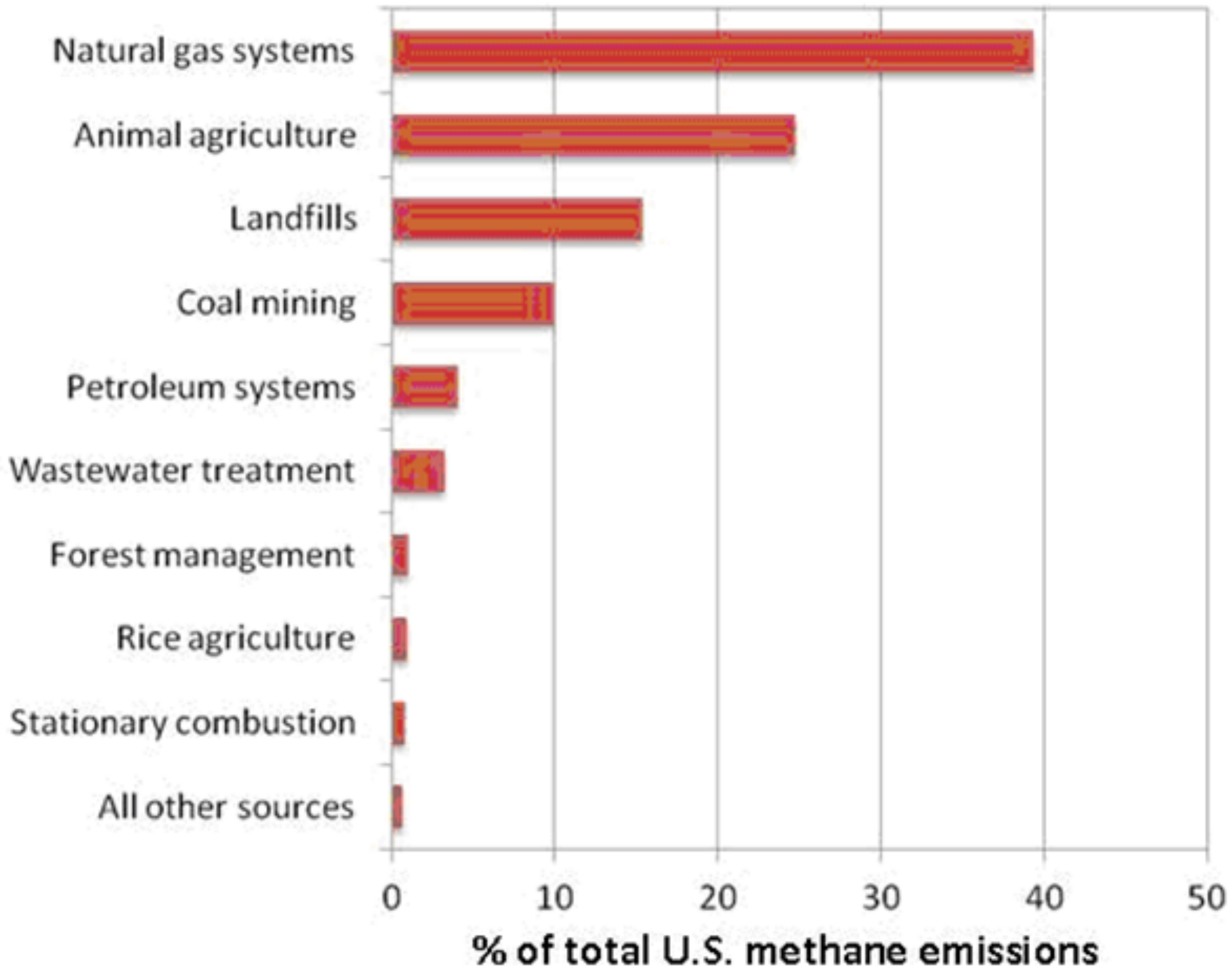
nell University, Ithaca, NY 14853, USA



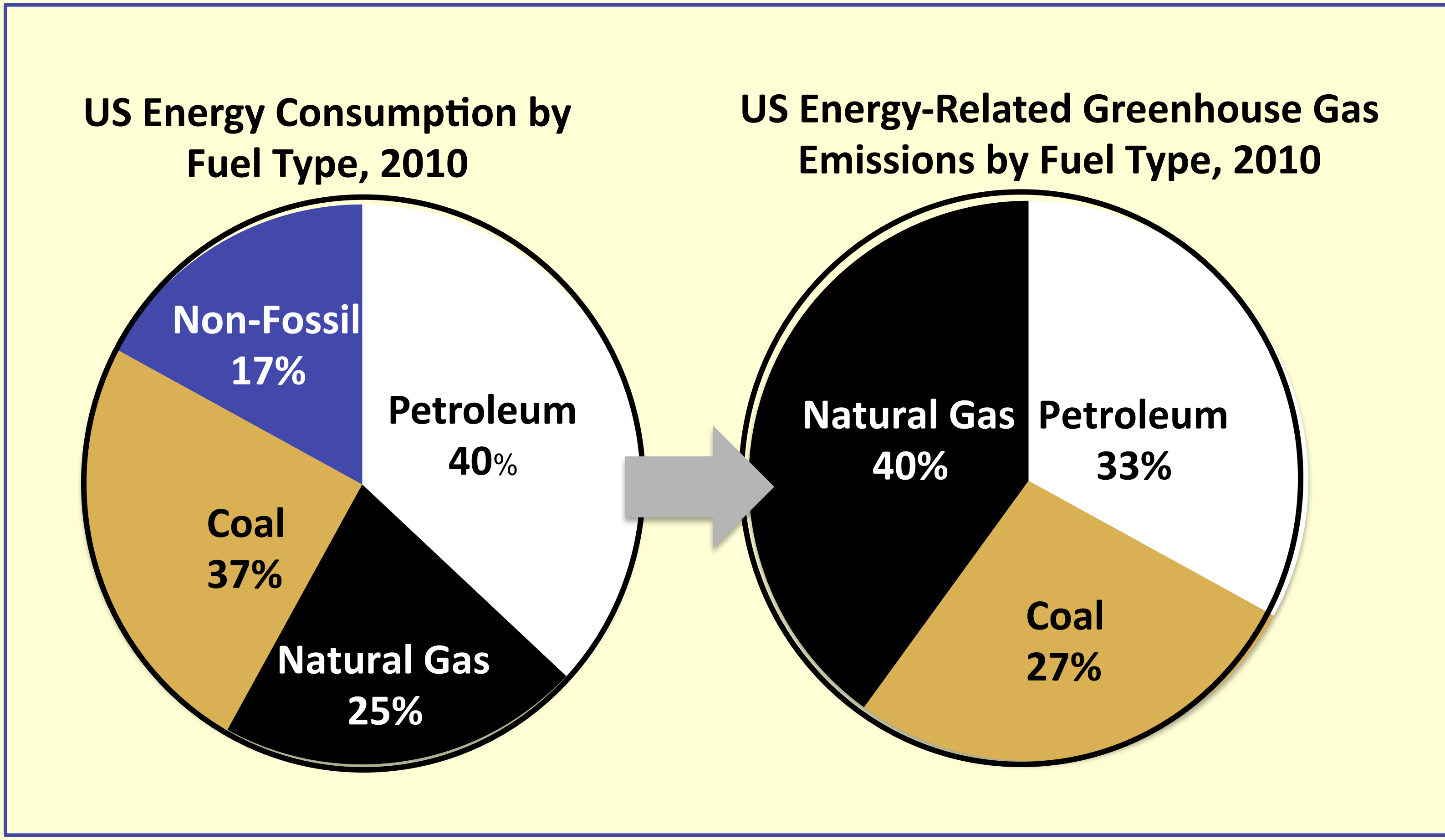


Published in April 2011

US National Methane Emissions for 2009



(Howarth et al. 2012, based on EPA (2011)



Energy consumption from US DOE Energy Information Agency. GHG emissions from EPA National GHG inventory, modified using mean methane emissions from Howarth et al. (2011) and 20-year methane global warming potential.

Can methane emissions be reduced?

Yes, and this helps, but:

-- a lot are purposeful venting (economic decision)

-- leakage from old tanks and pipelines would be very expensive to fix. Is it worth the investment for a "transitional fuel?"

-- requires regulation, over industry opposition

(US EPA imposing "green completions" regulations in January 2015)

Shale gas will:

- aggravate global warming over next many decades

- distract politicians and the public from needed action

(and cause large pollution and disruption at local scale, across the globe)

BOSTON UNIVERSITY

Cornell University
College of Agriculture and Life Sciences

Questions? howarth@cornell.edu

Funding from Cornell University
(through endowments given by David R. Atkinson and Dwight C. Baum)
and the Park Foundation

Cornell University
College of Agriculture and Life Sciences

PARK
FOUNDATION