NASA Carbon Monitoring System Overview

George Hurtt
NASA-CMS Science Team Leader
Department of Geographical Sciences
University of Maryland
gchurtt@umd.edu

NASA Terrestrial Ecology Meeting
September 23rd – September 25th, 2019
College Park, MD

http://carbon.nasa.gov

nasa.carbon

@NASA_CARBON

Congressional Direction (Summary)

Congressional Direction in 2010:
Also included within the funds provided for other mission and data analysis, the conference agreement provides $6,000,000 for pre-phase A and pilot initiatives for the development of a carbon monitoring system. Any pilot developed shall replicate state and national carbon and

…"pilot initiatives for the development of a carbon monitoring system…"

..."replicate state and national carbon and biomass inventory processes that provide statistical precision and accuracy with geospatially explicit associated attribute data…"

…"development of a prototype Monitoring Reporting and Verification (MRV) system which can provide transparent data products achieving levels of precision and accuracy required by current carbon trading protocols…."

..."[development of] a plan…incorporating such a [MRV] system into its operating plan and long-term budget projection…"

sampling, quantification, and development of a prototype Monitoring Reporting and Verification [MRV] system which can provide transparent data products achieving levels of precision and accuracy required by current carbon trading protocols. The Committee is concerned that NASA has not established a program of record around the development of MRV system, and therefore expects a plan from NASA not later than 90 days after enactment of this act incorporating such a system into its operating plan and long-term budget projection. The Committee recognizes that the current orbital and suborbital platforms are insufficient to meet these objectives. Therefore, the use of commercial off-the-shelf technologies is recommended as these products could provide robust calibration validation datasets for future NASA missions.

NASA-CMS Phase 1

Biomass Pilot. *The goals of the Biomass Pilot are to:*

- Utilize satellite and in situ data to produce quantitative estimates (and uncertainties) of aboveground terrestrial vegetation biomass on a national and local scale.
- Assess the ability of these results to meet the nations need for monitoring carbon storage/sequestration.

Flux Pilot. *The objectives of the Flux Pilot are to:*

- Combine satellite data with modeled atmospheric transport initiated by observationally-constrained terrestrial and oceanic models to tie the atmospheric observations to surface exchange processes.
- Estimate the atmosphere-biosphere CO_2 exchange.

Scoping Efforts. *The objectives of the Scoping Efforts are to:*

- Identify research, products, and analysis system evolutions required to support carbon policy and management as global observing capability increases.

Global Surface-Atmosphere Flux
2011: 2
2013: 3 (2)
2014: 1 (1)
2015: 1 (1)
2016: 2
2018: 2

Land-Atmosphere Flux
2011: 6 (5)
2013: 8 (6)
2014: 2 (2)
2015: 12 (10)
2016: 8 (4)
2018: 3

Land Biomass
2011: 7 (5)
2013: 9 (9)
2014: 9 (7)
2015: 7 (5)
2016: 8 (8)
2018: 6

Ocean-Atmosphere Flux
2011: 1
2016: 1

Ocean Biomass
2011: 3
2016: 1
2018: 3

Land-Ocean Flux
2011: 1
2014: 1 (1)

CMS Solicitation year:
2011: 20
2013: 17
2014: 15
2015: 15
2016: 14
2018: 15

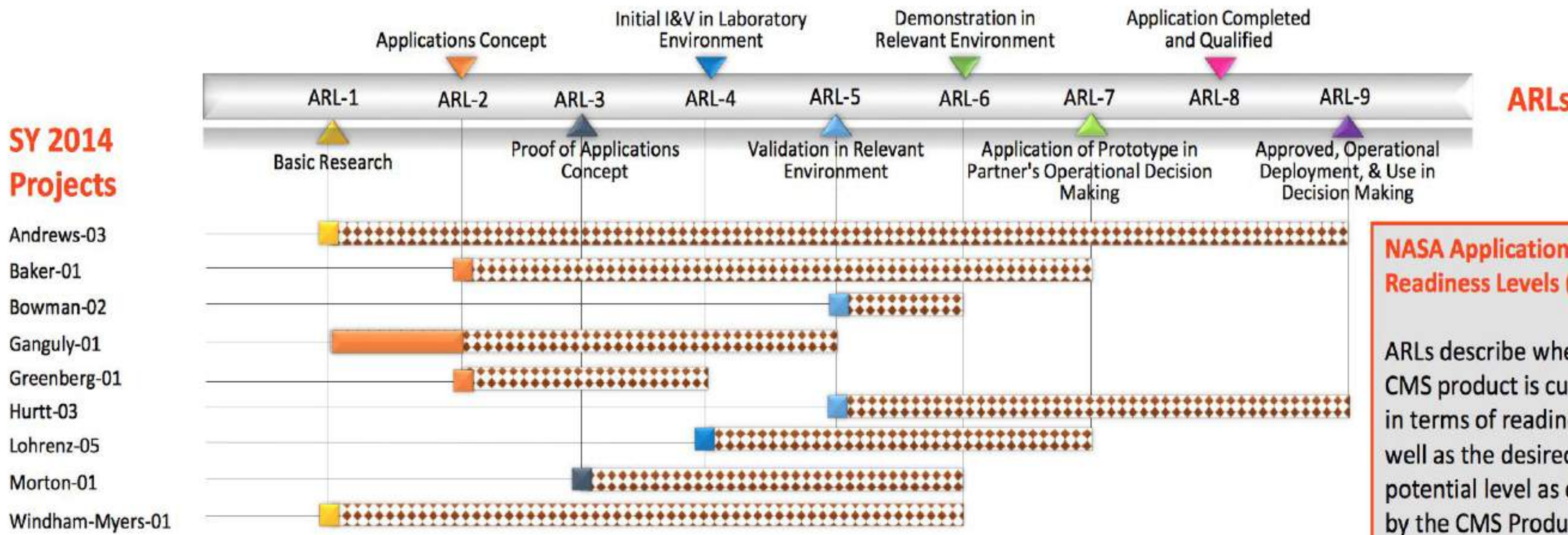
Solicitation Year and Themes Addressed

Year	Land biomass	Ocean biomass	Land-Atmos. Flux	Ocean-Atmos. Flux	Land-Ocean Flux	Global Flux	Decision Support	MRV	Atmos. Transport
2010	20%	20%	20%	40%	40%	20%	0%	0%	0%
2011	45%	15%	55%	30%	5%	10%	35%	15%	15%
2013	76%	0%	71%	0%	0%	0%	18%	82%	12%
2014	67%	0%	89%	27%	20%	20%	60%	80%	27%
2015	53%	0%	73%	0%	0%	7%	20%	100%	13%
2016	57%	7%	57%	7%	0%	14%	7%	50%	14%
2018	40%	13%	20%	0%	0%	13%	7%	60%	0%

Participants by Organization Type and Country

TYPE (# unique)	US	Can	UK/EU	Brazil	Mexico	Gabon	Indonesia	Total
University (43)	82	1	3	1	3		1	91
National (19)	102		2	2	1	1		108
State (2)	3							3
Private (11)	16		1					17
NGO (7)	10			1	2			14
Total	**213**	**1**	**7**	**3**	**7**	**1**	**1**	**233**

CMS Application Readiness Levels (ARLs)



Fatoyinbo-01
Hudak-01
Jacob-02
Ott-01
Walker-W-01
Williams-C-01

Different ARLs are provided for the products in these projects. Refer to individual corresponding charts describing the product ARLs.

Project ID
PI-Project # (Andrews-02)-Each CMS Project is represented by its color and identified by the PI on the project

Solid color: each solid bar is indicative of where the PI feels their project is NOW in terms of application readiness.

Pattern fill: indicates the level each PI is striving for and the application readiness level they feel their project can ultimately satisfy.

Gradient fill: indicates current level has not been reached fully.

NASA Application Readiness Levels (ARLs)

ARLs describe where the CMS product is currently in terms of readiness, as well as the desired and potential level as defined by the CMS Product Scientist.

The ARLs were provided by the CMS Product Scientist and represent the most accurate representation of the state of each product.

Products can start at any level. It is not expected they will start at ARL1 and end at ARL9.

CMS Products and Policy Support Examples

CMS PI and Product	Organization & POC	Policy of Interest
Fatoyinbo-01 Mangrove canopy height	**USDA Forest Service**, Carl Trettin	REDD+, Le Gabon Emergent, Gabon Forest Carbon Assessment, Silvacarbon, GEO-FCT
Hudak-01 Aboveground biomass maps	**Northwest Management, Inc.**, Mark Corrao	Forest Vegetation Simulator (FVS), SilvaCarbon, REDD+, NACP, IPCC
Hurtt-03 Aboveground biomass maps, canopy height and forest/non-forest maps, land cover maps	**Maryland Department of Natural Resources**, Christine Conn and Rob Feldt	FIA, Federal Land Policy and Management Act (FLPMA), Maryland Greenhouse Gas Emissions Reduction Act Plan, Maryland Climate Action Plan, Chesapeake Bay TMDL, Maryland Forest Preservation Act, Maryland No Net Forest Loss Act, Climate Framework for Delaware, Forest Legacy Program, Pennsylvania Climate Change Act, TreeVitalize Program
Jacob-02 Gridded inventory of North American methane emissions	**U.S. EPA**, Bill Irving	Global Climate Change and Clean Air Initiative of the US State Department, Global Methane Initiative of the US EPA, CAA, NGHGI, President Obama's Climate Action Plan (CAP), NALS, national methane inventory reports to UNFCCC
Windham-Myers-01 Maps of coastal wetland carbon stocks	**U.S. EPA**, Tom Wirth	REDD+, NGHGI, Global Methane Initiative of the US EPA, Blue Carbon Initiative, Coastal Wetland Planning, Protection, and Restoration Act, NOAA Habitat Restoration Monitoring

CMS Products and Policy Support Examples Con't

CMS PI and Product	Organization & POC	Policy of Interest
Cochrane-01 Estimates of burned area, land cover changes, peat fire-related emissions, timing of fire activity	**Indonesia Ministry of Environment and Forestry**, Israr Albar	REDD+, Indonesian National Carbon Accounting System (INCAS), Mega Rice Project (MRP), NFMS, US-Indonesia Partnership, Indonesia-Australia Forest Carbon Partnership, Doha/Kyoto
Dubayah-04 Canopy height and forest/non-forest maps for Sonoma County	**Sonoma County Agriculture & Open Space Preservation District**, Tom Robinson and Karen Gaffney	REDD+, Sonoma County initiatives, California Assembly Bill 32: Global Warming Solutions Act (CA-AB32), CAP
Duren-01 Carbon Mapper and white papers	**California Air Resources Board**, Bart Croes **U.S. Department of State**, David Reidmiller	Many (multi- and bi-lateral international agreements; domestic regulation and voluntary programs; sub-national federations; private markets)
Morton-02 & Cook-03 Maps of carbon stocks with pixel-level carbon estimates	**USDA Forest Service**, Hans Andersen	FIA, FLPMA
Nehrkorn-01 DARTE Annual On-road CO2 Emissions on a 1-km Grid	**Providence City Hall**, Leah Bamberger	City emissions inventories, RGGI, C40 Cities Climate Leadership Group, ICLEI Local Governments for Sustainability, FLPMA, CAA

- 418 unique publications (papers, book chapters)
  - 34 publications in Nature, Science and PNAS including 16 currently on the NACP Citations Classics list with over 100 citations

- Baccini, A., Walker, W., Carvalho, L., Farina, M., Sulla-Menashe, D., Houghton, R. A. **2017**. Tropical forests are a net carbon source based on aboveground measurements of gain and loss. Science. 358(6360), 230-234. doi: 10.1126/science.aam5962 *(Baccini (CMS 2015) Walker (CMS 2014))*
- Bond-Lamberty, B., Bailey, V. L., Chen, M., Gough, C. M., Vargas, R. **2018**. Globally rising soil heterotrophic respiration over recent decades. Nature. 560(7716), 80-83. doi: 10.1038/s41586-018-0358-x *(Vargas (CMS 2016))*
- Hengl, T., Mendes de Jesus, J., Heuvelink, G. B. M., Ruiperez Gonzalez, M., Kilibarda, M., Blagotic, A., Shangguan, W., Wright, M. N., Geng, X., Bauer-Marschallinger, B., Guevara, M. A., Vargas, R., MacMillan, R. A., Batjes, N. H., Leenaars, J. G. B., Ribeiro, E., Wheeler, I., Mantel, S., Kempen, B. **2017**. SoilGrids250m: Global gridded soil information based on machine learning. PLOS ONE. 12(2), e0169748. doi: 10.1371/journal.pone.0169748 *(Vargas (CMS 2013)*, **)** NACP Citation Classic with 317 Citations
- Houghton, R. A., House, J. I., Pongratz, J., van der Werf, G. R., DeFries, R. S., Hansen, M. C., Le Quere, C., Ramankutty, N. **2012**. Carbon emissions from land use and land-cover change. Biogeosciences. 9(12), 5125-5142. doi: 10.5194/bg-9-5125-2012 *(Houghton (CMS 2011)*, NACP Citation Classic with 394 Citations
- Sargent, M., Barrera, Y., Nehrkorn, T., Hutyra, L. R., Gately, C. K., Jones, T., McKain, K., Sweeney, C., Hegarty, J., Hardiman, B., Wofsy, S. C. **2018**. Anthropogenic and biogenic CO2fluxes in the Boston urban region. Proceedings of the National Academy of Sciences. 115(29), 7491-7496. doi: 10.1073/pnas.1803715115 *(Nehrkorn (CMS 2015))*
- Olofsson, P., Foody, G. M., Herold, M., Stehman, S. V., Woodcock, C. E., Wulder, M. A. **2014**. Good practices for estimating area and assessing accuracy of land change. Remote Sensing of Environment. 148, 42-57. doi: 10.1016/j.rse.2014.02.015 *(Stehman (CMS 2013)*, NACP Citation Classic with 518 Citations

NASA's Approach to CMS/MRV

- Recognizes that a sustained, observationally-driven carbon monitoring system using remote sensing data has the potential to significantly improve the relevant information base for the U.S. and world;
- Recognizes multiple users, multiple scales, multiple quantities, and multiple frameworks for MRV (e.g. International, national and subnational, markets);
- Recognizes the importance of user engagement to be responsive to stakeholder needs;

The goal for NASA's CMS project is to prototype the development of carbon monitoring capabilities needed to support stakeholder needs for MRV.

*NASA-CMS (2014) Progress Report

Lidar Facilitates Aboveground Biomass Carbon (AGBC) Estimation Across Space And Time

P. Fekety, M. Falkowski, A. Hudak (PI) (Project: 14-CMS14-0026; Award: NNH15AZ06I)

Background:
Regional forest planning is challenging for USFS managers faced with budget constraints.

Analysis:
Evaluated transferability of lidar-derived AGBC estimates from models trained with plot data that were collected neither locally (Fig. 1) nor contemporaneously (Fig. 2).

Findings:
Losses in accuracy and precision from AGBC models based on spatially or temporally disjunct observations are acceptable.

Significance:
Given consistently processed lidar collections, inventory plot data can be leveraged broadly in space and time to more efficiently manage regional forest AGBC sequestration.

Fig. 1. Six spatially disjunct project areas with lidar and forest inventory plot data.

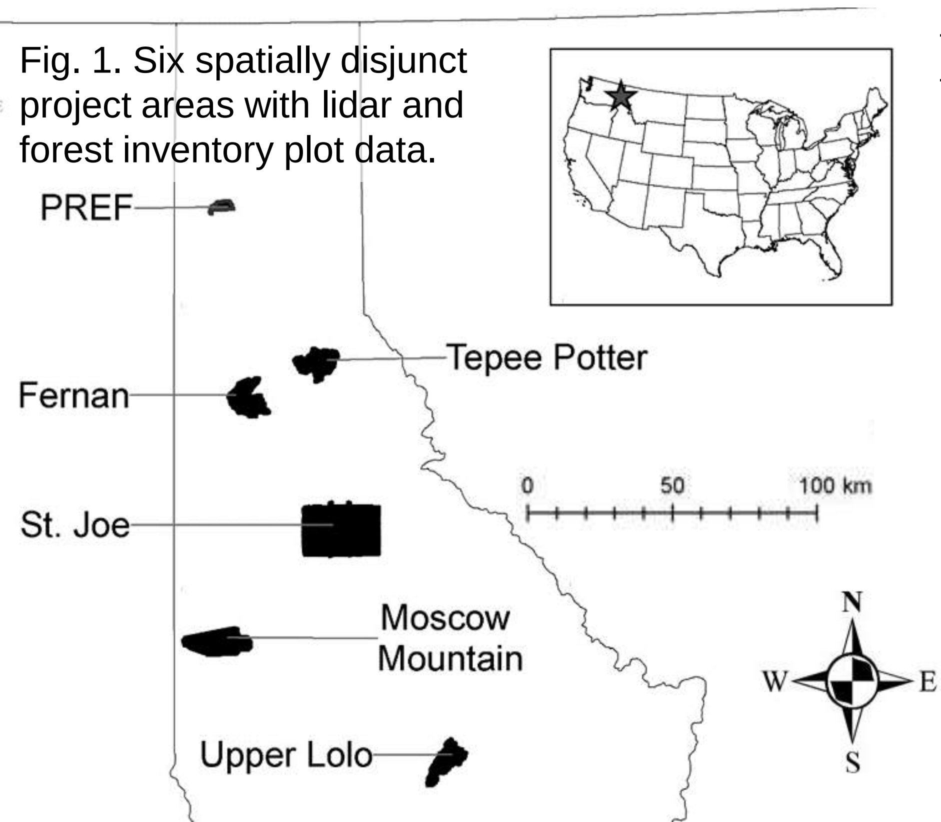
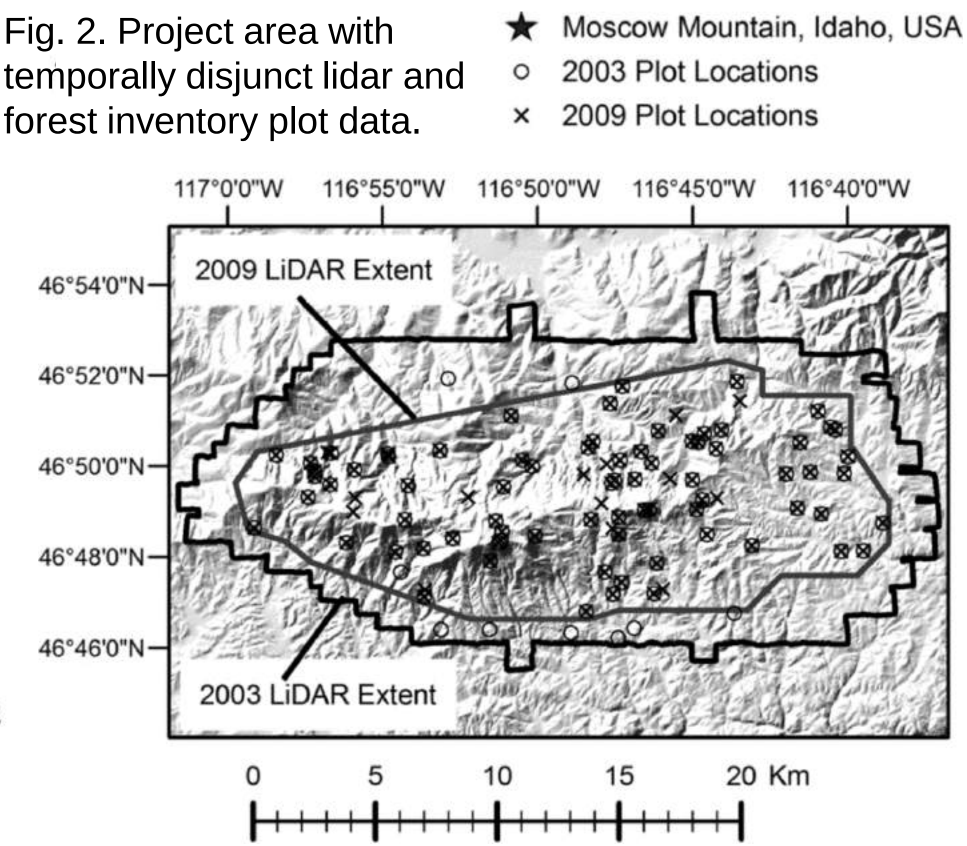


Fig. 2. Project area with temporally disjunct lidar and forest inventory plot data.



A Comparison of Mangrove Canopy Height Using Multiple Independent Measurements from Land, Air, and Space

David Lagomasino, Temilola Fatoyinbo, SeungKuk Lee, Emanuelle Feliciano, Carl Trettin & Marc Simard

Tree height is a strong predictor of biomass in forests. Very high resolution optical (VHR) and TanDEM-X radar (TDX) satellite imagery can be used to create highly accurate canopy models for remote mangrove forests, providing a step forward for repeat and cost-effective measures for monitoring Blue Carbon ecosystems.

- Repeat 3D models highlight the importance of developing height-based allometric equations
- Vertical accuracy (±2m) of VHR and TanDEM-X canopy models allow for cost-effective monitoring compared to airborne lidar

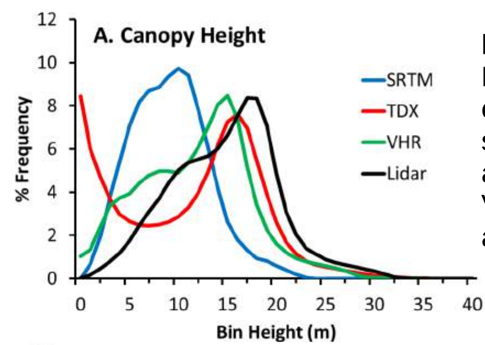


Figure 1
Height distributions for each of the remote sensing models. There is a close match between VHR, TanDEM-X (TDX), and airborne lidar

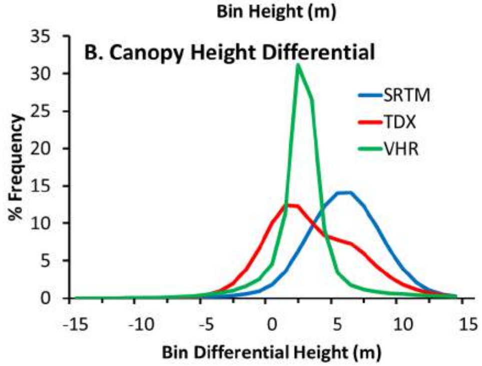


Figure 2
Distribution of the height differences between airborne lidar and each of the spaceborne models; SRTM, VHR, and TDX.

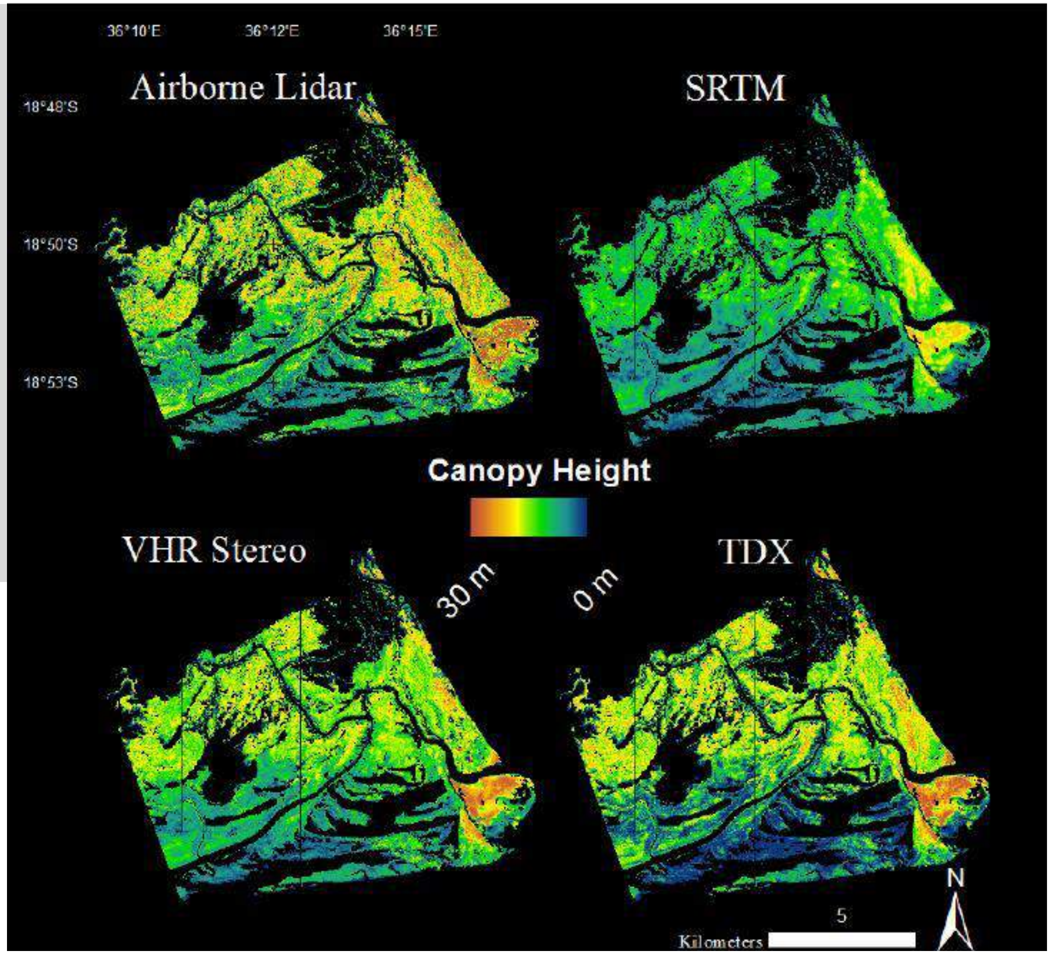


Figure 3: Four canopy height maps for the Zambezi delta modeled using four different sensors: airborne lidar, SRTM, very-high resolution (VHR) and TanDEM-X (TDX). VHR and TDX canopy models closely match height estimates from airborne lidar.

Supported by the NASA Carbon Monitoring System Program

Remote Sensing. **2016**, *8*(4), 327; doi:10.3390/rs8040327

National Aeronautics and Space Administration

NASA Carbon Monitoring System

UNIVERSITY OF MARYLAND

Beyond MRV: High-resolution forest carbon modeling for climate mitigation planning over Maryland, USA

Hurtt, G., Zhao, M., Sahajpal, R., Armstrong, A., Birdsey, R., Campbell, E., Dolan, K.A., Dubayah, R., Fisk, J.P., Flanagan, S.A., Huang, C., Huang, W., Johnson, K., Lamb, R., Ma, L., Marks, R., O'Leary, D., O'Neil-Dunne, J., Swatantran, A., Tang, H., 2019. *Environmental Research Letters*.
https://doi.org/10.1088/1748-9326/ab0bbe

Science Questions

- How can we accurately monitor current forest cover and carbon stocks to aid policy efforts aimed at reducing deforestation and degradation as well as increasing afforestation and reforestation for climate mitigation?
- How can ecological modeling quantitatively estimate future carbon sequestration potential in response to land-use and management decisions?

Analysis

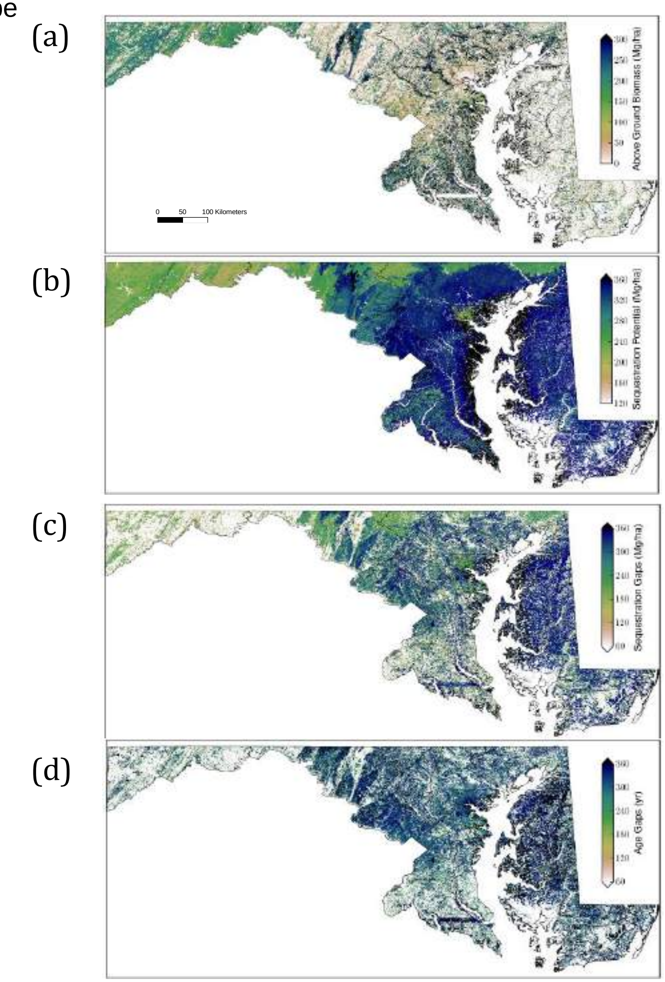
The study presents a new forest carbon monitoring and modeling system that combines high-resolution remote sensing of forest height, field data, optical remote sensing and ecological modeling (Ecosystem Demography model). We estimate contemporary above-ground forest carbon stocks, and project future forest carbon sequestration potential for the state of Maryland at 90 m resolution, over approximately 3.2 million grid cells. This is nearly 100,000 times the resolution at which global carbon models are run.

Results

In Maryland, the contemporary above-ground carbon stock was estimated to be 110.8 Tg C (100.3-125.8 Tg C). The forest above-ground carbon sequestration potential for the state was estimated to be much larger at 314.8 Tg C, and the forest above-ground carbon sequestration potential gap was estimated to be 204.1 Tg C, nearly double the current stock. The time needed to reach this potential, or carbon sequestration potential time gap was estimated to be 228 years statewide, with 50% of the gap being realized in 80 years. These results imply a large statewide potential for future carbon sequestration from afforestation and reforestation activities.

Significance

With this approach, it is now possible to quantify both the forest carbon stock and future carbon sequestration potential over large policy relevant areas with sufficient accuracy and spatial resolution to significantly advance planning. These data products are now being used by the state of Maryland to plan for the Greenhouse Gas Reduction Act (GGRA). With the launch of NASA-GEDI mission, these analyses can be scaled to national, continental and global domains.



a) AGB Spatial pattern of 90-m biomass estimated by Lidar-initialized ED
b) CSP Map of carbon sequestration potential estimated by Lidar-initialized ED
c) CSPG Map of gap to carbon sequestration potential estimated by Lidar-initialized ED
d) CSPTG Map of carbon sequestration potential time gap estimated by Lidar-initialized ED

Predicting biomass over large areas from GEDI lidar footprints

Patterson, P. L., Healey, S. P., Ståhl, G., Saarela, S.,and others. (2019). Statistical properties of hybrid estimators proposed for GEDI—NASA's Global Ecosystem Dynamics Investigation. Environmental Research Letters, 14(6)

Science Question

NASA's GEDI (Global Ecosystem Dynamics Investigation) Mission uses lidar to sample the Earth's surface at 25-m footprints (see figure). GEDI needs a method for making statistically viable biomass estimates for larger areas, accounting for uncertainty due to GEDI's sample and the fact that biomass is modeled, not measured, at each GEDI footprint.

Analysis

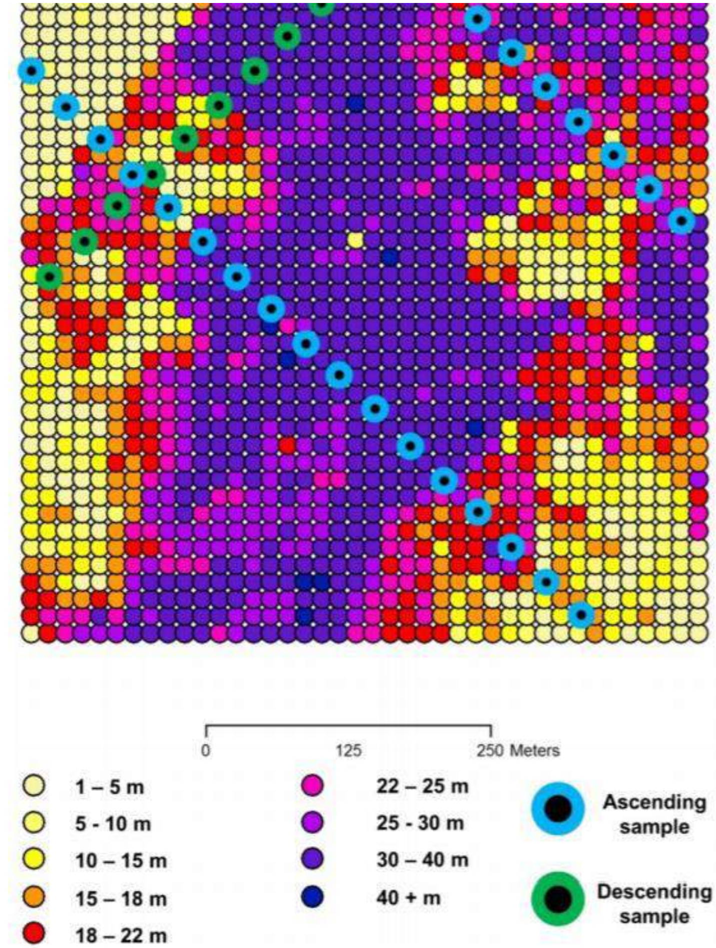
Using airborne lidar collected under a preceding CMS project (Cohen, 2012), we simulated GEDI waveforms and tested an approach to biomass inference called hybrid model-based estimation.

Results

Hybrid estimates of mean biomass are unbiased in the GEDI context, and estimates of the variance around those means are asymptotically unbiased (slightly low when only two or three overpasses are available).

Significance

Hybrid inference appropriately accounts for two important sources of uncertainty: how accurately GEDI predicts biomass at the footprint level; and how much of the target area is actually measured. Like all remote sensing-based approaches, hybrid inference is limited by a lack of field data in some areas.



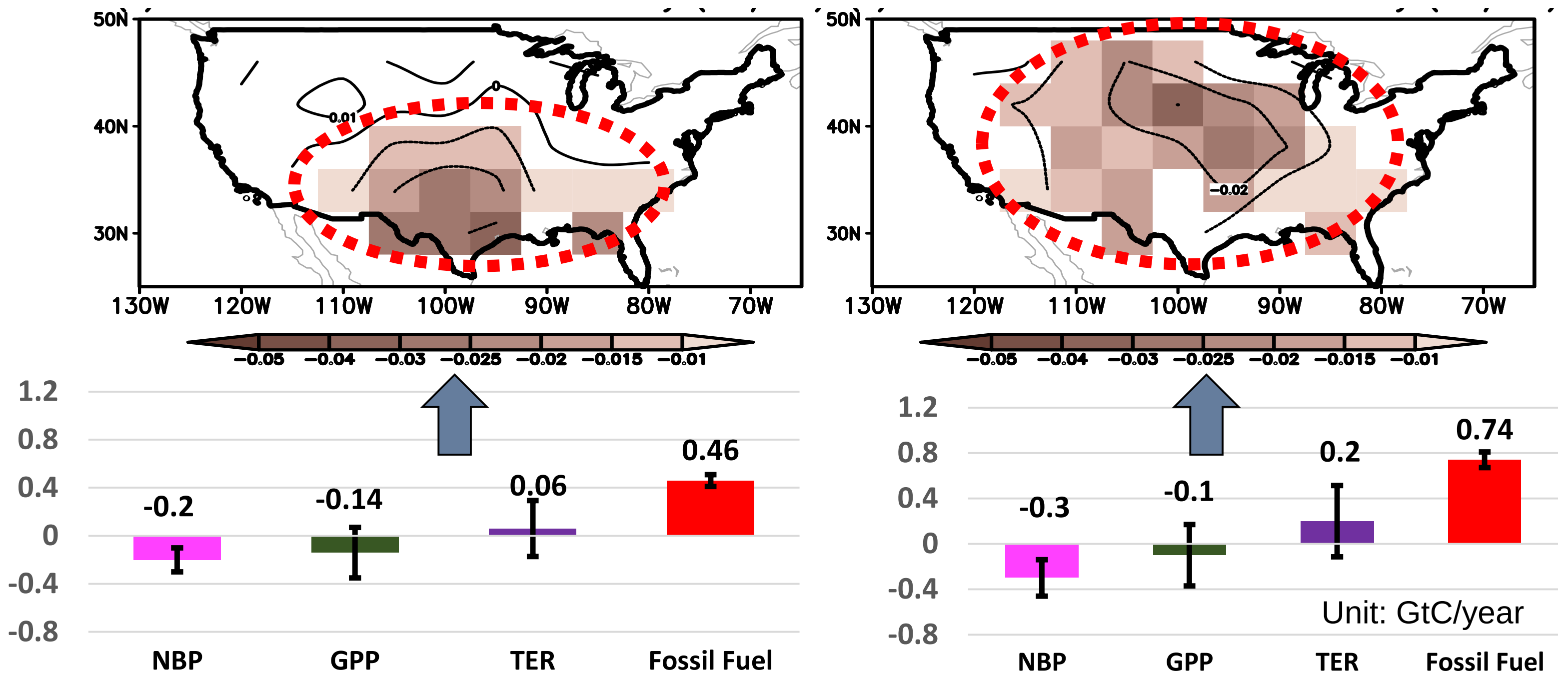
GEDI's lidar based system will provide 25-m measurements of canopy height in a lattice pattern around the world. Our work shows that hybrid inference is an appropriate way to use those measurements to infer biomass in larger areas.

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Detecting drought impact on terrestrial biosphere carbon fluxes over contiguous US with satellite observations

Liu, J. et al. (2018), Environ. Res. Lett., Vol 3

2011 mean soil moisture anomaly **2012 mean soil moisture anomaly**



Brown color indicates drought impacted region.

Biosphere carbon flux anomalies from drought in comparison to regional fossil fuel emissions.

Science Question: The 2011 dry spell in Texas was the worst one-year period of drought since 1895, and the area span of 2012 summer drought was comparable to the dust bowl era. Liu et al addressed the following questions: 1) What are the impacts of these two severe droughts on terrestrial biosphere net biosphere production (NBP)? 2) what are the driving processes (growth vs. decomposition)? 3) How significant of the biosphere flux anomaly relative to regional fossil fuel emissions?

Data and Results: We used NASA CMS-Flux inversion system to infer monthly NBP and GPP from GOSAT B7.3 xCO2 and Solar induced fluorescence (SIF) over 2010-2015, calculating TER as a residual. Over the drought impacted region, the annual NBP decreased by 0.2 ± 0.1 GtC and 0.3 ± 0.16 GtC respectively in 2011 and 2012, equal to 40% of the mean fossil fuel emission over these regions. About half of the NBP reduction was due to a decrease of GPP, and the other half was due to an increase of respiration.

Significance: The large magnitude of natural biosphere carbon flux anomalies relative to regional fossil fuel emissions indicate that any mitigation policy to reduce regional contributions to atmospheric CO_2 growth needs to consider the interannual variability and long-term trend of the natural carbon cycle.

Spatio-temporally resolved methane fluxes from the Los Angeles Megacity

Yadav, V., Duren, R., Mueller, K., Verhulst, K. R., Nehrkorn, T., Kim, J., et al. (2019). Spatio-temporally resolved methane fluxes from the Los Angeles megacity. Journal of Geophysical Research: Atmospheres, 124, 5131–5148.https://doi.org/10.1029/2018JD030062

Science Focus/Objectives

1. Characterize basin and sub-basin scale temporal variability in fluxes including the onset and disappearance of large CH_4 sources in SoCAB and Los Angeles Megacity,
    - Aliso Canyon Natural Gas Leak Anomaly and closure of Puente Hills Landfill
2. Identify the spatial locations sources of major CH_4 emissions in the basin,
    - Hot-spots and cold-spots of emissions
3. Evaluate the ability of a relatively sparse measurement network to update fluxes and identify spatio-temporal anomalies.
    - Fluxes constraints by the network

Methodology (Inverse Modeling)

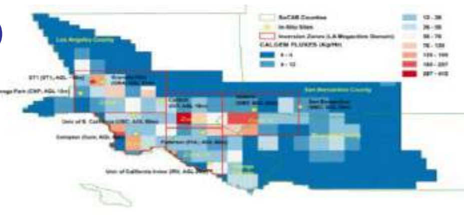
$$L_{\mathbf{s},\boldsymbol{\beta}} = \frac{1}{2}(\mathbf{z}-\mathbf{Hs})^T\mathbf{R}^{-1}(\mathbf{z}-\mathbf{Hs}) + \frac{1}{2}(\mathbf{s}-\mathbf{X}\boldsymbol{\beta})^T\mathbf{Q}^{-1}(\mathbf{s}-\mathbf{X}\boldsymbol{\beta}) \quad (1)$$

$\mathbf{z}_{(n,1)}$ are hourly CH_4 measurements, $\mathbf{H}_{(n,p)}$ is a Jacobian matrix representing the sensitivity of measurements to underlying flux, $\mathbf{s}_{(p,1)}$ are the CH_4 fluxes to be estimated, $\mathbf{R}_{(n,n)}$ is the model-data mismatch error covariance matrix, $\mathbf{X}_{(p,k)}$ is a matrix of covariates, $\boldsymbol{\beta}_{(k,1)}$ are the coefficients or weights of individual covariates to be estimated, and $\mathbf{Q}_{(p,p)}$ is the error covariance matrix (aka prior covariance) that describes the deviations of $\mathbf{s}$ from $\mathbf{X}\boldsymbol{\beta}$.

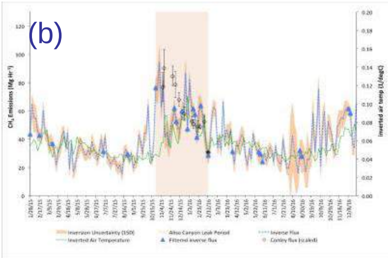
- Transport: WRF-STILT
- Non-negativity constraint: Lagrange Multiplier
- Uncertainty: Simulations
- Result Evaluation: RMSE, Correlation Coefficient, Reduced Chi-Square and Model Resolution (Averaging Kernel) matrix

Results

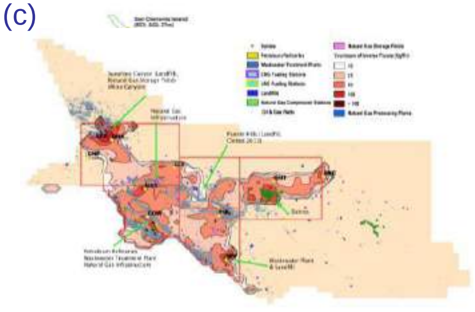
(a)



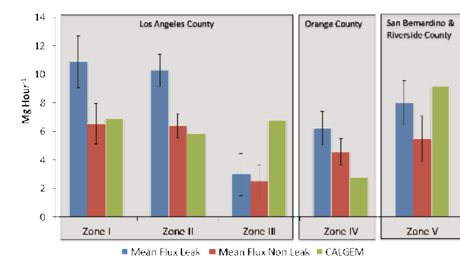
(b)



(c)



(d)



Conclusions

1. The onset of the Aliso Canyon leak was captured by inversions. However, sustained contribution of the leak to basin CH_4 emissions was not captured due to limited sensitivity of the network to the leak location.
2. The closure of the Puente Hills landfill that represents a policy decision was captured in inversions and we are not aware of any other regional inverse modeling study (not based on dedicated aircraft flights) that has accomplished this in an area with a dense CH_4 emanating infrastructure such as SoCAB.
3. Spatially, the study utilized model resolution matrix to identify sources of major emissions in the basin. These sources were aligned with facilities identified with infrastructure inventory
4. The study also reaffirmed existing theories that a fraction of variability in enhancement and emissions in the basin is correlated with air temperature and energy demand.

Key Questions for CMS Phase 2 Report

- What have NASA-CMS projects attempted in Phase 2?
- What major results/findings have been made?
- What major gaps, uncertainties, remain?
- What are the recommended next steps?