Mapping Of Urban Expansion Using Multi-Decadal Landsat And Nightlights Data Over North America

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Motivation

- The world population is increasingly becoming urban -- projected at 70% by 2050
- Urban land transformation is permanent
- Built environment alters surface fluxes of heat, water, and carbon with effects on climate, weather, water, carbon and energy cycles
- Globally, urbanization still poorly characterized, with little information on:
  - rates of expansion of built environment
  - horizontal expansion versus increase in density
  - effect of urbanization on biophysical properties (changes in impervious versus vegetation fractions)
Goal: To develop a scalable, physically-based methodology for characterization of urban expansion using Landsat observations from 1990 to present over North America, with the potential of adapting the methodology globally.
Objectives

• Develop an urban land cover change detection approach that will be adaptable to, and informed by, the high spectral heterogeneity of urban areas across different geographic, environmental and socio-economic regions;

• Provide the tools for understanding the biophysical changes brought on by urbanization by distinguishing between the built-up and vegetation fractions components of urban areas, and the effects of these fractions on albedo;

• Identify hotspots of urban growth to understand where the most rapid land cover changes are taking place and what land covers are being replaced.
Linear Spectral Mixture Models

The integrated radiance of a spectrally heterogeneous surface can be described as a linear combination of spectral endmember radiances. (7, 8, 1, 2)

\[ R(\lambda) = f_1E_1(\lambda) + f_2E_2(\lambda) + f_3E_3(\lambda) \]

Spectral endmembers can be inferred from the apexes of a spectral mixing space defined by the Principal Components of a multispectral image (5, 8, 3, 4).

If the number of spectral endmembers (E) is less than the number of spectral bands (\(\lambda_1...\lambda_N\)), the model is overdetermined and the endmember fractions (f) for each pixel can be estimated by inverting a linear mixture model to minimize the misfit \(\varepsilon\) between model & data. (1, 8, 6, 3, 4)

\[ r = f E + \varepsilon \quad \text{and} \quad f = (E^T E)^{-1} E^T r \]

1) Adams et al, 1985
2) Adams & Smith, 1986
3) Boardman, 1993
4) Boardman, 1994
5) Johnson et al, 1985
6) Settle & Drake, 1993
7) Singer & McCord, 1979
8) Smith et al, 1985
The Landsat ETM+ Global Mixing Space

- 30 Environments
- 27,000 square kilometers
- 30,000,000 spectra
- 3 dimensions contain >98% spectral variance.

3D Visible/IR mixing space

- Side View
  - Vegetation
  - High Albedo Substrate
  - Non-Reflective Dark Surface
- End View
  - Ice
  - Water
  - Reef
- Top View
  - Dark Surface
  - High Albedo Substrate
  - Ice

Generic Global Endmembers & Binary Mixtures

- Exoatmospheric Reflectance
  - Vegetation
  - Substrate
  - Dark Surface

Dimension 1

Dimension 2

Dimension 3

Small (2004)
Urban Spectral Diversity and Heterogeneity

The composite urban mixing space strongly resembles the composite global mixing space:

- Same endmembers & topology

- Strongly linear mixing of dark surface (shadow) with vegetation and high albedo substrates

- Heterogeneous internal structure

10x10 km urban cores almost as diverse as full mixing space - But different cities occupy different regions w/in space.

Most spectrally pure pixels at the periphery of the space are associated with urban periphery and surrounding land covers.

*Small (2008)*
Spectral Mixture Analysis

- Spectral mixing space topology is defined by endmember spectra at apexes and mixed pixels interior.
- Mixed spectra can be described as linear mixtures of endmembers.

- Low order Principal Components contain most of the variance (information) in high dimensional optical imagery. *6D to 3D mixing space*

New York, 23/09/99
Validation of Vegetation Fractions

WorldView-2 vs Landsat TM & ETM+ Vegetation Fractions

Orthorectification of both WorldView2 & Landsat reduces terrain displacement and improves spatial coregistration.

Use of global vegetation EM for Landsat more closely approximates spectrally pure illuminated foliage.

Improved radiometric calibration of TM and ETM+ sensors improves consistency with global endmembers.

Landsat fractions consistently ~4% low but with only ~2% misfit at all fractions. Simple bias correction.
Applying SMA to California

43 TM and ETM+ scenes from summer 2004-2006, 19 from GLS 2005, 24 from the archive
SMA to map urban change

High Albedo
Vegetation
Dark surface

Sacramento, CA
7/25/1991

Sacramento, CA
7/26/2006
Fractional changes by land cover

- Lake
- Urban Park
- Downtown Residential
- Airport Tarmac
- New Residential
SMA Vegetation change

1991 to 2006

• Crop rotations dominate vegetation changes
• Need to control for climatic effects on phenology
SMA Built-up change

- The metropolitan area is dominated by dark reflective surfaces

- Need to separate dark impervious surfaces due to built construction from other surfaces
From Dark fraction to Impervious fraction

1. Dark Fraction

2. NDVI<0, f_D<0

3. Lights<12, f_D<80%

4. NASS CDL>0, f_V<1%

- Mask Water+High albedo
- Mask Rural, Leave Roads
- Mask Crops+ fallow near urban

Dark Fraction (f_D)
SMA vs NLCD 2006 Impervious fraction

SMA 2006 impervious displays very strong similarities with NLCD 2006 ISA, but overall higher values.

SMA 2006
14.2% of the scene is impervious

NLCD 2006
10.2% of the scene is impervious
SMA Impervious change

1991 to 2006

- Largest growth at the periphery
- Some intensification of previously urbanized pixels
Conclusions

• SMA offers a robust method to map urbanization translating spectral radiance into physical measure of the areal fractions of landcovers, and requires minimum training and assumptions

• The dark fraction strongly relates to impervious surfaces

• Biophysical changes of urbanization through the relative fractions of impervious, vegetation fractions, albedo

• Preliminary vicarious validation of vegetation fractions from Landsat with WV-2 for NYC shows accuracy of 96%
Next Steps

• Refine the selection of endmembers for atmospherically corrected global Landsat mixing space

• Vicariously validate impervious fractions with multispectral high resolution commercial imageries from WARP database in collaboration with de Colstoun

• Extend the multi-temporal analysis to 1991, 2000, 2010 to all of US, Canada and Mexico

Thank you!