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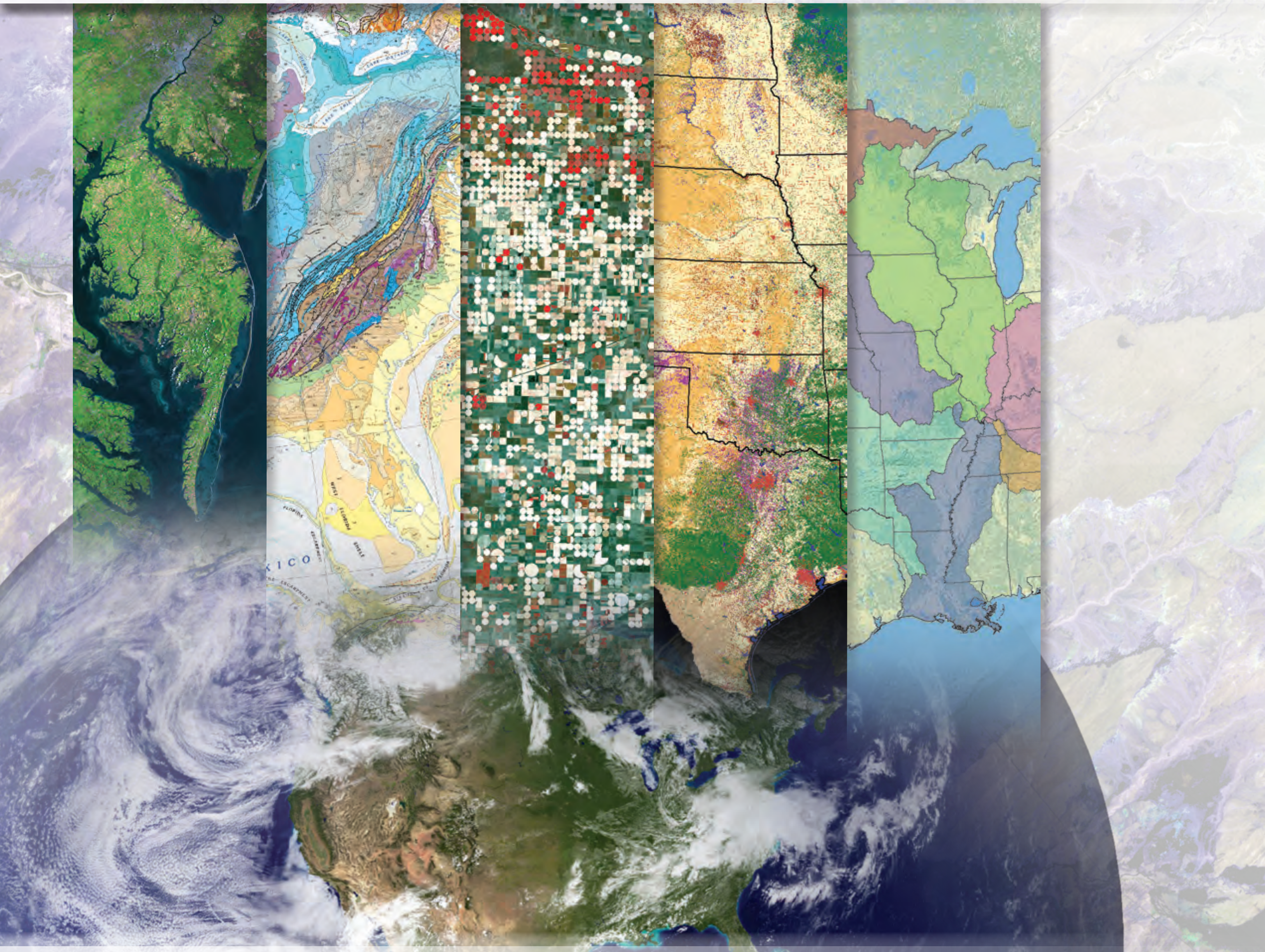
U.S. Geological Survey Core Science Systems Strategy—Characterizing, Synthesizing, and Understanding the Critical Zone through a Modular Science Framework



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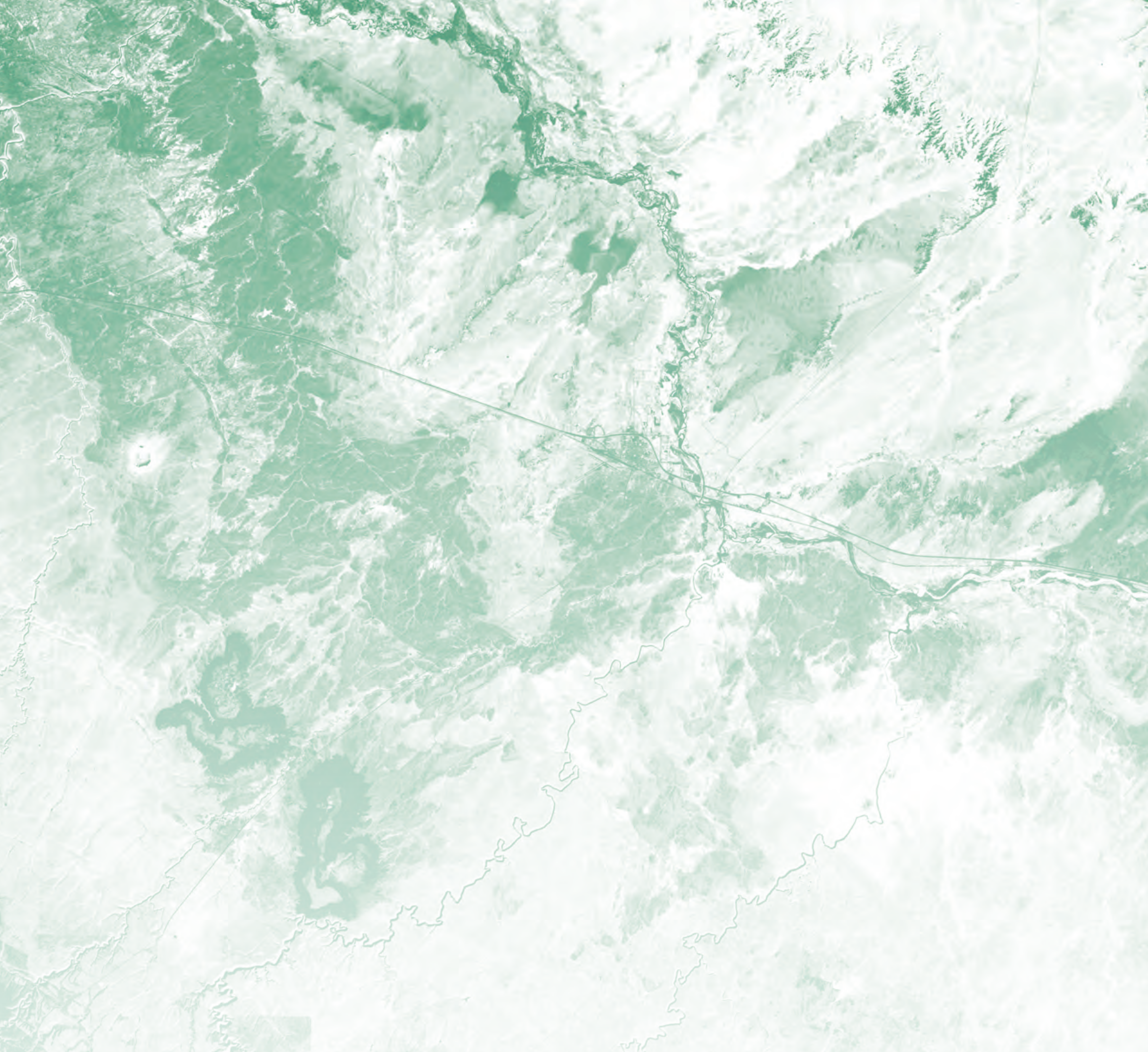

Cover. Clockwise left to right:

Landsat 5 mosaic of the Greater Chesapeake Bay region available from *http://landsat.usgs.gov/*.

A slice of the Geologic Map of North America available from *http://esp.cr.usgs.gov/data/geomap_natatlas/*.

Landsat 7 scene of croplands near Garden City, Kansas, acquired September 2000, available from *http://landsat.usgs.gov/*.

A slice of the Gap Analysis Program (GAP) National Land Cover map, 2009, available from *http://gapanalysis.usgs.gov/*.

A slice of a map showing Mississippi River Basin watersheds derived from hydrologic data available from *The National Map* (*http://www.nationalmap.gov*).

The Blue Marble. Image by NASA Goddard Space Flight Center. Image available from *http://rsd.gsfc.nasa.gov/rsd/bluemarble/index.html*.

Background. Desert to forest: Landsat 5 image, March 28, 2009. In the American Southwest, transitions from one ecosystem to another can be dramatic and abrupt. This is true in northern Arizona, where the parched Painted Desert, shown in a palette of purples, adjoins Sitgreaves National Forest (shades of green), a realm of pine woodlands with abundant wildlife. Image available from *http://landsat.usgs.gov/*.

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By R. Sky Bristol, Ned H. Euliss, Jr., Nathaniel L. Booth, Nina Burkardt, Jay E. Diffendorfer, Dean B. Gesch, Brian E. McCallum, David M. Miller, Suzette A. Morman, Barbara S. Poore, Richard P. Signell, and Roland J. Viger

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U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2013

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Foreword

In 2007, the U.S. Geological Survey (USGS) published a Bureau Science Strategy *Facing Tomorrow's Challenges—U.S. Geological Survey Science in the Decade 2007–2017*. It provided a view of the future, establishing science goals that reflected the USGS's fundamental mission in areas of societal impact such as energy and minerals, climate and land use change, ecosystems, natural hazards, environmental health, and water. Intended to inform long-term program planning, the strategy emphasizes how USGS science can make substantial contributions to the well-being of the Nation and the world.

In 2010, I realigned the USGS management and budget structure, changing it from a structure associated with scientific disciplines—Geography, Geology, Biology and Hydrology—to an issue-based organization along the lines of the Science Strategy. My aim was to align our management structure with our mission, our science priorities, our metrics for success, and our budget. An added benefit was that the USGS immediately appeared relevant to more Americans, and it became easier for those outside the agency to navigate our organizational structure to find where within the USGS they would find the solution to their problem. External partners rarely approached us with a problem in "geology," but they might need help with an issue in climate change or energy research.

The new organization is focused on seven science mission areas:

- Climate and Land Use Change
- Core Science Systems
- Ecosystems
- Energy and Minerals
- Environmental Health
- Natural Hazards
- Water

The scope of each of these new mission areas is broader than the science directions outlined in the USGS Science Strategy and together cover the scope of USGS science activities.

In 2010, I also commissioned seven Science Strategy Planning Teams (SSPTs) to draft science strategies for each USGS mission area. Although the existing Bureau Science Strategy could be a starting point for this exercise, the SSPTs had to go well beyond the scope of the existing document. What is of value and enduring from the work of the programs that existed under the former science disciplines needed to be reframed and reinterpreted under the new organization of the science mission areas. In addition, new opportunities for research directions have emerged in the five years since the Bureau Science Strategy was drafted, and exciting possibilities for cooperating and collaborating in new ways are enabled by the new mission focus of the organization.

Scientists from across the Bureau were selected for these SSPTs for their experience in strategic planning, broad range of experience and expertise, and knowledge of stakeholder needs and relationships. Each SSPT was charged with developing a long-term (10-year) science strategy that encompasses the portfolio of USGS science in the respective mission area. Each science strategy will reinforce others because scientific knowledge inherently has significance to multiple issues. Leadership of the USGS and the Department of the Interior will use the science vision and priorities developed in these strategies for program guidance, implementation planning, accountability reporting, and resource allocation. These strategies will guide science and technology investment and workforce and human capital strategies. They will inform our partners regarding opportunities for communication, collaboration, and coordination.

The USGS has taken a significant step toward demonstrating that we are ready to collaborate on the most pressing natural science issues of our day and the future. I believe a leadership aligned to support these issue-based science directions and equipped with the guidance provided in these new science strategies in the capable hands of our scientists will create a new era for USGS of which we can all be proud.

Marcia McNutt
Director

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Executive Summary

Core Science Systems is a new mission of the U.S. Geological Survey (USGS) that resulted from the 2007 Science Strategy, "Facing Tomorrow's Challenges: U.S. Geological Survey Science in the Decade 2007–2017." This report describes the Core Science Systems vision and outlines a strategy to facilitate integrated characterization and understanding of the complex Earth system. The vision and suggested actions are bold and far-reaching, describing a conceptual model and framework to enhance the ability of the USGS to bring its core strengths to bear on pressing societal problems through data integration and scientific synthesis across the breadth of science.

The context of this report is inspired by a direction set forth in the 2007 Science Strategy. Specifically, ecosystem-based approaches provide the underpinnings for essentially all science themes that define the USGS. Every point on Earth falls within a specific ecosystem where data, other information assets, and the expertise of USGS and its many partners can be employed to quantitatively understand how that ecosystem functions and how it responds to natural and anthropogenic disturbances. Every benefit society obtains from the planet—food, water, raw materials to build infrastructure, homes and automobiles, fuel to heat homes and cities, and many others—are derived from or affect ecosystems.

The vision for Core Science Systems builds on core strengths of the USGS in characterizing and understanding complex Earth and biological systems through research, modeling, mapping, and the production of high quality data on the Nation's natural resource infrastructure. Together, these research activities provide a foundation for ecosystem-based approaches through geologic mapping, topographic mapping, and biodiversity mapping. The vision describes a framework founded on these core mapping strengths that makes it easier for USGS scientists to discover critical information, share and publish results, and identify potential collaborations that transcend all USGS missions. The framework is designed to improve the efficiency of scientific work within USGS by establishing a means to preserve and recall data for future applications, organizing existing scientific knowledge and data to facilitate new use of older information, and establishing a future workflow that naturally integrates new data, applications, and other science products to make interdisciplinary research easier and more efficient. Given the increasing need for integrated data and interdisciplinary approaches to solve modern problems, leadership by the Core Science Systems mission will facilitate problem solving by all USGS missions in ways not formerly possible.

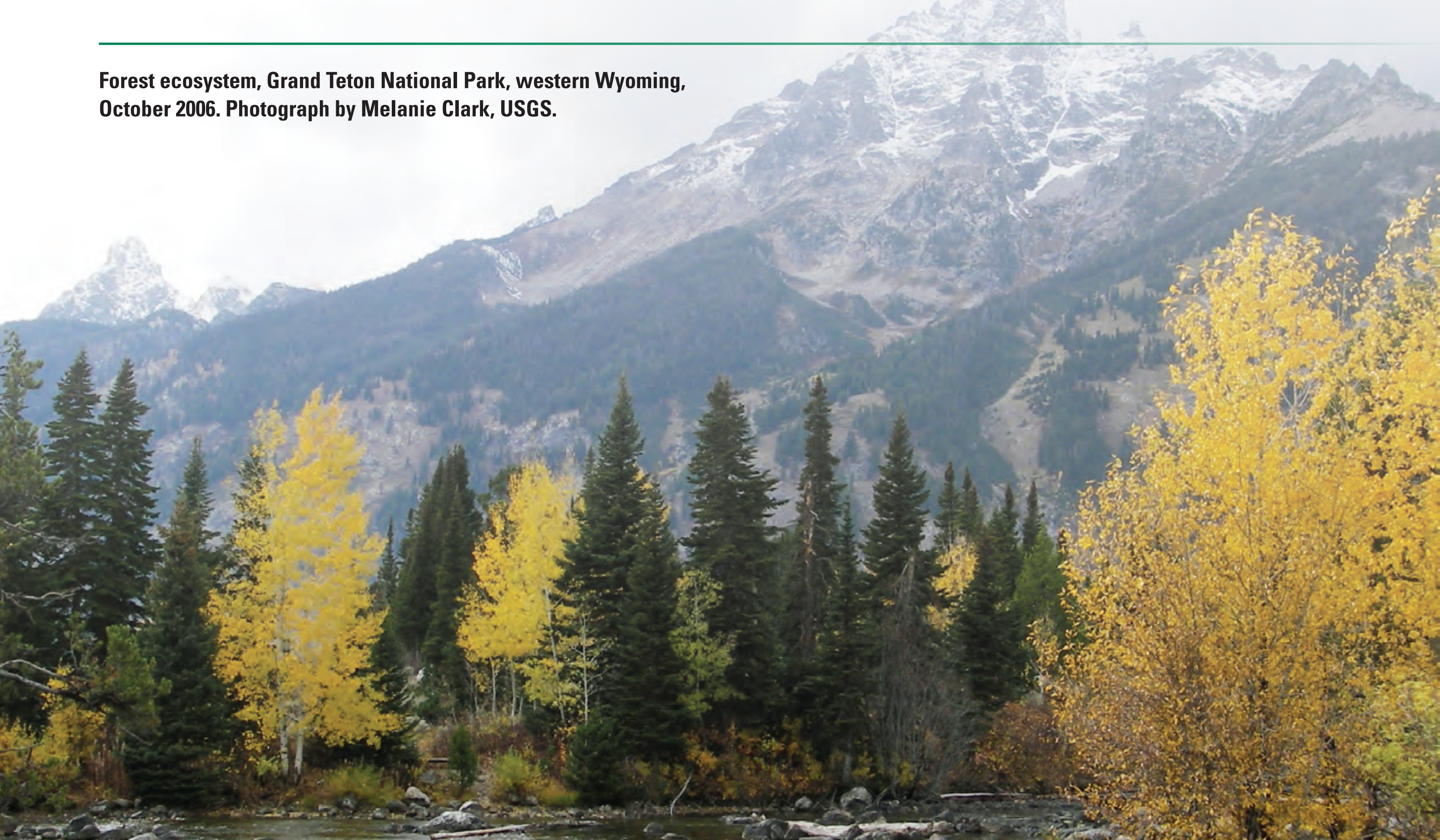
The report lays out a strategy to achieve this vision through three goals with accompanying objectives and actions. The first goal builds on and enhances the strengths of the Core Science Systems mission in characterizing and understanding the Earth system from the geologic framework to the topographic characteristics of the land surface and biodiversity across the Nation. The second goal enhances and develops new strengths in computer and information science to make it easier for USGS scientists to discover data and models, share and publish results, and discover connections between scientific information and knowledge. The third goal brings additional focus to research and development methods to address complex issues affecting society that require integration of knowledge and new methods for synthesizing scientific information. Collectively, the report lays out a strategy to create a seamless connection between all USGS activities to accelerate and make USGS science more efficient by fully integrating disciplinary expertise within a new and evolving science paradigm for a changing world in the 21st century.

Overview: Science for a Changing World—Evolving a Science Paradigm for the 21st Century

Many problems affecting the Nation and the increasingly interconnected world are consequences of anthropogenic change. Humanity's growing planetary footprint is having unintended and negative effects on basic Earth system processes, human welfare, and the sustainability of the planet. The relation between humans and the Earth has changed markedly over evolutionary history, from being minor components of ecosystems to being major drivers of ecosystems and change on a global scale. The geologist A.P. Pavlov (1854–1929) was perhaps the first to recognize the magnitude of human influence on global ecosystems, referencing his contemporary time as the "anthropogenic era" (Vernadsky, 2005); many years later, the "Anthropocene" has been proposed as a new geologic epoch (Zalasiewicz, 2008). During this period of human influence, the USGS and others have documented that climate change is intertwined in such a way that the complexity of most modern problems is without historical precedent. For the USGS to be successful in solving the problems affecting the Nation, it is essential that two core science needs come together, which include characterizing and understanding complex Earth system processes fundamental to all science disciplines and integration across scientific disciplines to generate new interdisciplinary knowledge and approaches to solve modern problems.

This document describes a decadal vision for Core Science Systems, a mission of the USGS to collaboratively pursue the evolving paradigm for how greater quantity and complexity of scientific information can be linked to a deeper understanding of component Earth system processes to answer some of the most difficult challenges facing the Nation. The report begins with three examples to illustrate the unique strengths the USGS can bring to science in the 21st century. Specifically, the examples describe modern data-intensive techniques used to integrate large and disparate datasets to produce new interdisciplinary synthesis products and an interdisciplinary approach to developing the process-based understanding needed to solve complex problems. The stories illustrate the connected nature of the USGS science missions and the role Core Science Systems fulfills in providing critical characterization and understanding of complex Earth systems.

In these examples, situations are highlighted that required the expertise of USGS and partners to illustrate the value and relevancy of interdisciplinary and often interagency approaches to solve problems. Each story illustrates unique challenges that science in the 21st century must address to be successful—specifically what is happening on the planet, where is it happening, and why is it happening. All three types of questions are needed to properly frame modern problems and identify effective solutions. The remainder of the report describes a framework for Core Science Systems that will accelerate the identification and understanding of the what, where and why questions at increasing scale and complexity.



Forest ecosystem, Grand Teton National Park, western Wyoming, October 2006. Photograph by Melanie Clark, USGS.

What is the Distribution of Forest Biomass Across the Nation?

Josef Kellndorfer and Wayne Walker, two researchers at the Woods Hole Research Center, created the National Biomass and Carbon Dataset. The dataset was used to build a 30-meter resolution map of the forest structure and carbon storage for the continental United States, the highest resolution ever assembled for any country (fig. 1). This product provided the ability to understand forests down to the scale at which parking lots, developments, and deforested regions are visible—resource managers have critical information to begin asking questions about why certain phenomena are being observed and how better management scenarios can be pursued. With this baseline data, the Nation can monitor and predict how important carbon resources will respond to changes induced by humans and climate.

To generate the National Biomass and Carbon Dataset, the researchers took advantage of what most scientists considered noise in the data. They used the difference between the NASA Shuttle Radar Topography Mission digital terrain model and the USGS National Elevation Dataset to estimate forest canopy height. The resulting data were then merged with the USGS National Land Cover Dataset to create a model for forest biomass that was calibrated and groundtruthed using information provided by the U.S. Forest Service. Their scientific creativity, combined with access to and understanding of datasets from multiple agencies, allowed them to create an entirely new synthesized data asset. Their work created a tool for understanding the role that trees play in the global carbon cycle, and a visual product that raises questions about occurrences of forest distribution patterns and how they may change in the future.

The next major scientific breakthrough and its source are as yet unknown, but fostering these breakthroughs can rapidly advance scientific understanding in the 21st century and beyond. The Core Science Systems mission is focused on activities that facilitate this type of synthesis, from development of authoritative data, to providing services that make data accessible, interoperable and usable, to fostering development of new synthesis products demanded by *Science for a Changing World*.

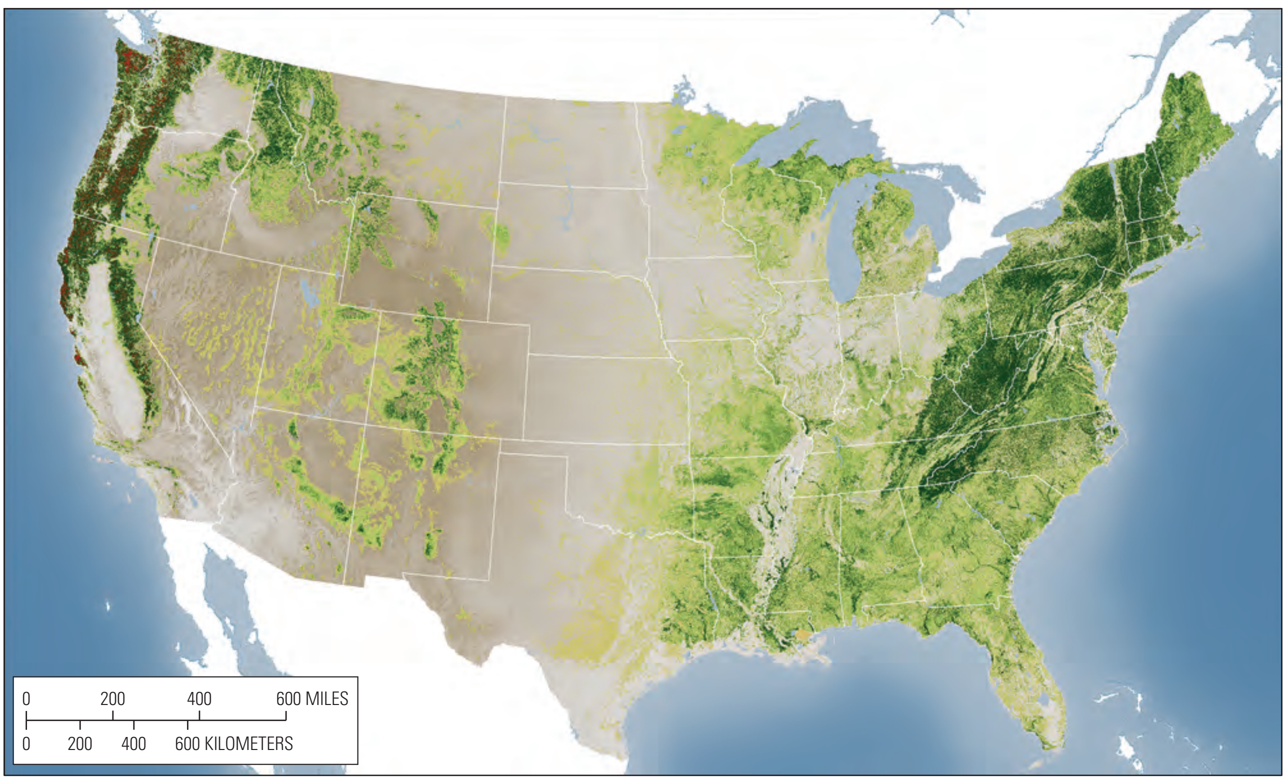


Figure 1. The map depicts the biomass density—a proxy measure of the amount of organic carbon—stored in the woody components of trees. The darkest green and red colors show areas with the largest biomass and carbon values. The map was produced from the National Biomass and Carbon Dataset (J. Kellndorfer, written commun., March 15, 2012).

EXPLANATION

Biomass

0 50 100 150 200 Greater than 350

0 25 50 75 100 Greater than 175

Carbon, in tons per hectare

No biomass (shaded relief)

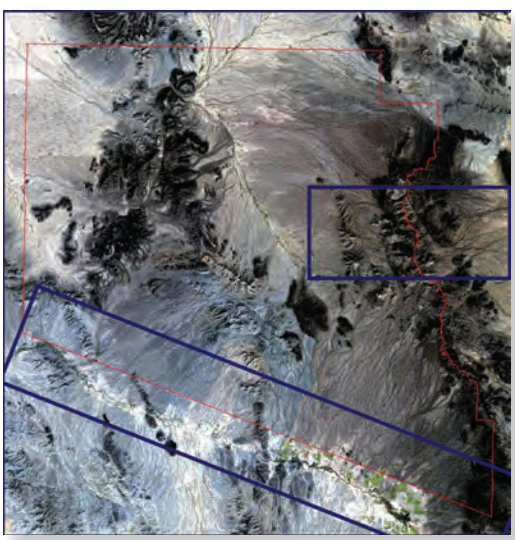
Highlight

Highlight

Where Does Valley Fever Pose Serious Disease Threats to Humans?

Public health officials are concerned about the increasing rates of Coccidioidomycosis or Valley Fever, a fungal disease that infects more than 100,000 people and animals annually in the southwestern United States. One of several emerging or reemerging zoonotic or vector borne diseases of concern, coccidioidomycosis is a systemic infection caused by the inhalation of the airborne fungal spores of *Coccidioides immitis*. In most cases of acute Coccidioidomycosis, the body's own immune system, if it is not impaired, is sufficient for recovery; however, about 10 percent of cases are severe enough to require hospitalization and may progress to chronic or disseminated Coccidioidomycosis and sometimes death. In the past decade several states have seen increased rates of Coccidioidomycosis. In California, for example, reported cases have more than doubled (from 1483 in 2001 to 4508 in 2010; Bultman, 2008). As the organism is found only in the dry desert soil of the United States, Mexico, and Central and South America, defining factors such as soil type, temperature, and salinity that encourage organism growth could aid researchers in identifying areas of risk.

Developing new map products that identify where humans are at greatest risk has far-reaching public health implications. Mark Bultman, a USGS researcher, teamed with university and other USGS researchers to identify the factors that affect the growth of the fungus to determine if sufficient information was available to model favorable habitat for *Coccidioides immitis*. Bultman was able to locate the data resources he needed for his model from the USGS and other Federal agencies. He used many sources of spatial data, including USGS map products (Geologic Maps, National Elevation Dataset), soils from the U.S. Department of Agriculture and mineralogy information from NASA's Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) satellite. The resultant maps show an entirely new and innovative way for USGS to inform public health decisions by identifying where soils and other conditions interact to create ideal conditions for propagation of the disease organism (fig. 2). As rate increases have been associated with environmental factors such as climate and earthquake triggered landslides (Jibson, 2002), maps such as Bultman's could be correlated with other USGS products such as those produced by the Earthquakes Hazards Program. The USGS is positioned to leverage its existing data to enable public health officials to elucidate critical environmental factors such as habitat and natural dissemination processes (landslides) that contribute to emerging zoonotic and vector borne diseases. This is a high priority for the Centers for Disease Control and Prevention (Centers for Disease Control, 2011) as they partner with public health communities to modernize disease surveillance for emerging zoonotic and vector borne diseases such as Coccidioidomycosis.



Coccidioides **habitat modeling**

Data used in the Organ Pipe Cactus National Monument analysis:

- Geology
- Elevation [30-meter digital elevation model (DEM)]
- Slope/aspect
- Thematic Mapper clay map
- Thematic Mapper biological soil crust map
- Soil texture
- Soil salinity
- Soil water holding capacity
- Digital orthophoto quarter quandrangle (DOQQ) vegetation density
- AVIRIS clay mineralogy
- AVIRIS borate mineralogy

Figure 2. This map shows areas in Organ Pipe Cactus National Monument (outlined in blue boxes) determined, through a "fuzzy system" model by USGS scientist Mark Bultman, to predict favorable environments for the growth of *Coccidioides immitis* (Bultman, 2008). Model input included geology, elevation, slope, salinity, vegetation density through Digital Orthoimagery Quarter Quadrangles (DOQQ), and clay and borate mineralogy through the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) sensor. The red line shows the property boundary for Organ Pipe Cactus National Monument.

Facing page: San Carlos River near Peridot, Arizona, 2000. Non-native tamarisk is adjacent to the river channel. Photograph by USGS.

Why is an Invasive Species Successful in Taking Over Native Habitat?

Land managers are often faced with objectives that are especially difficult to achieve and often are met with limited or poor success. Salt cedar (*Tamarix ramosissima*) is an invasive species that often replaces native vegetation along southwestern rivers and riparian areas (fig. 3). The plant has reduced the value of vast expanses of arid riparian areas valuable for extensive provisioning of ecosystem services such as wildlife habitat, including public lands managed by the U.S. Fish and Wildlife Service (USFWS). Traditional methods of controlling salt cedar, such as removing vegetation with heavy equipment followed with herbicide application, did not provide lasting results because salt cedar often reinvaded areas and the methods were costly.

In the early 1990s, John Taylor, a USFWS biologist at the Bosque del Apache National Wildlife Refuge teamed with university researchers David Wester and Loren Smith to identify a more effective management solution (Taylor and others, 1999). Using their knowledge of local river dynamics, the team hypothesized that upstream dams had interrupted spring flooding and overbanking events that were a common process before the river was impounded. Working with the U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers, an experiment was conducted to raise the river flow during a time of year when the desired vegetation, native willows and cottonwoods, were most likely to be established. The team and other partners demonstrated how hydrological processes could be manipulated to promote the life history of desired vegetation and sustain the desired ecosystem (Taylor and others, 1999). The USGS provided water flow gauging information and hydrographs to ensure that adequate water was delivered to the ecological target without damaging human infrastructure.

Following this experiment, the practice of simulating the hydrological environmental stimulus, and thus giving the desired native plant community a competitive advantage over the invasive salt cedar, has developed in other areas. This direct application illustrates the importance of how modern data can be evaluated in new ways spanning many scientific disciplines to gain an understanding of why salt cedar became invasive and how management practices applied to ecosystem processes could achieve desired outcomes. The solution to controlling salt cedar using a process-based ecosystem approach is a good example of how integrated scientific measurements can help to address the cause of the issue, answering the question of why is something happening in this location, instead of merely identifying the issue. Other issues affecting society are far more complex and will require greater integration of knowledge and new methods of synthesizing information.

Highlight

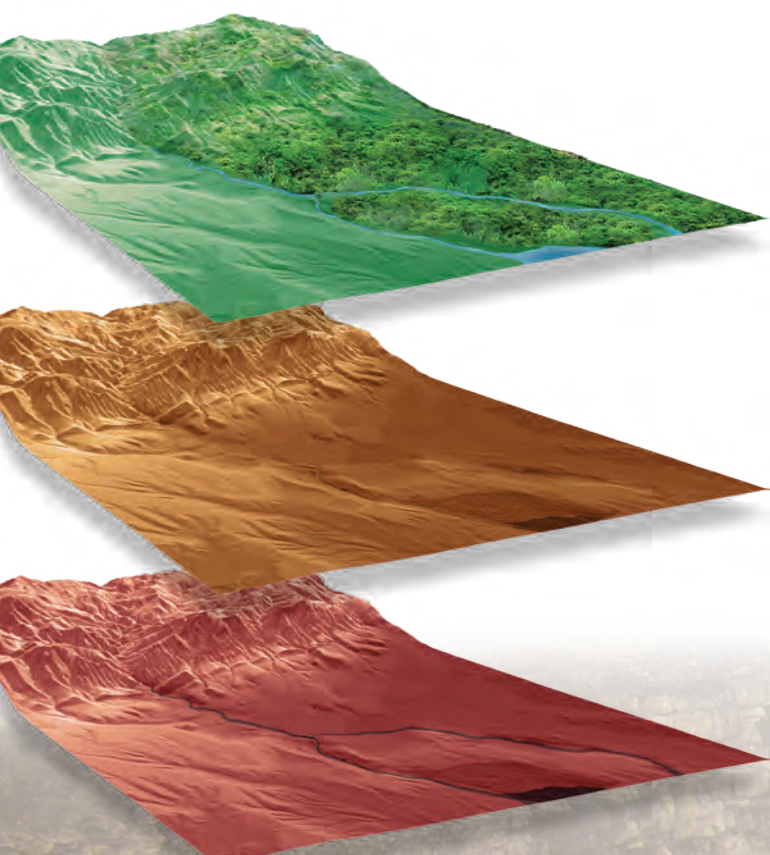
Figure 3. The Rio Grande near Bosque del Apache National Wildlife Refuge, New Mexico. Photograph on left shows typical dense invasive salt cedar, whereas photograph on right shows native cottonwood/willow habitat (photographs by Joydeep Bhattacharjee).

Introducing the Core Science Systems Mission

Highlight

Core Sciences

The Core Science Systems mission is founded on basic and applied research into the Earth's complex geologic structure, a comprehensive and high resolution characterization of the Nation's land surface, and analytical methods of understanding and characterizing biological habitats and biodiversity. These three core sciences, referred to in this manner throughout the strategy, span the Critical Zone (fig. 4) and provide context for nearly all other Earth system science conducted by the USGS and many partners around the world.



As discussed in the foreword, the USGS report, "Facing Tomorrow's Challenges—U.S. Geological Survey Science in the Decade 2007–2017," hereafter referred to as Science Strategy, helped to focus the organization toward a coherent approach to addressing major societal issues and resulted in creation of seven science missions. The USGS collects, monitors, analyzes, and provides scientific understanding of natural resource conditions, issues, and problems. For more than a century, the diversity of scientific expertise in USGS science programs has enabled the Bureau to carry out large-scale, multidisciplinary investigations and provide impartial scientific information to resource managers, planners, policymakers, and the public. As part of the Nation's largest water, Earth, and biological science and civilian mapping agency, the Core Science Systems mission provides science to understand the Earth's geologic framework and to characterize the Nation's land surface and biodiversity. The Core Science Systems mission conducts core science (refer to "Core Sciences" highlight) across a broad range of fields from structural geology, geomorphology, and geophysics to geography and remote sensing, evolutionary biology and biogeography, and is supported by computer and information science. The Core Science Systems mission focus on delivering and interpreting high resolution, comprehensive maps and other forms of data and information for scientists, resource managers, and the public brings together not only research scientists, but also specialists in data analytics, software engineering, library science, and data management. Through research and development programs, Core Science Systems provides scientific data, information, and knowledge that function as an underpinning for all USGS contributions to a broad base of scientific knowledge serving the world.

One of the critical functions of the USGS is to provide unbiased scientific expertise and information to help address the Nation's complex challenges in managing natural resources, preparing for and responding to natural hazards, and maintaining and enhancing quality of life. As the Nation's Earth and natural science agency, the USGS provides accurate and timely scientific information and knowledge based on a characterization of the Earth system from the underlying geologic structure to complete ecological systems, natural and anthropogenic. The Critical Zone concept, introduced by the National Research Council in 2001, is useful for visualizing and discussing the USGS area of interest encompassing the Earth system with which humans directly interact and is used to discuss the Core Science Systems mission (National Research Council, 2001; fig. 4).

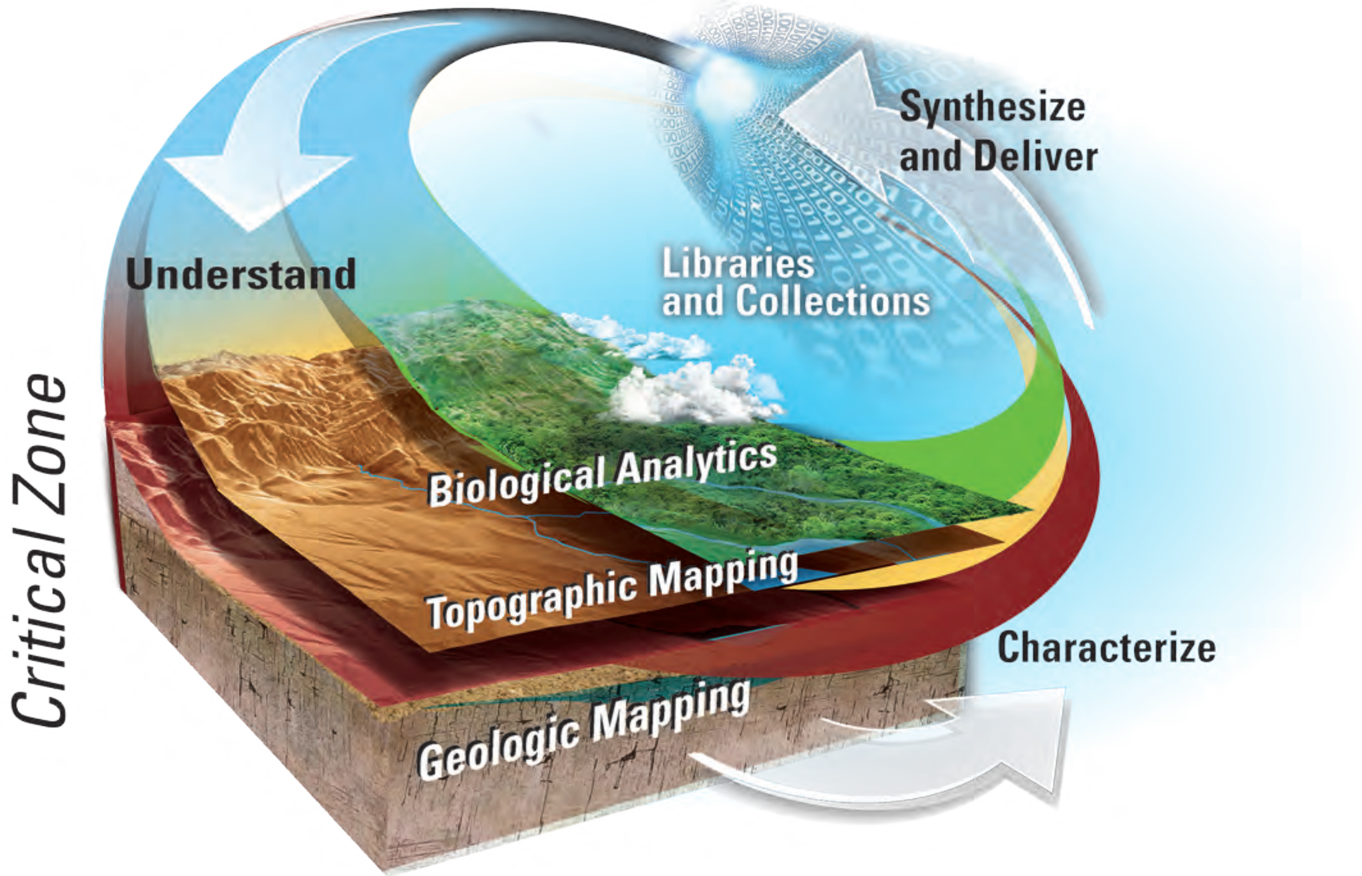


Figure 4. The Critical Zone is the seamless collection of all ecosystems that sustain life on the planet and is the area where humans interact with and often compromise ecosystem functions. The figure depicts the key elements of the Core Science Systems mission.

The USGS motto, *Science for a Changing World*, recognizes societal interactions with a complex Earth system, which necessitates a swift pace of scientific and technological discovery. The Science Strategy suggested a vision for a new mission in data integration and new methods of investigation and discovery. The core sciences associated with geologic mapping, topographic mapping, and biological analytics were brought together to advance the USGS motto and form the Core Science Systems mission. The mission organization includes geologic, geographic, and biologic science along with research capabilities in informatics, the combination of computer and information science needed to enable data intensive research in an era of increasingly large and complex information systems. The Core Science Systems mission also includes data and information management and archiving capabilities of the USGS Library and a data preservation capacity charged with ensuring long-term access to the Nation’s treasure of physical geoscience sample collections.

The complexity of processes sustaining ecosystems and the need to answer critical questions of immediate and future societal import, demands a framework where scientific research, regardless of disciplinary focus, can be organized to characterize, understand, and synthesize knowledge of physical and biological processes. The remainder of this document lays out a vision and identifies strategic actions for Core Science Systems to accelerate a global movement to create and sustain this framework.

Vision for Core Science Systems

This report describes a new and bold vision for the Core Science Systems mission to construct a framework that enables the seamless integration across all USGS missions to more effectively tackle 21st century problems. This framework will allow diverse science knowledge, products, and capabilities (for instance protocols, data assets, scenarios, methods, publications, projects, and scientists) to be organized into logical, fluid, and integratable modules (refer to "Modules Defined" highlight). The framework envisioned will accommodate the complete spectrum of USGS scientific assets to enable quick and efficient deployment of scientific resources and will focus on specific complex problems facing the Nation in the next decade and beyond. Although the framework is inherently a vision of Core Science Systems, it is designed to serve the broad needs of the Bureau and our partners in the larger scientific and natural resource management communities.

The Critical Zone represents a seamless collection of ecosystems that sustain life on the planet, and defines the area where humans interact with and often conflict with ecosystem functions. The Critical Zone recognizes that ecosystems are the result of and are sustained by unique spatial characteristics and temporal processes at specific geographic locales. Using Bailey's conceptual model (Bailey, 1996) as a guide, figure 5 illustrates how the features of ecosystems could be characterized as specific modules that correspond to how much of the Earth systems science research is organized, but also account for unique site-specific features that drive functions of ecosystems through time. The modules include a great diversity of science and scientific assets, ranging from data to projects, protocols, and programs. Moreover, the stack of modules groups unique ecosystem features and mimics how they occur and function in the Critical Zone. In this view, there is no single module that is more important than another because all are essential features that drive ecosystem functions sustaining the Critical Zone. The modules construct, thus, recognizes and respects the valuable disciplinary work conducted by scientists, using their expertise and stresses that interdisciplinary collaborative studies are required to understand the entire system. Collectively, the complete set of modules represents a Modular Science Framework, where each module and the scientific work it represents are essential system components that contribute to the development of lasting solutions to societal challenges. More importantly, organizing scientific assets within the Modular Science Framework will make it easier for USGS scientists to discover data and models, share and publish results, and discover new interdisciplinary connections and research opportunities.

Every scientific discipline and activity of the USGS can be fit into one or more modules. Research conducted within the distinct and fluid modules is often single disciplinary and highly focused to produce base data, information, and knowledge of site-specific features, such as soil development and chemical and hydrologic characteristics, and temporal processes sustaining specific ecosystems, such as natural drought and deluge cycles. The Modular Science Framework provides a context whereby the USGS can contribute to the Digital Earth, a vision being pursued by the global scientific community (refer to "Digital Earth" highlight). Whereas the organization of the modules is just as they occur in the Critical Zone,

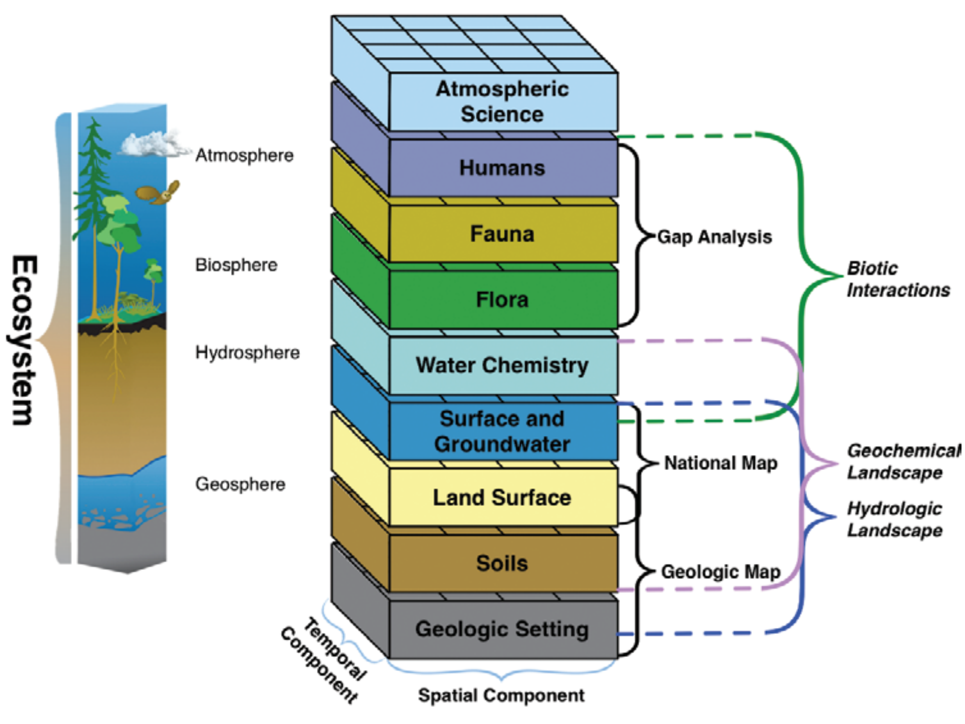


Figure 5. The Core Science Systems vision for a Modular Science Framework is illustrated as distinct and integrated modules stacked in their natural order based on a vertical slice of an ecosystem (Bailey, 1996). The Framework organizes data, scientific and technological methods, and models into relevant temporal and spatial scales (Euliss and others, 2004) to facilitate increased scientific understanding and decision support within the Critical Zone.

Modules Defined

The Modular Science Framework described for the Core Science Systems vision is a framework consisting of distinct units, called modules in this report, where like protocols, data assets, scenarios, methods, publications, projects, and even scientists can be organized to facilitate interdisciplinary Science for a Changing World. The "Modular" term is used because of its many meanings in science and mathematics. In general, modularity is the degree to which a system's components may be separated and recombined. In biology, this may refer to linking organisms or metabolic pathways; in ecology, it refers to diversity and feedback among ecosystem drivers responsible for resilience and sustainability; in cognitive science, it refers to the idea that the mind is composed of independent, closed, domain-specific processing modules that are linked to form complex thought; in architecture, it refers to objects that can be joined together to form larger objects; and in computer science, it refers to individual self-contained electronic components that can be linked to form a larger system. Modular Science Framework, as used in this report, has meaning in each of these areas plus the many specialized scientific disciplines the USGS represents and often may need to link together as part of a larger system to better understand complex modern problems and develop effective solutions.

Highlight

the Modular Science Framework provides a means to define where programs exist and where they need to be developed in the future to maintain USGS science relevancy. The Modular Science Framework thus provides a construct for developing integrated and interdisciplinary approaches to study, visualize, and evaluate ecosystem function and sustainability in a changing world while recognizing valuable disciplinary science and how it contributes to a more holistic understanding of the Critical Zone.

The stack of modules in figure 5 is simplified to illustrate how scientific knowledge and synthesis expressed and delivered as analyzable products can be arranged to examine and understand the complex relations within a given ecosystem across spatial and temporal dimensions. The disciplinary modules can be examined individually or may be collaboratively linked to understand complex functions of natural and impaired ecosystems, asking "why is this observation happening here" type questions as described in the story of salt cedar controls in the Rio Grande Bosque discussed in the Overview section. Sufficient scientific understanding across the modules can lead to the creation of synthesis products that facilitate new understanding and support resource management uses, hazards preparedness and mitigation, policymaking, and many other purposes. Figure 5 represents several example synthesis products, including Biotic Interactions (Hanson and others, 2005), Geochemical Landscapes (Smith and others, 2009), Hydrologic Landscapes (Winter, 2001), Gap Analysis (Edwards and others, 1993), and two national scale products—*The National Map* and the National Geologic Map. By consistently and systematically looking across the breadth of USGS digital knowledge and working to bring focus within the Modular Science Framework, the USGS can capitalize on new syntheses of its core assets to innovate understanding. The Modular Science Framework provides a means for scientists to identify new areas of fruitful work by examining within and across the modules for gaps in critical understanding. For instance, targeted social science research is needed to model social, economic, and institutional variables to provide insights into the dynamics of social-ecological systems (Berkes and Folke, 1998; Holling, 2001). The Modular Science

Digital Earth

Digital Earth is a concept that has been pursued by the global science community since 1998 (Gore, 1998). It began as a vision to develop a virtual representation of the Earth where georeferenced locations would be collaboratively linked with digital knowledge archives from around the globe to help understand the entire Earth system and the influence of human activities. This report uses the term digital knowledge to refer collectively to digital forms of data, information, and knowledge developed through scientific research. While there is much work to do, many aspects of this vision have been realized with Google Earth and growing sources of linked geospatial data applications serving as prime examples. However, the original vision describing a truly global system where collaborative linking of scientific and cultural information systems provide three-dimensional virtual views of the globe to improve understanding of the Earth and human social influences has not been accomplished. The Modular Science Framework described in this report provides the requisite framework for the USGS to organize its scientific assets to better understand the complex processes affecting the Earth system while providing leadership within the scientific community to help achieve the larger vision of Digital Earth.

Highlight

Framework provides a tool to identify important gaps in knowledge needed to solve current problems through cataloging existing digital knowledge from the USGS and partners around the world and systematically exploring the possibility of new synthesis products.

Using the Modular Science Framework as a conceptual structure to organize data assets and other products of scientific research provides a unique opportunity and the requisite structure to facilitate exploration and development of new analysis and synthesis methods in data intensive science. The story about the National Biomass and Carbon Dataset highlighted in the Overview section illustrates how science benefits from new techniques and capabilities. The framework also provides a means for the the USGS to help rapidly advance evolution of the Digital Earth through development of the Modular Science Framework and application to core mission responsibilities of the USGS. To generate the National Biomass and Carbon Dataset, several billion digital biodiversity records were used (J. Kellndorfer, written commun., March 15, 2012), which greatly exceeds the computing capacity of many contemporary investigations. Other potential uses of the envisioned Modular Science Framework would include digital data assets that may be many orders of magnitude larger than in the National Biomass and Carbon Dataset story. Although digital approaches do not replace traditional methods in scientific discovery, they can complement, inform, and improve them (Kell and Oliver, 2004).

The massive quantity of data that has been and will continue to be collected is enabling a paradigmatic shift to new kinds of science (Hey and others, 2009), but it is also creating a problem because data often are located in disparate and disconnected locations, in incompatible formats, and with incomplete information needed to make them seamless and interoperable. To answer more complex questions, the Modular Science Framework must be continually examined and augmented with finer spatial scale, increased temporal context, and greater detail in attribution, measurements, and simulation. This growing quantity and complexity of data, sometimes referred to as Big Data (White, 2010), results in data larger than can be reasonably handled by smaller data management systems and techniques. The Core Science Systems mission provides leadership in USGS use of and contributions to this new paradigm in scientific process and discovery. Data intensive science is becoming common and it will become larger and more important in scientific investigation in the future. Participation and leadership in this field, within the USGS and the larger scientific community, can greatly advance knowledge of the Critical Zone and inform decisions affecting Earth’s sustainability. An evolving cyberinfrastructure across science agencies, academic institutions, and commercial industries is available to advance and evolve the new scientific paradigm and develop new opportunities for collaboration, communication and translation of complex phenomena affecting ecosystems.

The USGS is part of a much larger international scientific community working toward systems that will allow Earth science digital knowledge to be rapidly assembled from sources across disciplines and from around the world. The USGS is in a unique position to make substantial contributions to realize the Digital Earth vision by providing critical scientific understanding and data, developing essential services, and creating new scientific synthesis applications and products. The USGS will provide leadership and scientific content to the rapidly developing comprehensive virtual environment being created by scientists across the world that supports Earth sciences during the next decade and beyond. A Digital Earth concept connected with a Modular Science Framework will enable scientists and decisionmakers to better understand, communicate, assemble, and integrate disparate research, knowledge, data assets, and technology. An established Modular Science Framework will provide a centralized, easily accessible platform, allowing sharing and advancing of scientific information. With a robust Modular Science Framework, the National Biomass and Carbon Dataset could be developed in 6 months, instead of 6 years, and automatically updated as new satellite imagery becomes available. Furthermore, rapidly accessible knowledge will allow us to answer why questions, or will allow finding effective solutions to problems, such as water management for salt cedar control, to be rapidly discovered and used by decisionmakers in other arenas.

USGS scientists are encouraged to deposit their project materials with the Field Records Collection, Denver Library. Materials in the collection are inventoried electronically and managed as Federal records to ensure ongoing access in perpetuity for future researchers. Photograph by Colleen Allen, USGS.

Guiding Concepts

While formulating the Core Science Systems strategy, a number of essential concepts emerged as part of the vision to help guide the development of goals, objectives, and actions. These concepts were discussed regularly in listening sessions and meetings with USGS scientists and other stakeholders. The concepts are provided here as an important guide to understand the drivers behind the goals, objectives, and actions because of their recurrence throughout the document.

Start with Science

"Start with Science" is an emerging USGS theme that developed during the course of the science strategy planning process. The significance to Core Science Systems, in particular, is twofold: the foundation for the Core Science Systems Mission Area is the scientific research conducted by its programs and projects, and the services provided by the Core Science Systems Mission Area to the USGS as a whole need to be conducted as part of a scientific program, using the scientific method to develop and improve services and capabilities. The stack of modules in the Modular Science Framework represent the science conducted within various USGS disciplines and focus areas, and the framework provides a set of methods whereby the science represented by the modules can be integrated and synthesized toward answering difficult and increasingly complex Earth system science questions. The Modular Science Framework represents a scientific pursuit founded in Earth system science and informatics research programs needed to characterize, understand, and synthesize the Earth's complex structure and function.

Inherent Integration and Interdependence

This report provides goals, objectives, and actions for improving core components of the overall USGS mission as described in the 2007 Science Strategy. Like all missions of the USGS, Core Science Systems crosses organizational unit boundaries through necessary interdependence and a need for tight integration across programs and projects. The Core Science Systems mission is ultimately a USGS-wide responsibility and not fully within the domain of any one program or organizational unit. This strategy also makes no presumptions about implementation strategies and other details from organizational units outside the USGS but it is written to facilitate and encourage broad collaboration with many partners. The text is written deliberately to allow for the creative process in how the mission strategy will be implemented while providing specific examples to help readers connect to more tangible activities.

Audience

The 10-year nature of the science strategy process introduced a challenge in addressing multiple audiences at different scales of complexity and detail. Much attention is focused toward USGS scientists and other staff of the programs in the Core Science Systems organization. The Core Science Systems strategy outlines a mission to provide primary Earth systems science data; such as mapping of topography, geology and biota; and capacity to integrate much broader USGS data and information. The latter comes with the responsibility for application of advanced technologies across all USGS missions. For this reason, the full USGS workforce is recognized as an important stakeholder and participant in the Core Science Systems vision. Yet, aspects of the Modular Science Framework and strategy that include delivery of data, services, and synthesis to specific partners such as DOI resource managers requires a focus on audiences across the broader scientific and resource management communities. Stakeholders provide critical philosophical, political, and financial support to the USGS; and members of the public and industry groups reap financial benefit from research and development in the USGS. Feedback from each of these audiences sometimes varied greatly, resulting in a very broad perspective for the Core Science Systems strategic vision.

Workforce Evolution

The vision described in the science strategy plans will only be realized through an evolving USGS workforce. The goals, objectives, and actions in the Core Science Systems vision are all founded on the history of USGS as an organization deeply committed to developing its workforce, through deliberate and calculated recruitment of new skills and abilities and through continuing education of its workforce throughout full careers. The rapid pace of technological advancement and the importance placed on wise applications of technology to science described in the Core Science Systems vision demand investment in continual learning and workforce modernization.

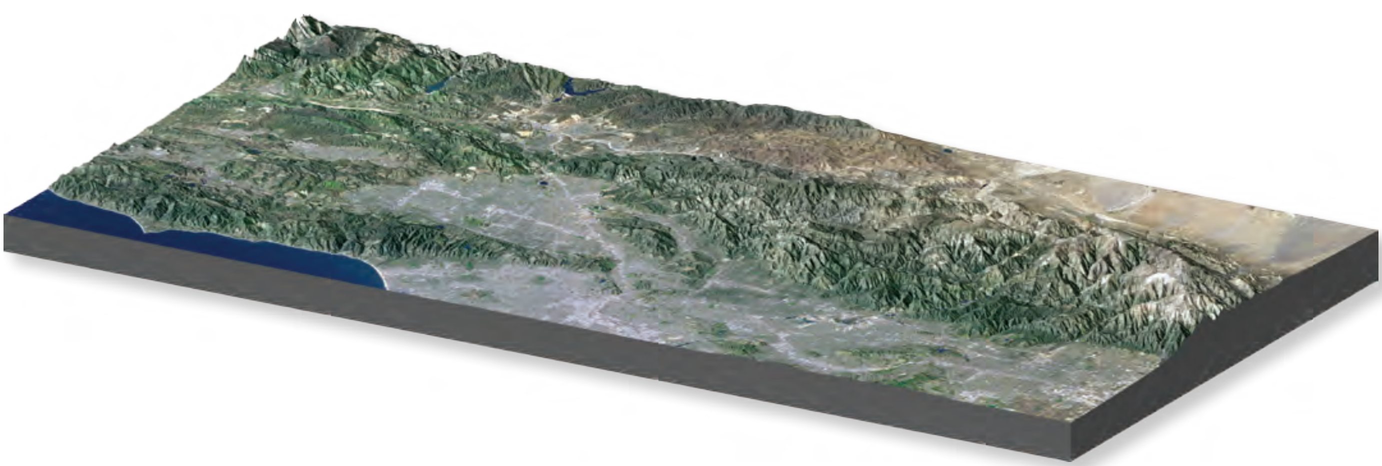
Cultural Evolution

Successful implementation of this strategy is dependent on the continued evolution of cultural norms within USGS that emphasize improved data management, archival, and access techniques in the context of interdisciplinary approaches to Earth science studies. This evolution places a burden on USGS researchers. However, individual scientists are part of a much larger worldwide network of researchers, and scientists themselves form the most critical aspect of the emerging Modular Science Framework described in this document.

The use of scientific programming, software development as part of scientific publication, articulating science stories with advanced visualization tools, and integration of mobile computer technology are rapidly becoming the norm for scientists today and must be an integral part of the USGS of the future. Several actions within the Core Science Systems Strategy point out areas where new norms can be identified, studied, and evaluated.

Interdisciplinary Science

As emphasized in the 2007 Science Strategy and in this report, the problems facing the DOI, the Nation, and the world are extremely complex and are the result of numerous interacting factors. As a consequence, interdisciplinary science must continue to grow as a way to address these complex problems (see Gunderson and Holling, 2002; Dietz and others, 2007; Liu and others, 2007). Interdisciplinary research and scientific synthesis are required for and an outcome from the Modular Science Framework. The Modular Science Framework relies on a foundation of modules (fig. 6), wherein disciplinary and interdisciplinary science occur to produce the fundamental understanding of its elements and the preparation of data and information resources such that integration is possible. Realizing the full benefits of integrated science will require a dedicated effort to ensure that the necessary workforce ingredients are in place to achieve the full potential of the USGS as an integrated science agency. The USGS must actively shift its data resources, knowledge resources, workforce, and tools toward a new paradigm of integrated science. While requiring active organizational methods to counter the drift toward balkanization in science (Van Alstyne and Brynjolfsson, 1996), integrated science is driven by integrated science questions that arise at the edges of disciplines represented by modules in the framework.



The Digital Earth will be achieved through innovative collaborations between government data agencies and many other partners. This example shows a snapshot of the Los Angeles Basin as a high resolution digital elevation model combining data from the USGS Landsat Mission and the NASA Shuttle Radar Topography Mission.

Goals, Objectives, and Actions

The following goals, objectives, and strategic actions provide an outline for program and project activities in the coming decade to develop the Modular Science Framework. Although the goals reflect fundamental strategic requirements to achieve the Modular Science Framework, implementation methods and other details will evolve through more detailed program and project plans. The goals, objectives, and strategic actions reflect the vision and guiding concepts described in the preceding Guiding Concepts in the Strategy Development section. They are not meant to be pursued in sequential order as written here, but the top three actions for each objective are considered of highest priority.

A conceptual model to serve as a guide in fitting the goals, objectives, and actions into the overall vision for the Modular Science Framework is provided in figure 6. At the top of figure 6, the Digital Earth concept discussed in the Vision for Core Science Systems section illustrates the large scientific and worldwide community to which USGS contributes digital knowledge and from which USGS extracts data, information, and knowledge resources developed in the broader science community. The research process engaged across the sciences in the USGS intersects with the Modular Science Framework, drawing digital knowledge from the framework and contributing new understanding and products of research to the framework. Steps are outlined where research teams and individual scientists can connect with the Modular Science Framework.

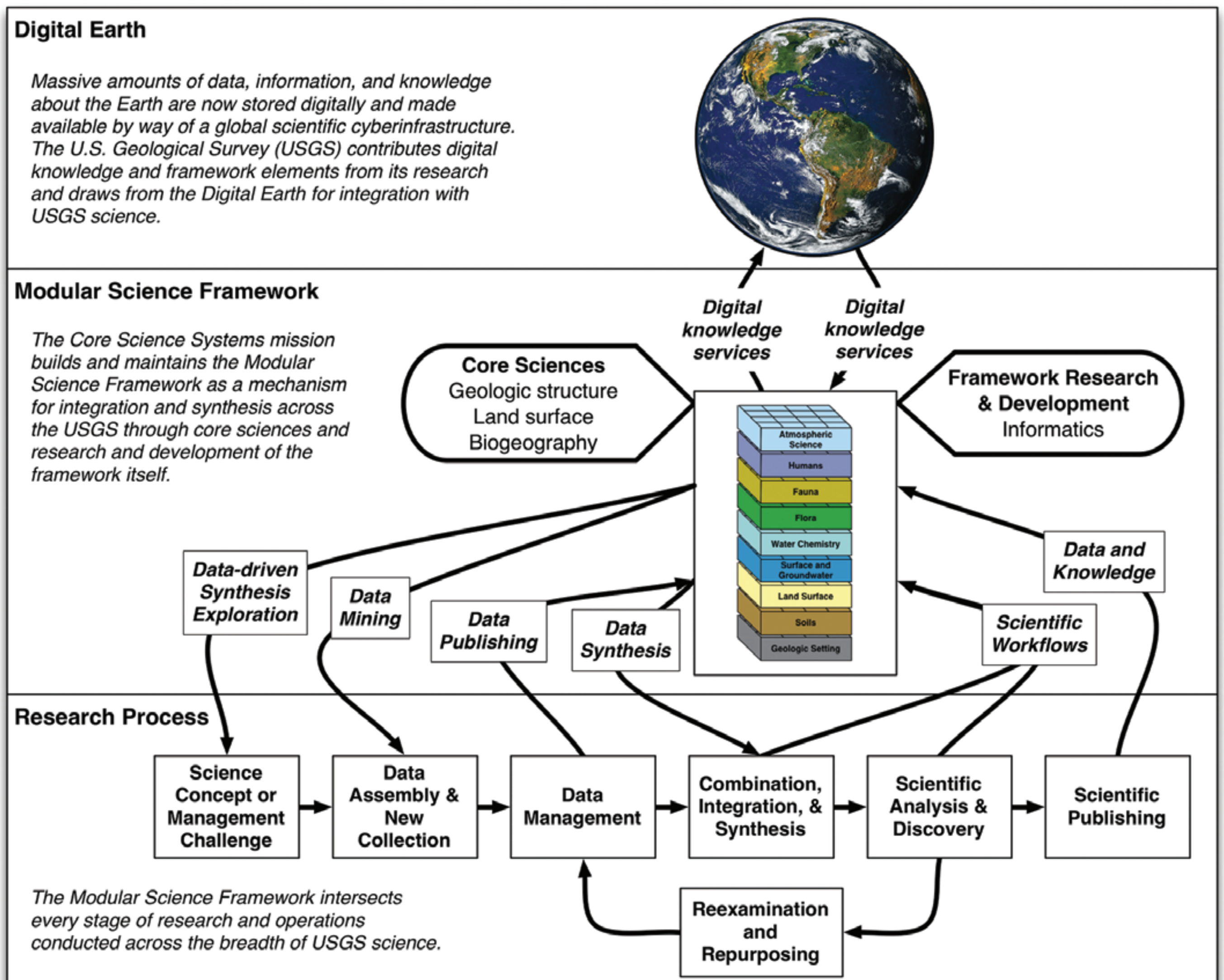


Figure 6. Conceptual model for how the Modular Science Framework envisioned for the Core Science Systems mission is developed through core sciences and informatics research and development, interfaces with the USGS research process, and draws from and contributes to the larger pursuit of the Digital Earth.

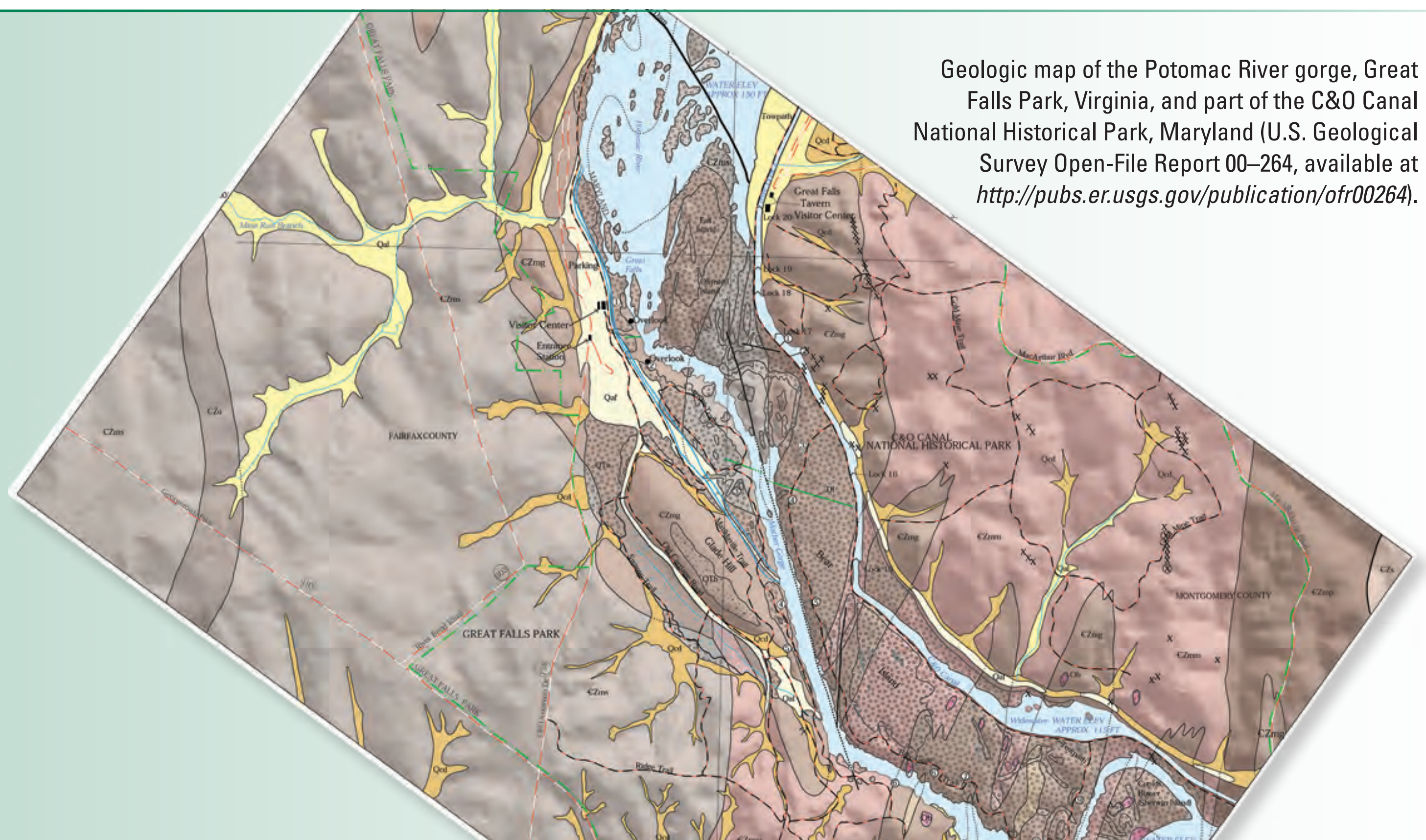
Goal 1: Provide Research and Data to Characterize and Understand the Critical Zone

Conduct research to produce timely, nationwide, seamless, authoritative, open-access digital knowledge for ecosystem processes sustaining the Critical Zone.

The rapidly expanding environmental footprint of humanity requires continually evolving Critical Zone research to characterize and understand the Earth's complex processes. One of the distinguishing characteristics of the USGS is its long-term commitment, arising from its geologic, water resource, and land survey roots; to the collection, maintenance, and provision of high quality data that spans a wide range of spatial and temporal scales. The Core Science Systems mission fulfills an important role in the USGS, providing core scientific data within several modules of the Modular Science Framework along with synthesis products such as *The National Map*, several national and continental geologic maps, and Gap Analysis Products depicted in figure 5. For more than 130 years, the USGS and its partners have led development of a geologic, geographic, and hydrographic framework of the Nation. Long before the Critical Zone concept came into wide use, the USGS has been characterizing the Earth's near-surface environment through its geologic and topographic maps and stream-gaging network. These maps and other data provide a basic foundation for models that inform ecosystem studies at multiple scales. With the introduction of biological science to the USGS in the last century, biogeographic modeling and mapping of species distribution and habitat through time has been added to the store of Critical Zone data.

Goal 1 highlights three core sciences that are integral to the Core Science Systems mission: geologic mapping, topographic mapping, and biodiversity mapping. Each of these components of the Modular Science Framework can be directed to better focus on challenges and strengthened to take advantage of emerging technologies. The goals are to provide outstanding map and other data products and to facilitate integration with other modules as a part of the overall framework that encompasses ecosystems in the Critical Zone and helps to bring context to other modules.

New technology and evolving societal needs demand that science delivers knowledge in a form that can be directly applied to forecasts of how the Earth and its living systems, including humans, influence and react to change. Improving the ability to map, model, and analyze information across space and time within individual modules will enhance the understanding of geologic, hydrologic, human, and biologic processes and their changes through time and in varying environmental conditions. The resulting characterization and understanding of processes will improve timely and accurate response to environmental and hazard challenges and better inform decisions, whether the challenges can be addressed with information from a single module or are better addressed through integration of knowledge across modules. An overall focus for the core sciences in the next decade will be to increase spatial and temporal resolution through research and development of products such as a full four-dimensional geologic map, showing how the complex geologic structure of the Earth has changed through time.



Geologic map of the Potomac River gorge, Great Falls Park, Virginia, and part of the C&O Canal National Historical Park, Maryland (U.S. Geological Survey Open-File Report 00–264, available at *http://pubs.er.usgs.gov/publication/ofr00264*).

Objective 1.1: Improve Characterization and Understanding of Geologic Framework to Inform Studies of the Earth's Complex Processes

The published strategy for geology research in the USGS (Gundersen and others, 2011) provides the following statement in a goal that closely aligns with Goal 1 in this plan and this objective:

> "A comprehensive understanding of the Earth's geologic framework is needed to inform the critical decisions the Nation and the world will make about resource utilization, environmental quality, and hazard mitigation."

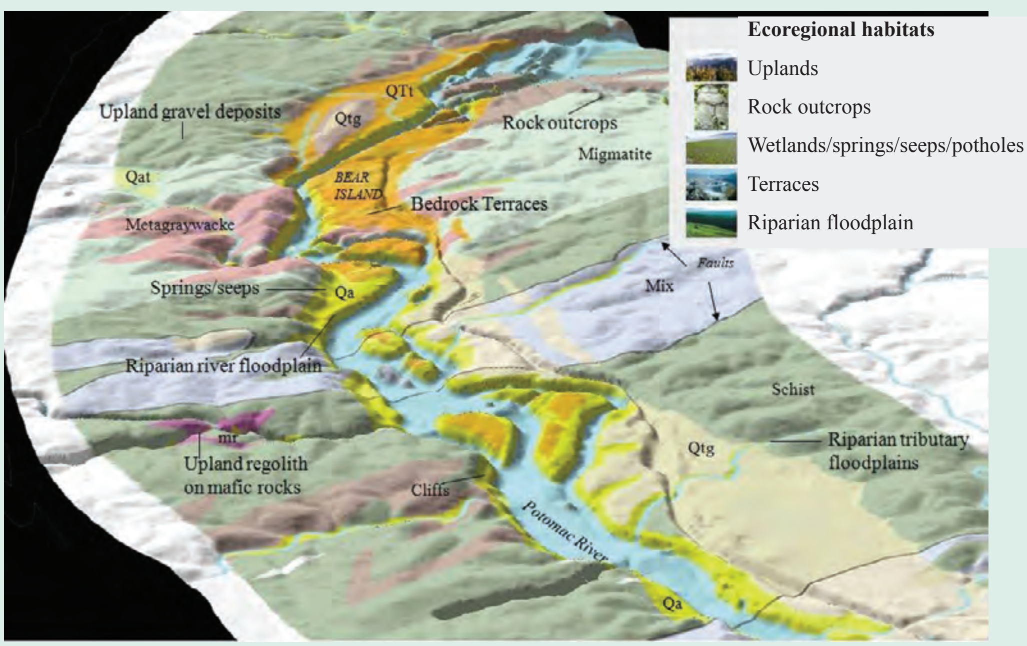
The Core Science Systems mission is responsible for the research that results in characterizing and understanding the Earth's geologic framework. Geologic maps represent multidisciplinary investigations that constrain evolving models of the Earth's structure, evolutionary history, and response to and interactions with humans. The geology in these models describes the history of geologic processes in a given area, that is, processes that represent temporal evolution of the area. As such, geologic models represented by maps present four dimensions, a three-dimensional volume of the Earth plus the fourth dimension of time. Mapping the Earth systems has moved to an era that improves the ability to deliver knowledge in a form that can be directly applied to forecasts of how the Earth and its living systems drive and react to change. Next generation studies will generate three dimensional Earth system models representing understanding of the geologic processes in the Critical Zone, and their alterations through time. The resulting understanding of processes will improve timely and accurate response to environmental and hazard challenges.

Strategic Actions

1. Develop three- and four-dimensional models of crustal characteristics and processes through expanded field investigations and improved laboratory and remote sensing technology.

Geologic Maps Used to Delineate Ecosystems and Critical Habitat

In the Potomac Gorge region near the Nation's capitol, study of bedrock geology by Southworth and Denenny (2004), funded by the National Cooperative Geologic Mapping (NCGM) Program, showed that the geology has a direct and predictable relation to rare plants, critical habitat, and plant communities. The bedrock controls these ecological attributes in several ways, such as the rocks that are more resistant to erosion forming topographic highs that have characteristic soils, and the less resistant rocks tending to host thicker sediment as well as more advanced soil development. In addition, the chemistry of specific rock formations lends a basic or acidic chemistry to the soil, further partitioning plant communities and animal habitat. In addition to controlling aspects of physical evolution of a watershed and river systems, the bedrock has a major influence on plant communities. This map of the bedrock and others of surficial geology developed by the NCGM Program provides a framework that aids with developing predictive ecohydrology models such as plant community patterns and wildlife habitat.



Ecology of the Potomac River Gorge showing geologic units and landforms as critical habitats and ecological land units.

Highlight

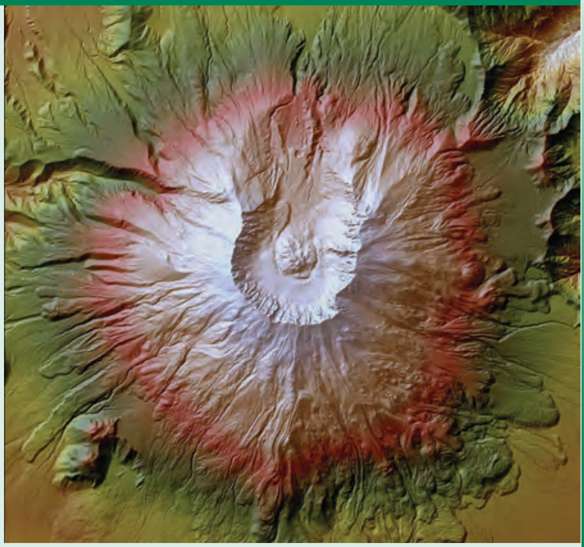
2. Use improved elevation data and landscape analytical techniques to advance geomorphology and active tectonic research.
3. Use advanced microanalytical techniques for dating and analyzing the composition of rocks and sediment, including measures of past environmental conditions, to refine the mapping of surface and near-surface geologic materials of the Critical Zone.
4. In collaboration with State Geological Surveys and other partners, create a common geologic map data model for the Nation through analysis and interpretation to correlate rock units and properly convey spatial resolution and map characteristics.
5. Apply geoinformatics to deliver seamless geologic maps for the Nation that honor scale and content requirements.
6. Improve understanding of deep geologic basin processes with cutting edge geophysical and geologic studies, employing three-dimensional modeling.
7. Expand understanding of dynamic crustal processes as they relate to sediment transport and landscape evolution.

Stream flowing into the Potomac River in Whites Ferry, Virginia. Photograh by Cynthia L. Cunningham, USGS.

Objective 1.2: Improve Land Surface Data to Better Characterize and Understand Relations Between Anthropogenic Influence and Natural Earth Surface Processes

Geospatial land surface data are primary resources required for Earth science research and applications. Since its inception, the USGS has collected, produced, and published geospatial data in the form of hardcopy topographic maps. As the USGS transitioned into the digital realm, the categories for features portrayed on a topographic map became segmented into data layers or themes, which were digitized into separate databases. Not only were these data layers maintained separately, but being derived from older topographic maps, were often out of date. Fundamental research in geographical information science is necessary to update these data and provide the foundation required for collaborative, integrated Earth science. These scientific advances will ensure that USGS can improve reliable, ready access to high-quality, authoritative, integrated, up-to-date, spatially-consistent geospatial data that fully support the interdisciplinary science called for in the

The National Enhanced Elevation Assessment (NEEA)



The NEEA project is led by National Geospatial Program (NGP) and the Land Remote Sensing Program in the Climate and Land Use Change mission area. The NEEA was completed in 2012, and provides key information about requirements for a national program for enhanced elevation data. The NEEA was sponsored by member agencies of the National Digital Elevation Program (NDEP), an interagency consortium dedicated to the collection, dissemination, and use of digital elevation data products. A primary objective accomplished in the NEEA is the documentation of technical requirements and business cases for development of a new national program focused on collection and provision of enhanced high-resolution, high-accuracy elevation data. The study also identifies national program implementation alternatives, costs, and benefits that meet the priority needs of Federal, State, and other stakeholders. The study results indicate the broad, mission-critical requirements for enhanced elevation data, literally hundreds of functional programmatic applications from 34 Federal agencies, 50 States, territories, tribes, local governments, and representatives from nonprofit groups and private industry.

NGP has a lead role in pursuing the follow-on steps, and current activities include formalizing program recommendations, intensifying outreach and coordination with potential partner agencies, and developing a funding strategy and implementation timeline. All the implementation scenarios for an enhanced national elevation program include recognition of the information technology infrastructure required to manage the massive amounts of data in this foundational Earth science dataset. Geoinformatics research through the Core Science Systems mission could make substantial contributions toward the information management practices that will be needed to efficiently administer the data and products in a new national elevation initiative.

The availability of significantly enhanced base elevation data will facilitate numerous developments and improvements in other core data assets and research activities that use those datasets. For instance, new consistently collected, high-resolution, high-accuracy elevation data would allow for development of significantly improved hydrography data to upgrade the National Hydrography Dataset, a key USGS data resource for distributed hydrologic modeling research. Such a development would eliminate the current condition with base elevation and hydrography layers in which users often need to account for the lack of precise vertical integration between the datasets. The availability of newer types of elevation products, such as full return waveform light detection and ranging (lidar) data, will also facilitate innovative applications across the USGS. Scientific investigations require more than just high-quality bare-Earth elevations, such as the characterization of vegetation canopy habitats or mapping of human-built structures in forest fire prone areas along the wildland-urban fringe. The Modular Science Framework will play a key role in developing and demonstrating these new applications of remote sensing based elevation products for interdisciplinary science, particularly through the Center of Excellence for Geospatial Information Science (CEGIS).

Highlight

USGS Science Strategy. By meeting the needs of USGS interdisciplinary science for base geospatial data, the requirements of other Federal, State, local agencies, and tribal nations, as well as nongovernmental and private entities and the general public, are also met.

Strategic Actions

1. Produce enhanced elevation data of higher resolution and accuracy for three-dimensional measurement of the Earth's land and coastal submerged topography and its natural and human-constructed features.
2. Conduct research on data structures and analytical methods for making these new types of geospatial content readily usable by scientists.
3. Ensure that all foundational geospatial data exhibit precise vertical integration. For instance, a waterbody, stream channel, or ocean shoreline should be exactly the same when extracted from elevation, land cover, boundaries, and hydrography layers.
4. Conduct studies to fully characterize, quantify, and document the data quality and uncertainty of foundational topographic data, including locational (coordinate) and attribute accuracy.
5. Research methods for instituting spatial/temporal data models so that the vast store of historical maps, aerial photography, and satellite imagery possessed by the USGS can be readily used for retrospective analyses.
6. Research and establish production methods for nationwide seamless, vertically integrated, high resolution data for topographic, geologic, biologic, and hydrologic applications and processes.
7. Research, develop, and implement new models for geospatial processing, data mining, exploration, management, archiving, and storage.

A part of the USGS enhanced elevation work, the image shows the Alamosa, Colorado area and the elevation difference derived from processing lidar data. Colors indicate the magnitude of the differences, and boundary line indicates where contour lines were delivered for the Federal Emergency Management Agency (FEMA) as part of a multi-agency cooperative lidar collection. Uses of these data include floodplain mapping and risk assessment, urban planning, invasive plant species mapping, tree-canopy height measurement, and elevation data improvement for *The National Map*. Lidar image by John Kosovich, USGS.

Objective 1.3: Increase Understanding of the Natural and Socio-Cultural Implications of Biological Diversity

Biogeographic information—biological information on species and when and where they occur on Earth—are basic requirements for understanding fundamental questions in ecology and conservation science. Biodiversity on Earth is not completely cataloged or quantified. Mapping and modeling of species and habitats are based on current knowledge of species and species assemblages, as well as classification systems and related information management. Current theories of speciation and community ecology recognize a temporal aspect to species relationships. Major drivers of landscape modification, including climate change, highlight the temporal dynamic in characterizing and understanding biodiversity, but current data are not adequate to understand and predict how species assemblages and species-habitat relationships might change. Given the importance of biodiversity to ecosystem studies and the social and natural values that underlie current efforts to understand the biological diversity, it is necessary to advance knowledge and capacity in this area.

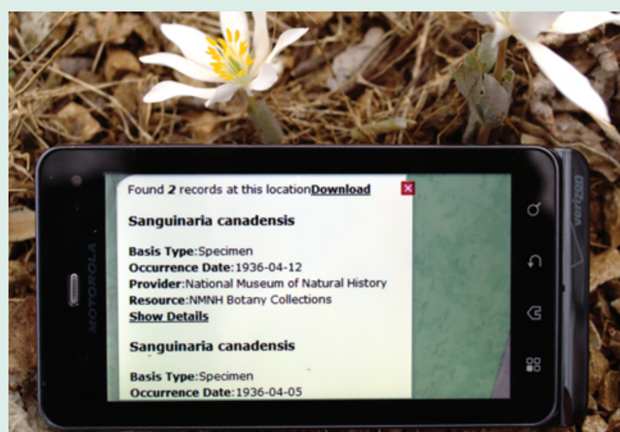
Strategic Actions

1. Enhance mapping of plant communities and animal habitats on a regular cycle in sufficient detail with thoughtful, detailed data organization to be flexible and adaptive given long-term change.
2. Determine the critical information necessary to confidently determine the status and condition of biological diversity through time.
3. Model species distributions across their full extent through studies that are comprehensive in terms of understanding biological diversity and adaptable with respect to data management.
4. Refine vegetation classification and mapping with new observations and improved integration methods to increase spatial and temporal resolution.
5. Improve biological occurrence data in terrestrial and marine environments through data integration of additional trusted source data.
6. Continue to develop taxonomic data, expertise, and an accessible standardized nomenclature.
7. Improve methods for modeling, mapping, and understanding how biodiversity varies across space and through time.

Highlight

Biodiversity Information Serving Our Nation

BISON is a comprehensive view of biological occurrences in the United States with more than 82 million records generated by approximately three-fourths of a million professional and citizen scientists across the Nation. A portal to one agency's data is useful but a resource that facilitates visualization and geospatial query and analysis of occurrence data from all Federal agencies combined with data from across the public and private sectors is transformative for science and society. BISON synthesizes the primary occurrence data (a species or other taxon, the location at which it was observed or collected, who made the scientific observation, and on what date). These points are then linked back to extended ancillary data and metadata in the original data set. The primary occurrences are viewable in an interactive geospatial environment for query, analysis, and downloading. Synthesis occurs through adherence to global standards such as Darwin Core, taxonomic integration through the Integrated Taxonomic Information System, and integrated high resolution geospatial layers. BISON also has access to some of the biggest supercomputing resources on Earth, so computed layers can be developed and made available to answer questions that were previously beyond the capability of most scientists.



Goal 2: Expand Applications of USGS Research Through Scientific Services

Improve the application and impact of USGS research products through development and testing of services, software, tools, and participatory frameworks that build and apply the Modular Science Framework.

One of the driving concepts in the 2007 Science Strategy and the aim of the Modular Science Framework is to provide increased capacity to answer more complex science questions related to societal challenges through digital knowledge. The Modular Science Framework needs to be a functioning system, able to be applied to science questions and management challenges to better inform decisions impacting society. Coupled with the core sciences described in Goal 1, the Modular Science Framework requires sustained and focused research and development in computer and information science to apply evolving theories of distributed complex scientific information networks to USGS digital knowledge. The Modular Science Framework is not envisioned as a monolithic software or data system; rather it provides a method of tying together many different data systems across the USGS and around the world.

Highlight

Services Defined

The concept of services within and from the Modular Science Framework is used to discuss how the framework is interacted with, either conducting research and organizing subsequent digital knowledge within the framework, or interfacing with the framework to address a societal challenge. Services may be used elsewhere in this report with concepts such as ecosystem services, but in this context they refer specifically to technological services, that provide interfaces to the digital knowledge brought together in the Modular Science Framework. Professional services, work conducted by people and organizations to grow and maintain the Modular Science Framework and its applications to science and decisionmaking, are critical. The terms, 'services' and 'service orientation', are used in this goal in a broad sense to describe the applications of the Modular Science Framework for scientific research and for addressing societal challenges. The fundamental point raised here is that pursuing service orientation, whether used in the technological sense (Erl, 2005) or the professional services sense (Teng and Barrows, 2009), forces the development of capabilities and resources that can be examined individually, quantitatively measured and analyzed for effectiveness, and improved incrementally.

Technological services include digital methods by which data and information are discovered, accessed, processed, and applied to various types of applications such as simulations and analytical systems. As in any technical field, there are broad-ranging debates about the efficacy of one service approach or another, and it is anticipated that debate in the field of technological services will carry on for many decades to come. The USGS is a leader in the development of services for its products such as *The National Map* data services (U.S. Geological Survey, 2012f), the National Water Information System web services for streamflow and water quality (U.S. Geological Survey, 2012c), and the suite of services from the National Earthquake Information Center providing information about seismic activity across the Earth (U.S. Geological Survey, 2012b). These example applications were initiated with the purpose of serving a particular application need and a specific group of stakeholders, but have resulted in many new innovative applications created by USGS and non-USGS scientists and developers. Whether directly or indirectly, services providing data in forms that can be used broadly by a multitude of applications are a core part of the Modular Science Framework.

Professional services in this goal refer to the ways in which people and organizations contribute to the functionality and ongoing development of the Modular Science Framework. A prime example of a service for the Modular Science Framework is the role of the USGS Library in the data mining and archiving processes described in the conceptual model (fig. 6). As data and other scientific products and tools are used to populate the Modular Science Framework, an archival and notification system, leveraging human-assisted technology, can constantly monitor the framework, keeping users aware of new data holdings, new techniques being employed, new scientific publications, and new research projects in a way never before possible. Professional services provided as components of the conceptual model can be evaluated and tested for effectiveness using empirical methods to measure and analyze everything from the effectiveness of tools to the recorded comments about interactions with people and organizations providing services.

Access to and incorporation of digital knowledge external to the USGS, such as data and partner researchers, are vitally important to the continued evolution of technological and professional services. The connection of the Modular Science Framework to the larger Digital Earth is illustrative of a complex challenge requiring research and development of services. To be effective, users must have access to the wealth of data, tools, and capabilities from other science agencies, academic institutions, resource management organizations, and monitoring networks. Technological services provide part of the pathway to seamless integration with these resources; however, there are many other aspects that require development and maintenance of research partnerships, data access agreements, and targeted research and development into new ways of tapping remote data streams. An overall focus for the informatics research of Core Science Systems is to continually test whether USGS digital knowledge is being served to the rest of the world in a way that supports anticipated and unanticipated but valid uses. USGS researchers must have access to the broadest possible base of digital knowledge from the rest of the world.

Objective 2.1: Modernize Information Management and Publication

The global pursuit of a Digital Earth by many organizations and the possibilities for creating new forms of interactive scientific content has launched many large and small scale efforts to transform the scholarly publishing paradigm (Attwood and others, 2009). Efforts include digitizing previously analog information into new archives accessible to digital analysis, improving information management throughout the duration of science projects, and establishing formal publication of data alongside traditional scientific publications. As the USGS is part of this global scientific community, the data produced and published by USGS scientists have a long-lasting scientific impact beyond an existing study or even the career of an individual scientist. Although many major USGS programs with coordinated, long-term observation or monitoring programs have well established methods for publishing and managing data, adapting and improving methods to promote use and ultimate impact of data should be a major focus across the USGS. The conceptual model for the Modular Science Framework (fig. 6) shows several steps where the research process intersects through data and information management to the framework—data mining, data publishing and archiving, scientific workflows, and final publishing. Each of these steps requires facilitation that can be provided through the Core Science Systems mission and also direct investment from all USGS missions, programs, science centers, and individual scientists. Figure 6 indicates that all steps in the science lifecycle conducted within USGS should be examined critically for how they can contribute to and take advantage of the data and information aspects of the Modular Science Framework.

Strategic Actions

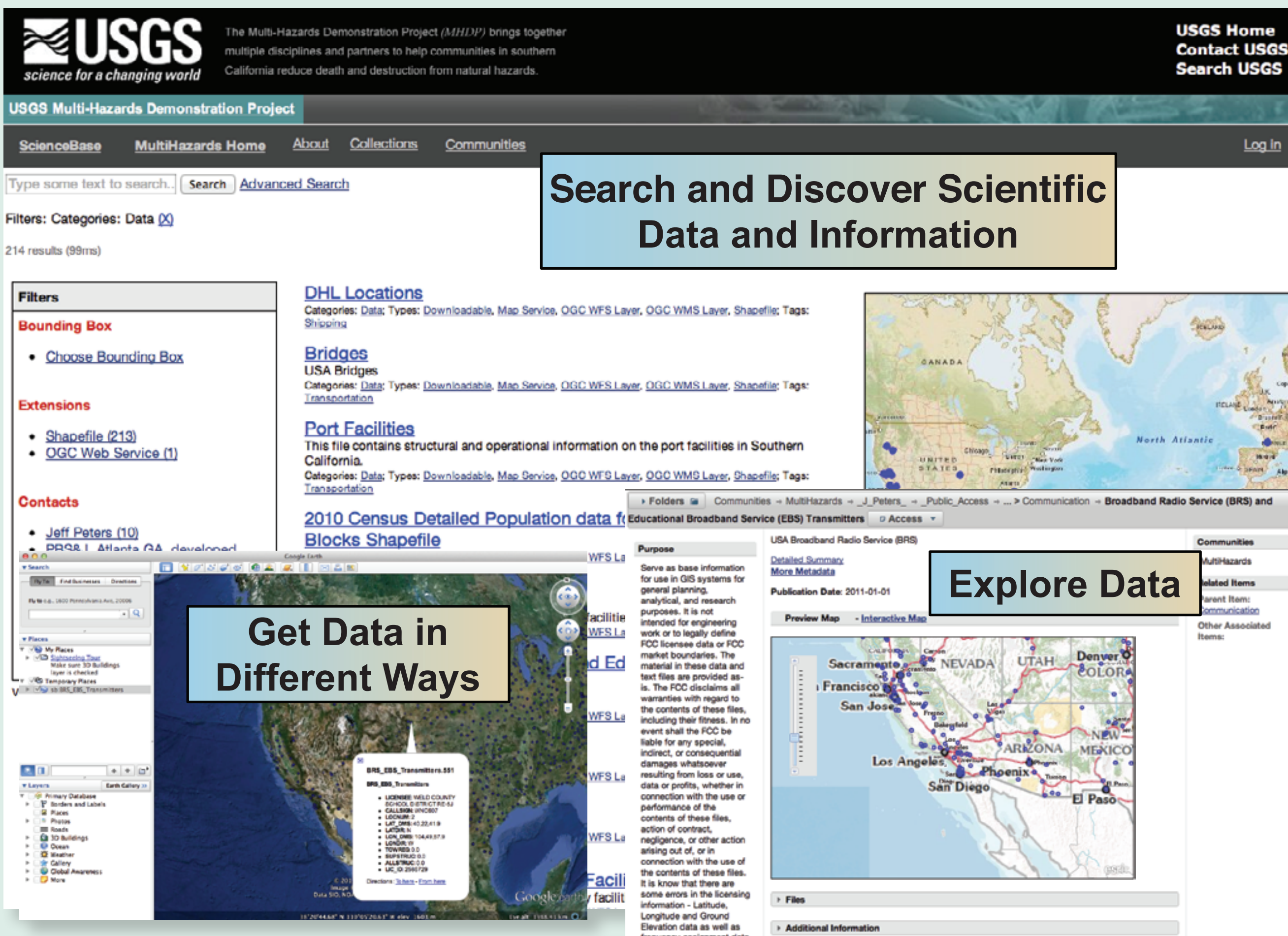
1. Facilitate more rapid and incremental release of quality scientific data and associated materials prior to and associated with final interpretive publications.
2. Increase the use of data citation methods across the breadth of USGS science in coordination with international standards bodies such as DataCite (DataCite, 2012), and incorporate data citation into the official research record of USGS scientists through automated methods wherever possible.
3. Improve rescue and curation of historical data, physical specimens, and samples throughout the USGS into robust archives that can be used for new research.
4. Research new methods of describing data, scientific workflows, and research such as videos published alongside a scientific paper that present a more nuanced understanding of the research.
5. Continue to develop and implement data documentation standards and new methods for computer-assisted metadata creation and maintenance.

The Castle Pines Core was a joint scientific venture between Federal, State, and local organizations to obtain detailed geologic and hydrologic data pertaining to the bedrock aquifers in the Denver Basin. After languishing unused and inaccessible in a local government office, a collaborative effort transferred the core to the USGS Core Research Center where information about the core and photos are available online and the physical data can be accessed by public and private entities for research.

Highlight

ScienceBase

Much more science is conducted in the USGS and many more products are produced than ever see the full light of day in scientific publications and USGS reports. Library scientists have begun calling this type of research information “dark data,” with the library community around the world working toward ways of managing, curating, archiving, and exposing these data for broader use (Heidorn, 2008). One USGS strategy to address this problem is the ScienceBase platform for scientific data and information management (U.S. Geological Survey, 2012e). ScienceBase takes the approach of providing a data management platform for use by individual scientists and science teams early enough in the research lifecycle that project data are identified and posted online sooner rather than later, professional and technological services that transform and expose data in ways that they can be accessed by a broad range of applications, and open methods of accessing ScienceBase data and documentation (metadata) so that they can be easily incorporated into other outlets such as Science Center web sites. Two parts of the Core Science Systems mission, a group focused on scientific data management at the project level and the USGS Library focused on long-term management and archiving of the USGS data record, are teaming together to extend the ScienceBase platform for broad use across the spectrum of formal USGS data publications and the so called, “long tail” of dark data. By collaborating with other projects who are also tackling this problem such as DataONE (DataONE, 2012), the USGS is contributing to and taking advantage of research activities such as formal data citation processes (DataCite, 2012), all part of the global pursuit of Digital Earth.



Research and Decisionmaking Scenario

John is a USGS researcher who specializes in sediment transport modeling in the coastal ocean. An interagency team addressing harmful algal blooms in the Gulf of Maine suspects that summer toxicity events are strongly affected by redistribution of cyst-laden sediment during the winter months and asks John to investigate with a numerical simulation. A decade ago, he would have started by asking his immediate colleagues if they had forcing models and parameterizations he might be able to use. Now he can quickly discover and review available scientific workflows in the Gulf of Maine involving wave modeling through discovery applications written within the Modular Science Framework and finds that the National Aeronautics and Space Administration has forcing and parameterizations that he can adapt for his study in the Gulf of Maine.

A decade ago he would have run the simulation on his local computer cluster, after writing custom scripts to download additional forcing data he identified from various FTP sites, data portals, and Web services. Now he simply selects components and parameters in a cloud-based environment used by the entire geosciences modeling community. Metadata are generated automatically for John's new workflow, including his model configuration parameters and quality information, indicating that this is an experimental product that has not been validated. John then publishes his new data and workflow to a repository within the Modular Science Framework.

Subsequently, Amy, a researcher from Boston University studying contaminated sediment in Boston Harbor, is notified that new model data meeting criteria she has specified are available from John's work. She uses his workflow with standardized components to interpolate the gridded model results for comparison with sediment profiles she has collected, with model output to her preferred spreadsheet. She finds that John's experimental model product matches her data better than any previously available simulation and adds this information to the metadata associated with John's dataset. Through a "subscription" to the Modular Science Framework, John is notified of Amy's use and change to the dataset and then uses her profile data to help quality control his final published model data product. While John is writing his scientific paper on harmful algal blooms, a Coastal and Marine Spatial Planning team in Maine uses bottom stress data from the model to help locate sites for submerged aquatic vegetation restoration.

A decade ago, John spent most of his time on routine tasks to produce data that were used almost exclusively by himself and his immediate colleagues. Now, based on the innovative data and tools provided by the Modular Science Framework, he spends less of his time on routine tasks and has substantially increased his scientific output while contributing to the efficiency of other scientific work.

Highlight

Objective 2.2: Research and Develop Technological Services that Support Advanced Research, Data Analysis, Visualization, and Information Processing

Scientific data search, access, analysis and visualization tools and techniques have become critically important for the execution of science. To lead integrated studies of Earth systems, the USGS must ensure that software tools and techniques are state-of-the-art, interface smoothly with infrastructure developed by various science communities, and are fully accessible to USGS scientists. In addition to speeding development and ultimate performance of software, the USGS can drastically improve the capacity for individual researchers to pursue science at a scale that has not been previously accessible to them. In addition to reducing time needed to conduct an analysis, visualize data, or develop a simulation model, applying software engineering rigor to the development of scientific software such as models, visualization systems, and analysis tools will improve sustainability and adaptability of scientific software. Synthesis across the Modular Science Framework will depend on the ability to integrate data and information among modules. The core sciences discussed in Goal 1 will provide an important aspect of contextualization in the geologic, topographic, and biogeographic framework. Comprehensive data integration services for the Modular Science Framework will depend on capturing and modeling data semantics or meaning across the breadth of information represented in the modules (Berners-Lee and others, 2002).

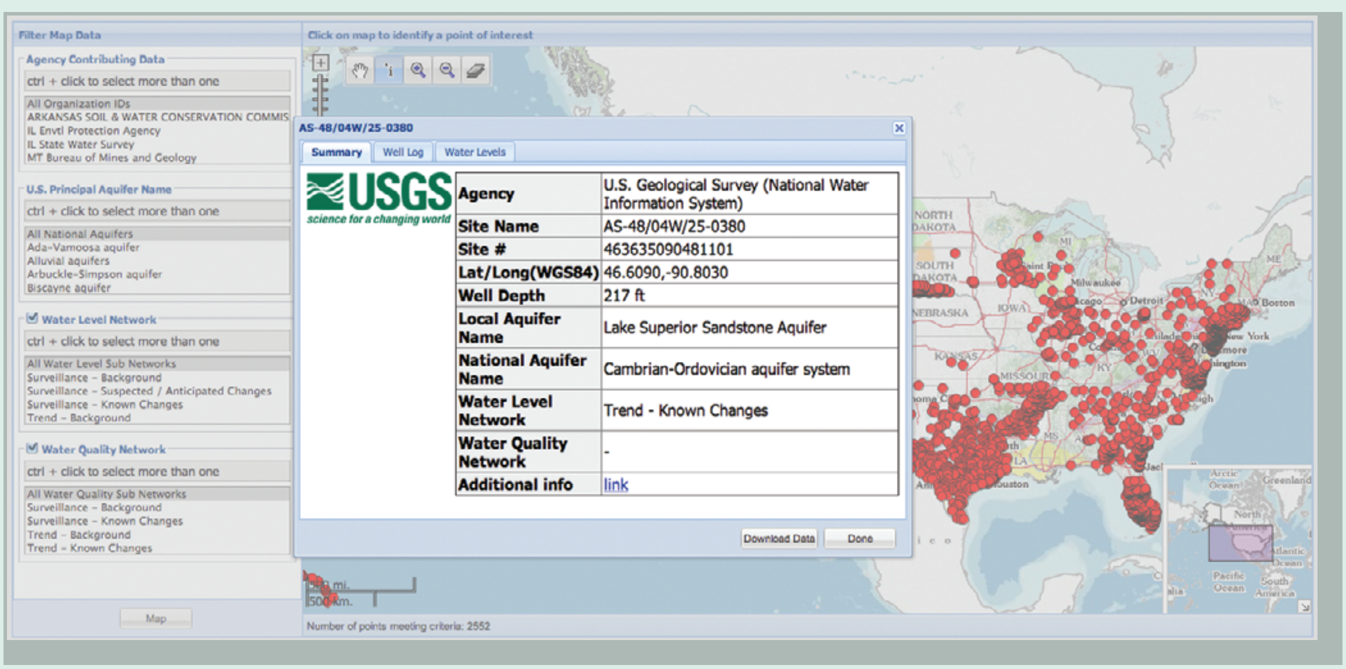
The following list of actions provides a broad view of the type of computer and information science work needed to advance the Modular Science Framework. Far more detailed research and development are required than may be articulated in this report or conducted in the USGS. Though often not considered within traditional views of the USGS scientific portfolio, it is vital for the Core Science Systems mission to lead in developing informatics as a research discipline. This will enable the USGS to participate in and take advantage of the tremendous pace of this research from academic and commercial sectors along with other government agencies.

Strategic Actions

1. Capture the knowledge of how data layers interact into services that describe how to negotiate interrelations between data themes for models and other analyses that explore pathways (for instance, contaminant pathways).
2. Enhance and publish methods of producing scientific software that facilitates repeatability of results to transfer application to other situations (also known as scientific workflows).
3. Exploit and further develop simulation modeling frameworks and other methods of coupling to explore how different Earth processes can be analyzed in novel combinations to address more complex Earth science questions.
4. Conduct research into methods and techniques for embedding data quality metrics and uncertainty information within derived and processed data at a sufficient level to aid in usage and application selection through automated and human-assisted means.
5. Develop a technological and methodological framework for incorporation of observations of physical and biological phenomena from public data networks.
6. Design and improve scientific computing systems, such as modeling frameworks, to allow computationally intensive operations to run through state-of-the-art technology platforms, from cloud-based resources to high-performance computing centers.
7. Conduct research into the development of ontologies specific to the fields of Earth systems science conducted by the USGS to aid in the interrogation of data assets and integration of disparate resources.
8. Conduct research into methods and techniques for monitoring data usage across disparate ways that data are accessed to facilitate comprehensive analyses of data use in distributed networks.

Highlight

As part of its role of providing leadership to communities of which the USGS is a part, there are important opportunities to coordinate federation of data networks of partner organizations into common, nationally consistent networks. The National Groundwater Monitoring Network is complementary to *The National Map* vision of a seamless data product comprising individual State and local contributions. To create this federation of State groundwater monitoring networks of water quantity and quality, the USGS has developed a portal to pull these data together in real time and mediate local formats so content is expressed according to international standards and terminology. This portal allows users to interact with the disparate State networks as though they were a single information system to evaluate historical and current conditions of the Nation's groundwater resources. This interaction enables analysis across a range of external data resources that would not be easily completed without the network. Additional examples in the USGS that demonstrate capacity to produce a seamless experience with all manner of data should form critical building blocks for the Modular Science Framework.



Objective 2.3: Design and Implement a Robust Suite of Professional Services to Aid in Implementation and Use of the Modular Science Framework

The Core Science Systems mission includes responsibilities for scientific data and information management, curation, archiving, preservation, and long term availability. This mission is evident across the spectrum of direct data holdings of geologic maps, topographic maps, biogeographic maps, and supporting data systems that make up the core of the Modular Science Framework. The USGS Library has been steadily growing from a physical resource of paper holdings, public spaces, and their curation to include a digital library at its core, which is part of an evolution in library systems around the world toward more holistic agents for information literacy (Bruce and Lampson, 2002). To continue to provide national historic resources to the Nation, the unique and irreplaceable physical collections in the USGS should continue to be preserved and maintained, while developing ways that researchers can leverage these resources using digital means. The arrows in the Modular Science Framework conceptual model (fig. 6) represent areas where technological and professional services are needed for efficient, timely, and robust interactions within the framework to occur. Coordination across the spectrum of data management responsibilities in the Core Science Systems mission and throughout the USGS can result in a powerful suite of professional services performing a critical core function in USGS research.

The ongoing development and growth of the Modular Science Framework is dependent on methods to continually test its effectiveness and impact on research across the USGS and its mission responsibilities to provide unbiased scientific information to the Nation. Effectiveness monitoring and regular adjustment to science and technology priorities needs to be an integral aspect of the Modular Science Framework. Testing and monitoring of the framework can take advantage of a number of different technologies and methods, but it is more than simply analyzing logs summarizing the usage of various technological systems. Effectiveness analysis should incorporate methods from social science and other nontraditional fields to define and conduct tests on the intended and actual application of the digital knowledge services shown in the conceptual model for the Modular Science Framework (fig. 6).

The number of tools and approaches has become overwhelming for many researchers. There is an increasing need for the USGS to provide support to the individual researcher in understanding, selecting, and applying the many software engineering, technology, and computer science options available.

Strategic Actions

1. Evolve a community of practice capacity to directly answer simple and complex scientific technology challenges posed by research teams across the USGS, creating a knowledge base of specific solutions and methods and supporting interactive sharing of ideas and methods between different parts of the organization.

2. Combine traditional library catalog holdings with a robust and comprehensive catalog of digital knowledge.

3. Initiate services in data analytics, the process of systematically analyzing increasingly complex and large data-sets to identify new patterns and suggest hypotheses, in cooperation with scientists from across the USGS to explore new syntheses.

4. Promote citizen science monitoring and mapping networks and protocols with development of technologies

National Phenology Network

The USGS partners with other agencies, nonprofit organizations, citizen scientists, educators, and students in the USA National Phenology Network (USA National Phenology Network, 2012). Phenology tracks recurring plant and animal life cycles such as the timing of plant leafing, flowering, and bird migration. Volunteers not only track and report changes in plants and animals but also help digitize handwritten Migration Observer Cards containing observations on bird migration from the late 19th century to the 1950s. National Phenology Network volunteers provide current and historical data that document the effects of climate change on flora and fauna. Jack Meixner, a rancher in central Texas, observes and reports phenology of juniper trees (*Juniperus* spp.) as part of a USA National Phenology Network regional campaign to understand and forecast production of juniper pollen for human health applications.

Highlight

and methods through specialists in the USGS and with partner organizations.

5. Participate in the development and engineering of global scientific cyberinfrastructure through general international standards bodies such as the Open Geospatial Consortium and the International Organization for Standardization, as well as national and discipline-specific organizations such as the U.S. Geoscience Information Network, the Data Observation Network for Earth, the National Ecological Observatory Network, and the National Science Foundation EarthCube initiative.

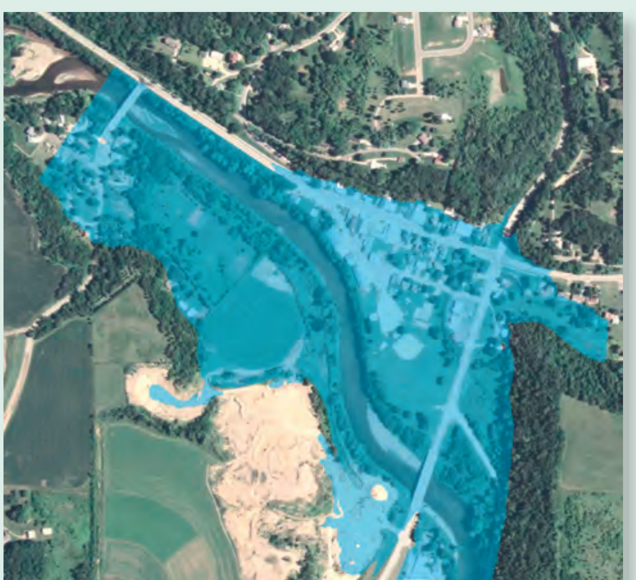
USGS Community for Data Integration (*http://goo.gl/855cU*) Photograph by Ricardo McClees-Funinan, USGS.

Goal 3: Conduct Scientific Analysis and Synthesis to Improve Coverage, Scientific Quality, Usability, and Timeliness of Information

Highlight

Flood Inundation Mapping

The evolution of technology and science to display flood inundation maps based upon USGS streamgaging real-time readings has revealed a myriad of opportunities for conveying how a significant hydrologic event can impact citizens' lives, the economy, and the ecosystem within the watershed. New techniques of merging hydrologic information with Hazus social and economic data from Federal Emergency Management Agency (FEMA) allows for unique scenarios of impacts based upon each incremental reading of the USGS streamgage—allowing emergency managers to know what the potential impacts could be before the first raindrop falls.



Pursue broad Earth science challenges that synthesize digital knowledge across multiple scientific disciplines.

> "We are drowning in information, while starving for wisdom. The world henceforth will be run by synthesizers, people able to put together the right information at the right time, think critically about it, and make important choices wisely." (Wilson, 1999)

The Modular Science Framework is a key to the Core Science Systems mission. It will help drive scientific synthesis by organizing massive quantities of information to facilitate understanding the operation of the entire Earth system. For the purpose of this report, synthesis is defined broadly, from applications that generate new science products by integrating and merging traditional data products to highly sophisticated data-driven science that employs high-speed computers to generate interdisciplinary syntheses and hypotheses. Synthesis exploration may range from a simple mashup, a term used broadly to describe combinations of two or more information sources to create something new, to the refined creation of an entirely new and seamlessly integrated product. One of the most vital contributions the USGS brings to the increasing amount of government, academic, and industry scientific data available for syntheses is a long history of scientific excellence, critical review, and standards for accuracy. While synthesis may begin with either a working hypothesis or a broad ranging exploration of compatible data assets, it must ultimately be grounded in the scientific method to produce results meaningful to science and societal challenges.

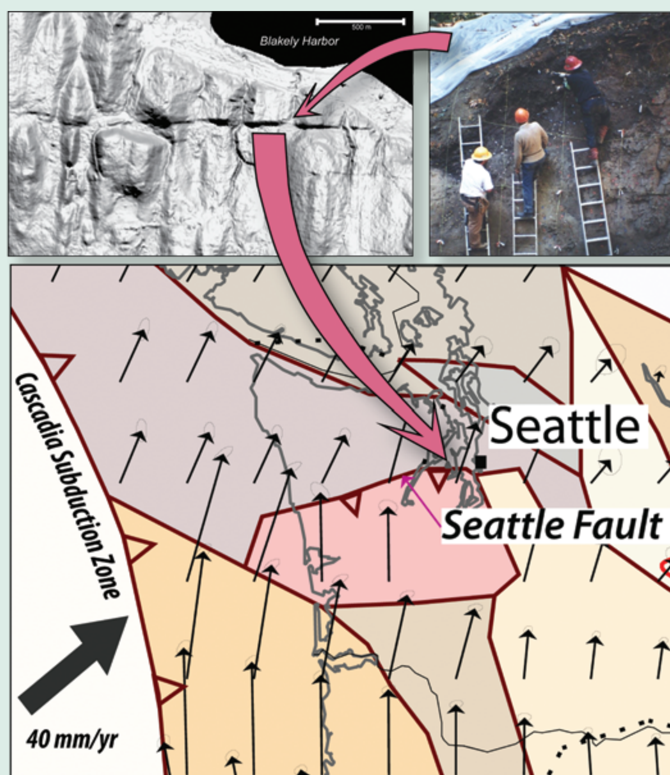
Systematic research aided by the Modular Science Framework will produce visualization tools needed to understand key physical and ecological processes to help identify solutions to complex problems facing society at scales ranging from site specific to landscape. Synthesis provides effective ways to examine what and why questions using new digital techniques not possible with traditional approaches and computing platforms common in the 20th century. As science evolves toward what is often referred to as a fourth paradigm, data-intensive scientific discovery (Hey and others, 2009), virtual floods of data records will be concentrated into more specialized modules. Increased scale and complexity of information will require greater computational capacity and interactions between scientists, resource managers, citizens, and many others to effectively integrate science for relevance to future societal needs.

Studies of the Earth provide the foundation for understanding most geologic, hydrologic, and biologic processes of societal significance. Integrating these components in a whole Earth systems approach requires new geospatial science research, developing higher resolution datasets such as elevation and land cover, more efficient field data acquisition, and new instrumentation and processing methods for remote sensing and other techniques. It also involves developing new scientific technology platforms, from laboratory microanalytical techniques for investigating processes on a microscopic scale to global observation networks. These approaches offer prospects for enhancing the ability to understand the Earth and how it functions. Global change will require an increased emphasis on understanding linkages among bedrock, soil, topography, hydrology, biological systems, oceans, and the atmosphere. Scientific computational technology and the ability to portray and analyze data in four dimensions will accelerate the pace of scientific discovery and understanding in the coming decade. As the pace of new interdisciplinary methods and techniques accelerates, capturing the scientific workflow in a way that can be used to repeat results, develop methods, and make connections between scientists and across disciplines will become increasingly important.

A fundamental understanding of the Earth system across the spectrum of the full vertical ecosystem as described by Bailey (1996) is vital to improving understanding of energy, mineral, soil, water, and biological resources, as well as effects of climate change, where and when hazards will occur, and the sustainability of life itself. Processes that form soils and topography influence the Critical Zone, and an understanding of how geologic and geomorphic structures affect the availability and quality of water resources, along with societal decisions that influence most hydrologic processes, must be applied to science questions arising across all USGS missions. Processes that determine where habitats arise and are sustained and the

Cascadia Subduction Zone

Insights into active faults above the Cascadia subduction zone from integrated study.—Integration of datasets from diverse sources has yielded fresh insights into the Cascadia subduction zone. Oblique underthrusting of the Juan de Fuca plate beneath North America contributes to northward motion of crustal blocks along the Cascadia zone. These motions, modeled from plate tectonic theory, have been documented by recent Global Positioning Satellite (GPS) results (black arrows) from an NSF consortium. USGS scientists have used lidar topography to reveal precise locations for surface-rupturing, active faults along the block boundaries, which were previously demarcated by poorly defined boundaries on geologic and geophysical maps created by USGS and its partners in the National Cooperative Geologic Mapping Program. On Bainbridge Island, the Seattle Fault breaks the surface (left image), providing a location to trench the fault and document a history of several large earthquakes during the past 2000 years (right image). Similar work is underway to investigate suspected active faults in the Puget-Willamette Urban Corridor revealed by lidar; more than 20 active faults have been documented. Modeling is underway to test the hypothesis that the rupture history of the block-boundary faults may be related to the history of great subduction zone earthquakes on the Cascadia subduction zone.



Highlight

occurrence and movement of biological species are critical to understanding and predicting where change will occur under different scenarios. Likewise, processes that determine patterns of human settlement through time often are related to how societies are affected by hazards and climate change and how human actions affect ecosystems. Understanding the connections between human actions and the Earth system is critical because decisionmakers consider the effects of management actions on natural and human systems.

The Modular Science Framework serves an important function in helping identify gaps within the vertical structure of the modules and critical missing knowledge vital to making connections between modules and underlying data resources. Examination of the Modular Science Framework and concentrating on synthesis possibilities can help identify opportunities for collaboration across the USGS and with partners from other science and resource management agencies. Examination of the full breadth of information available through the Modular Science Framework may lead to the formulation of entirely new hypotheses about the nature of Earth systems or interactions between ecosystem components. For example, *The National Map* might be examined in relation to other available information within the Modular Science Framework to evaluate a new hypothesis that may enhance its value, such as asking why specific patterns of vegetation show up in certain geographic locations—could variations in space or time be isolated from the data and examined for existence of vegetation patterns under past or future conditions? Information from modules of the Modular Science Framework such as hydrosphere, hydrologic landscapes, weather, and geochemical information might be used in sophisticated analyses to evaluate the hypothesis while contributing to knowledge of how climate and land-use impacts may affect other resources characterized through *The National Map*. As an evolving framework for scientific synthesis, the Modular Science Framework will improve the capacity of the USGS to conduct whole systems research needed to better inform the diverse decisionmaking community.

Objective 3.1: Accelerate Use of Data-Driven Science for New Synthesis Products and to Identify New Hypotheses of the Earth System

One of the primary purposes of the Modular Science Framework is to organize and bring together an ever growing suite of digital knowledge in a way that suggests opportunities for analysis and synthesis. Deliberate focus on gaps in the Modular Science Framework is necessary to identify constraints on the ability to properly frame and develop solutions

Highlight

Cottonwood Lake Study Area (CLSA)

The CLSA is perhaps the oldest example of integrated ecological science in the USGS. Located in the northern prairies, work at the site began in 1967 by a U.S. Fish and Wildlife Service (USFWS) laboratory that later became a USGS facility with the formation of the Biological Resources Discipline. Initial work focused on the relations among waterfowl and wetlands but shifted in 1979 to an integrated effort between USFWS ecologists and USGS hydrologists. Over time, the effort grew as the need for new integrated studies in chemistry and geology were identified. Today, CLSA is aimed to improve understanding of complex ecological relationships through integrated studies by biologists, hydrologists, geochemists, and others within USGS. Studies at the site have formed much of the basis for current understanding of wetland ecology in the United States and elsewhere. During its 43-year history, CLSA has also attracted many scientists from universities and other Federal agencies (for example, USFWS, Bureau of Reclamation, and U.S. Army Corps of Engineers) that conducted multidisciplinary or interdisciplinary investigations. This important work is the result of an entirely grass-roots effort in which scientists came together through mutual scientific interests; this has been the primary factor contributing to the success of this important scientific work (U.S. Geological Survey, 2012d). The journal, Wetlands, published a commemorative issue that recognized 30 of the papers published over the past 3 decades that had the greatest impact on wetland science (Society of Wetland Scientists, 2012). Three of the papers (Euliss and others, 2004, 2008; Winter and Rosenberry, 1995) were from research conducted at CLSA by USGS scientists.

to problems affecting society and enhance collaboration for consistent maximized beneficial use in scientific synthesis. Figure 5 illustrates synthesis products that have developed inductively through hypothesis-driven scientific research incidental to the existence of the framework (Hydrologic Landscapes) along with products that were developed through deliberate focus on synthesizing multidisciplinary information (*The National Map*). Science projects in the USGS that are focused on a particular problem or geographic area often produce new synthesized data products, methods of processing and presenting data, and suggested enhancements to national data assets that might prove scalable and applicable to many other areas. To build these ideas into new national data assets, research must be conducted to determine suitability of the concepts and methods for larger scales, and development resources must be applied to either enhance an existing data system or establish something new. Although not all good ideas for new major data assets are achievable, the USGS could substantially increase its portfolio of high-quality scientific data by creating opportunities and a venue for science teams to propose such products. In addition, the existence of the Modular Science Framework and continual growth of data available for computational analysis can open new avenues for data-driven or inductive research, complementary to synthesis exploration initiated with hypotheses (Kell and Oliver, 2004).

Synthesis Scenarios

A researcher within the Climate and Land Use Change mission area of USGS has just processed and performed quality assurance on a year's worth of environmental monitoring data from a distributed network of on-the-ground sensors. Using software tools developed for the Modular Science Framework, she automatically populates database attributes that describe the physical setting of each sensor location. These attributes are pulled from an automated query of the data contained in *The National Map* and the National Geologic Map Database, and the sensor site attributes include information such as elevation and derived terrain descriptors (slope and aspect), land cover type, landscape position, soil type, bedrock unit, closest stream, watershed (hydrologic unit code), and closest road. Now that the fully attributed observational data have been posted to a Web service for public distribution, they are linked to other monitoring datasets contained in the observation registry so that users querying one monitoring network's data are also notified of other available sampling data in their region of interest. This functionality was implemented based on informatics research on spatial and temporal linking of heterogeneous, distributed databases.

A research ecologist is investigating the effects of land-use change, recreational use, and water quality degradation on the habitat of a species of concern on a National Wildlife Refuge. As she begins her investigations, she is able to access data that tell the complete story of the area of interest: historical photographs; archived data covering a long period of record; satellite imagery at multiple points in time; studies of the biota; surveys of public opinion about what is valued on the refuge; longitudinal data from the National Survey of Fishing, Hunting, and Wildlife-Associated Recreation; records that document the establishment of the refuge; planning documents; studies of water quality. These information resources can be accessed on a tablet computer in the field and are organized to present the most relevant information based on exact location and context.

Highlight

Strategic Actions

1. Develop methods and techniques to anchor scientific data across all Earth systems studies to core science data (for example, anchoring all water measurement data to the National Hydrography Dataset).
2. Research and develop methods for a comprehensive virtual observatory containing relevant observations of physical and biological phenomena important to USGS research, including plant and animal species occurrence and human structures of importance to hazards characterization and risk assessment.
3. Monitor emerging issues of societal concern in a systematic and focused way and develop new synthesis products for visualizing or summarizing issues in the context of space and time.
4. Produce digital thematic products through synthesis, interpretations, and maps that include geologic and biologic scenarios, simulations, and predictive models relevant to ecosystem change and health, groundwater flow, resource assessment, carbon sequestration, and potential hazards.
5. Evaluate spatial and temporal impacts of human activities on the Earth system by merging social and economic data with Earth process data using novel approaches to provide more robust knowledge to decisionmakers, scientists, and the public.
6. Promote use of high-speed computers and advanced methods in semantics and other data-driven techniques to quantify linkages in digital knowledge to properly frame ecological processes in space and time and uncover interdisciplinary hypotheses useful for developing solutions to complicated cross-cutting problems affecting the Nation.
7. Support development of novel scenario evaluation tools for asking and answering applied science questions in collaboration with resource managers.

Objective 3.2: Develop a Workplace Model for Interdisciplinary Science

> "When you are a mature scientist or becoming a mature scientist, the most important attribute is to identify the problem that needs to be solved and then apply whatever tools are needed. That is not a very easy thing to do. First, the hardest thing is to identify the problems that need to be solved. Secondly, how do you train people to use these tools? I don't look at science as compartmentalized. I look at it as a wonderful tool set." (William A. Haseltine, from Brint and others, 2009)

This model has had an incredible impact throughout the history of science. "It took an ex-physicist—Francis Crick—and a former ornithology student—James Watson—to crack

Highlight

Synthesis Centers

The John Wesley Powell Center for Earth System Analysis and Synthesis (U.S. Geological Survey, 2012a) was established as a USGS Earth system science 'think tank'. Its goal is to develop new and innovative approaches that apply scientific understanding to resolve significant and complex issues. Synthesis projects derive from scientist proposals, where researchers on the cutting edge of their fields determine needs and assemble the best teams to combine knowledge and data. The Powell Center has launched 15 Working Groups that consist of teams that cross disciplines and organizations. With a dedication to producing and publishing newly synthesized data for the larger scientific community and decisionmakers, the Powell Center serves as a prototype for integrating science in the USGS.

The creation of the National Water Center, in Tuscaloosa, Alabama, is an example of a brick and mortar approach to facilitating integrated research and science operations. At this Center, scientists from the National Weather Service, USGS, and U.S. Army Corps of Engineers will collaborate to create new scientific approaches and merge operational systems to create the ability to forecast hydrologic conditions from the summit to the sea.

The National Water Center is located on the University of Alabama Campus in Tuscaloosa, Alabama. A groundbreaking ceremony was held for the 65,000-square-foot building on February 21, 2012. A 200-member staff is expected to occupy the center in June 2013.

the secret of life. They shared a certain wanderlust, an indifference to boundaries." (Robert Wright, 1999).

> "We are not students of some subject matter, but students of problems. And problems may cut right across the borders of any subject matter or discipline." (Popper, 1963).

The central role of the Modular Science Framework to the Core Science mission and to the entire USGS is that it permits us to incorporate the indifference to disciplinary boundaries valued by Watson and Crick, the interdisciplinary problem solving philosophy recognized by Popper, and accommodate the need for discovery of diverse tools by developing scientists recognized by Haseltine. The Modular Science Framework organizes USGS science, including knowledge, data, tools, technology and other aspects of scientific discovery into a common framework that depicts the intricate relations among them under a single auspice, just as they occur in nature. There is no single module that is more important than another because all are essential to Critical Zone functions. All the scientific components within each module of the Modular Science Framework, including humans, are also all essential disciplinary components that must work together to develop lasting solutions to modern problems. To meet this challenge, a cultural change within the scientific community will be required that is without historic precedent.

Strategic Actions

1. Develop funding models that reward interdisciplinary science proposals that transcend discipline and mission area boundaries, including a competitive grants process.
2. Reduce cultural and spatial barriers to interdisciplinary research, such as creating virtual laboratories and collaborative offices, linking field scientists directly to the Modular Science Framework, and relocating scientists to high-level collaborative centers, such as the Powell Center or the National Water Center (refer to "Synthesis Centers" highlight).
3. Continually study the USGS and conduct comparative analyses with other organizations to identify best practices and approaches to interdisciplinary science.
4. Promote and facilitate employee involvement with communities of practice (Wenger, 1998) such as the Community for Data Integration (Community for Data Integration, 2012) to create more opportunities for collaborative learning and advancement of science.
5. Collaborate with organizations that conduct and support research of social and ecological systems to better inform decisionmaking for coupled human and natural systems.
6. Embrace the development of more reimbursable opportunities at high levels to facilitate accountability in collaborative partnerships with governmental organizations.

Conclusion

The rapid expansion of humanity across the Earth and an increasing environmental footprint lead to growing challenges for which the USGS can help understand and inform through research and characterization of complex Earth system processes. The Core Science Systems vision for a Modular Science Framework, based on research of ecosystem processes sustaining the Critical Zone, will accelerate the movement in the global scientific community toward the Digital Earth and an ability to address societal challenges in interactions with the Earth. This science strategy plan has outlined three goals along with specific actions to achieve the Modular Science Framework vision. First, conduct research to produce timely, nationwide, seamless, authoritative, open-access digital knowledge for ecosystem processes sustaining the Critical Zone from the geologic framework to land surface characteristics and biological diversity. Second, improve the application and impact of USGS research products through development and testing of services, software, tools, and participatory frameworks that build and apply the Modular Science Framework. Third, pursue broad Earth science challenges that synthesize digital knowledge across scientific disciplines through systematic examination of the Modular Science Framework, taking the necessary steps to develop cultural norms that enable scientific synthesis.

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