Measuring Economies from Space

Adam Storeygard, Tufts University

Chinese Economists Society North America Virtual Conference

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Overview

- Remote sensing data in economics
- Night lights and economic activity

- More details can be found in:
  - Donaldson, Dave, and Adam Storeygard. 2016. "The View from Above: Applications of Satellite Data in Economics." *Journal of Economic Perspectives*, 30 (4): 171-98.
  - Storeygard, Adam. 2020 forthcoming, Measuring Economies from Space, in *Alternative Economic Indicators*, forthcoming e-book, C. James Hueng ed. Kalamazoo, Michigan: W.E. Upjohn Institute for Employment Research.
  - Henderson, J. Vernon, Adam Storeygard, and David N. Weil. 2012. "Measuring Economic Growth from Outer Space." *American Economic Review*, 102 (2): 994-1028.

Remote sensing data

- Data about the earth, collected from above
- Some Electromagnetic signals are correlated with things we care about
- Dates back to late 19th century
  - International Society for Photogrammetry (and Remote Sensing) founded Vienna, 1910
- Various methods: balloons, planes…

Boston, 1860
James Wallace Black, Metropolitan Museum of Art

…pigeons!

- The Bavarian pigeon corps, 1903

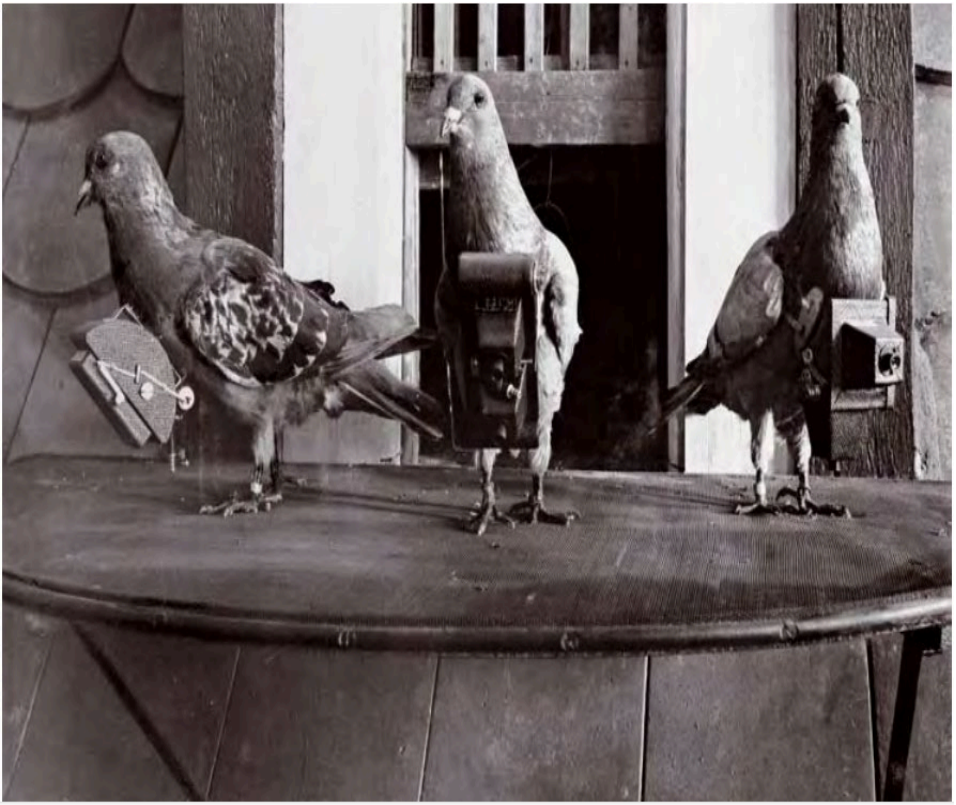


Image source: http://www.cameramuseum.ch/fr/N31124/des-pigeons-photographes.html

Aerial photography in economic policy

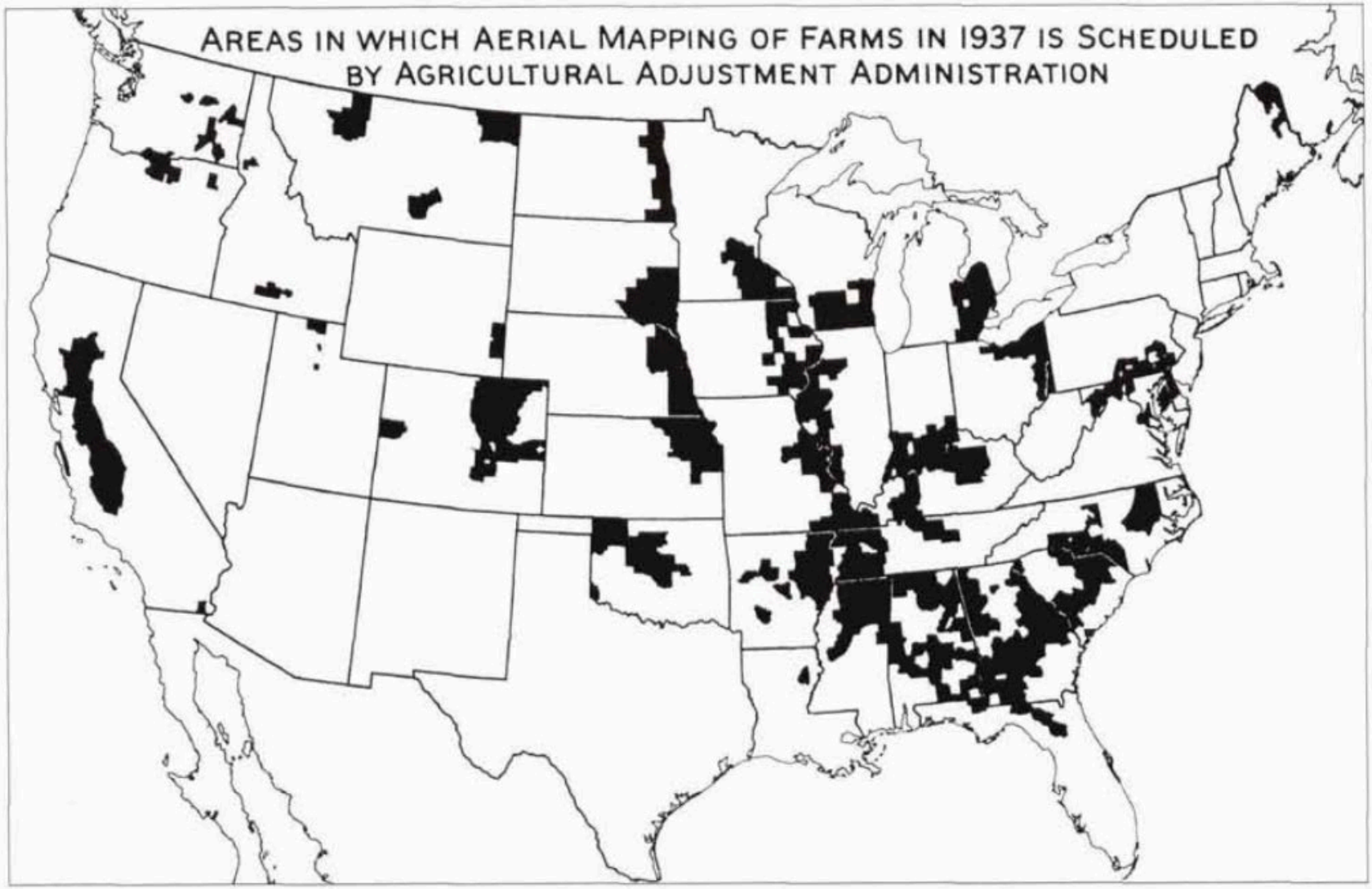


Figure 1. Areas selected for aerial compliance mapping by the Agricultural Adjustment Administration during 1937. Source: Tubis (1937, p. 22).

Source: Monmonier (2002)

Aerial photography in economic policy

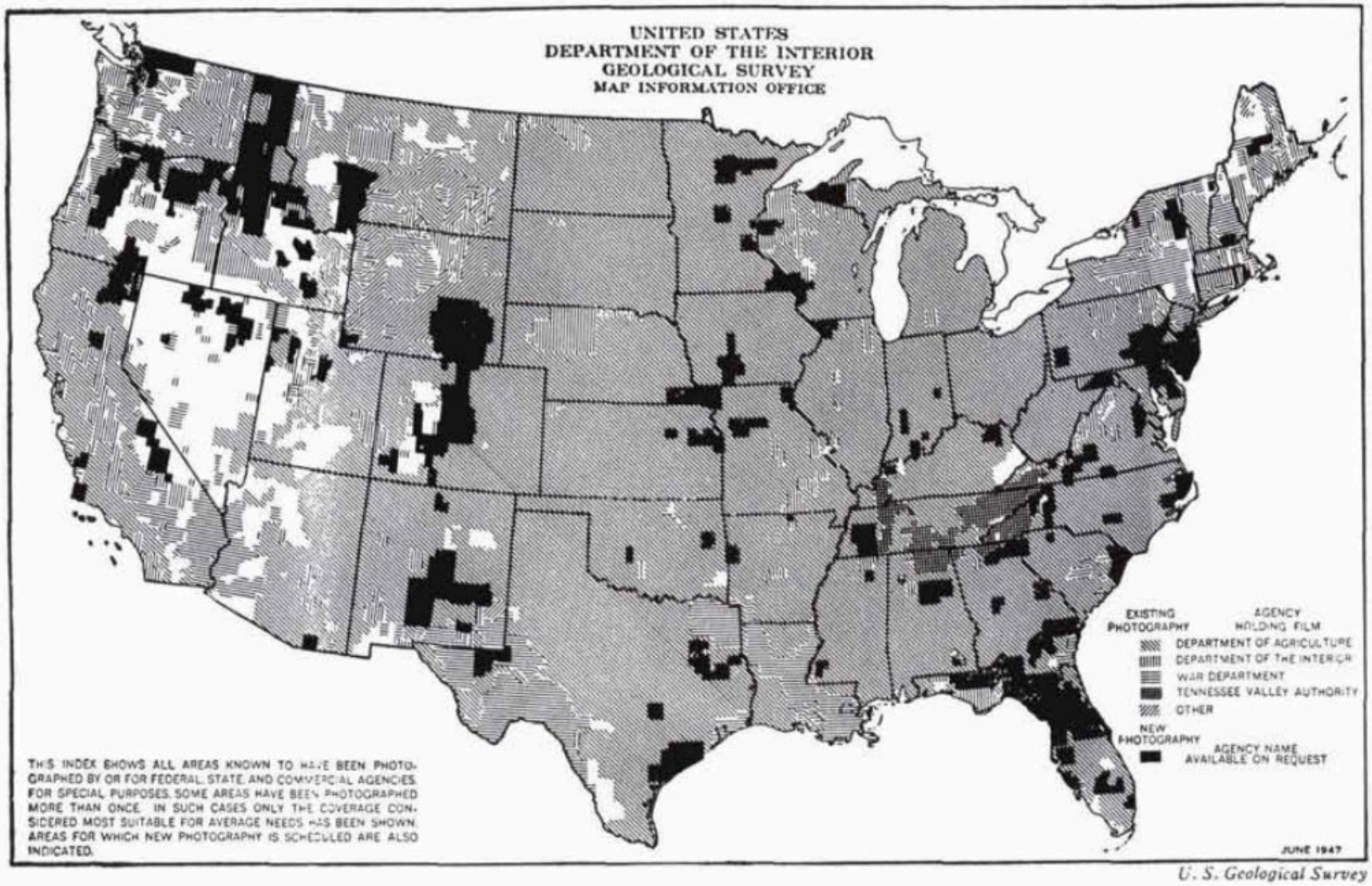
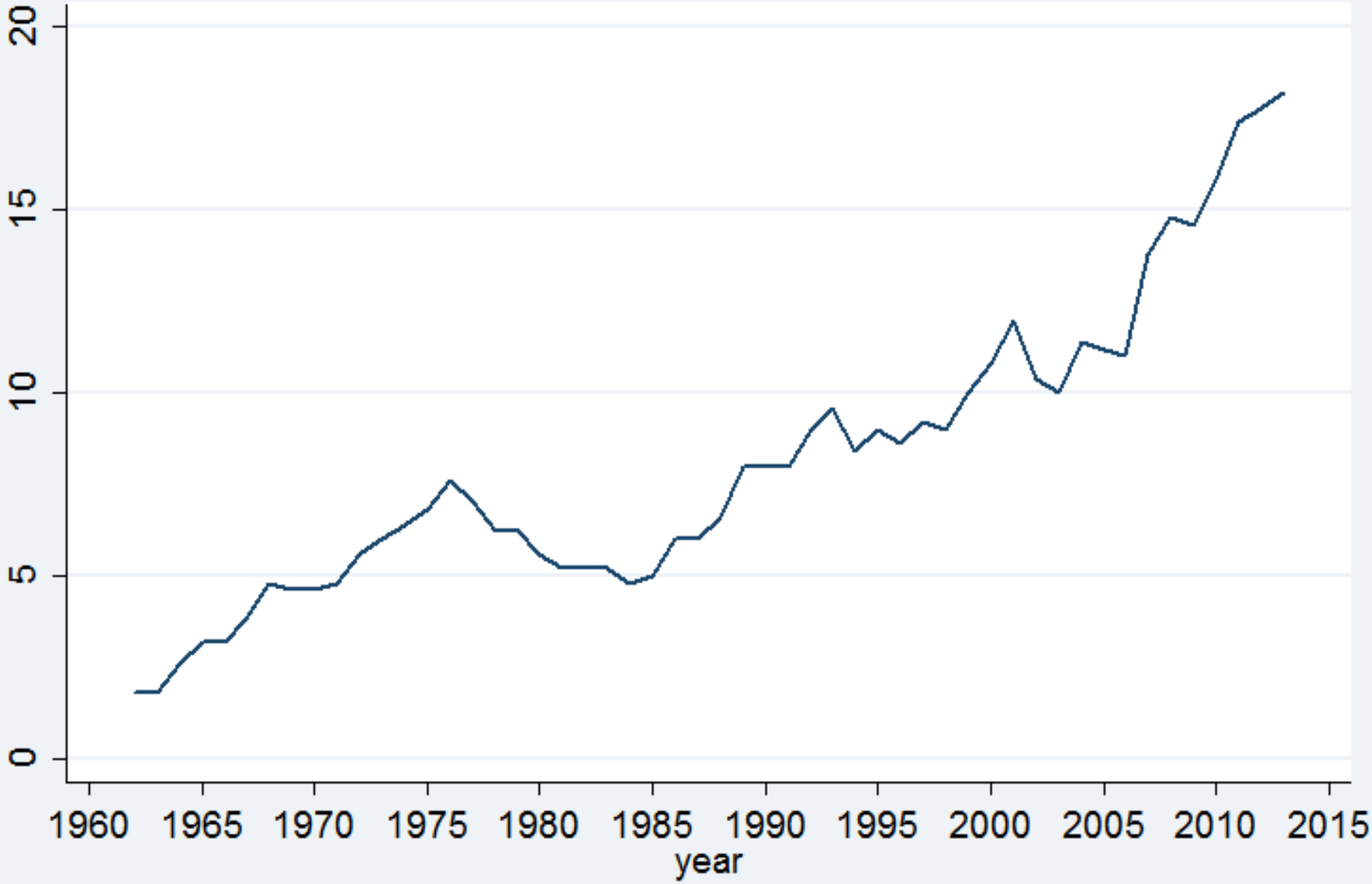


Figure 2. Status map of aerial photography in the United States, June 1947. U.S. Geological Survey map reproduced in Spurr (1948, p. 66).

Source: Monmonier (2002)


Союз

Global remote sensing satellites launched per year



Data Source: WMO OSCAR database. 5-year moving average. Excludes nanosats cubesats and smaller.

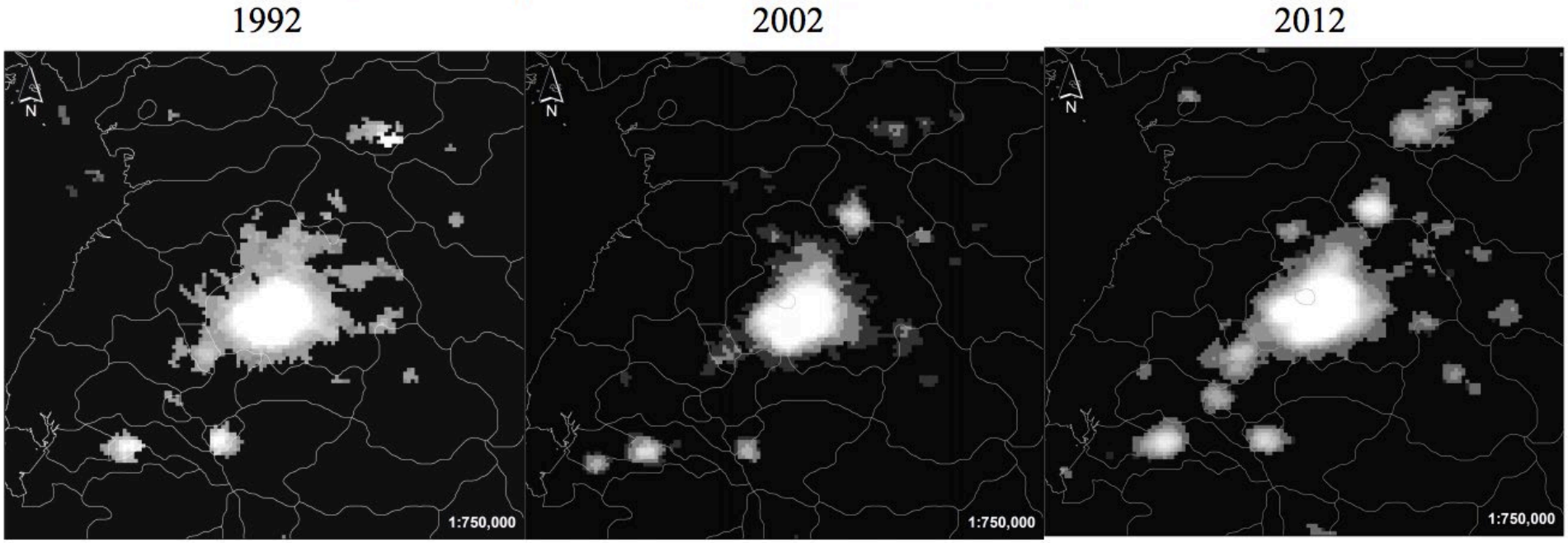
Facilitating trends

- Cheaper satellites
  - Off-the-shelf components
    - Smartphone + radio transmitter + accelerometer and a magnetometer + extra batteries ≈ $3500 satellite: PhoneSat 1.0
- Cheaper launches
  - Lighter components
  - Many lightweight satellites in one launch
    - Microsatellites: 10 - 100 kg
    - Nanosatellites: 1 - 10 kg
    - Picosatellites: 0.1 - 1 kg
    - Femtosatellites (“sprites”) as small as 5 grams: microchips
  - Competition in launch market: SpaceX, etc.
  - New launch technologies
    - e.g. reusable rockets

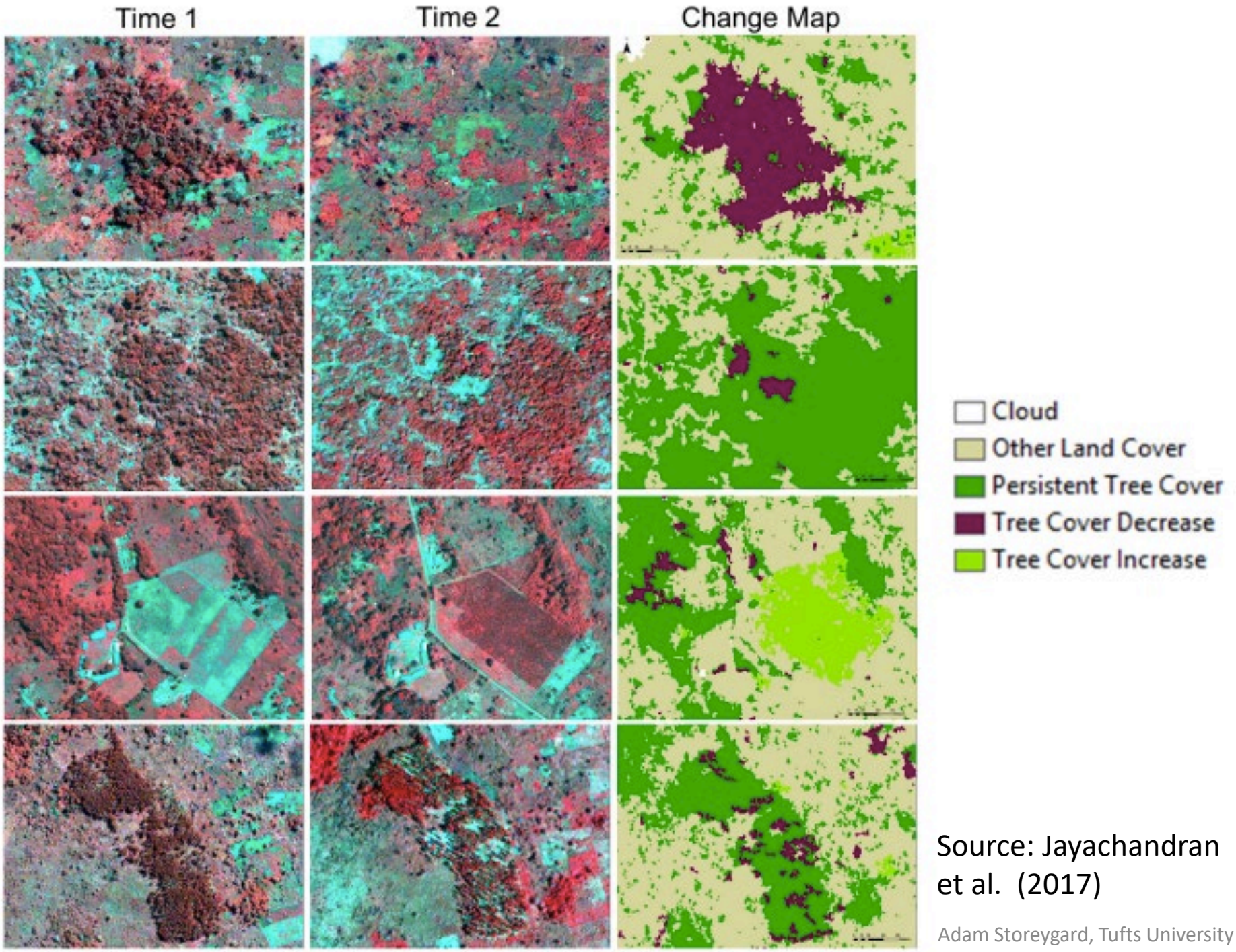
Advantage 1: satellite data exist where other data do not

North Korea responds to sanctions by shifting activity toward Pyongyang, Chinese trade hubs (Lee 2018)

Figure 6. Lights near Pyongyang in 1992, 2002, and 2012.



Advantage 2: High spatial resolution



Source: Jayachandran et al. (2017)

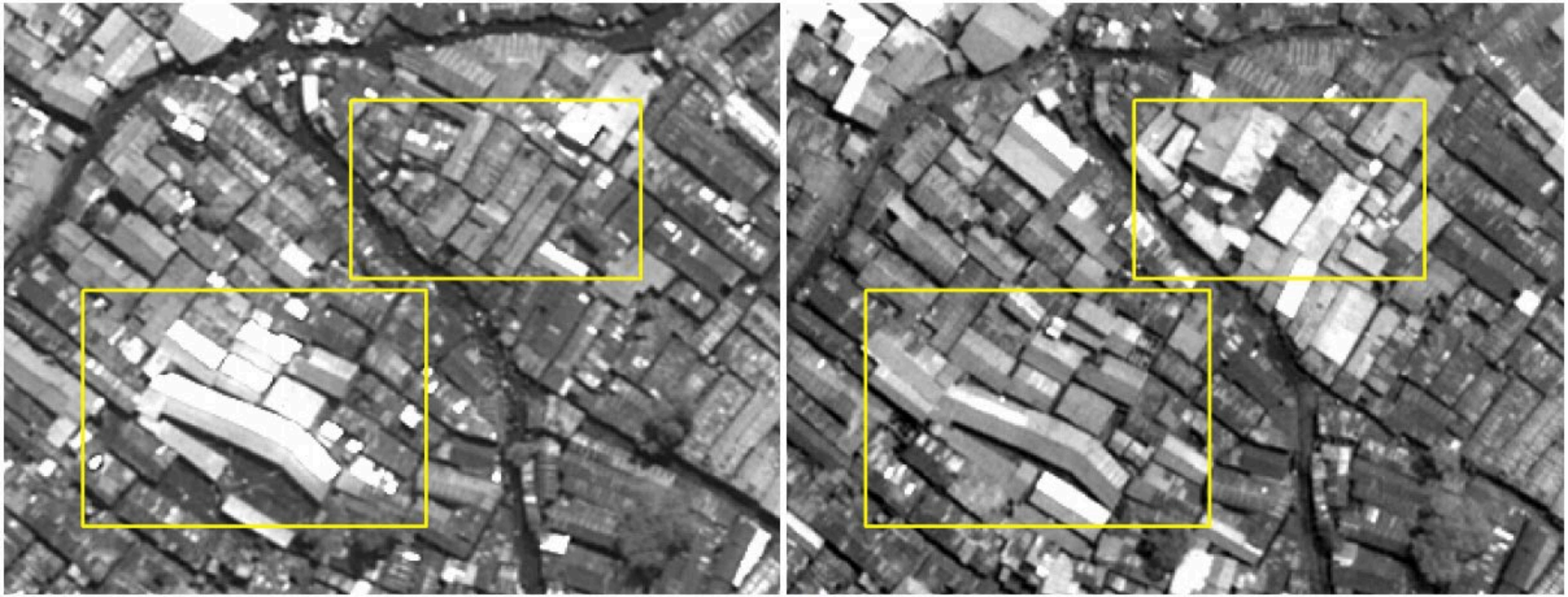
Policy lesson

- Paying people in Uganda to preserve their trees had a substantial impact
  - did not displace deforestation to neighbors
- This is cost-effective carbon emission reduction *even if trees would be cut down immediately after the program ends*

Advantage 3: cheap/easy repeat measurements

Urban land cover: roofs

Appendix Figure A2: Old and New Roofs in Kibera



Note: Both pictures are taken over the same area of the slum with the same resolution (0.5 meters panchromatic).
The picture in the left panel was taken in July 2009 and that in the right panel in August 2012.
The yellow rectangles highlight clusters of roofs that markedly evolved over the period.
Roofs highlighted in the bottom rectangle degraded while roofs within the top rectangle were upgraded in the same timeframe.
The picture area is approximately 175 meters long and 140 meters wide.

Source: Marx et al. (2019)

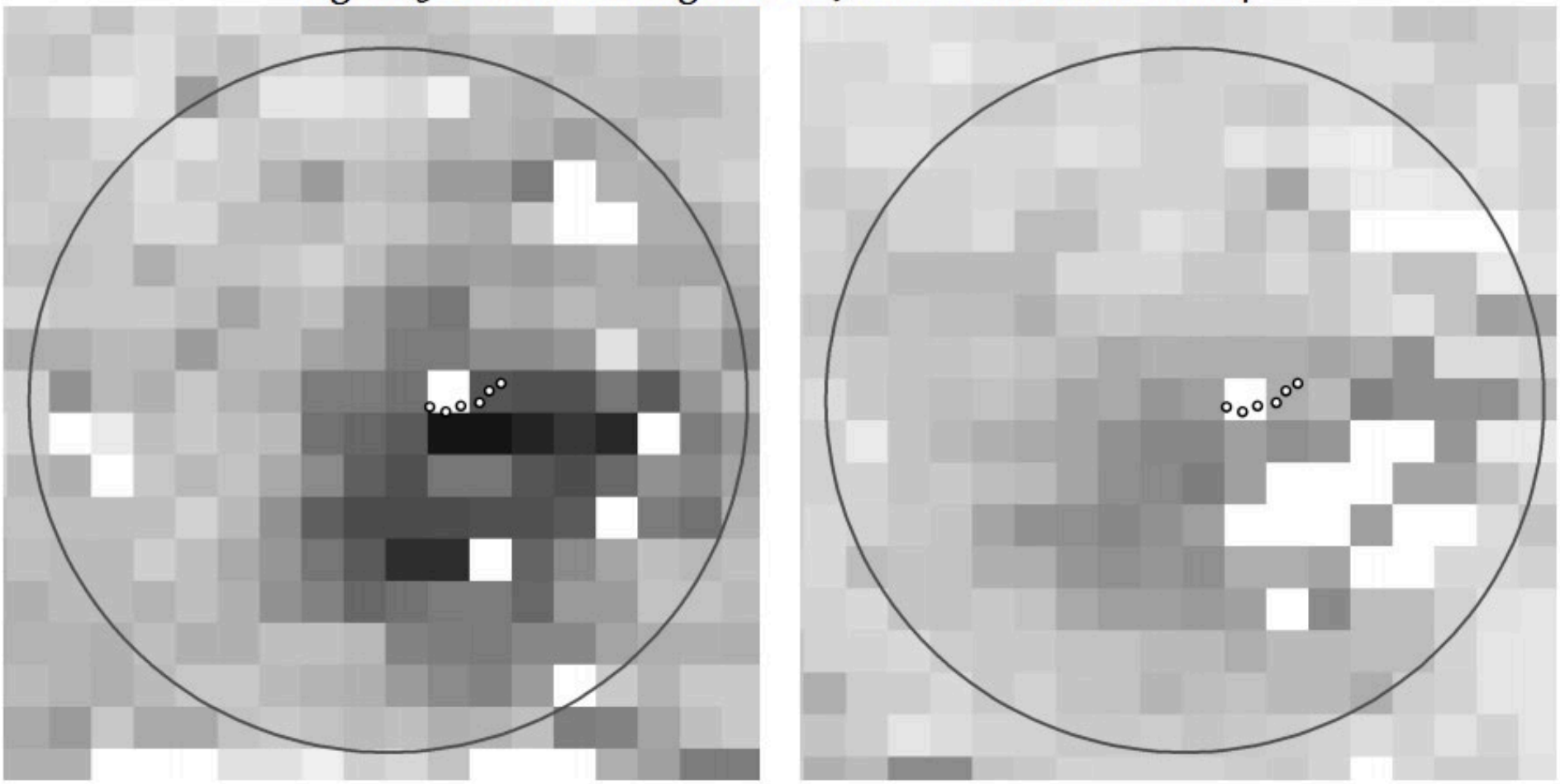
Policy lesson

- Renters pay less and get more when local political boss is co-ethnic
- They pay more and get less when the landlord is co-ethnic with the political boss

Advantage 4: Near-global coverage

Measuring pollution effects of 42 subway openings worldwide 2000-2014

Figure 3: AOD for Bangalore in June and December 2014



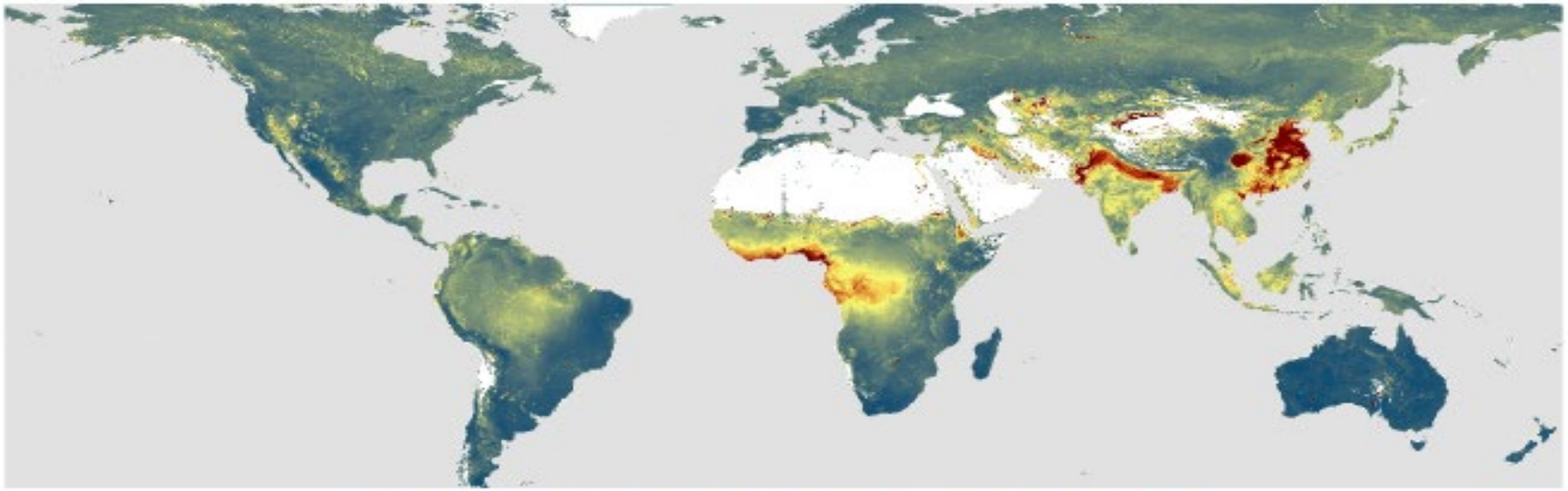
(a) Bangalore, June 2014

(b) Bangalore, December 2014

Source: Gendron-Carrier et al. (2018)

Figure 2: Two maps showing AOD. Red indicates higher levels of AOD

Aerosol Optical Depth, June 1st, 2014 Terra



Aerosol Optical Depth, Average 2000-2014, Terra

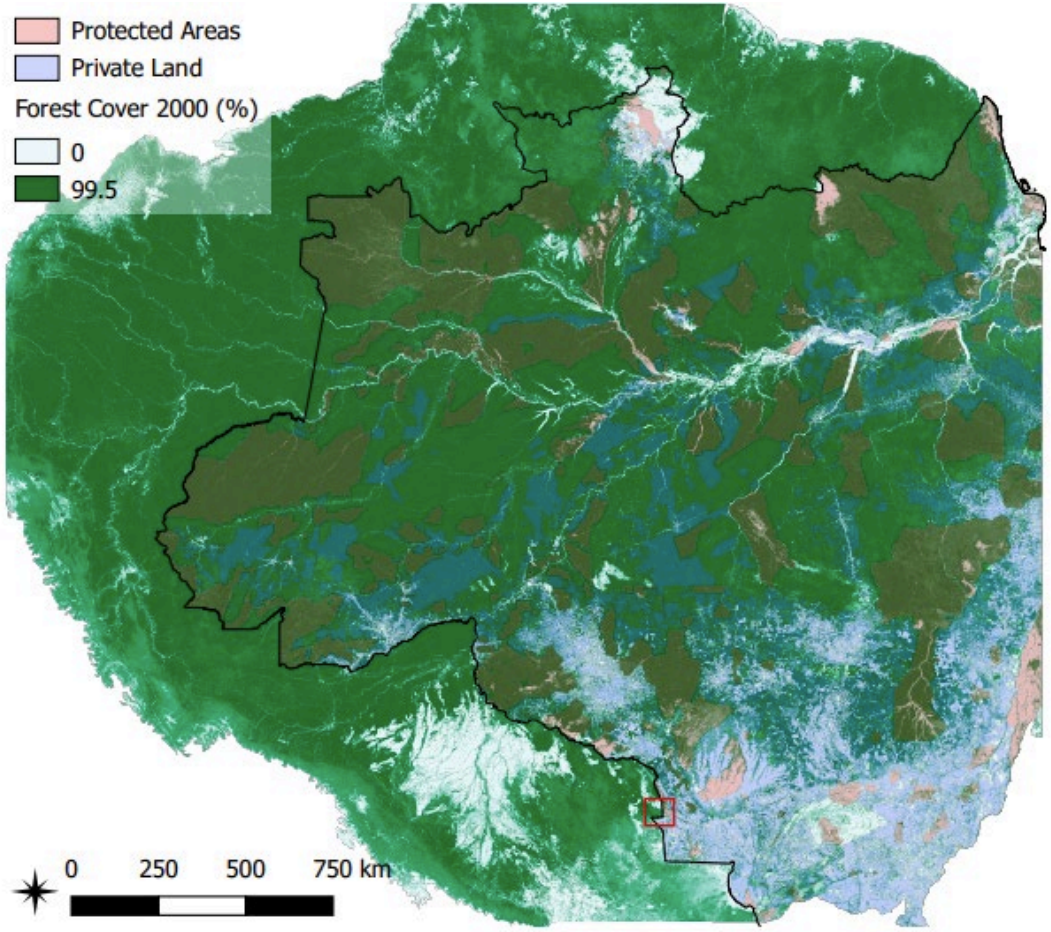
Source: Gendron-Carrier et al. (2018)

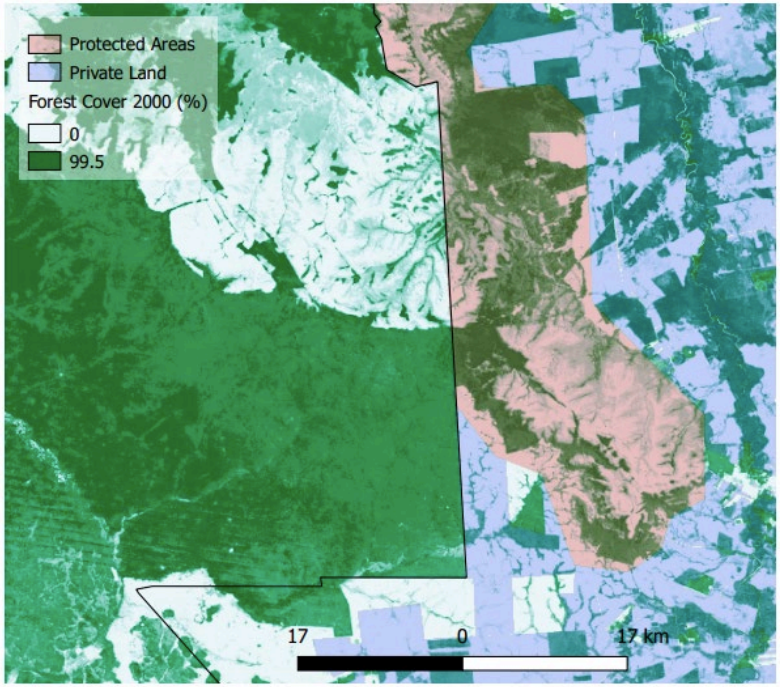
Policy lesson

- Subways reduce particulate emissions immediately after opening
- Effects appear to last (at least) 8 years

Advantage 5: Consistent coverage across borders

Deforestation in Brazil vs. neighbors

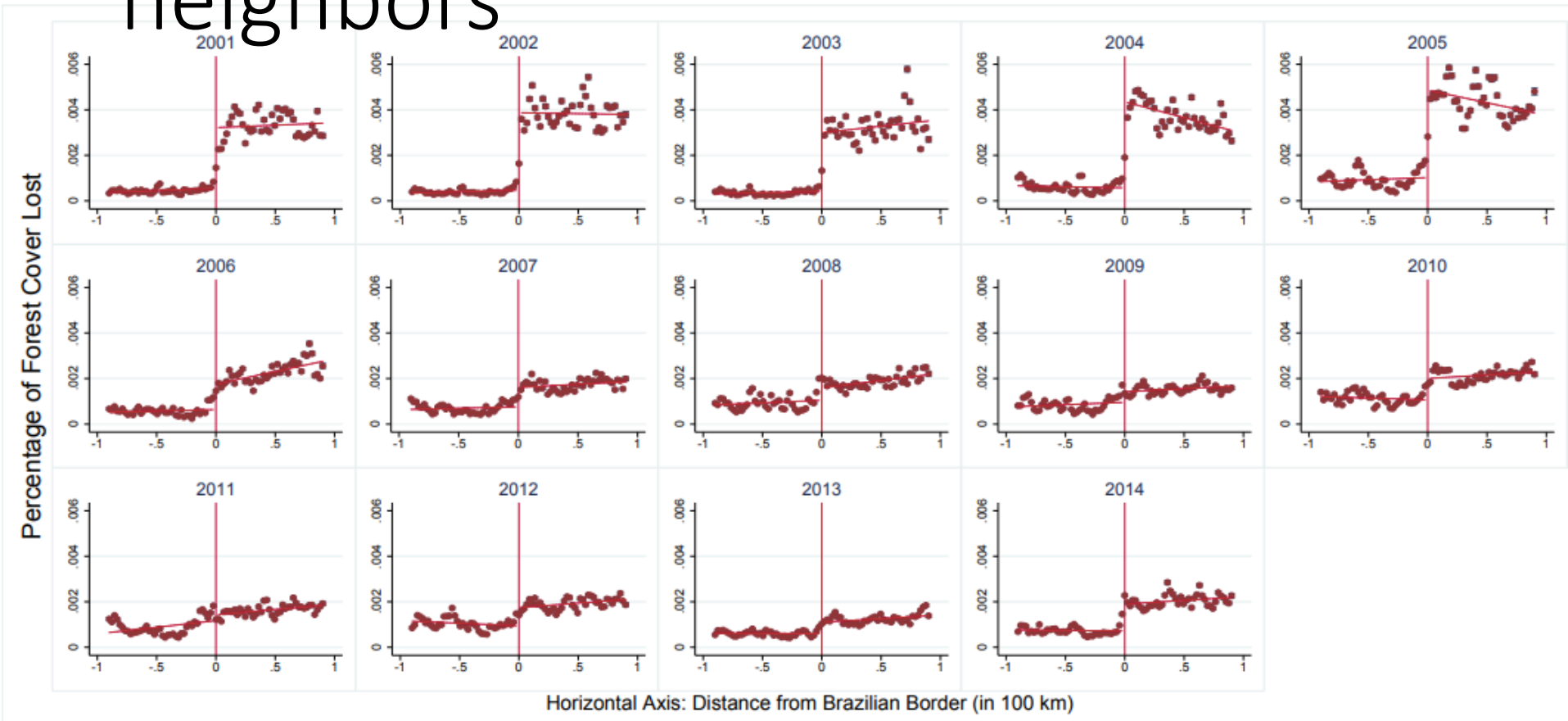




(b) Example of area of border with Bolivia

Source: Burgess, Costa and Olken (2018)

Deforestation in Brazil vs. neighbors

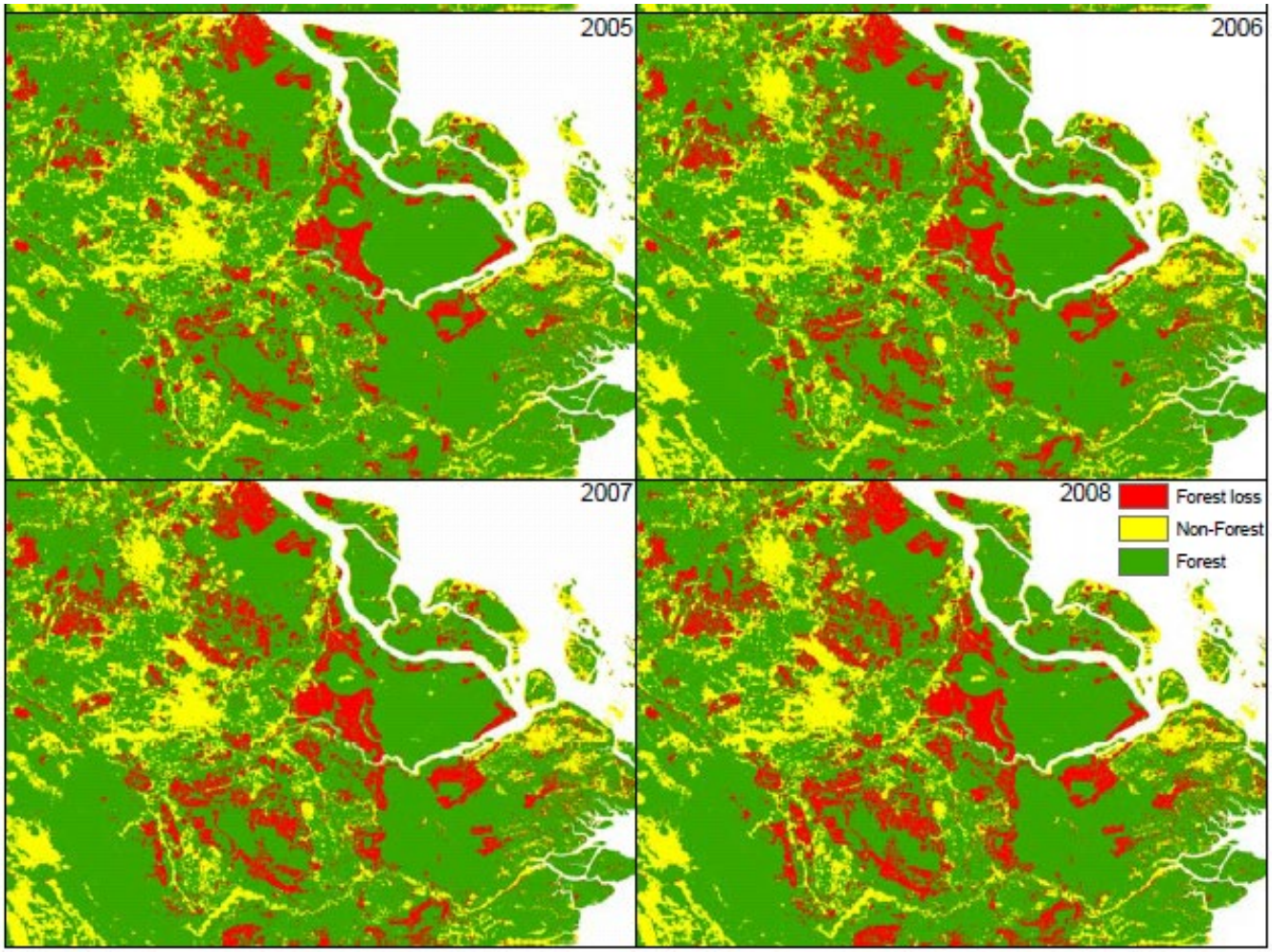


Conclusion: Brazil's policy had a large impact reducing deforestation starting in 2006

Advantage 6: Independent of official reporting mechanisms

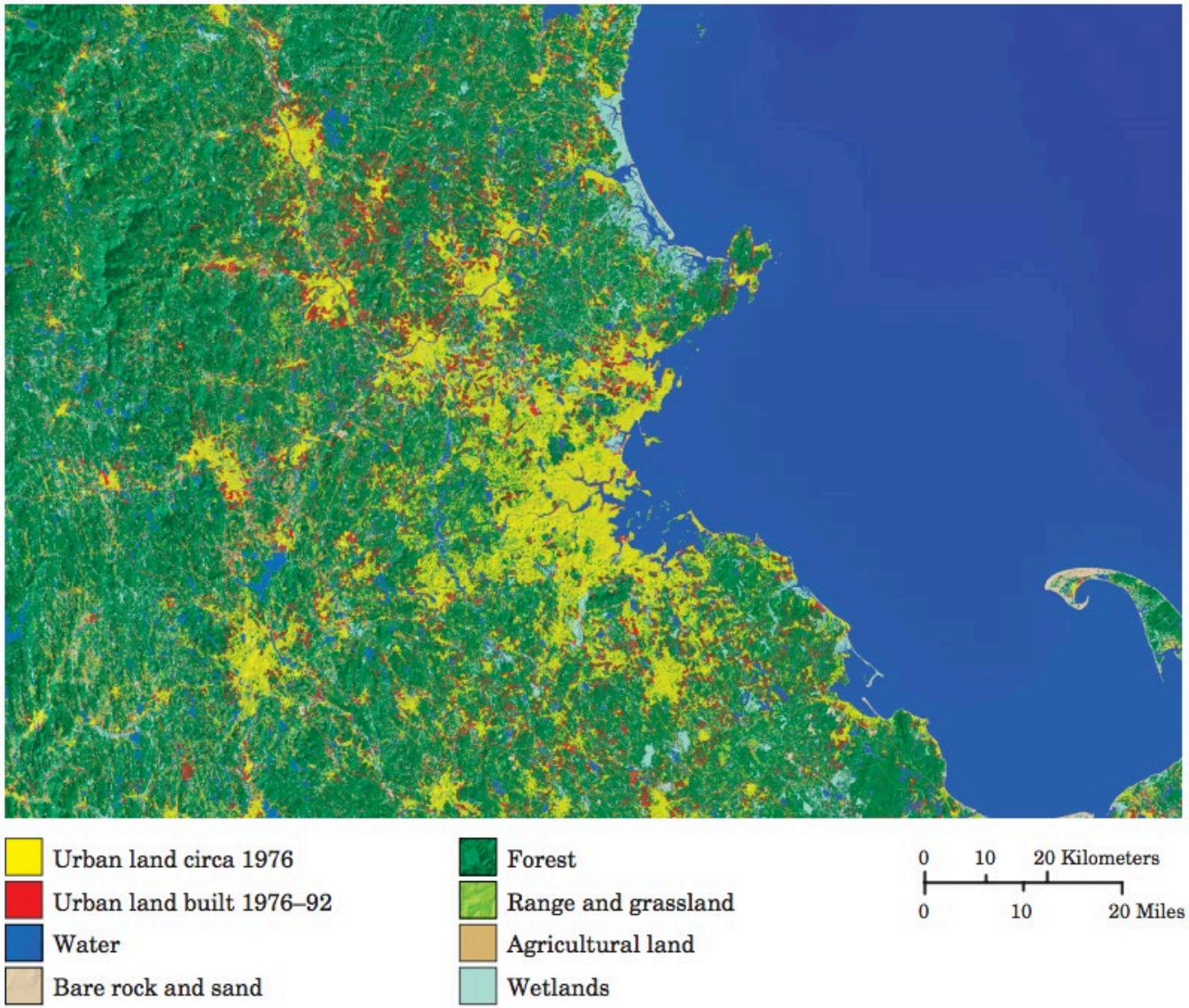
Deforestation in Indonesia

- Conclusion: Redistricting leads to increased deforestation



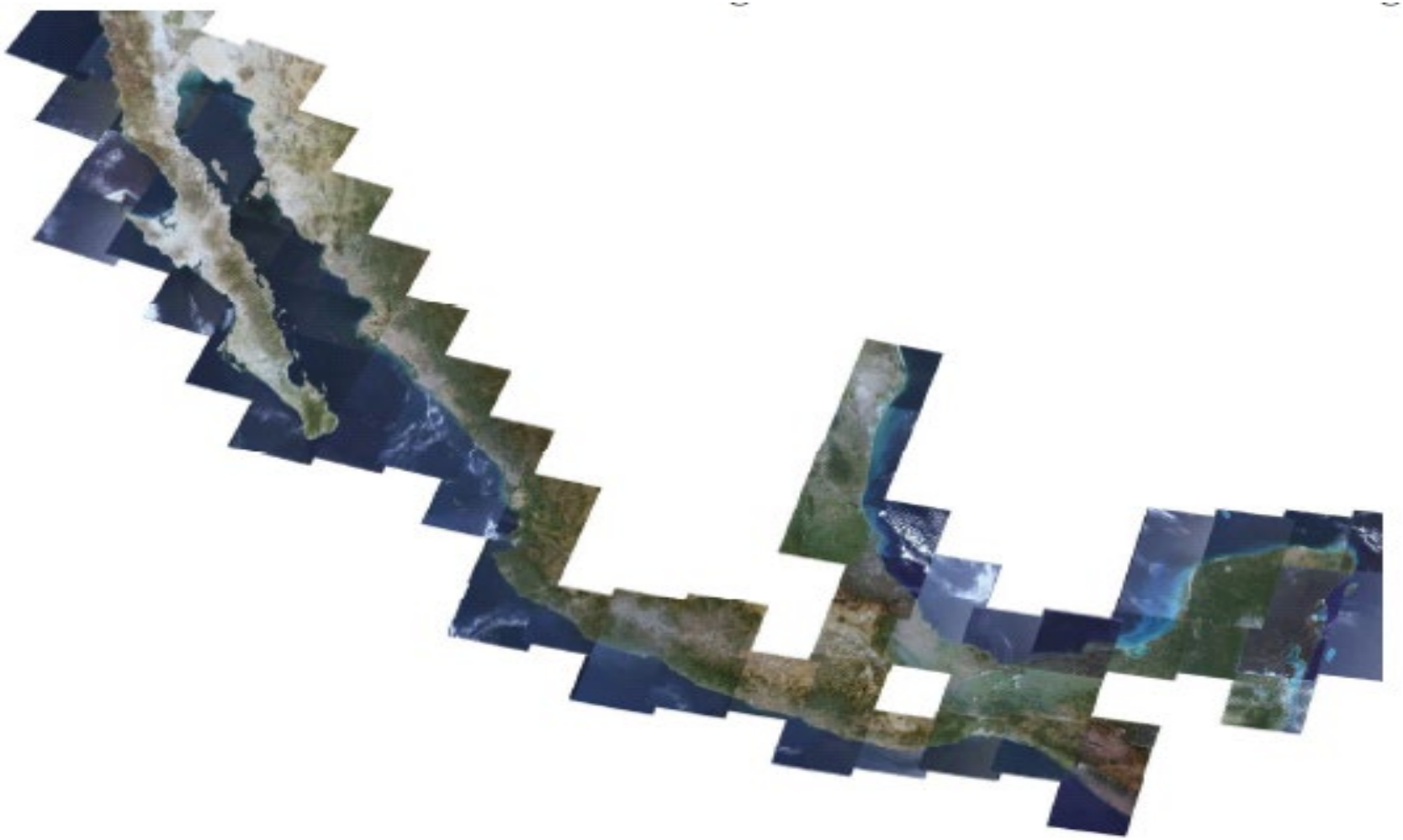
Source: Burgess et al. (2012)

Other land cover: built-up



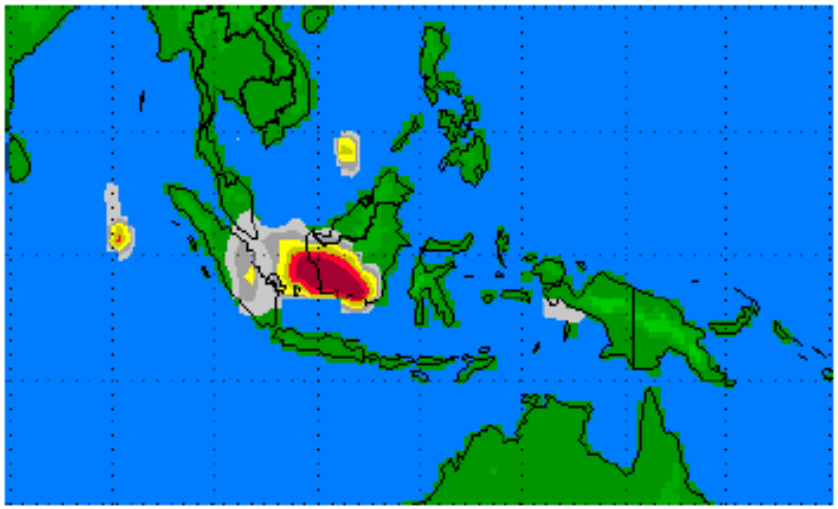
Source: Burchfield et al. (2005)

Other land cover: beaches

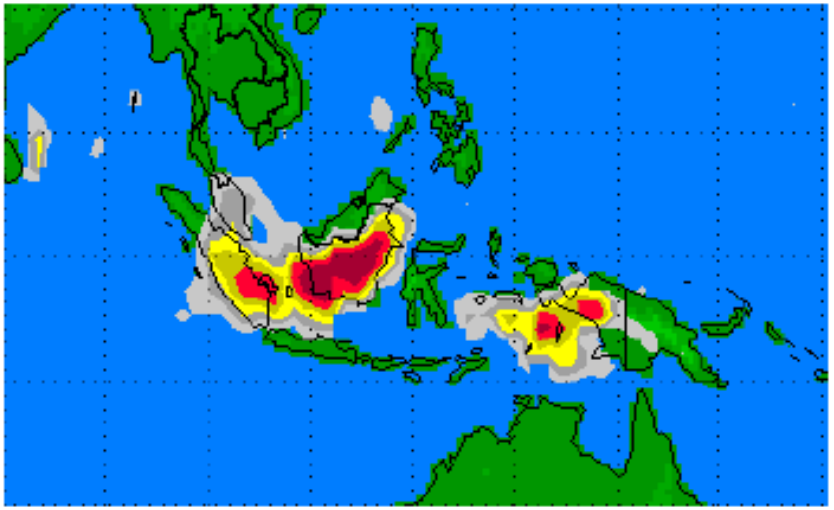


Source: Faber and Gaubert (2019)

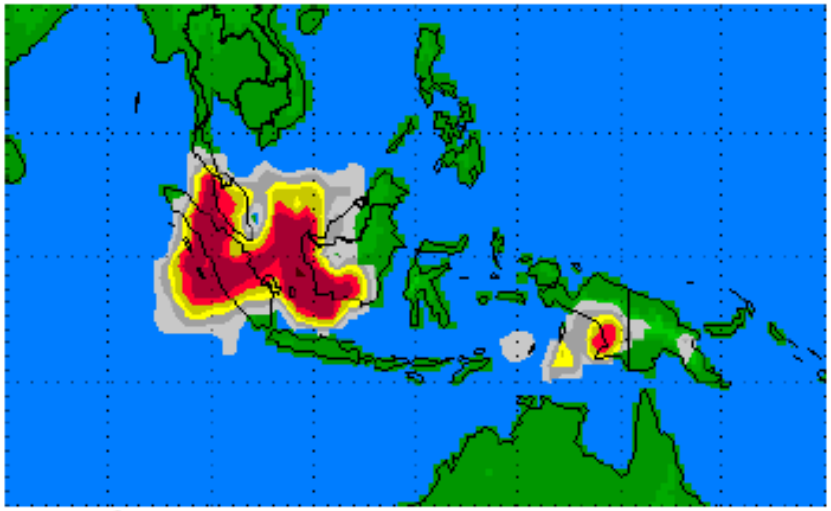
Pollution (particulates, SO2)



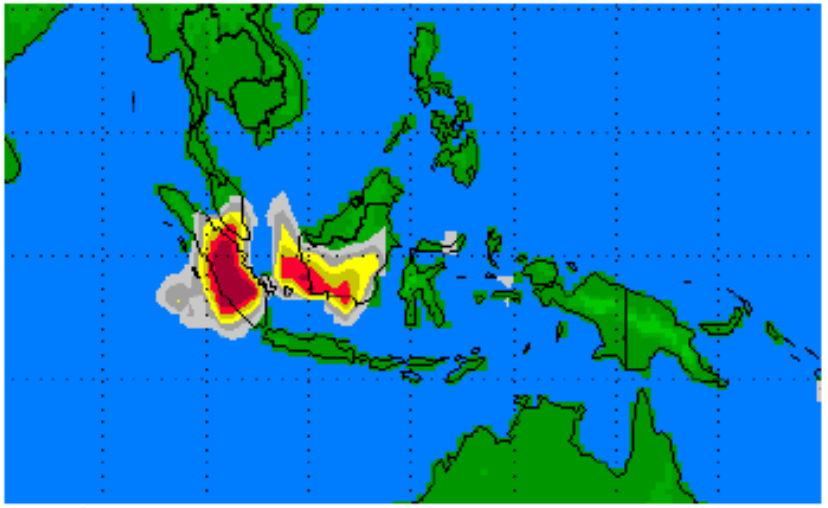
September 5, 1997



September 15, 1997



September 25, 1997



October 5, 1997

Source: Jayachandran (2009) slides

Weather and climate

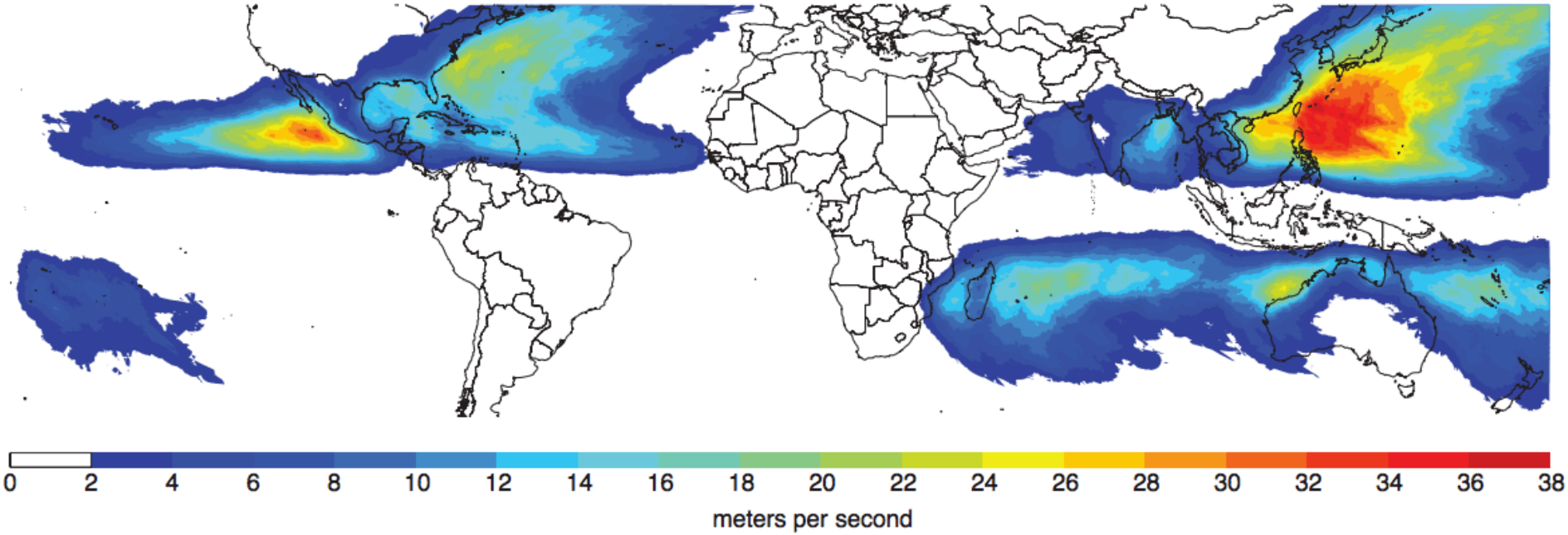


Figure 5: Global tropical cyclone exposure climatology derived from LICRICE. Colors denote the average (across years) maximum wind speed for all tropical cyclone events during 1950-2008. See Figure 4 for year-by-year data.

Source: Hsiang and Jina (2014)

Note: early years do not use satellite data

Agricultural output

- harvested area
- crop type?
- Yield?

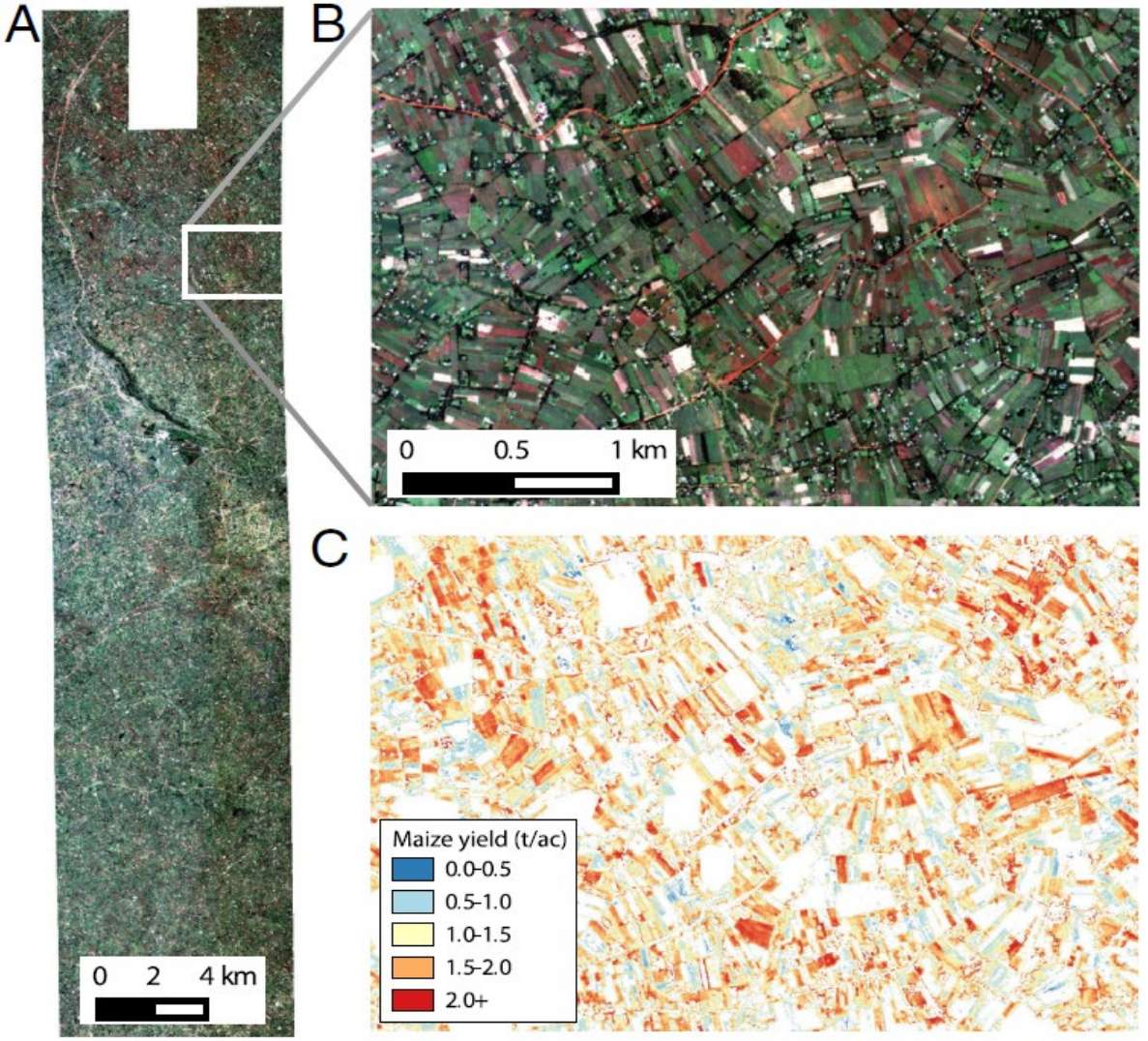
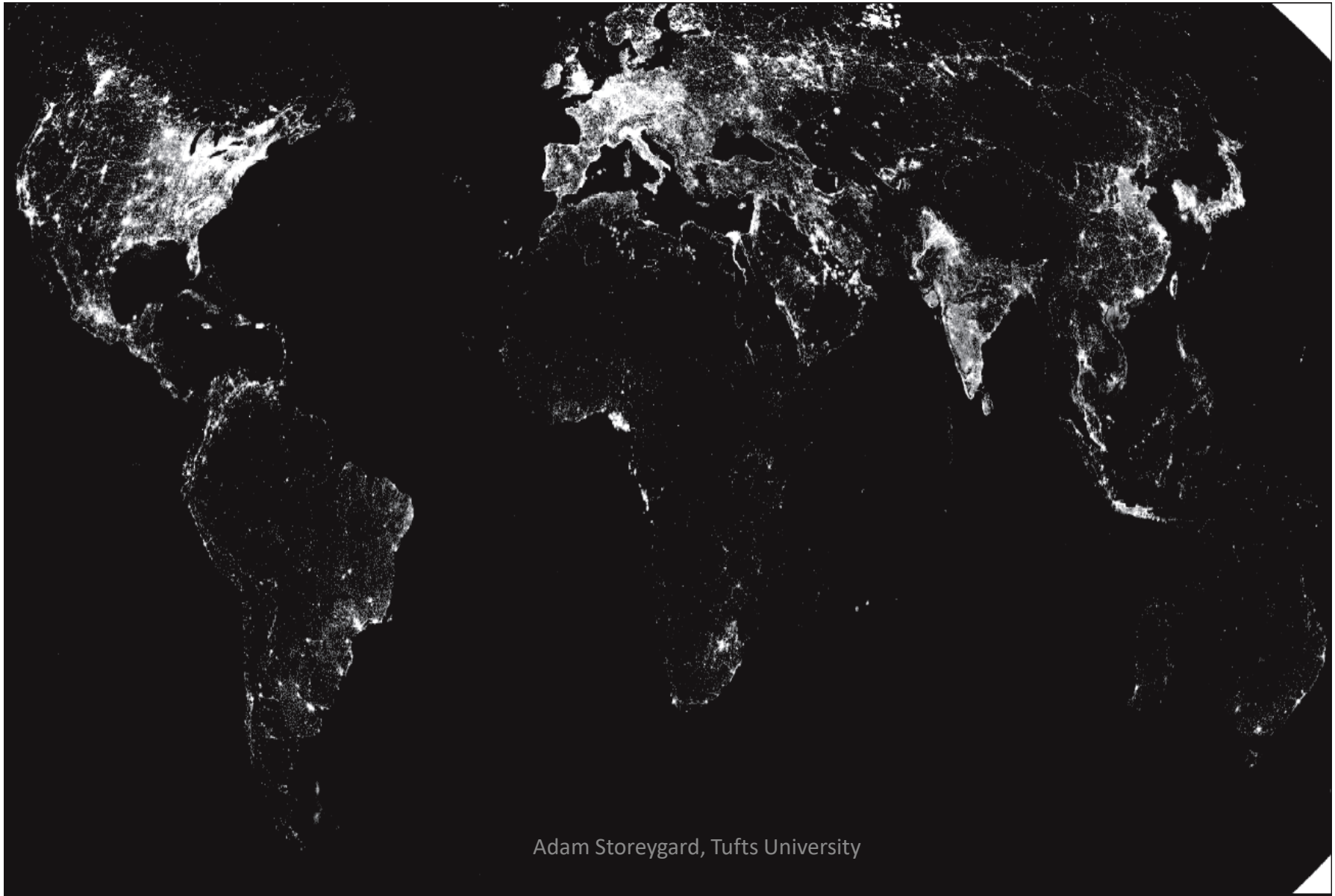


Fig. 5. Maize yield map for the study region, 2015. (*A* and *B*) One-meter image from Terra Bella of the study region (*A*) and zoom-in of that image (*B*) (see Fig. S3 for a higher-resolution version). (*C*) Yield map of the zoomed-in region for pixels classified as maize.

Source: Burke and Lobell (2017)

Night lights



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Night lights: General idea

- Light at night is many, many orders of magnitude weaker than daytime light
  - A typical nighttime photo is based on ~1-millionth the light of a daytime photo
- Magnification ("gain") is needed to see it
- A limited set of satellite sensors is capable of such magnification
  - Defense Meteorological Satellite Program (DMSP) satellites: 1962-2013
  - Visible Infrared Imaging Radiometer Suite (VIIRS): 2011-
- They have a "dynamic range" of ~10,000,000

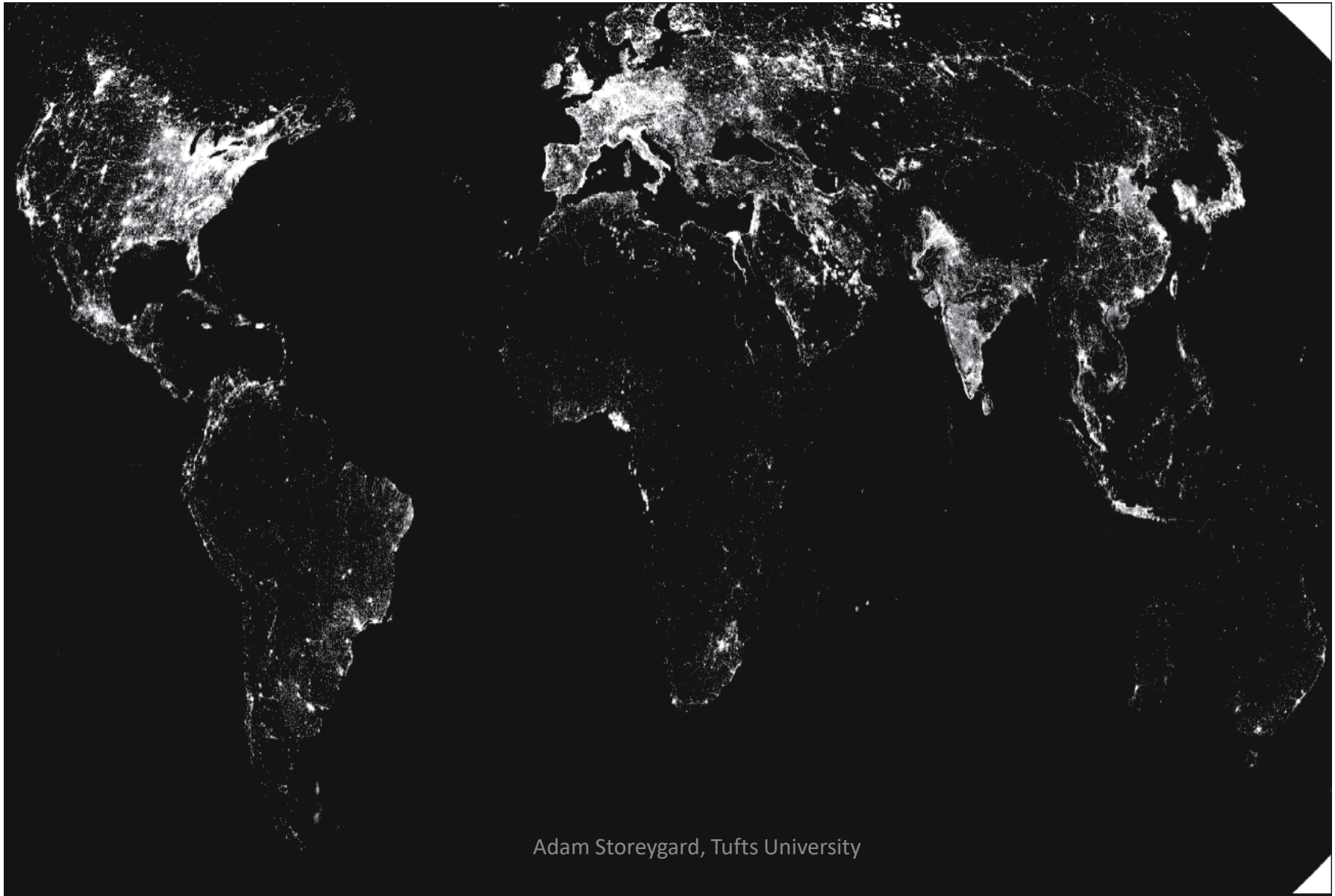
DMSP history

- Primary purpose has always been US military weather reports
- First launched in 1962
  - Ensuring cloud-free reconnaissance
  - Weather forecasts for Vietnam War bombing
- Declassified in 1972
- Digital archive begun 1992 (earlier images are on film)
- Much work to process and interpret in 1990s and 2000s
  - Christopher Elvidge, US National Oceanic and Atmospheric Administration
- First global composite in late 1990s for 1994-95
- Starting 1997, occasional military-scientific collaborations to change settings for science
- First panel in 2007 (1992-2003). Economists enter
- No data released for after 2013

Fig. 1 The Earth at night as seen in the 0.4 to 1.1 μm band. This view extends from the equator to 65° north, and the left edge is roughly 5° east.

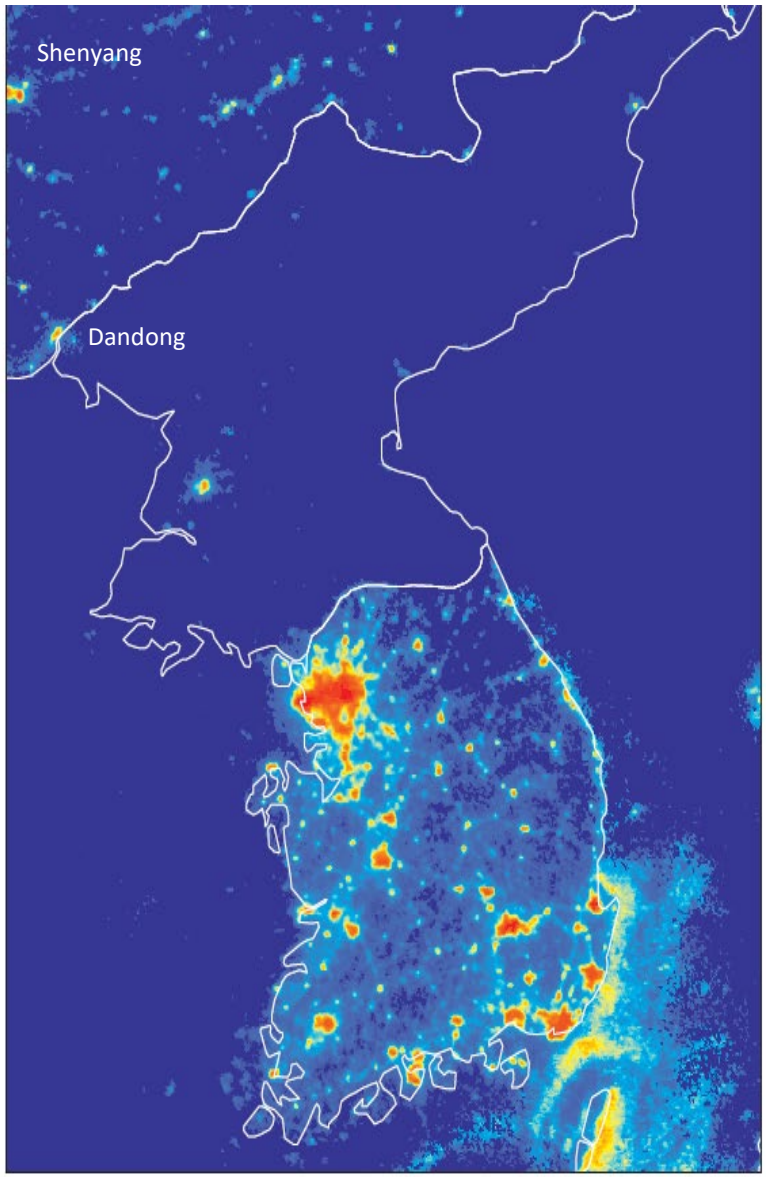
Image source: Croft (1973)

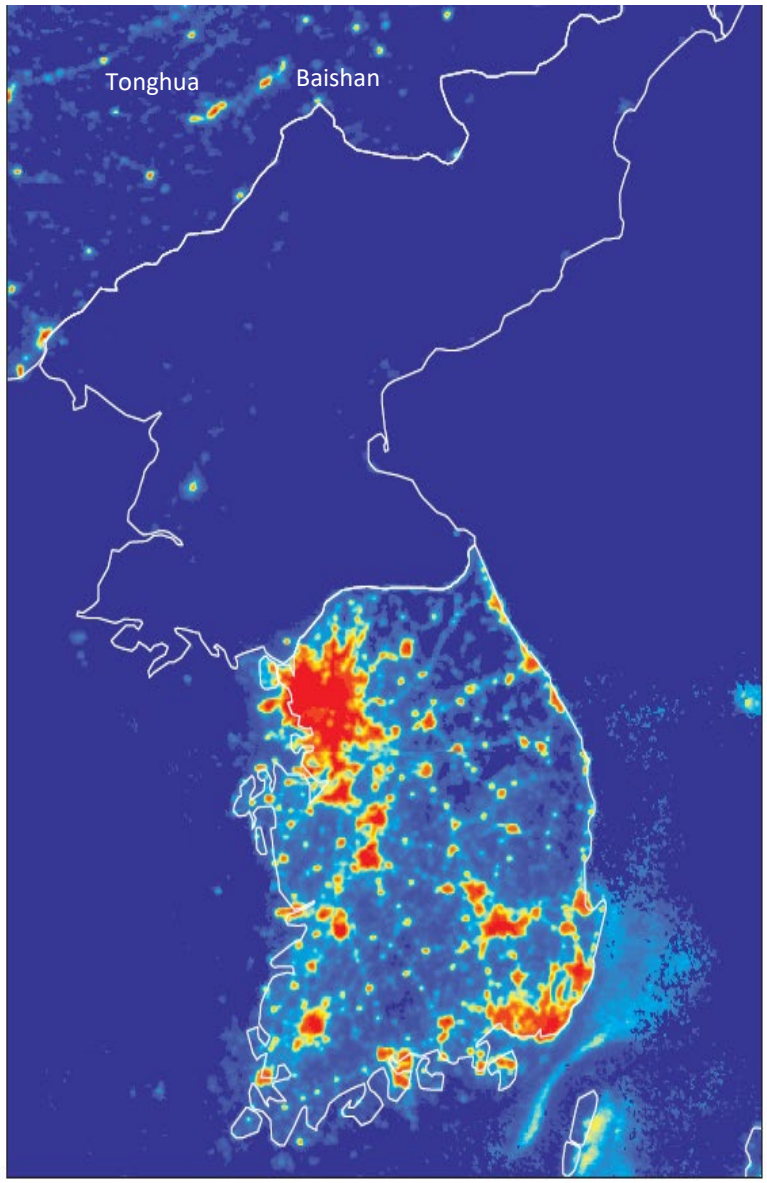
Lights are correlated with human activity



Lights are correlated with economic activity

- Growth
- South v. North
- Lights in water





Digital Number

High : 65

Low : 0

F-10, 1992

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F-16, 2008

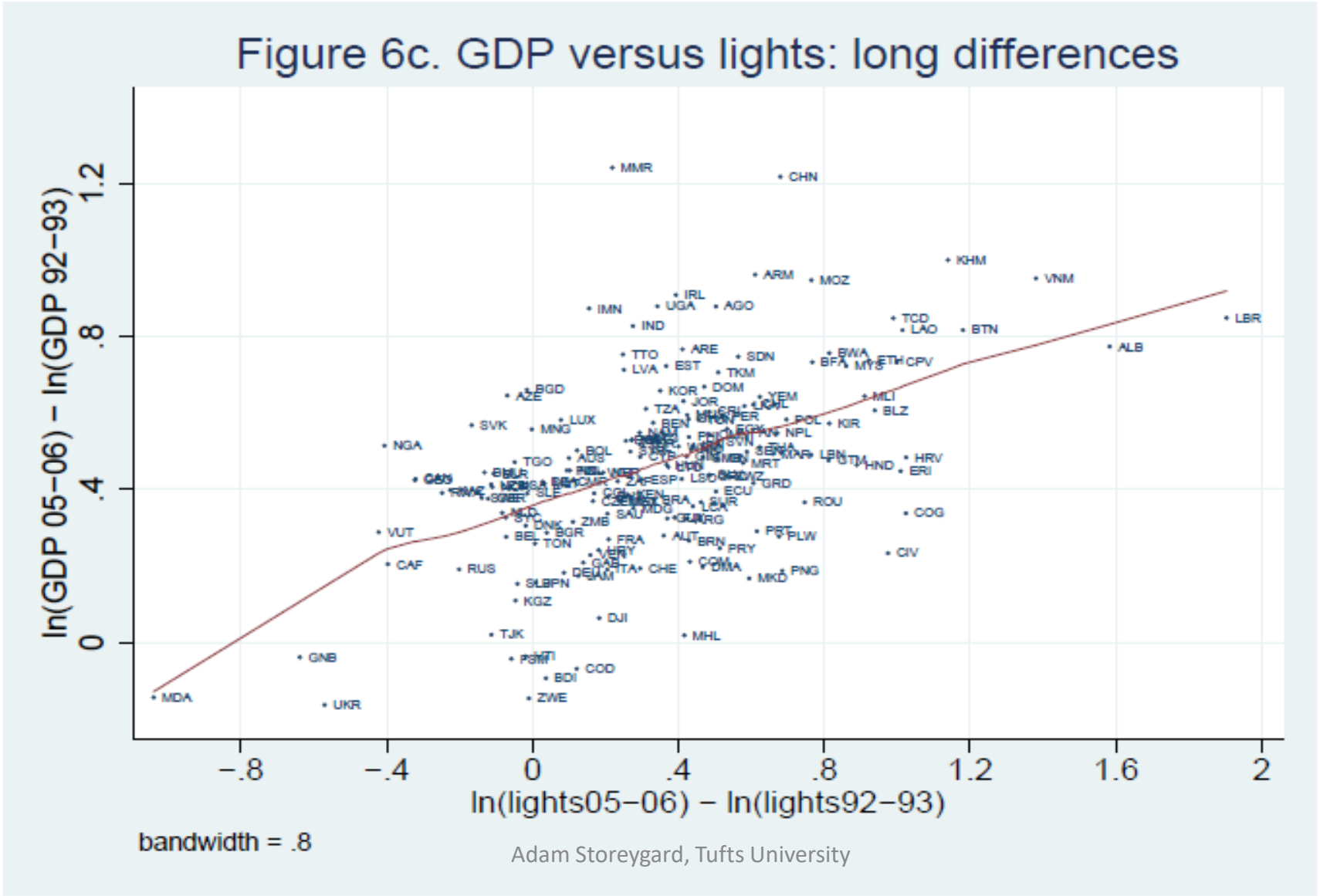
Lights-GDP relationship may not be the same everywhere

Las Vegas

Lights-GDP relationship may not be the same everywhere

Salt Lake City

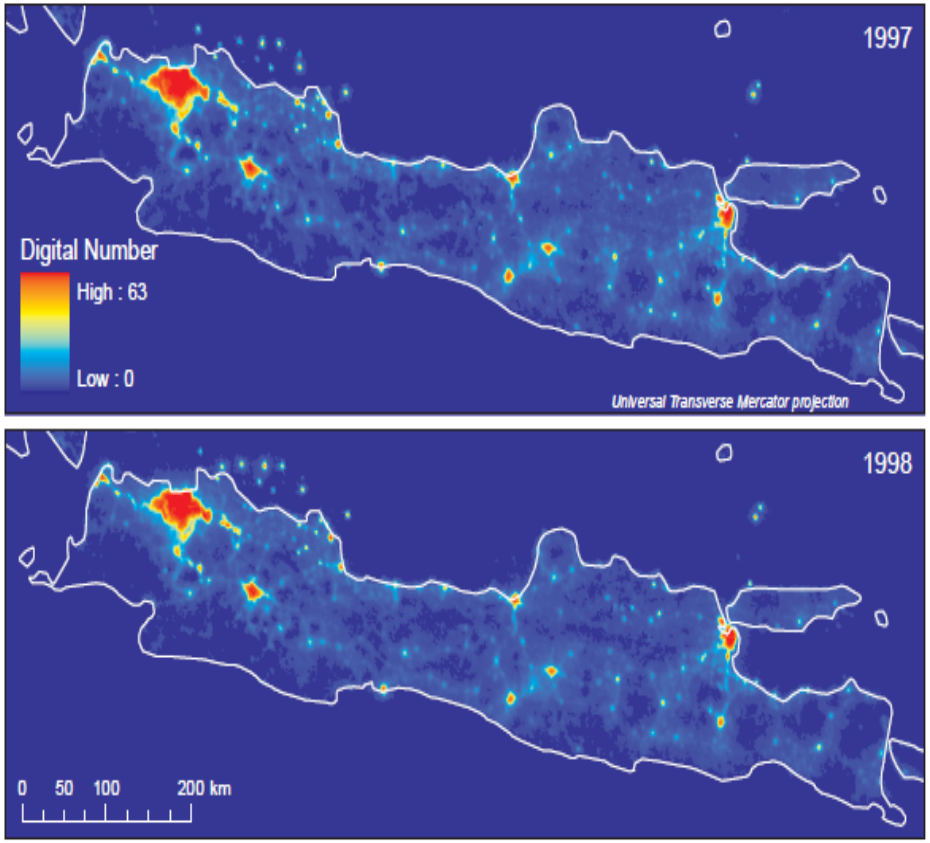
Instead, let's compare %age changes

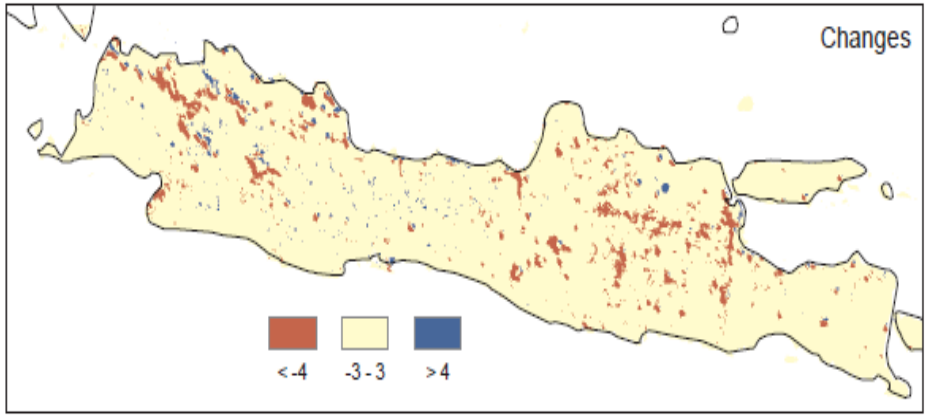


Features of the lights-GDP relationship

- Similar for poor and rich countries
- Similar for increases and decreases
- Not affected by how concentrated or spread-out lights are

Decreases appear as well





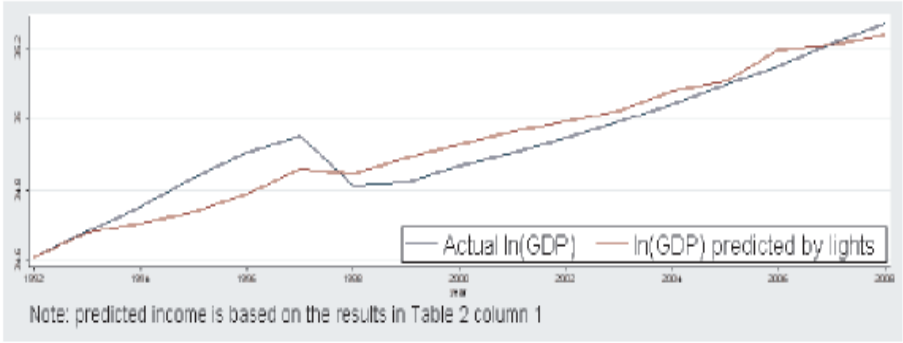
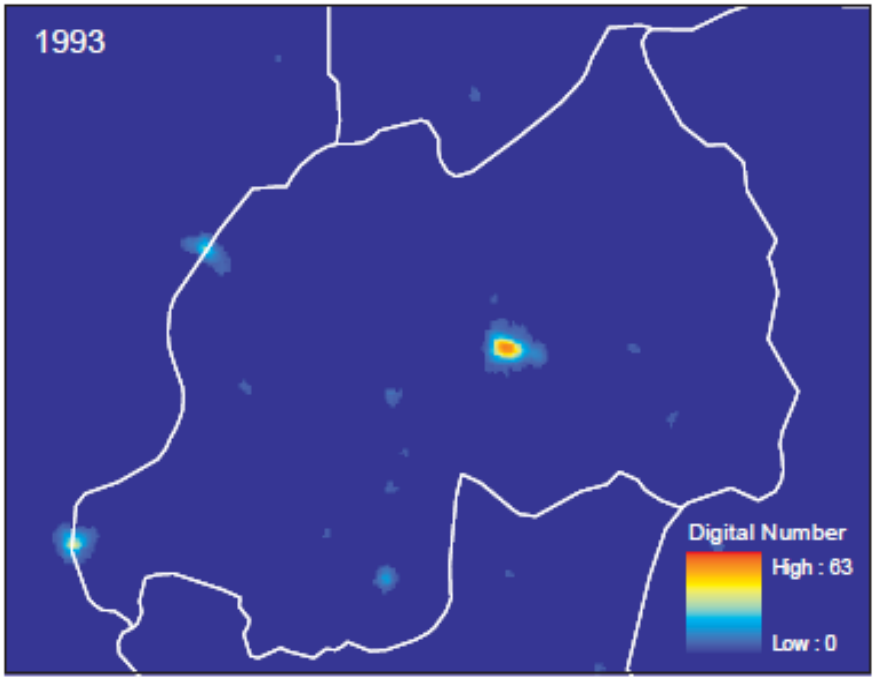
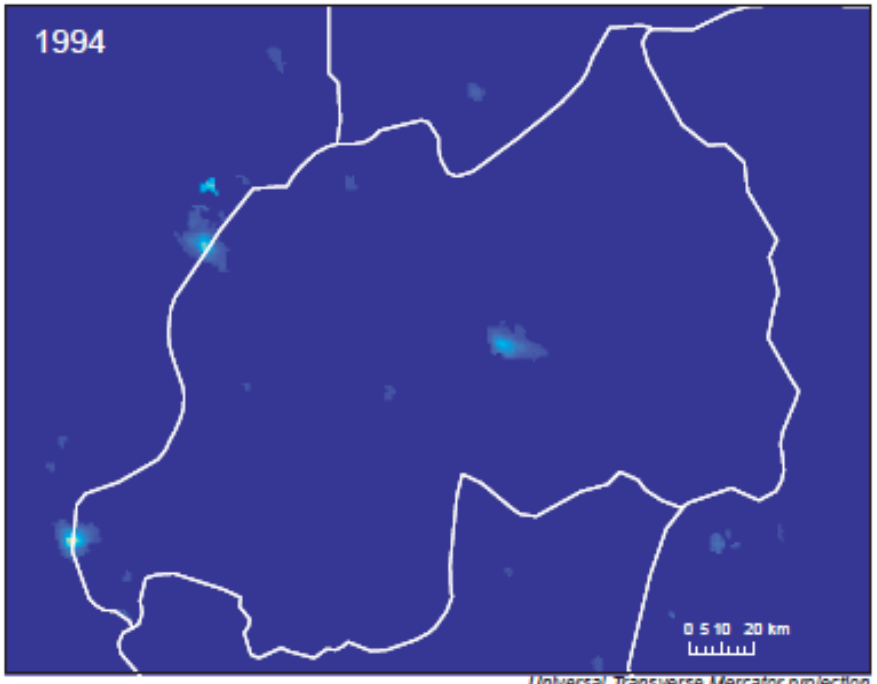
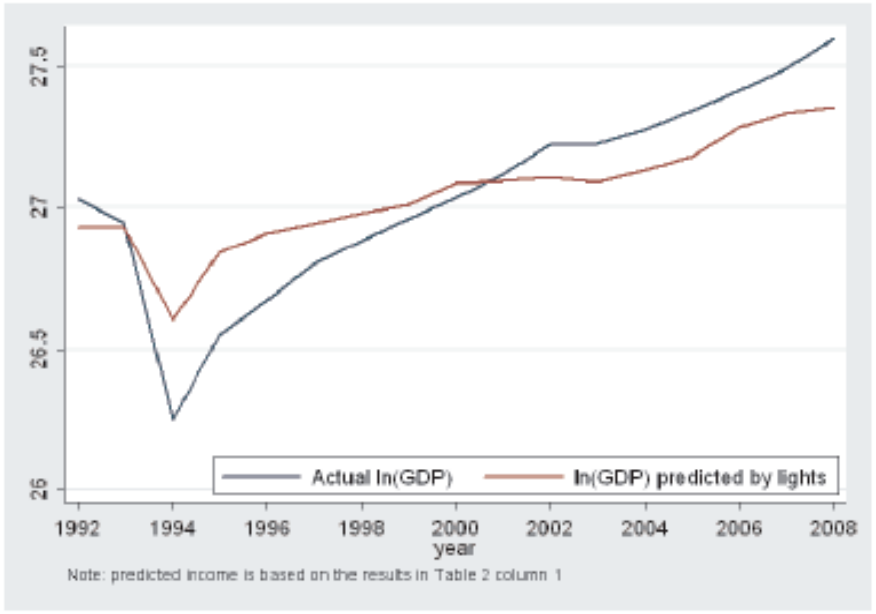


Figure 3: Asian financial crisis: Java, Indonesia







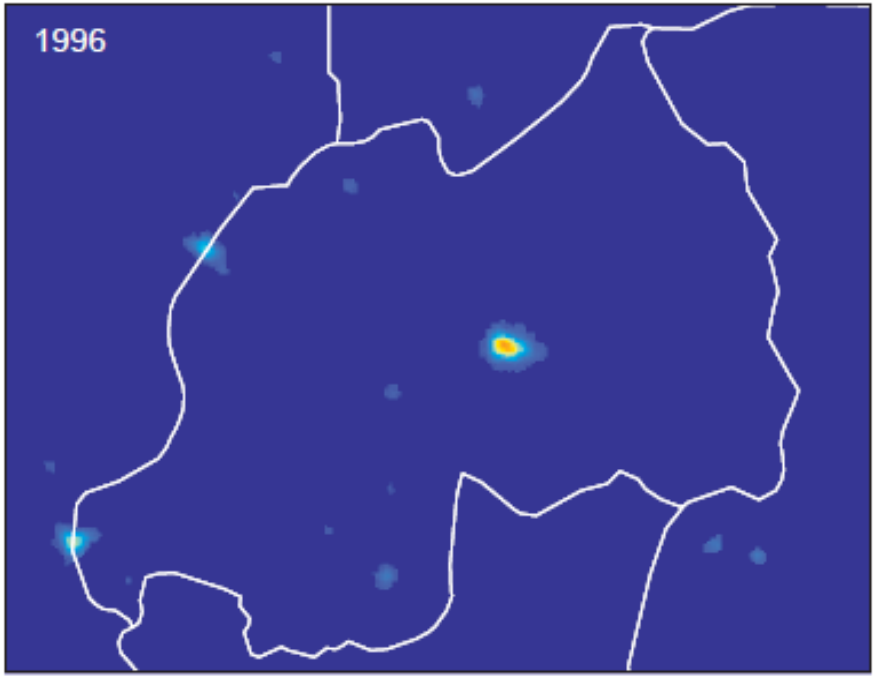


Figure 4: Genocide event: Rwanda

Event study

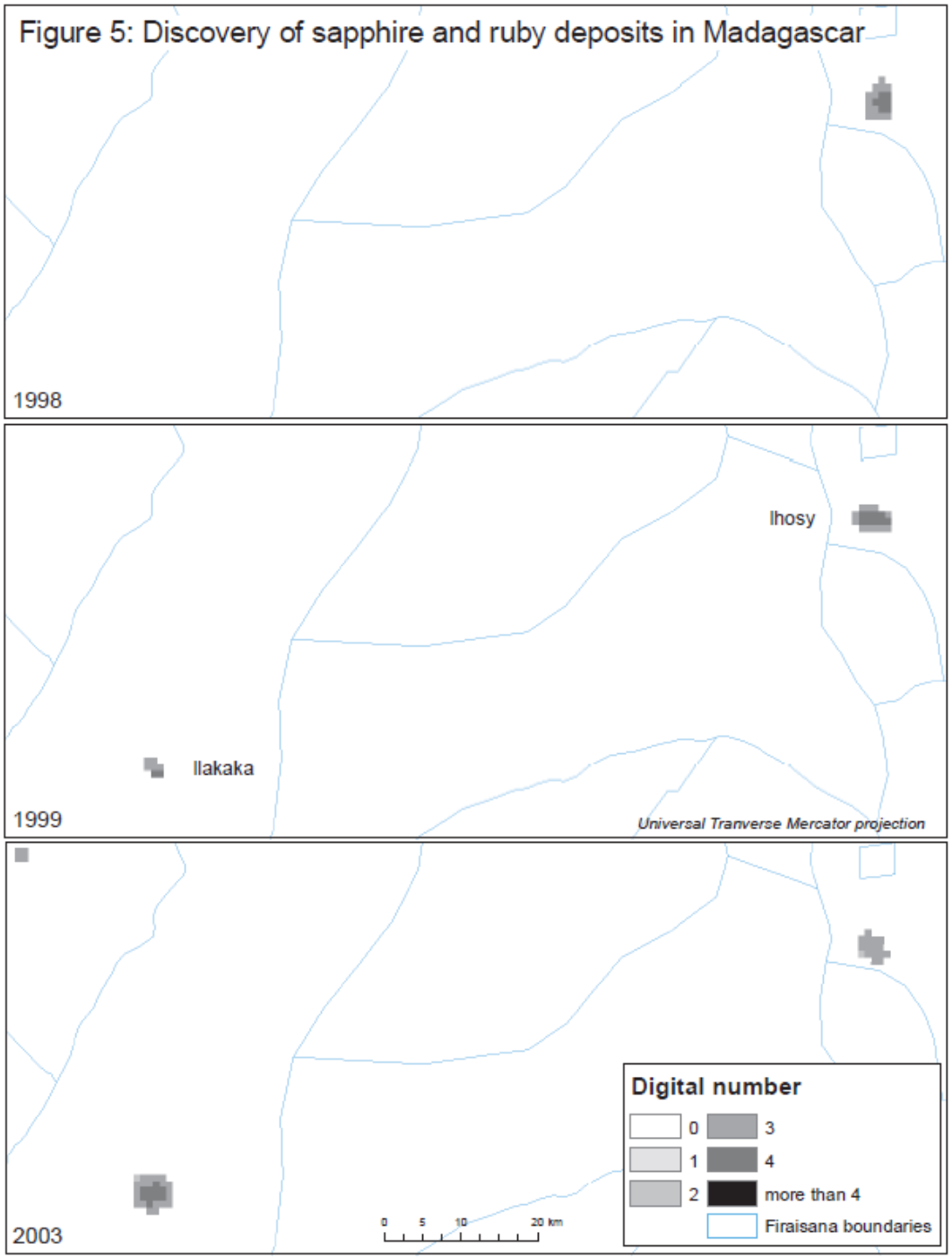


Figure 5: Discovery of sapphire and ruby deposits in Madagascar
1998
Ihosy
Ilakaka
1999
Universal Tranverse Mercator projection
2003
0 5 10 20 km
Digital number
0
1
2
3
4
more than 4
Firaisana boundaries

OK, there's a correlation. What are night lights good for?

- 1. Use lights to benchmark GDP growth measurement
  - Some countries' measures of GDP growth may be inaccurate
  - Lights provide a second **independent** measure
  - My work with Vernon Henderson and David Weil
    - Hu and Yao (2019): also measurement error
    - Martinez (2019) on GDP in dictatorships: bias
- 2. Use lights to measure GDP where we don't have data
  - Countries that don't provide any data: North Korea
  - States/counties/cities in poor countries
  - Work by many

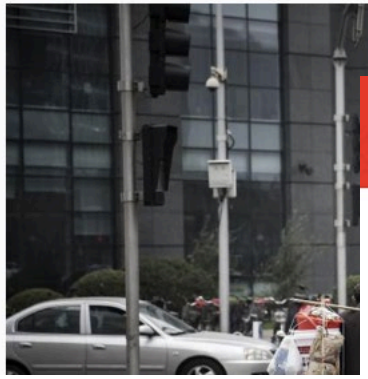
GDP is badly measured in some places

Forbes Billionaires Innovation Leadership Money Consumer Industry Li

China's GDP Numbers: Can We Trust The Data?

Sara Hsu Contributor

I write about the Chinese economy and financial sector.



MORTEN JERVEN

POOR NUMBERS

HOW WE ARE MISLED BY AFRICAN DEVELOPMENT STATISTICS AND WHAT TO DO ABOUT IT

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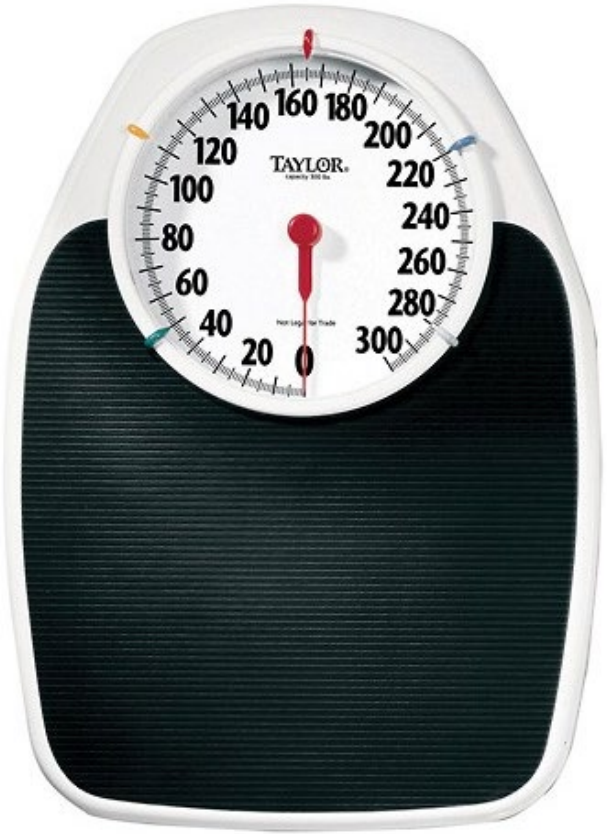
How Nigeria's economy grew by 89% overnight

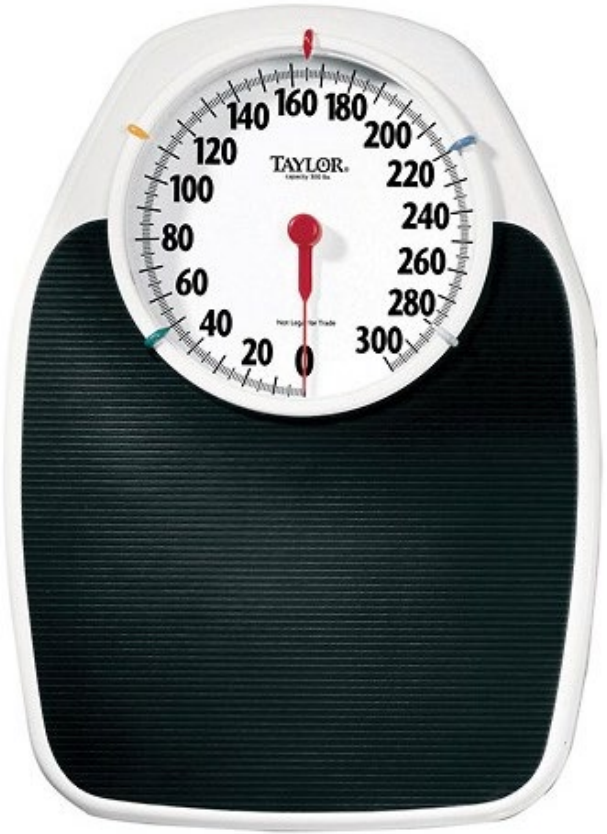
Using lights to benchmark GDP

- Say you want to weigh yourself but you have a very cheap scale and you are not sure if it is working correctly
- It could be too tight or too loose – you don't know



Using lights to benchmark GDP

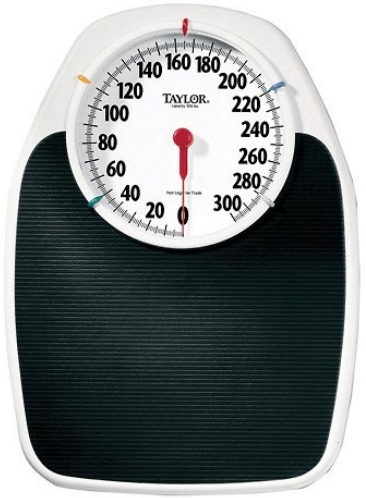
- Weighing yourself twice on the same scale may not help
- If there's a systematic error it will appear the second time



Using lights to benchmark GDP

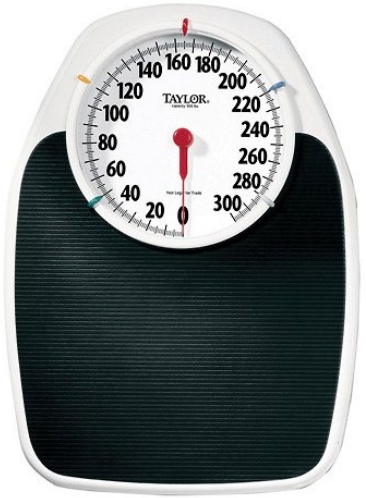
- If you have two scales, you can use both and average the two values

- Even if they are both imprecise, the average will be a better estimate



Using lights to benchmark GDP

- What if the units of the second scale are unknown?

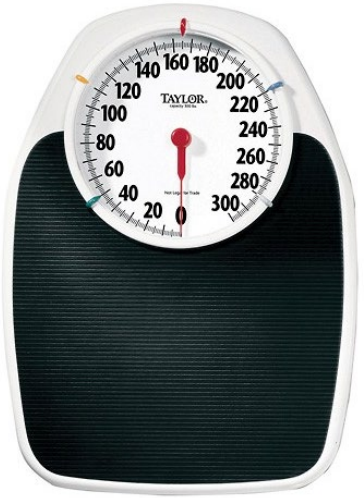


Kilograms

Tod

Using lights to benchmark GDP

- What if the units of the second scale are unknown?
- This is what we are doing with lights growth and GDP growth
- Key advantage of the lights data: they are **independent** of GDP measurement
  - Satellite doesn't know when it crosses a border

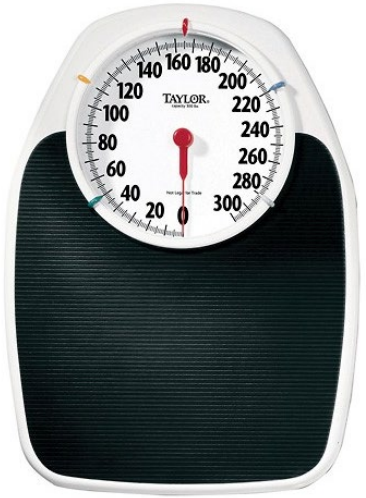


Kilograms

Tod

Using lights to benchmark GDP

- An added complication is that we think the reliability of GDP growth measures will vary by country
- So we use the lights-GDP relationship for the countries we think measure GDP better to benchmark countries where we think it is measured worse

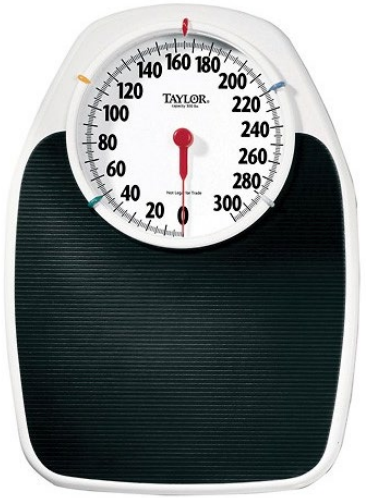


Measured GDP growth

Lights growth

Using lights to benchmark GDP

- Our optimal estimate of growth is a weighted average of measured GDP growth and lights growth
- In technical terms: we choose the weight on lights that minimizes the variance of the difference between true GDP growth and our optimal combination
  - Requires an assumption about how good the data are in “good data” countries



Measured GDP growth

Lights growth

Average annual growth rates in true income, for bad data countries (1992/93-2005/06): 1

Country	World Bank estimate	Fitted lights	Optimal combo of WDI & fitted lights	Difference
Liberia	6.8%	7.0%	6.9%	0.1%
Central Afr. Rep.	1.6%	1.9%	1.8%	0.2%
Mauritania	3.7%	4.0%	3.9%	0.2%
Swaziland	3.4%	3.9%	3.7%	0.3%
Lebanon	3.9%	4.5%	4.2%	0.3%
Madagascar	2.7%	3.4%	3.1%	0.3%
Eritrea	3.5%	5.0%	4.3%	0.8%
Guinea-Bissau	-0.3%	1.4%	0.6%	0.9%
Congo, Rep.	2.6%	5.0%	3.9%	1.2%
Haiti	-0.3%	2.7%	1.3%	1.6%
Côte d'Ivoire	1.8%	4.9%	3.4%	1.6%
Congo, DR	**-0.5%**	**3.0%**	**1.3%**	**1.8%**
Burundi	**-0.7%**	**2.9%**	**1.1%**	**1.8%**

Average annual growth rates in true income, for bad data countries (1992/93-2005/06): 2

Country	World Bank estimate	Fitted lights	Optimal combo of WDI & fitted lights	Difference
Myanmar	**10.0%**	**3.3%**	**6.5%**	**-3.5%**
Angola	7.0%	3.9%	5.4%	-1.6%
Nigeria	4.0%	1.9%	2.9%	-1.1%
Sudan	5.9%	4.0%	4.9%	-1.0%
Vietnam	7.6%	5.8%	6.7%	-0.9%
Burkina Faso	5.8%	4.5%	5.1%	-0.7%
Benin	4.5%	3.5%	4.0%	-0.5%
Ghana	4.6%	3.7%	4.1%	-0.5%
Rwanda	3.1%	2.2%	2.6%	-0.5%
Algeria	3.3%	2.8%	3.1%	-0.2%
Oman	4.3%	3.8%	4.1%	-0.2%
Mali	5.1%	4.8%	4.9%	-0.2%
Cameroon	3.3%	3.0%	3.1%	-0.2%
Niger	3.5%	3.2%	3.3%	-0.2%
Iran	4.0%	3.7%	3.9%	-0.1%
Sierra Leone	3.0%	2.8%	2.9%	-0.1%
Gambia, The	3.8%	3.8%	3.8%	0.0%

Use lights to measure GDP where we don’t have data: examples

More economic activity happens in leader's home region, especially in dictatorships, especially in Africa and Asia (Hodler and Raschky 2014)

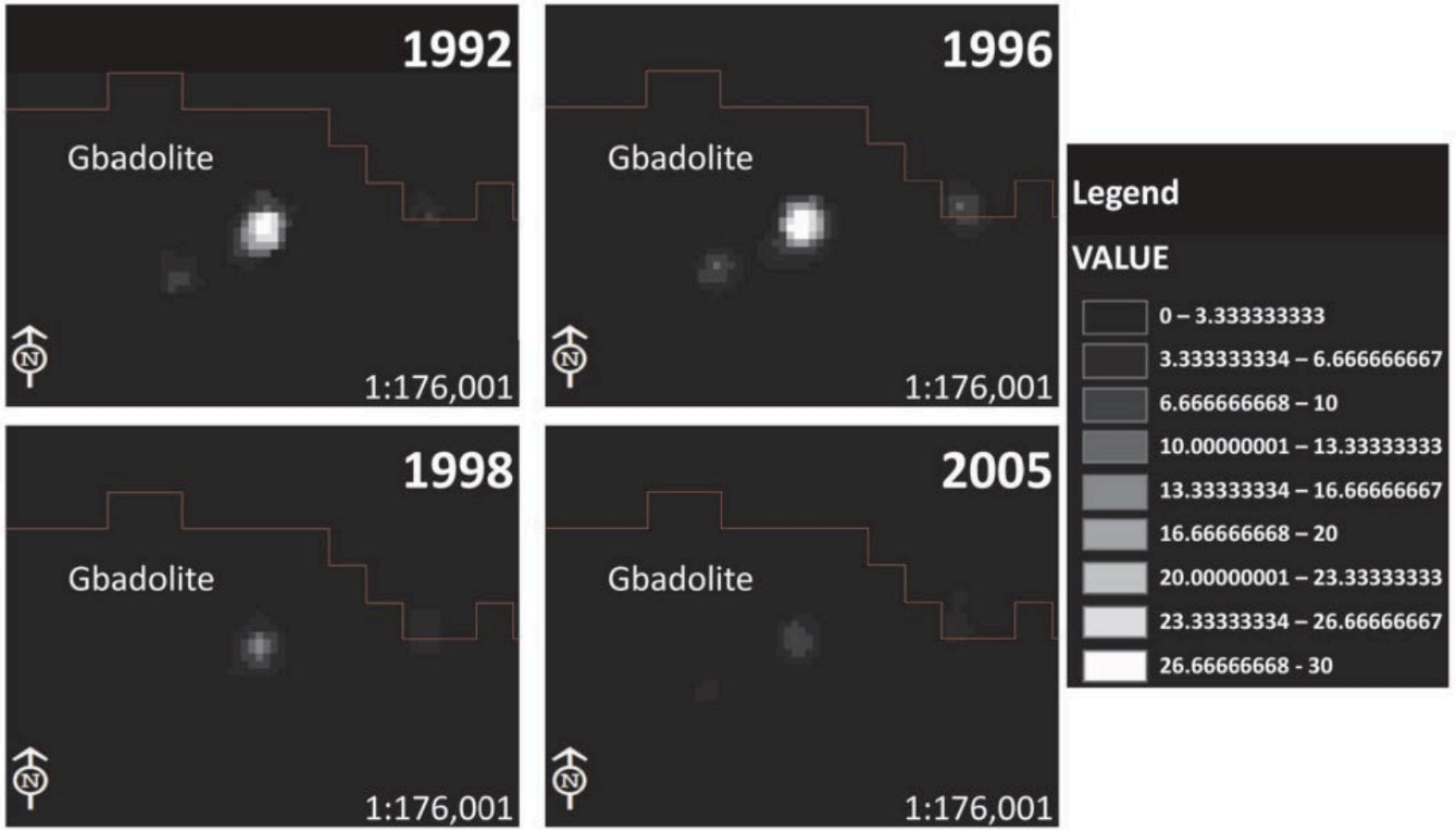


FIGURE I

Nightime Light Intensity in Gbadolite in 1992, 1996, 1998, and 2005

Mobutu Sese Seko was president of Zaire until 1997.

High transport costs hurt inland African cities a lot (Storeygard 2016)

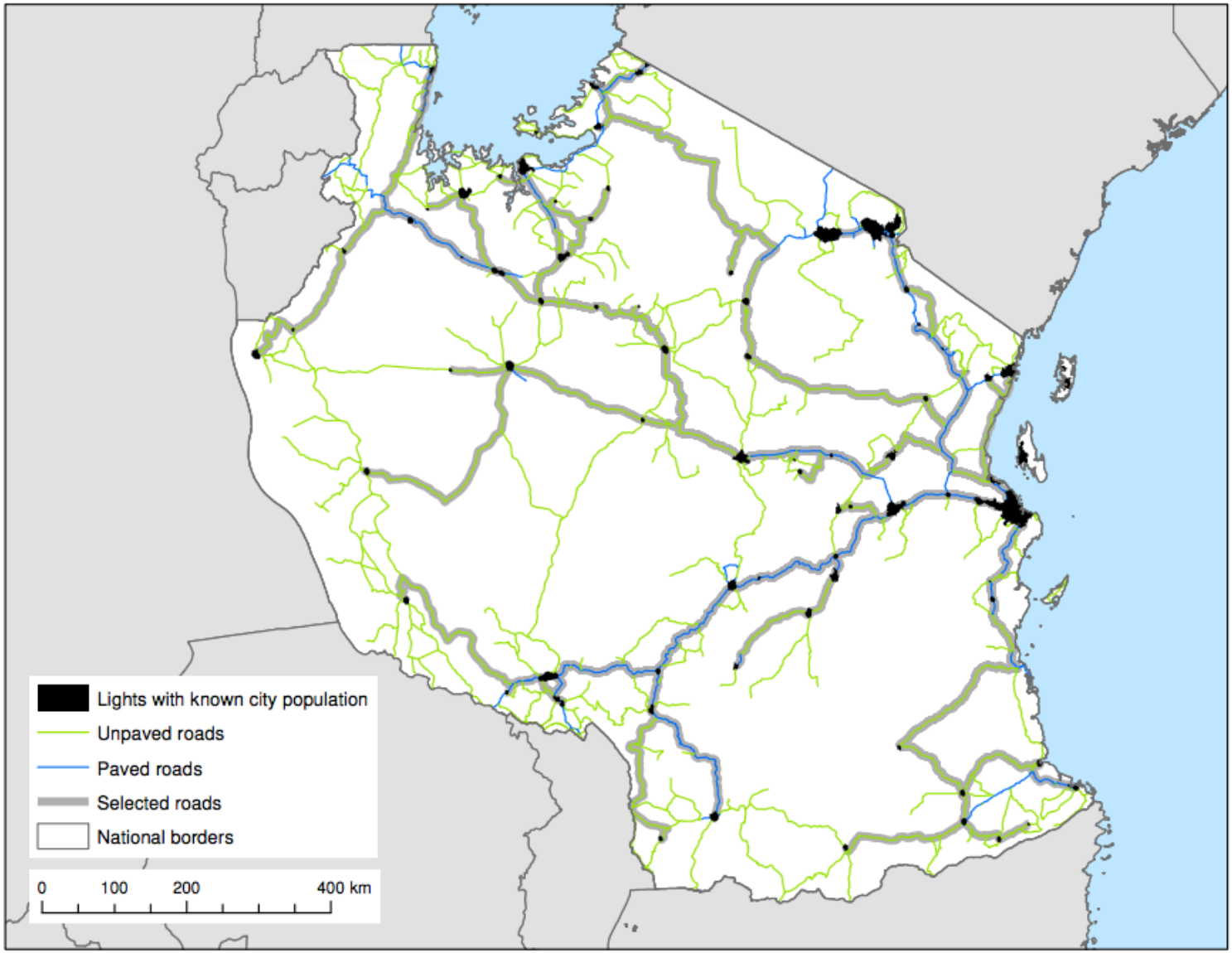
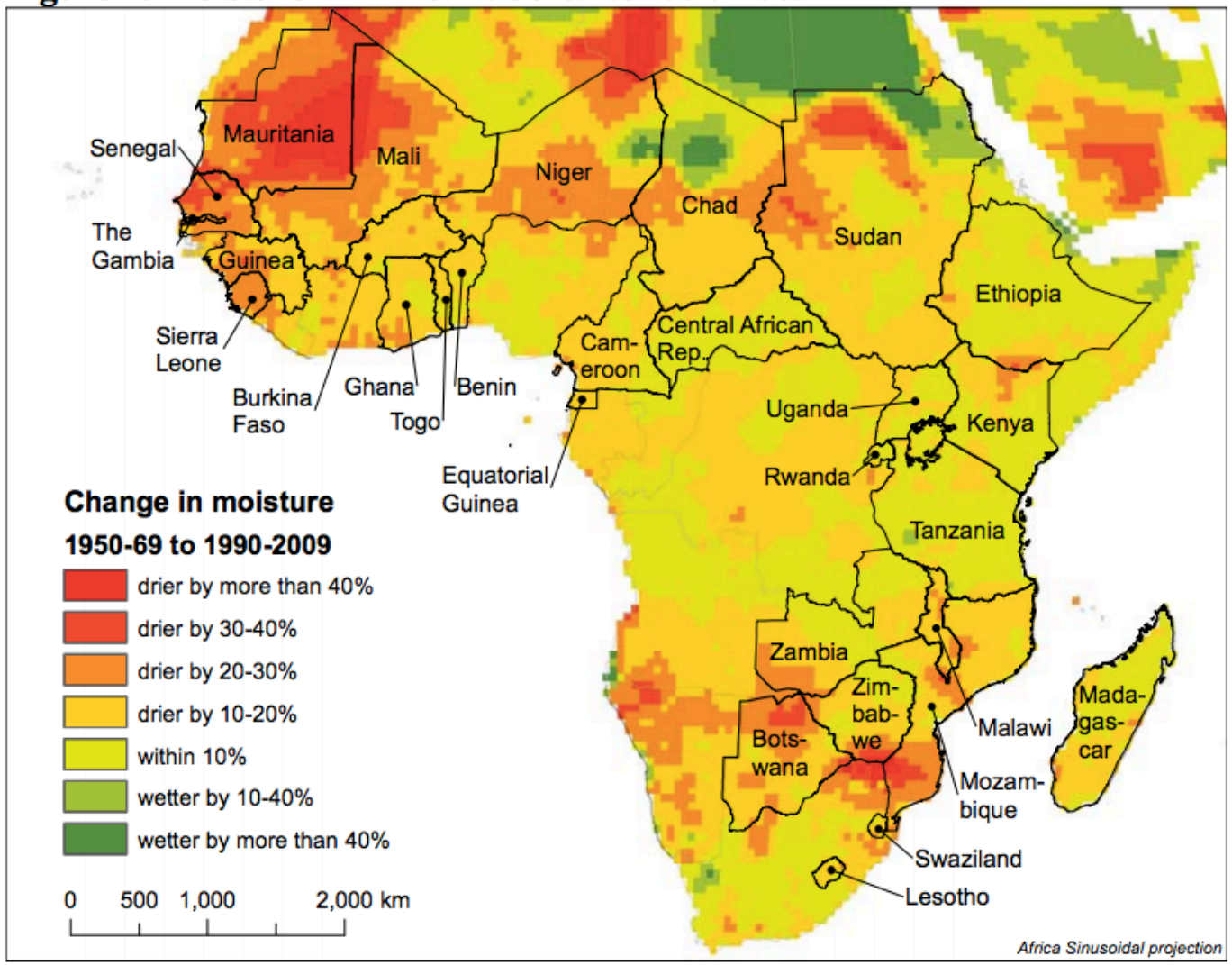


Figure 4: Shortest road routes from cities with known populations to Dar es Salaam, Tanzania

A drying climate has pushed activity into **some** African cities: those most likely to have a manufacturing base (Henderson, Storeygard, Deichmann, 2017)

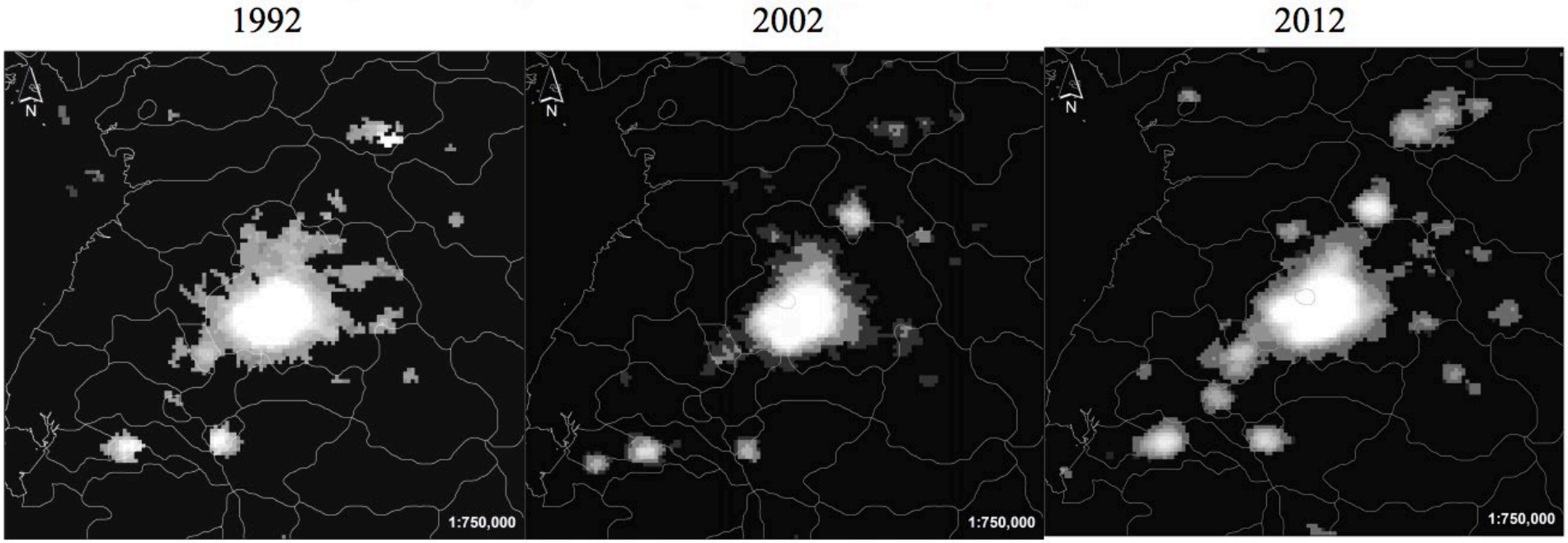
Figure 2. Moisture in Africa 1950-69 to 1990-2009



Adam Storeygard, Tufts University

North Korea responds to sanctions by shifting activity toward Pyongyang, Chinese trade hubs (Lee 2018)

Figure 6. Lights near Pyongyang in 1992, 2002, and 2012.



Some caveats on satellite data

- One perspective (from above)
  - Not magic
- One snapshot
  - Perhaps a bigger problem for pollution than others
  - c.f. lights in new (~2am) vs. old (~9pm) satellite
- Seeing objects (buildings, etc.) is getting easier but still hard
- Technical consistency is not all that matters: context
  - Detecting a city in a jungle vs. desert
- Large datasets
  - e.g. global 1-byte cross-section: 1km~1GB, 30m~1TB, 1m~1PB
- Know your data

Future promise

- Costs of data collection are still falling
- Resolution and coverage are still increasing
  - US Regulatory changes allowing for sub-meter imagery is still recent (2014)
- Algorithms for processing are being refined
- Agriculture is especially promising
  - 1-3 cross-sections per season vs. daily
  - Several companies using this as a business model
- We are in early days of this data revolution

To summarize, satellites

- provide data for data-poor contexts,
- often at high resolution,
- with frequent repeat measurement,
- for the whole world,
- consistently across borders,
- in a way that is difficult to falsify.

- They are not magic,
- but they hold enormous potential