# BAE 820 Physical Principles of Environmental Systems

## Combustion smoke Fundamentals

Dr. Zifei Liu

# Combustion and smoke

- Combustion (fire) is the first controlled chemical reaction discovered by humans, and is widely used
  - to produce energy.
  - to destroy (incinerate) waste.
- It is a high-temperature chemical reaction between a fuel and an oxidant.
  - It releases heat (exothermic).
  - It produces smoke and ash.


A complex mixture of oxidized products including gases and particles

Smoke

Ash

Heat

# Stoichiometric combustion

- Stoichiometry is the calculation of relative quantities of reactants and products in chemical reactions. In stoichiometric combustion, there is no remaining fuel and no remaining oxidant.
- Complete combustion is stoichiometric, and it produces primarily the most common oxides (maximum degree of oxidation).
  - E.g. Carbon will yield $CO_2$, sulfur will yield $SO_2$.
- A simple chemical equation for combustion of a hydrocarbon in $O_2$ is

$$C_xH_y + zO_2 \rightarrow xCO_2 + \frac{y}{2}H_2O$$

For stoichiometric combustion, $z = x + \frac{1}{4}y$.

In the above equation, when z falls below roughly 50% of the stoichiometric value, $CH_4$ can become an important combustion product; when z falls below roughly 35% of the stoichiometric value, elemental carbon may become stable.

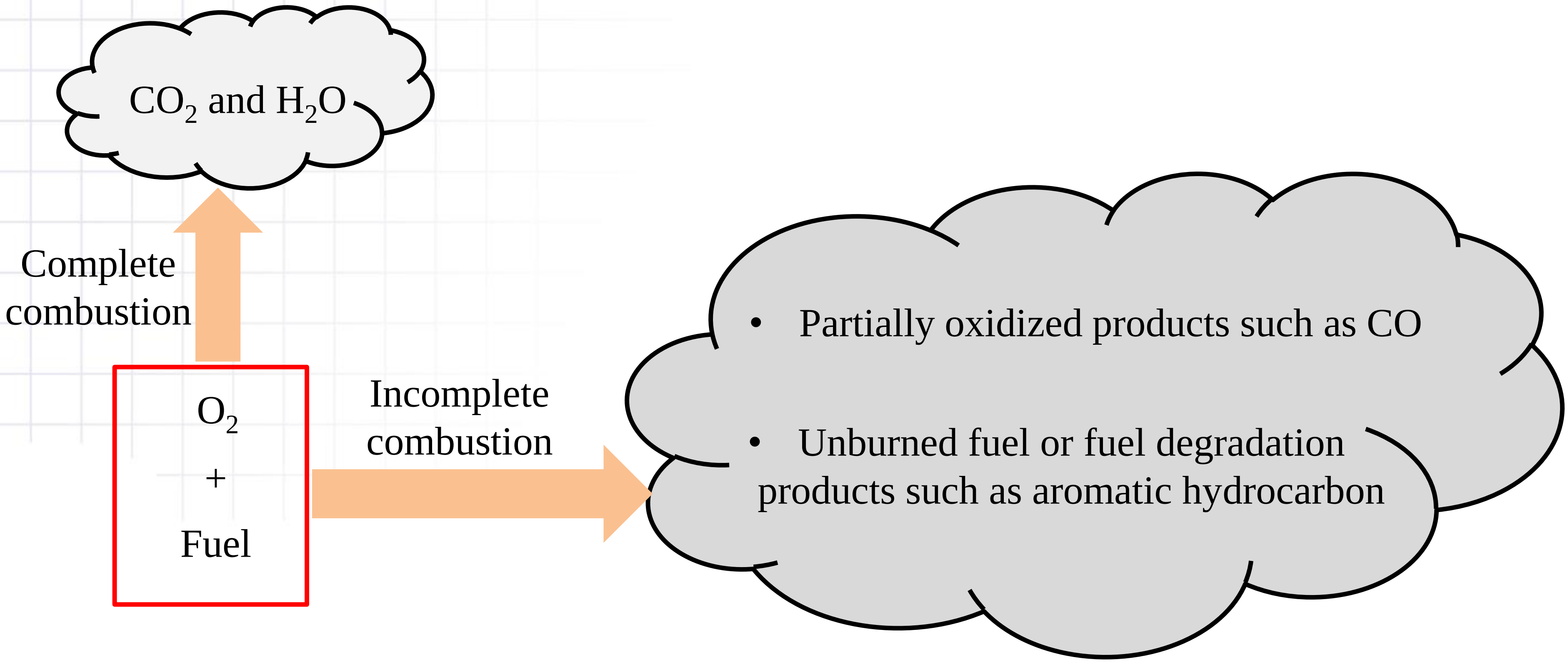
# Incomplete combustion

In reality,

- Combustion typically involve hundreds of chemical species reacting according to thousands of reactions. It is a chain reaction in which many distinct radical intermediates participate.
  - For any C-H-O system, combustion products mainly include $CO_2$ and $H_2O$ and their dissociated products, including CO, $H_2$, $O_2$, OH, H, O, $O_3$, C, $CH_4$. For a C-H-O-N system, $N_2$, N, NO, $NH_3$, and $NO^+$ could be added.
  - Any combustion at high temperatures in atmospheric air, which is 78% $N_2$, will also create small amounts of $NO_x$.
  - It is not necessarily favorable to the maximum degree of oxidation, and it can be temperature-dependent.

- Complete combustion is almost impossible to achieve.
  - In a typical fire, substantial temperature and concentration gradient exist in the buoyancy-induced turbulent flow. Incomplete combustion will occur when there is no enough $O_2$ or when there is a heat sink causing low temperature.
  - Incomplete combustion results in unburnt or partially oxidized compounds.

# Smoke is mainly a product of incomplete combustion




Smoke compounds depend on both the fuel properties (especially the elemental composition) and the combustion conditions.

# Air-to-fuel ratio

- Air–fuel ratio is the mass ratio of air to fuel present in a combustion process. If exactly enough air is provided to completely burn all of the fuel, the ratio is known as the stoichiometric ratio. Different hydrocarbon fuels have a different contents of carbon, hydrogen and other elements, thus their stoichiometry varies.

**Stoichiometric air-to-fuel ratios of common fuels**

| Fuel | Ratio by mass |
|---|---|
| Gasoline | 14.7 : 1 |
| Diesel | 14.5 : 1 |
| Natural gas | 17.2 : 1 |
| Propane (LP) | 15.67 : 1 |
| Ethanol | 9 : 1 |
| Hydrogen | 34.3 : 1 |

# Fuel-air equivalence ratio

- Fuel-air equivalence ratio Φ is defined as

$$\Phi = \frac{\text{actual fuel to air ratio}}{\text{stoichiometric fuel to air ratio}}$$

| | | Typical $CO/CO_2$ ratio (v/v) |
|---|---|---|
| Φ <1 | Well-ventilated flames | <0.05 |
| Φ =1 | Stoichiometric flames | ~0.05 |
| Φ >1 | Under-ventilated flames | 0.2-0.4 |

# ISO classification of fire stages

| Fire stages | Smoke Temp (ºC) | Fuel-air equivalence ratio | Typical $CO/CO_2$ ratio (v/v) | Combustion efficiency (%) |
|---|---|---|---|---|
| 1. Non-flaming | | | | |
| 1a. Self-sustained smouldering | 25-85 | - | 0.1-1 | 50-90 |
| 1b. External radiation (pyrolysis) | - | - | - | - |
| 2. Well-ventilated flaming | 50-500 | <1 | <0.05 | >95 |
| 3. Under-ventilated flaming (post-flashover) | >600 | >1 | 0.1-0.4 | 70-90 |

*(Adapted from ISO 19706 and fire toxicity)*

- Combustion of solid fuels first need to undergo pyrolysis (chemical decomposition) to produce more easily oxidized gaseous fuels, and then they volatilize from the surface and enter the flame.
- Self-sustained smouldering can only occur to porous material. Smouldering of biomass can exist after flaming has ceased for days or weeks.

# Smouldering

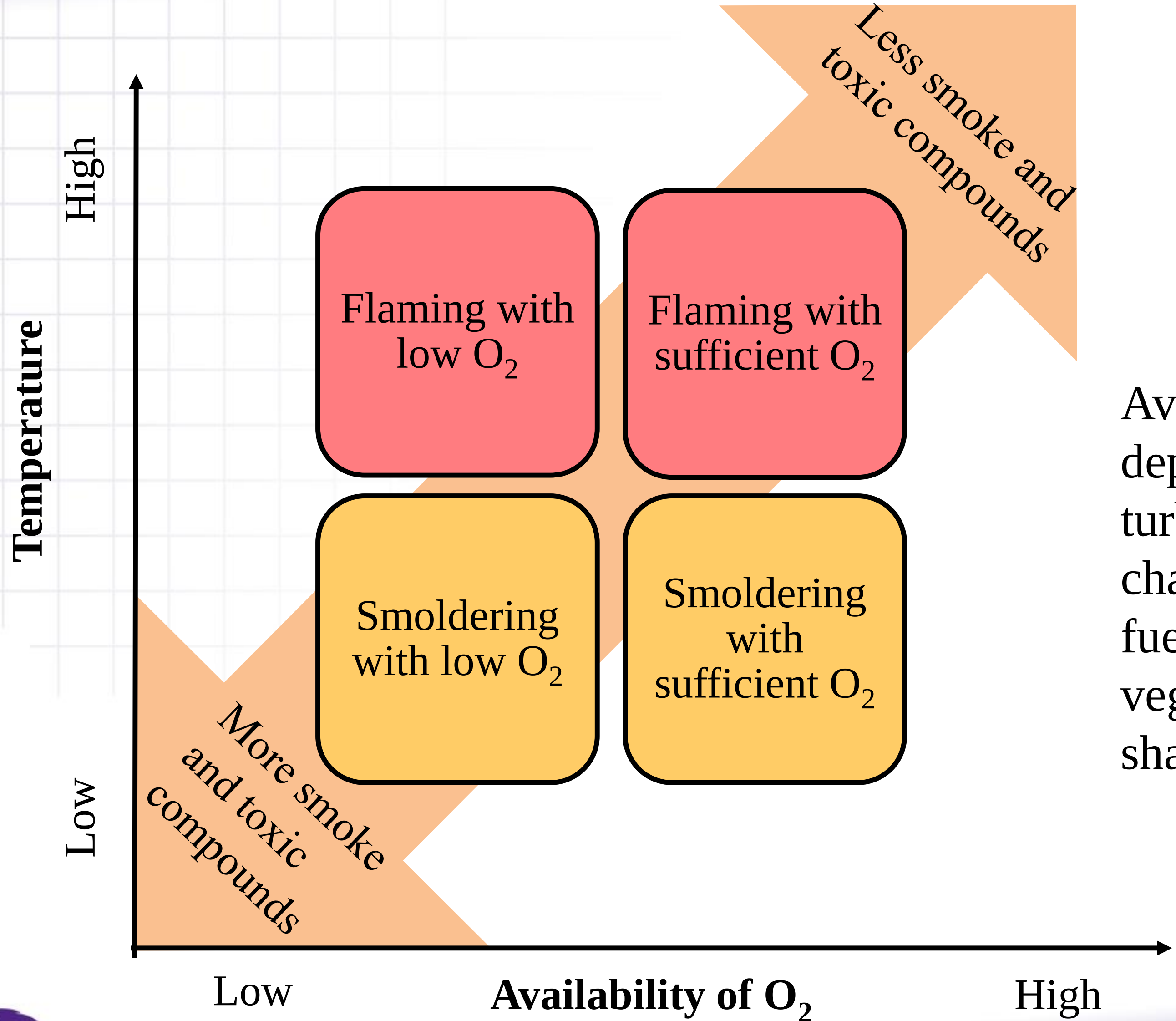
- Smouldering is the slow, low-temperature, flameless form of combustion, sustained by the heat evolved when oxygen directly attacks the surface of a condensed-phase fuel.
  - A typically incomplete combustion.
  - Low temperature.
  - A surface phenomenon (occurs on the surface of solid rather than in gas phase).
  - Slow but persistent (about ten times slower than flames spread over a solid).
  - A significant fire hazard.
  - Emits much more toxic smoke than flaming fires.

- A burning cigarette is a familiar example of smoldering combustion.

Many solid materials can sustain a smouldering reaction, including cellulose and wood.

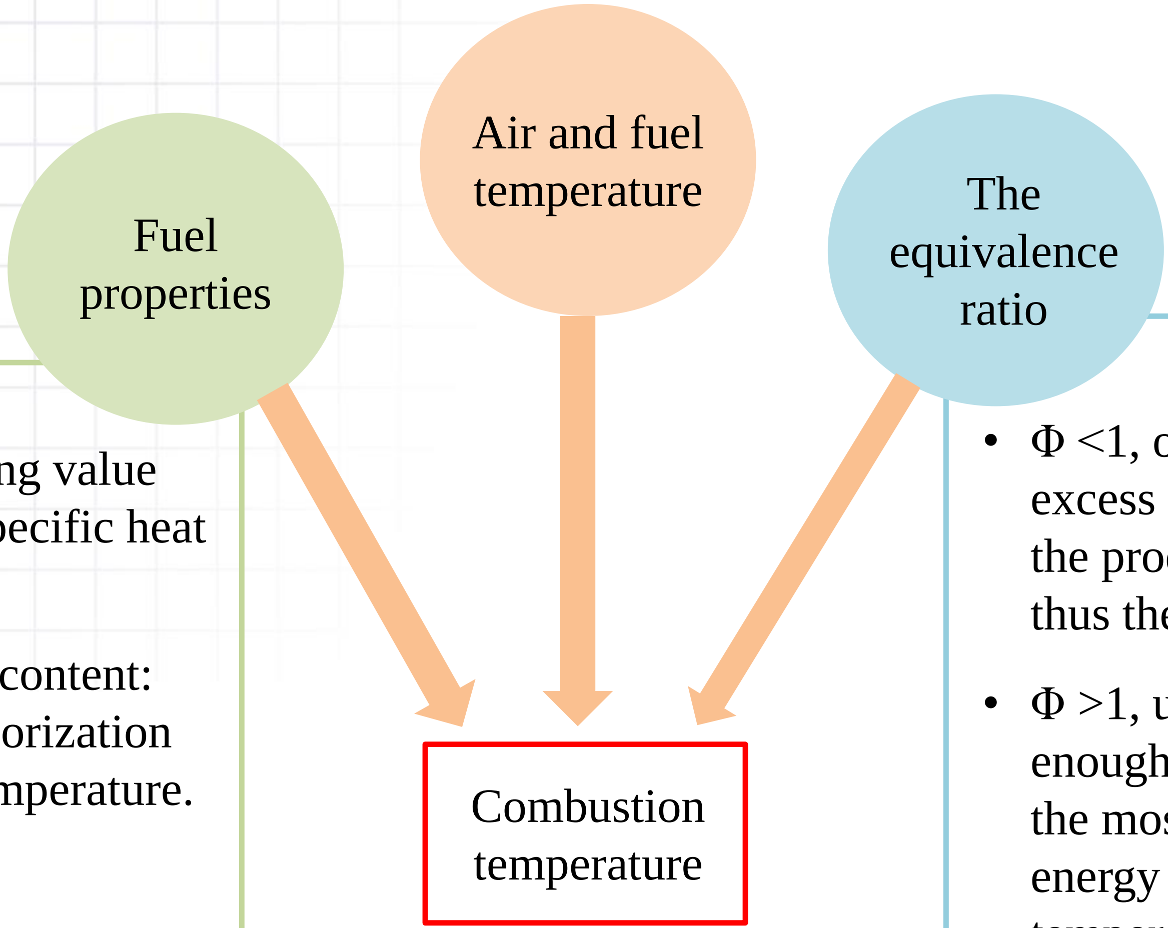

*(Photo credit: Rein, 2009)*

# Smoke and combustion conditions




Availability of $O_2$ depends on wind, turbulence, and characteristics of the fuel, such as vegetation density, shape, and structure.

# Combustion temperature




- The heating value and the specific heat capacity.
- Moisture content: water vaporization lowers temperature.

- $\Phi < 1$, overoxidized, the excess $O_2$ must be heated to the product temperature and thus the temperature drops.
- $\Phi > 1$, underoxidized, no enough $O_2$ to burn fuel to the most oxidized state, so energy released is less and temperature drops as well.

# Open vegetation fires

- In open vegetation fires, a moving fire front passes through a fuel bed, such as a grassland or forest. Different combustion conditions may occur simultaneously at different locations within the fire environment. Their proportions and the prevalent conditions vary over time, typically with more flaming in the earlier part of the fire and more smoldering during the latter part.

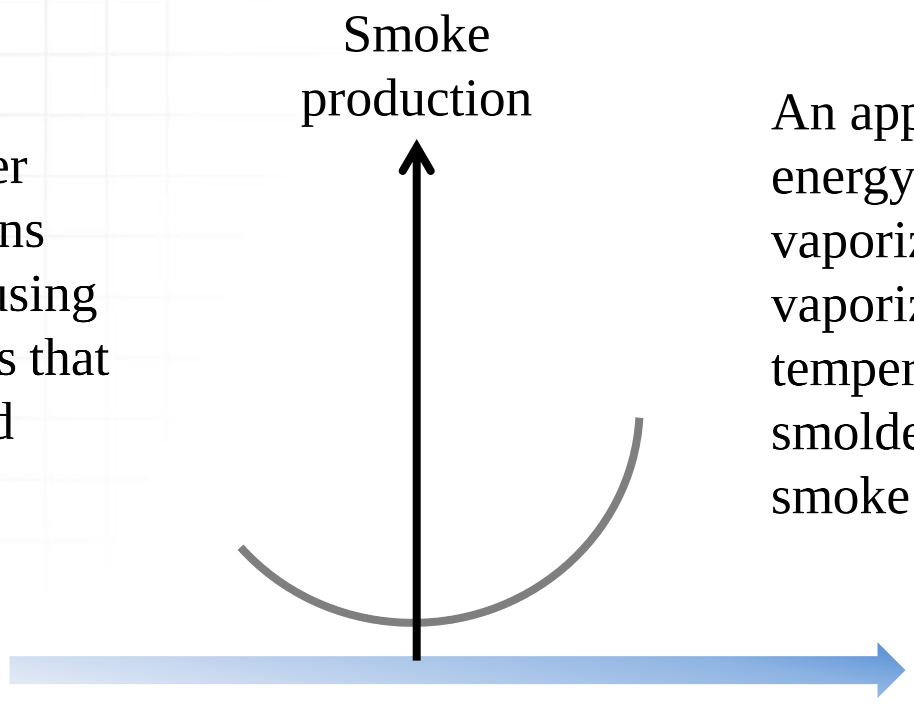
# Not all smoke is equal

- Fuel characteristics
- Combustion conditions
  - Weather conditions
  - Fuel conditions

- **The overall mixture of combustion products is usually determined by the amount of smoldering combustion.**

- Nature thick fuel and organic soil prone to smouldering combustion. Natural thick fuels include stumps, snags, downed logs, large branches and roots. Organic soils include hummus, duff, peat, coal seams and others.

# Effect of moisture content of vegetation fuel




Vegetation with lower moisture content burns faster, eventually causing $O_2$-limited conditions that also lead to increased smoke formation.

An appreciable amount of energy is necessary to vaporize the water. Water vaporization lowers temperature, which favors smoldering and increased smoke formation.

Lower moisture content

Higher moisture content

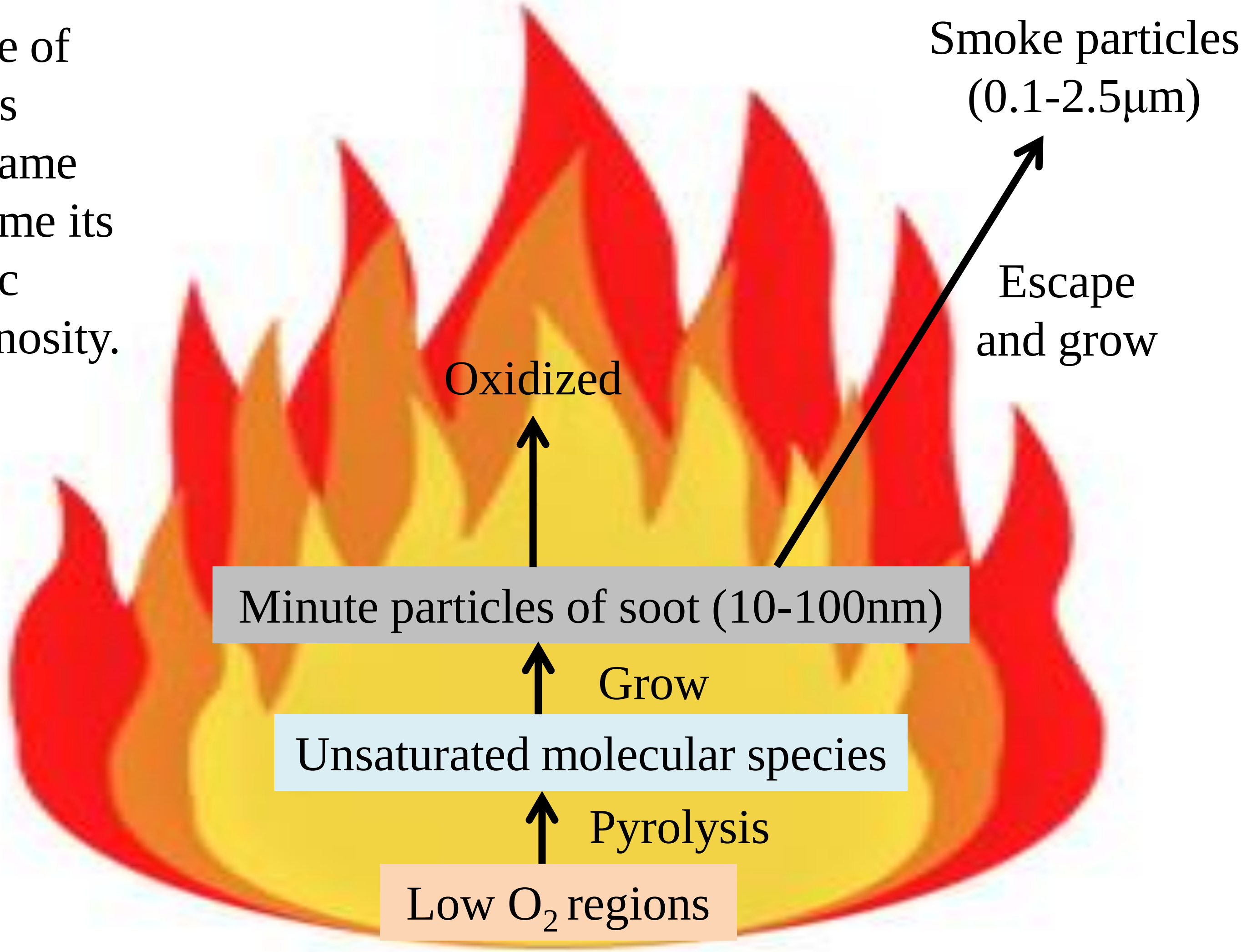
The optimal moisture content in terms of minimizing PM emissions is 20–30% for wood combustion.

# Main components of vegetation fire smoke

| | |
|---|---|
| Particulate matter | Complex mixtures of EC, OC and inorganic ash; 70–90% of PM is $PM_{2.5}$ |
| VOCs | Acrolein, formaldehyde, isocyanic acid, … |
| SVOCs | Polycyclic aromatic hydrocarbons (PAHs), … |
| Permanent gases | $CO_2$, CO, $CH_4$, $NO_x$, … |
| Water vapor | Reduce visibility |
| $O_3$ | Secondary product of $NO_x$, VOCs and CO |

# Generation of particulates in smoke

The presence of soot particles within the flame gives the flame its characteristic yellow luminosity.



# Generation of particulates in smoke

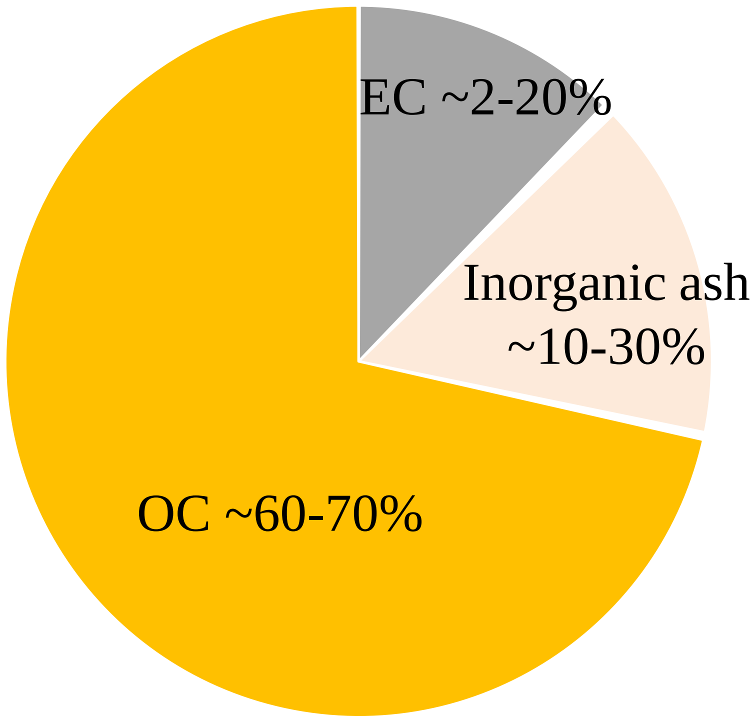
PM is the solid or liquid component of smoke, which is highly visible and is the principal public health concern from smoke exposure.

*(Photo credit: S. O'Neill)*

# Particulate matter (PM) in smoke

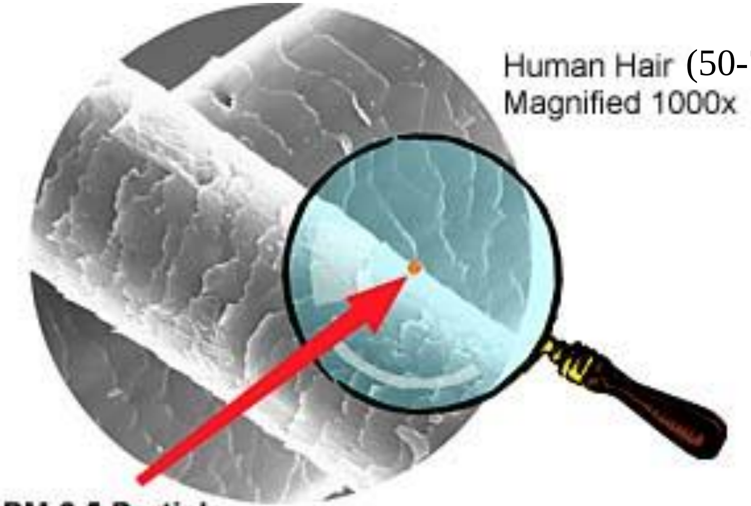
- Smoke PM acts as a vehicle to carry absorbed hazardous compounds into the respiratory tract. The adsorbed hazardous compounds may include VOCs such as formaldehyde and acrolein, SVOCs such as PAHs and dioxin, gases such as $NO_2$, and toxic metal elements such as lead and mercury.
- PM from air in an urban area and that near a wildfire induced different inflammatory, oxidative stress, and xenobiotic responses in human bronchial epithelial cells.

**Composition of smoke PM**



# Size of smoke PM

- ~90% of PM in biomass smoke is $PM_{10}$
  ~70–90 % of PM is $PM_{2.5}$
- Particles of this size range are not easily removed by gravitational settling and therefore can be transported over long distances.




- The depth of particle penetration into the lungs and the likelihood of them being exhaled depend on their size. Coarse particles affect nasopharyngeal region, whereas fine particles can penetrate the large airways of the trachea, bronchi, and bronchioles, and even reach the alveoli.
- Smoke PM has a size range near the wavelength of visible light (0.4–0.7µm) and therefore can efficiently scatter light and reduce visibility.

# Volatile organic compounds (VOCs)

- Organic irritants
  - Aldehydes:
    - Combustion of cellulose-based material such as wood has been demonstrated to evolve significant quantities of formaldehyde and acrolein.
  - Isocyanic acid:
    - Recently identified in outdoor air under the influence of wild fires, a potentially toxic compound found in both cigarette smoke and vegetation fire smoke.
- Precursor of $O_3$

# Semi-volatile organic compounds (SVOCs)

- Complex molecules such as polycyclic aromatic hydrocarbons (PAHs).
  - Benzo(a)pyrene (BaP), naphthalene, and anthracene, …
  - Specific species varies with composition of vegetation.
  - Condense or adsorbed onto fine particles or as volatiles in the vapor phase.
  - Carcinogenic and mutagenic.

- PAHs emissions were more strongly influenced by burning conditions than by the type of fuel
  - For low-intensity backing fires, the ratio of BaP to PM is higher by almost 2 orders of magnitude over that for heading fires

# Permanent gases

- $CO_2$, $CH_4$
  - Greenhouse gases
- CO
  - Toxic
- $NO_x$ (NO and $NO_2$)
  - Due to the low combustion temperatures in vegetation fires, the nitrogen species emissions are mainly based only on fuel nitrogen.
  - Precursor of $O_3$

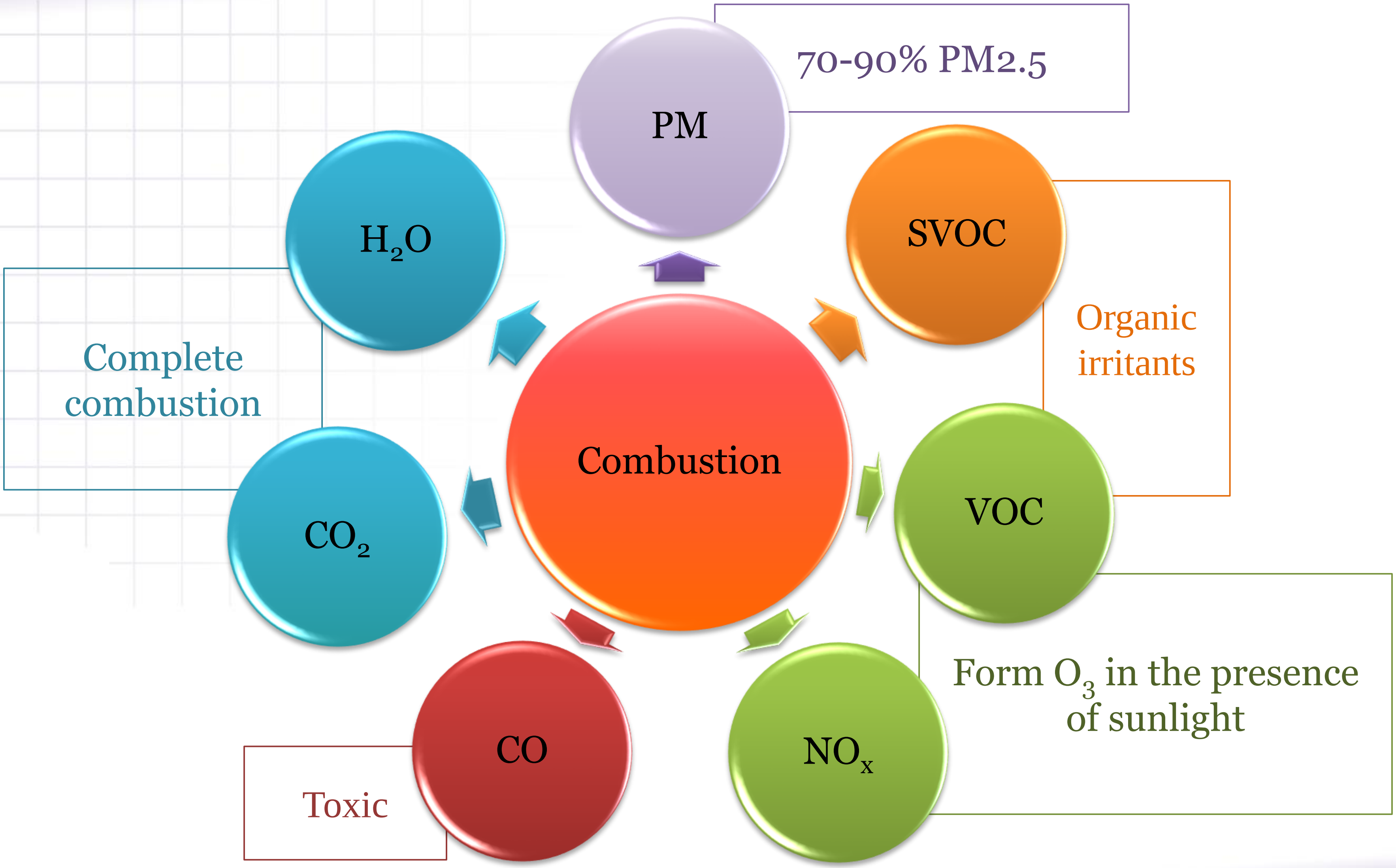
# Secondary products of the smoke plume

- Secondary products can be produced in the smoke plume through photochemical reactions under solar radiation.
- The production of $O_3$ occurs either in the original plume or as a result of the smoke plume interacting with existing pollutants in the atmosphere.
- Precursors in smoke: VOCs, NOx, and CO.

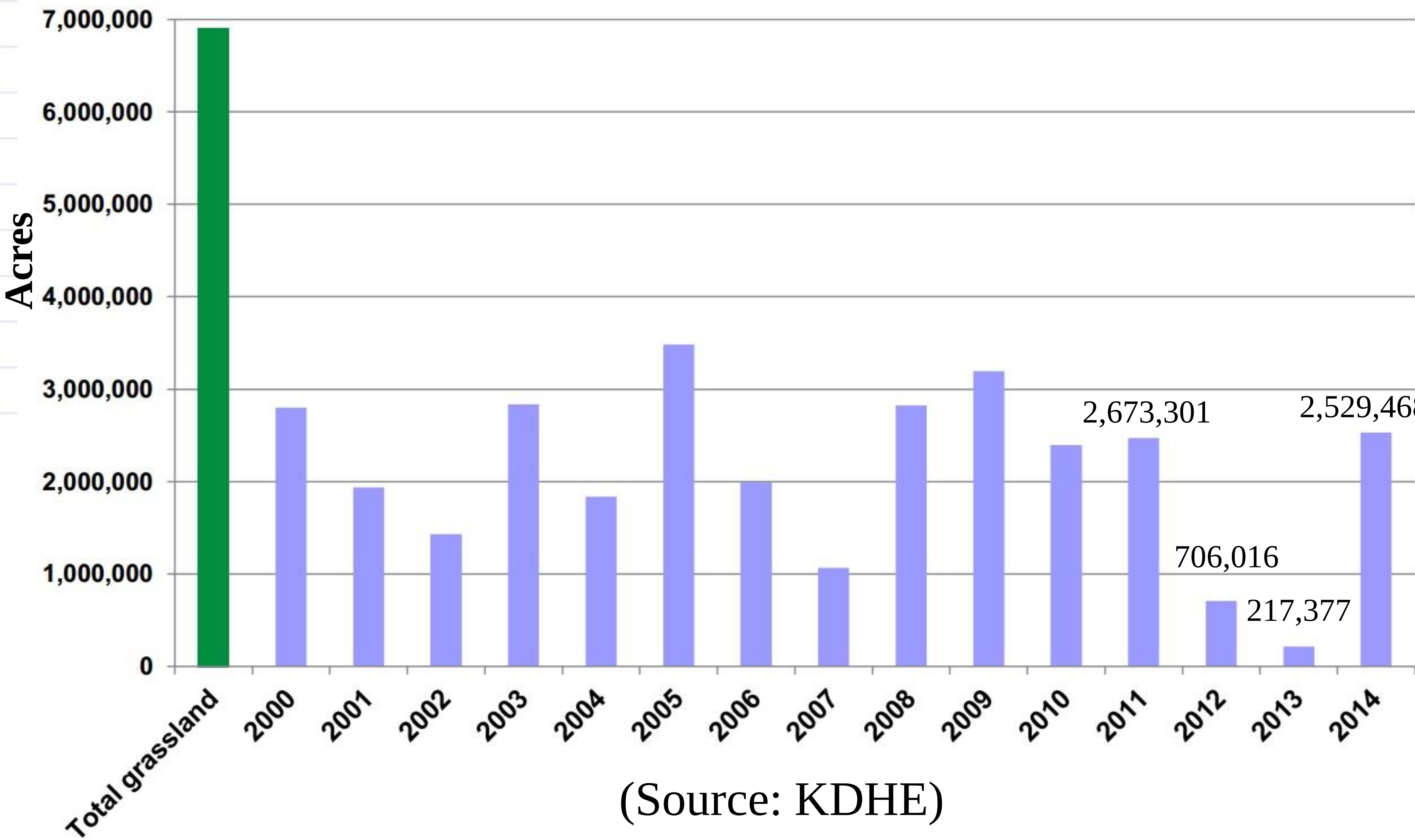
# Other trace combustion products

- Herbicides and insecticides
  - may become re-suspended in the air.
- Dioxins
  - are found in soils in remote areas and are sometimes present in vegetation fire smoke
- Sulfur-based compounds
  - can be produced when sulfur-rich vegetation or soil are burned.
- Free radicals
  - may persist up to 20 min following formation and may be of concern to people exposed to them because free radicals may react with human tissues

# Summary of smoke composition

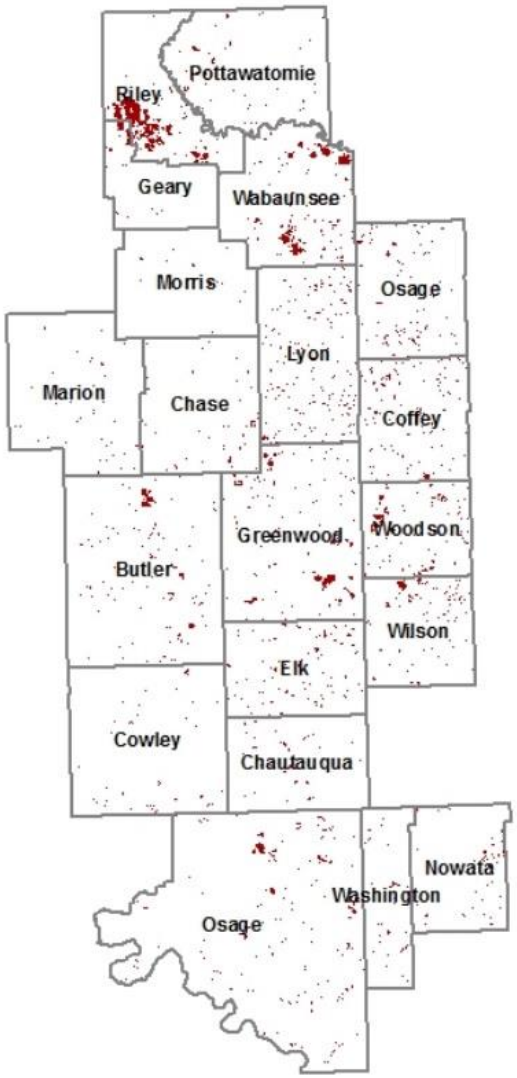


# Flint Hills acres burned 2000-2014



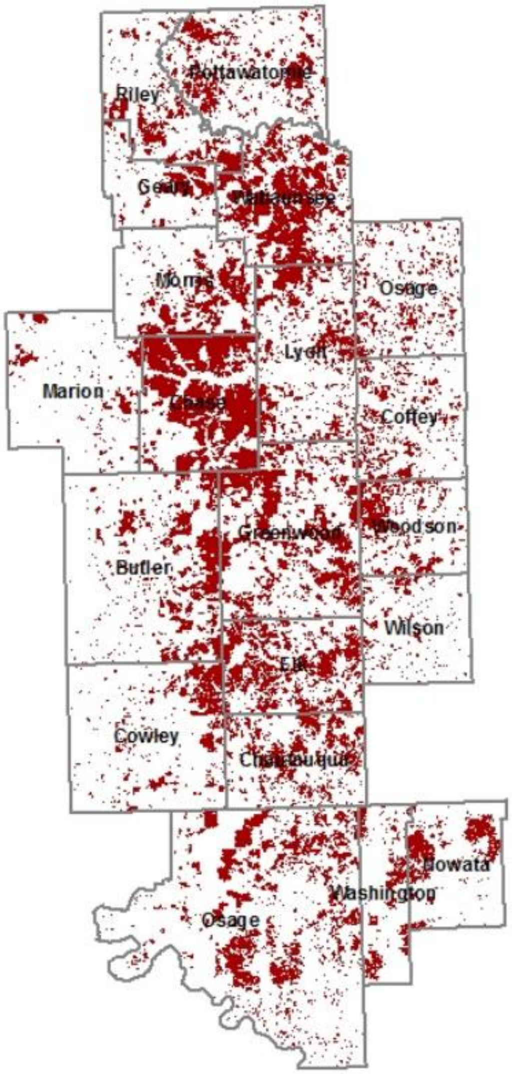

(Source: KDHE)

# 2013 Flint Hills Burning



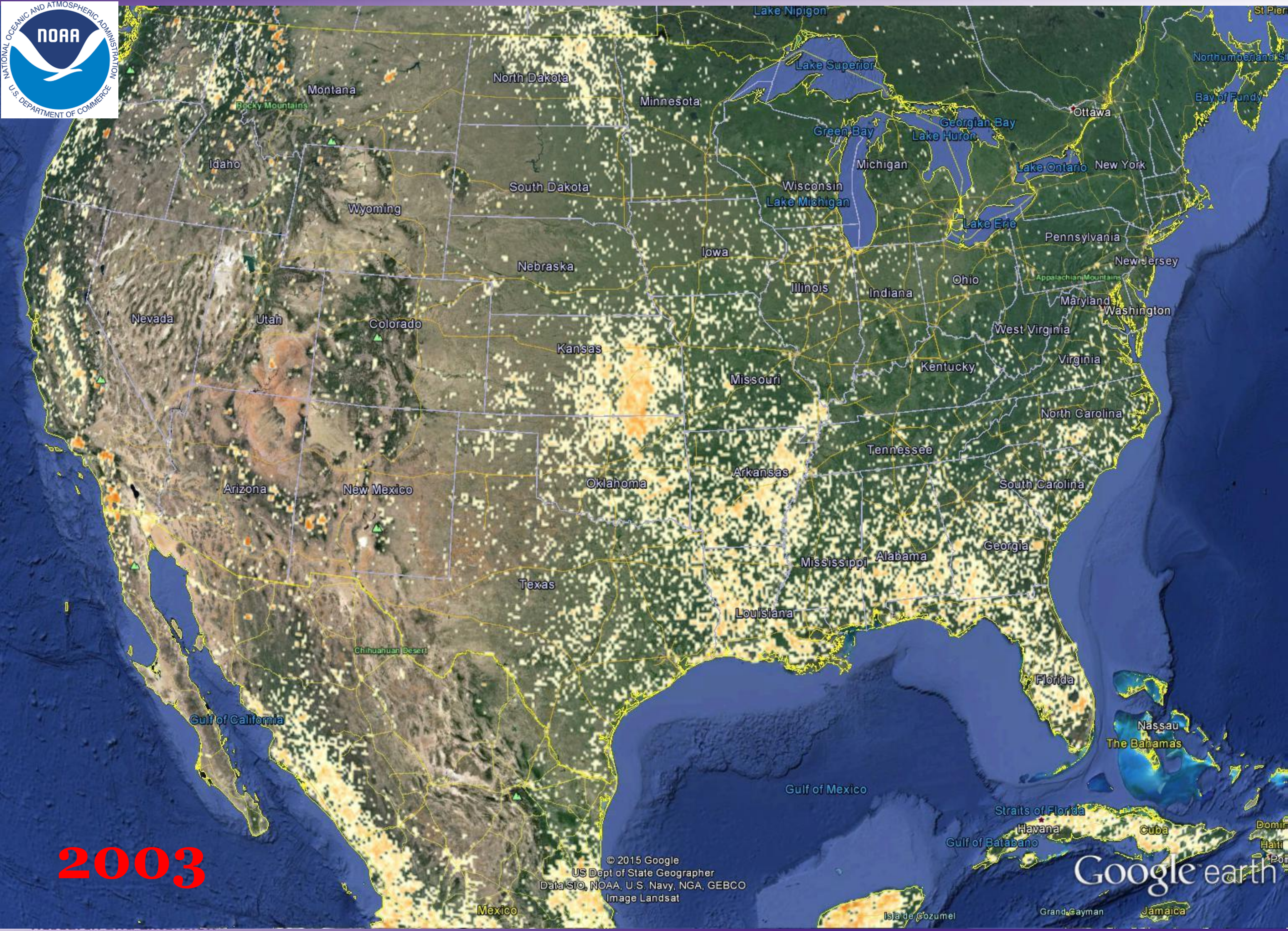

217,377 burned acres

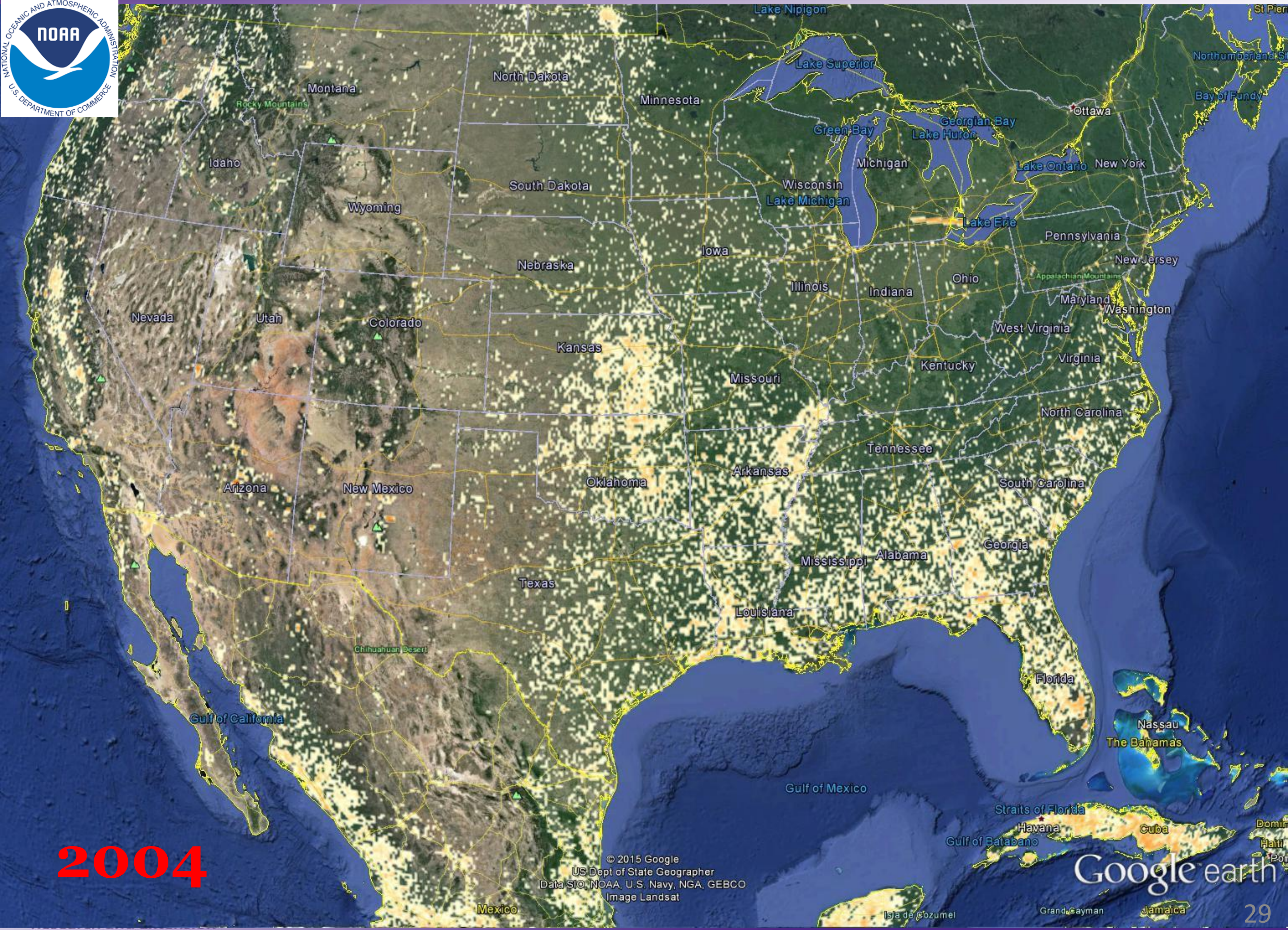
# 2014 Flint Hills Burning



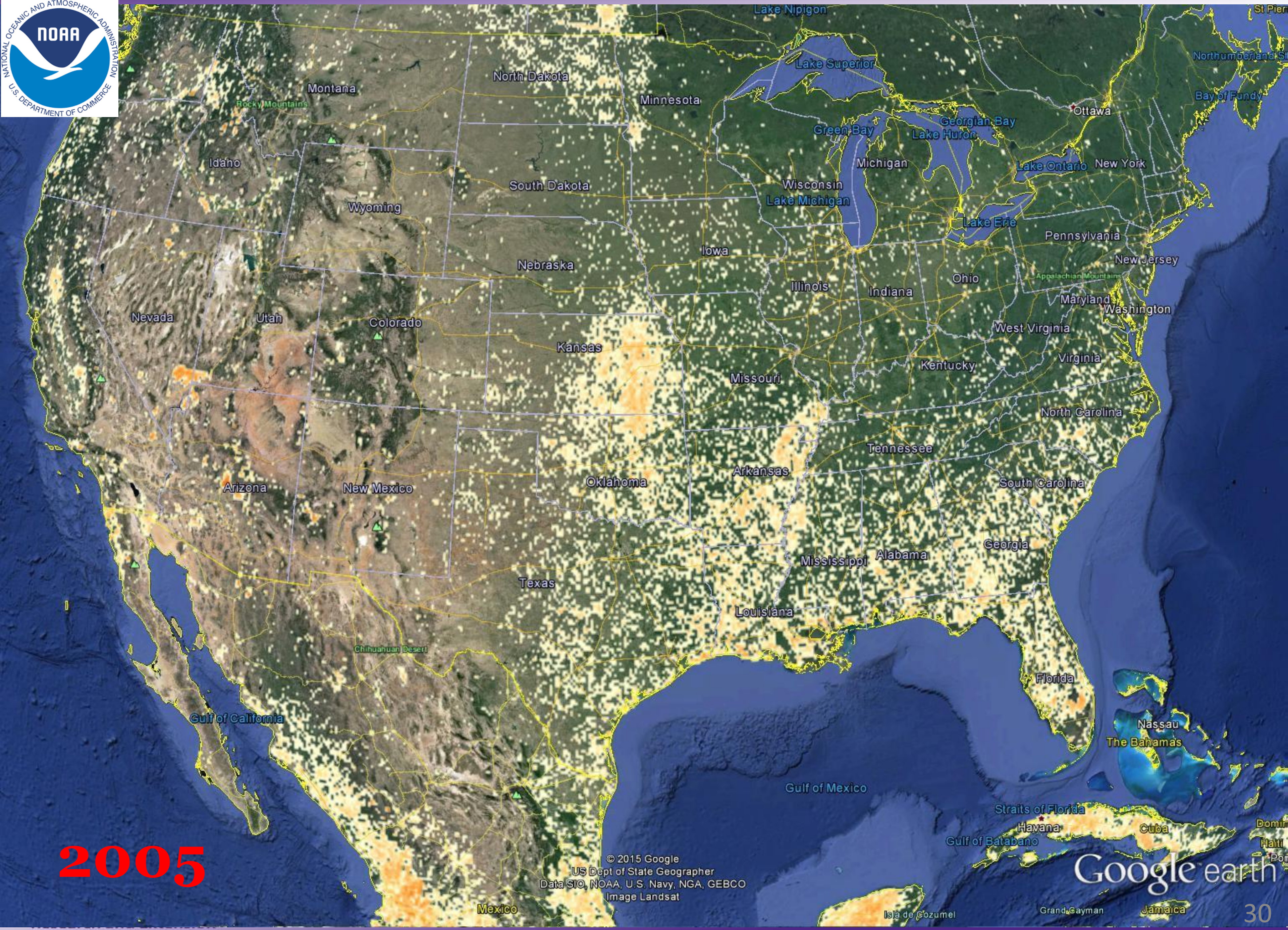

2,529,468 burned acres

(Source: KDHE)

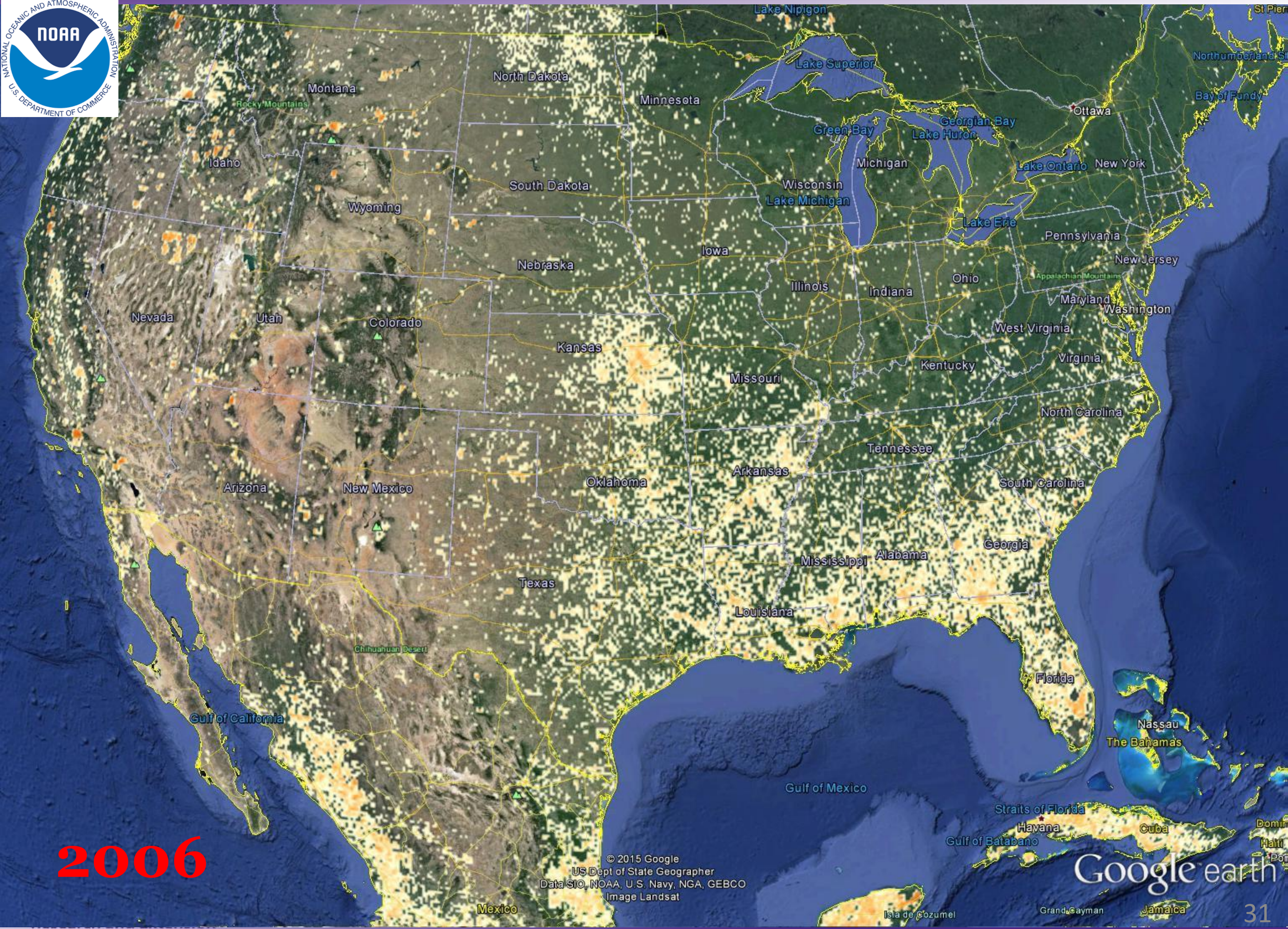

NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE
Lake Nipigon
Lake Superior
Northumberland St
Bay of Fundy
Ottawa
Montana
Rocky Mountains
North Dakota
Minnesota
Green Bay
Georgian Bay
Lake Huron
Michigan
Lake Ontario
New York
Idaho
South Dakota
Wisconsin
Lake Michigan
Wyoming
Lake Erie
Pennsylvania
Iowa
Nebraska
New Jersey
Appalachian Mountains
Illinois
Indiana
Ohio
Maryland
Washington
Nevada
Utah
Colorado
West Virginia
Kansas
Virginia
Kentucky
Missouri
North Carolina
Tennessee
Arkansas
Oklahoma
Arizona
New Mexico
South Carolina
Georgia
Alabama
Mississippi
Texas
Louisiana
Chihuahuan Desert
Florida
Nassau
The Bahamas
Gulf of California
Gulf of Mexico
Straits of Florida
Havana
Cuba
Gulf of Batabano
2003
© 2015 Google
US Dept of State Geographer
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
Google earth
Mexico
Isla de Cozumel
Grand Cayman
Jamaica

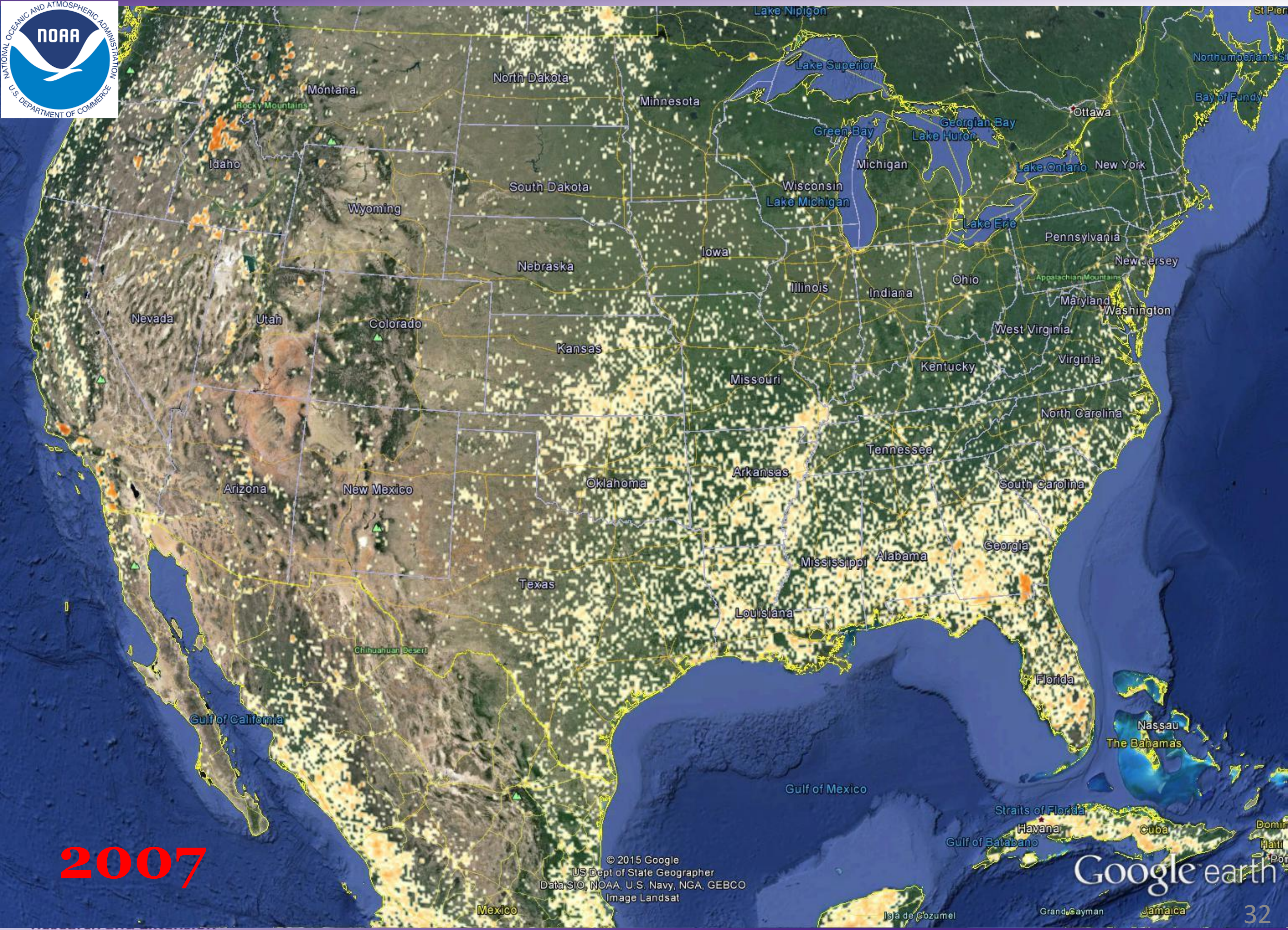

Lake Nipigon
Lake Superior
North Dakota
Montana
Rocky Mountains
Minnesota
Ottawa
Georgian Bay
Green Bay
Lake Huron
Idaho
Michigan
Lake Ontario
New York
South Dakota
Wisconsin
Lake Michigan
Wyoming
Lake Erie
Pennsylvania
Iowa
Nebraska
New Jersey
Illinois
Indiana
Ohio
Appalachian Mountains
Maryland
Washington
Nevada
Utah
Colorado
West Virginia
Kansas
Virginia
Kentucky
Missouri
North Carolina
Tennessee
Arkansas
Arizona
New Mexico
Oklahoma
South Carolina
Georgia
Mississippi
Alabama
Texas
Louisiana
Chihuahuan Desert
Florida
Gulf of California
Nassau
The Bahamas
Gulf of Mexico
Straits of Florida
Havana
Cuba
Gulf of Batabano
Northumberland Str
Bay of Fundy
© 2015 Google
US Dept of State Geographer
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
Google earth
Mexico
Isla de Cozumel
Grand Cayman
Jamaica

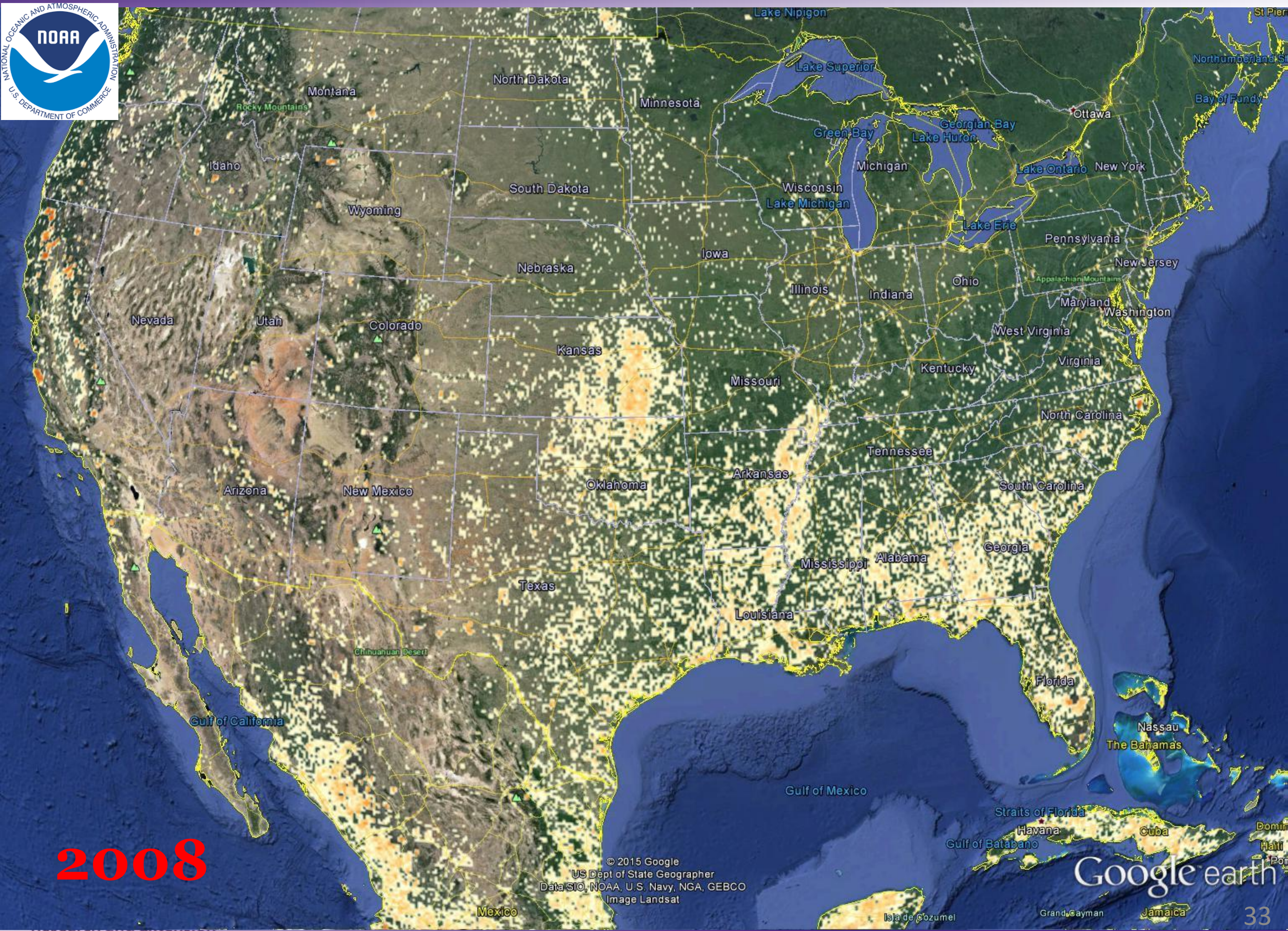
2004

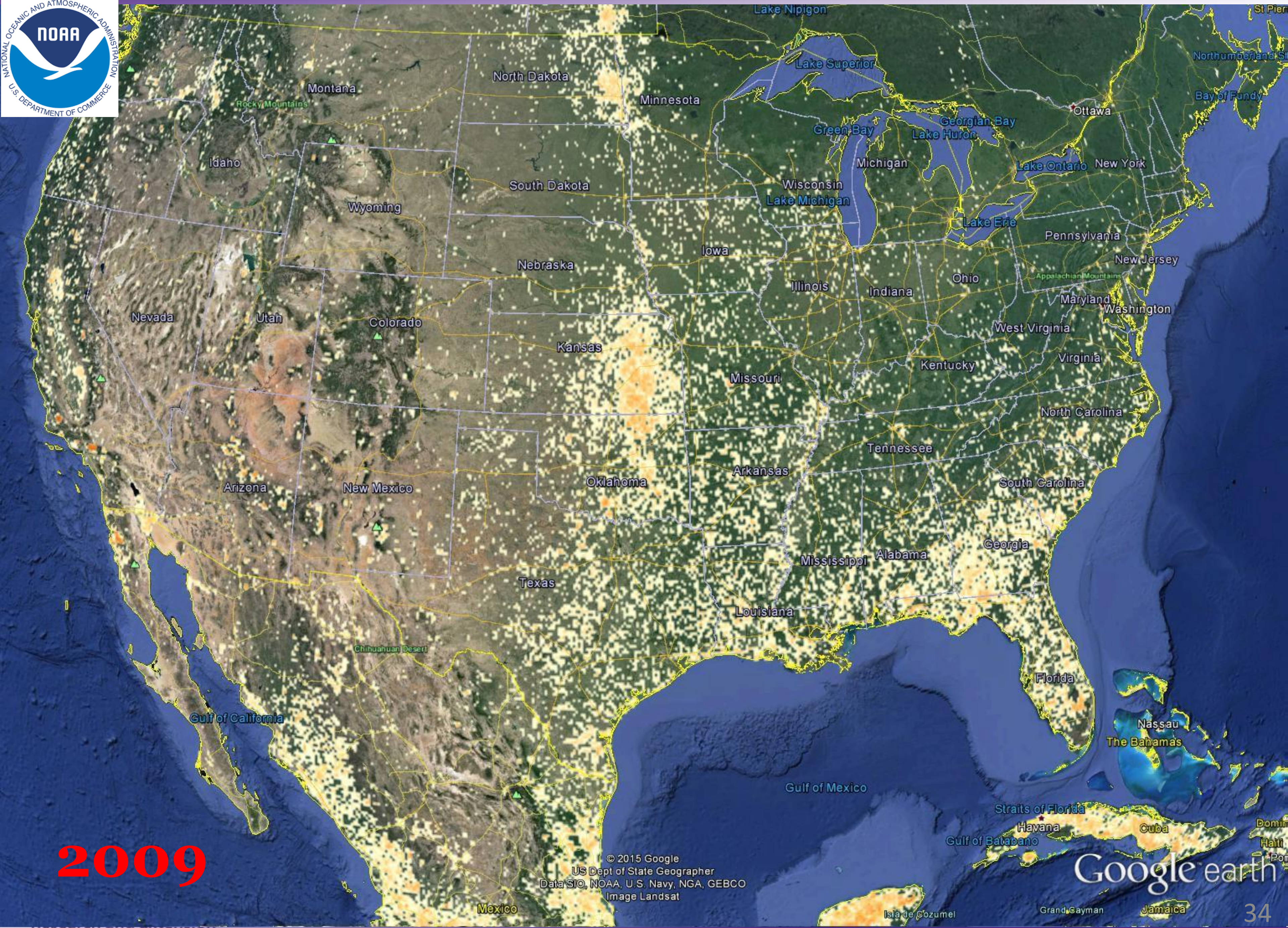


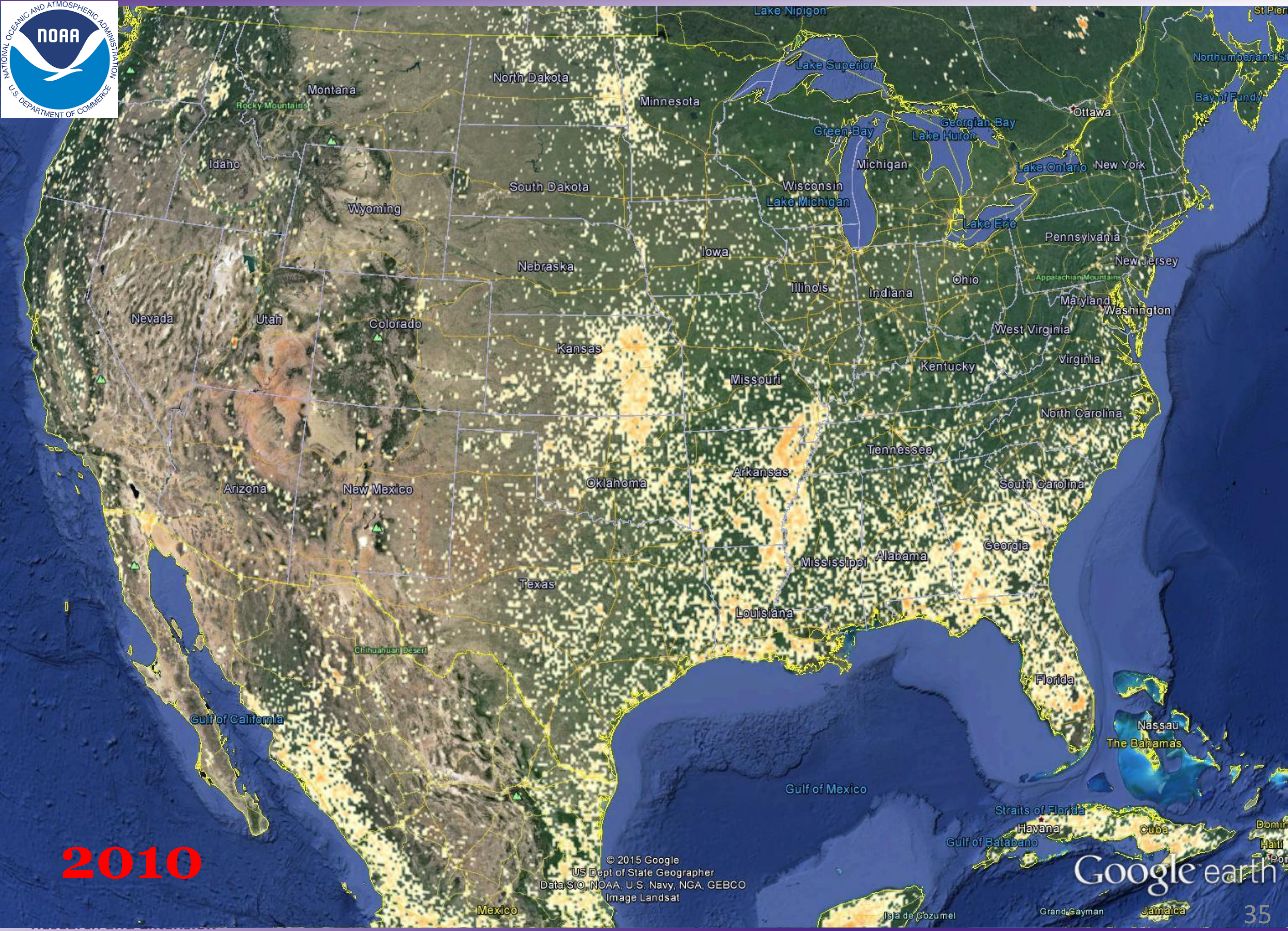
Lake Nipigon
Lake Superior
North Dakota
Montana
Minnesota
Rocky Mountains
Ottawa
Northumberland St
Bay of Fundy
Georgian Bay
Green Bay
Lake Huron
Idaho
Michigan
Lake Ontario
New York
Wisconsin
South Dakota
Lake Michigan
Wyoming
Lake Erie
Pennsylvania
Iowa
Nebraska
New Jersey
Ohio
Appalachian Mountains
Illinois
Indiana
Maryland
Washington
Nevada
Utah
Colorado
West Virginia
Kansas
Virginia
Kentucky
Missouri
North Carolina
Tennessee
Arkansas
Oklahoma
South Carolina
Arizona
New Mexico
Georgia
Alabama
Mississippi
Texas
Louisiana
Chihuahuan Desert
Florida
Gulf of California
Nassau
The Bahamas
Gulf of Mexico
Straits of Florida
Havana
Cuba
Gulf of Batabano
Mexico
Isla de Cozumel
Grand Cayman
Jamaica
Haiti
© 2015 Google
US Dept of State Geographer
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
Google earth
2005

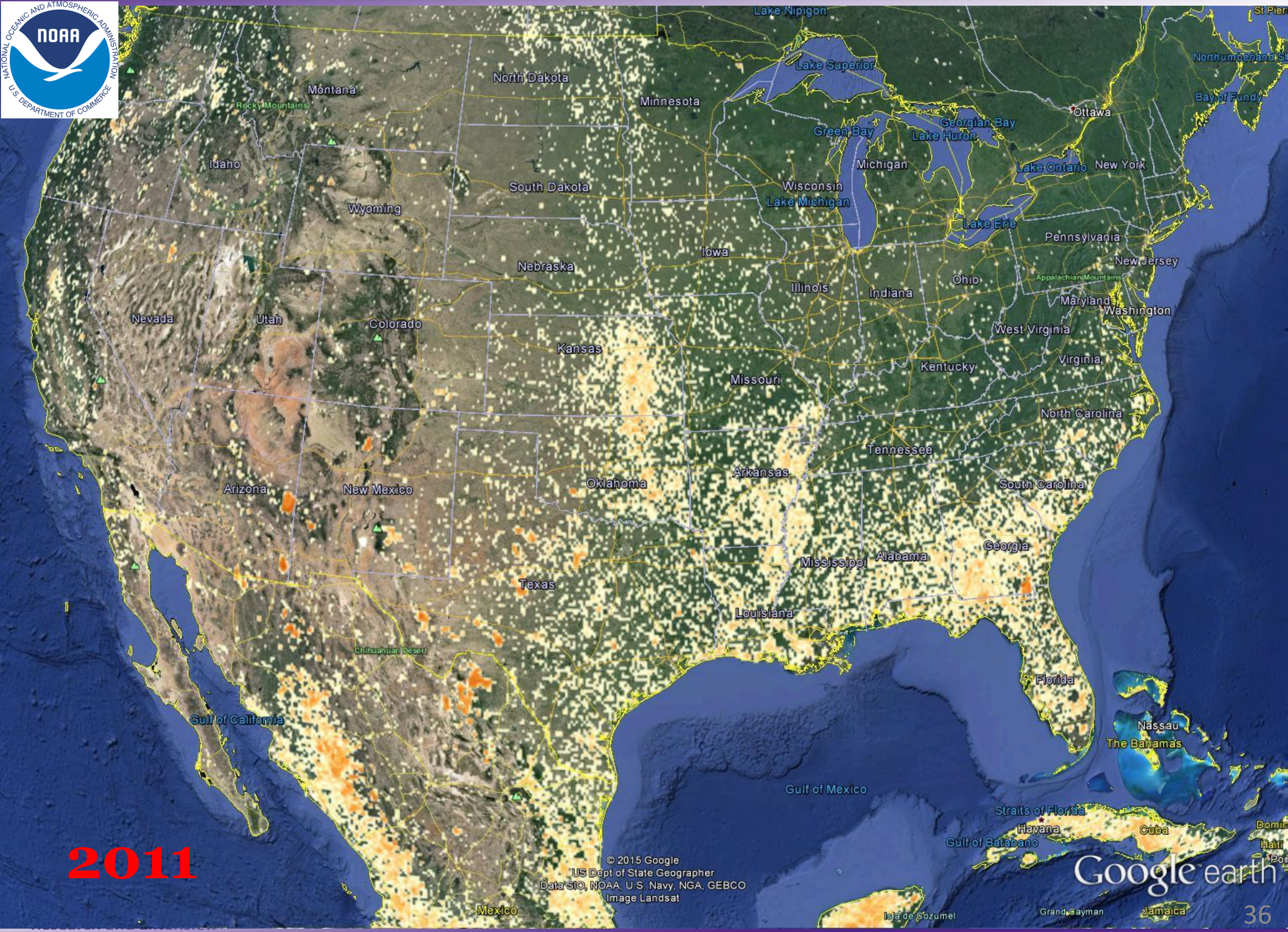

2006
Lake Nipigon
Lake Superior
North Dakota
Montana
Minnesota
Rocky Mountains
Ottawa
Northumberland St
Bay of Fundy
Georgian Bay
Green Bay
Lake Huron
Idaho
Michigan
Lake Ontario
New York
South Dakota
Wisconsin
Lake Michigan
Wyoming
Lake Erie
Pennsylvania
Iowa
Nebraska
New Jersey
Appalachian Mountains
Illinois
Ohio
Indiana
Maryland
Washington
Nevada
Utah
Colorado
West Virginia
Kansas
Virginia
Missouri
Kentucky
North Carolina
Tennessee
Arkansas
Arizona
New Mexico
Oklahoma
South Carolina
Georgia
Alabama
Mississippi
Texas
Louisiana
Chihuahuan Desert
Florida
Nassau
The Bahamas
Gulf of California
Gulf of Mexico
Straits of Florida
Havana
Cuba
Gulf of Batabano
© 2015 Google
US Dept of State Geographer
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
Google earth
Mexico
Isla de Cozumel
Grand Cayman
Jamaica

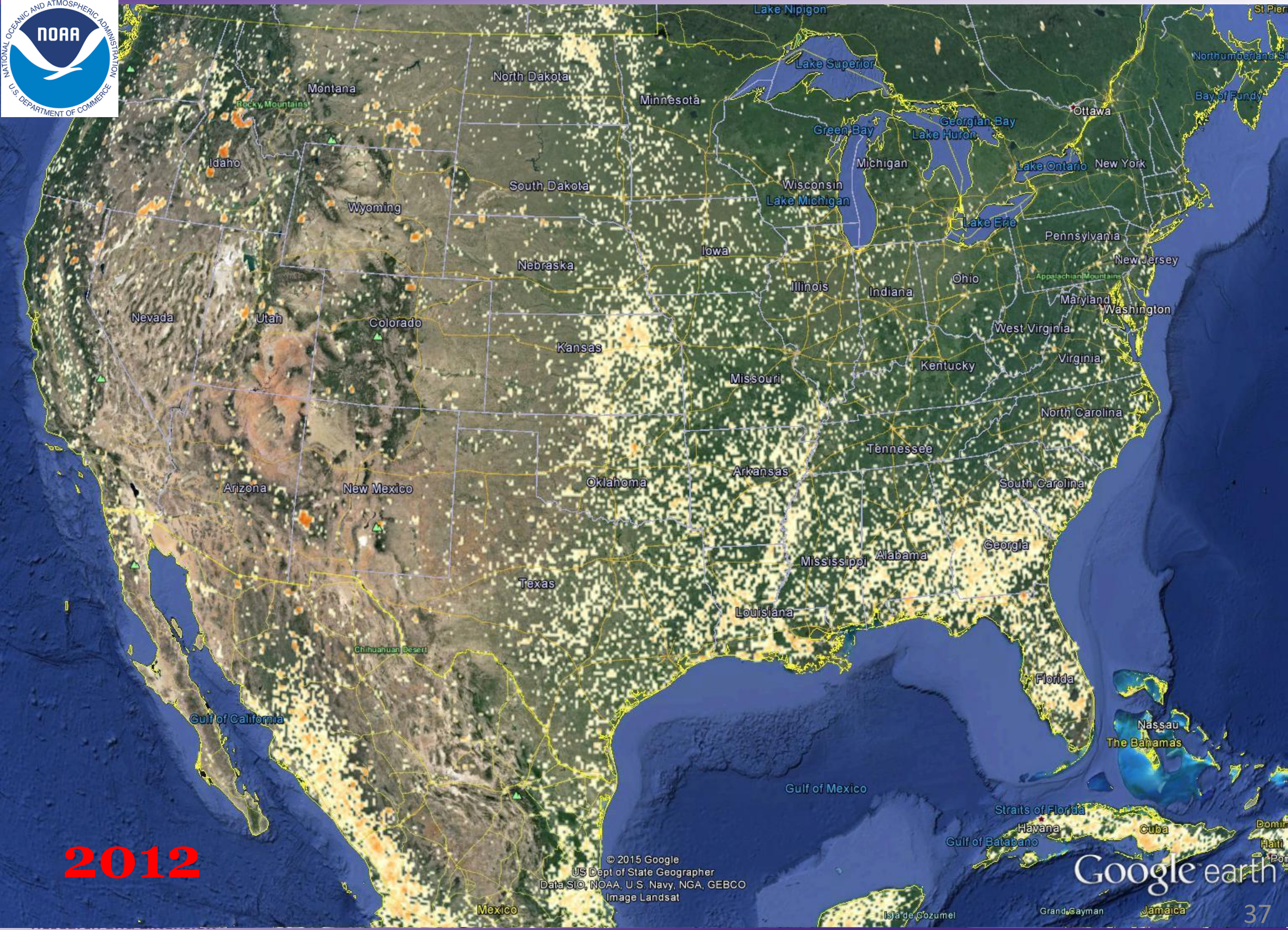

NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE
Lake Nipigon
Lake Superior
North Dakota
Montana
Minnesota
Rocky Mountains
Ottawa
Georgian Bay
Green Bay
Lake Huron
Michigan
Lake Ontario
New York
Idaho
South Dakota
Wisconsin
Lake Michigan
Wyoming
Lake Erie
Pennsylvania
Iowa
Nebraska
New Jersey
Illinois
Indiana
Ohio
Maryland
Washington
Nevada
Utah
Colorado
West Virginia
Kansas
Virginia
Kentucky
Missouri
North Carolina
Tennessee
Arkansas
Arizona
New Mexico
Oklahoma
South Carolina
Georgia
Alabama
Mississippi
Texas
Louisiana
Chihuahuan Desert
Florida
Nassau
The Bahamas
Gulf of California
Gulf of Mexico
Straits of Florida
Havana
Cuba
Gulf of Batabano
Mexico
Bay of Fundy
2007
© 2015 Google
US Dept of State Geographer
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
Google earth
Isla de Cozumel
Grand Cayman
Jamaica

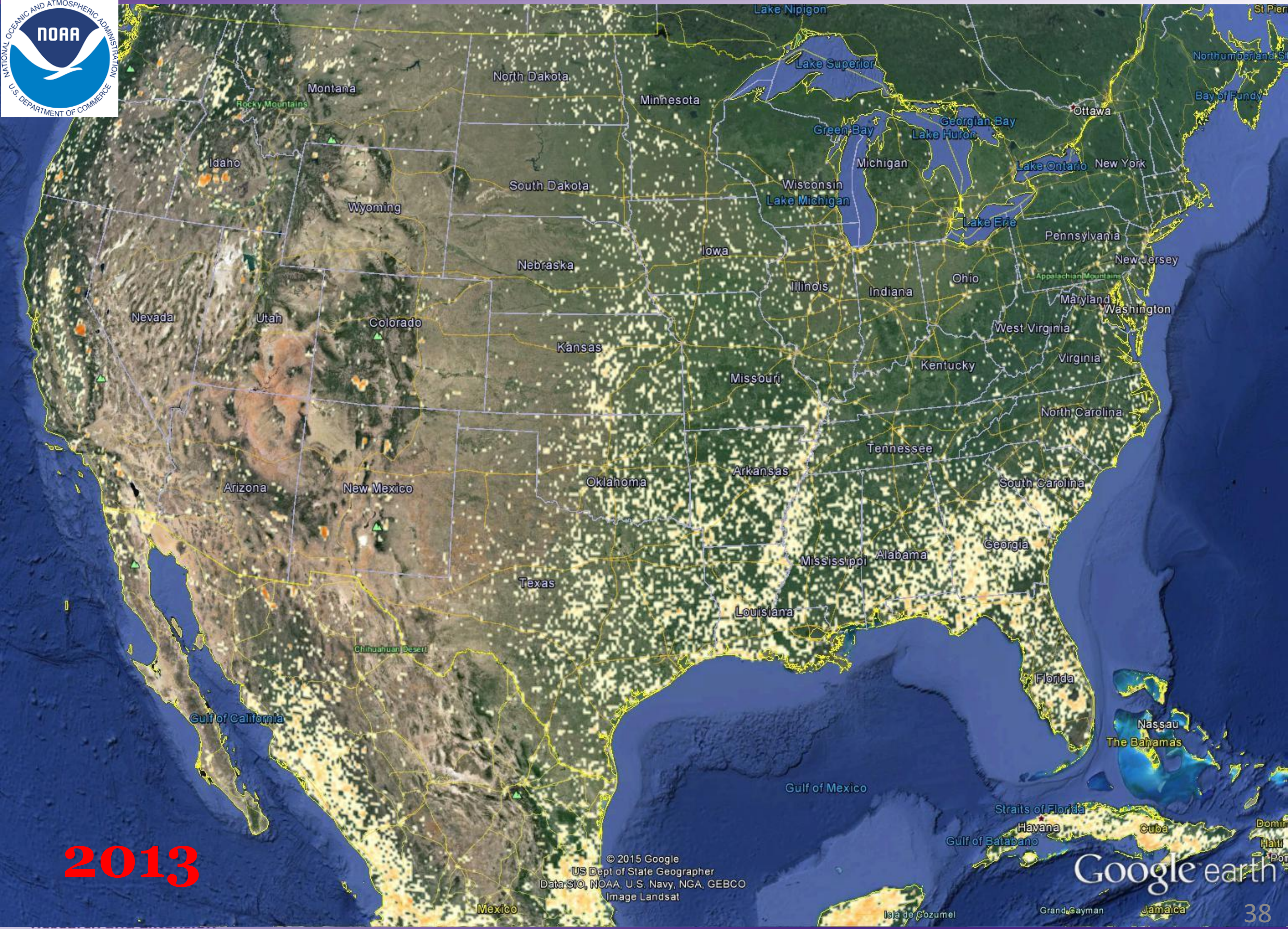

NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE
Lake Nipigon
Lake Superior
Ottawa
Northumberland St
Bay of Fundy
North Dakota
Montana
Rocky Mountains
Minnesota
Green Bay
Georgian Bay
Lake Huron
Idaho
Michigan
Lake Ontario
New York
South Dakota
Wisconsin
Lake Michigan
Wyoming
Lake Erie
Pennsylvania
Iowa
Nebraska
New Jersey
Appalachian Mountains
Illinois
Indiana
Ohio
Maryland
Washington
Nevada
Utah
Colorado
West Virginia
Kansas
Virginia
Kentucky
Missouri
North Carolina
Tennessee
Arkansas
Oklahoma
South Carolina
Arizona
New Mexico
Georgia
Alabama
Mississippi
Texas
Louisiana
Chihuahuan Desert
Florida
Gulf of California
Nassau
The Bahamas
Gulf of Mexico
Straits of Florida
Havana
Cuba
Gulf of Batabano
© 2015 Google
US Dept of State Geographer
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
Mexico
Isla de Cozumel
Grand Cayman
Jamaica
Google earth
2008

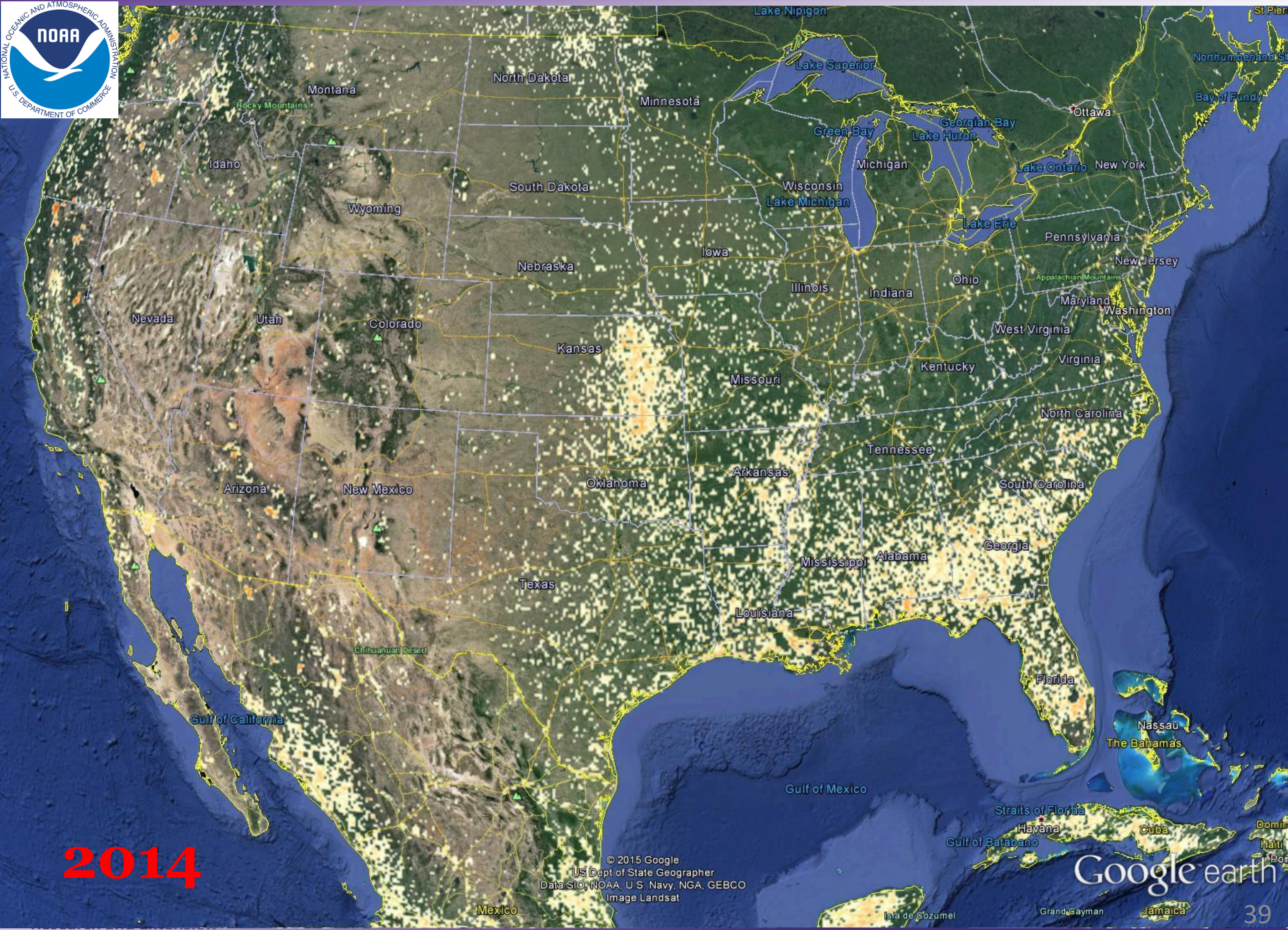

Lake Nipigon
Lake Superior
North Dakota
Montana
Rocky Mountains
Minnesota
Ottawa
Northumberland St
Bay of Fundy
Green Bay
Georgian Bay
Lake Huron
Idaho
Michigan
Lake Ontario
New York
South Dakota
Wisconsin
Lake Michigan
Wyoming
Lake Erie
Pennsylvania
Iowa
New Jersey
Nebraska
Appalachian Mountains
Illinois
Indiana
Ohio
Maryland
Washington
Nevada
Utah
Colorado
West Virginia
Kansas
Virginia
Kentucky
Missouri
North Carolina
Tennessee
Arkansas
Oklahoma
South Carolina
Arizona
New Mexico
Georgia
Alabama
Mississippi
Texas
Louisiana
Chihuahuan Desert
Florida
Nassau
The Bahamas
Gulf of California
Gulf of Mexico
Straits of Florida
Havana
Cuba
Gulf of Batabano
© 2015 Google
US Dept of State Geographer
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
Google earth
Mexico
Isla de Cozumel
Grand Cayman
Jamaica
2009

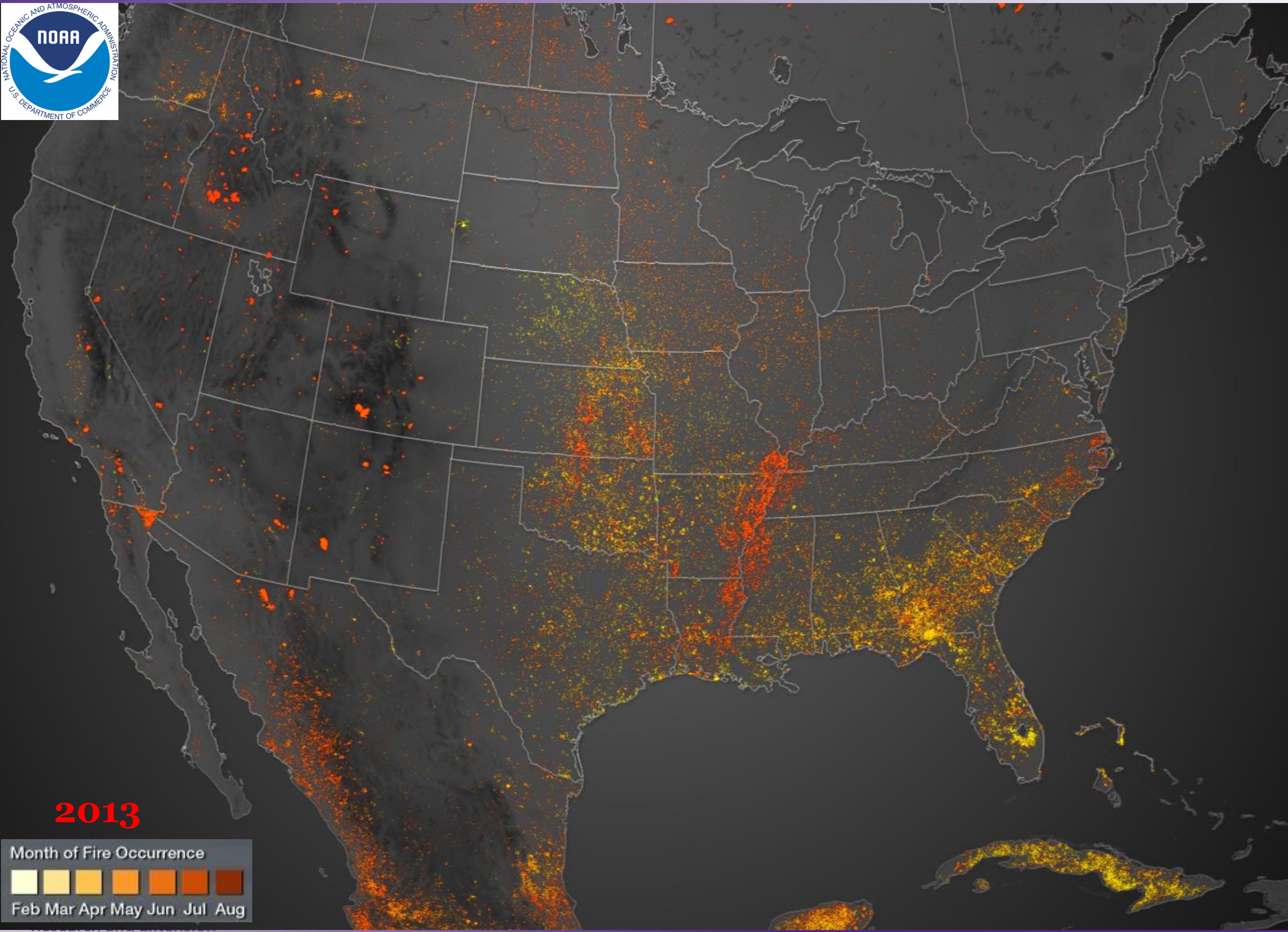

NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE
Lake Nipigon
Lake Superior
Montana
Rocky Mountains
North Dakota
Minnesota
Ottawa
Northumberland St
Bay of Fundy
Georgian Bay
Green Bay
Lake Huron
Michigan
Idaho
Lake Ontario
New York
South Dakota
Wisconsin
Lake Michigan
Wyoming
Lake Erie
Pennsylvania
Iowa
Nebraska
New Jersey
Ohio
Illinois
Indiana
Appalachian Mountains
Maryland
Nevada
Utah
Colorado
Washington
West Virginia
Kansas
Virginia
Missouri
Kentucky
North Carolina
Tennessee
Arkansas
Arizona
New Mexico
Oklahoma
South Carolina
Georgia
Alabama
Mississippi
Texas
Louisiana
Chihuahuan Desert
Florida
Nassau
The Bahamas
Gulf of California
Gulf of Mexico
Straits of Florida
Havana
Cuba
Gulf of Batabano
2010
© 2015 Google
US Dept of State Geographer
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
Google earth
Mexico
Isla de Cozumel
Grand Cayman
Jamaica


2011
North Dakota
Montana
Minnesota
Rocky Mountains
Idaho
South Dakota
Wyoming
Nebraska
Iowa
Nevada
Utah
Colorado
Kansas
Missouri
Illinois
Indiana
Ohio
Wisconsin
Michigan
Lake Superior
Lake Nipigon
Green Bay
Lake Michigan
Lake Huron
Georgian Bay
Lake Ontario
Lake Erie
Ottawa
New York
Pennsylvania
New Jersey
Appalachian Mountains
Maryland
Washington
West Virginia
Virginia
Kentucky
North Carolina
Tennessee
South Carolina
Arkansas
Oklahoma
Arizona
New Mexico
Texas
Mississippi
Alabama
Georgia
Louisiana
Florida
Chihuahuan Desert
Gulf of California
Gulf of Mexico
Mexico
Straits of Florida
Havana
Gulf of Batabano
Cuba
Nassau
The Bahamas
Northumberland St
Bay of Fundy
Isla de Cozumel
Grand Cayman
Jamaica
© 2015 Google
US Dept of State Geographer
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
Google earth

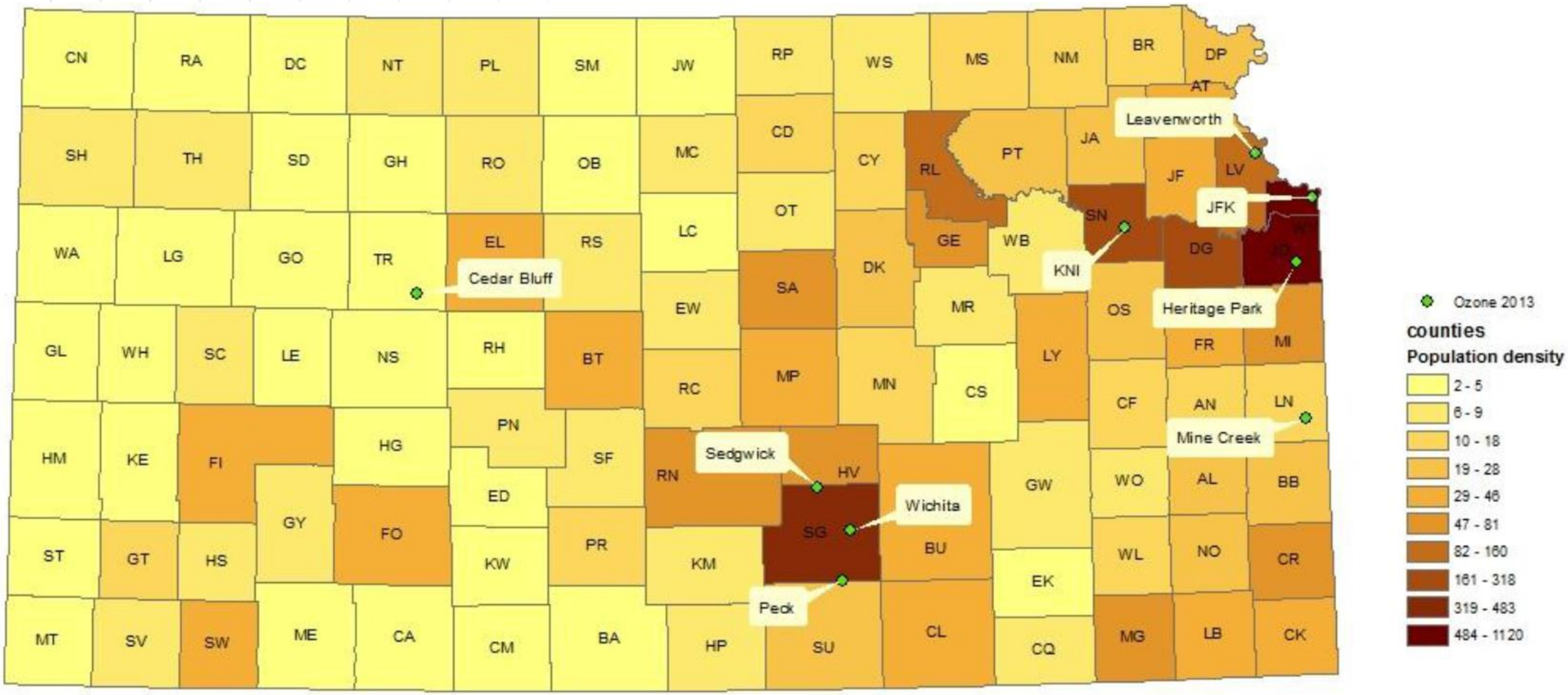

2012
Montana
North Dakota
Minnesota
Lake Nipigon
Lake Superior
Ottawa
Idaho
Rocky Mountains
South Dakota
Wyoming
Wisconsin
Michigan
Green Bay
Georgian Bay
Lake Huron
Lake Ontario
New York
Lake Michigan
Lake Erie
Pennsylvania
New Jersey
Iowa
Nebraska
Illinois
Indiana
Ohio
Appalachian Mountains
Maryland
Washington
Nevada
Utah
Colorado
Kansas
West Virginia
Virginia
Kentucky
Missouri
North Carolina
Tennessee
Arkansas
Oklahoma
Arizona
New Mexico
South Carolina
Georgia
Alabama
Mississippi
Texas
Louisiana
Chihuahuan Desert
Florida
Gulf of California
Nassau
The Bahamas
Gulf of Mexico
Straits of Florida
Havana
Cuba
Gulf of Batabano
Mexico
Isla de Cozumel
Grand Cayman
Jamaica
Northumberland St
Bay of Fundy
© 2015 Google
US Dept of State Geographer
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
Google earth


Lake Nipigon
Lake Superior
North Dakota
Montana
Rocky Mountains
Minnesota
Ottawa
Northumberland Strait
Bay of Fundy
Georgian Bay
Green Bay
Lake Huron
Michigan
Lake Ontario
New York
Idaho
South Dakota
Wisconsin
Lake Michigan
Wyoming
Lake Erie
Pennsylvania
Iowa
Nebraska
New Jersey
Appalachian Mountains
Illinois
Indiana
Ohio
Maryland
Washington
Nevada
Utah
Colorado
West Virginia
Kansas
Virginia
Kentucky
Missouri
North Carolina
Tennessee
Arkansas
Arizona
New Mexico
Oklahoma
South Carolina
Georgia
Alabama
Mississippi
Texas
Louisiana
Chihuahuan Desert
Florida
Gulf of California
Nassau
The Bahamas
Gulf of Mexico
Straits of Florida
Havana
Gulf of Batabano
Cuba
2013
© 2015 Google
US Dept of State Geographer
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
Google earth
Mexico
Isla de Cozumel
Grand Cayman
Jamaica

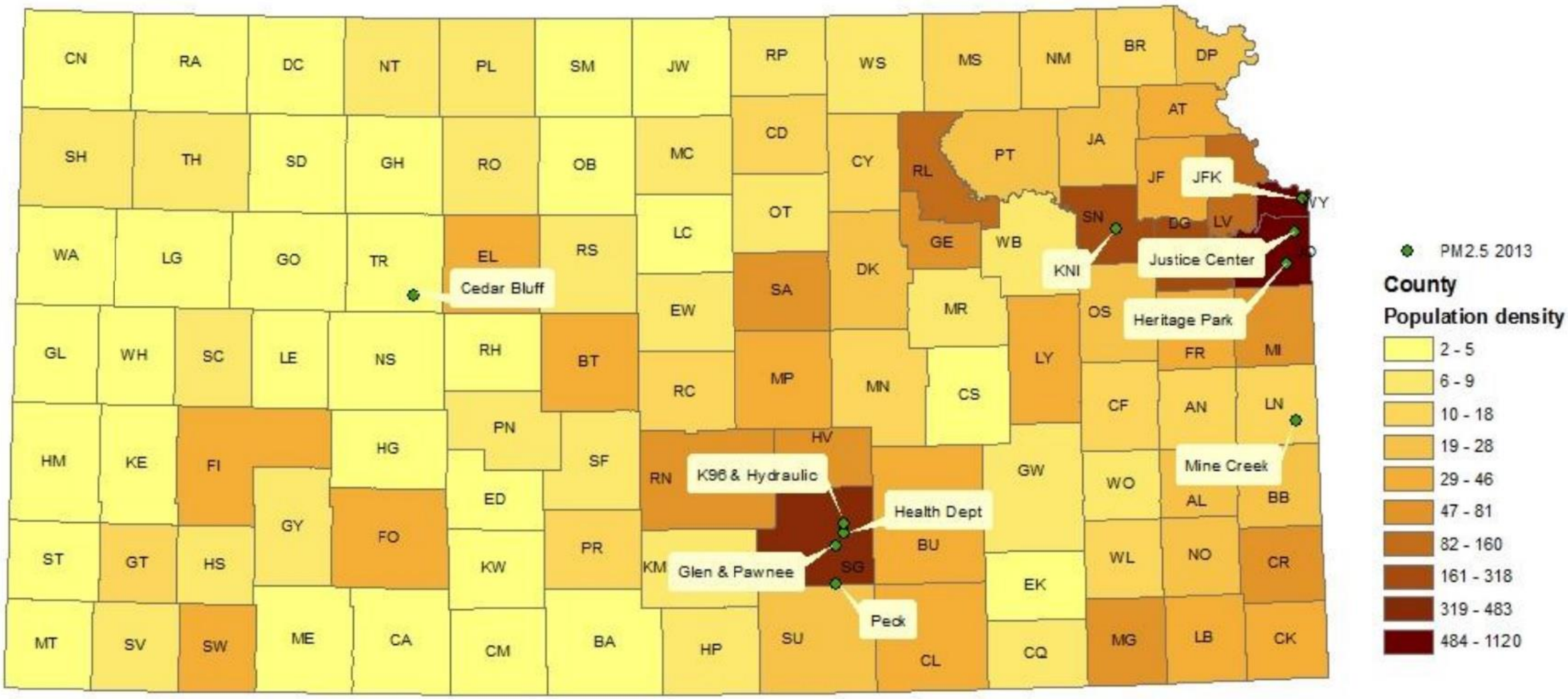

2014
Lake Nipigon
Lake Superior
North Dakota
Montana
Rocky Mountains
Minnesota
Ottawa
Northumberland Strait
Bay of Fundy
Georgian Bay
Green Bay
Lake Huron
Michigan
Idaho
South Dakota
Wisconsin
Lake Michigan
Lake Ontario
New York
Wyoming
Lake Erie
Pennsylvania
Iowa
Nebraska
New Jersey
Ohio
Appalachian Mountains
Illinois
Indiana
Maryland
Washington
Nevada
Utah
Colorado
West Virginia
Kansas
Virginia
Kentucky
Missouri
North Carolina
Tennessee
Arkansas
Arizona
Oklahoma
New Mexico
South Carolina
Georgia
Alabama
Mississippi
Texas
Louisiana
Chihuahuan Desert
Florida
Gulf of California
Nassau
The Bahamas
Gulf of Mexico
Straits of Florida
Havana
Gulf of Batabano
Cuba
Mexico
Isla de Cozumel
Grand Cayman
Jamaica
Haiti
© 2015 Google
US Dept of State Geographer
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
Google earth


2013
Month of Fire Occurrence
Feb Mar Apr May Jun Jul Aug

# Population density map and location of the 9 $O_3$ monitoring sites run by KDHE



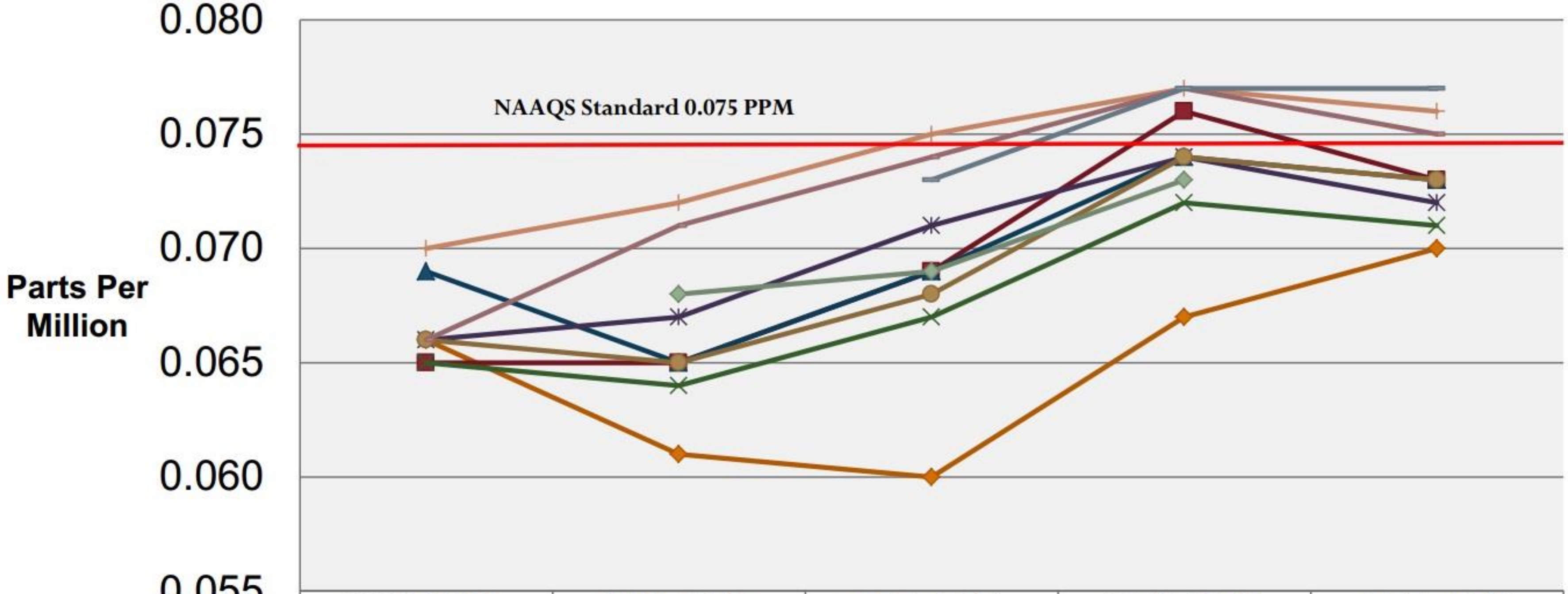
# Population density map and location of the 10 $PM_{2.5}$ monitoring sites run by KDHE



- The Clean Air Status and Trends Network (CASTNET) is a national network designed to provide long-term monitoring of air quality in rural areas.
- Data is available at http://epa.gov/castnet/

# The two CASNET sites run by EPA

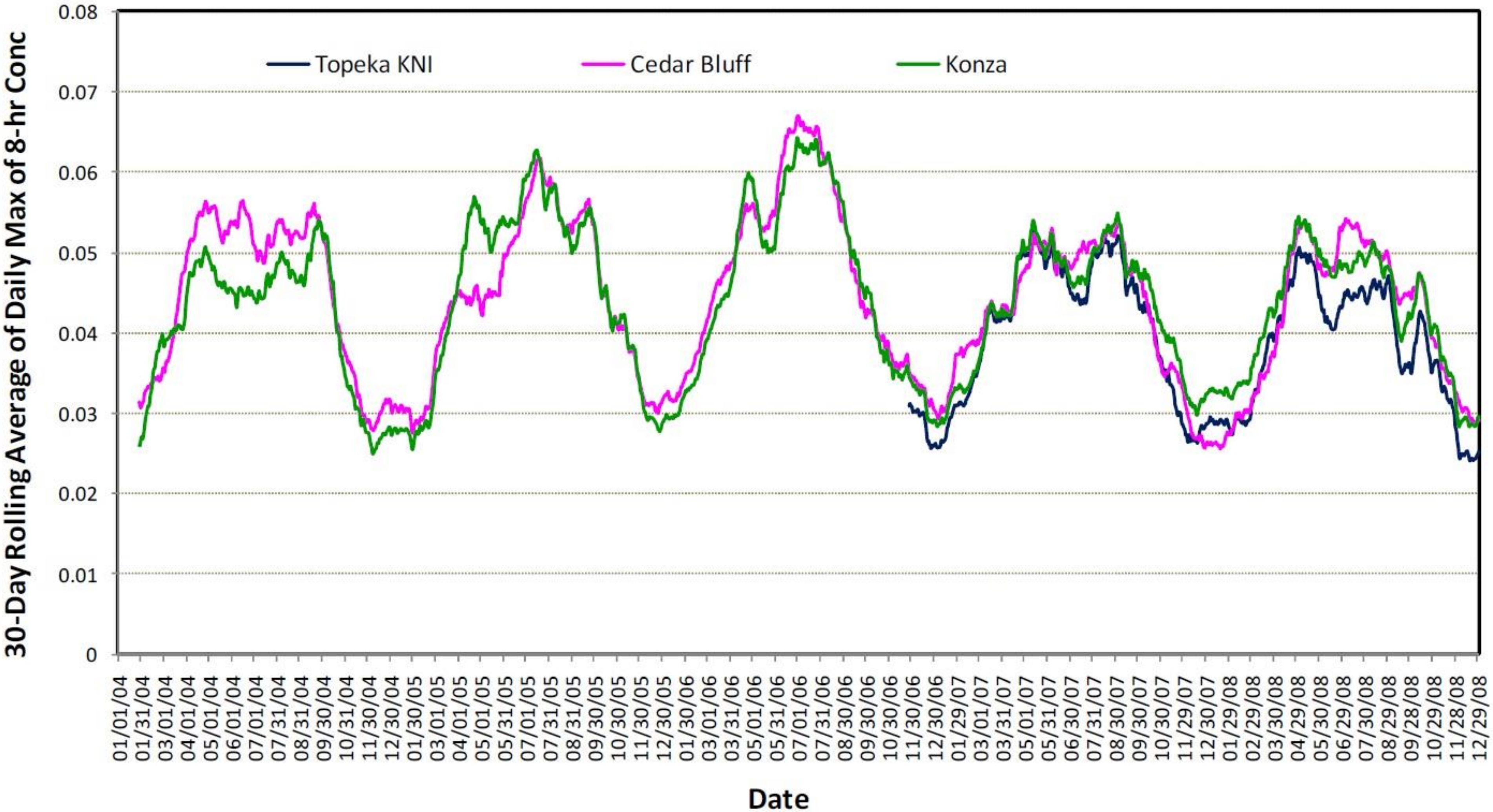

# Kansas 8 Hour Ozone Design Values




| | 2007-2009 | 2008-2010 | 2009-2011 | 2010-2012 | 2011-2013 |
|---|---|---|---|---|---|
| JFK | 0.066 | 0.061 | 0.060 | 0.067 | 0.070 |
| Heritage Park | 0.065 | 0.065 | 0.069 | 0.076 | 0.073 |
| Leavenworth | 0.069 | 0.065 | 0.069 | 0.074 | 0.073 |
| Mine Creek | 0.065 | 0.064 | 0.067 | 0.072 | 0.071 |
| Cedar Bluff | 0.066 | 0.067 | 0.071 | 0.074 | 0.072 |
| KNI/Topeka | 0.066 | 0.065 | 0.068 | 0.074 | 0.073 |
| Peck | 0.070 | 0.072 | 0.075 | 0.077 | 0.076 |
| Wichita HD | 0.066 | 0.071 | 0.074 | 0.077 | 0.075 |
| Sedgwick | | | 0.073 | 0.077 | 0.077 |
| Konza Casnet | | 0.068 | 0.069 | 0.073 | |

(Reference: Thomas Gross, KDHE)

# 30-day Rolling Average of Daily Maximum 8-hour O3 Concentration at three sites




(Reference: Kansas 5-year monitoring network assessment, KDHE)