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The NASA Carbon Monitoring System Phase 2 synthesis: scope, findings, gaps and recommended next steps

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Supplementary material for this article is available [online](#)

Abstract

Underlying policy efforts to address global climate change is the scientific need to develop the methods to accurately measure and model carbon stocks and fluxes across the wide range of spatial and temporal scales in the Earth system. Initiated in 2010, the NASA Carbon Monitoring System is one of the most ambitious relevant science initiatives to date, exploiting the satellite remote sensing resources, computational capabilities, scientific knowledge, airborne science capabilities, and end-to-end system expertise that are major strengths of the NASA Earth Science program. Here we provide a synthesis of ‘Phase 2’ activities (2011–2019), encompassing 79 projects, 482 publications, and 136 data products. Our synthesis addresses four key questions: What has been attempted? What major results have been obtained? What major gaps and uncertainties remain? and What are the recommended next steps? Through this review, we take stock of what has been accomplished and identify future priorities toward meeting the nation’s needs for carbon monitoring reporting and verification.

1. Introduction

Anthropogenic emissions of greenhouse gases are the highest in history, and changes in the Earth’s climate are having widespread impacts on both natural and human systems. In response, local, state, national, and international policies are in discussion and under development to reduce greenhouse gas emissions in the future. Foundational to these efforts is the scientific ability to accurately measure, and model, carbon stocks and fluxes throughout the Earth system and across a range spatial and temporal scales.

Initiated in 2010, a congressional appropriation directed NASA to initiate work towards a carbon monitoring system (CMS) and provided specific guidance. The approach NASA developed in following these directions emphasized exploitation of the satellite remote sensing resources, scientific knowledge, and end-to-end system expertise that are major strengths of the NASA Earth Science program. The approach also took into account data and expertise that are the domain of other U.S. Government agencies and anticipates close communications and/or partnerships with those agencies and their

scientific and technical experts. Additionally, it laid the groundwork for CMS-related applications of current and future satellite sensors.

In Phase 1 (2010–2012), NASA's CMS activities were directed through NASA centers and involved two pilot studies and two scoping efforts (Hurtt *et al* 2014a). The Biomass Pilot focused on quantifying the terrestrial vegetation aboveground carbon stock using consistent approaches and performing uncertainty analyses on its magnitude and spatial distribution. The initial emphasis was on production and evaluation of both local and U.S.-wide biomass products. The Flux Pilot produced an integrated emission/uptake product through a combination of space-based measurements of atmospheric carbon dioxide, carbon cycle models and assimilation systems, and information about the processes that couple the surface to the atmosphere. Scoping studies focused on quantifying carbon in the oceans and the potential of NASA products to meet policy and decision-making requirements. In addition, more than a dozen Science Definition Team Projects were carried out. This work was synthesized in the Phase 1 Report (Hurtt *et al* 2014a).

In Phase 2 (2011–2016), consistent with Congressional direction, NASA took steps to ensure substantial external (i.e. non-government) participation in CMS research by requiring individual projects to have greater than 50% of their funding directed to activities within external organizations. New projects were competitively selected to build upon initial efforts, with a large expansion in prototyping activities across a diversity of systems, scales, and regions, including research focused on prototype monitoring, reporting, and verification (MRV) systems for specific carbon management projects. In 2013, studies were added to advance MRV-relevant studies in support of reducing emissions from deforestation and degradation (REDD) and REDD+ projects, and the U.S. SilvaCarbon program, using commercial off-the-shelf technologies. Selections in 2014 included studies to improve the CMS biomass and flux products and to conduct new MRV-relevant projects at local to regional scales, including several state-level biomass mapping projects within the U.S. and projects to quantify carbon in coastal ecosystems relevant to 'blue carbon' objectives of reducing carbon emissions by conserving and sustainably managing a coastal carbon sink. In 2014, a congressionally mandated report documented NASA's approach to MRV (Hurtt *et al* 2014b). The report summarized progress to date within the Carbon Monitoring System project and described NASA's longer term strategy for CMS and its vision regarding NASA's role in MRV. In 2015 and 2016, project selections continued to advance biomass mapping efforts, flux quantification, and blue carbon mapping. Throughout, work was conducted to improve the characterization

of errors and uncertainties in existing products and to engage stakeholders, identify their needs, and seek inputs on the value of CMS prototype products.

In all, during Phase 2 NASA supported 79 projects prototyping carbon monitoring activities around the world, in every major component of the Earth system, and linked to a diverse set of stakeholders and applications across a variety of domains. The effort represents one of the largest and most ambitious collections of applied carbon monitoring research created around the world. The goal of this paper is to synthesize the results from all completed Phase 2 projects into summary findings relevant to the program and the broader scientific community.

2. Methods

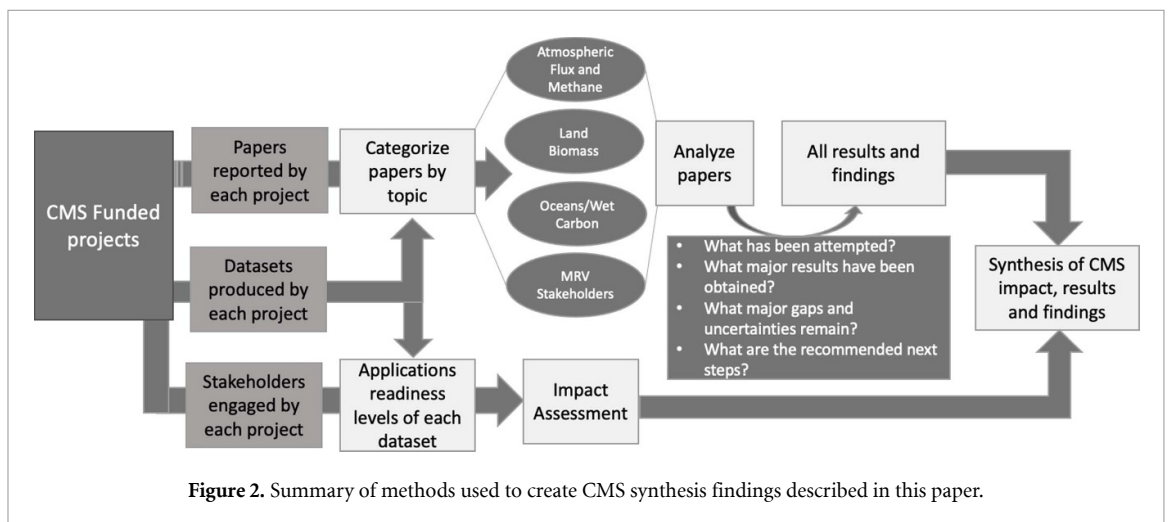
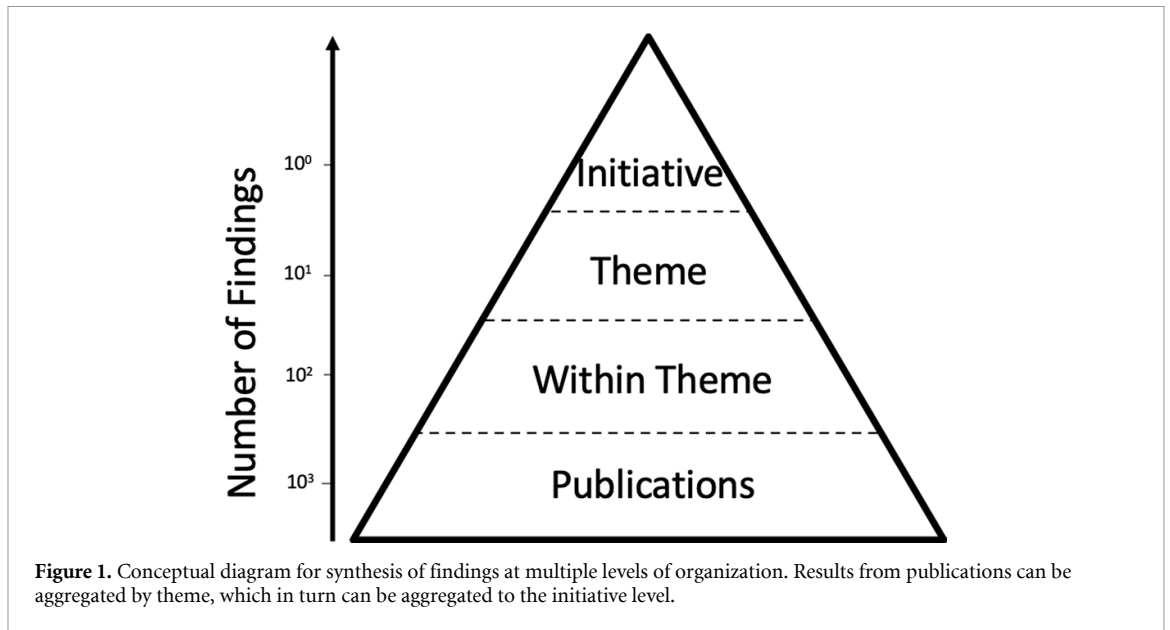
The scope of this report includes all CMS Phase 2 projects, publications, and archived data products as of August 2021. This included all projects initiated between 2011 and 2016 and completed as of this report.

To conduct the synthesis, we reviewed the CMS products hierarchically first within theme, then by theme, and finally at the initiative level (figure 1). More specifically, we collected a comprehensive set of all projects and their resulting publications and archived datasets and stakeholders (figure 2). To organize the analysis, each project, publication, and data product was assigned a primary theme based on the science being completed. Primary themes included: land biomass, atmospheric flux and methane, stakeholder, and oceans/wet carbon. For each product, we also analyzed important metrics including domain, resolution, citation, downloads, and application readiness level (ARL).

ARL is an index adapted from the NASA technology readiness levels in order to track and guide application efforts of NASA funded projects such as those under the CMS program. The levels range from 1–basic science to 9–in mature and in operational use. These levels are used as a communication tool to give a clear picture of the current and projected 'readiness' of each CMS projects' involvement in decision-making and operational platforms. Products are assigned ARLs by the principal investigator annually and change as the products mature and are used in different ways by stakeholders. We measure the change in product maturity by comparing the ARL at the start of the project to those at the end.

A subset of experts was then assigned to each of the primary themes to review the products in that theme and developed detailed findings centered around four key questions:

- What have NASA-CMS projects attempted in Phase 2?
- What major results and findings have been made?



- What major gaps and uncertainties remain?
- What are the recommended next steps?

The findings were then further aggregated to initiative level. Finally, feedback was sought from the community during sessions at the CMS Science Team Meeting in November 2019 and at the AGU Fall Meeting in December 2019.

3. Results

First, a series of quantitative summary metrics were calculated to describe CMS projects, and products. These metrics are presented below.

3.1. Summary metrics

In total, CMS Phase 2 consisted of 79 projects, and resulted in 482 publications and 136 data products (table 1). Biomass represented the largest theme, with 37 projects, 252 publications and 59 archived data products. Atmosphere flux was second largest and

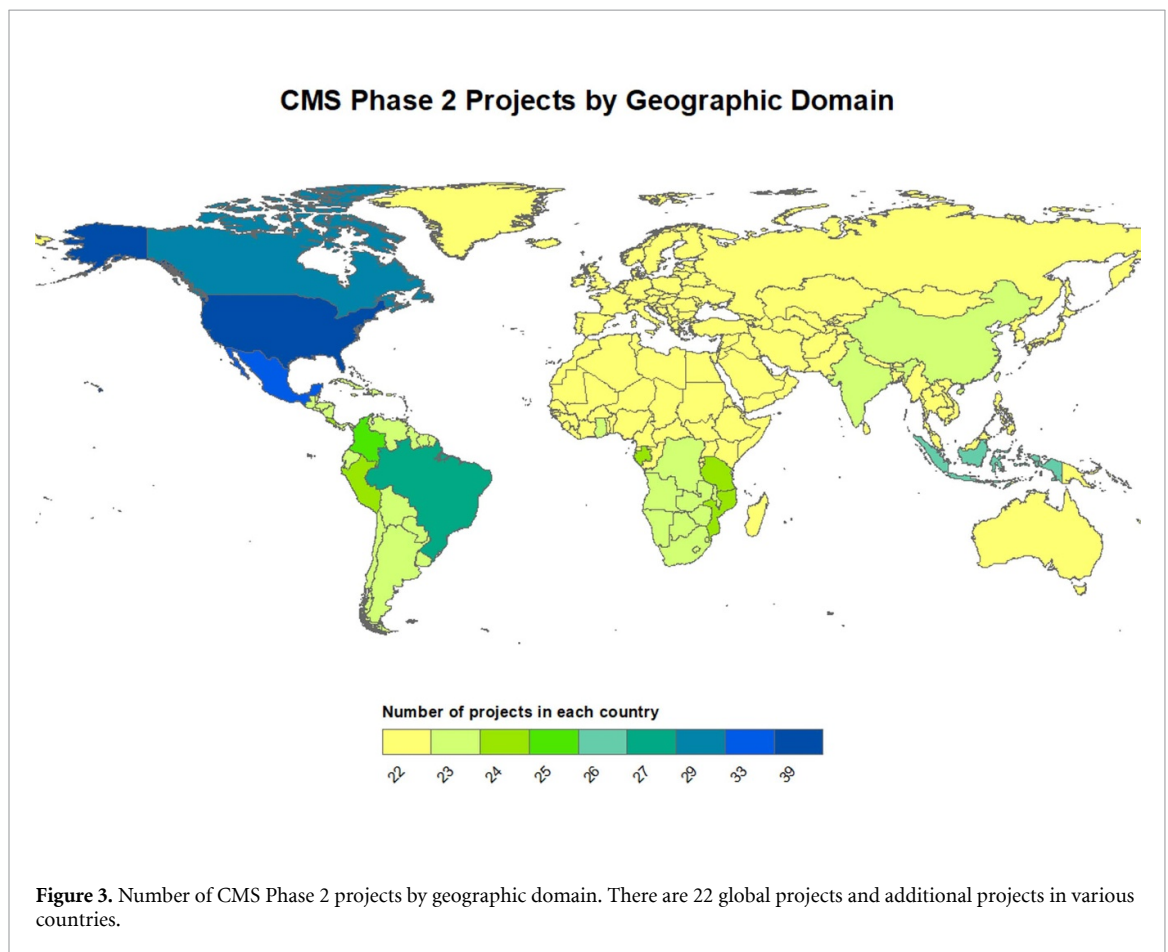
had 33 projects, with 164 publications and 60 data products. Wet carbon/ocean had 7 projects, 63 publications and 17 data products. Stakeholder has 2 projects, 3 publications, and no data products.

Projects covered a wide range of geographic domains (figure 3). There were 22 projects with a global domain. Additional regional projects increased the total number of projects unevenly in different areas around the world. In Southeast Asia, Indonesia, South Africa, and South America an additional 1–5 regional projects produced a total for those regions of 23–27. The highest concentration of projects was focused on North America with 29 total projects and the U.S. with 39 total projects.

Archived data products provide a more detailed measure of data availability around the world (figure 4). Similar to the project level map, the data product coverage is uneven around the world and has the highest concentration over North America and the U.S. Additional product coverage over S. Africa, China, and India were primarily more local

Table 1. CMS Phase 2 projects, publications, and data products.

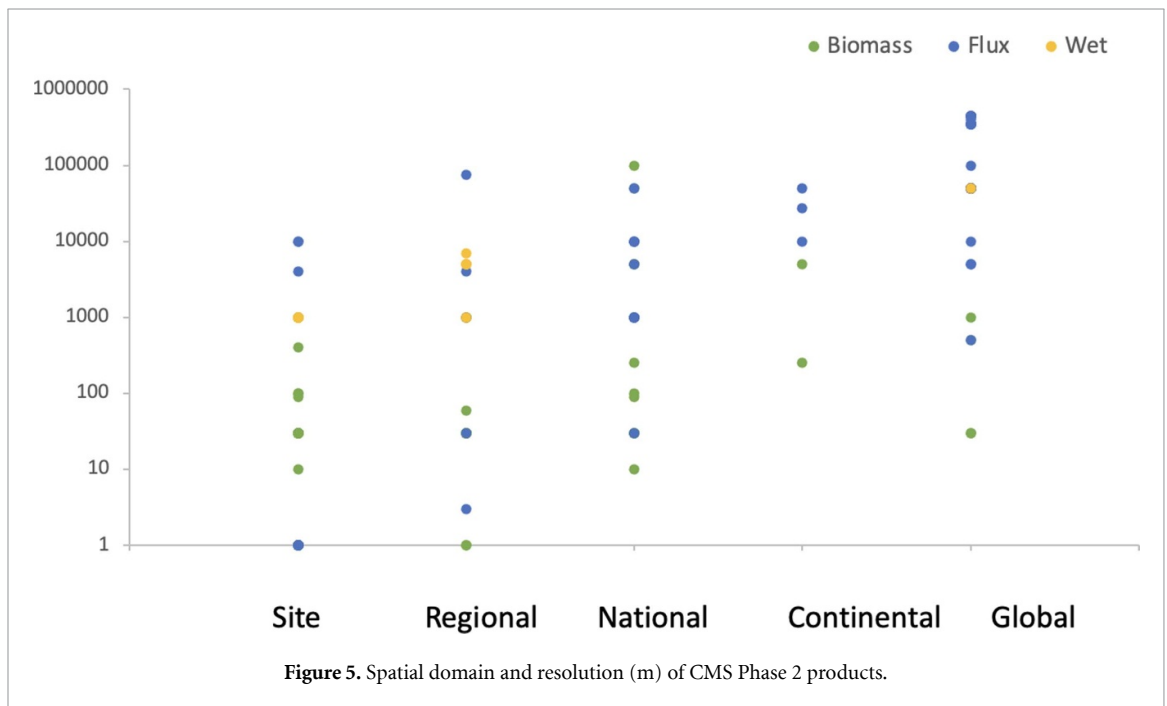
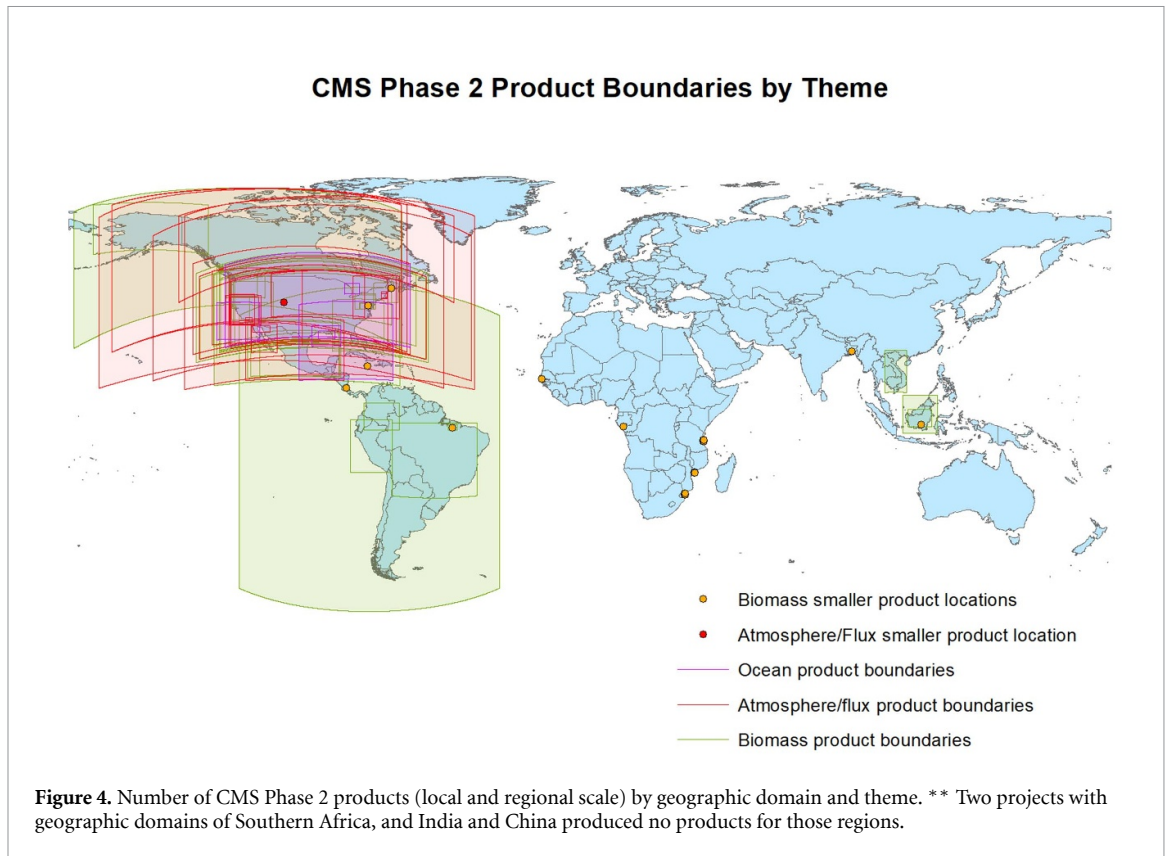
Theme	Sub-theme	Number of projects	Number of publications	Number of archived data products
Biomass	Land biomass	37	252	59
Atmosphere/Flux	Global-surface atmosphere flux	33	164	60
	Land-atmosphere flux			
	Methane			
Ocean	Ocean biomass	7	63	17
	Ocean-atmosphere flux			
	Land-ocean flux			
Stakeholder	Decision support	2	3	N/A
	MRV			
Total:		79	482	136



in focus. Investigating these patterns further, there were significant differences between Biomass and Flux products in terms of coverage (tables S1–S3 (available online at stacks.iop.org/ERL/17/063010/mmedia)). Flux products tended to represent a larger domain, with 50% (30/60) providing global coverage and fewer at all smaller domains including 17% (10/60) local. In contrast, Biomass products tended to represent smaller areas, with 46% (27/59) local, and only 8% (5/59) global. Likewise, ocean/wet carbon products tended to be even more clustered in small domains, with 88% (15/17) at local or subnational scale, and 12% (2/17) global.

Spatial resolution varied by domain size and by theme (figure 5, table S4). Flux products tended to have relatively coarse resolution with 82% (49/60) >1 km. Biomass products tended to have higher spatial resolution with 83% (49/59) ≤1 km. As expected, there was generally an inverse relationship between domain size and spatial resolution consistent with these differences, with local scale products (e.g. biomass) tended to have higher spatial resolution, and larger domain products (e.g. flux) tended to have coarser resolution.

The temporal domain of products varied and spanned a range of pre-1960 to post-2060 (figure 6).



The majority of products were focused on the recent past, with 82% (111/136) of CMS products covering the period 2000–2020, 15% (21/136) extending pre-2000, and 3% (4/136) of products extending post-2020. Biomass had 75% (44/59) covering the period 2000–2020, 24% (14/59) products extending pre-2000 and 2% (1/59) post-2020. Flux had 85% (51/60) covering 2000–2020, 12% (7/60) products extending pre-2000, and 3% (2/60) post-2020.

The distribution of ARL and ARL change was calculated for Phase 2 products as a measure of application readiness and change in application readiness (figure 7, table S5). The distribution of ARL values followed a modal distribution, with the most common ARL values in the intermediate range of 5–6 (51), and many fewer examples at beginning ARL 1–2 (11), or most mature status ARL 8–9 (15). All products experienced maturation during the period

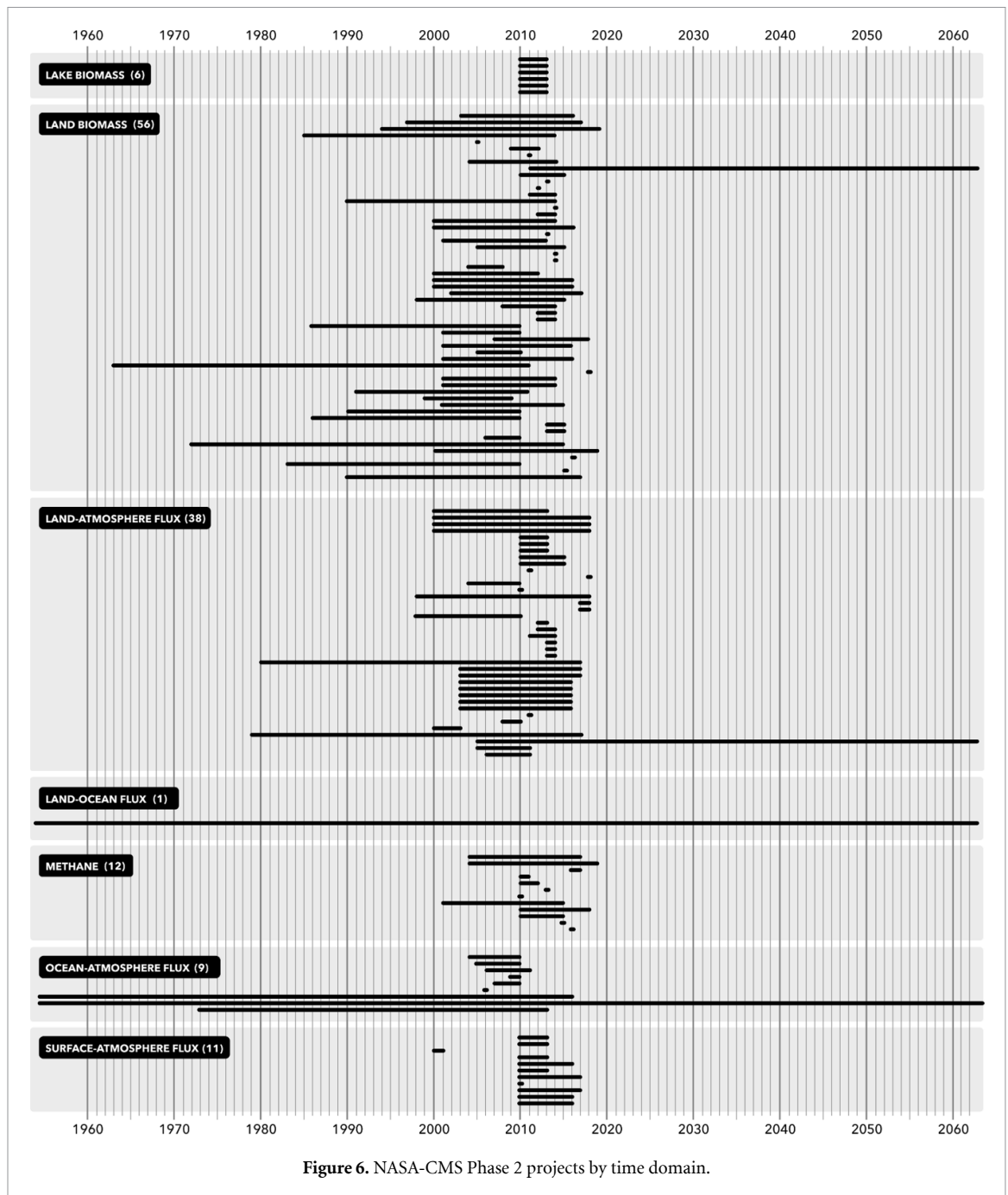


Figure 6. NASA-CMS Phase 2 projects by time domain.

of development. The distribution of ARL change (Final ARL–Initial ARL) followed a decreasing function, with the largest category of projects increasing 1 ARL value and steadily declining to those advancing a full 8 ARL values over the project.

Stakeholders are defined as users actively engaged in CMS science projects. There were 132 different stakeholders working with CMS scientists in Phase 2 representing different types of organizations, science themes, and nationalities (figure 8). CMS projects engaged stakeholders from a wide variety of organizational types, with the most common types being Federal Government (15%), Company (15%), Non-Governmental Organization (15%), State Government (14%) and University (14%). Additional

stakeholders represented Local government (6%), Research Institutes (6%), Intergovernmental Organizations (3%), Media (2%), Museums (1%) and Other (9%). Stakeholders also represented different science themes, with Biomass accounting for 53%, and Flux 30%, and MRV 17%. Stakeholders also represented different nationalities, with U.S. 73%, and followed by a variety of other countries each $\leq 5\%$.

3.2. Thematic

Qualitative results were synthesized at the thematic level. These results are presented below and in table form in supplementary material (tables S6–S11).

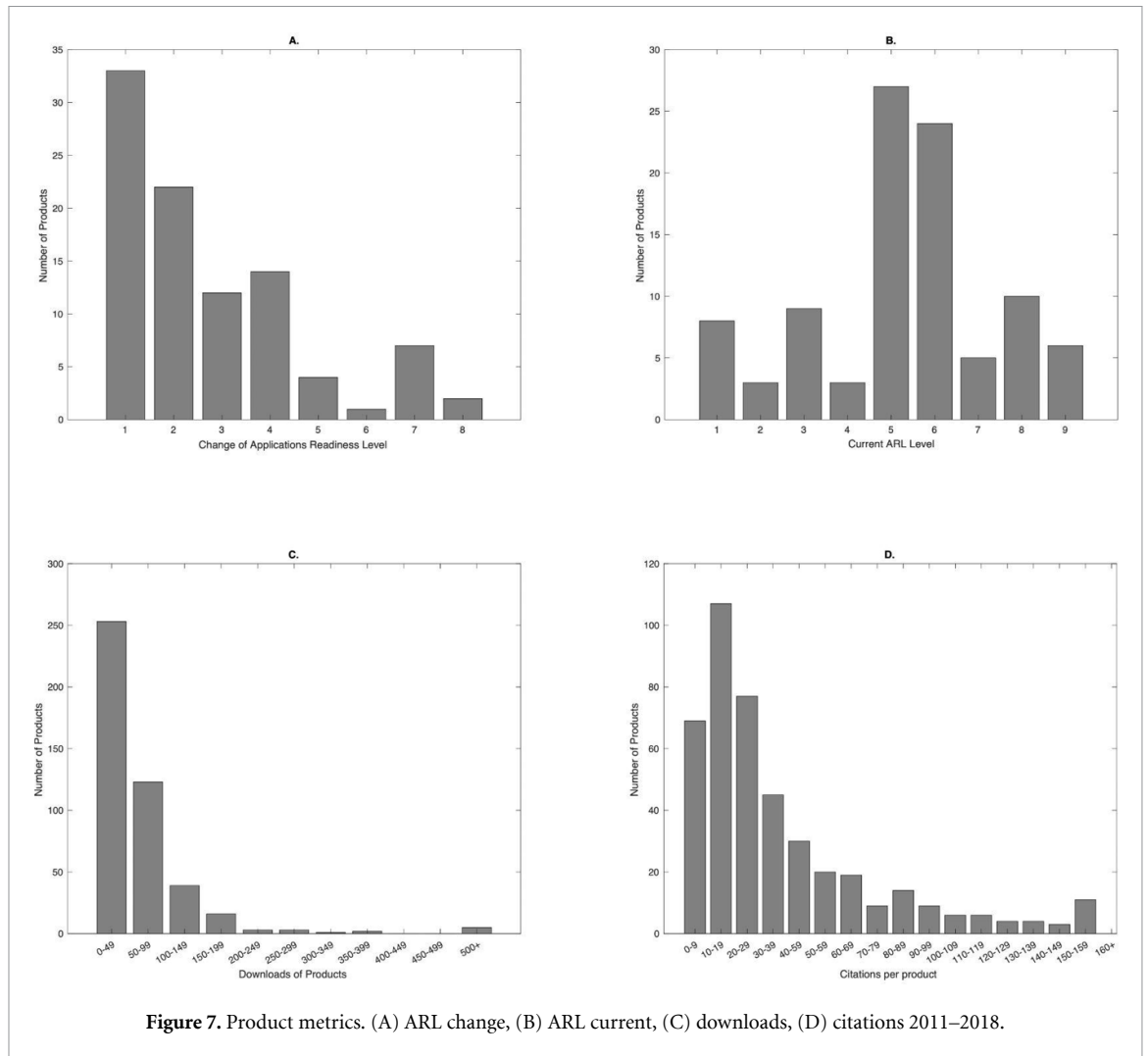


Figure 7. Product metrics. (A) ARL change, (B) ARL current, (C) downloads, (D) citations 2011–2018.

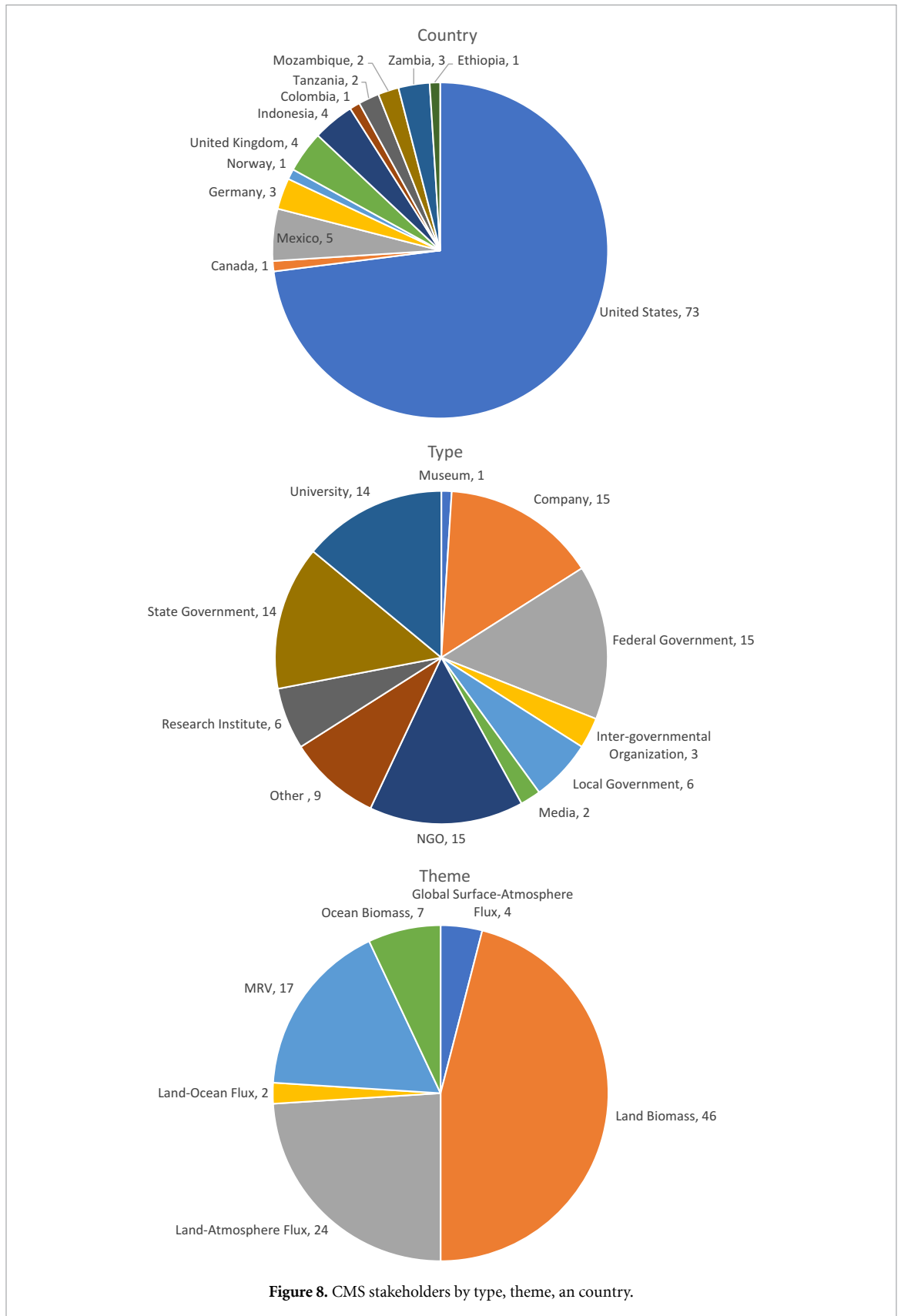
3.2.1. Biomass

Tracking plant biomass in terrestrial ecosystems is an essential component of CMSs. Biomass has been a focus of the NASA CMS since the program's inception, and many CMS projects have advanced our understanding of methods to map, track changes over time, characterize uncertainties in biomass estimates and project future storage potential. In addition, from these results CMS projects have been able to improve our understanding of the controls on biomass accumulation and loss in natural and managed systems.

Methodologically, CMS projects have shown that biomass mapping is achievable at multiple scales, and that such mapping is defensible in the context of MRV and international carbon programs such as REDD+. Mapping is possible through a combination of lidar, optical data, radar data, forest inventory data, and emerging statistical and machine learning methods (Junttila *et al* 2013, Tyukavina *et al* 2013, Montesano *et al* 2013, Zhang *et al* 2014, Potapov *et al* 2014, Lagomasino *et al* 2015, Babcock *et al* 2015, Duncanson *et al* 2015, Huang *et al* 2015, Gu *et al* 2016, Babcock *et al* 2016, Swatantran *et al* 2016, Deo *et al* 2016, 2017, Huang *et al* 2017, Treuhaft *et al* 2017,

Fekety *et al* 2018, Babcock *et al* 2018, Thomas *et al* 2018, Rappaport *et al* 2018, Saarela *et al* 2018, Xu *et al* 2018, Kennedy *et al* 2018, Alonzo *et al* 2018, Huang *et al* 2019, Simard *et al* 2019, Patterson *et al* 2019, Bullock *et al* 2020, Arevelo *et al* 2020). In particular, many CMS projects have advanced the statistical tools needed to make such mapping defensible (Montesano *et al* 2013, Finley *et al* 2013, 2014, Cooke *et al* 2016, Datta *et al* 2016, Reimer *et al* 2016, Finley *et al* 2017, Babcock *et al* 2018, Saarela *et al* 2018, Patterson *et al* 2019, Olofsson *et al* 2020). Importantly, these new methods are also highly generalizable and can also provide quantitative assessments of product uncertainties. In addition, the work has been conducted across a range of diverse ecosystems and are applicable to new space-borne lidar missions such as GEDI (Healey *et al* 2012, Duncanson *et al* 2019, Patterson *et al* 2019).

CMS studies have also contributed significantly to our understanding of the patterns of biomass, drivers of biomass change, and storage potential in vegetation and the soil. For example, human-caused forest disturbance (deforestation and degradation) remains the key driver of biomass and carbon loss in



temperate and tropical forest systems, with fire, climate, and longer-duration stressors (drought, insect pests) playing an important role in some systems (e.g. boreal, savanna, peatland) (French et al 2014, Morton 2016, Longo et al 2016, Cohen et al 2016,

Baccini et al 2017, Noojipady et al 2017, Rappaport et al 2018, Rangel Pinage et al 2019, Li et al 2020, Tang et al 2020). There is evidence of recent diminishment of fire in regions of low- to intermediate-forest cover, perhaps because of transitions in human

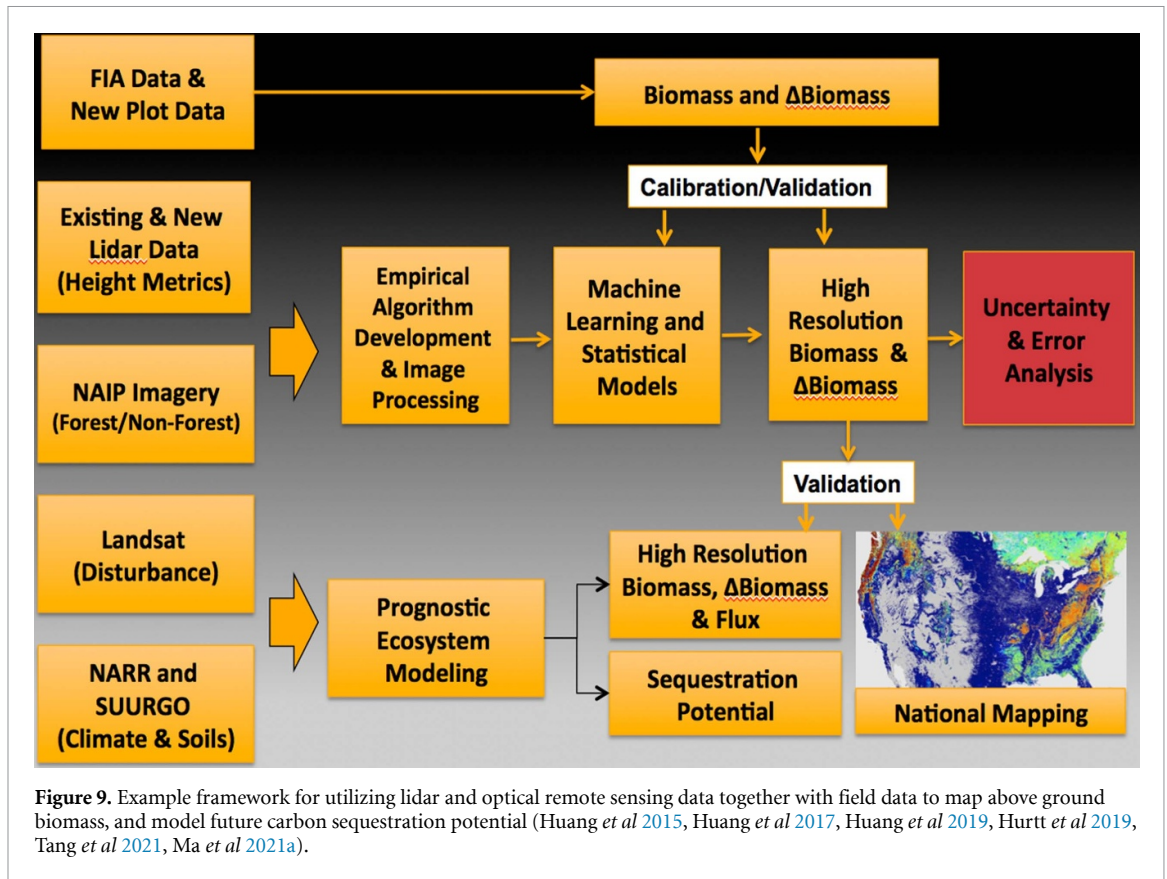


Figure 9. Example framework for utilizing lidar and optical remote sensing data together with field data to map above ground biomass, and model future carbon sequestration potential (Huang *et al* 2015, Huang *et al* 2017, Huang *et al* 2019, Hurtt *et al* 2019, Tang *et al* 2021, Ma *et al* 2021a).

management associated with economic development and increase in closed canopy forests (Andela *et al* 2017). In global drylands systems, there is a strong link between precipitation and the rate and timing of carbon uptake and storage, but which is also mediated by plant adaptation strategies, including higher than expected investment in leaf-level photosynthetic machinery in global drylands ecosystems, with possibly important implications for response to climate change (Biederman *et al* 2016, 2017, Hinojo-Hinojo *et al* 2018). At the same time, increasing prevalence of prolonged drought periods may significantly outweigh any mediation by plant adaptation strategies leading to a chronic reduction in vegetation biomass in dryland systems, including the western U.S. Studies utilizing mechanistic ecosystem modeling have leveraged the high resolution lidar and optical data to move beyond traditional MRV and map both current stocks and future storage potentials for use in planning scenarios (Hurtt *et al* 2019, Ma *et al* 2021a; figure 9). The most recent results from these products are in active use in state-level carbon inventories and climate mitigation planning.

Despite these advances, gaps remain. Major areas of the world, including a diversity of different ecosystems, disturbance regimes, land-use activities, etc have yet to be mapped or modeled or validated at high spatial resolution. Research has identified that a key bottleneck and source of uncertainty in gridded

products is accurate quantification and application of the allometric equations needed to create and scale-up reliable biomass reference data (Xu *et al* 2018). Additionally, approaches to scale-up established methods to continental and global domains are needed. While the separate mapping of biomass and biomass change from disturbance has been successful, a more coordinated effort is needed to help reconcile issues related to biomass and disturbance loss and recovery in space and/or time. The spatial resolution and temporal mismatch in biomass and disturbance mapping efforts complicates the fusion of these datasets to inform C management, including adequately capturing uncertainties related to these isolated mapping efforts. In addition, a major challenge for the mapping of biomass in some high-latitude or tropical regions, is the general lack of suitable measurements needed to train upscaling approaches. This includes both the training data (e.g. measurements of plant height, structure, biomass) themselves and also the remote sensing observations needed for scaling and creating the maps. Finally, despite better inclusion of methodological uncertainties in estimation, it is unclear how to advise practitioners when uncertainties from different sources disagree.

From these findings, challenges, and knowledge gaps, several important next steps emerge. Efforts must continue to expand biomass mapping over broad (continental to global) domains at a fine spatial

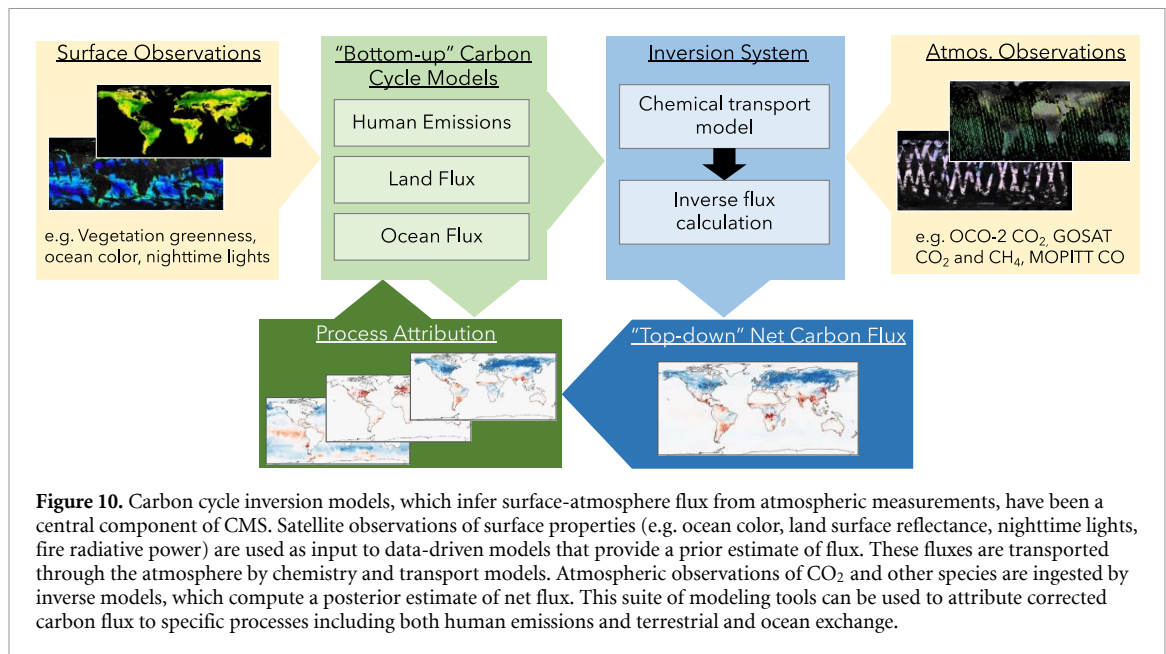
resolution (appropriate to capture variability in both natural patterning and in human interventions that drive change) and linked to models for attribution of changes and future projections needed for planning. Validation frameworks are needed to assess accuracy at a variety of scales against high-quality reference data (e.g. Menlove and Healey 2020). In addition, clear protocols for the collection of measurements to use with biomass mapping (including clearly defining how to incorporate measurement uncertainties into scaling efforts) need to be provided to influence how large-scale measurements efforts (e.g. FIA) develop the essential datasets used for biomass accounting. While the goals for MRV are defensible, broad-scale biomass estimates and novel approaches should continue to be explored to help understand the influence of fine-scale variation on scaling efforts and how fine-scale patterns influence larger scale, but more coarse resolution, mapping efforts. These include the continued use of detailed *in-situ* measurements and validation of allometry using lidar tools (e.g. Xu *et al* 2018), as well as the incorporation of other novel platforms such as unoccupied aerial systems (Alonzo *et al* 2020) to provide both fine-scale, targeted (e.g. using UAS to fill in critical observation gaps) and spatially-extensive information on plant structure and biomass to inform scaling approaches or validate other products. Similarly, the temporal cadence of biomass mapping should increase to improve our understanding of biomass change, thus allowing better attribution of changes to drivers. At the same time, a tighter coupling of efforts between biomass and disturbance mapping should be explored as this will be essential for increasing the temporal frequency of biomass estimates and also ensure landscape changes are correctly accounted for. The incorporation of more model-driven biomass upscaling should also be considered, which would allow for the fusion of observation data and process models to infer biomass state based on measurements and mechanistic modeling of plant growth (Fer *et al* 2018). In general, these improved maps of change must continue to be better integrated into process-based models and with tower-based flux observations. Throughout all of these steps, clearer definitions of product uncertainties are needed, particularly relative to the types of factors included within uncertainty estimates for different products.

3.2.2. Flux

Flux activities in CMS Phase 2 focused on developing new methods for estimating carbon fluxes, characterizing key sources of uncertainty, and deploying new measurements to support flux evaluation. CMS flux products represent both bottom-up (e.g. process models, inventories combined with land surface remote sensing data) and top-down (atmospheric inversion) approaches. CMS investigators have developed multiple observationally constrained

bottom-up estimates of the major flows of carbon including fossil fuel (Asefi *et al* 2014, Gately and Hutyra 2017, Oda *et al* 2018) and fire emissions (Andela *et al* 2019) and land (Hardiman *et al* 2017, Weir *et al* 2021a) and ocean (Brix *et al* 2015, Gregg *et al* 2017, Carroll *et al* 2020) carbon flux. They have also improved inverse methods that use atmospheric observations to infer surface sources and sinks with a focus on attributing net flux to underlying processes at both regional (Fischer *et al* 2017, Graven *et al* 2018, Hu *et al* 2019) and global (Liu *et al* 2017, Wang *et al* 2018) scales (figure 10). Phase 2 projects also improved characterization of major sources of uncertainty including atmospheric transport model errors (Brophy *et al* 2019, Diaz-Isaac *et al* 2019, Butler *et al* 2020) and deployed both ground-based (Fischer *et al* 2017, Graven *et al* 2018) and aircraft measurements (Wolfe *et al* 2018, Hannun *et al* 2020) to validate local to regional scale flux estimates. CMS Phase 2 also included the first project designed to evaluate the consistency and completeness of CMS products for estimating global and regional carbon budgets.

CMS projects yielded a diverse set of results that represent an increased understanding of both anthropogenic and natural flux processes. These findings show that global inverse models that incorporate satellite CO₂ observations are able to reduce flux uncertainty and quantify the relative distribution of regional net fluxes (Liu *et al* 2014, Wang *et al* 2020). When combined with other types of observations (e.g. shorter-lived trace gasses, indicators of vegetation productivity), such models can provide additional information about specific flux processes including respiration, gross primary production, and fire emissions (e.g. Liu *et al* 2017, Konings *et al* 2019, Magney *et al* 2019). Multiple studies focused on quantifying the impact of El Niño events on atmospheric CO₂ and on understanding the regional mechanisms that control these changes in the tropics (Bowman *et al* 2017, Chen *et al* 2017b, Liu *et al* 2017) and midlatitudes (Hu *et al* 2019). CMS Phase 2 projects also demonstrated the ability to constrain and validate anthropogenic emissions estimates on regional scales using a combination of *in situ* measurements and remote sensing data (Chen *et al* 2016, Fischer *et al* 2017, Graven *et al* 2018, Sargent *et al* 2018). During the COVID-19 pandemic, global data assimilation systems were able to detect the small decrease in global fossil fuel emissions and to evaluate independent country-level estimates of emissions changes (Weir *et al* 2021b). Bottom-up datasets also yielded new insights into the key processes and trends driving flux changes across land (Chen *et al* 2017a, Andela *et al* 2019, Fu *et al* 2019, Bloom *et al* 2020) and ocean ecosystems (Gregg *et al* 2017, Carroll *et al* 2020). This progress, particularly at global scales, supports the capacity building potential of CMS. Many global flux products provide detailed information for



non-Annex I countries that may improve national level reporting mandated by the Paris climate accord.

In addition to demonstrating understanding of processes, many CMS projects focused on highlighting the observational and modeling priorities that are needed to further refine flux estimates. The availability of high-resolution, low-latency global flux and emissions datasets remains an unmet need in the atmospheric carbon monitoring community (Oda *et al* 2018, Weir *et al* 2021a). Though uncertainty quantification (UQ) methods have improved throughout CMS (e.g. Bousseret *et al* 2015, Oda *et al* 2019), atmospheric transport remains a sizable source of uncertainty for inverse estimates at both regional and global scales (Brophy *et al* 2019, Diaz-Isaac *et al* 2019, Butler *et al* 2020). Many critical carbon cycle processes are poorly captured by climate models (Andela *et al* 2019, Fu *et al* 2019) despite research advances in recent years.

While Phase 2 CMS flux projects reflected progress in quantifying both human emissions and natural fluxes, many challenges remain. Large differences in bottom-up flux estimates persist despite incorporation of satellite data in land and ocean models (Ott *et al* 2015). There is a lack of independent atmospheric data at appropriate spatio-temporal scales for evaluating fluxes (Wolfe *et al* 2018), especially in the tropics. Though substantial improvements have been made over the past decade, satellite bias and coverage gaps limit both the accuracy (Basu *et al* 2018) and spatial scale of top-down global fluxes (Wang *et al* 2018). Regional top-down estimates, which can help improve the spatial scale of flux estimates in key regions like the United States where denser observations are available, are complicated by a lack of boundary condition information. Uncertainty estimates, a required element for

all CMS products, are often difficult to interpret because of differences in the quantification method used by various projects. In addition to challenges that influence product quality, flux projects have also had more difficulty connecting with stakeholders than some other areas within CMS. Relevant factors include technical roadblocks like a lack of familiarity with scientific data formats among stakeholders, incompatibility between geographical boundaries and spatial resolution of models, and differences in scientific and policy-relevant carbon accounting definitions. In addition, most CMS research products have long latencies and irregular update schedules, which also limits relevance to stakeholder communities.

Progress made across individual CMS projects provides the opportunity for substantial advances in flux estimation in coming years. Quasi-operational flux modeling systems are reducing latency in flux estimates to support research and stakeholder communities. Better integration of regional and global modeling activities could help support more robust and reliable flux estimates across scales with improved characterization of uncertainties. Net flux estimates may also be improved through incorporation of observations from multiple satellites, allowing either a longer period of record for better understanding of interannual variability and trends (e.g. GOSAT and OCO-2) and/or denser observations in key regions (e.g. OCO-2 and GeoCarb). Integration of multiple types of observations that simultaneously constrain flux, stocks, and disturbance into dynamical data assimilation systems can improve consistency of flux products and improve their ability to yield policy relevant information. New observations that support evaluation of regional flux evaluation can improve confidence in flux estimates. Cross-project

coordination is also critical in addressing several known gaps. Improving consistency in uncertainty methods of bottom-up CMS flux datasets would allow them to better inform top-down estimates and to improve quantification of top-down uncertainties. CMS also needs to work toward an integrated approach for engaging potential flux stakeholders, particularly at national and global scales where it is important for NASA and other government agencies to provide consistent, regularly updated, high-quality flux information.

3.2.3. Methane

CMS methane activities in Phase 2 focused on enabling the use of satellite observations of atmospheric methane to quantify and attribute emissions on local, regional, and global scales. The work involved strong collaborations with climate policy stakeholders including the California Air Resources Board (CARB), the U.S. Environmental Protection Agency (EPA), Environment and Climate Change Canada, the Mexican National Institute of Ecology and Climate Change, the Integrated Global Greenhouse Gas Information System, and the Rocky Mountain Institute.

A major component of CMS methane activities has been the exploitation of GOSAT satellite observations (2011–present) to quantify methane emissions, the methane sink (mainly tropospheric OH), and their trends on the global scale (Maasakkers *et al* 2019, Zhang *et al* 2021, Lu *et al* 2021). Other GOSAT analyses have focused on North America (Turner *et al* 2015, 2016, Sheng *et al* 2018a, Maasakkers *et al* 2021), and on tropical wetlands (Parker *et al* 2018). CMS investigators have conducted atmospheric measurement campaigns to quantify methane emissions on urban to regional scales and support satellite observations. This has involved evaluation of commercial solar-viewing shortwave infrared (SWIR) spectrometers with the TCCON satellite validation standard (Hedelius *et al* 2016, 2017), and application of these spectrometers to study emissions in Boston (McKain *et al* 2015) and from dairies (Viatte *et al* 2017). It has also involved inversion of ground-based network observations to quantify emissions in the Los Angeles Basin (Yadav *et al* 2019), inversion of NASA SEAC⁴RS aircraft observations to quantify emissions in the Southeast U.S. (Sheng *et al* 2018b), and aircraft campaigns using the AVIRIS-NG imaging spectrometer to map methane plumes from point sources and infer emissions (Duren *et al* 2019, Thorpe *et al* 2020, Cusworth *et al* 2020a). Combined analysis of satellite, aircraft, and surface observations over the Los Angeles Basin demonstrated the power of the integrated observing system (Cusworth *et al* 2020b), as did the combined analysis of multiple satellite data streams to quantify emissions from a gas well blowout (Cusworth *et al* 2021a).

Inversions of satellite data to infer methane emissions require high-quality, spatially resolved emission inventories to serve as prior estimates. Developing such inventories has been a priority for CMS and has focused globally on wetlands (Tian *et al* 2015a, Bloom *et al* 2017, Poulter *et al* 2017, Zhang *et al* 2017, Treat *et al* 2018), rice (Zhang *et al* 2016), livestock (Wolf *et al* 2017), and fossil fuels (Scarpelli *et al* 2020a). It has also involved spatial disaggregation of national inventories for the U.S. (Maasakkers *et al* 2016) and Mexico (Scarpelli *et al* 2020b). A detailed map of methane-emitting infrastructure has been developed for the Los Angeles Basin to guide atmospheric measurements (Carranza *et al* 2018).

Another priority for CMS has been to enable the next generation of satellite observations of methane. The new high-density TROPOMI satellite observations have been used to infer methane emissions on the ~10 km scale (Varon *et al* 2019, Zhang *et al* 2020, Shen *et al* 2021). Studies have determined the combined value of thermal and shortwave IR (TIR + SWIR) measurements to resolve lower-tropospheric methane (Worden *et al* 2015) and infer trends in tropospheric OH (Y Zhang *et al* 2018). CMS has contributed to specifications for future geostationary instruments such as GeoCARB and GeoFTS to constrain methane emissions from the regional scale down to the scale of individual facilities (Cusworth *et al* 2018, Turner *et al* 2018, Sheng *et al* 2018b). CMS has been a mechanism for developing the power of GHGSat and imaging spectrometers such as PRISMA and Sentinel-2 to observe point sources of methane (Cusworth *et al* 2019, 2021a, Varon *et al* 2018, 2019, 2020, 2021).

CMS methane activities have yielded a number of important results. They have established that inundation and ecosystem respiration are major drivers of variability and trends in methane emissions from wetlands, as shown by GOSAT observations (Parker *et al* 2018) and biogeochemical models (Bloom *et al* 2017, Poulter *et al* 2017, Zhang *et al* 2017). Wetland models with low methane to temperature sensitivity generally agree better with satellite observations (Ma *et al* 2021b). Through the development of spatially-resolved national inventories and their application to inversion of satellite observations, CMS has shown that emissions from the oil sector are underestimated by a factor of 2 in the national inventories for the U.S. (Maasakkers *et al* 2021) and Mexico (Shen *et al* 2021). On a point source level, CMS investigators have achieved better understanding of the role of ‘super-emitters’ in contributing disproportionately to state and national methane emissions (Duren *et al* 2019, Varon *et al* 2019, 2021, Cusworth *et al* 2021b) and have identified the underlying processes for landfills (Cusworth *et al* 2020a) and gas storage facilities (Thorpe *et al* 2020). Results from these point-source CMS studies were shared directly

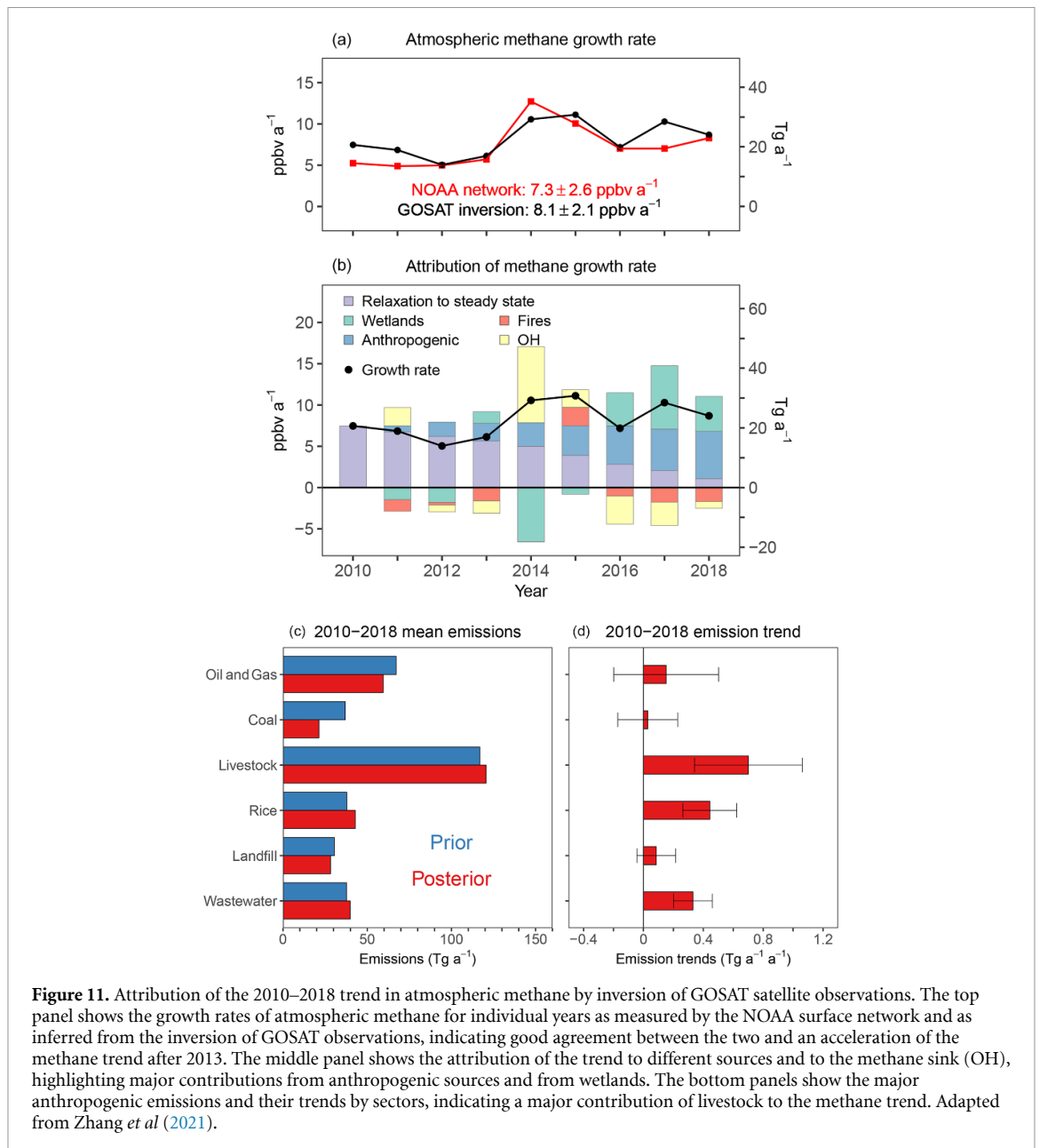


Figure 11. Attribution of the 2010–2018 trend in atmospheric methane by inversion of GOSAT satellite observations. The top panel shows the growth rates of atmospheric methane for individual years as measured by the NOAA surface network and as inferred from the inversion of GOSAT observations, indicating good agreement between the two and an acceleration of the methane trend after 2013. The middle panel shows the attribution of the trend to different sources and to the methane sink (OH), highlighting major contributions from anthropogenic sources and from wetlands. The bottom panels show the major anthropogenic emissions and their trends by sectors, indicating a major contribution of livestock to the methane trend. Adapted from Zhang *et al* (2021).

with industry and agency stakeholders who conducted follow-up site visits with surface sensors to verify and further refine source attribution. In roughly 50% of those cases, facility operators indicated that the confirmed super-emitters were fixable and a subset of those were repaired. The net magnitude of mitigated methane emissions from those studies is currently being reviewed.

Better understanding has also been achieved of the drivers of global methane trends over the past decade, as illustrated by figure 11. Inversion of GOSAT data suggests that tropical livestock could be a major driver for the decadal trend, while wetlands may contribute to the acceleration of the trend since 2016 (Zhang *et al* 2021). Changes in OH concentrations could greatly contribute to the interannual variability of methane (Turner *et al* 2017) though probably not to the decadal trend (Zhang *et al* 2021).

Major gaps remain in our understanding of methane emissions. There is considerable uncertainty in quantifying wetland emissions and how these emissions contribute to the global methane trend. This includes uncertainties in the carbon respiration rate (Bloom *et al* 2017), inundation dynamics (Parker *et al* 2018), and contributions from the non-growing season (Treat *et al* 2018). Improved biogeochemical models for methane emission from wetlands are needed (Xu *et al* 2016). The factors contributing to the global trend in atmospheric methane over the past decade are also still open to debate.

The next several years offer considerable opportunity for improving our ability to use satellite data for quantifying methane emissions on all scales (Jacob *et al* 2016). Planet and Landsat products can enable better understanding of land surface characteristics to improve our ability to quantify wetland methane

emissions. TROPOMI observations should be transformative for improving the capability of inversions of atmospheric methane to constrain the methane budget on global to regional scales. GeoCARB geostationary observations over the Americas should enable better quantification of emissions from South American wetlands. The emerging constellation of satellite instruments able to quantify point sources (GHGSat, PRISMA, S-2, EnMAP, EMIT, MethaneSat, Carbon Mapper) opens up the possibility for operational leak detection and sustained emissions quantification at the scale of individual facilities. The ability to constrain global OH trends from satellite observations of methane should improve through exploitation of TROPOMI and CrIS data.

3.2.4. Marine, freshwater and wet carbon

CMS projects have contributed to various efforts to better characterize the role of oceans and coastal interfaces in global carbon cycling. Some of this work has been summarized in the Second State of the Carbon Cycle Report (USGCRP 2018) as well as published papers on the North American coastal carbon cycle (Fennel *et al* 2019) and the carbon budget of Eastern North America (Najjar *et al* 2018). Additionally, Benway *et al* (2016) produced a synthesis of current information about coastal carbon budgets and provided a series of recommendations for future research.

Some CMS projects have considered the nature of coastal margins as boundaries to the continental carbon cycle. Related to this is improved observation and modeling of lateral transport of terrestrial carbon and nutrients into the watershed and ultimately to coasts (Liu *et al* 2013, Lohrenz *et al* 2013, Xue *et al* 2013, Tao *et al* 2014, Ren *et al* 2015, 2016, Tian *et al* 2015b, 2015c, 2020; figure 12). A key to understanding this important term is how land use and land cover along with other drivers such as human activity and climate-related changes affect lateral transport processes.

Considerable focus was given to the potentially large reservoirs of carbon biomass undergoing substantial change in sensitive coastal ecosystems. Both mangrove and tidal wetland ecosystems are critical coastal buffer zones and are undergoing rapid changes. CMS efforts include studies of mangroves (Lee and Fatoyinbo 2015, Lagomasino *et al* 2015, 2016, Fatoyinbo *et al* 2018, Simard *et al* 2019) and tidal wetlands (Hopkinson *et al* 2012, Morris *et al* 2016, Hinson *et al* 2017, Byrd *et al* 2018, Holmquist *et al* 2018a, 2018b). Mangroves account for a substantial amount of carbon biomass and various CMS efforts examined Lidar-based algorithms for refining aboveground biomass estimates (Lagomasino *et al* 2015, Fatoyinbo *et al* 2018, Simard *et al* 2019). Tidal wetlands also represent an important coastal carbon reservoir (Hopkinson *et al* 2012, Byrd *et al* 2018, Windham-Myers *et al* 2018, Holmquist *et al* 2018a,

2018b). CMS projects have also evaluated sources of methane and nitrous oxide emissions. This included examination of tidal wetlands and aquaculture sites (Poulter *et al* 2017, Zhang *et al* 2017, EPA 2019), as well as more comprehensive assessments over North America and globally (Xu *et al* 2012, Tian *et al* 2012b, 2015a, 2016).

CMS efforts have greatly expanded the information about oceans and coastal interfaces and their key role in global carbon cycling. Efforts such as the Second State of the Carbon Cycle Report (USGCRP 2018, Fennel *et al* 2019) have provided an initial assessment of air-sea and land-ocean fluxes for North America. CMS investigators contributed to chapters covering Inland Waters (Ch 14), Tidal Wetlands and Estuaries (Ch 15), Coastal Ocean and Continental Shelves (Ch 16), and Biogeochemical Effects of Rising Atmospheric Carbon Dioxide (Ch 17). Coastal margins in North America act as a net sink of carbon. The North American Exclusive Economic Zone is estimated to be a net sink for carbon on the order of $160 \pm 80 \text{ Tg C y}^{-1}$ (Fennel *et al* 2019). The estimated carbon input from land is $106 \pm 30 \text{ Tg C y}^{-1}$. A global inventory of carbon dioxide fluxes in coastal margins influenced by large rivers (Cai *et al* 2013) found that estuaries were a net source of CO_2 due to metabolism of terrestrial carbon entering these systems. In contrast, a global assessment of coastal areas influenced by large river plumes found that they were a net sink for CO_2 . Considerable focus was given to the northern Gulf of Mexico and the Mississippi River plume, including extensive ship-based mapping and buoy measurements of pCO_2 (Guo *et al* 2012, Cai *et al* 2013, Huang *et al* 2013, 2015a, 2015b) as well as model simulations using a coupled physical-biogeochemical model (Xue *et al* 2014) and satellite-derived estimation of pCO_2 and air-sea flux of CO_2 (Lohrenz *et al* 2018). The biological dynamics influencing carbon dynamics were considered by Chakraborty *et al* (Chakraborty and Lohrenz 2015, Chakraborty *et al* 2017), who explored the relationships between phytoplankton community composition and physiological properties of populations and relationships to environmental conditions. Other efforts have examined carbon properties in both the Gulf of Mexico and the Atlantic coast (Wang *et al* 2013, Najjar *et al* 2018).

Impacts of human and climate-related forcing on terrestrial watersheds affect export of carbon and other materials to the coastal margins. Changes in land cover and land use along with climate-related factors were determined to impact lateral movement of carbon and other materials through the watershed. Work by Tian *et al* and others utilized the Dynamic Land Ecosystem Model along with extensive satellite and ground-based observations to examine historical trends and patterns as well as modeled simulations of future scenarios under differing climate and atmospheric carbon forcing (Tian *et al* 2012a,

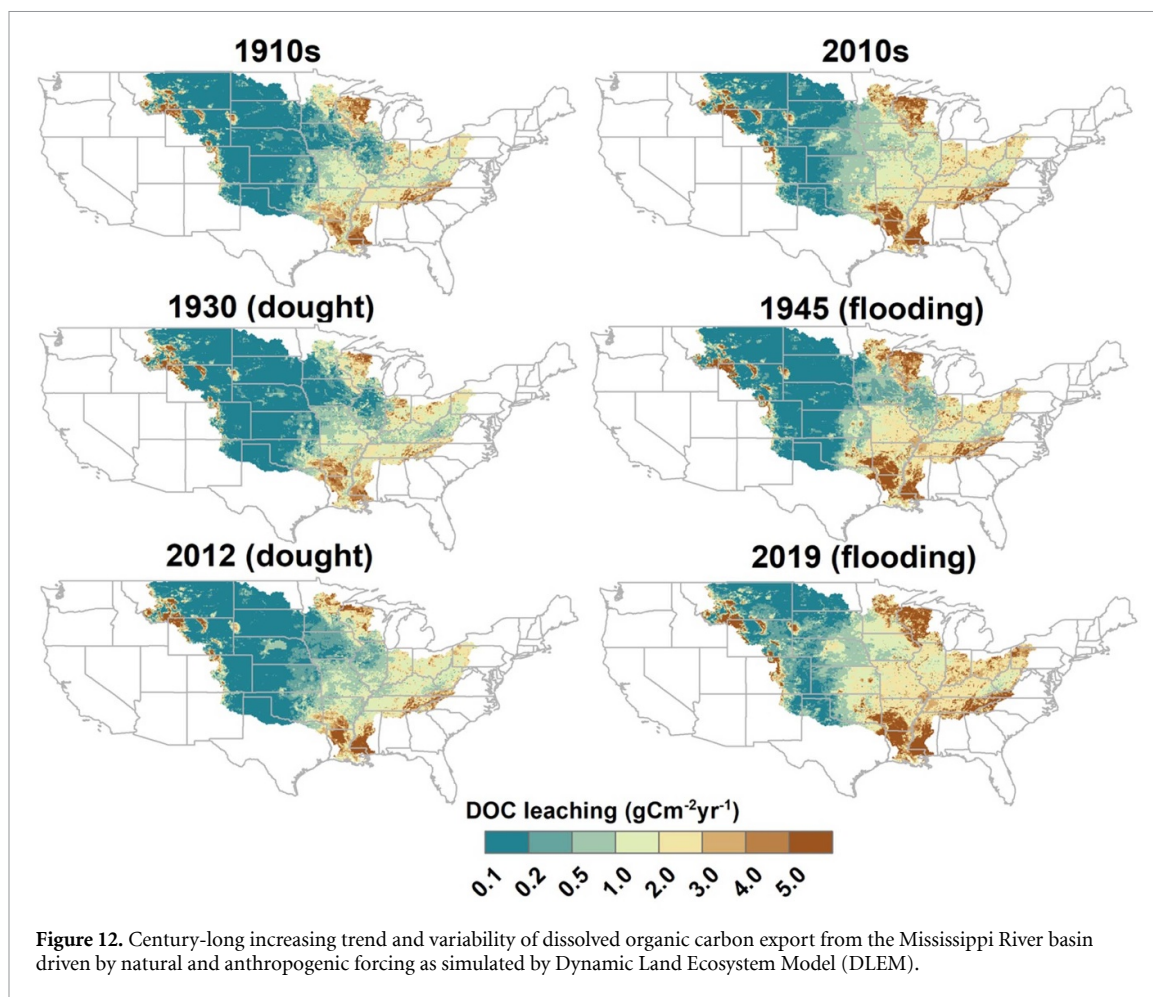


Figure 12. Century-long increasing trend and variability of dissolved organic carbon export from the Mississippi River basin driven by natural and anthropogenic forcing as simulated by Dynamic Land Ecosystem Model (DLEM).

2015b, 2015c, Liu *et al* 2013, Lohrenz *et al* 2013, Xue *et al* 2013, Tao *et al* 2014, Ren *et al* 2015, 2016, Yu *et al* 2018). Urban land conversion (Zhang *et al* 2012, 2014), livestock manure nutrient production (Yang *et al* 2016), crop production (Lu *et al* 2018), forest disturbance (Chen *et al* 2013), drought (Chen *et al* 2012), and large fires (Yang *et al* 2015) were considered as significant factors in terrestrial carbon dynamics. More recent work has addressed factors affecting nitrogen loading to the Mississippi River basin (Lu *et al* 2020, Tian *et al* 2020). An additional carbon-related concern for coastal ecosystems is ocean acidification and its implications for coastal ecology and carbon cycling. Increasing ocean acidification may also reduce the buffering capabilities of coastal waters diminishing their capacity as carbon sinks (Wang *et al* 2013, Salisbury *et al* 2015, Fennel *et al* 2019).

Consideration by CMS projects was given to productivity and influencing factors in the Upper Great Lakes (Yousef *et al* 2014, Fahnenstiel *et al* 2016). Information about primary productivity in the upper Great Lakes was significantly expanded through CMS efforts. Primary production in Lake Michigan was found to decrease over the 1998–2010 period, largely attributed to a decline in chlorophyll biomass as a result of the quagga mussel activity (Yousef *et al* 2014).

A comprehensive assessment of primary production was done for the upper Great Lakes for the period 2010–2013 (Fahnenstiel *et al* 2016), thereby providing a baseline for future study.

Despite progress in understanding marine, freshwater and wet carbon dynamics, scientific uncertainties and priorities remain. These include continued refinement of terrestrial ecosystem models needed to reduce uncertainties in carbon flux quantification. Improvements are needed in parameterization in areas such as in-stream organic production and transformation, as well as hydrological processes including effects of dams and rivers require further study. Constraining estimates of contributions by coastal margins and inland waters to continental and global carbon budgets requires improved assessments of exchange fluxes and the associated seasonal and interannual variability. While the amount of information has grown substantially, uncertainties represent a challenge because carbon is exchanged across multiple interfaces (land-coastal ocean, coastal ocean-open ocean, ocean-benthic, ocean-atmosphere). There is a need for improved characterization of spatial patterns and relationships to forcing, as well as assessments of these exchange fluxes and the associated seasonal and interannual variability. How coastal margins will be affected by

changing climate forcing, sea level rise, and human impacts remains an important question. Tidal wetlands and mangroves represent large reservoirs of carbon and are important as potential sources of carbon dioxide and other greenhouse gases. Contributions of coastal margins to methane budgets are still poorly understood. Also, contributions of tidal wetlands and marshes to nitrous oxide budgets need to be examined. Tidal wetlands and mangroves have been identified as important sinks and sources, but still associated with significant uncertainties. Continental to global assessments are needed, but current knowledge is very limited regarding coastal margins as sources of methane or nitrous oxide.

Although considerable progress has been made in understanding contributions of coastal margins to global carbon, these contributions are still not well constrained, particularly with regard to seasonal and spatial patterns. There is a need for coordinated modeling and observations across the land-ocean continuum, including continued and expanded time-series observations to better discern temporal variability. Approaches should integrate observations, modeling and stakeholder needs (Fennel *et al* 2019). There is also a need for better quantification of methane and nitrous oxide fluxes in different coastal types (e.g. river, estuary, tidal wetland, mangrove, etc). Continued advancement of novel approaches such as remote sensing techniques for characterizing changes in carbon biomass and fluxes in coastal environments will be important for reducing uncertainty in these variables. Uncertainties in feedbacks need also to be addressed—how will future changes including climate, human impacts, and increasing atmospheric CO₂ affect efficiency of ocean uptake? Improved understanding of how coastal margins and associated carbon dynamics will change and what factors, including human activity, will influence that change will be important considerations for policy and decision-making.

3.2.5. Stakeholder

During Phase 2, stakeholder engagement accelerated at the federal, state, and local level, and with international partners. The CMS program funds basic and applied research that is created while engaging with a user community in a way that bridges carbon science and user communities to better serve societal needs (Brown *et al* 2020; figure 13).

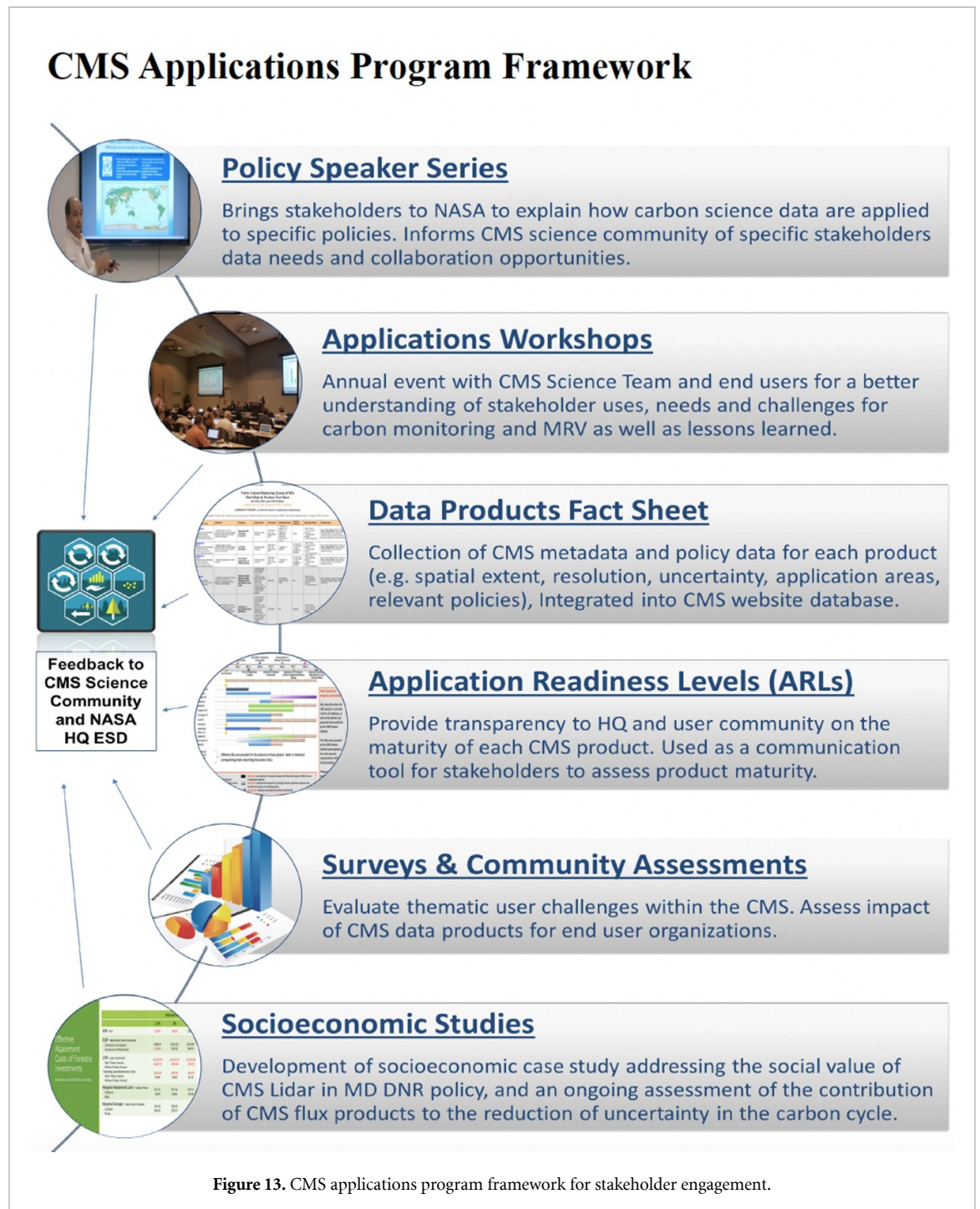
By connecting carbon cycle science research to stakeholders who use the data in their decision making, NASA CMS contributes to understanding and meeting the needs of the climate data user community. For example, Phase 2 produced novel data products on forest carbon product designed to meet state needs beginning in Maryland (Huang *et al* 2015, Hurtt *et al* 2019, Lamb *et al* 2021a), and later expanding to the multi-state Regional Greenhouse Gas Initiative (RGGI) region (Tang *et al* 2021, Ma *et al*

2021a, Lamb *et al* 2021b). New efforts on mapping and monitoring methane across California and other regions (Carranza *et al* 2018) engaged the CARB to identify and remove methane ‘hotspots’ across urban areas. Other stakeholders across a wide variety of CMS projects include Northwest Management Inc. The Nature Conservancy, Worcester Tree Initiative, Maryland Valleys Planning Council, World Resources Institute, Blue Source, Chesapeake Conservancy, U.S. Forest Service, the Environmental Defense Fund, the Sonoma County Agricultural Preservation and Open Space District, among many others.

Ensuring that critical information on carbon is used in day-to-day decisions and policy making by stakeholders such as governments, businesses, and institutions requires early engagement and frequent communication between the user and the producer of the information (Cash *et al* 2006). The CMS program allows scientists to build mature relationships with stakeholders that result in greater success in moving a carbon cycle product from conceptualization to actual use within a decision-making context. It is only through funding a single individual who provides consistent engagement and builds relationships among and between the scientists and these institutions is CMS able to accelerate uptake of datasets in Phase 2 (Brown *et al* 2020).

Major gaps from Phase 2 include the need for carbon products to be repeated, updated regularly, and for CMS to provide information that describes change through time instead of a single point in time. Change products would require standardization and repeat acquisition of input data, ongoing support of computing resources, access services, and for the policy relevance of the product to be clearly acknowledged and articulated. Gaps also include a relative lack of products that describe the sensitive ecosystems of mangroves and urban forests, and products that link biomass to methane emissions. Economic studies are needed to demonstrate the value of these ecosystems and how information on them can be used in decision making in ways that may result in improved resilience and functioning (Horita *et al* 2017). Economic analysis of the value of information may include data documenting impact of carbon cycle uncertainty (Cooke *et al* 2016), and the costs and benefits of forest policy that incorporates carbon sequestration. For example, Lamb *et al* (2021b) describe how afforestation and reforestation in Maryland can provide both carbon sequestration potential and economic opportunity via forest carbon pricing verified through the use of geospatial products generated through the CMS program.

Recommendations include increased focus on: reconciling carbon stocks and fluxes, developing consistency across scales, quantifying movement and transport of carbon, attributing carbon emissions and sinks to respective sources, cross-sectoral accounting, and UQ (West *et al* 2013). More data products



are needed in new regions and new ecosystems with new stakeholders supporting city, state, and national/international initiatives where demand for decision support is increasing. Capacity to use carbon data products for people who are developing policy is a critical need, as Lamb *et al* (2021a) demonstrated. With an improved understanding of the value of carbon and the alternative land uses, appropriate incentives and policies can be developed that increase the value of land use while sequestering more carbon.

CMS has developed a community of practice where scientists have learned how to do

meaningful stakeholder engagement, the value of this engagement, and have learned through annual Science Team meetings and stakeholder workshops about applications of CMS products (Brown *et al* 2020). This engagement by each funded project is one of the most novel parts of the CMS program and results in rapid prototyping and discovery of new carbon cycle data and models. By emphasizing in future funding opportunities the need for proposers to identify and engage with stakeholders before proposing, more rapid uptake of new carbon cycle products can be achieved (Brown *et al* 2020). As Arnott *et al* (2020) points out, funders of science

are receptive to new ways of revisiting the ‘social contract’ for science so that co-production of knowledge can be prioritized. Ensuring CMS scientists prioritize relationships as well as producing products and writing papers is essential.

3.3. Initiative

CMS Phase 2 has engaged a large and diverse set of scientists and stakeholders in prototyping novel approaches to carbon monitoring in all major components of the Earth system (land, atmosphere, ocean/wet carbon), for both biomass and fluxes, and over a variety of spatial (local to global) and temporal domains. The projects and their results have been described in multiple publications and synthesized at the thematic level above. Here they are aggregated up and synthesized at the initiative level toward a systems perspective.

For biomass, it is clear CMS has demonstrated through multiple efforts that high-resolution mapping and modeling of forest biomass enabled by LiDAR/Radar and optical remote sensing is now possible across a range of systems, at multiple scales and ARLs, and is defensible in the context of MRV and REDD+. The advances thus far based largely on airborne data have yielded important applications in their own right and have also paved the way for subsequent orbital missions such as GEDI and ICESat-2 and others. For flux, atmospheric research and inverse modeling techniques have also qualitatively advanced and led to important new capabilities and findings for carbon. CMS has advanced two state of the art global flux systems, able to track sources and sinks and 3-D transport of carbon in the atmosphere. Importantly, regional networks of *in situ* and remote-sensing measurements of greenhouse gas concentrations have been shown capable of validating emission estimates. For methane, satellite and aircraft observations have been demonstrated to usefully monitor methane emissions from the national/regional scale down to the scale of point sources. The resulting capabilities can be used in national inventories, and in the identification of superemitter point sources. For wet carbon, research has quantified the importance of coastal margins as a sink of carbon—with high temporal and spatial variability, and that the impacts of human and climate-related forcing on terrestrial watersheds affect export of carbon and other materials to the coastal margins, and subsequently influence coastal carbon dynamics. Wetland and mangrove ecosystems have been shown to represent important reservoirs of carbon undergoing rapid change and may also be important sources of methane and other greenhouse gases. Across all of these themes, and perhaps most importantly, CMS has demonstrated that addressing stakeholder needs and advancing science are mutually beneficial, with societal needs driving new science requirements and resulting in new scientific results of high societal relevance.

Despite these advances, additional uncertainties and challenges remain. For example, the mapping of land biomass and biomass change, while promising, has yet to be accomplished with sufficient accuracy and resolution or attribution across all ecosystems, regions, disturbance regimes, and land-use classifications and time domains to meet stakeholder needs. Challenges remain to continue to improve atmospheric flux products and their connection with stakeholders. Net fluxes from atmospheric data do not have clearly defined stakeholders. Long latency and intermittent availability impacts relevancy for stakeholders. Lack of independent data hampers flux validation. Technical issues—data formats, geographic boundaries, accounting definitions can be improved. Coastal margins are a substantial and highly variable signal in global carbon budgets, but this contribution is still not well constrained, particularly with regard to seasonal and spatial patterns. Limited work on aquatic ecosystems and oceans has been done to date. There is considerable uncertainty in quantifying wetland emissions and how they contribute to total national emissions and the global methane trend. Uncertainties in carbon respiration rate, inundation dynamics, non-growing season emissions all contribute. Different CMS studies suggest that wetlands, livestock, oil/gas exploitation, OH concentrations could all have contributed. Looking across projects, it is not clear how different estimates of uncertainty can be reconciled, or combined, or applied, or how/how well various CMS products could be combined into global system level assessments, and once realized how such advances could be maintained over time. There are many important advances still needed to realize the full potential including: advances in remote sensing and modeling, coordinated advances in computing and data, and new partnerships and stakeholders.

In the future, additional efforts are needed to prototype carbon monitoring capabilities to meet stakeholder needs across a full range of systems, scales, quantities, and stakeholders. It is unreasonable to assume that progress can be made evenly in all areas, or that there is a single system that can meet all of these needs. Future efforts should build on successes, scale-up existing successful approaches, and initiate new activities in areas and domains most needed. Projects are needed that build upon airborne-based prototypes and incorporate new orbital remote sensing datasets to improve and extend coverage of carbon monitoring capabilities, expand the coverage of forest carbon monitoring and modeling capabilities globally (GEDI, ICESat-2), and exploit the next generation of satellite observations to constrain methane fluxes in a way that serves stakeholder needs (GOSAT, TROPOMI, etc). The impact on flux estimates from integration of multiple sensors needs to be assessed (OCO-2, GeoCARB, etc). Projects should continue emphasis on validation and

improve and coordinate quantitative estimates of uncertainties to facilitate interoperability of products and their applications. To connect system components, integrated approaches for models and observations across scales, and across the land-ocean-atmosphere continuum, are needed. For maximum utility, an increased emphasis is needed on coupling models and observations to expand the time domain of products from contemporary periods, both backward to reach policy base year, and forward to include planning for climate mitigation. To ensure maximum relevance, continued emphasis on end-to-end stakeholder engagement, a hallmark of CMS, should be continued and expanded, and a plan must be developed to sustain key science advances and update products of high stakeholder importance.

4. Conclusion and discussion

Over the past 10 years (2011–2021), NASA Phase 2 has supported 79 projects to completion prototyping innovative scientific approaches to carbon monitoring on land, atmosphere, and ocean, including fluxes between. The result is one of the largest collections of applied carbon monitoring research to date, evidenced by numerous publications, citations, products, and product downloads.

Key to this effort has been exploitation of the remote sensing and modeling expertise of NASA, collaboration with scientists and data products from other agencies, and the end-to-end focus on stakeholder engagement to meet societal needs. CMS projects have utilized both airborne and orbital remote sensing products and have led the integration of these data with some of the most advanced process models for both biomass and atmospheric fluxes.

In addition to products and metrics, there are numerous qualitative success stories that have emerged. The 2014 Farm Bill directed the U.S Forest Service (USFS) both to increase operational cooperation with NASA and to address monitoring of large areas of uninventoried forest in Interior Alaska. CMS has partnered with USFS to advance the national forest inventory in Alaska utilizing remote sensing over some of the most inaccessible areas. Over Maryland, high resolution forest carbon monitoring and modeling products have been implemented to meet the state's needs, becoming the first state in the nation utilizing remote sensing-based assessment. Over wetlands, CMS products have pioneered mapping forest biomass and providing a global assessment of their carbon stocks in some of the most carbon rich ecosystems in the world. Internationally, CMS innovated a framework for forest MRV for other developing countries. CMS has also had multiple success stories in atmospheric flux. For example, carbon emissions from Indonesian fires, of global importance, have been quantified and used in official IPCC reporting.

Innovations quantifying methane flux have identified important, but previously unknown, point sources within the US, and lead to an update of U.S. reporting of methane emissions nationwide. CMS also quantified land-ocean exchange of carbon in the Mississippi river basin, a key missing link in carbon accounting. Two global atmospheric flux systems provide state-of-the-art synthesis and tracking of emissions and fluxes worldwide.

Looking ahead, two key questions emerge. First, how can past advances of societal importance be sustained and updated and utilized? To meet these needs, all NASA CMS products are permanently archived and made freely available via Distributed Active Archive Centers. Beyond that, additional efforts and partnerships are needed to support capacity building to utilize new data products, and to refresh and update important data products over time.

Next, what should be done to meet evolving needs for carbon monitoring? This report details a series of remaining science gaps and science next steps in both thematic areas and initiative wide. These recommendations need to be married to the stakeholder context, in which there is a growing need for carbon data at a variety of policy scales. Numerous cities have climate mitigation goals and carbon budgets, evidenced by the Compact of Mayors. More than 25 states in the U.S. are members of the U.S. Climate Alliance and have climate mitigation goals set in state policy. Most recently, the U.S. has rejoined the Paris Climate Accord and has made new commitments in the Glasgow Pact. These different policy needs at different scales likely drive important differences in science requirements. These needs must be met with expanded and coordinated science advances designed to meet stakeholder needs in a flexible CMS, or system of systems.

Despite NASA's leadership in CMS, it is clear that NASA does not and cannot do this work alone (Hurtt *et al* 2014b). The vast majority of CMS projects involve critical interagency collaborations with other federal agencies with complementary strengths, including USDA, NOAA, DOE, and others. There is tremendous opportunity now to strategically integrate and deepen these interagency collaborations further toward the development of the most robust CMS capabilities to meet societal needs.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://carbon.nasa.gov/data.html>.

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References

- Alonzo M, Andersen H, Morton D and Cook B 2018 Quantifying boreal forest structure and composition using UAV structure from motion *Forests* **9** 119
- Alonzo M, Dial R J, Schulz B K, Andersen H, Lewis-Clark E, Cook B D and Morton D C 2020 Mapping tall shrub biomass in Alaska at landscape scale using structure-from-motion photogrammetry and lidar *Remote Sens. Environ.* **245** 111841
- Andela N et al 2017 A human-driven decline in global burned area *Science* **356** 1356–62
- Andela N, Morton D C, Giglio L, Paugam R, Chen Y, Hantson S, van der Werf G R and Randerson J T 2019 The Global Fire Atlas of individual fire size, duration, speed and direction *Earth Syst. Sci. Data* **11** 529–52
- Arevalo P, Bullock E L, Woodcock C E and Olofsson P 2020 A suite of tools for continuous land change monitoring in google earth engine *Front. Clim.* **2** 1–19
- Arnott J C, Kirchhoff C J, Meyer R M, Meadow A M and Bednarek A T 2020 Sponsoring actionable science: what public science funders can do to advance sustainability and the social contract for science *Curr. Opin. Environ. Sustain.* **42** 38–44
- Asefi-Najafabady S, Rayner P J, Gurney K R, McRobert A, Song Y, Coltin K, Huang J, Elvidge C and Baugh K 2014 A multiyear, global gridded fossil fuel CO₂ emission data product: evaluation and analysis of results *J. Geophys. Res.: Atmos.* **119** 10213–31
- Babcock C et al 2018 Geostatistical estimation of forest biomass in interior Alaska combining Landsat-derived tree cover, sampled airborne lidar and field observations *Remote Sens. Environ.* **212** 212–30
- Babcock C, Finley A O, Bradford J B, Kolka R, Birdsey R and Ryan M G 2015 LiDAR based prediction of forest biomass using hierarchical models with spatially varying coefficients *Remote Sens. Environ.* **169** 113–27
- Babcock C, Finley A O, Cook B D, Weiskittel A and Woodall C W 2016 Modeling forest biomass and growth: coupling long-term inventory and LiDAR data *Remote Sens. Environ.* **182** 1–12
- Baccini A, Walker W, Carvalho L, Farina M, Sulla-Menashe D and Houghton R A 2017 Tropical forests are a net carbon source based on aboveground measurements of gain and loss *Science* **358** 230–4
- Basu S, Baker D F, Chevallier F, Patra P K, Liu J and Miller J B 2018 The impact of transport model differences on CO₂ surface flux estimates from OCO-2 retrievals of column average CO₂ *Atmos. Chem. Phys.* **18** 7189–215
- Benway H M et al 2016 A science plan for carbon cycle research in North American coastal waters *Report of the Coastal Carbon Synthesis (CCARS) Community Workshop (19–21 August 2014)* (Woods Hole, MA: Ocean Carbon and Biogeochemistry Program and North American Carbon Program) p 84
- Biederman J A et al 2016 Terrestrial carbon balance in a drier world: the effects of water availability in southwestern North America *Glob. Change Biol.* **22** 1867–79
- Biederman J A et al 2017 CO₂ exchange and evapotranspiration across dryland ecosystems of southwestern North America *Glob. Change Biol.* **23** 4204–21
- Bloom A A et al 2020 Lagged effects regulate the inter-annual variability of the tropical carbon balance *Biogeosciences* **17** 6393–422
- Bloom A A, Bowman K W, Lee M, Turner A J, Schroeder R, Worden J R, Weidner R, McDonald K C and Jacob D J 2017 A global wetland methane emissions and uncertainty dataset for atmospheric chemical transport models (WetCHARTs version 1.0) *Geosci. Model Dev.* **10** 2141–56
- Bousserez N, Henze D K, Perkins A, Bowman K W, Lee M, Liu J, Deng F and Jones D B A 2015 Improved analysis-error covariance matrix for high-dimensional variational inversions: application to source estimation using a 3D atmospheric transport model *Q. J. R. Meteorol. Soc.* **141** 1906–21
- Bowman K W et al 2017 Global and Brazilian carbon response to El Nino Modoki 2011–2010 *Earth Space Sci.* **4** 637–60
- Brix H, Menemenlis D, Hill C, Dutkiewicz S, Jahn O, Wang D, Bowman K and Zhang H 2015 Using Green's Functions to initialize and adjust a global, eddying ocean biogeochemistry general circulation model *Ocean Modell.* **95** 1–14
- Brophy K, Graven H, Manning A J, White E, Arnold T, Fischer M L, Jeong S, Cui X and Rigby M 2019 Characterizing uncertainties in atmospheric inversions of fossil fuel CO₂ emissions in California *Atmos. Chem. Phys.* **19** 2991–3006
- Brown M E, Cooper M W and Griffith P C 2020 NASA's carbon monitoring system and arctic-boreal vulnerability experiment (ABOVE) social network and community of practice *Environ. Res. Lett.* **15** 115014

- Bullock E L, Woodcock C E, Souza C and Olofsson P 2020 Satellite-based estimates reveal widespread forest degradation in the Amazon *Glob. Change Biol.* **26** 2956–69
- Butler M P, Lauvaux T, Feng S, Liu J, Bowman K W and Davis K J 2020 Atmospheric simulations of total column CO₂ mole fractions from global to mesoscale within the carbon monitoring system flux inversion framework *Atmosphere* **11** 787
- Byrd K B, Ballanti L, Thomas N, Nguyen D, Holmquist J R, Simard M and Windham-Myers L 2018 A remote sensing-based model of tidal marsh aboveground carbon stocks for the conterminous United States *ISPRS J. Photogramm. Remote Sens.* **139** 255–71
- Cai W-J, Chen C A and Borges A 2013 Carbon dioxide dynamics and fluxes in coastal waters influenced by river plumes *Biogeochemical Dynamics at Major River-Coastal Interfaces: Linkages with Global Change* ed Bianchi T, Allison M and Cai W (Cambridge: Cambridge University Press) pp 155–73
- Carranza V, Rafiq T, Frausto-Vicencio I, Hopkins F M, Verhulst K R, Rao P, Duren R M and Miller C E 2018 Vista-LA: mapping methane-emitting infrastructure in the Los Angeles megacity *Earth Syst. Sci. Data* **10** 653–76
- Carroll D et al 2020 The ECCO-Darwin data-assimilative global ocean biogeochemistry model: estimates of seasonal to multi-decadal surface ocean pCO₂ and air-sea CO₂ flux *J. Adv. Model. Earth Syst.* **12** e2019MS001888
- Cash D W, Borck J C and Patt A G 2006 Countering the loading-dock approach to linking science and decision making: comparative analysis of El Niño/Southern Oscillation (ENSO) forecasting systems *Sci. Technol. Human Values* **31** 465–94
- Chakraborty S and Lohrenz S E 2015 Phytoplankton community structure in the river-influenced continental margin of the northern Gulf of Mexico *Mar. Ecol. Prog. Ser.* **521** 31–47
- Chakraborty S, Lohrenz S E and Gundersen K 2017 Photophysiological and light absorption properties of phytoplankton communities in the river-dominated margin of the northern Gulf of Mexico *J. Geophys. Res.: Oceans* **122** 4922–38
- Chen G S, Tian H Q, Zhang C, Liu M L, Ren W, Zhu W Q, Chappella A H, Prior S A and Lockaby G B 2012 Drought in the Southern United States over the 20th century: variability and its impacts on terrestrial ecosystem productivity and carbon storage *Clim. Change* **114** 379–97
- Chen G, Tian H, Huang C, Prior S A and Pan S 2013 Integrating a process-based ecosystem model with Landsat imagery to assess impacts of forest disturbance on terrestrial carbon dynamics: case studies in Alabama and Mississippi *J. Geophys. Res.: Biogeosci.* **118** 1208–24
- Chen J, Viatte C, Hedelius J K, Jones T, Franklin J E, Parker H, Gottlieb E W, Wennberg P O, Dubey M K and Wofsy S C 2016 Differential column measurements using compact solar-tracking spectrometers *Atmos. Chem. Phys.* **16** 8479–98
- Chen M et al 2017a Regional contribution to variability and trends of global gross primary productivity *Environ. Res. Lett.* **12** 105005
- Chen Y, Morton D C, Andela N, van der Werf G R, Giglio L and Randerson J T 2017b A pan-tropical cascade of fire driven by El Niño/southern oscillation *Nat. Clim. Change* **7** 906–11
- Cohen W, Yang Z, Stehman S V, Schroeder T A, Bell D M, Masek J G, Huang C and Meigs G W 2016 Forest disturbance across the conterminous United States from 1985–2012: the emerging dominance of forest decline *For. Ecol. Manage.* **360** 242–52
- Cooke R M, Saatchi S and Hagen S 2016 Global correlation and uncertainty accounting *Depend. Model.* **4** 000010151520160009
- Cusworth D H et al 2019 Potential of next-generation imaging spectrometers to detect and quantify methane point sources from space *Atmos. Meas. Tech.* **12** 5655–68
- Cusworth D H et al 2020a Using remote sensing to detect, validate, and quantify methane emissions from California solid waste operations *Environ. Res. Lett.* **15** 054012
- Cusworth D H et al 2021b Intermittency of large methane emitters in the Permian Basin *Environ. Sci. Technol. Lett.* **8** 567–73
- Cusworth D H, Duren R M, Yadav V, Thorpe A K, Verhulst K, Sander S, Hopkins F, Rafiq T and Miller C E 2020b Synthesis of methane observations across scales: strategies for deploying a multitiered observing network *Geophys. Res. Lett.* **47** 7
- Cusworth D H, Jacob D J, Sheng J, Benmergui J, Turner A J, Brandman J, White L and Randles C A 2018 Detecting high-emitting methane sources in oil/gas fields using satellite observations *Atmos. Chem. Phys.* **18** 16885–96
- Cusworth D et al 2021a Multi-satellite imaging of a gas well blowout provides new insights for methane monitoring *Geophys. Res. Lett.* **48** e2020GL090864
- Datta A, Banerjee S, Finley A O and Gelfand A E 2016 On nearest-neighbor Gaussian process models for massive spatial data *Wiley Interdiscip. Rev. Comput. Stat.* **8** 162–71
- Deo R K, Froese R E, Falkowski M J and Hudak A T 2016 Optimizing variable radius plot size and LiDAR resolution to model standing volume in conifer forests *Can. J. Remote Sens.* **42** 428–42
- Deo R K, Russell M B, Domke G M, Woodall C W, Falkowski M J and Cohen W B 2017 Using Landsat time-series and LiDAR to inform aboveground forest biomass baselines in northern Minnesota, USA *Can. J. Remote Sens.* **43** 28–47
- Diaz-Isaac L I, Lauvaux T, Bocquet M and Davis K J 2019 Calibration of a multi-physics ensemble for estimating the uncertainty of a greenhouse gas atmospheric transport model *Atmos. Chem. Phys.* **19** 5695–718
- Duncanson L I, Dubayah R O, Cook B D, Rosette J and Parker G 2015 The importance of spatial detail: assessing the utility of individual crown information and scaling approaches for lidar-based biomass density estimation *Remote Sens. Environ.* **168** 102–12
- Duncanson L et al 2019 The importance of consistent global forest aboveground biomass product validation *Surv. Geophys.* **40** 979–99
- Duren R M et al 2019 California's methane super-emitters *Nature* **575** 180–4
- EPA 2019 Land use, land-use change, and forestry *Inventory of U.S. Greenhouse Gas Emissions and Sinks* EPA 430-R-19-001 (Washington, DC: EPA) ch 6 pp 6-1–120
- Fahnenstiel G L, Sayers M J, Shuchman R A, Yousef F and Pothoven S A 2016 Lake-wide phytoplankton production and abundance in the Upper Great Lakes: 2010–2013 *J. Great Lakes Res.* **42** 619–29
- Fatoyinbo T, Feliciano E A, Lagomasino D, Lee S K and Trettin C 2018 Estimating mangrove aboveground biomass from airborne LiDAR data: a case study from the Zambezi River delta *Environ. Res. Lett.* **13** 025012
- Fekety P A, Falkowski M J, Hudak A T, Jain T B and Evans J S 2018 Transferability of lidar-derived basal area and stem density models within a Northern Idaho ecoregion *Can. J. Remote Sens.* **44** 131–43
- Fennel K et al 2019 Carbon cycling in the North American coastal ocean: a synthesis *Biogeosciences* **16** 1281–304
- Fer I, Kelly R, Moorcroft P R, Richardson A D, Cowdery E M and Dietze M C 2018 Linking big models to big data: efficient ecosystem model calibration through Bayesian model emulation *Biogeosciences* **15** 5801–30
- Finley A O, Banerjee S, Cook B D and Bradford J B 2013 Hierarchical Bayesian spatial models for predicting multiple forest variables using waveform LiDAR, hyperspectral imagery, and large inventory datasets *Int. J. Appl. Earth Obs. Geoinf.* **22** 147–60
- Finley A O, Banerjee S, Weiskittel A R, Babcock C and Cook B D 2014 Dynamic spatial regression models for space-varying forest stand tables *Environmetrics* **25** 596–609
- Finley A O, Banerjee S, Zhou Y, Cook B D and Babcock C 2017 Joint hierarchical models for sparsely sampled

- high-dimensional LiDAR and forest variables *Remote Sens. Environ.* **190** 149–61
- Fischer M L *et al* 2017 Simulating estimation of California fossil fuel and biosphere carbon dioxide exchanges combining *in situ* tower and satellite column observations *J. Geophys. Res.: Atmos.* **122** 3653–71
- French N H F *et al* 2014 Modeling regional-scale wildland fire emissions with the wildland fire emissions information system *Earth Interact.* **18** 1–26
- Fu Z, Stoy P C, Poulter B, Gerken T, Zhang Z, Wakbulcho G and Niu S 2019 Maximum carbon uptake rate dominates the interannual variability of global net ecosystem exchange *Glob. Change Biol.* **25** 3381–94
- Gately C K and Hutryra L R 2017 Large uncertainties in urban-scale carbon emissions *J. Geophys. Res.: Atmos.* **122** 11242–60
- Graven H *et al* 2018 Assessing fossil fuel CO₂ emissions in California using atmospheric observations and models *Environ. Res. Lett.* **13** 065007
- Gregg W W, Rousseaux C S and Franz B A 2017 Global trends in ocean phytoplankton: a new assessment using revised ocean colour data *Remote Sens. Lett.* **8** 1102–11
- Gu H, Williams C A, Ghimire B, Zhao F and Huang C 2016 High-resolution mapping of time since disturbance and forest carbon flux from remote sensing and inventory data to assess harvest, fire, and beetle disturbance legacies in the Pacific Northwest *Biogeosciences* **13** 6321–37
- Guo X *et al* 2012 Carbon dynamics and community production in the Mississippi River plume *Limnol. Oceanogr.* **57** 1–17
- Hannun R A *et al* 2020 Spatial heterogeneity in CO₂, CH₄, and energy fluxes: insights from airborne eddy covariance measurements over the Mid-Atlantic region *Environ. Res. Lett.* **15** 035008
- Hardiman B S, Wang J A, Hutryra L R, Gately C K, Getson J M and Friedl M A 2017 Accounting for urban biogenic fluxes in regional carbon budgets *Sci. Total Environ.* **592** 366–72
- Healey S P, Patterson P L, Saatchi S, Lefsky M A, Lister A J and Freeman E A 2012 A sample design for globally consistent biomass estimation using lidar data from the Geoscience Laser Altimeter System (GLAS) *Carbon Balance Manage.* **7** 10
- Hedelius J K *et al* 2016 Assessment of errors and biases in retrievals of XCO₂, XCH₄, XCO, and XN₂O from a 0.5 cm⁻¹ resolution solar-viewing spectrometer *Atmos. Meas. Tech.* **9** 3527–46
- Hedelius J K *et al* 2017 Intercomparability of XCO₂ and XCH₄ from the United States TCCON sites *Atmos. Meas. Tech.* **10** 1481–93
- Hinojo-Hinojo C, Castellanos A E, Llano-Sotelo J, Penuelas J, Vargas R and Romo-Leon J R 2018 High V_{cmax}, J_{max} and photosynthetic rates of Sonoran Desert species: using nitrogen and specific leaf area traits as predictors in biochemical models *J. Arid Environ.* **156** 1–8
- Hinson A L, Feagin R A, Eriksson M, Najjar R G, Herrmann M, Bianchi T S, Kemp M, Hutchings J A, Crooks S and Boutton T 2017 The spatial distribution of soil organic carbon in tidal wetland soils of the continental United States *Glob. Change Biol.* **23** 5468–80
- Holmquist J R *et al* 2018a Uncertainty in United States coastal wetland greenhouse gas inventorying *Environ. Res. Lett.* **13** 115005
- Holmquist J R *et al* 2018b Accuracy and precision of tidal wetland soil carbon mapping in the conterminous United States *Sci. Rep.* **8** 9478
- Hopkinson C S, Cai W-J and Hu X 2012 Carbon sequestration in wetland dominated coastal systems; a global sink of rapidly diminishing magnitude *Curr. Opin. Environ. Sustain.* **4** 186–94
- Horita F E A, de Albuquerque J P, Marchezini V and Mendiondo E M 2017 Bridging the gap between decision-making and emerging big data sources: an application of a model-based framework to disaster management in Brazil *Decis. Support Syst.* **97** 12–22
- Hu L *et al* 2019 Enhanced North American carbon uptake associated with El Niño *Sci. Adv.* **5** eaaw0076
- Huang W-J, Cai W J, Wang Y, Hu X, Chen B, Lohrenz S E, Chakraborty S, He R, Brandes J and Hopkinson C S 2015b The response of inorganic carbon distributions and dynamics to upwelling-favorable winds on the northern Gulf of Mexico during summer *Cont. Shelf Res.* **111** 211–22
- Huang W-J, Cai W-J, Castelao R M, Wang Y and Lohrenz S E 2013 Effects of a wind-driven cross-shelf large river plume on biological production and CO₂ uptake on the Gulf of Mexico during spring *Limnol. Oceanogr.* **58** 1727–35
- Huang W-J, Cai W-J, Wang Y, Lohrenz S E and Murrell M C 2015a The carbon dioxide system on the Mississippi River-dominated continental shelf in the northern Gulf of Mexico: 1. Distribution and air-sea CO₂ flux *J. Geophys. Res.: Oceans* **120** 1429–45
- Huang W, Dolan K A, Swatantran A, Johnson K D, Tang H, O'Neil-Dunne J, Dubayah R and Hurtt G 2019 High-resolution mapping of aboveground biomass for forest carbon monitoring system in the Tri-State region of Maryland, Pennsylvania and Delaware, USA *Environ. Res. Lett.* **14** 095002
- Huang W, Swatantran A, Duncanson L, Johnson K, Watkinson D, Dolan K, O'Neil-Dunne J, Hurtt G and Dubayah R 2017 County-scale biomass map comparison: a case study for Sonoma, California *Carbon Manage.* **8** 417–34
- Huang W, Swatantran A, Johnson K, Duncanson L, Tang H, Dunne J O, Hurtt G and Dubayah R 2015 Local discrepancies in continental scale biomass maps: a case study over forested and non-forested landscapes in Maryland, USA *Carbon Balance Manage.* **10** 19
- Hurtt G *et al* 2014a NASA carbon monitoring system: phase 1 report (NASA) pp 1–78 (available at: https://carbon.nasa.gov/pdfs/CMS_Phase-1_Report_Final.pdf)
- Hurtt G *et al* 2014b NASA carbon monitoring system: prototype monitoring, reporting, and verification (NASA) pp 1–37 (available at: https://carbon.nasa.gov/pdfs/2014_Carbon_MonitoringSystem_ProgressReport.pdf)
- Hurtt G *et al* 2019 Beyond MRV: high-resolution forest carbon modeling for climate mitigation planning over Maryland, USA *Environ. Res. Lett.* **14** 45013
- Jacob D J, Turner A J, Maasakkers J D, Sheng J, Sun K, Liu X, Chance K, Aben I, McKeever J and Frankenberg C 2016 Satellite observations of atmospheric methane and their value for quantifying methane emissions *Atmos. Chem. Phys.* **16** 14371–96
- Junttila V, Finley A O, Bradford J B and Kauranne T 2013 Strategies for minimizing sample size for use in airborne LiDAR-based forest inventory *For. Ecol. Manage.* **292** 75–85
- Kennedy R E *et al* 2018 An empirical, integrated forest biomass monitoring system *Environ. Res. Lett.* **13** 025004
- Konings A G, Bloom A A, Liu J, Parazoo N C, Schimel D S and Bowman K W 2019 Global satellite-driven estimates of heterotrophic respiration *Biogeosciences* **16** 2269–84
- Lagomasino D, Fatoyinbo T, Lee S K and Simard M 2015 High-resolution forest canopy height estimation in an African blue carbon ecosystem *Remote Sens. Ecol. Conserv.* **1** 51–60
- Lagomasino D, Fatoyinbo T, Lee S, Feliciano E, Trettin C and Simard M 2016 A comparison of mangrove canopy height using multiple independent measurements from land, air, and space *Remote Sens.* **8** 327
- Lamb R L *et al* 2021a Context and future directions for integrating forest carbon into sub-national climate mitigation planning in the RGGI region of the U.S *Environ. Res. Lett.* **16** 063001
- Lamb R L, Ma L, Sahajpal R, Edmonds J, Hultman N E, Dubayah R O, Kennedy J and Hurtt G C 2021b Geospatial assessment of the economic opportunity for reforestation in Maryland, USA *Environ. Res. Lett.* **16** 084012
- Lee S and Fatoyinbo T E 2015 TanDEM-X Pol-InSAR inversion for mangrove canopy height estimation *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **8** 3608–18

- Li F, Zhang X, Kondragunta S and Lu X 2020 An evaluation of advanced baseline imager fire radiative power based wildfire emissions using carbon monoxide observed by the tropospheric monitoring instrument across the conterminous United States *Environ. Res. Lett.* **15** 094049
- Liu J et al 2014 Carbon monitoring system flux estimation and attribution: impact of ACOS-GOSAT XCO₂ sampling on the inference of terrestrial biospheric sources and sinks *Tellus B* **66** 22486
- Liu J et al 2017 Contrasting carbon cycle responses of the tropical continents to the 2015-2016 El Nino *Science* **358** eaam5690
- Liu M, Tian H, Yang Q, Yang J, Song X, Lohrenz S E and Cai W-J 2013 Long-term trends in evapotranspiration and runoff over the drainage basins of the Gulf of Mexico during 1901-2008 *Water Resour. Res.* **49** 1–25
- Lohrenz S E, Cai W J, Chakraborty S, Huang W J, Guo X, He R, Xue Z, Fennel K, Howden S and Tian H 2018 Satellite estimation of coastal pCO₂ and air-sea flux of carbon dioxide in the northern Gulf of Mexico *Remote Sens. Environ.* **207** 71–83
- Lohrenz S E, Cai W-J, Chakraborty S, Gundersen K and Murrell M C 2013 Nutrient and carbon dynamics in a large river-dominated coastal ecosystem: the Mississippi-Atchafalaya River system *Biogeochemical Dynamics at Major River-Coastal Interfaces: Linkages with Global Change* ed T S Bianchi, M A Allison and W-J Cai (Cambridge: Cambridge University Press) pp 448–72
- Longo M, Keller M, Dos-santos M N, Leitold V, Pinage E R, Baccini A, Saatchi S, Nogueira E M, Batistella M and Morton D C 2016 Aboveground biomass variability across intact and degraded forests in the Brazilian Amazon *Glob. Biogeochem. Cycles* **30** 1639–60
- Lu C, Yu Z, Tian H, Hennessy D A, Feng H, Al-Kaisi M, Zhou Y, Sauer T and Arritt R 2018 Increasing carbon footprint of grain crop production in the U.S. Western Corn Belt *Environ. Res. Lett.* **13** 124007
- Lu C, Zhang J, Tian H, Crumpton W G, Helmers M J, Cai W-J, Hopkinson C S and Lohrenz S E 2020 Increased extreme precipitation challenges nitrogen load management to the Gulf of Mexico *Commun. Earth Environ.* **1** 21
- Lu X et al 2021 Global methane budget and trend, 2010–2017: complementarity of inverse analyses using *in situ* (GLOBALVIEWplus CH₄ ObsPack) and satellite (GOSAT) observations *Atmos. Chem. Phys.* **21** 4637–57
- Ma L et al 2021a High-resolution forest carbon modelling for climate mitigation planning over the RGGI region, USA *Environ. Res. Lett.* **16** 045014
- Ma S et al 2021b Satellite constraints on the latitudinal distribution and temperature sensitivity of wetland methane emissions *AGU adv.* **2** e2021AV000408
- Maasakkers J D et al 2016 Gridded national inventory of U.S. methane emissions *Environ. Sci. Technol.* **50** 13123–33
- Maasakkers J D et al 2019 Global distribution of methane emissions, emission trends, and OH concentrations and trends inferred from an inversion of GOSAT satellite data for 2010–2015 *Atmos. Chem. Phys.* **19** 7859–81
- Maasakkers J D et al 2021 2010–2015 North American methane emissions, sectoral contributions, and trends: a high-resolution inversion of GOSAT observations of atmospheric methane *Atmos. Chem. Phys.* **21** 4339–56
- Magney T S et al 2019 Mechanistic evidence for tracking the seasonality of photosynthesis with solar-induced fluorescence *Proc. Natl Acad. Sci.* **116** 201900278
- McKain K et al 2015 Methane emissions from natural gas infrastructure and use in the urban region of Boston, Massachusetts *Proc. Natl Acad. Sci.* **112** 1941–6
- Menlove J and Healey S P 2020 A comprehensive forest biomass dataset for the USA allows customized validation of remotely sensed biomass estimates *Remote Sens.* **12** 4141
- Montesano P M, Cook B D, Sun G, Simard M, Nelson R F, Ranson K J, Zhang Z and Luthcke S 2013 Achieving accuracy requirements for forest biomass mapping: a spaceborne data fusion method for estimating forest biomass and LiDAR sampling error *Remote Sens. Environ.* **130** 153–70
- Morris J T et al 2016 Contributions of organic and inorganic matter to sediment volume and accretion in tidal wetlands at steady state *Earth's Future* **4** 110–21
- Morton D C 2016 Forest carbon fluxes: a satellite perspective *Nat. Clim. Change* **6** 346–8
- Najjar R G et al 2018 Carbon budget of tidal wetlands, estuaries, and shelf waters of Eastern North America *Glob. Biogeochem. Cycles* **32** 389–416
- Noojipady P, Morton C D, Macedo N M, Victoria C D, Huang C, Gibbs K H and Bolfe L E 2017 Forest carbon emissions from cropland expansion in the Brazilian Cerrado biome *Environ. Res. Lett.* **12** 025004
- Oda T et al 2019 Errors and uncertainties in a gridded carbon dioxide emissions inventory *Mitig. Adapt. Strateg. Glob. Change* **24** 1007–50
- Oda T, Maksyutov S and Andres R J 2018 The open-source data inventory for anthropogenic CO₂, version 2016 (ODIAC2016): a global monthly fossil fuel CO₂ gridded emissions data product for tracer transport simulations and surface flux inversions *Earth Syst. Sci. Data* **10** 87–107
- Olofsson P, Arevalo P, Espejo A B, Green C, Lindquist E, McRoberts R E and Sanz M J 2020 Mitigating the effects of omission errors on area and area change estimates *Remote Sens. Environ.* **236** 111492
- Ott L E et al 2015 Assessing the magnitude of CO₂ flux uncertainty in atmospheric CO₂ records using products from NASA's carbon monitoring flux pilot project *J. Geophys. Res.: Atmos.* **120** 734–65
- Parker R J, Boesch H, McNorton J, Comyn-Platt E, Gloor M, Wilson C, Chipperfield M P, Hayman G D and Bloom A A 2018 Evaluating year-to-year anomalies in tropical wetland methane emissions using satellite CH₄ observations *Remote Sens. Environ.* **211** 261–75
- Patterson P L et al 2019 Statistical properties of hybrid estimators proposed for GEDI–NASA's global ecosystem dynamics investigation *Environ. Res. Lett.* **14** 065007
- Potapov P V et al 2014 National satellite-based humid tropical forest change assessment in Peru in support of REDD+ implementation *Environ. Res. Lett.* **9** 124012
- Poulter B et al 2017 Global wetland contribution to 2000–2012 atmospheric methane growth rate dynamics *Environ. Res. Lett.* **12** 094013
- Rangel Pinage E, Keller M, Duffy P, Longo M, dos-Santos M and Morton D 2019 Long-term impacts of selective logging on amazon forest dynamics from multi-temporal airborne LiDAR *Remote Sens.* **11** 709
- Rappaport D I, Morton D C, Longo M, Keller M, Dubayah R and dos-Santos M N 2018 Quantifying long-term changes in carbon stocks and forest structure from Amazon forest degradation *Environ. Res. Lett.* **13** 065013
- Reimer J J, Cueva A, Gaxiola-Castro G, Lara-Lara R and Vargas R 2016 Random error analysis of marine xCO₂ measurements in a coastal upwelling region *Prog. Oceanogr.* **143** 1–12
- Ren W, Tian H, Cai W-J, Lohrenz S E, Hopkinson C S, Huang W-J, Yang J, Tao B, Pan S and He R 2016 Century-long increasing trend and variability of dissolved organic carbon export from the Mississippi River basin driven by natural and anthropogenic forcing *Glob. Biogeochem. Cycles* **30** 1288–99
- Ren W, Tian H, Tao B, Yang J, Pan S, Cai W J, Lohrenz S E, He R and Hopkinson C S 2015 Large increase in dissolved inorganic carbon flux from the Mississippi River to Gulf of Mexico due to climatic and anthropogenic changes over the 21st century *J. Geophys. Res.: Biogeosci.* **120** 724–36
- Saarela S, Holm S, Healey S, Andersen H, Petersson H, Prentius W, Patterson P, Naesset E, Gregoire T and Stahl G 2018 Generalized hierarchical model-based estimation for aboveground biomass assessment using GEDI and landsat data *Remote Sens.* **10** 1832
- Salisbury J, Vandemark D, Jönsson B, Balch W, Chakraborty S, Lohrenz S, Chapron B, Hales B, Mannino A and Mathis J

- 2015 How can present and future satellite missions support scientific studies that address ocean acidification? *Oceanography* **25** 108–21
- Sargent M et al 2018 Anthropogenic and biogenic CO₂ fluxes in the Boston urban region *Proc. Natl Acad. Sci.* **115** 7491–6
- Scarpelli T R, Jacob D J, Maasakkers J D, Sulprizio M P, Sheng J, Rose K, Romeo L, Worden J R and Janssens-Maenhout G 2020a A global gridded (0.1deg x 0.1deg) inventory of methane emissions from oil, gas, and coal exploitation based on national reports to the United Nations framework convention on climate change *Earth Syst. Sci. Data* **12** 563–75
- Scarpelli T R, Jacob D J, Octaviano Villasana C A, Ramirez Hernandez I F, Cardenas Moreno P R, Cortes Alfaro E A, Garcia Garcia M A and Zavala-Araiza D 2020b A gridded inventory of anthropogenic methane emissions from Mexico based on Mexico's national inventory of greenhouse gases and compounds *Environ. Res. Lett.* **15** 105015
- Shen L et al 2021 Unravelling a large methane emission discrepancy in Mexico using satellite observations *Remote Sens. Environ.* **260** 112461
- Sheng J et al 2018a 2010–2016 methane trends over Canada, the United States, and Mexico observed by the GOSAT satellite: contributions from different source sectors *Atmos. Chem. Phys.* **18** 12257–67
- Sheng J, Jacob D J, Turner A J, Maasakkers J D, Sulprizio M P, Bloom A A, Andrews A E and Wunch D 2018b High-resolution inversion of methane emissions in the Southeast U.S. using SEAC4RS aircraft observations of atmospheric methane: anthropogenic and wetland sources *Atmos. Chem. Phys.* **18** 6483–91
- Simard M, Fatoyinbo L, Smetanka C, Rivera-Monroy V H, Castañeda-Moya E, Thomas N and Van der Stocken T 2019 Mangrove canopy height globally related to precipitation, temperature and cyclone frequency *Nat. Geosci.* **12** 40–45
- Swatantran A, Tang H, Barrett T, DeCola P and Dubayah R 2016 Rapid, high-resolution forest structure and terrain mapping over large areas using single photon lidar *Sci. Rep.* **6** 28277
- Tang H, Ma L, Lister A, O'Neill-Dunne J, Lu J, Lamb R L and Dubayah R 2021 High-resolution forest carbon mapping for climate mitigation baselines over the RGGI region, USA *Environ. Res. Lett.* **16** 035011
- Tang X, Hutyrá L R, Arévalo P, Baccini A, Woodcock C E and Olofsson P 2020 Spatiotemporal tracking of carbon emissions and uptake using time series analysis of Landsat data: a spatially explicit carbon bookkeeping model *Sci. Total Environ.* **720** 137409
- Tao B, Tian H, Ren W, Yang J, Yang Q, He R, Cai W and Lohrenz S 2014 Increasing Mississippi river discharge throughout the 21st century influenced by changes in climate, land use, and atmospheric CO₂ *Geophys. Res. Lett.* **41** 4978–86
- Thomas N, Bunting P, Lucas R, Hardy A, Rosenqvist A and Fatoyinbo T 2018 Mapping mangrove extent and change: a globally applicable approach *Remote Sens.* **10** 1466
- Thorpe A K et al 2020 Methane emissions from underground gas storage in California *Environ. Res. Lett.* **15** 045005
- Tian H et al 2012a Century-scale responses of ecosystem carbon storage and flux to multiple environmental changes in the southern United States *Ecosystems* **15** 674–94
- Tian H et al 2012b Contemporary and projected biogenic fluxes of methane and nitrous oxide in North American terrestrial ecosystems *Front. Ecol. Environ.* **10** 528–36
- Tian H et al 2015a Global methane and nitrous oxide emissions from terrestrial ecosystems due to multiple environmental changes *Ecosyst. Health Sustain.* **1** art4
- Tian H et al 2015b Climate extremes dominating seasonal and interannual variations in carbon export from the Mississippi River Basin *Glob. Biogeochem. Cycles* **29** 1333–47
- Tian H et al 2016 The terrestrial biosphere as a net source of greenhouse gases to the atmosphere *Nature* **531** 225–8
- Tian H et al 2020 Long-term trajectory of nitrogen loading and delivery from Mississippi River Basin to the Gulf of Mexico *Glob. Biogeochem. Cycles* **34** e2019GB006475
- Tian H, Yang Q, Najjar R G, Ren W, Friedrichs M A M, Hopkinson C S and Pan S 2015c Anthropogenic and climatic influences on carbon fluxes from eastern North America to the Atlantic Ocean: a process-based modeling study *J. Geophys. Res.: Biogeosci.* **120** 757–72
- Treat C C, Bloom A A and Marushchak M E 2018 Nongrowing season methane emissions—a significant component of annual emissions across northern ecosystems *Glob. Change Biol.* **24** 3331–43
- Treuhafth R, Lei Y, Goncalves F, Keller M, Santos J, Neumann M and Almeida A 2017 Tropical-forest structure and biomass dynamics from TanDEM-X radar interferometry *Forests* **8** 277
- Turner A J et al 2015 Estimating global and North American methane emissions with high spatial resolution using GOSAT satellite data *Atmos. Chem. Phys.* **15** 7049–69
- Turner A J, Frankenberg C, Wennberg P O and Jacob D J 2017 Ambiguity in the causes for decadal trends in atmospheric methane and hydroxyl *Proc. Natl Acad. Sci.* **114** 5367–72
- Turner A J, Jacob D J, Benmergui J, Brandman J, White L and Randles C A 2018 Assessing the capability of different satellite observing configurations to resolve the distribution of methane emissions at kilometer scales *Atmos. Chem. Phys.* **18** 8265–78
- Turner A J, Jacob D J, Benmergui J, Wofsy S C, Maasakkers J D, Butz A, Hasekamp O and Biraud S C 2016 A large increase in U.S. methane emissions over the past decade inferred from satellite data and surface observations *Geophys. Res. Lett.* **43** 2218–24
- Tyukavina A, Stehman S V, Potapov P V, Turubanova S A, Baccini A, Goetz S J, Laporte N T, Houghton R A and Hansen M C 2013 National-scale estimation of gross forest aboveground carbon loss: a case study of the Democratic Republic of the Congo *Environ. Res. Lett.* **8** 044039
- USGCRP 2018 *Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report* (Washington, DC: U.S. Global Change Research Program) p 878
- Varon D J, Jacob D J, Jervis D and McKeever J 2020 Quantifying time-averaged methane emissions from individual coal mine vents with GHGSat-D satellite observations *Environ. Sci. Technol.* **54** 10246–53
- Varon D J, Jacob D J, McKeever J, Jervis D, Durak B O A, Xia Y and Huang Y 2018 Quantifying methane point sources from fine-scale satellite observations of atmospheric methane plumes *Atmos. Meas. Tech.* **11** 5673–86
- Varon D J, Jervis D, McKeever J, Spence I, Gains D and Jacob D J 2021 High-frequency monitoring of anomalous methane point sources with multispectral Sentinel-2 satellite observations *Atmos. Meas. Tech.* **14** 2771–85
- Varon D J, McKeever J, Jervis D, Maasakkers J D, Pandey S, Houweling S, Aben I, Scarpelli T and Jacob D J 2019 Satellite discovery of anomalously large methane point sources from oil/gas production *Geophys. Res. Lett.* **46** 13507–16
- Viatte C et al 2017 Methane emissions from dairies in the Los Angeles Basin *Atmos. Chem. Phys.* **17** 7509–28
- Wang J S, Kawa S R, Collatz G J, Sasakawa M, Gatti L V, Machida T, Liu Y and Manyin M E 2018 A global synthesis inversion analysis of recent variability in CO₂ fluxes using GOSAT and *in situ* observations *Atmos. Chem. Phys.* **18** 11097–124
- Wang J S, Oda T, Kawa S R, Strode S A, Baker D F, Ott L E and Pawson S 2020 The impacts of fossil fuel emission uncertainties and accounting for 3-D chemical CO₂ production on inverse natural carbon flux estimates from satellite and *in situ* data *Environ. Res. Lett.* **15** 085002
- Wang Z A, Wanninkhof R, Cai W-J, Byrne R H, Hu X, Peng T-H and Huang W-J 2013 The marine inorganic carbon system along the Gulf of Mexico and Atlantic coasts of the United States: insights from a transregional coastal carbon study *Limnol. Oceanogr.* **58** 325–42
- Weir B et al 2021b Regional impacts of COVID-19 on carbon dioxide detected worldwide from space *Sci. Adv.* **7** 45

- Weir B, Ott L E, Collatz G J, Kawa S R, Poulter B, Chatterjee A, Oda T and Pawson S 2021a Bias-correcting carbon fluxes derived from land-surface satellite data for retrospective and near-real-time assimilation systems *Atmos. Chem. Phys.* **21** 9609–28
- West T O, Brown M E, Duren R M, Ogle S M and Moss R H 2013 Definition, capabilities and components of a terrestrial carbon monitoring system *Carbon Manage.* **4** 413–22
- Windham-Myers L *et al* 2018 Chapter 15: tidal wetlands and estuaries *Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report* ed N Cavallaro, G Shrestha, R Birdsey, M A Mayes, R G Najjar, S C Reed, P Romero-Lankao and Z Zhu (Washington, DC: U.S. Global Change Research Program) pp 596–648
- Wolf J, Asrar G R and West T O 2017 Revised methane emissions factors and spatially distributed annual carbon fluxes for global livestock *Carbon Balance Manage.* **12** 1
- Wolfe G M *et al* 2018 The NASA carbon airborne flux experiment (CARAFE): instrumentation and methodology *Atmos. Meas. Tech.* **11** 1757–76
- Worden J R *et al* 2015 Quantifying lower tropospheric methane concentrations using GOSAT near-IR and TES thermal IR measurements *Atmos. Meas. Tech.* **8** 3433–45
- Xu Q, Man A, Fredrickson M, Hou Z, Pitkanen J, Wing B, Ramirez C, Li B and Greenberg J A 2018 Quantification of uncertainty in aboveground biomass estimates derived from small-footprint airborne LiDAR *Remote Sens. Environ.* **216** 514–28
- Xu X F, Tian H Q, Chen G S, Liu M L, Ren W, Lu C Q and Zhang C 2012 Multifactor controls on terrestrial N₂O flux over North America from 1979 through 2010 *Biogeosciences* **9** 1351–66
- Xu X, Yuan F, Hanson P J, Wullschlegel S D, Thornton P E, Riley W J, Song X, Graham D E, Song C and Tian H 2016 Reviews and syntheses: four decades of modeling methane cycling in terrestrial ecosystems *Biogeosciences* **13** 3735–55
- Xue Z, He R, Fennel K, Cai W-J, Lohrenz S and Hopkinson C 2013 Modeling ocean circulation and biogeochemical variability in the Gulf of Mexico *Biogeosciences* **10** 7219–34
- Xue Z, He R, Fennel K, Cai W-J, Lohrenz S, Huang W-J and Tian H 2014 Modeling pCO₂ variability in the Gulf of Mexico *Biogeosci. Discuss.* **11** 12673–95
- Yadav V *et al* 2019 Spatio-temporally resolved methane fluxes from the Los Angeles Megacity *J. Geophys. Res.: Atmos.* **124** 5131–48
- Yang J, Tian H, Tao B, Ren W, Pan S, Liu Y and Wang Y 2015 A growing importance of large fires in conterminous United States during 1984–2012 *J. Geophys. Res.: Biogeosci.* **120** 2625–40
- Yang Q, Tian H, Li X, Ren W, Zhang B, Zhang X and Wolf J 2016 Spatiotemporal patterns of livestock manure nutrient production in the conterminous United States from 1930 to 2012 *Sci. Total Environ.* **541** 1592–602
- Yousef F, Charles Kerfoot W, Shuchman R and Fahnenstiel G 2014 Bio-optical properties and primary production of Lake Michigan: insights from 13-years of SeaWiFS imagery *J. Great Lakes Res.* **40** 317–24
- Yu Z, Lu C, Cao P and Tian H 2018 Long-term terrestrial carbon dynamics in the Midwestern United States during 1850–2015: roles of land use and cover change and agricultural management *Glob. Change Biol.* **24** 2673–90
- Zhang B, Tian H, Lu C, Chen G, Pan S, Anderson C and Poulter B 2017 Methane emissions from global wetlands: an assessment of the uncertainty associated with various wetland extent data sets *Atmos. Environ.* **165** 310–21
- Zhang B, Tian H, Ren W, Tao B, Lu C, Yang J, Banger K and Pan S 2016 Methane emissions from global rice fields: magnitude, spatiotemporal patterns, and environmental controls *Glob. Biogeochem. Cycles* **30** 1246–63
- Zhang C *et al* 2012 Impacts of urbanization on carbon balance in terrestrial ecosystems of the Southern United States *Environ. Pollut.* **164** 89–101
- Zhang C, Tian H, Pan S, Lockaby G and Chappelka A 2014 Multi-factor controls on terrestrial carbon dynamics in urbanized areas *Biogeosciences* **11** 7107–24
- Zhang Y *et al* 2020 Quantifying methane emissions from the largest oil-producing basin in the United States from space *Sci. Adv.* **6** eaaz5120
- Zhang Y *et al* 2021 Attribution of the accelerating increase in atmospheric methane during 2010–2018 by inverse analysis of GOSAT observations *Atmos. Chem. Phys.* **21** 3643–66
- Zhang Y, Jacob D J, Maasackers J D, Sulprizio M P, Sheng J, Gautam R and Worden J 2018 Monitoring global tropospheric OH concentrations using satellite observations of atmospheric methane *Atmos. Chem. Phys.* **18** 15959–73