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Tools for a Rapid Assessment of Carbon Accumulation and Storage in USACE Civil Works Terrestrial and Aquatic Holdings

Aerial view of Hancock Brook Lake, tributary of Naugatuck River in Plymouth, Connecticut.

USACE CLIMATE PREPAREDNESS AND RESILIENCE

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14. ABSTRACT
This report describes the tools created and now deployed by USACE for rapid assessments of carbon accumulation and storage at USACE Civil Works terrestrial and aquatic holdings. The report includes discussion of data sources and utility, methods, and suggested means for improving estimates of carbon accumulation and storage rates, and changes in those rates, from large-scale landscape disturbances including fires and floods.

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Executive Summary

The U.S. Army Corps of Engineers (USACE) is the oldest and largest manager of water resources in the U.S. The USACE Climate Preparedness and Resilience program supports the development and deployment of data, model outputs, and tools for analysis to inform decisions about adapting those resources to climate threats to USACE projects, programs, operations, and missions, as well as mitigating the sources of those threats. A key aspect of this program is the integration of climate adaptation measures (reducing vulnerabilities and managing current and projected future climate impacts to water resources) with work on climate mitigation [reducing emissions and the atmospheric concentration of greenhouse gases (GHG)] to ensure that programs at the USACE can be efficient and effective in both approaches.

This project, Tools for a Rapid Assessment of Carbon Accumulation and Storage in USACE Civil Works Terrestrial and Aquatic Holdings, produced a suite of tools using data from multiple sources to assess the existing stock and accumulation rates of carbon in USACE-owned and -managed properties. In addition, this work also piloted an approach for considering variation in carbon storage from coarse-scale disturbances like floods and fires on the landscape. The data and tools developed for this study provide rapid, quantitative, screening-level estimates of existing carbon storage and accumulation rates. However, because this is a screening-level project, no new data on local-scale accumulation rates and storage amounts were generated, and those data are missing across large sections of the U.S. USACE is pursuing refinements in the data and the analytic approach developed here, subject to future funding and other resource constraints.

The database and associated tools are available to USACE staff online at the Carbon Storage Information Portal. This report describes development of the Carbon Storage Information Portal and the data, methods, and assumptions of this work in an overview of the portal.

These first estimates of carbon storage are necessarily rudimentary, based as they are on existing data and the statistical relationships used here to extrapolate to areas without relevant data. These are baseline estimates from which any ecological, vegetation, management, or sedimentation changes can be compared to quantify trajectories or to model potential future scenarios. One notable gap identified during this project was the lack of geospatial boundary information for all projects. A separate effort was undertaken to produce these boundaries, which supports improvements to these estimates as well as a number of other USACE efforts.

The chief product of this project is a set of estimates across the contiguous U.S. of the current storage and rates of accumulation of carbon already in place. This does not support estimates of the potential for new atmospheric carbon to be permanently sequestered. However, the estimates reported here will be the basis for computing the potential for sequestering atmospheric carbon in the future, since the current storage of carbon and rate of accumulation will in part determine the limit of that potential to sequester new carbon. These estimates deal only with current carbon stocks and rates, and as such do not support decisions at this time about operational changes to the lands and waters USACE owns or manages for the nation to enhance future sequestration. Additional planned work is directed toward improving our knowledge to eventually support these types of decisions.

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Background

Carbon sequestration, or the isolation of carbon from the atmosphere through permanent burial or other means, is a natural process on lands and waters, including those owned or managed by the U.S. Army Corps of Engineers (USACE), the nation's oldest and largest manager of water resources. Water-resource systems are important for carbon sequestration because reservoir sediments are among the most active carbon sequestration sites on Earth [*Dean and Gorham*, 1998; *Downing et al.*, 2008]. This Rapid Assessment of Carbon Accumulation and Storage on USACE Civil Works Terrestrial and Aquatic Holdings project collected data from disparate sources and produced a suite of tools to help assess future potentials for aquatic and terrestrial carbon sequestration. In addition, an approach for considering possible changes in those potentials from coarse-scale disturbances was investigated. The data and tools developed for this study provide rapid, quantitative, screening-level estimates of existing carbon stocks and rates of accumulation.

This project provides a rapid assessment of carbon stocks and accumulation rates in lands and waters on USACE Civil Works sites, including reservoirs, other impoundments, wetlands, and associated terrestrial ecosystems adjacent to water bodies owned or managed by USACE within the conterminous United States.

The work here estimated carbon storage for aquatic and terrestrial systems. Aquatic carbon storage was calculated from statistical techniques and empirical relationships identified with data from a subset of model calibration locations, then extrapolated to other USACE waters for which estimates are absent. USACE property terrestrial carbon storage data were extracted from existing above-ground land cover, calculated net primary production (NPP), and soil carbon datasets. No new base-level information was created for this screening-level project, and through this work we have identified substantial data gaps in areas across the U.S.

Pilot studies were used to estimate accumulation and storage terms within USACE project boundaries; new methods were developed to account for the differences in land cover types and areal extents that can strongly affect accumulation and storage estimates. A database of USACE lands and waters and associated geospatial information was developed which is the basis for extrapolating existing accumulation and storage estimates from the pilot study projects to similar lands and waters nationwide.

Aquatic and terrestrial accumulation and storage amounts and potentials were estimated using databases and geospatial data sets, as described in the following sections. The estimates were combined in a geographic information system (GIS) product to provide carbon estimates of carbon accumulation and storage for 590 USACE reservoir project sites totaling 18,603 square kilometers (7183 square miles) of land and water surface area. In addition, long-term satellite datasets were used to identify trends in net primary productivity and vegetation (taking into account changes such as wildfire, die-offs, vegetation conversion, and urban development) on USACE project lands in order to understand the rate at which terrestrial carbon accumulation rates may be changed by these disturbances.

Aquatic Carbon Accumulation and Storage in Reservoirs

Organic and inorganic carbon accumulates in reservoirs primarily by two processes; see Figure 1. First, carbon is transported to the water body by streamflow as either dissolved [dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC)] or particulate matter [particulate organic carbon (POC) and particulate inorganic carbon (PIC)]. Second, carbon is derived from biological activity in the water column (autochthonous carbon).

Once in the reservoir, carbon as carbon dioxide (CO2) and methane (CH4) can evolve directly to the atmosphere, be consumed by biological processes, or depart in outflow. Alternatively, carbon in reservoir waters can be deposited to the lake or river bed as organic particles, as organic matter adsorbed onto sediment particles, or as inorganic carbon. Anoxic bottom waters or rapid sedimentation can bury this carbon.

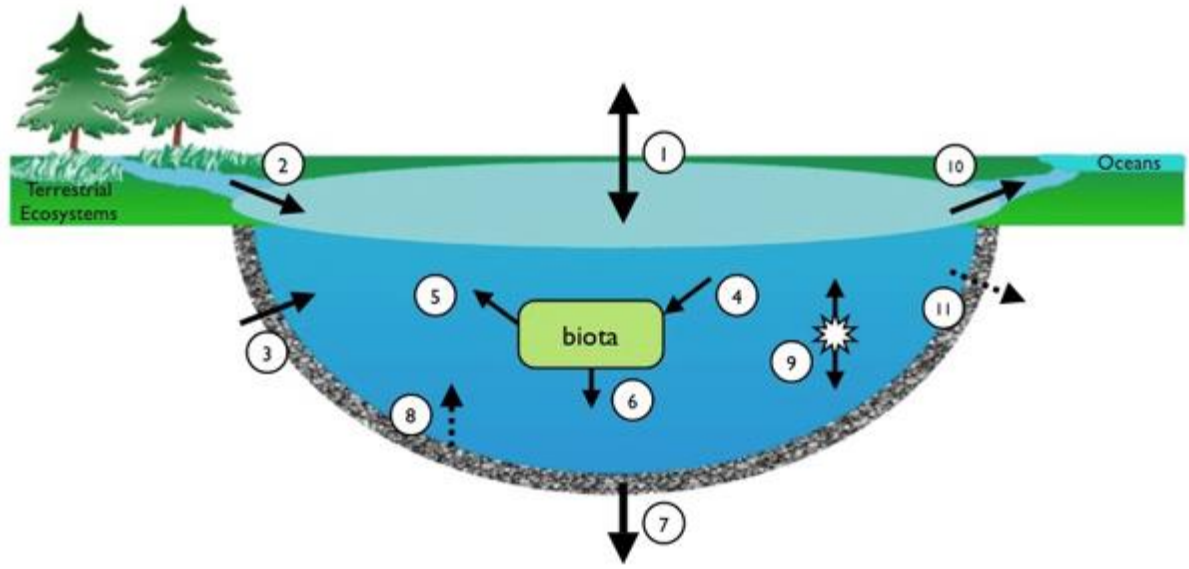

Figure 1 - Major carbon fluxes in reservoirs [*USGS*, 2012].

Major carbon fluxes in lakes and reservoirs: (1) air-water gas (CO_2 and CH_4) exchange, (2) surface water inflow plus atmospheric C inputs, (3) groundwater seepage (4) phytosynthetic uptake of dissolved inorganic carbon, (5) respiration, (6) settling of particulate organic carbon, (7) sediment C burial, (8) methane evasion, (9) calcification (biotic and abiotic), (10) tributary outflows, and (11) groundwater outflows.

The predominant type of terrestrial carbon transported to a reservoir varies with watershed climate, area, soil texture, soil biogeochemistry, and land cover. In temperate forests and in boreal biome regions underlain by carbonate terrain, the dominant form of aquatic carbon is DIC, resulting from high soil respiration, carbonate weathering, and groundwater flow [*Tranvik et al.*, 2009]. DOC dominates in the humid tropics and noncarbonate boreal forest [*Tranvik et al.*,

2009]. Biological production, respiration, and deposition within reservoirs are functions of lake size, latitude, insolation, and nutrient availability

[*Tranvik et al.*, 2009]. Surrounding land use in particular can influence biological productivity in reservoirs, as documented in heavily farmed watersheds with high nutrient/fertilizer runoff [*Mulholland and Elwood*, 1982].

Reservoir carbon accumulation rates and stock carbon totals can be estimated based on watershed size and reservoir surface area [*Downing et al.*, 2008] where: watershed size is a proxy for sediment amount and therefore carbon transported to a reservoir from runoff and stream flow; and reservoir surface area is a proxy for the reservoir's biological productivity.

Downing et al. [2008] noted that both the rate of sediment burial and the sediment organic carbon vary systematically with surface area and watershed area. They used these relationships to estimate rates of organic carbon burial in both small eutrophic agricultural impoundments and large reservoirs.

Downing et al. [2008] also noted that the relationship between watershed size and sediment delivery is not uniform, varying regionally with geomorphic history and topography. These differences arise because of differences in conveyance losses, slope, channel gradients, opportunities for deposition, and the fraction of a watershed affected by a given precipitation event, which is likely to be a smaller fraction of the whole watershed in large watersheds. Regional climate is also likely to influence sedimentation rate and organic carbon fraction via such factors as land use, land cover, and soils. For these reasons, carbon accumulation rates vary strongly by region.

Methods

Estimating Aquatic Carbon Accumulation and Storage in USACE Reservoirs

This assessment of carbon accumulation and storage in USACE reservoirs is based on reservoir surface area, watershed area, and neighboring watershed land use and land cover (LULC). Relationships among these variables are determined at a watershed or sub-division level using the data sources and combinatorial methods discussed below.

Data Sources for Estimating Aquatic Reservoir Sedimentation Rates

Three data sources were used to estimate sedimentation rates in USACE reservoirs:

- The Reservoir Sedimentation Database (RESSED)
- The National Inventory of Dams (NID)
- The National Land Cover Database (NLCD)

The national **Reservoir Sedimentation Database (RESSED)** is the primary data source used to estimate sedimentation rates in reservoirs for this project [*Gray et al.*, 2010]. RESSED is maintained for participating agencies of the Advisory Committee on Water Information's (ACWI) Subcommittee on Sedimentation by the U.S. Geological Survey (USGS), and can be accessed online at http://water.usgs.gov/osw/ressed/ (current as of 9 November 2015). The database contains sediment survey data and information for 1,823 reservoirs nationwide taken

from more than 6,617 surveys conducted between 1755 and 1997 (most surveys in RESSED were conducted between 1930 and 1990) [*Ackerman et al.*, 2009]. No reservoirs from Florida, Vermont, Rhode Island, or Delaware are included in RESSED [*Ackerman et al.*, 2009]. These surveys varied across space and time in quality and method, and in more recent years include data from remote sensing methods [*Gray et al.*, 2010].

This analysis used a subset of data from RESSED consisting of 2,915 surveys from 1,418 impoundments. Reservoirs were excluded from this subset if they were replicates, did not quantify changes in sediment volume between surveys, or were small ponds (<10,000 m^2 surface area). A related project has collected updated information on sediment conditions at USACE projects in a Reservoir Sediment Information Portal. This updated reservoir sediment information will be used in the next update to this suite of tools to estimate carbon accumulation and storage.

The second key database used in this analysis was the **National Inventory of Dams (NID)** (http://www.agc.army.mil/Media/FactSheets/FactSheetArticleView/tabid/11913/Article/480923/national-inventory-of-dams.aspx and http://nid.usace.army.mil/cm_apex/f?p=838:12, current as of 9 November 2015), which is maintained and published by USACE in cooperation with the Association of State Dam Safety Officials (ASDSO), states and territories, and federal dam-regulating agencies. NID was published in 2013 and is updated every two years with information for about 87,000 dams including each dam's location, size, purpose, type, date of last inspection, and regulatory facts. These 87,000 dams include both USACE and non-USACE dams nationwide meeting one of the following criteria: (a) greater than 25 ft (7.62 meters) in height with 15+ acre-feet (af) of storage, or greater than 6 ft (1.83 m) in height with more than 50 af of water, or (b) may be a significant hazard if they fail [*USACE and ASDSO*, 2008]. For this analysis, NID data were used to develop consistent measurements of reservoir surface area, drainage area, and the other characteristics for USACE dams relevant for this study.

The **National Land Cover Database** (NLCD 2011) is a 30-meter (98.4 ft) resolution land cover database for the entire U.S. based on Landsat data [*Homer et al.*, 2012; *Homer et al.*, 2015]. It divides the nation into 16 land cover classes and provides spatial reference and descriptive data for characteristics of the land surface, including thematic class (e.g., urban, agriculture and forest), percent impervious surface, and percent tree canopy cover. Because the NLCD is regularly updated, comparison between datasets enables the NLCD to track land cover change over time. The NLCD is published by the Multi-Resolution Land Characteristics Consortium (MRLC) at http://www.mrlc.gov/ supported by several Federal agencies including USACE.

Statistical Methods for Estimating Carbon Accumulation and Storage

Estimation of carbon storage totals and accumulation rates at USACE reservoirs was complicated by two issues at the beginning of this study: unknown sedimentation rates and unknown quantities of carbon content of sediment being deposited at many U.S. reservoirs. For this work, both of these unknowns were estimated using the procedures explained below.

Few USACE dams have records in the RESSED database, so sedimentation data for USACE reservoirs is incomplete in RESSED. Since USACE reservoirs are comprehensively represented in the NID, a statistical model was used to relate sedimentation rates from RESSED to dam physical attributes (size, surface area, watershed area, and land use) in NID based on non-USACE dams present in both databases. Within relatively homogeneous geographic regions, this

relationship between sedimentation and physical features (surface area, drainage area, and land use) at mainly non-USACE reservoirs was used to predict the rate of sediment accumulation per unit water surface area of similar USACE reservoirs not found in RESSED.

Using the combined RESSED and NID information, District-specific sedimentation regression models could be developed for 24 of the 34 USACE Districts in the continental U.S. For the remaining Districts, data from RESSED and/or NID presented problems that precluded inclusion in the current modeling effort (Table 3). This gap area has since been addressed by information collected by the Reservoir Sediment Information work effort, which will be used to refine the results here.

Many of the largest rivers could not be included in this study. Carbon storage in the Illinois River and the Upper Mississippi pools were analyzed in the first year of the study, but similarly fine-scaled, recent data are not available for most other rivers. Further, the geomorphology of the Upper Mississippi is unlike the other large rivers in the conterminous U.S., so it was not possible to extrapolate the relations from the Upper Mississippi to other large rivers. Consequently, carbon storage and accumulation rates for mainstem reservoirs on the Columbia, Arkansas, Kentucky, Kanawha, and Green Rivers were not included in this study.

Finally, the far West posed distinct issues not seen in other areas. Districts including Los Angeles, Sacramento, and Walla Walla span diverse ecosystems, ranging from desert to coastal forest. A single region-wide regression model for sediment and carbon content could not be reliably applied across this diversity.

For each reservoir, the reservoir sedimentation rate (kg/y) was calculated as:

$$Sedimentation\ Rate = (\ V_{SEDt2} - V_{SEDt1}\ /\ \ t_2 - t_1) * \rho$$

Where V_{SEDt} is the volume of sediment at time t, and ρ is the density of that sediment in kg/m^3.

Mean period length between sedimentation surveys in the database was 8.6 years and ranged from 0.1 – 200 years. Mean sediment density was 1082 (± 289 std. dev.) kg/m^3. Measured values for sediment density were included in the database for only 56.3 % of the surveys, thus to estimate sedimentation mass rate in the remaining 43.7 % of the surveys, the mean sediment density was used. Most reservoirs only had one survey reported in the database, but the number of surveys per reservoir varied up to 26. To avoid introducing a bias toward reservoirs with several surveys, all analyses using sedimentation rates were conducted using reservoir-specific mean values. Other variables in the database that were extracted for this analysis included reservoir location, drainage area, reservoir size, annual precipitation, annual runoff, and reservoir capacity (note: not all variables were provided for all reservoirs). Where suitable data were available in RESSED, sedimentation rates were calculated on a district-by-district basis to account for regional differences in vegetation, soil, and climate that affect sediment transport to reservoirs. However, in some cases, as noted above, a USACE district may span a vast and diverse area (e.g., forests and grasslands), and thus is not a suitable unit for developing a single, predictive model of sedimentation or carbon content.

For those districts having suitable data and relatively homogeneous conditions, sedimentation rates were estimated for each USACE reservoir. The next step was to estimate the fraction of the entering sediment that contains carbon (the carbon content). Multiplying the carbon content by the rate of sediment deposition yielded the rate of carbon deposition in each reservoir. Carbon content of the sediment was estimated from land cover types in NLCD 2011, aggregated by

HUC-8 watershed. Percent organic carbon content of sediment is partly a function of soil type, climatology, percent vegetation cover in a watershed and of the watershed area. The percent of undisturbed watershed (forest or grass) estimated from the NLCD 2011 and the drainage area was used to estimate the percent organic content of accumulated reservoir sediment.

Pilot Study Tests of the Method

Pilot studies were conducted in three USACE districts to validate the approach used. The three districts chosen – New England, Omaha, and Savannah – represent hydrologically distinct regions of the country and therefore are a good test of the method to provide plausible results across a range of reservoir conditions. Data used in the pilot studies come from 52 impoundments across the three districts, excluding dry dams. The impoundments differ greatly in their individual size and total area, ensuring a wide testing range for these methods. The equations defining the sedimentation rate at each pilot district and the derivation of the organic fraction for the sediment are presented in Table 1.

Table 1 - Formulas Used to Determine the Carbon Content of Reservoir Sediments in the New England, Omaha, and Savannah District Pilot Studies *(SA=reservoir surface area; DA= drainage basin area).*

Sedimentation Rate Calculation	
For New England District: $\text{Log10(Sedimentation(kg y}^{-1}\text{))} = 5.85 + 0.5690*\text{Log10DA} + 0.4047*\text{Log10SA}$	(eq. 1a)
For Omaha District: $\text{Log10(Sedimentation(kg y}^{-1}\text{))} = 6.49 + 0.304*\text{Log10DA} + 0.77752*\text{Log10SA}$	(eq. 1b)
For Savannah District: $\text{Log10(Sedimentation(kg y}^{-1}\text{))} = 7.03 + 0.118*\text{Log10DA} + 0.8651*\text{Log10SA}$	(eq. 1c)
Organic Fraction (Organic Carbon Content) Calculation	
Base Fraction of Organic Material: $\text{Log}(OC_{frac}) = -1.1471 - 0.1054*\text{Log(DA:SA)}$	(eq. 2)
Land Use Multiplier: Log(Land Use Multiplier) = 0.4 *(Percent Undisturbed)/100) - 0.2	(eq. 3)
Final Estimate of Organic Fraction: $\text{Log}(OC_{frac}) = \text{Log}(OC_{frac}) + \text{Log(Land Use Multiplier)}$	(eq. 4)
Rate of Carbon Deposition	
Rate of Carbon Deposition = Sedimentation Rate * Organic Fraction	(eq. 5)

Broad surveys of reservoir sediments by *Mulholland and Elwood* [1982] and *Ritchie* [1989] suggest that reservoir sediment has an average carbon content of about 2 %. The USACE model gives carbon contents ranging from 2.9 to 5.2 % with a mean and median of 4.1 % for the pilot study areas. In total, these impoundments in the pilot studies represent approximately 0.3 % of their total drainage area, and are estimated to store ~ 4.5 Teragrams (Tg) of carbon per year, approximately equal to 3 million acres of forest; see Figure 2.

However, the error in these calculations can be large. In 95 % of cases, the annual accumulation rate at the pilot study reservoirs will fall between about 20 % and 500 % of the predicted value. The large error is a result of: (1) a broad spread of data around the regression line (indicating the influence of variables other than drainage area and lake surface area); (2) the large spatial scale of the data relative to the geographic footprint of the lands and waters managed by USACE, and; (3) errors and biases in the source data that have not yet been accounted for in this project.

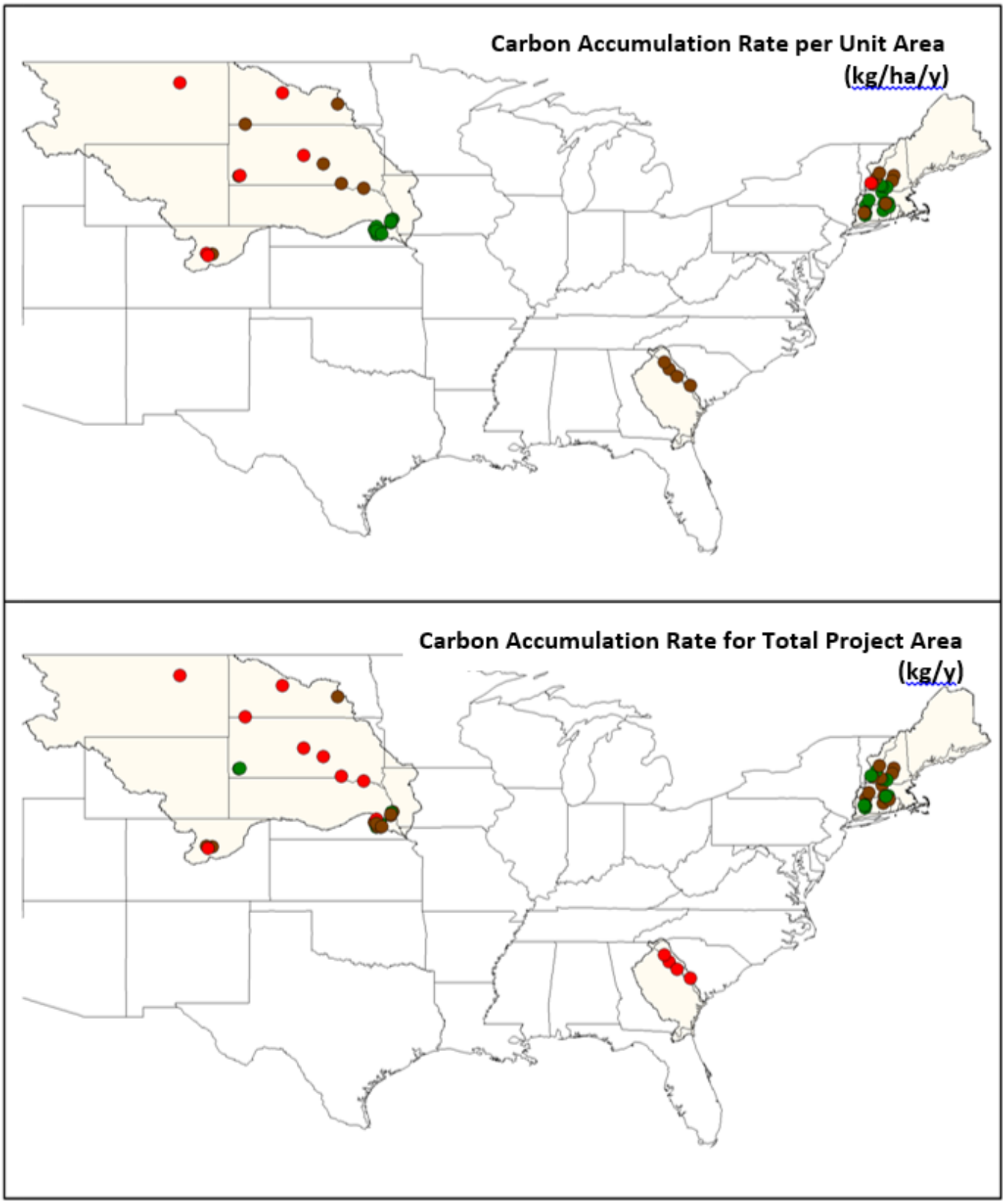

Figure 2 - Outline of the three Districts included in the Phase I assessment showing location of USACE reservoirs and their estimated total mass of deposited carbon (kg/y) in the lower panel coded as green (< 900), brown (900-1500) and red (> 1500).

Terrestrial Carbon Accumulation and Storage

In many locations where USACE has a reservoir, USACE has ownership or operational control of lands immediately adjacent to the reservoir that can be inundated during large flood events and which can be authorized for other purposes, such as recreation. Therefore, it is necessary to collect information on USACE lands adjacent to reservoirs when accounting for carbon storage and accumulation at USACE projects nationwide.

The role of terrestrial carbon sources and sinks in the global carbon cycle is well-established. Three basic variables are recognized:

- **Plant biomass** refers to the quantity (measured as mass) of plant material in an area, which is determined by land use, climate, soils, and history. Plant biomass is generally considered to be 45 to 50 % carbon, with the remainder being hydrogen, oxygen, and other elements.
- **Soil organic carbon (SOC)** refers to the quantity of carbon stored in soils in an area. All soils by definition contain organic carbon, unless they have been severely degraded by natural or anthropogenic causes [*Lal et al.*, 2004]. Biological activity in the upper layers of the soil is typically responsible for the incorporation of organic matter into the soil. The amount of carbon stored is a function of climate, landscape, vegetation, relief, and topography [*Jenny*, 1941]. Land management can also impact carbon storage, especially in agricultural systems [*West and Post*, 2002]. Wet, humid, forested regions typically have thicker, richer organic layers compared to desert regions, where the organic layer is thin and very slow to develop. Grasslands and wetlands have the highest belowground biomass and contain large reserves of soil carbon. SOC is typically reported as mass/area of land. Because soil types are defined in part by the carbon content of the upper layers, SOC is typically estimated based on soil maps that show the extent of soil types. Inorganic carbon is also present in soils, particularly in desert areas, but the processes by which they accumulate are much slower (tens of thousands of years). Consequently, soil inorganic carbon is typically not included in estimates of soil carbon.
- **Net Primary Productivity (NPP)** is a measure of the rate at which carbon is fixed in plant biomass. It can be thought of as the difference between primary productivity (the rate at which carbon is taken up from the atmosphere by plants) and plant respiration (the rate at which carbon is released by plants during normal metabolic activity). Unlike plant biomass, NPP is expressed as a rate. Typical units are kg m^{-2} y^{-1} and are a much smaller number per unit area than plant biomass.

Taken together, SOC and plant biomass carbon provide an estimate of the existing carbon in a landscape. NPP provides an estimate of how fast the above ground biomass is changing due to natural processes (such as plant growth) and in light of disturbances such as drought and fire, and changes in LULC (Figure 3).

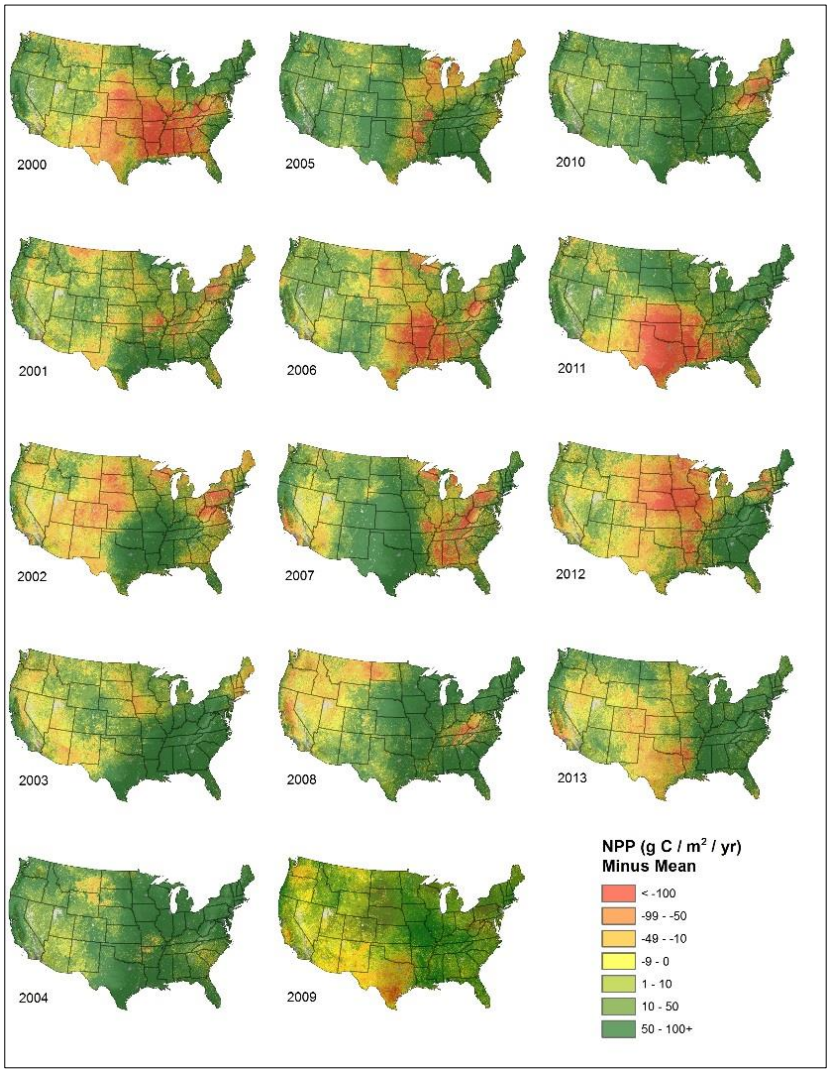

Figure 3 - Maps showing 2000-2013 NPP minus the average for the conterminous U.S. The red and orange patches show below-average NPP due to intensive regional drought.

Terrestrial Carbon Accumulation and Storage at USACE Lands and Waters

SOC, plant biomass and NPP are well-studied variables whose values are established in the literature. For large area assessments, SOC is typically measured by soil type, while plant biomass and NPP are typically prescribed by vegetation type or LULC type. More recently, however, remote sensing and modeling tools have been used to improve our understanding of terrestrial carbon. Remote sensing datasets and their widely applied indices [e.g., Normalized Difference Vegetation Index (NDVI)] have been used with land cover to describe more explicitly biomass and NPP behavior seasonally and over the last few decades. Models have also been used to successfully estimate past SOC behavior over years to decades.

Data Sources for Estimating Terrestrial Accumulation and Storage Rates

Estimation of terrestrial carbon storage and accumulation rates at USACE lands relied on a variety of spatial datasets discussed below. These datasets can be divided into static and time-variant datasets.

Static Datasets

The **National Biomass and Carbon Dataset** for the year 2000 is a high-resolution (30-m), baseline estimate to be the source for estimates of plant biomass at USACE lands.

The **National Land Cover Database 2011** (**NLCD 2011**), described above, was used to track existing land use and land cover characteristics for project lands.

The **National Atlas** (also **National Atlas of the United States**) is a now-legacy USGS geo-database that included an ecoregion data layer also previously maintained by the USGS. The most recent 1997-2014 edition of the National Atlas of the United States was retired on 1 October 2014 (although it is still accessible at http://viewer.nationalmap.gov/viewer/). The geodatabase data layer used in this study consists of Bailey's ecoregions and subregions of the U.S. used to characterize the land cover in areas managed by USACE in conjunction with their reservoirs and to provide information on biophysical drivers and gradients unique to each area.

Soil organic carbon data was derived from the **Gridded Soil Survey Geographic Database** (**gSSURGO**) data from the Natural Resources Conservation Service (NRCS) Geospatial Data Gateway (https://gdg.sc.egov.usda.gov/). The gSSURGO dataset is a raster version of the vector-based Soil Survey Geographic Database of soil types across the U.S. at a 10 m scale. One attribute is average soil organic carbon, a weighted average given in units of g/m^2 for 11 standard layers or zone depths for each soil type [*USDA NRCS*, 2014].

Time Variant Datasets

Land cover change and disturbances, whether human or natural, affect fundamental aspects of energy, water, and carbon cycles [*Bonan*, 2002; *Foley et al.*, 2005; *Zhu et al.*, 2010], and these impacts vary in duration. Change in primary production, and therefore carbon storage, in an area fluctuates over time as disturbances such as wildfire, drought, storms, late freezes, disease and other factors adjust both plant growth and community composition. Remote sensing-based datasets are available on an annual basis to track aboveground vegetation characteristics and how they respond to annual differences in temperature, water, and disturbance. Importantly, dataset duration is limited by sensor longevity and continuity, with better estimates of biophysical variables being developed over the last decade.

The MODIS GPP/NPP Project (MOD17) Dataset provides worldwide estimates of gross and net primary production using estimates of absorbed photosynthetically active radiation detected by the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments flown on the National Aeronautics and Space Administration (NASA) Terra and Aqua spacecrafts (available online at http://modis.gsfc.nasa.gov/).

Longer-term (decadal) change in primary production and carbon accumulation in an area fluctuates over time as disturbances such as wildfire, drought, disease, and other factors adjust both plant growth and community composition. Whereas NPP provides a one-time snapshot of primary productivity in an area, long-term satellite data can be used to monitor change over time in vegetation health and distribution. For this project, vegetation change, disturbance, and

changes in health vigor were assessed using the NDVI data from the USGS Remote Sensing Phenology Dataset (http://phenology.cr.usgs.gov/). NDVI is calculated from 1 km resolution multi-visible and NIR spectral data collected by the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) satellite platforms.

The MODIS NPP dataset extends from 2000 to 2013, while the NDVI dataset from AVHRR includes a longer period (1989-2013). The overlap in the record was investigated for the Omaha District to determine whether NPP could be estimated from NDVI. Although the two measures are correlated, NDVI values plateau in the higher-productivity portion of the record while NPP continues to increase. Consequently, long-term change in NPP could not be accurately estimated from NDVI. However, NDVI can give a long term assessment about changes in productivity over a longer time span and more confidence about the susceptibility to disturbance of USACE lands and waters.

Available boundaries of USACE-owned recreational area properties were used where available. Where they were not available, a 0.5 km buffer around the reservoir footprint was assumed to represent project lands. Four districts fall into this category: New England, Los Angeles, Albuquerque, and Norfolk. The buffered areas in the New England and Los Angeles Districts include over 289 km^2 (111.6 square miles) and 201 km^2 (77.6 mi^2) of land area, respectively. The buffered area for reservoir projects in the Albuquerque District totaled 229 km^2 and 24 km^2 for Norfolk District. This study highlighted the lack of availability of project boundaries for USACE projects. As a result, an effort was begun in late 2014 to collect these boundaries in geospatial format.

Methods to Estimate Terrestrial Carbon Accumulation Storage and Change

Plant biomass carbon, NPP, and SOC at each reservoir were assessed by clipping thematic layers with the USACE project boundary files for each project area, then aggregating by district. Figure 4 shows how a buffer around a USACE reservoir was used to clip the NLCD 2011 layer, and the resulting information about land cover in the area around the reservoir.

A similar method was used to extract changes in vegetation health and distribution over time in maximum and growing season length NDVI values.

The end products of the analysis were polygons delineating NLCD 2011 land cover types in the recreation areas or buffer zones within the assessment areas (e.g., Figure 4). Each polygon was attributed with unit area plant biomass C, 2000-2013 NPP carbon, maximum NDVI, growing season duration, and calculated SOC. This geospatial data layer depicts the spatial variation of soil carbon stock data as a function of biophysical driver variables likely to control terrestrial carbon dynamics and land cover amenable to change from natural causes or anthropogenic land management. From these data, carbon stocks were computed for each district. Figure 5 shows the organic carbon as biomass carbon and SOC by NLCD 2011 land cover type for a reservoir in the Upper Mississippi Basin. Figure 6 shows the changes in NPP over time in the same region caused primarily by changes in precipitation (e.g., drought or wet years).

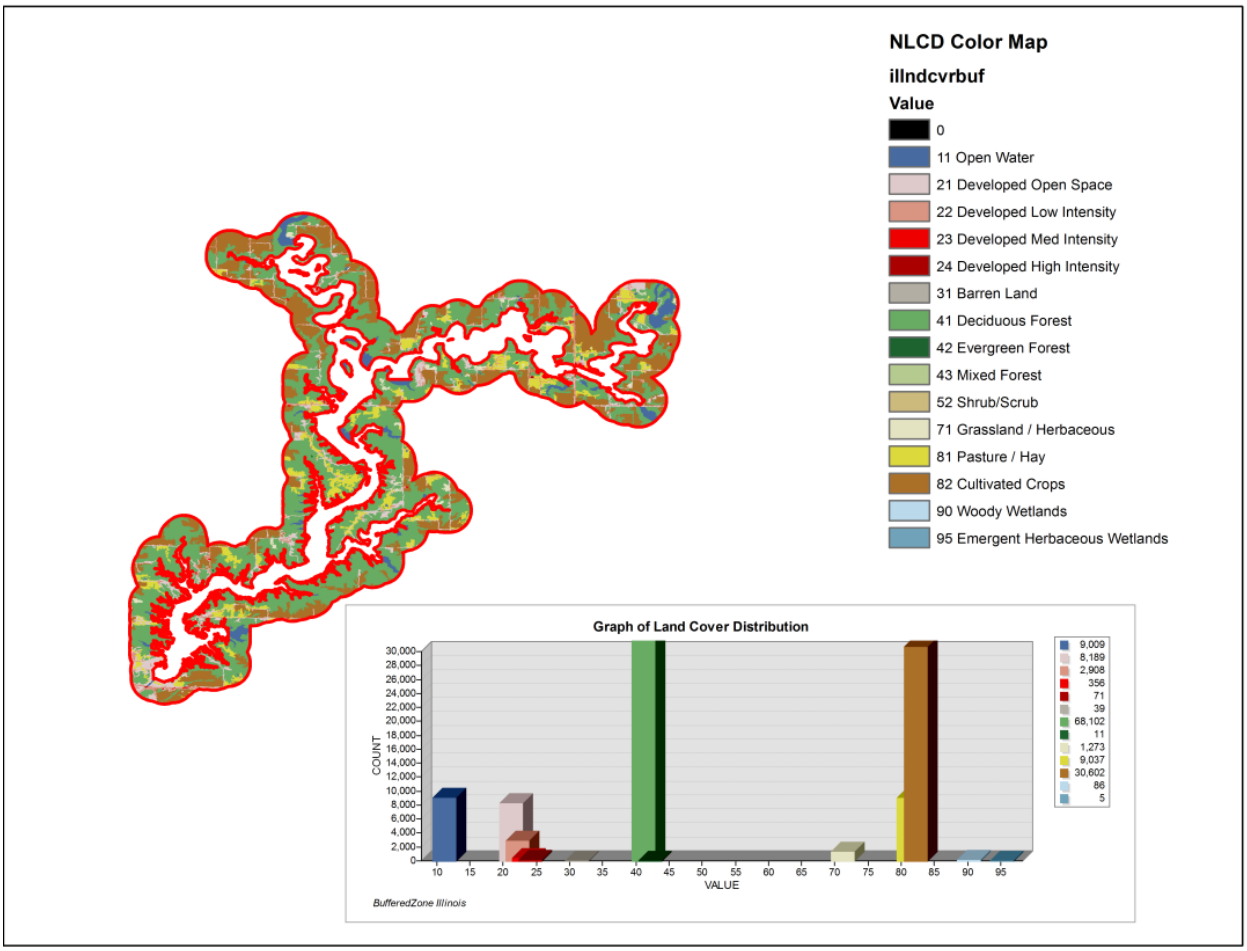

Figure 4 - Example of NLCD data layer clipped by a buffer around a USACE reservoir project.

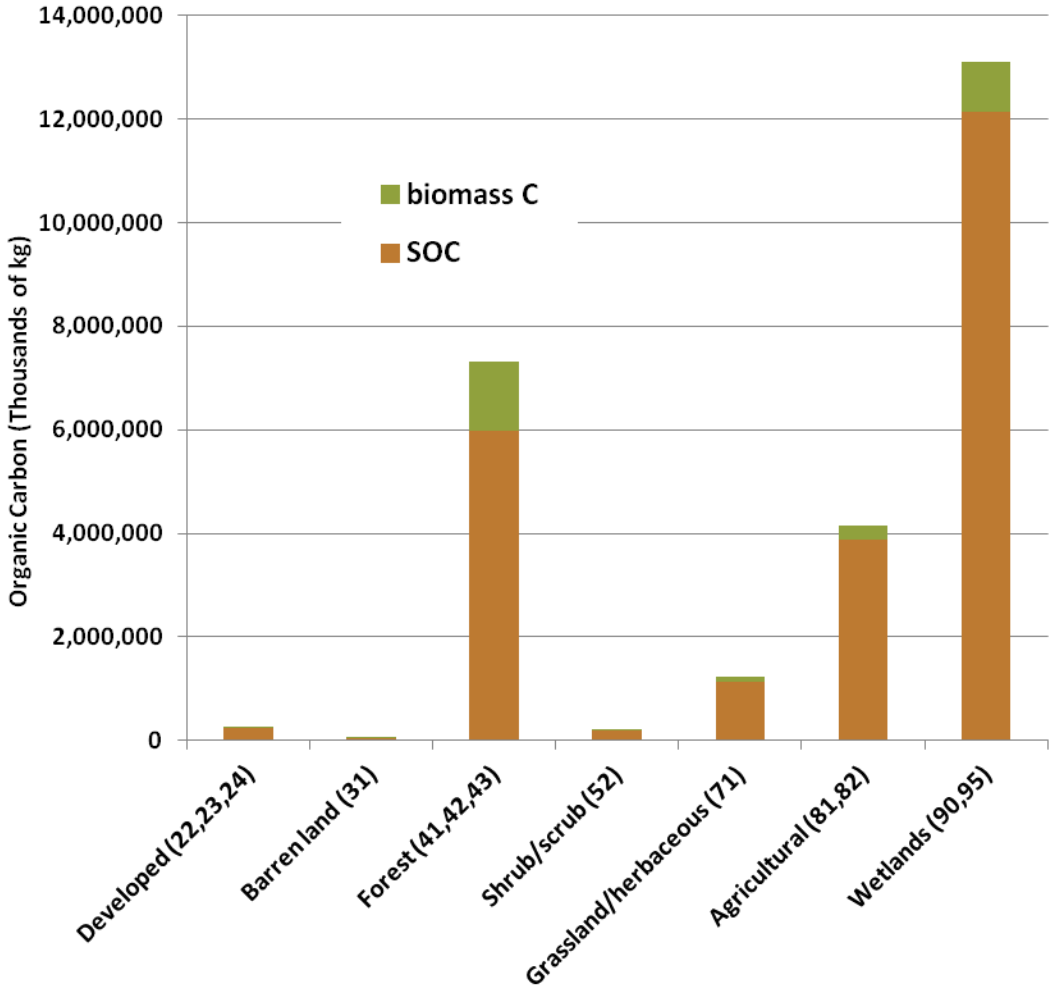

Figure 5 - Example showing biomass C (carbon) and SOC by NLCD 2011 land cover type for a reservoir project in the Upper Mississippi basin.

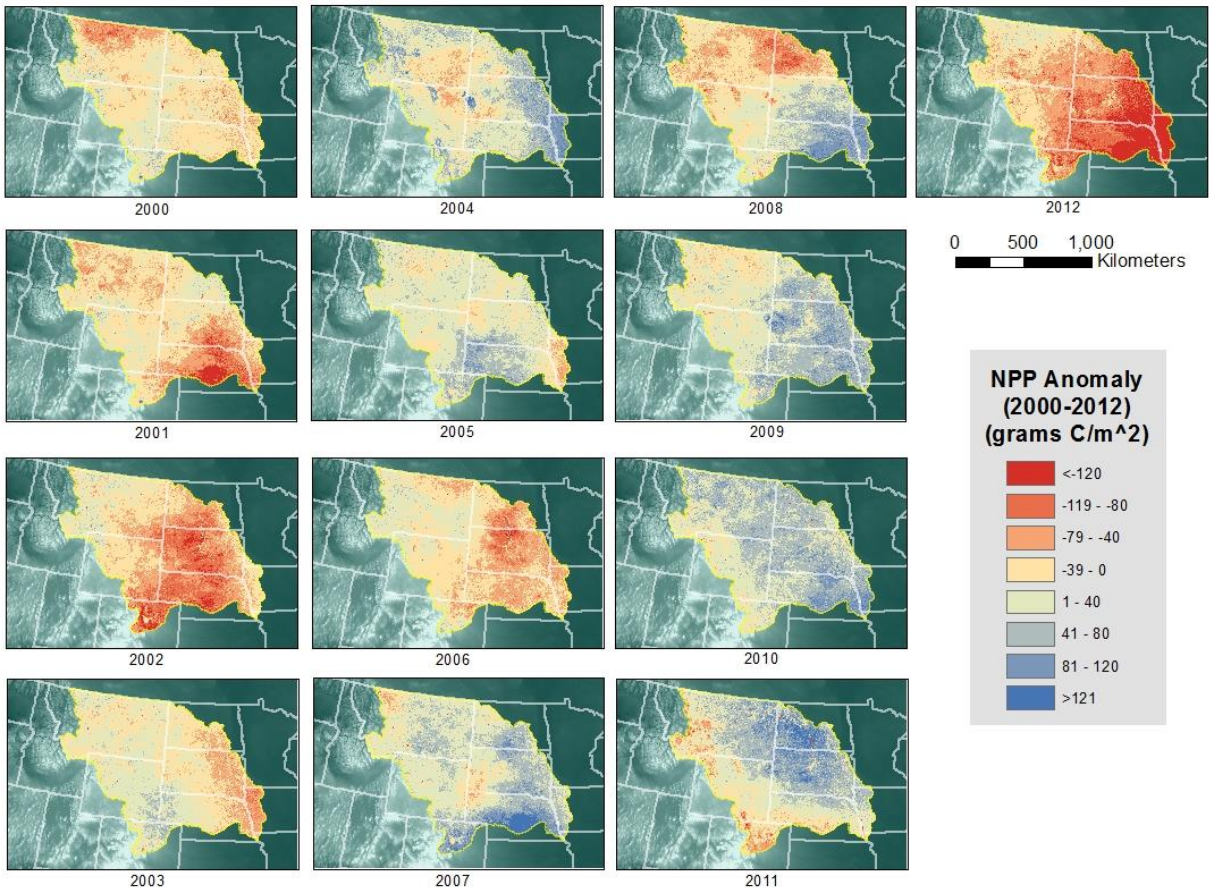

Figure 6 - Example showing inter-annual changes in NPP in the Upper Mississippi basin.

Pilot Study Tests of the Method

Pilot study tests of the methods conducted in the New England, Omaha, and Savannah Districts showed significant amounts of carbon stored as organic carbon in the plant cover and soils on lands managed by or adjacent to USACE water resource projects. In total, the terrestrial areas are estimated to accumulate and store ~ 0.9 Tg of carbon per year, in addition to the combined estimated soil and biomass carbon stocks between 235 and 400 Tg of carbon.

For the Savannah District (Figure 7), the largest terrestrial carbon pool in the USACE recreation areas is the biomass pool, with 10.2 Tg of carbon. The total SOC was estimated as ~ 0.33 Tg. The total 2013 NPP carbon fixation rate for Savannah is ~ 0.06 Tg y^{-1}.

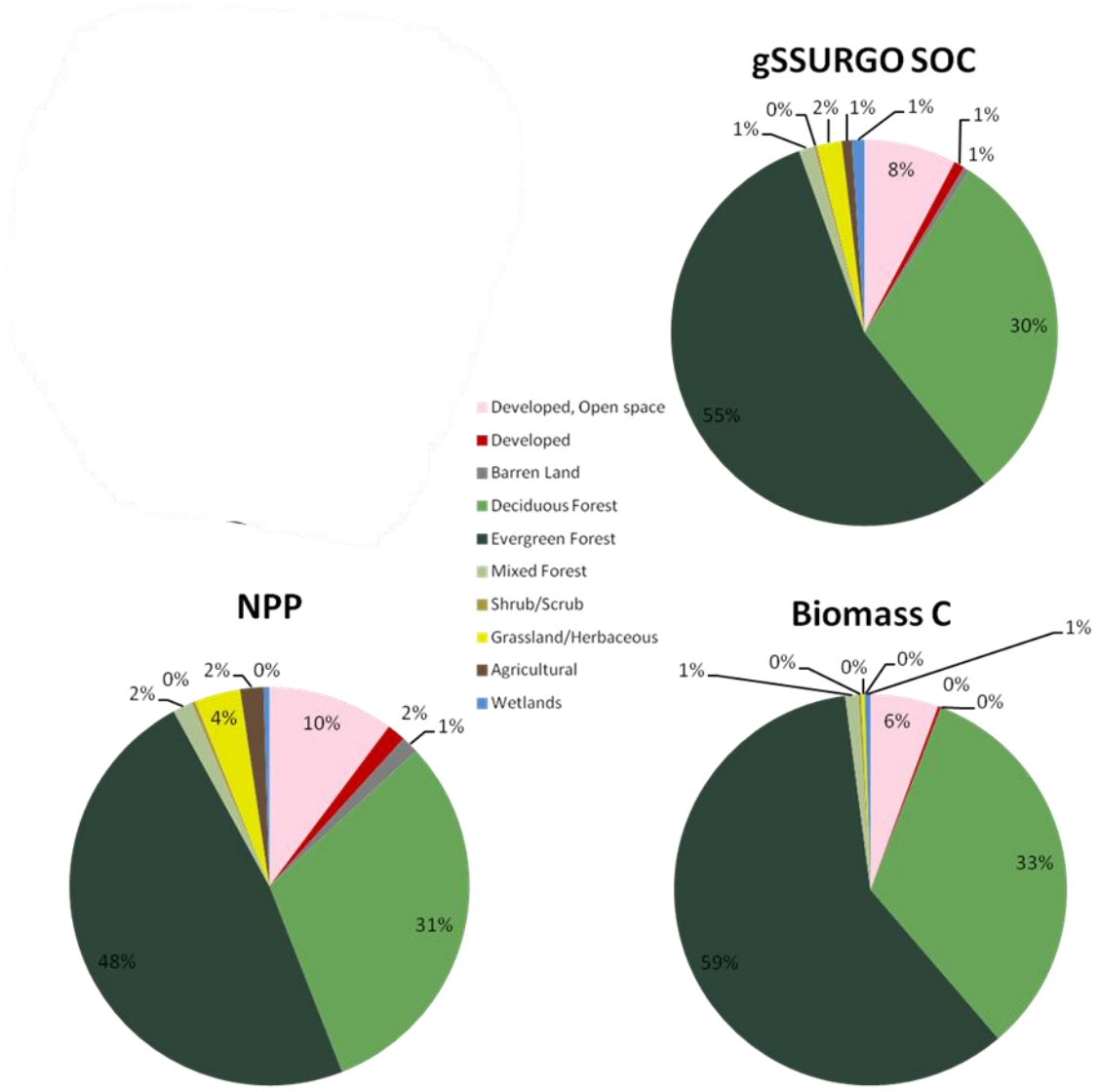

Figure 7 - Proportional distribution of organic carbon in recreation areas in the Savannah District in soil (gSSURGO Soil Organic Carbon), biomass, and carbon fixation rate (NPP) among several major land cover classes.

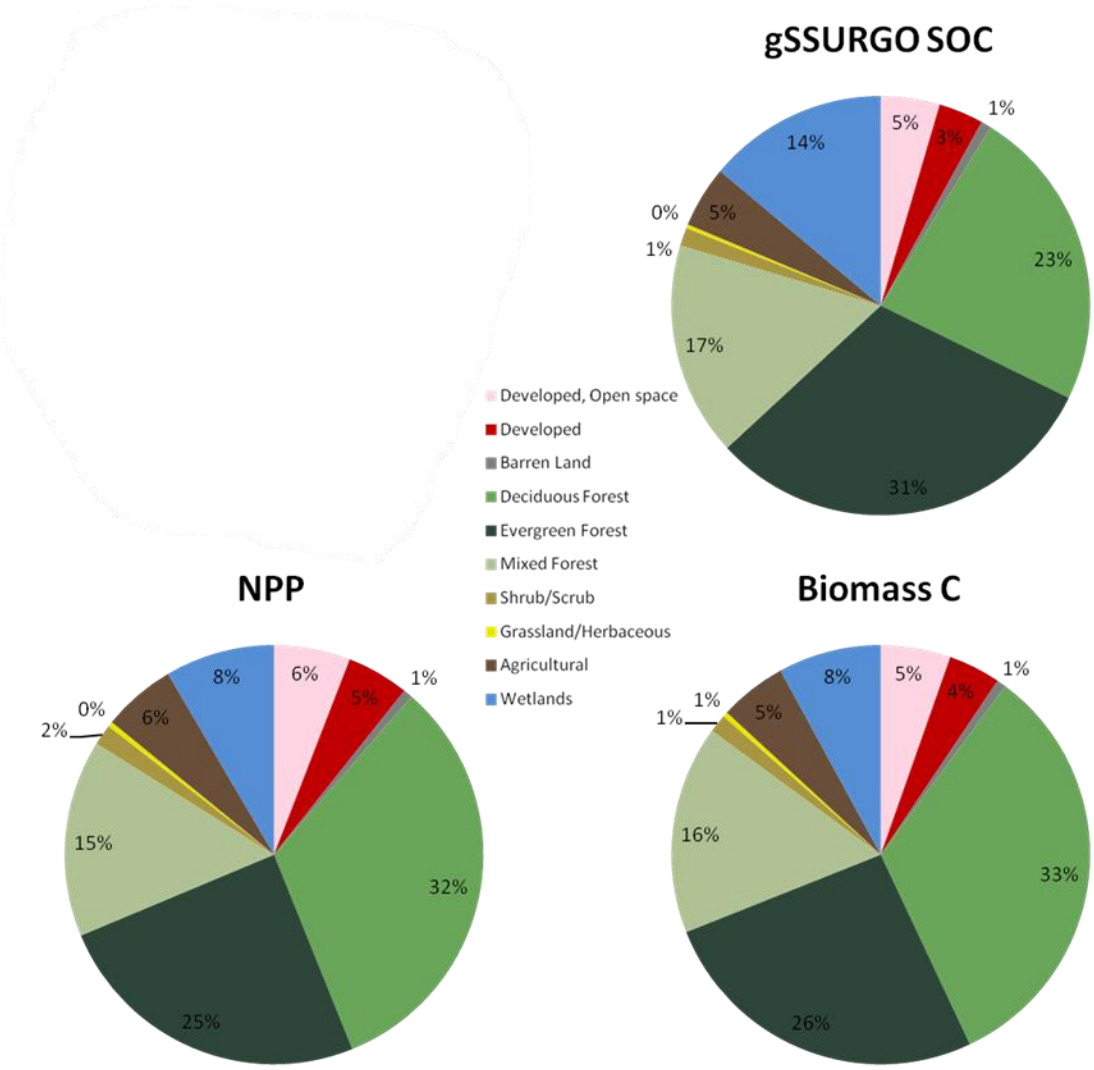

Figure 8 - Proportional distribution of organic carbon in recreation areas in the New England District in soil Gridded Soil Survey Geographic (gSSURGO Soil Organic Carbon), biomass, and carbon fixation rate (NPP) among several major land cover classes.

For the New England District (Figure 8), the largest terrestrial carbon pool is also likely the biomass pool, with 96.1 Tg of carbon. The total SOC is 11.6 Tg carbon. The total 2013 NPP carbon fixation rate for New England is ~ 0.6 Tg y^{-1}.

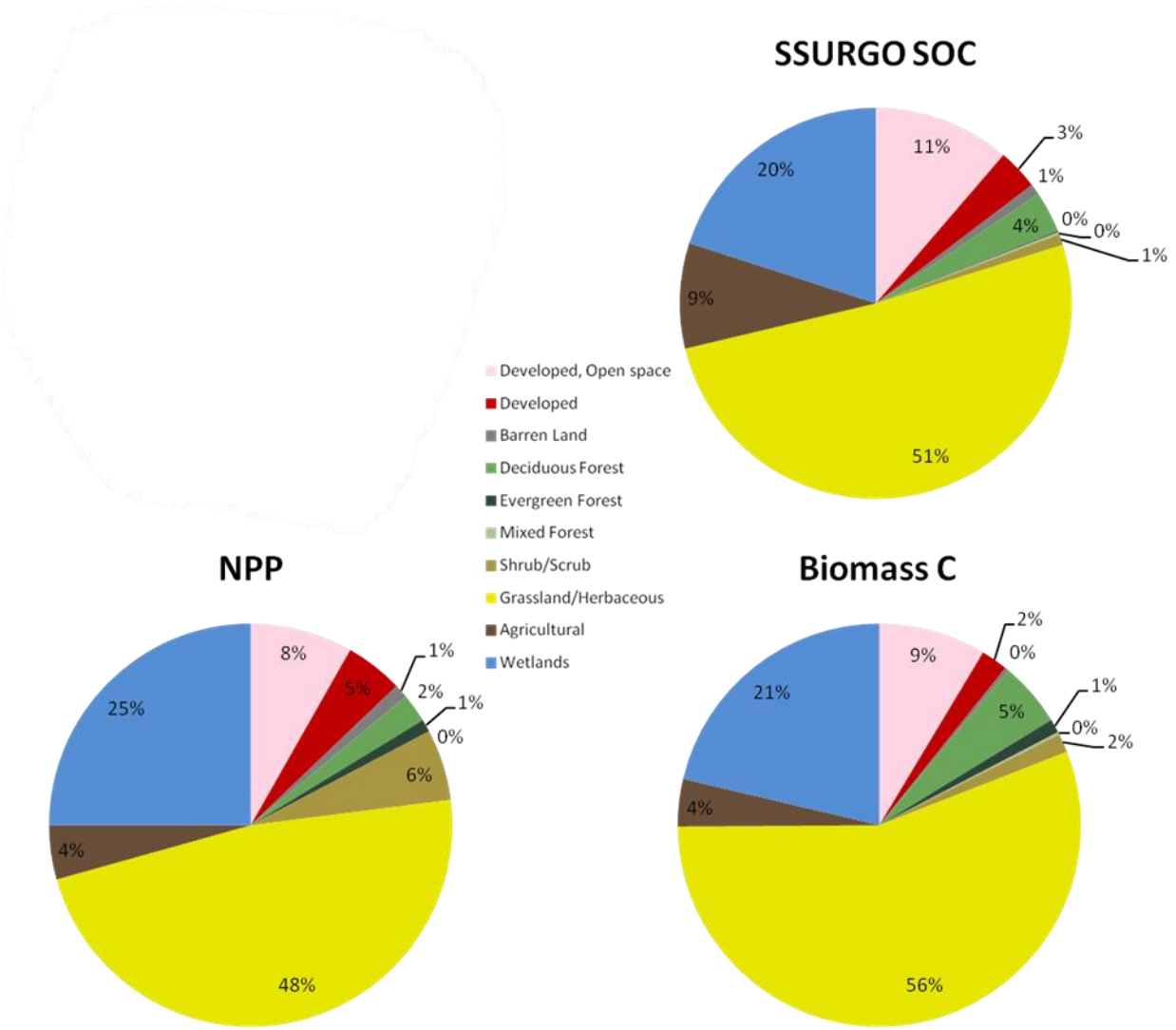

Figure 9 - Proportional distribution of organic carbon in recreation areas in the Omaha District in soil (gSSURGO Soil Organic Carbon), biomass, and carbon fixation rate (NPP) among several major land cover classes.

For the Omaha District (Figure 9), the largest terrestrial carbon pool is the biomass carbon pool with 4.8 Tg carbon. The total SOC is estimated as ~ 1.1 Tg carbon. For the Omaha District, note that gSSURGO data for the state of Montana could not be obtained at the time of the assessment, so the SOC values are known to be underestimates. The total 2013 NPP carbon fixation rate for Omaha is ~ 0.2 Tg y^{-1}.

The extensive areas of forest land cover in the Savannah and New England Districts, coupled with the associated high SOC per unit and the high standing live plant biomass carbon per unit area, are the likely dominant factors controlling pool size. The high unit area biomass carbon for

the wetlands (particularly woody wetlands) and forested cover types is consistent with the biomass carbon vegetation physiognomy relationships as found in the literature.

Final Model Generation

The final regression equations used to model aquatic carbon accumulation and storage in USACE reservoirs are presented in Table 2.

Once the sedimentation rate is calculated, the formulas for organic fraction and rate of carbon deposition (Table 1) were applied to estimate the amount of carbon present in waters managed by USACE.

Calculation of terrestrial biomass, SOC, and NPP values in the final database were unchanged from those used in the pilot studies. A District-level breakdown of data in the current database is provided in Table 3.

Finally, data for five USACE dams gave unrealistic values in the model:

- The Abiquiu and Conchas Dams (New Mexico) receive abundant sediment that is unusually low in organic carbon. The carbon model was inappropriate for these reservoirs, and they were not included in the totals.
- The Seven Oaks (California) and Jemez Dam (New Mexico) are mostly (but not always) dry dams, so the carbon model was also not appropriate and the dams were excluded from the database.
- The model assigned all sedimentation in Lake Superior to the Soo Locks between Lake Superior and the lower Great Lakes. The carbon model could not be applied here.

Table 2 - Aquatic carbon storage in USACE reservoirs.

District	Model DF	Regression Models*	R squared	Root mean squared error
Albuquerque	27	= 7.272 + 0.791*Log10(SA) + 0.241*Log10(DA)	0.759	0.624
Baltimore	21	= 6.438 + 0.725*Log10(SA) + 0.318*Log10(DA)	0.680	0.526
Buffalo	5	= 5.827 + 0.331*Log10(SA) + 0.58*Log10(DA)	0.841	0.296
Detroit	11	= 7.444 + 1.19*Log10(SA) + -0.177*Log10(DA)	0.735	0.448
Fort Worth	69	= 7.014 + 0.746*Log10(SA) + 0.182*Log10(DA)	0.855	0.390
Galveston	6	= 6.011 + 0.153*Log10(SA) + 0.526*Log10(DA)	0.923	0.307
Huntington	32	= 6.103 + 0.37*Log10(SA) + 0.533*Log10(DA)	0.831	0.341
Kansas City	19	= 6.987 + 0.962*Log10(SA) + 0.16*Log10(DA)	0.851	0.518
Little Rock	17	= 6.413 + 0.424*Log10(SA) + 0.417*Log10(DA)	0.942	0.356
Los Angeles	38	= 5.875 + -0.102*Log10(SA) + 0.851*Log10(DA)	0.635	0.679
Louisville	22	= 6.449 + 0.409*Log10(SA) + 0.451*Log10(DA)	0.804	0.429
Mobile	7	= 6.996 + 0.894*Log10(SA) + 0.076*Log10(DA)	0.753	0.574
Nashville	25	= 6.505 + 0.686*Log10(SA) + 0.25*Log10(DA)	0.870	0.318
Omaha	39	= 6.374 + 0.739*Log10(SA) + 0.365*Log10(DA)	0.906	0.389
Pittsburgh	14	= 6.297 + 0.596*Log10(SA) + 0.452*Log10(DA)	0.898	0.299
Portland	4	= 6.65 + 1.426*Log10(SA) + 0.031*Log10(DA)	0.882	0.457
Rock Island	15	= 6.937 + 0.655*Log10(SA) + 0.177*Log10(DA)	0.889	0.367
Sacramento	38	= 5.212 + 0.24*Log10(SA) + 0.861*Log10(DA)	0.853	0.499
San Francisco	7	= 6.631 + 0.967*Log10(SA) + 0.311*Log10(DA)	0.785	0.504
St. Louis	23	= 6.773 + 1.032*Log10(SA) + 0.142*Log10(DA)	0.907	0.336
St. Paul	13	= 5.843 + -0.032*Log10(SA) + 0.476*Log10(DA)	0.549	0.464
Tulsa	72	= 7.263 + 0.746*Log10(SA) + 0.137*Log10(DA)	0.885	0.343
Vicksburg	5	= 6.834 + 0.654*Log10(SA) + 0.281*Log10(DA)	0.814	0.625
Walla Walla	4	= 4.529 + -0.231*Log10(SA) + 1.036*Log10(DA)	0.773	0.638
Wilmington	7	= 5.826 + 0.591*Log10(SA) + 0.565*Log10(DA)	0.956	0.332

**General formula:*

$$Log10(sedimentation\ ^{kg}/_{y}) = B0 + B1*Log10(Surface\ Area\ km^2) + B2*Log10(DA\ km^2)$$

Table 3 - Availability of data by USACE Division and District.

		AQUATIC					TERRESTRIAL					
Division	**District**	**Surface Area***	**Biomass**	**Accumulation Rate**	**Land Class**	**Basin Info****	**Surface Area*****	**Biomass**	**Accumulation Rate**	**Land Class**	**SOC**	**NDVI**
Great Lakes & Ohio River	Buffalo	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
	Chicago						Y	Y	Y	Y	Y	Y
	Detroit	Y		Y	Y	Y						
	Huntington	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
	Louisville	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
	Nashville	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
	Pittsburgh	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
Mississippi Valley	Memphis						Y	Y	Y	Y	Y	Y
	New Orleans						Y	Y	Y	Y	Y	Y
	Rock Island						Y	Y	Y	Y	Y	Y
	St. Louis						Y	Y	Y	Y	Y	Y
	St. Paul						Y	Y	Y	Y	Y	Y
	Vicksburg	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
North Atlantic	Baltimore	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
	New England	Y		Y	Y	Y	Buffered	Buffered	Buffered	Buffered	Buffered	Buffered
	Norfolk						Buffered	Buffered	Buffered	Buffered	Buffered	Buffered
	Philadelphia						Y	Y	Y	Y	Y	Y

Northwestern	Kansas City	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
	Omaha	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
	Portland	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
	Seattle						Y	Y	Y	Y	Y	Y
	Walla Walla	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
South Atlantic	Jacksonville						Y	Y	Y	Y	Y	Y
	Mobile	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
	Savannah	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
	Wilmington	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
South Pacific	Albuquerque	Y		Y	Y	Y	Buffered	Buffered	Buffered	Buffered	Buffered	Buffered
	Los Angeles	Y		Y	Y	Y	Buffered	Buffered	Buffered	Buffered	Buffered	Buffered
	Sacramento	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
	San Francisco	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
Southwestern	Fort Worth	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
	Galveston	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
	Little Rock	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
	Tulsa	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y

NOTES

**Aquatic area is reservoir surface area.*

*** Aquatic basin info includes characteristics such as project drainage area; percent area of associated HUC 8 in forest, shrub, grass, or row crop.*

****Terrestrial area is based on actual property parcel boundary, else 0.5km buffer around water feature as noted.*

The Carbon Storage Information Portal

The pilot study methods were applied to USACE Civil Works lands and waters and adjacent lands in 34 districts across the conterminous U.S. The data are stored in the USACE Enterprise CorpsMap database with a web-based interface. The end product is the Carbon Storage Information Portal.

The Main tab portal information for the nation is shown in Figure 10 and for the Sacramento District in Figure 11. In both figures, the left side of the panel provides a map of the area of interest, showing the lands and waters managed by USACE. Hovering the cursor over one of the circles brings up information about that management unit. The lands and waters are color coded by the average annual carbon accumulation rate (kg/m^3) and sized by total annual carbon storage (MT).

The central panel shows the distribution of land cover area by NLCD 2011 land cover type (sub class), allowing the user to better understand the relative abundance land cover types that are contributing to terrestrial carbon accumulation and storage at USACE lands. The lower graphic shows the average soil organic carbon (g/m^3) by depth (cm), which is a good estimate of how much long-term storage has occurred at that location or area.

The menus on the right side of the tab control the spatial scale of the information displayed in the viewer. Using the System Type dropdown menu, the user can select either the Aquatic or Terrestrial type, or both. The user can specify a district using the Select a District pull-down menu, or can select one or more projects by name in under project name(s). In the NLCD Sub Class menu, the user can specify whether to view all land cover types, or to view a more restricted set of types. Finally, the Project Site Area Name tab can be used to directly view individual project data.

Figure 11 shows carbon accumulation and storage in the Sacramento District where the System Type dropdown menu has been used to limit the display to “Terrestrial” systems only. In most Districts, carbon in reservoirs dominates the storage totals. Filtering out the “aquatic” sub class provides more clarity about the allocation of terrestrial carbon accumulation and storage among land cover sub classes.

Because this was a screening-level project, the analysis did not generate new data on local-scale accumulation and storage which are missing across large sections of the U.S. USACE intends to pursue refinements in the data and the analytic approach developed here, subject to funding and other resource constraints in the future. These first estimates of carbon storage are necessarily rudimentary, based as they are on those existing data and the statistical relationships used here to extrapolate to areas without relevant data. These are baseline estimates from which any ecological, vegetation, management, or sedimentation changes can be compared to quantify trajectories or to model potential future scenarios.

The chief product of this project is a set of estimates across the contiguous U.S. of the current storage and rates of accumulation of carbon already in place, not of the potential for new atmospheric carbon to be permanently sequestered. However, the estimates reported here are the first USACE has produced and will be the basis for computing the potential for sequestering atmospheric carbon in the future, since the current storage of carbon and rate of accumulation will in part determine the limit of that potential to sequester new carbon. In a related way, those limitations mean that these estimates cannot be the basis for considering operational changes to the lands and waters USACE owns or manages for the nation to enhance future sequestration since they deal only with current carbon stocks and rates.

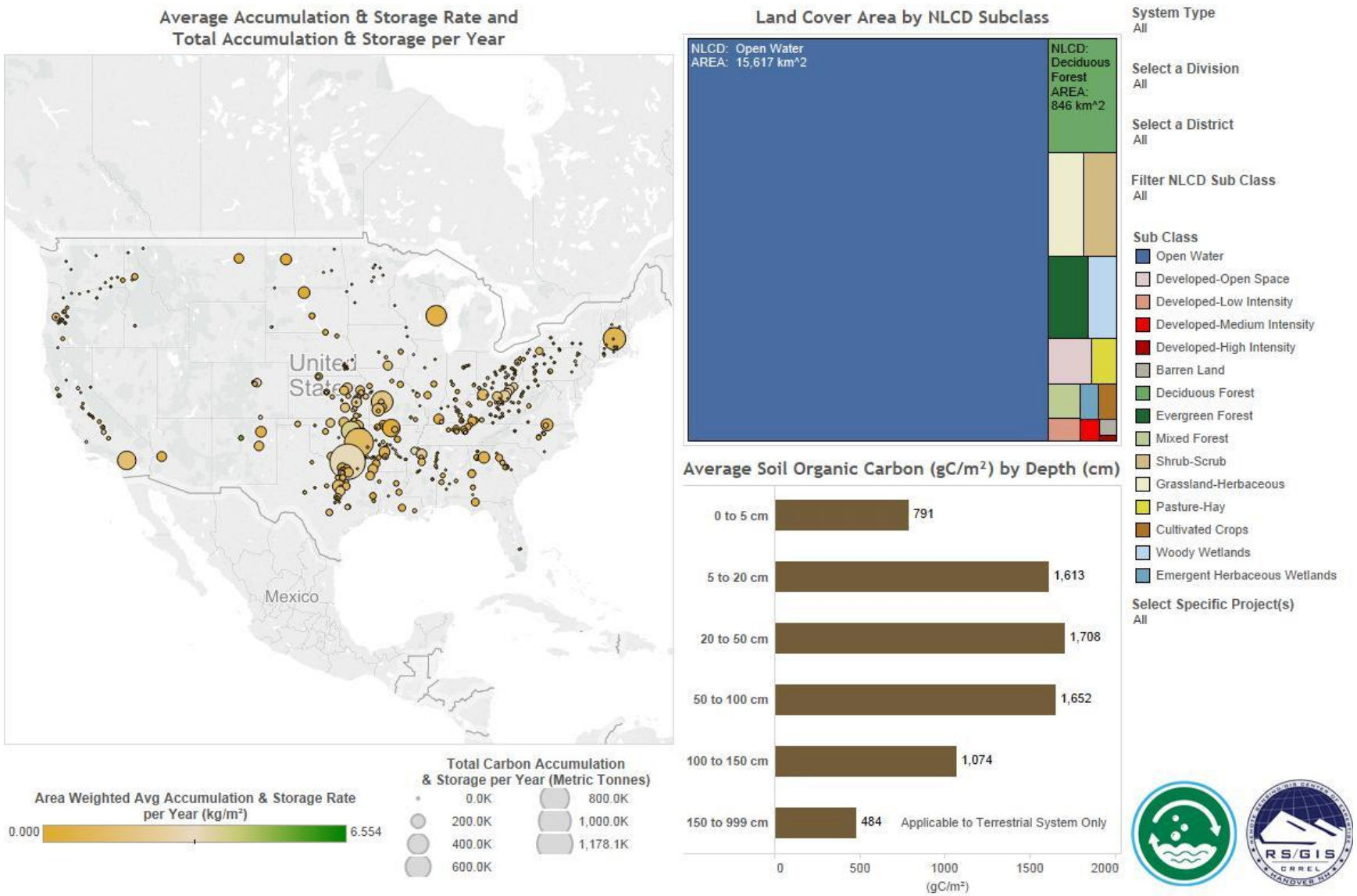

Figure 10 - Carbon Storage Information Portal main page, showing data for the conterminous United States.

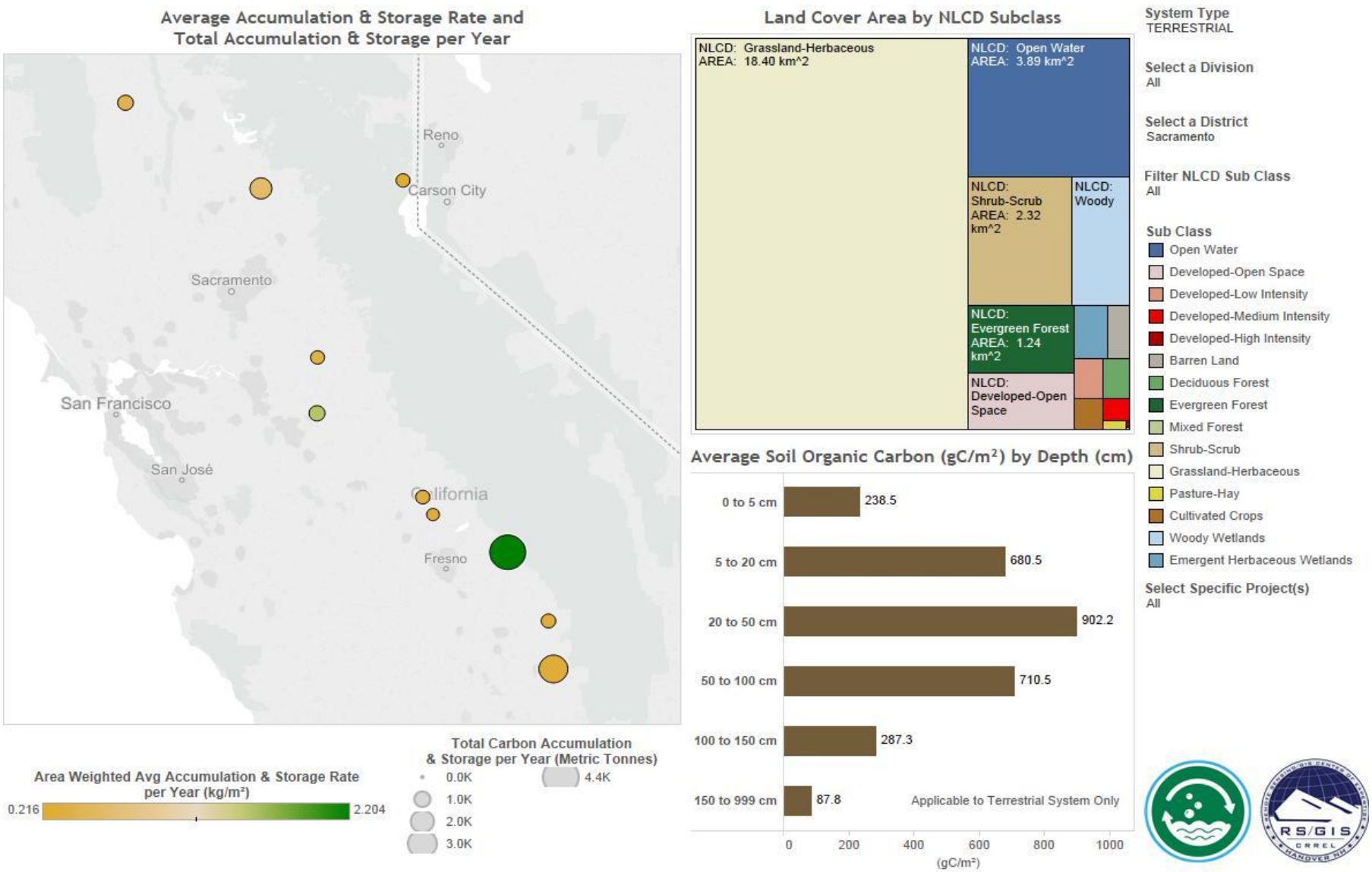

Figure 11 - Carbon Storage Information Portal main page, showing data for the Sacramento District.

Future Work

The Carbon Storage Information Portal provides an initial assessment of the rates and storage capacity for carbon in USACE lands and waters using a range of existing information to provide a national view of those rates and quantities. While the information is valid at this scale, it may not be accurate at finer spatial resolutions used in individual project planning, or at larger scales owing to the strong heterogeneity of information across space demonstrated here. A key goal of this project is to identify where additional information will be useful to narrow the uncertainty ranges for the data and final estimates produced here. Two gaps identified in this work effort have already been rectified by the collection of geospatial project boundaries and more complete reservoir sediment information. As data becomes available at finer spatial scales, these results will be updated and the estimates refined.

For example, to improve the rough estimates of aquatic carbon accumulation developed here, districts could develop project-specific sediment data or conduct more sophisticated sediment delivery and retention modeling for reservoirs of highest interest. Also, measurements of actual carbon content from sediments in the priority reservoir systems would be useful to refining these general estimates based on statistical relationships and extrapolation from known values. Methods are available using bulk density, for example, to develop estimates of carbon totals and of uncertainty around those totals from rapid-assessment techniques.

In addition, better quantitative relationships could be developed from published literature, specific watershed models, and local measurements fit particularly to the watershed sediment yield and sediment carbon content specific to watersheds. Producing this new information would advance the work in both key directions identified here: more specific for individual watersheds around projects, and more certainty when those watersheds are aggregated to larger regional or national averages.

To assess terrestrial carbon accumulation and storage at finer spatial scales will require refined spatial data for soils and ecosystems, and field data providing location-specific carbon fluxes for each location. In addition, local changes in LULC could be assessed and the impact of these changes on carbon fluxes determined empirically, each of which will help narrow the spatial variability and the final uncertainty around these estimates of accumulation and storage, thereby supporting better estimates of the potential for future sequestration of atmospheric carbon to help mitigate climate change.

Abbreviations

ACWI	Advisory Committee on Water Information
af	acre-feet
ASDSO	Association of State Dam Safety Officials
AVHRR	Advanced Very High Resolution Radiometer
C	carbon
CH_4	methane
CO_2	carbon dioxide
DA	drainage area
DIC	dissolved inorganic carbon
DOC	dissolved organic carbon
GHG	greenhouse gas
GIS	geographic information system
GPP	gross primary production
gSSURGO	gridded Soil Survey Geographic Database
IPCC	Intergovernmental Panel on Climate Change
IWR	USACE Institute for Water Resources
LULC	land use and land cover
MODIS	Moderate Resolution Imaging Spectroradiometer
MRLC	Multi-Resolution Land Characteristics Consortium
NASA	National Aeronautics and Space Administration
NDVI	normalized difference vegetation index
NID	National Inventory of Dams
NLCD 2011	National Land Cover Database 2011
NOAA	National Oceanic and Atmospheric Administration
NPP	net primary production
NRCS	Natural Resources Conservation Service
OC	organic carbon
OC_{frac}	organic carbon fraction
Pg	Petagram
PIC	particulate inorganic carbon
POC	particulate organic carbon
ppm	parts per million
RESSED	Reservoir Sedimentation Database
SA	reservoir surface area
SOC	Soil Organic Carbon
SSURGO	Soil Survey Geographic Database
STATSGO	State Soil Geographic Database
Tg	Teragram
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
USDA	U.S. Department of Agriculture
y	year

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