Measuring Sustainability of Urban Systems: An Exploration based on Two Metrics for the Chicago Metropolitan Area

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Outline

- Rationale
- Methodology
- Preliminary Results
- Future Work
- References

Rationale

- Urban populations inherently depend on resources obtained from extra-urban ecosystems (Rees, 2001).
- Urban demand for natural resources is rising over time: The world is urbanizing rapidly; cities and urban agglomerations increasingly drive concern for global sustainability (Moore et al., 2013).
- Urban areas should be sustainable, thereby minimizing the inordinate depletion of environmental and natural resources.
- EPA Research: Develop sustainability metrics at regional/local scale to help decision makers regarding sustainable solutions.
- The assessment of urban sustainability should be effected with metrics that permit rapid elucidation of sustainability trends.

Rationale (Cont'd.)

- Two of such integrated metrics are Ecological Footprint Analysis (EFA) and Green Net Metropolitan Product (GNMP); Other integrated metrics under SHC research project "Sustainability Assessment and Management of Urban Systems": Fisher Information, Emergy, Net Energy, and Human Well-being Index (HWBI).
  - EFA aims at capturing the impacts (expressed in space units) of human consumption on the regenerative capacity of ecosystems (Chambers et al., 2000) via an ecological accounting system.
  - GNMP is an economic measure of sustainability that adjusts Net Metropolitan Product (NMP) for environmental and natural resource degradation.

Rationale (Cont'd.)

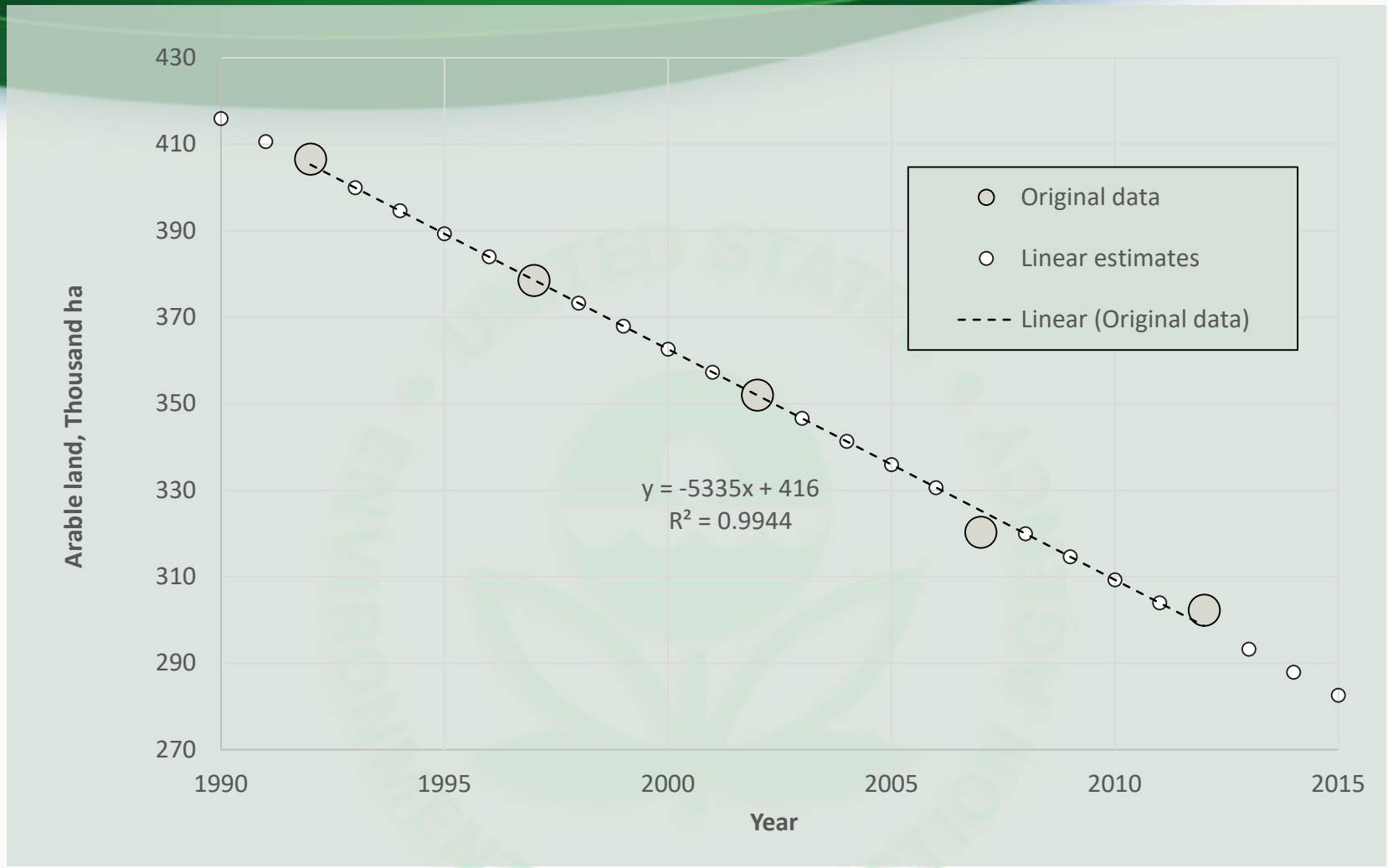
- EFA and GNMP are estimated for the Chicago Metropolitan Area (CMA); 7 counties.
- EFA and GNMP might have the potential to guide policy-making regarding the sustainability of urban areas in general and the Chicago Metropolitan Area (CMA) in particular.

Methodology: EFA

- EFA: Preliminary exploration performed by adapting the methodology provided in Hopton and White (2012) incorporating top-down and bottom-up computational approaches
  - Top-down approach: National and/or state data are properly scaled down, thereby serving as a proxy for the urban area's consumption patterns.
  - Bottom-up approach: City-level data on consumption are directly employed in the computations.

Methodology: EFA (Cont'd.)

- Land/space classification: Energy (CO_2-sequestering), Arable, Forest, Pasture, and Built-up lands, and Lake space
- Consumption categories (items): Energy (coal, natural gas, and petroleum) and Food (meat, poultry, dairy, fish, grains, fruit & vegetables, roots & tubers, and pulses)
- Data sources: State data (total energy consumption), National data (food consumption per capita), local data (total amounts of land/space); missing data estimated by interpolation or extrapolation whenever possible and/or appropriate



Estimation of missing arable land figures for CMA between 1990 (year 0) and 2015 (year 25): Original data have been obtained from USDA Agricultural Statistics for 1992, 1997, 2002, 2007, and 2012.

Methodology: EFA (Cont'd.)

- Ecological demand (footprint): Sum of footprints computed for each category of land/space expressed in global hectares (gha) per capita in a given time period
  - **Itemized footprint (demand) computation**: Each item in consumption category is expressed per capita, adjusted by equivalence factors to report it in global hectares (gha), and assigned to a land/space classification.

Methodology: EFA (Cont'd.)

- Ecological supply (biocapacity): Sum of amounts of land/space available expressed in global hectares (gha) per capita in a given time period
  - **Itemized supply (biocapacity) computation**: Each land/space classification available is expressed per capita and adjusted by yield factors to report it in global hectares (gha).
- Ecological remainder: Difference between supply (biocapacity) and demand (footprint)

Footprint for a consumption item (Beef)

$$\frac{\underbrace{227.2\ lb\ per\ capita}_{National\ consumption} * \overbrace{7{,}319{,}322}^{CMA\ Population} * \underbrace{\left(\frac{1}{2.2046\frac{lb}{kg}}\right)}_{Conversion\ factor}}{\underbrace{CMA\ apparent\ consumption}_{CMA\ consumption\ per\ capita}} * \left(\frac{1}{\underbrace{7{,}319{,}322}_{CMA\ population}}\right) * \left(\frac{1}{\underbrace{32\frac{kg}{ha}}_{global\ yield}}\right)$$

$$= \underbrace{3.22\ ha\ per\ capita}_{Footprint} * \overbrace{0.49}^{Equivalence\ factor} = 1.58\ gha\ per\ capita \rightarrow assigned\ to\ Pasture\ land$$

Supply of Pasture land

$$\underbrace{35{,}314\ ha}_{Estimated\ CMA\ supply} * \left(\frac{1}{\underbrace{7{,}319{,}322}_{CMA\ population}}\right) * \overbrace{1.63}^{yield\ factor} = \underbrace{0.01\ gha\ per\ capita}_{Equivalent\ supply}$$

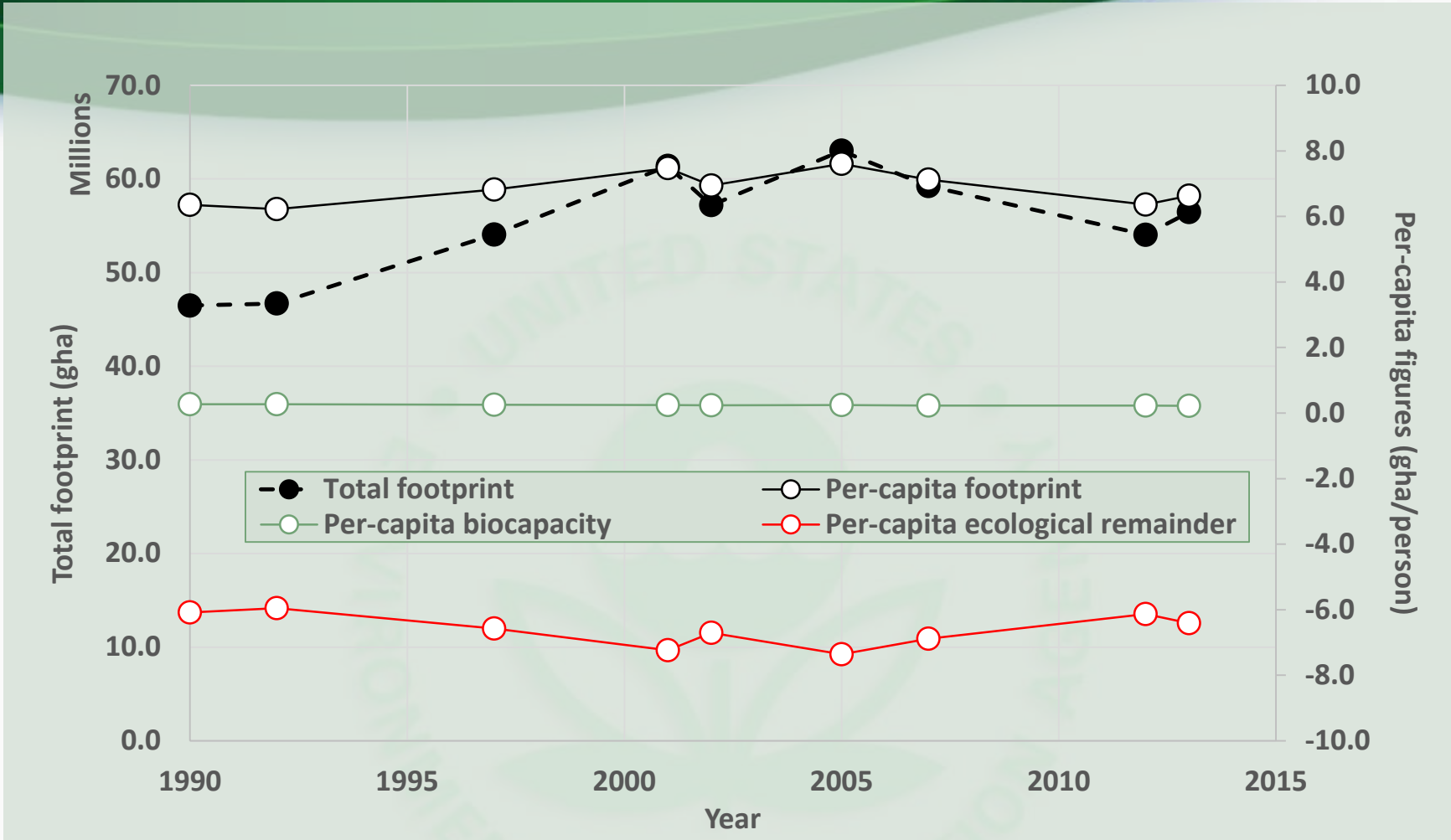
Instances of the computation of CMA's footprint corresponding to beef consumption and CMA's supply of Pasture land in 1990: Similar computations are performed for each consumption item and for each land/space classification to determine the total regional footprint (demand) as well as the total regional supply (biocapacity).

DEMAND - FOOTPRINT	Footprint (ha per capita)	Equivalence factor	Equivalence (gha per capita)
Energy (CO_2-sequestering) land	3.37	1.17	3.94
Built-up land	0.05	2.22	0.11
Arable land	0.07	2.22	0.16
Pasture land	4.21	0.49	2.07
Forest land	0.00	1.35	0.00
Lake space	0.19	0.36	0.07
Totals	**7.90**		**6.35**
SUPPLY - EXISTING METROPOLITAN CAPITAL	**Supply (ha per capita)**	**Yield factor**	**Equivalence (gha per capita)**
Built-up land	0.05	1.42	0.07
Arable land	0.06	1.42	0.08
Pasture land	0.00	1.63	0.01
Forest land	0.02	1.97	0.03
Lake space	0.06	1.28	0.07
Totals	**0.19**		**0.27**
ECOLOGICAL REMAINDER	**-7.71**		**-6.08**

Estimated figures for CMA's total footprint (demand) and total supply (biocapacity) in 1990.

Results and Discussion: EFA

- EFA for CMA has been performed between 1990 and 2013.
- Demand for energy land and pasture land appears to drive footprint figures.
- As an urban area, CMA is inherently a consumer entity; consequently, it exhibits a significant ecological deficit (footprint greater than biocapacity) over the years.
- It is exceedingly difficult to account for every single item consumed in the area; thus, EFA's resolution in determining sustainability will be limited by the availability of data.



Evolution of the demand (footprint), supply (biocapacity), and ecological remainder of CMA between 1990 and 2013: Circles (○) represent the years for which any available land/space data could be obtained from public sources.

Methodology: GNMP

- **Sustainable development**: Development that meets the needs of current generation without compromising the ability of future generations to meet their own (Brundtland Report: Our Common Future 1987)
- Economics: Maintenance of non-declining Utility (consumption) or non-declining wealth over time (Intergenerational fairness).
  - At macro-economy level, Green Net National Product (GNNP) and Genuine Savings (GS) are measures of sustainability.
  - GNNP adjusts GDP for depreciation of man-made capital and Natural Capital.

Methodology: GNMP (Cont'd)

- GNMP: Regional counterpart of GNNP; initial exploration performed in light of the methodologies provided in Pezzey et al. (2006), Heberling et al. (2012), and Wu and Heberling (2016) for national and regional accounts.
  - GMP (Gross Metropolitan Product) is the total value of final goods and services produced in the metropolitan area in a given year.
  - NMP (Net Metropolitan Product) adjusts GMP by incorporating the depreciation of man-made capital.
  - GNMP adjusts NMP by incorporating the costs associated with the degradation of environmental and natural resources.

Model for computing GNMP

$$\underbrace{NMP(t)}_{\text{Net Metropolitan Product}} \approx \underbrace{GMP(t)}_{\text{Gross Metropolitan Product}} - \overbrace{\left[GMP(t) * \left(\frac{CFC_{US}}{GDP_{US}}\right)\right]}^{\text{Depreciation of man-made capital}}$$

$$GNMP(t) = NMP(t) - \underbrace{\boldsymbol{e} \cdot \boldsymbol{E}}_{\text{Pollution}} + \underbrace{(vV - G)}_{\text{Ecosystem}} - \overbrace{R \cdot \dot{\boldsymbol{S}}}^{\text{Rents from resource depletion}} + \underbrace{Q^t}_{\text{Value of time}}$$

R=Price-Marginal Extraction Cost; $\dot{\boldsymbol{S}}$ *= change in resource stock=dS/dt*

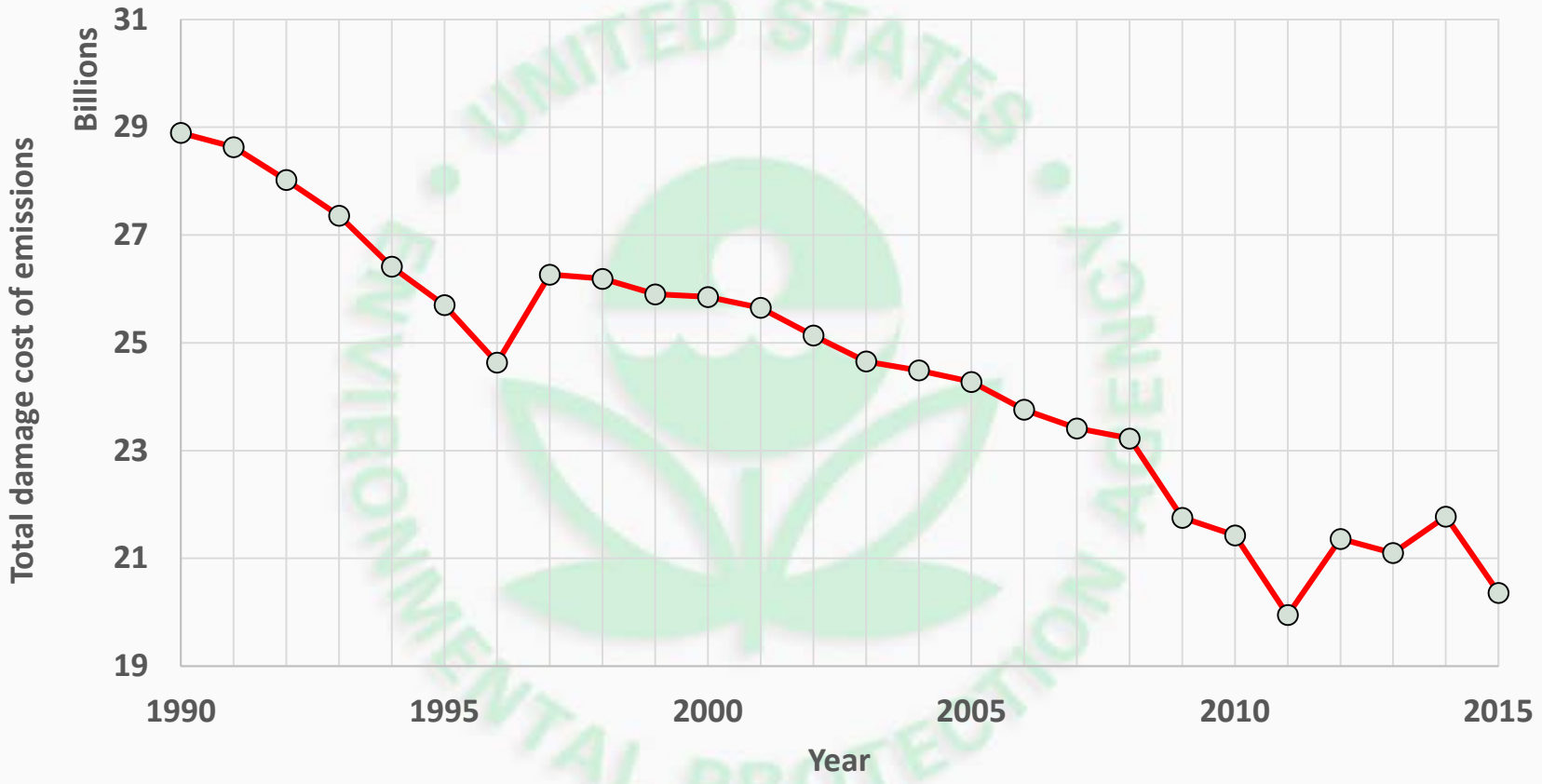
Methodology: GNMP (Cont'd.)

- Vector of pollution emissions, **E**: NO_X, VOC, SO_2, NH_3, particulate matter ($PM_{2.5}$ and PM_{10}), GHG, and landfilled solid waste.
- Vector of pollutant marginal damage costs, **e**: Costs associated to the damages caused by one additional ton of a given pollutant; cost estimation via benefit-transfer approach
- ***v*** marginal Benefit of Environmental Scheme: example Green infrastructure. ***G*** government spending on environmental scheme
- Data sources: National, state, and local sources; missing data estimated by interpolation or extrapolation.

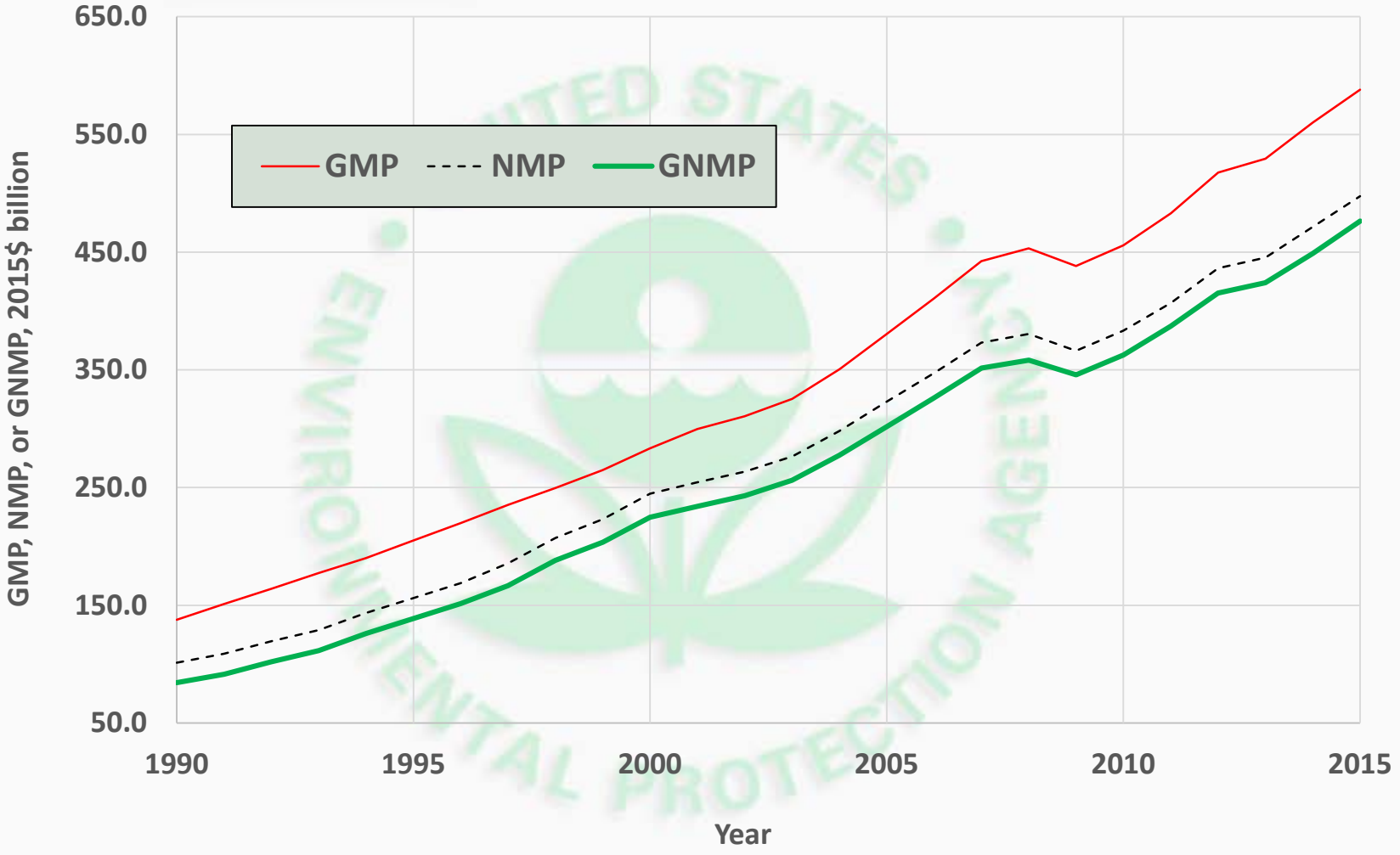
Values of Marginal Damage Costs for Pollutant Emissions

Pollutant	Marginal damage cost per ton	Source
PM_{10}	$500	Muller and Mendelsohn (2007)
VOC	$500	
NH_3	$4,200	
NO_X	$7,600	
SO_2	$48,000	Fann et al., (2012)
$PM_{2.5}$	$320,000	
CO_2	$20	Tol, 2008
Municipal solid waste (landfilled)	$43.50	Miranda and Hale (2005)

Estimated Damage Cost of Associated Emissions and Solid Waste



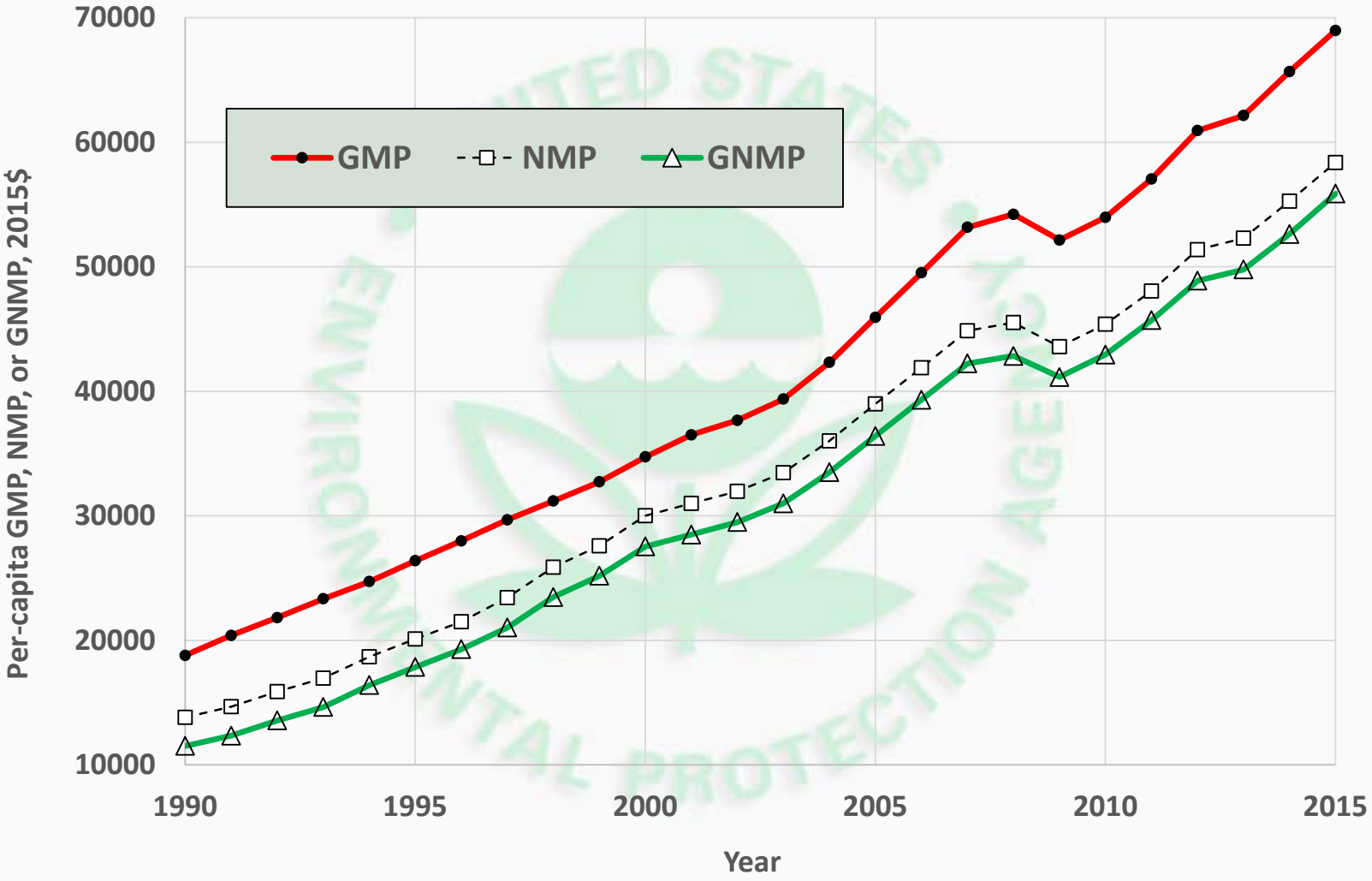
GNMP, 1990 to 2015



Preliminary Results: GNMP

- GNMP for CMA has been computed annually between 1990 and 2015
- GNMP is a weak indicator of weak sustainability (Pezzey et al., 2006); thus, an increasing GNMP indicates that there is no evidence that the region under consideration is unsustainable. A decreasing GNMP indicates that the region is not sustainable.
- GNMP exhibits an increasing trend over the years (Except 2008-2009)

Per-capita GNMP



GNMP as a percentage of GMP and NMP

Year	$\left(\frac{GNMP}{GMP}\right) \times 100$	$\left(\frac{GNMP}{NMP}\right) \times 100$
1990	61.3	83.4
1995	67.6	88.8
2000	79.3	91.8
2005	79.3	93.4
2010	79.6	94.6
2015	81.0	95.7

Summary

- GNMP for CMA has been computed between 1990 and 2015.
- GNMP exhibits an increasing trend over the years
- CMA exhibits a significant ecological deficit
- The capability of EFA and GNMP in representing the sustainability trend of the region will be improved as additional data are incorporated in the calculations.

Future Work

- EFA: Incorporation of additional consumption categories in the next round of calculations depending on their relevance and availability of the corresponding data. Possible adaptation of methodologies in the available literature related to EFA of urban areas, such as Santiago de Chile (Wackernagel, 1998), Piacenza, Italy (Scotti et al., 2009), San Francisco MSA (Moore, 2011), Vancouver (Moore et al., 2013) or various Mediterranean cities (Baabou et al., 2017).
- GNMP: Incorporation of the value of green infrastructure; green-space/urban forest, and groundwater depletion. Incorporation of value of technological progress (value of time) and computation of Genuine Savings (GS).

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Disclaimer

The views expressed in this presentation are those of the authors and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency.

Thank You!

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