
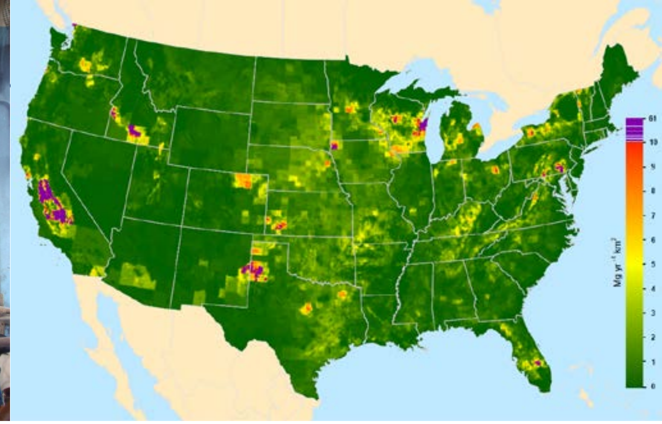


County-level Gridded Livestock Methane Emissions for the Contiguous United States

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The Pennsylvania State University and ExxonMobil Research and Engineering

USEPA Emissions Inventory Conference August 14-18, 2017

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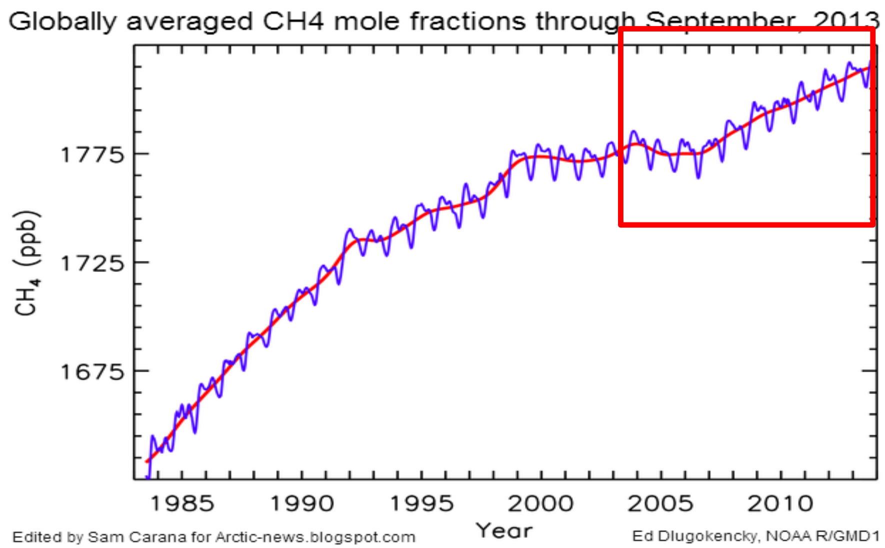
Global methane inventories



1. **Is this a real growth?**
2. **CH_4 + ·OH → ·CH_3 + H_2O**

Q1: Our approach indicates that significant OH-related uncertainties in the CH_4 budget remain, and we find that it is not possible to implicate, with a high degree of confidence, rapid global CH_4 emissions changes as the primary driver of recent trends when our inferred OH trends and these uncertainties are considered.

Rigby et al., 2017 (PNAS)

3. If the growth is real, what is causing it?

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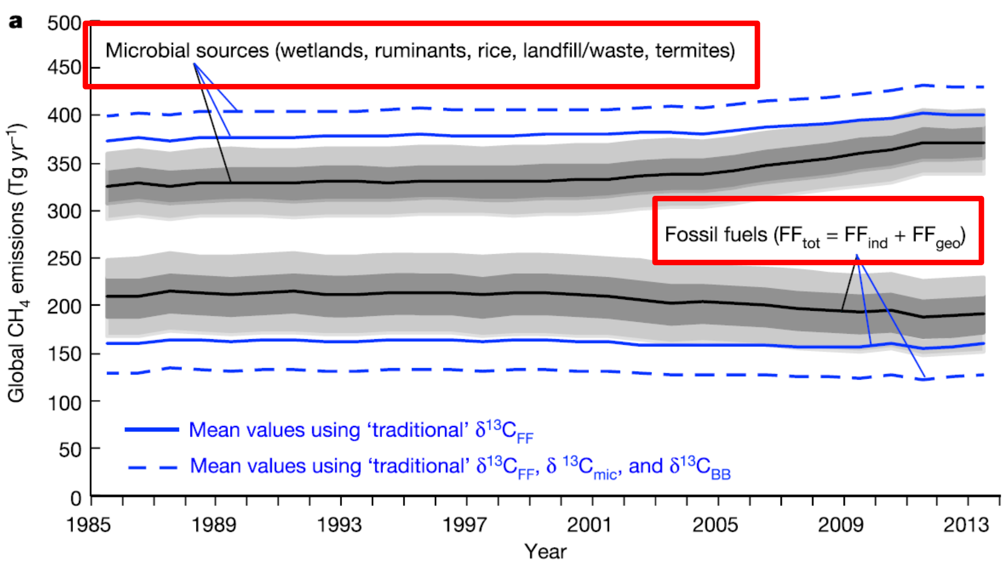
Global methane inventories

Schwietzke et al., 2016 (Nature)



Schwietzke et al., 2016 (Nature)

......the recent temporal increases in microbial emissions have been substantially larger (than from fossil fuel)

Schaefer et al., 2016 (Science)

.....Post-2006 source increases are predominantly biogenic, outside the Arctic, and arguably more consistent with agriculture than wetlands

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How reliable are the isotope data?

Turner et al., 2017 (PNAS)

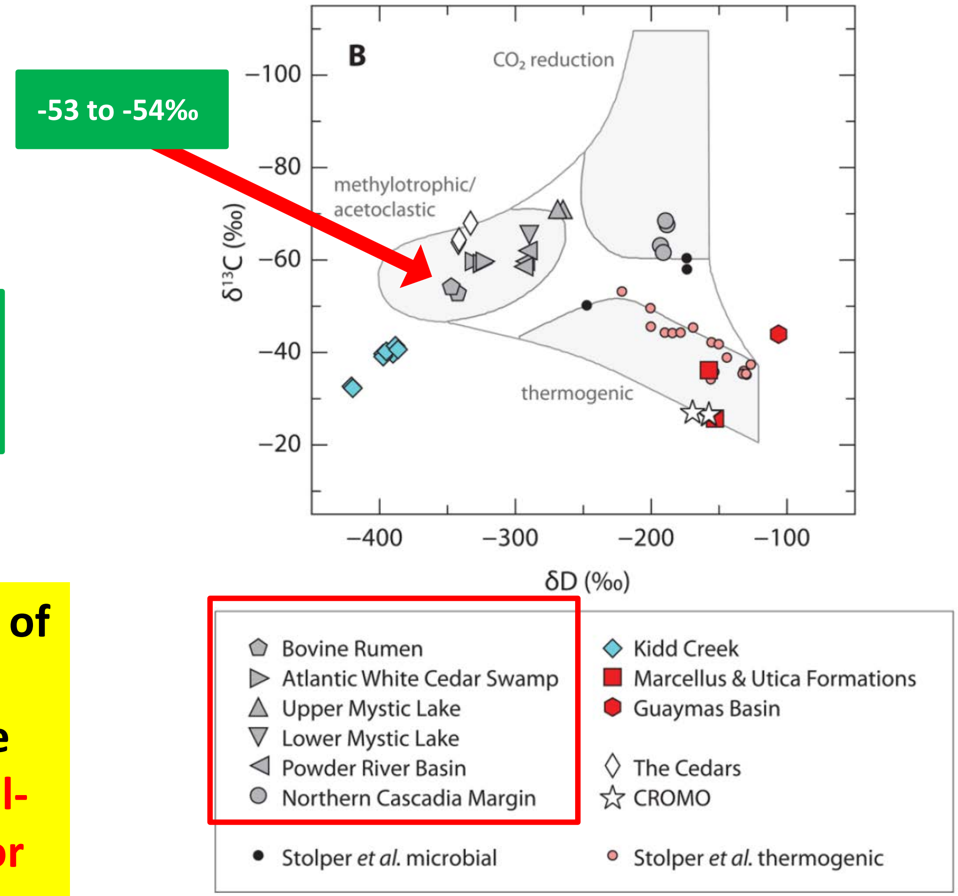
$\delta^{13}CH_4$; fossil-fuel

-15‰ to -76‰

-31‰ to -93‰

$\delta^{13}CH_4$; biogenic

….a large overlap in isotopic signatures of fossil fuel and non-fossil methane……..analysis presented here demonstrates that an increase in fossil-fuel methane sources could be a major contributor to the renewed growth in atmospheric methane since 2007



Wang et al., 2016 (Science)

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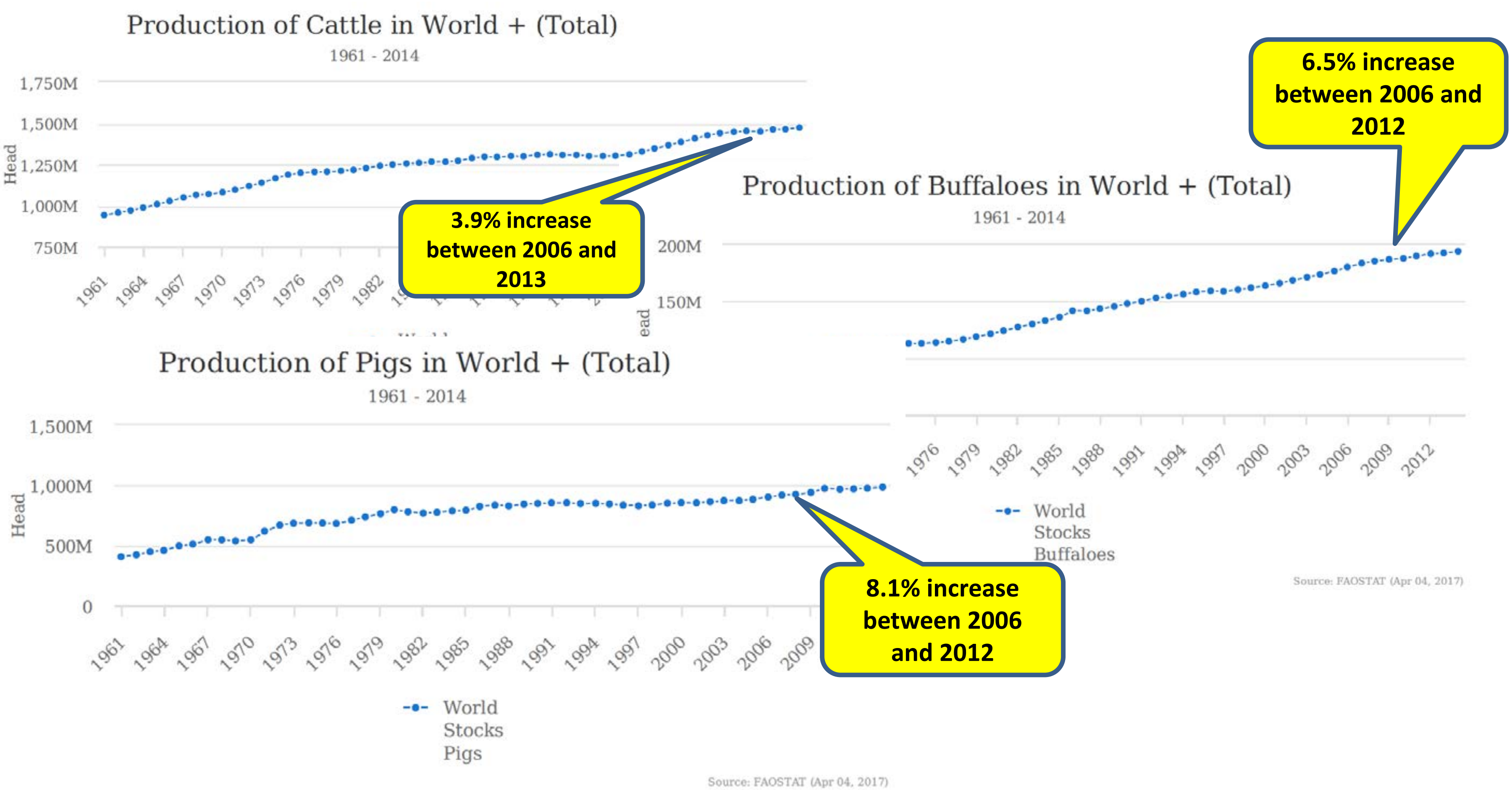
We have to consider how these predictions agree with global livestock population trends



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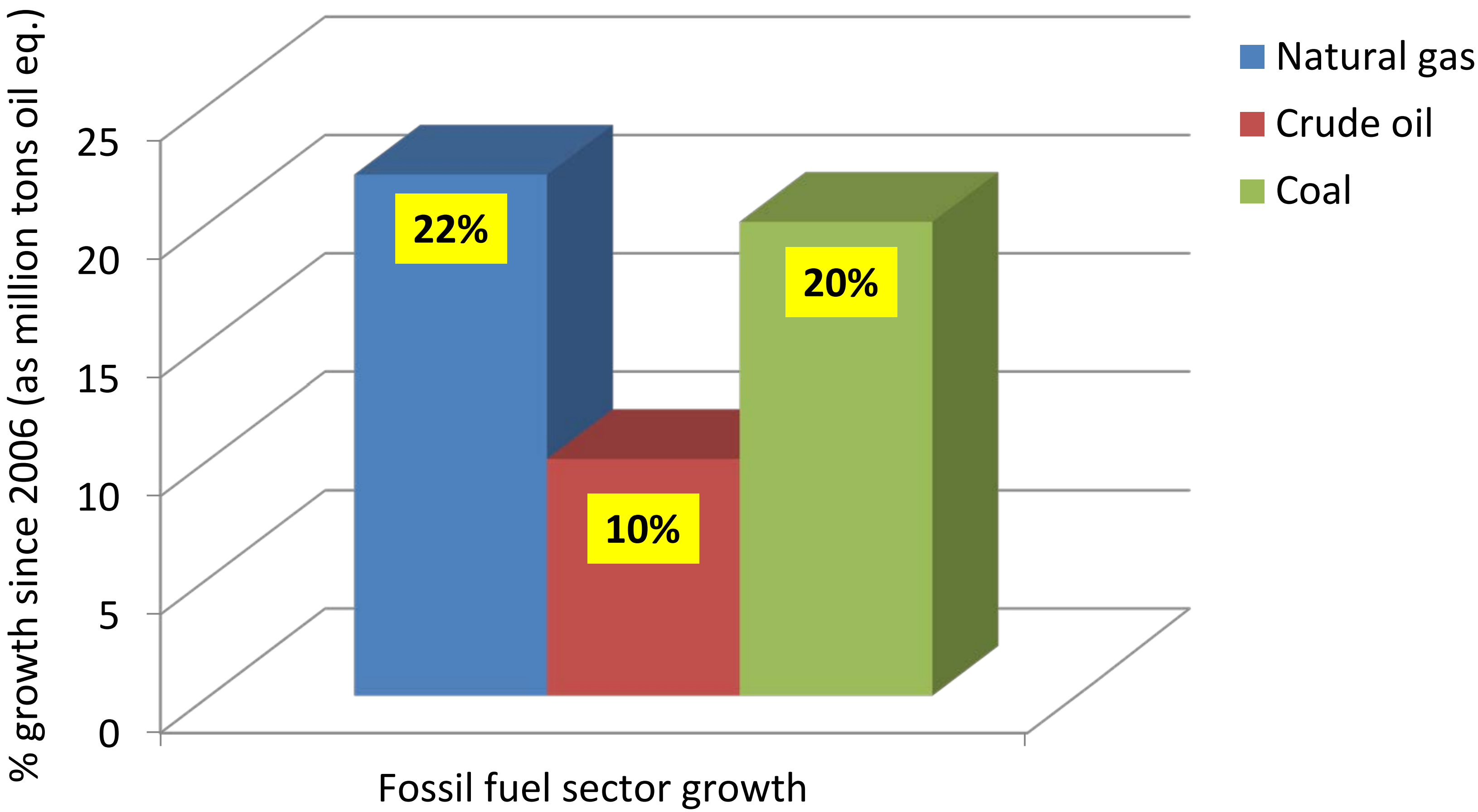
BP Statistical Review of World Energy, June 2016

Trends in global fossil fuel production, 2006 - 2015



Wecht et al., 2014

US methane accounting controversy

Table 1. U.S. Fluxes of Methane in 2004 [Tg a^{-1}]

Source Type	*EPA* [2013][a]	EDGAR v4.2[b]	*Miller et al.* [2	ork[d]
Total			47.2 ± 1.9	37.0 ± 1.4
Anthropogenic	28.3 (24.6, 32.3)	25.8	44.5 ± 1.9	30.1 ± 1.3
Livestock	8.8 (7.7, 10.4)	8.5	16.9 ± 6.7	12.2 ± 1.3
Natural Gas and Oil	9.0 (7.2, 13.4)	6.3		7.2 ± 0.6
Landfills	5.4 (2.5, 7.9)	5.3		5.8 ± 0.3
Coal Mining	2.7 (2.3, 3.2)	3.9		2.4 ± 0.3

40 to 90% higher than USEPA's estimates

PNAS

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LETTER

Livestock methane emissions in the United States

The recent study by Miller et al. (1) provides a comprehensive, quantitative analysis of anthropogenic methane sources in the United States using atmospheric methane observations, spatial datasets, and a high-resolution atmospheric transport model. The authors conclude that "...emissions due to rumi-

beef and dairy cattle requirements and ranged from 3.8 (calves < 500 lbs live weight), to 9–10 (cattle on feed or other steers and heifers > 500 lbs), 11 (beef cows), and 22 kg/d (dairy cows). Methane production rates were estimated at 8–13 (cattle on feed) or 20 g/kg (all other cate-

be unsubstantiated by the above "bottom-up" approach. There is a need for a detailed inventory of manure systems for all farm animal species and categories, which will help to more accurately estimate greenhouse gas (and ammonia) emissions from animal manure in the United States.

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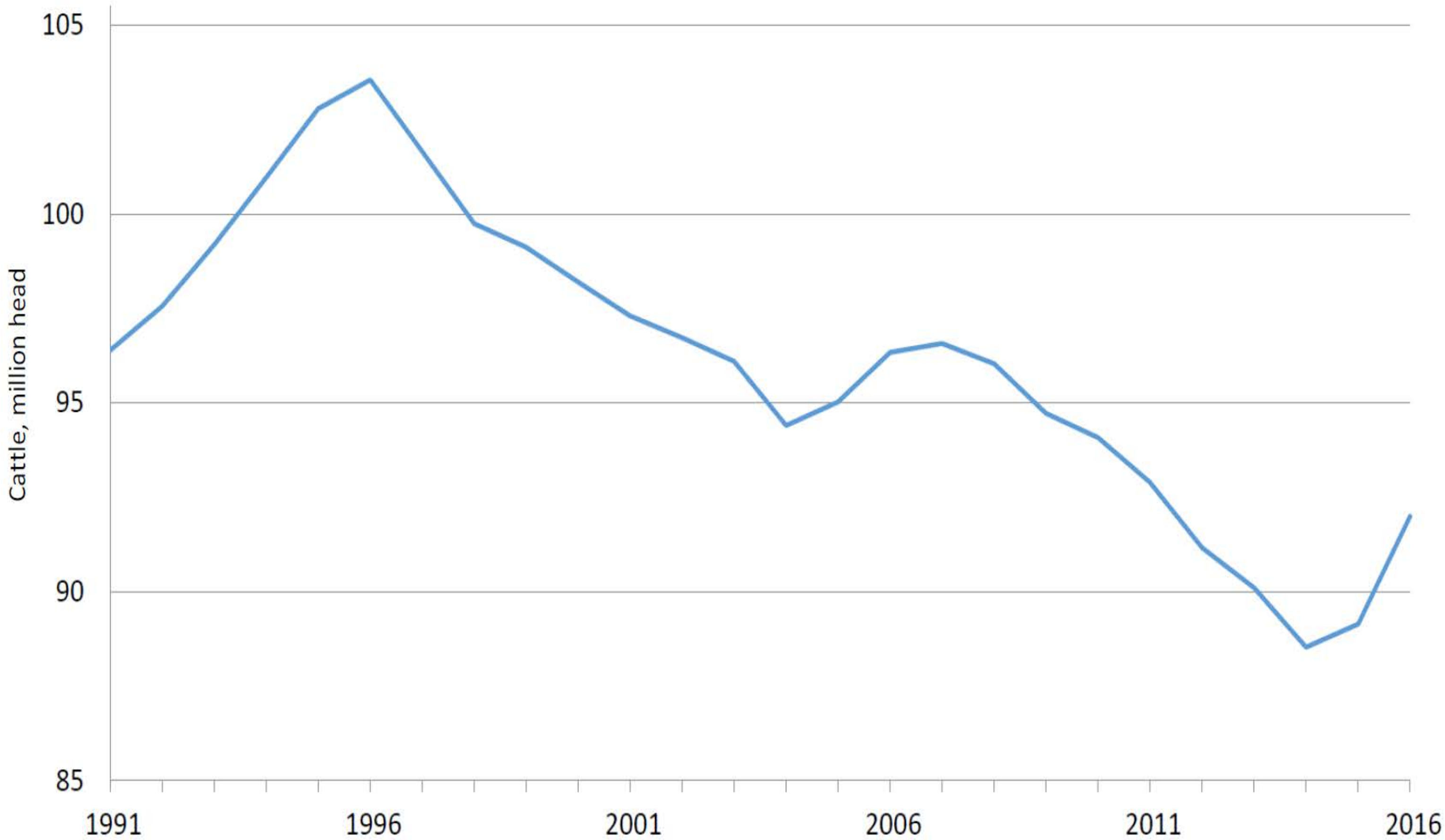
USDA-NASS, 2017

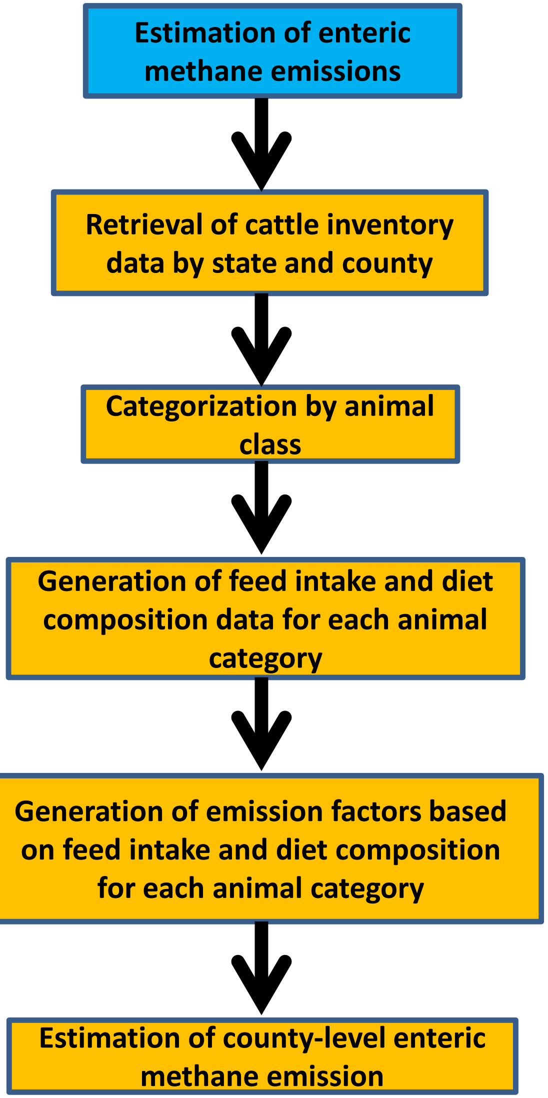
US cattle population trends



Objectives

- There is a need for spatially-accurate emission inventories for non-CO_2 GHG emissions
- Using a bottom-up approach, estimate livestock (cattle, swine, and poultry) methane emissions in the contiguous United States
- Develop a spatially-explicit, gridded (0.1° x 0.1°) methane emissions inventory and maps for the livestock sector
- Compare this bottom-up analysis with other existing gridded inventories (Maasakkers et al., 2016 and EDGAR)

Inventory development process: enteric



Methane emissions from enteric fermentation (Gg/yr) = Feed dry matter intake (DMI; kg/head/d) × methane emission factor (g/kg DMI) × 365 (d/yr) × county animal population by animal category (head)

Cattle: database includes estimates for 3,063 counties

Swine and poultry: databases included 469 and 728 counties, respectively

GLOBAL NETWORK individual animal database (>5,200 individual dairy cow data)

Less complex models requiring only DMI, or DMI plus NDF had predictive ability similar to more complex models

Niu et al., in preparation

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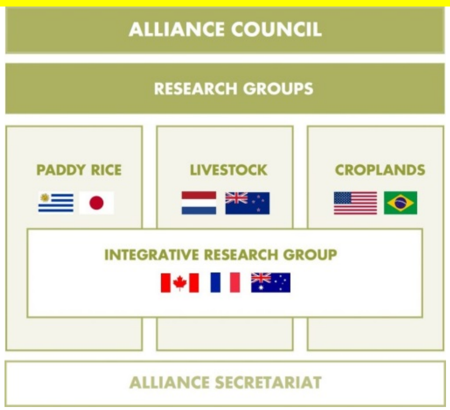
The Feed and Nutrition Network

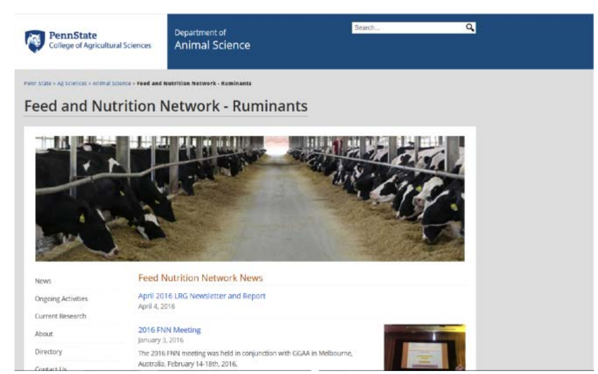
Global Research Alliance on Agricultural GHG



Livestock Research Group

International collaboration in database development: THE GLOBAL NETWORK PROJECT

Research Networks, including FNN



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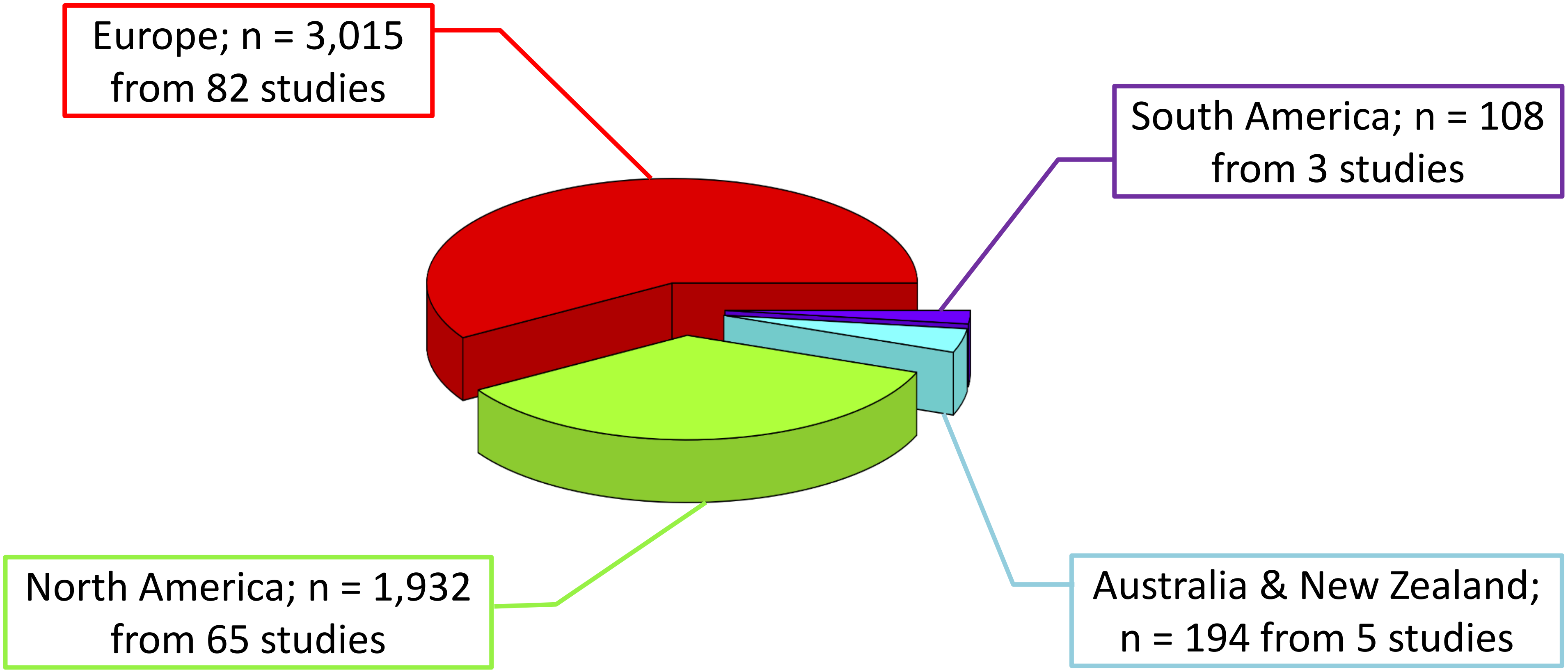
Dairy database (n = 5,249)



Enteric CH_4 Production Models

Model Development			Model Performance
Level	Model	Predictor	RMSPE, %
1	GEI Level	GEI	15.8
2	DMI Level	DMI	15.6
3	**DMI & NDF Level**	**DMI, NDF**	**14.5**
4	DMI & EE Level	DMI, EE	15.8
8	ECM Level	ECM	[illegible]
9	Performance	ECM, MP	17.7
10	**Animal Level**	**DMI, EE, NDF, MF, BW**	**14.5**
11	Animal without DMI Level	EE, NDF, MP, ECM, BW	16.3
-	IPCC, 2006	GEI	16.1
-	IPCC, 1997	GEI	16.6

Conclusion: simpler models had predictive ability close to complex models

Niu et al., in preparation

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Dry matter intake estimation

Table S1. Equations used to estimate dry matter (DMI) or Net Energy of Maintenance (NE_m) intakes for various categories of cattle

Cattle category[a]	DMI (kg/head/d) or NE_m intake (Mcal/head/d) equations[b]	Source
Beef cows	$DMI = SBW^{0.75} \times (0.0194 + 0.0545 \times NE_m)$	NRC[2,3]
Dairy cows		
Dry cows	$DMI = 0.0968 \times BW^{0.75}$	NRC[4]
Lactating cows[c]	$DMI = 0.372 \times FCM + 0.0968 \times BW^{0.75}$	NRC[4]
Bulls	$DMI = 0.0968 \times BW^{0.75}$	NRC[4]
Beef replacement heifers	$NE_m\ intake = BW^{0.75} \times (0.2435 \times NE_m - 0.0466 \times NE_m^2 - 0.1128) \div NE_m$	NRC[3]
Dairy replacement heifers[d]	$DMI = BW^{0.75} \times (0.2435 \times NE_m - 0.0466 \times NE_m^2 - 0.1128) \div NE_m$	NRC[4]
Cattle on feed	$DMI = [BW^{0.75} \times (0.2453 \times NE_m - 0.0466 \times NE_m^2 - 0.0869)] \div NE_m$	NRC[5]
Heifer and steers (>500 lbs or 227 kg live weight)[e]	$NE_m\ intake = BW^{0.75} \times (0.2435 \times NE_m - 0.0466 \times NE_m^2 - 0.1128)$	NRC[3]
Calves (<500 lbs or 227 kg live weight)	$DMI = [BW^{0.75} \times (0.2453 \times NE_m - 0.0466 \times NE_m^2 - 0.1128)] \div NE_m$	NRC[5]

[a]Based on NASS[1].

[b]SBW, shrunk body weight (0.96 × full BW), kg; NE_m, net energy of maintenance concentration in the diet, Mcal/kg dry matter; BW, body weight, kg; FCM (4% fat-corrected milk), kg/d = (0.4 × milk production, kg/d) + [15 × (milk fat, % ÷ 100) × milk production, kg/d].

[c]Stage of lactation was omitted from the DMI equation. Average daily milk yield and milk fat content specific to each state were used to calculate DMI for that state[1].

[d]No adjustments were made to the DMI equation, including for the last trimester of pregnancy.

[e]Heifer and steers that are not replacement heifers or cattle on feed.

Table 1. Cattle categories, inventories, dry matter intake (DMI), and methane emission factors used to estimate county-level enteric emissions for the continental United States

Cattle category[a]	2012 cattle inventory, × 1,000 head[b]	Live weight, kg[c]	Source for DMI or NE_m intake equations[d]	NE_m concentration, Mcal/kg[e]	Predicted DMI, kg/d (lower and upper bounds)[d]	Methane emission yield, g/kg DMI (lower and upper bounds)[f]	Methane emission factor, g/head/d (lower and upper bounds)[g]
Beef cows (1)	28,860	613	NRC[18,19]	1.09	9.4 (7.5, 11.3)	22 (19.5, 24.5)	207 (147, 277)
Dairy cows (2)	(9,262)						
Dry cows	1,762	670	NRC[20]	N/A	12.7 (10.2, 15.3)	22 (19.5, 24.5)	280 (199, 375)
Lactating cows[h]	7,500	670	NRC[20]	N/A	22.9 (18.3, 27.5)	19 (15.2, 22.8)	436 (278, 628)
Bulls (3)	2,125	920	NRC[20]	N/A	16.2 (12.9, 19.4)	22 (19.5, 24.5)	356 (252, 476)
Beef replacement heifers (4)	5,636	406	NRC[19]	1.12	8.2 (6.6, 9.8)	22 (19.5, 24.5)	180 (128, 241)
Dairy replacement heifers (5)	4,785	409	NRC[20]	1.19	8.5 (6.8, 10.2)	19 (15.2, 22.8)	161 (103, 232)
Cattle on feed (6)	14,377	441	NRC[21]	2.05	10.3 (8.3, 12.4)	10 (7.5, 12.5)	103 (62, 155)
Heifer and steers (>500 lbs or 227 kg live weight)[i] (7)	12,084	325	NRC[19]	1.41	7.5 (6.0, 9.0)	22 (19.5, 24.5)	165 (117, 220)
Calves (<500 lbs or 227 kg live weight) (8)	14,209	123	NRC[21]	1.41	3.7 (2.9, 4.4)	19 (15.2, 22.8)	70 (45, 101)

[a]Based on NASS[14].
[b]Animal inventories from the 2012 Census of Agriculture[14]; total cattle = 91,338,162; dry cows = 15% of all dairy cows.
[c]Reference: categories 1, 3, 4, 5, 7, and 8, from USEPA[15]; category 2, from USEPA[15] and Hardie et al.[16]; category 6, from Anele et al.[17].
[d]For DMI equations, see Table S1. Lower and upper bounds were assumed at -20 and +20%, respectively.
[e]Dietary concentration of Net Energy of Maintenance: categories 1, 4, 7, and 8, from Beef NRC[19]; category 5, from Dairy NRC[20]; category 6, from Anele et al.[17].
[f]Reference: for categories 1 and 2 (dry cows), from Herd et al.[22]; for categories 2 (lactating cows), 5, and 8, from Hristov et al.[23-25]; for categories 3, 4, and 7, from Herd et al.[22]; and for category 6, based on[26-28]. Lower and upper bounds were based on ± 1 SD from the original publications or data

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Inventory development process: manure emissions

- Manure emission estimates were calculated using published US EPA protocols and factors

- ***Methane emission from manure (kg/yr) = (Animal population × VSE × B_o) × [(WMS$_1$ × MCF$_1$) + ….. + (WMS$_n$ × MCF$_n$)] × (Methane density)***

- National Agricultural Statistic Services (NASS) data was utilized to provide animal populations
  - Cattle values were estimated for every county in the 48 contiguous states of the United States
  - Swine and poultry estimates were conducted on a county basis for states with the highest populations of each species and on a state-level for less populated states

- Uncertainty bounds for manure methane emissions were taken from USEPA: -18% (lower) and +20% (upper)

Gridded inventory maps

- County-level total enteric and total manure methane values were allocated based upon the relative percentage of feed sources (based on USDA-NASS CropScape data) within each county
- All emission rasters were projected to geographic coordinates (latitude/longitude, WGS84 datum) and resampled to 0.1 decimal degree cells
- Gridded emissions inventories were produced for:
  - Cattle enteric
  - Cattle manure management
  - Total cattle emissions
  - Total manure emissions
  - Total combined emissions
  - The gridded inventory can be accessed at: Penn State Gridded Livestock Methane Inventory.

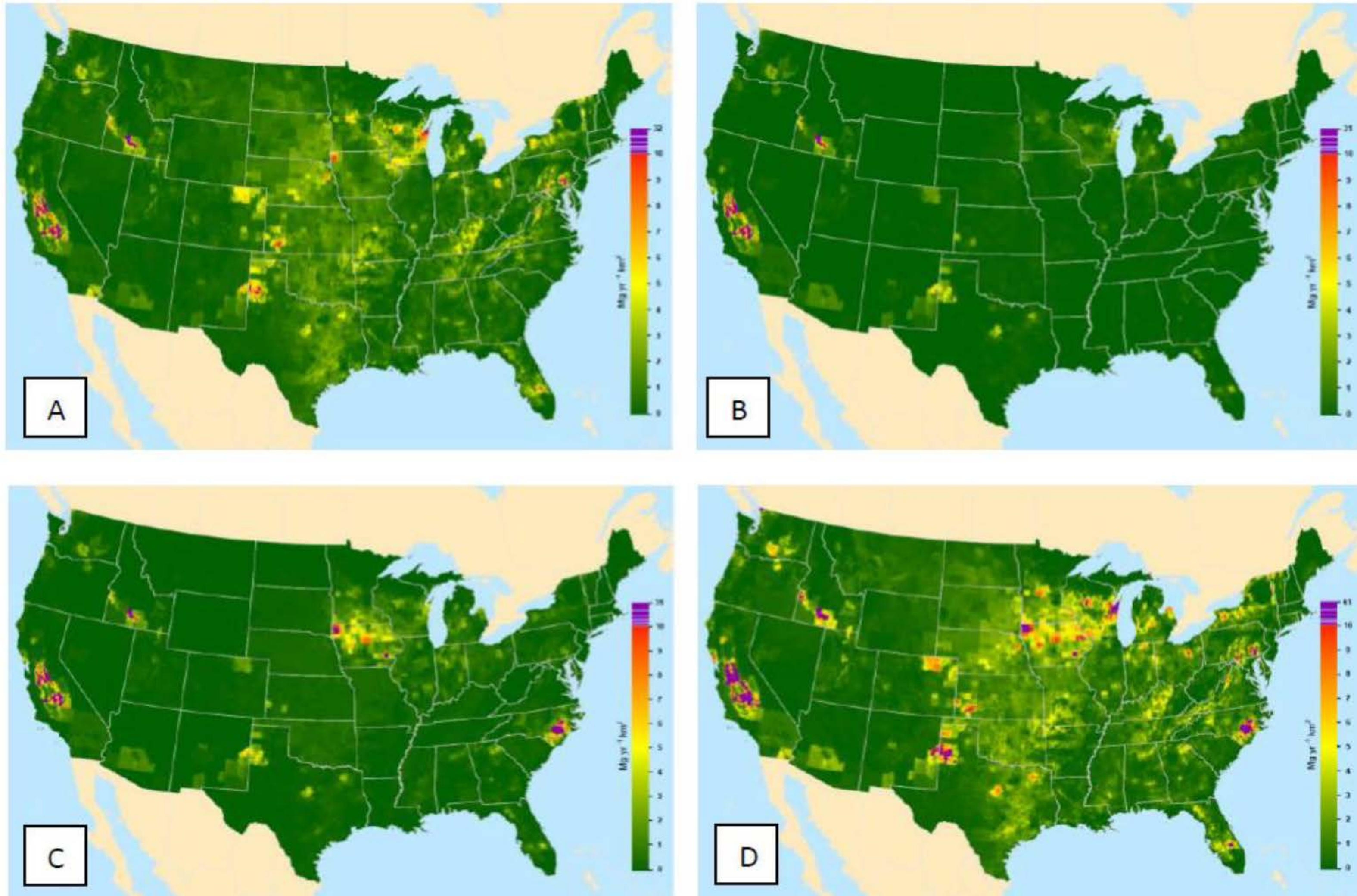

Figure 1. Gridded (0.1° × 0.1°) county-level livestock methane emissions for the contiguous United States: Enteric fermentation, cattle (panel A); Manure management, cattle (panel B), Manure management, cattle, swine, and poultry (panel C), and Cattle enteric and livestock (cattle, swine, and poultry) manure management (panel D, which is the sum of A and C).

Total methane emissions

Table 2. Comparison of methane emissions from the livestock sector across alternate bottom-up emissions inventories

Emissions inventory	Year	Average annual emissions from the continental United States (Gg/year)		
		Enteric fermentation	Manure management	Total
EDGAR[13]	2010	6,580[a]	2,148[a]	8,728
Maasakkers et al.[12]	2012	6,433[b]	2,534[c]	8,967
USEPA[1]	2012	6,433[b]	2,611[c]	9,044
This study	2012	6,201 (4,197, 8,582)[b,d]	2,715 (2,226, 3,258)[c,d]	8,916 (6,423, 11,840)[d]

[a]All species.
[b]Cattle only.
[c]Cattle, swine, and poultry.
[d]Lower and upper bounds in parentheses.

- **Comparable total methane emissions between our analysis and USEPA or EDGAR**

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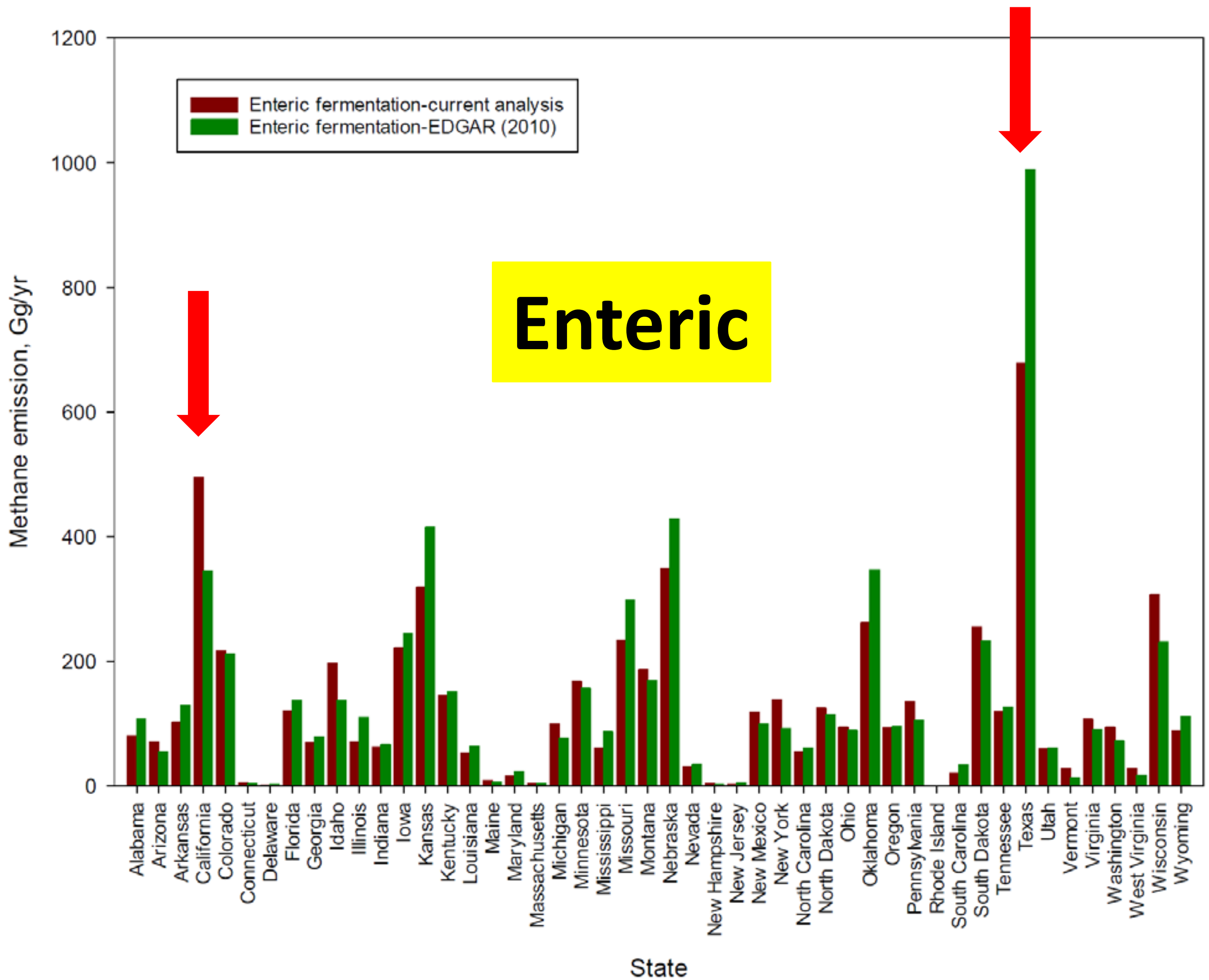
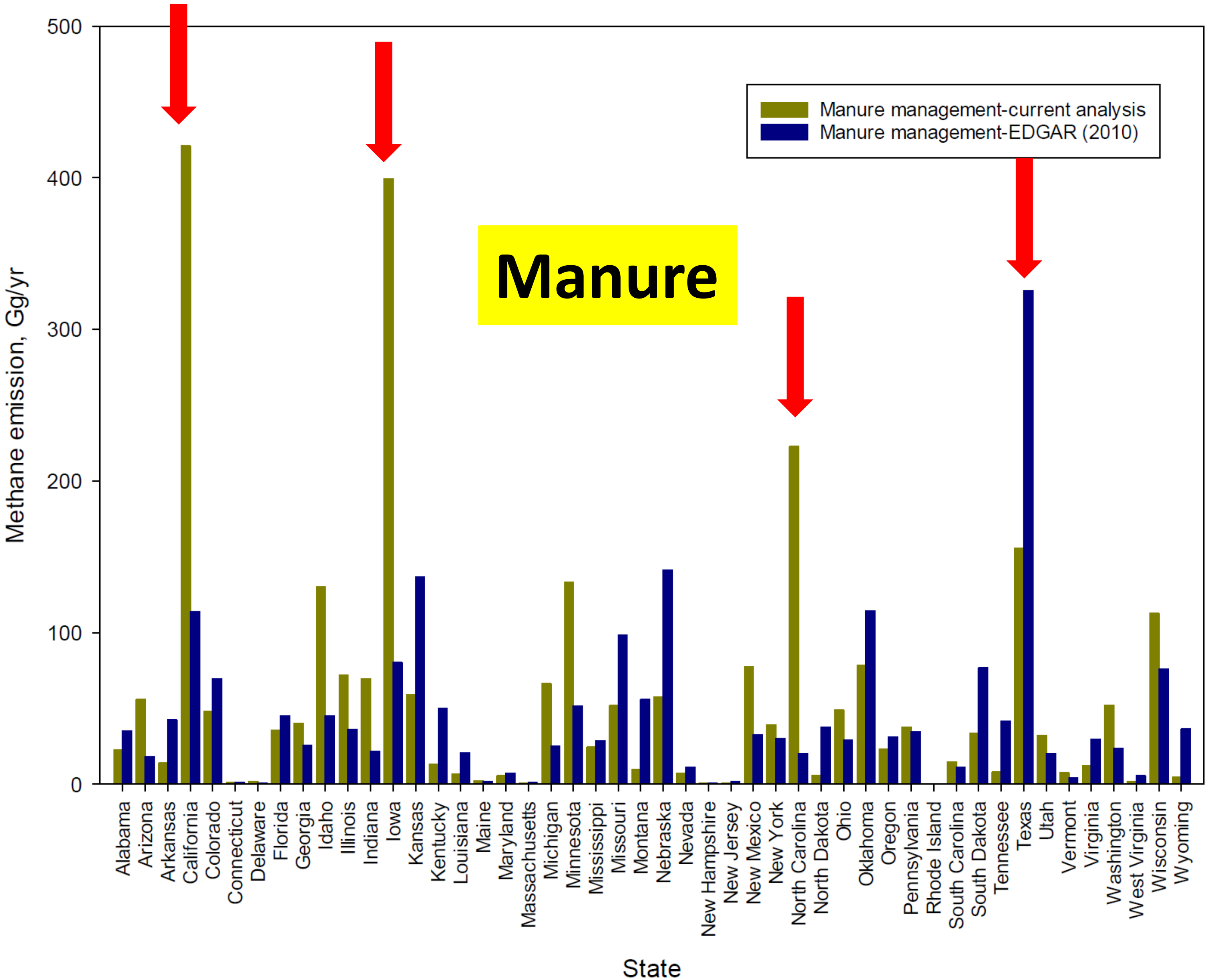
➢ **However, the spatial distribution of emissions differed significantly from that of EDGAR (and USEPA)**




Manure
Manure management-current analysis
Manure management-EDGAR (2010)
Methane emission, Gg/yr
0
100
200
300
400
500
Alabama
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
Florida
Georgia
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming
State

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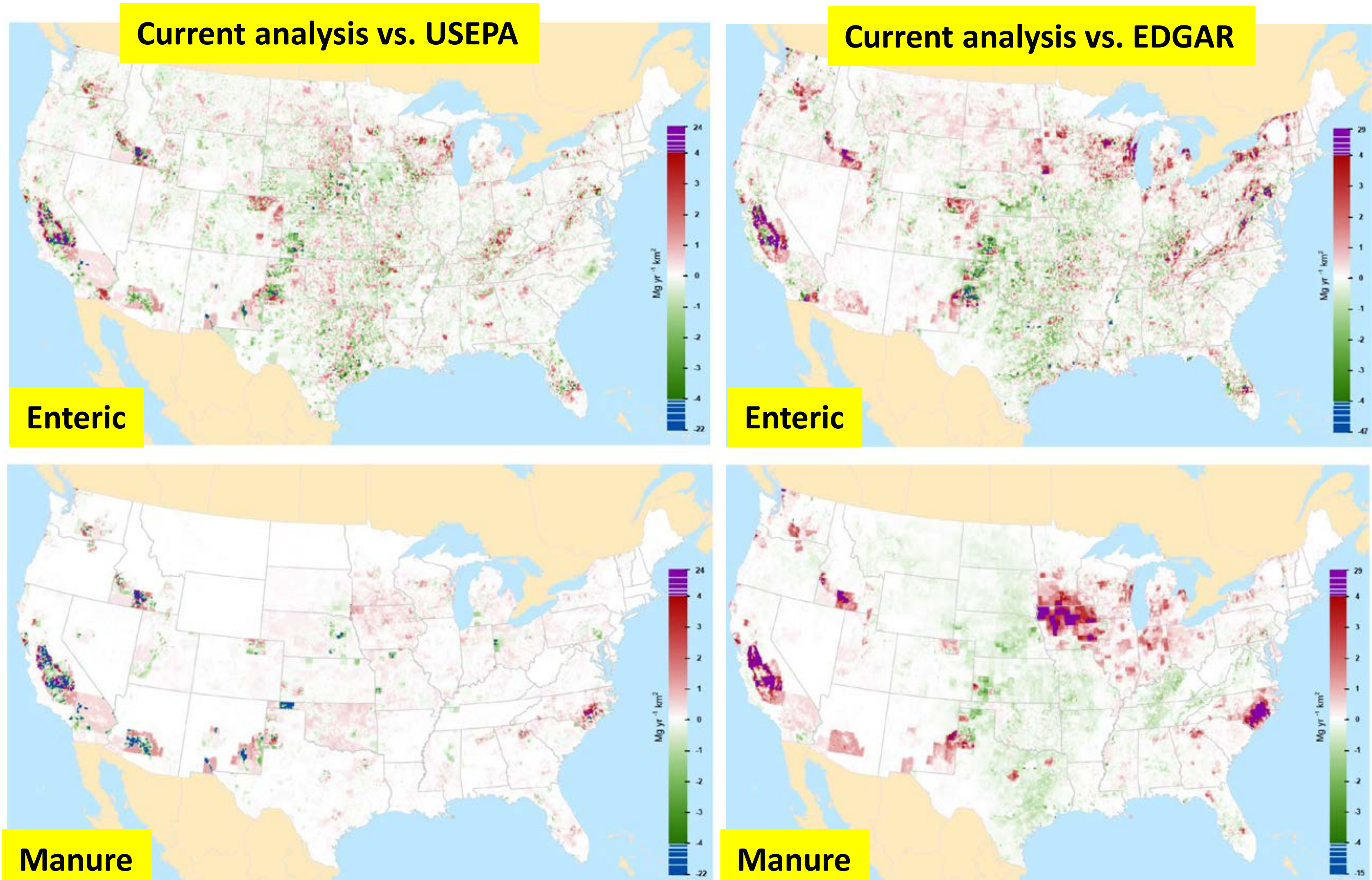
Gridded differences in emissions between bottom-up approaches



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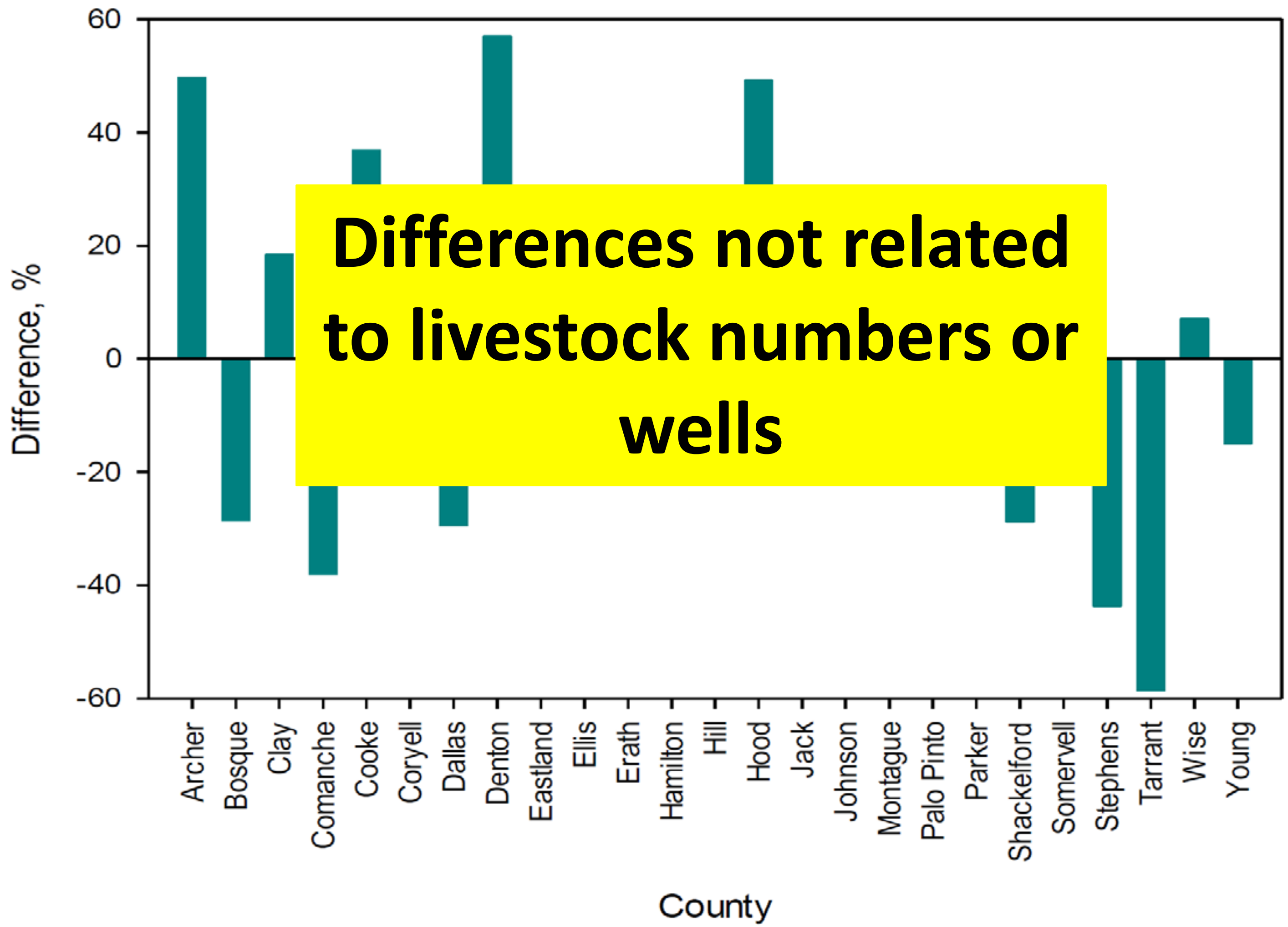
Lyon et al., 2015 vs. this analysis: 25 counties in the Barnett Shale region of Texas



Conclusions

- Atmospheric methane concentrations are increasing since 2006
  - Reasons are unknown
  - Cannot be attributed to a specific source based on isotopic data
- For inventory purposes, DMI and methane yield are sufficient to estimate cattle enteric methane emission factors
- **Manure emission factors are more complex (very diverse manure systems!)**
- Good agreement in total emission estimates among bottom-up approaches (this analysis, USEPA, EDGAR)
  - **Large discrepancies in spatial distribution of emissions**
- Conclusions from top-down inventories that use inaccurate spatial distribution emission data from gridded bottom-up inventories may be misleading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2134
Control
1940
Control
2082
2026
1997
1845
1831
1940

QUESTIONS?