

1 *US Carbon Cycle Science Program – Carbon Cycle Science Working Group*

2 **Scoping Paper¹**

3 **Summary**

4 The global carbon cycle is changing rapidly as a result of human actions, altering Earth’s climate. Many
5 research priorities identified in the 1999 U.S. Carbon Cycle Science Plan remain important, including
6 improved measurement, observations, and monitoring of the carbon cycle, experiments that manipulate
7 the carbon cycle on land and in the oceans, and observation and modeling studies of processes that control
8 the current and future carbon balance. However, new priorities for carbon cycle research are also needed.
9 These priorities include studies of: 1) the effects of human activities on carbon cycling, 2) the vulnerability
10 and resilience of ecosystems to changes in carbon cycling and associated changes in climate, and 3) the
11 efficacy and environmental consequences of carbon management policies, strategies, and technologies.
12 Additional emphasis is also needed to evaluate uncertainties in our understanding of the global carbon
13 cycle and to coordinate researchers from different scientific disciplines to study a common problem.
14 These new priorities will enable progress in the basic sciences, and will provide stronger scientific input
15 to decision makers for carbon cycle management.

16 **Introduction**

17 Research on the cycling of carbon, including where the carbon comes from and where it ultimately goes,
18 is central to addressing the climate change problem. Sustained atmospheric measurements of carbon
19 dioxide started in the 1950s and continue today as a coordinated global monitoring network. From these
20 and other observations of the global carbon cycle, it is clear that atmospheric carbon dioxide and methane
21 concentrations are increasing, driven largely by the burning of fossil fuels and the loss of carbon from
22 forests, terrestrial soils, and melting permafrost. Process-based understanding of the global carbon cycle is
23 needed to determine how that cycle is being modified by people and to develop sound climate change
24 mitigation and adaptation strategies, including ways to minimize or manage adverse impacts on the
25 Earth’s climate and ecosystems.

26 In 1998-1999, a Working Group of 16 carbon-cycle researchers prepared a science plan to focus and
27 coordinate carbon-cycle research conducted by researchers in the United States. The intent was “to
28 develop a strategic and optimal mix of essential components, which include sustained observations,
29 modeling, and innovative process studies, coordinated to make the whole greater than the sum of its
30 parts” (J.L. Sarmiento and S.C. Wofsy, *A U.S. Carbon Cycle Science Plan*, University Corporation for
31 Atmospheric Research, Washington, D. C., 1999). In the decade since the Science Plan was published,
32 carbon-cycle researchers have been working to improve carbon-observing networks and to coordinate
33 research projects addressing the goals of the plan. While much progress has been made, funding
34 constraints have prevented some aspects of the original plan from being fully realized. Furthermore,
35 carbon-cycle research over the last decade has identified new issues that were not considered in the
36 original plan. It is time for the research community to update the 1999 Science Plan, re-examining the
37 research and policy needs, outlining the funding necessary to meet those needs, and prioritizing the
38 research directions.

39 A working group of 27 scientists was formed in 2008 under the United States Carbon Cycle Science
40 Program’s Science Steering Group to review the 1999 Plan and to develop an updated strategy for
41 research on the global carbon cycle to be conducted by U.S. researchers for the period from 2010 to 2020.
42 A comprehensive review is being conducted with wide input from the research and stakeholder

¹ This paper represents informal perspectives of individuals participating in the US Carbon Cycle Science Program Carbon Cycle Science Working Group, led by Anna Michalak (University of Michigan), Rob Jackson (Duke University), Gregg Marland (Oak Ridge National Laboratory), and Chris Sabine (National Oceanic and Atmospheric Administration) . It does not represent official federal positions or opinions of all participants.

1 communities. This report summarizes the initial evaluation of the plan and the developing strategy for the
2 next decade. The strategies described here align well with independent recommendations in the National
3 Academy of Sciences' new report, "Restructuring Federal Climate Research to Meet the Challenges of
4 Climate Change" (National Research Council, Washington, D.C., 2009).

5 **Goals**

6 An analysis of progress over the last decade suggests several priorities for the revised plan. We must
7 strengthen our commitments to natural carbon cycle research and long-term monitoring as outlined in the
8 1999 Science Plan. We must also devote more attention to the human component of the carbon cycle,
9 including the influences of social, political, and economic processes. Although human activities were
10 discussed in the original plan, the social science and the natural science components of the carbon cycle
11 research have not been well integrated.

12 Another new priority is to study the direct effects of increased CO₂ on ocean ecosystems. The original
13 science plan focused primarily on carbon cycle processes and their feedbacks to the global carbon cycle
14 and climate. It did not adequately address issues, such as ocean acidification, that can have a dramatic
15 impact on ecosystems, species, and human food supply, but that do not necessarily have a substantial
16 feedback to the global carbon cycle itself.

17 A third new priority is to expand the carbon science program to include research that is more responsive
18 to decision support. In particular, scientists need to understand and inform decision makers, both in and
19 out of government, of the carbon cycle consequences of societal practices, including both inadvertent
20 carbon cycle management and proposed active management strategies. Aspects of these new priorities
21 were highlighted in all six recommendations of the new NAS Report, including suggestions to reorganize
22 the Climate Change Science Program around scientific-societal issues and to establish a U.S. Climate
23 Observing System

24 As with the original plan, the new US Carbon Cycle Science Plan will focus on a limited number of
25 overarching science questions in the coming decade, currently identified as:

- 26 1) How do natural processes and human actions affect the carbon cycle, on land, in the atmosphere, and in
27 the oceans?
- 28 2) How do policy and management decisions affect the levels of atmospheric carbon dioxide and
29 methane?
- 30 3) How are ecosystems, species, and resources impacted by increasing greenhouse gas concentrations, the
31 associated changes in climate, and carbon management decisions?

32 The first question encompasses the primary focus of the 1999 science questions, with an enlarged
33 emphasis on human processes and added emphasis on understanding the role of methane, the second most
34 important carbon based greenhouse gas, in the global carbon cycle. The second and third questions
35 address the new priorities identified by the current working group.

36 In an effort to focus the development of the program goals and elements, the working group compiled a
37 partial list of accomplishments that should be possible by 2020, given adequate support. These
38 accomplishments include:

- 39 1) Provide the public with a timely explanation for observed variations in atmospheric CO₂ and CH₄
40 growth, up to and including the present;
- 41 2) Convert the current ad-hoc carbon-cycle monitoring and observations into an optimally designed and
42 integrated network of sustained physical, biological, and socio-economic measurements so that
43 scientists can evaluate trends, feedbacks, and the possible occurrence of abrupt changes over the next
44 50 years;
- 45 3) Quantify which processes, ecosystems, and carbon reservoirs are most vulnerable and most resilient to

- 1 changes in the carbon cycle and climate interactions and large-scale disturbances;
- 2 4) Develop quantitative measures for understanding the uncertainty of current and projected carbon flows;
- 3 5) Work with the integrated assessment community to verify regional carbon budgets and carbon
- 4 contracts, and improve climate projections at scales of 10 to 100 km; work with the same community
- 5 to explore the implications of projected trends and alternative socioeconomic futures - from emissions
- 6 to land use - that will influence the overall carbon cycle;
- 7 6) Prioritize the socioeconomic, biological, and physical variables that will most determine whether the
- 8 ocean and terrestrial biospheres will be a source or sink for carbon and methane in the future;
- 9 7) Provide the scientific understanding to evaluate the efficacy and potential environmental side effects of
- 10 carbon management policies and technologies.

11 These potential achievements, as well as the program elements and funding levels required to make them

12 a reality, will be further refined and described in the full new U.S. Carbon Cycle Science Plan to be

13 completed over the next year. The carbon cycle working group will integrate recommendations from the

14 new NAS report and point out some areas absent from that document. For instance, the “Report in Brief”

15 does not mention the carbon cycle or the importance of carbon reservoirs to climate, species or

16 biodiversity, and the importance of biotic or ecosystem feedbacks with climate.

17 **Enabling contributions and collaborations**

18 There are a number of key components within the scientific community that are central to the successful

19 advancement of global carbon cycle research over the next decade.

20 *Carbon cycle observations and observational networks* are essential for maintaining and expanding the

21 global monitoring of atmospheric CO₂ and CH₄. Measurements, including the global flask network,

22 continuous concentration measurement sites, and aircraft profiles, help to document the variations in

23 atmospheric growth rates that form the basis for many climate studies. Measurement networks for

24 collecting long-term observations of the ocean, land, and freshwater carbon reservoirs need to be further

25 developed. For the oceans, this includes global networks of surface and atmospheric CO₂ measurements,

26 as well as full water-column hydrographic surveys from ships. On land, forest and soil carbon inventories

27 need to be expanded, and additional CO₂ flux towers and manipulative experiments need to be established

28 in untested biomes. An integrated carbon monitoring program needs to be established in coastal regions

29 where land, ocean, atmosphere, and humans all intersect. A wealth of related atmospheric and earth

30 surface remote sensing observations are provided by existing and planned satellites. Ensuring continuity

31 of these and improved remote sensing observations of carbon-cycle parameters, through the support of the

32 missions recommended in the NASA Decadal Survey, is of critical importance. The Orbiting Carbon

33 Observatory was intended to provide NASA’s first remote sensing measurements of CO₂ with the

34 precision and coverage required to constrain the global carbon cycle on regional scales. With the loss of

35 the Orbiting Carbon Observatory, we need to begin examining existing remote sensing instruments

36 capable of quantifying atmospheric CO₂ distributions. Finally, we need to support a global network

37 collecting relevant demographic and socio-economic variables to understand and constrain the human

38 component of the carbon cycle. In all cases the archiving, management, and access to data need to be

39 carefully planned and thoughtfully implemented.

40 *Process experiments and manipulations* complement the global observing networks and provide a

41 mechanistic understanding for changes observed. On land, individual experiments and experimental

42 networks manipulate ecosystem temperature, precipitation, atmospheric CO₂, and other environmental

43 factors that affect the carbon cycle. Monitoring networks of carbon stocks and ecosystem exchange, such

44 as long-term forest inventory measurements and the AmeriFlux network, provide observations of the

45 reservoirs and flows of carbon dioxide and methane, energy, and other important factors. In the oceans,

46 gas exchange parameterization studies continue to increase our understanding of factors controlling air-

47 sea CO₂ flows. Process and manipulative studies improve our understanding of biological and physical

1 factors affecting carbon cycling in the ocean. These studies can also identify potential tipping points in
2 the system, and can be used to refine and improve observational networks at larger scales. The
3 importance of high latitude and tropical systems dictates studies that extend globally.

4 *Models that elucidate the processes, feedbacks and balances of carbon* among the Earth reservoirs are
5 needed to take full advantage of the observing networks and the measurements described above. These
6 models must capture the processes controlling the spatial and temporal variability in carbon flows, and,
7 ultimately, provide accurate visions of how an evolving carbon cycle will alter the climate and how an
8 evolving climate will alter the carbon cycle. Development of models that can merge carbon system data
9 from multiple sources and across scales, within a framework of rigorously quantified model uncertainty,
10 must be supported. In order to increase the pace at which data and models are available to carbon cycle
11 scientists, agencies should coordinate the development of a joint data-sharing strategy. The sharing of
12 data, models, and model results should be a required step in carbon cycle research. In addition, more
13 effort is needed with treatment of reciprocal feedbacks as carbon cycle models contribute to Earth system
14 and climate analysis. Changes in carbon cycle forcings theoretically affect climate, and inversely, climate
15 changes influence carbon cycle processes, sinks and sources of CO₂. Scientific understanding of these
16 feedbacks and relationships, and their representation in coupled models, is a challenge for next generation
17 prognostic modeling of climate and other Earth phenomena.

18 *Carbon cycle science is at a crossroads*, with a need to continue long-term measurements and to initiate
19 new observations and manipulations. Many tools providing long-term measurements of the carbon cycle
20 may diminish or disappear in the near future unless they are continued or replaced. Examples include the
21 35-year record provided by Landsat satellites, ocean color measurements from SeaWiFS, and river and
22 stream gauging stations that integrate carbon cycle processes in their watersheds. Additionally, funding is
23 needed to initiate new programs and fill data gaps in existing ones.

24 *Carbon is an integral part of life on Earth.* With the ongoing modifications of the carbon cycle and the
25 climate, marine and terrestrial ecosystems will also be affected. Inevitably there will be winners and
26 losers as species compete to adapt. Additional research is needed to understand the ecosystem changes
27 and the implications of these changes for our society. For example, to understand the implications of
28 increasing ocean acidity resulting from atmospheric CO₂ uptake we need new monitoring approaches that
29 fully characterize the biological and chemical changes, new laboratory studies to understand the
30 physiological effects, and new manipulative studies to directly quantify the ecosystem responses to
31 increased CO₂ levels. Similar studies need to be further developed on land.

32 *The driving role of the human component of the carbon cycle* is being increasingly recognized, and this
33 means that direct consideration of social, cultural, and economic data and processes in carbon cycle
34 models is required, but it also means that more interdisciplinary studies and improved linkage with the
35 social and political sciences are needed. The interface of traditional carbon-cycle science with integrated
36 assessment studies and studies of carbon management is not clear and we need to ensure that there is
37 support for interdisciplinary and cross-disciplinary studies and that human elements are incorporated into
38 carbon-cycle studies when appropriate. Better understanding of the role of uncertainty and the limitations
39 of predictions can provide useful insight for current decisions and future planning. These collaborations
40 and interactions, along with enhanced understanding of the needs of decision makers, should lead to
41 better understanding of the current carbon cycle, better projections of the carbon cycle into the future, and
42 better-informed decision making for public policy and carbon management.

43 *Substantial new resources will be required* to pursue this multitude of aspects of the carbon cycle research
44 plan. The plan will also require improved interaction and information exchange within and among
45 different scientific disciplines. Scientists also need to interact closely with stakeholders and with decision
46 makers who require up-to-date assessments, including improved approaches for understanding,
47 quantifying, and dealing with uncertainty. These groups will need to work together to carefully evaluate
48 research priorities and options for responding to observed trends in the carbon cycle and climate.

1 **Pathways and options**

2 *An established tradition of strong collaboration*, both within the community and with related scientific
3 groups, has been characteristic of the carbon-cycle-science research community. In order to maintain and
4 enhance the overall relevance and impact of carbon cycle science, interdisciplinary studies and
5 collaborations must be extended even further. The formation of the U.S. Carbon Cycle Science Program
6 and the Carbon Cycle Interagency Working Group has helped to advance coordinated carbon cycle
7 research within the United States, by breaking through agency boundaries and promoting collaborative
8 research and coordinated funding across multiple agencies. This collaboration among agencies should be
9 strengthened and expanded over the next decade, as necessary, to address the new research priorities
10 outlined here.

11 *Two national research directions were established* to address major goals of the 1999 Carbon Cycle
12 Science Plan: the North American Carbon Program (NACP) and the Ocean Carbon and Climate Change
13 (OCCC) program. While these components of the U.S. carbon cycle research plan have made progress in
14 improving our understanding of the sources and sinks for carbon in North America and adjacent coastal
15 oceans, respectively, they have yet to reach their full potential as research programs. Both of these
16 programs should be continued into the next decade with adjustments to their structure and composition as
17 necessary to accommodate developing research priorities.

18 *The issue of ocean acidification* cuts across the traditional disciplines of climate and ecosystem research.
19 Legislation is currently being discussed in the U.S. Congress to direct tens of millions of new research
20 dollars toward ocean acidification. Much of this research can leverage and complement existing or
21 developing carbon cycle research in the oceans. A proper support structure, either through the Ocean
22 Carbon and Biogeochemistry (OCB)/OCCC programs or as a new independent national research
23 program, needs to be established with a clear research strategy that builds on existing strengths within the
24 community. Other direct impacts of increased atmospheric CO₂ on terrestrial ecosystems should be
25 examined as well.

26 *Human contributions and responses* had been an explicit component of, for example, the NACP, but that
27 program has struggled with how to properly engage the social, political, and economic research
28 communities. Agencies should be promoting stronger interactions between natural and social scientists
29 through the interagency working group (e.g. with directed multidisciplinary funding opportunities). A
30 coordinating committee that would bridge the divide between the Modeling Building Blocks IWG, which
31 includes the Integrated Assessment Modeling community, the Human Contributions and Response IWG,
32 and the Carbon Cycle IWG would present some promising opportunities to advance this interdisciplinary
33 agenda with the key technical communities. The focus of this crosscutting committee, especially in
34 promoting connections between the carbon-cycle-research community and the integrated-assessment
35 community, would be to examine both opportunities to manage the carbon cycle and the impacts and
36 implications of doing so, including the full impact of management decisions on the climate system.

37 *Stronger links with related research programs* on the global carbon cycle and with continental-scale
38 carbon assessment programs in Europe and Asia should be encouraged, to ensure that the U.S. research
39 program contributes fully to the development of global-scale understanding and remains complementary
40 to similar efforts in other regions. Continued participation in, and contribution to, global-scale studies
41 such as in the IPCC process are critical. Given the increasing role of remote sensing in Earth system
42 science, there is an increased need for close collaboration between NASA, agencies coordinating ground-
43 based measurements of carbon cycle relevant parameters, and international and non-U.S. agencies that
44 collect important data streams. These agencies include NOAA, USGS, EPA, USDA, DOE, NSF, the
45 United Nations, the European Space Agency, and Japan's Space Agency, among many others.

46 *Carbon cycle monitoring and analysis* are critical for documenting the evolution of the global carbon
47 cycle. A proper support structure for long-term monitoring of carbon on the land and in the ocean and
48 atmosphere needs to be further developed and coordinated at the agency level. The typical model of three

1 year proposal-based funding is not appropriate for developing the sustained carbon cycle records
2 necessary to evaluate and understand a changing world. While several agencies have historically funded
3 long-term measurements, these programs have not necessarily been focused on acquiring the most
4 appropriate measurements for understanding carbon cycle changes. Long-term commitment and
5 coordination is needed for the collection and archiving of critical physical, chemical, ecosystem,
6 demographic, and socio-economic data. We need to anticipate and collect the data that will be required
7 well into the future.