Federal Land Management, Carbon Sequestration, and Climate Change in the Southeastern U.S.: A Case Study with Fort Benning

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Land use activities can have a major impact on the temporal trends and spatial patterns of regional land–atmosphere exchange of carbon. Federal lands generally have substantially different land management strategies from surrounding areas, and the carbon consequences have rarely been quantified and assessed. Using the Fort Benning Installation as a case study, we used the General Ensemble biogeochemical Modeling System (GEMS) to simulate and compare ecosystem carbon sequestration between the U.S. Army's Fort Benning and surrounding areas from 1992 to 2050. Our results indicate that the military installation sequestered more carbon than surrounding areas from 1992 to 2007 (76.7 vs 18.5 g C m^{-2} yr^{-1}), and is projected to continue sequestering more carbon from 2008 to 2050 (75.7 vs 25.6 g C m^{-2} yr^{-1}), mostly because of the proactive management approaches adopted on military training lands. Our results suggest that federal lands might play a positive and important role in sequestering and conserving atmospheric carbon because some anthropogenic disturbances (e.g., urbanization, forest harvesting, and agriculture) can be minimized or prevented on federal lands.

1. Introduction

Land use and land cover change (LUCC), which directly affects the biogeochemical interactions between the terrestrial biosphere and the atmosphere (*1, 2*), is responsible for large carbon fluxes in and out of terrestrial ecosystems (*3–5*). To accurately quantify the geographic distributions, magnitudes, and mechanisms of terrestrial carbon sequestration at local to global scales, it is critical to estimate the carbon exchange between the terrestrial biosphere and the atmosphere because of LUCC.

Federal lands offer a special case for examining how LUCC can affect biological carbon sequestration because these lands generally have substantially different land management strategies from surrounding areas and the federal can adopt proactive management approaches (*6*). Unfortunately, there have been few studies conducted to quantify and assess the carbon consequences on federal lands, especially biological carbon sequestration potential. Here, using the Fort Benning Installation as a case study, we used the General Ensemble biogeochemical Modeling System (GEMS), which is capable of dynamically assimilating LUCC information into the simulation process over large areas, to simulate and compare spatiotemporal patterns in ecosystem carbon sequestration between the Fort Benning installation and surrounding areas from 1992 to 2050. Fort Benning Installation was selected for analysis because (1) The Department of Defense (DoD) is one of the largest federal land managers in the United States with approximately 12.3 Mha under its control (*7*), and (2) The DoD has adopted an ecosystem approach for land management to maintain and improve the sustainability of military lands while supporting the DoD mission. The Strategic Environmental Research and Development Program (SERDP) Ecosystem Management Program (SEMP) was established in 1997 to help address critical deficiencies in knowledge which prohibit the DoD from fully achieving this goal. The Fort Benning installation was selected as the first test site for implementation of the objectives of the SEMP (*8*).

2. Data and Methods

2.1. Study Area. The study area consists of four counties: Chattahoochee, Marion, and Muscogee counties in Georgia, and Russell county in Alabama. The total area is 3852 km^2, of which Fort Benning is 738 km^2 (Figure 1). The study area has a subtropical climate, with an annual mean precipitation of 1245 mm and annual mean temperature of 17.8 °C between 1972 and 2007. The majority of the study area is forested, with intensive industrial forestry resulting in rapid cycling between clear-cutting and regenerating forest in at least parts of the region. The city of Columbus, Georgia, and the Fort Benning military complex account for much of the developed land. Other common land uses and land covers include agricultural land and wetlands. More background information can be found in the Supporting Information (SI).

2.2. LUCC Databases. Consistent, high-quality, and spatially explicit LUCC databases at 250 × 250 m resolution were developed using the FOREcasting SCEnarios of future land cover (FORE-SCE) model (*9*). FORE-SCE projects future land use changes based on historical land cover change trends, spatial characteristics of recent land cover change, and probability-of-occurrence surfaces for each unique land cover type. FORE-SCE relies heavily on USGS Land Cover Trends data (*10*) for model parametrization. We extrapolated Land Cover Trends results from the 1992 to 2000 time period, providing annual "prescriptions" for key variables (e.g., the rates of change for individual land cover types, likelihood of specific land cover transitions, and basic characteristics of patch size) required by FORE-SCE. Logistic regression was used to develop probability-of-occurrence surfaces for each land cover type based on biophysical and socioeconomic drivers related to land use type at a given location. Individual patches of new land cover were placed on the landscape in an iterative process until the annual scenario prescriptions were met. Patch sizes were uniquely assigned to each new patch by approximating the historical distribution of patch sizes for each land cover type. The process continues with yearly iterations, with a history variable tracking age classes for forest and other classes. A more detailed description of the model can be found in ref *11*.

2.3. Model Simulations. GEMS has been developed to upscale carbon stocks and fluxes from sites to regions with

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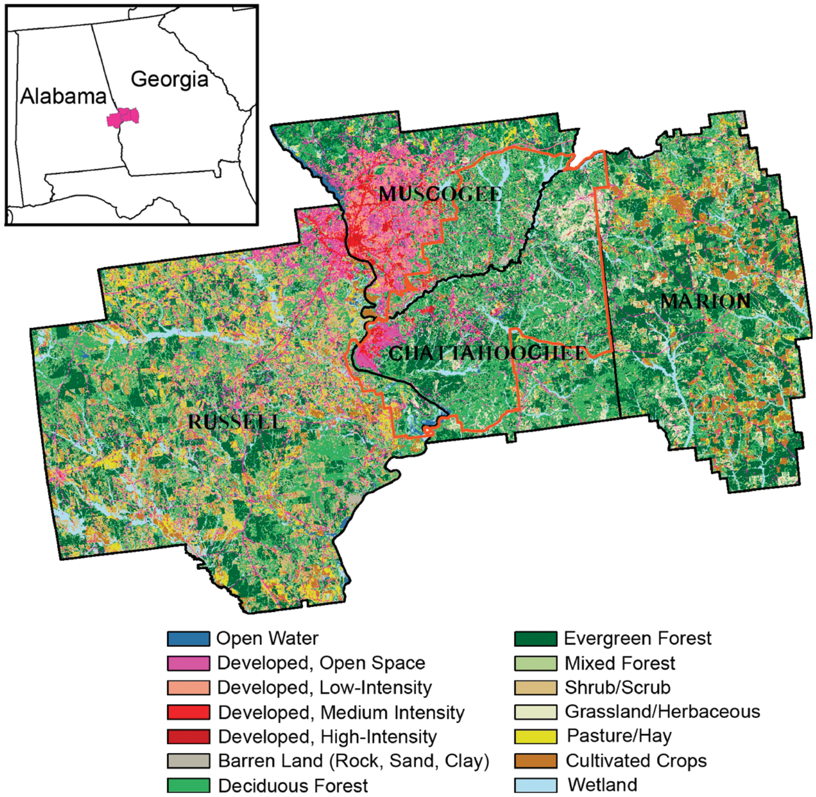

FIGURE 1. Geographic location and land cover of Fort Benning and its surrounding areas. Nearly 75% of the study area is forested, with cropland, developed land, and wetland covering most of the rest of the region. The area within the orange line is Fort Benning. The central-north part of the region (classified as "developed, open space") is the Columbus city.

a spatially explicit, dynamic consideration of LUCC information (*12–17*). GEMS relies on a site-scale biogeochemical model, the Erosion-Deposition-Carbon Model (EDCM) (*18*), to simulate carbon dynamics at the local scale. The spatial deployment of the site-scale model in GEMS is based on the spatial and temporal joint frequency distribution (JFD) of major driving variables (e.g., land use and land cover change, climate, soils, disturbances, and management). The JFD was generated by overlaying these geospatial data layers with a common grid size of 250 × 250 m. Model simulation units were the unique combinations of these data layers with the finest simulation unit being one grid cell (i.e., 250 × 250 m). The uncertainties of data layers at coarser resolutions were incorporated into GEMS simulations via a Monte Carlo approach. This approach embedded in GEMS maximally uses the finest information contained in some data layers (LUCC data in this study, for example), and other coarser resolution data layers are scaled down to the finest resolution through representation of uncertainty. A more detailed description of the model can be found in Liu et al. (*12, 18*) and Liu (*14*).

Major forest types in the region were deciduous, mixed, and pine forest. Frequent, low-intensity prescribed burning is a major forest management practice at Fort Benning and the surrounding areas. Prescribed burns and wildfires have been a part of the landscape for at least thousands of years. In part, they have been used as a tool to sustain the existence of longleaf pine forests in the south. In recent history, fires have been used as an efficient way of controlling the development of understory to improve human and machinery traffic at the installation and plantations outside. In our model, a two-year fire frequency was implemented to control the understory. We used the same fire regime for both Fort Benning and surrounding areas. In the model, the prescribed burns removed all aboveground biomass and litter, but had no direct impact on canopy trees. For clear-cutting events, it was assumed that only stems were removed from the site, other materials including branches and leaves were left on-site decaying.

GEMS was run from 1992 to 2050 using LUCC FORE-SCE projections and other databases described in the SI. In order to investigate temporal changes of carbon sequestration in the region, we divided the study period into the contemporary or current (1992−2007) and the future (2008−2050). Results on model validation can be found in SI Figure S2.

2.4. Analysis. Carbon sequestration was calculated by the difference between current year's and previous year's ecosystem carbon stock, which was equal to net biome productivity (NBP) using the carbon cycle concepts and terminology of Chapin et al. (*19*). Ecosystem carbon sequestration included the amount of net carbon accrued in live biomass, the forest floor, and the soil. Positive values represent uptake, and negative values indicate carbon loss from the biome. All the fluxes (e.g., grain yield, wood harvest, and carbon sequestration) were calculated on the basis of total land area in the region. To compare ecosystem carbon dynamics between Fort Benning and surrounding areas, we calculated the carbon sequestration at Fort Benning and surrounding areas.

3. Results

3.1. Comparisons of Spatiotemporal Patterns in Carbon Sequestration. The distributions of carbon sequestration for Fort Benning and surrounding areas showed a high degree of spatial heterogeneity both currently (1992−2007) and in the future (2008−2050) (Figure 2). It was apparent that the spatial occurrence or extent of carbon loss (red and pink) at Fort Benning was markedly lower than that in surrounding areas, whereas the area frequency of carbon sequestration (green and blue) was notably higher. From the land cover map (Figure 1), we can see that land use in the west (i.e., Russell County in Alabama) had more lands in pasture/hay, grasslands, and shrub/scrub than in the eastern part of the

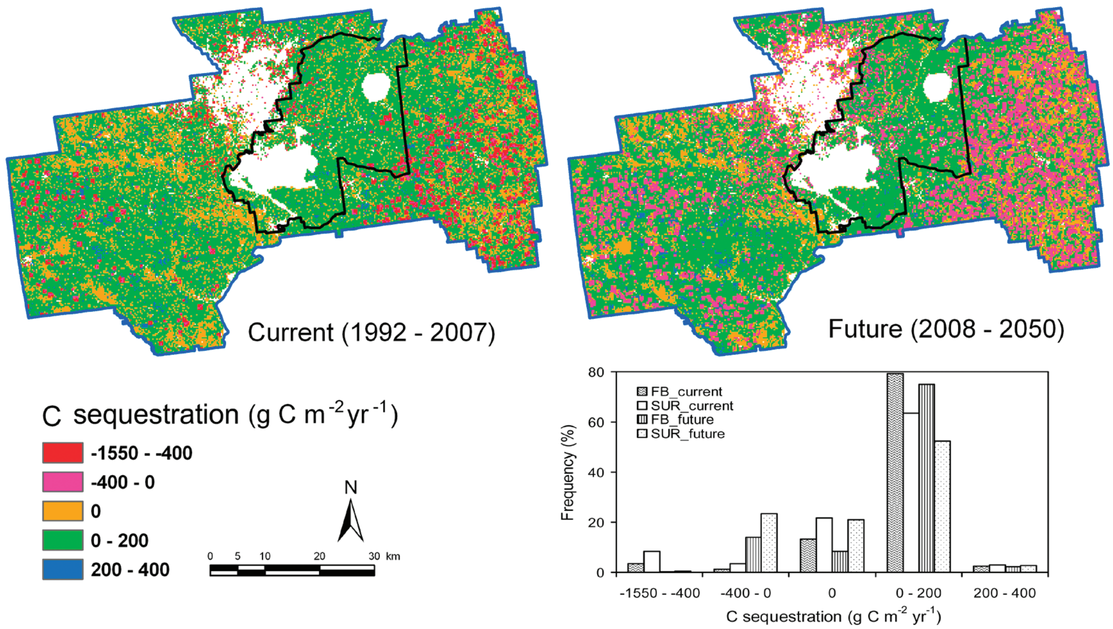

FIGURE 2. Spatial distributions of carbon (C) sequestration for Fort Benning (FB) and surrounding areas (SUR) during the periods 1992–2007 (current) and 2008–2050 (future). The inset graph denotes the area frequency distribution of C sequestration. A negative sequestration represents a movement of C from the landscape.

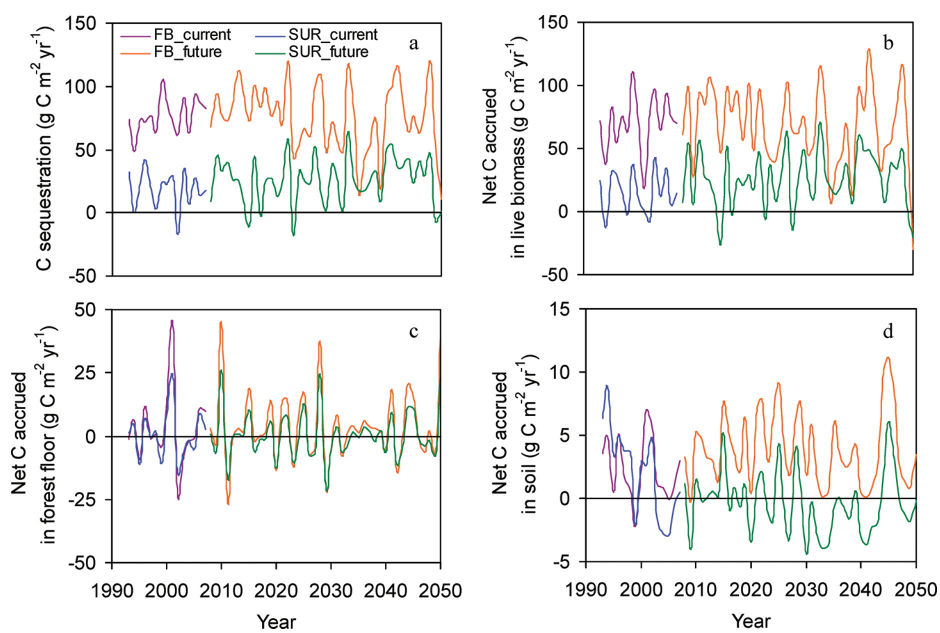

FIGURE 3. The contributions of net C accrued in live biomass (b), forest floor (c), and soil (d) to ecosystem C sequestration (a).

region (i.e., three counties in Georgia). Although forest was the dominant land cover in the eastern part, active and widespread forest cutting under short rotation forestry only happened in Marion County while land use change in other two counties was relatively small (except urbanization) (Figure 5). This east-to-west difference in land use practices across political boundaries resulted in obvious differences in carbon dynamics (Figure 2).

Overall, from 1992 to 2007, 4.8% of Fort Benning land area lost carbon, 13.3% was carbon neutral (orange), and 81.9% gained carbon. In contrast, the area losing carbon in surrounding areas was 11.9%, the carbon neutral area was 21.6%, and the area sequestering carbon was 66.5%. From 2008 to 2050, the areas losing carbon, carbon neutral, and carbon sequestration were 14.3, 8.5, and 77.2% and 24, 21, and 55% for Fort Benning and surrounding areas, respectively. Meanwhile, the total area losing carbon increased from the period 1992–2007 to 2008–2050 for both Fort Benning and surrounding areas, but the magnitude of carbon release rate significantly declined, especially for surrounding areas.

The Fort Benning installation sequesters more carbon than surrounding areas and is projected to continue this in the future. Average carbon sequestration rates from 1992 to 2007 and from 2008 to 2050 were 76.7 vs 18.5 g C m^{-2} yr^{-1} and 75.7 vs 25.6 g C m^{-2} yr^{-1} for Fort Benning and surrounding areas, respectively (Figure 3a). Both current and future carbon sequestration demonstrated strong synchronized interannual variability for Fort Benning and surrounding areas. However, the carbon sequestration at Fort Benning was consistently higher than that in surrounding areas.

3.2. Partitioning Carbon Sequestration. We partitioned the ecosystem carbon sequestration into the carbon accrued in live biomass, the forest floor, and the soil. The amount of carbon accrued in live biomass is the sum of net carbon

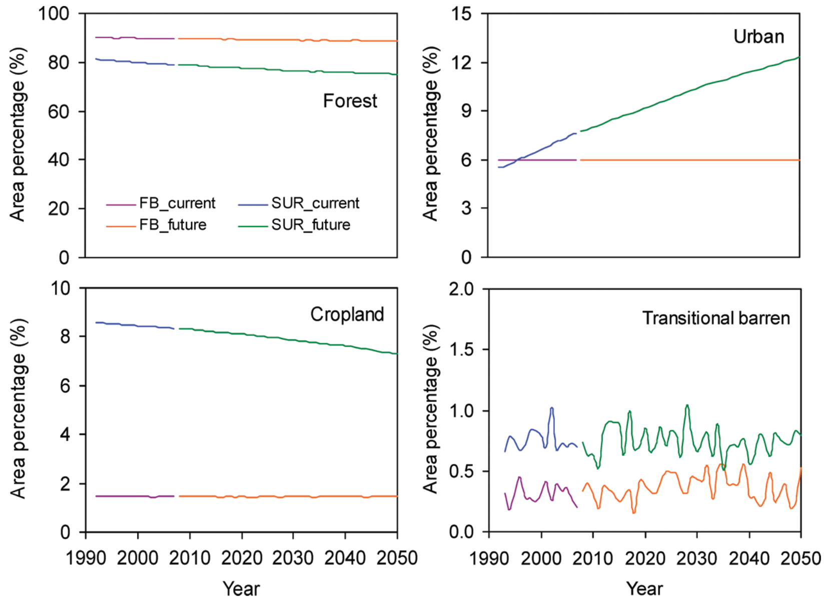

FIGURE 4. Current and future land cover dynamics for three major land cover types (forest, urban, and cropland) and transitional barren (caused primarily by forest harvesting) in Fort Benning and surrounding areas.

accumulation in ecosystem live components, including leaf, fine root, fine branch, large wood, and coarse root. The amount of carbon accrued in the forest floor is the sum of net carbon accumulation in fine and coarse woody debris, and surface litter. The amount of carbon accrued in the soil is the net accumulation of organic carbon in the top 20 cm of soil. The results demonstrated that carbon accrued in live biomass accounted for most of the carbon sequestration for Fort Benning and surrounding areas both at present and in the future (Figure 3a–d). From 1992 to 2007, the contributions of carbon accrued in live biomass, the forest floor, and the soil to ecosystem carbon sequestration for Fort Benning and surrounding areas were 92.8, 4.2, and 3.0% vs 85.8, 2.9, and 11.3%. From 2008 to 2050, the amount of net carbon accumulated in live biomass, the forest floor, and the soil accounted for 89.7, 5.1, and 5.2% of ecosystem carbon sequestration at Fort Benning and 99.5, 1.7, and −1.2% in surrounding areas.

3.3. Differences between Fort Benning and Surrounding Areas. Annual precipitation and mean annual temperature were not significantly different between Fort Benning and surrounding areas. Temporal changes of annual precipitation and mean annual temperature for Fort Benning and surrounding areas at present and in the future are detailed in SI Figure S1. However, drastic differences in land cover change were found between Fort Benning and surrounding areas. Land cover composition was relatively stable over time at Fort Benning, whereas rapid urban development at the expense of forest and cropland occurred in surrounding areas. The coverage of transitional barren (primarily caused by forest harvesting), which was negatively related to the amount of carbon accrued in live biomass, was higher in surrounding areas than at Fort Benning. From 1992 to 2050, the areal extent of transitional barren varied between 0.2 and 0.6% at the installation. In contrast, transitional barren ranged from 0.5 to 1.0% in the surrounding areas (Figure 4).

4. Discussion

LUCC is critical in determining the distribution, magnitude, and mechanisms of terrestrial carbon sources and sinks at local to global scales (*20–23*). Military installations generally have substantially different land management strategies from surrounding areas, and the carbon consequences have never been quantified and assessed. Our results indicate that the Fort Benning military installation sequestered more carbon than surrounding areas at present, and is projected to continue sequestering more carbon in the future, mostly because of differences in land use activities. The frequency of land cover change at Fort Benning was much less than that in surrounding areas (Figure 5). The areal extent of land cover that changed at some point between 1992 and 2007 was 4.6 vs 11.4% for Fort Benning and surrounding areas, respectively. About 15.4% of Fort Benning vs 29% of surrounding areas changed land cover at some point between 2008 and 2050. The total land cover change consisted of clear-cutting and subsequent regeneration of forest lands and urban development. Forest cutting occurred both in Fort Benning and surrounding areas but was concentrated in the eastern part of surrounding areas. Urban development was significant around Columbus, Georgia within the surrounding areas. The spatial occurrence or extent of carbon loss from the biome corresponded well with the areas where land cover changes happened (Figures 2 and 5). This suggests that LUCC is responsible for large carbon fluxes out of the terrestrial ecosystems, and higher amounts of land cover change in surrounding areas led to lower rates of carbon sequestration in these areas than at the Fort Benning installation.

As shown in Figure 3, the net carbon accrued in live biomass accounted for most of the carbon sequestration for both Fort Benning and surrounding areas. Therefore, the comparison of carbon fluxes out of the ecosystem directly from live biomass between Fort Benning and surrounding areas might help explain why Fort Benning sequesters more carbon than surrounding areas. The carbon removal from the biome by forest harvesting was generally lower at Fort Benning than that in surrounding areas except 2035 and 2050, when the carbon removal at Fort Benning was higher (Figure 6a), leading to less net carbon accumulations in live biomass for these two years (Figure 3b). Overall, average carbon removals from 1992 to 2007 by forest harvesting and crop yield were 15.7 vs 39.1 g C m^{-2} yr^{-1} and 1.6 vs 9.2 g C m^{-2} yr^{-1} for Fort Benning vs surrounding areas, respectively. The removals from 2008 to 2050 were 27 vs 44.8 g C m^{-2} yr^{-1} and 1.9 vs 8.9 g C m^{-2} yr^{-1}. The higher carbon removals from live biomass in surrounding areas resulted in lower carbon sequestration in surrounding areas than the sequestration at Fort Benning.

Carbon sequestration demonstrated strong synchronized interannual variability for Fort Benning and surrounding

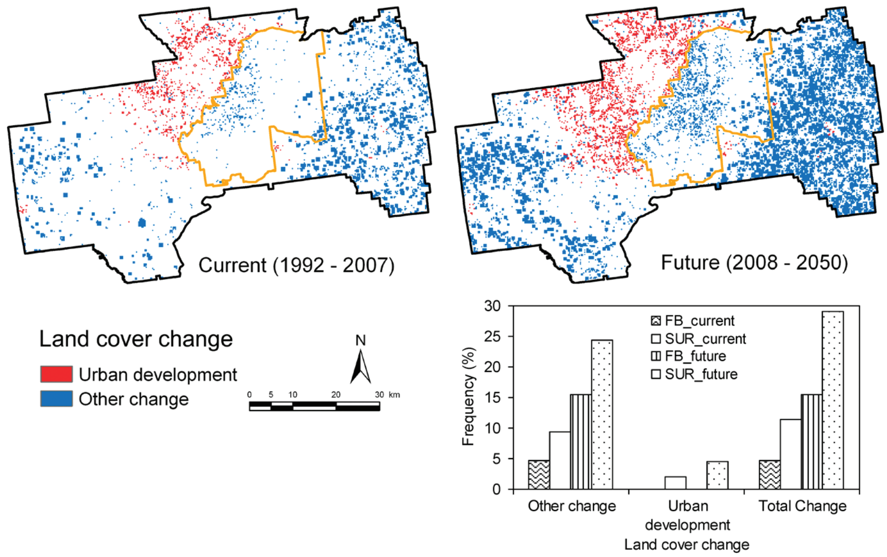

FIGURE 5. The distributions of land cover changed from 1992 to 2007 and from 2008 to 2050 in Fort Benning and surrounding areas. Urban development (in red) was primarily on the outskirts of Columbus, Georgia. Other changes, dominated by clear-cutting and subsequent regeneration of forest lands, primarily occurred in surrounding areas.

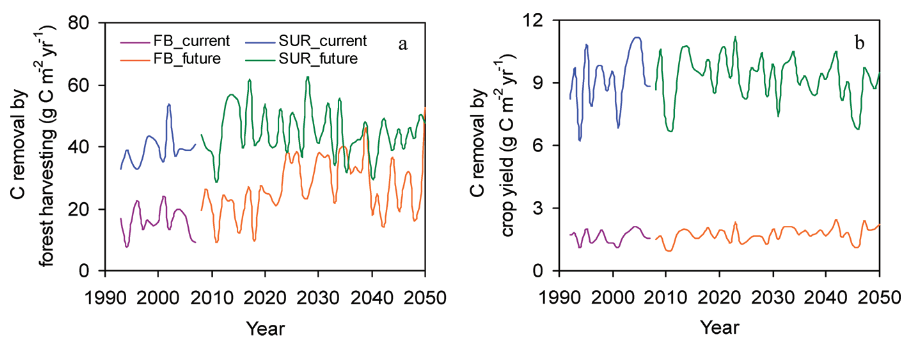

FIGURE 6. C removals by forest harvesting (a) and crop yield (b) in Fort Benning and surrounding areas at present and in the future.

areas (Figure 3). Apparently, the synchronized variation was controlled by the interannual variability of climate. The climate between Fort Benning and surrounding areas was not significantly different and manifested strong interannual synchronization (see SI Figure S1). The differences in land use activities between Fort Benning and surrounding areas were not strong enough to change the synchronization because most land use change activities at regional scales occurred at site scale with limited areal extent. Interannual climate variability-driven fluctuations in regional and global ecosystem carbon exchange between the land and atmosphere have been reported in many previous studies (*24–26*). However, land cover and land use change that occurred at local scale substantially affected the spatial distribution and magnitude of regional carbon sequestration, accounting for most of the differences in the carbon sequestered between Fort Benning and surrounding areas (Figures 2 and 5).

Current prescribed burns effectively prevent the accumulation of carbon in understory and litter. Without burning, litter (including course woody debris) and understory can potentially accumulate to about 5−15 Mg C ha^{-1} in forests in the region (*27*). However, controlled burns and wildfires have been an intrinsic part of the forest ecosystems in the region. Elimination of burns would change forest types and structure, and therefore is not likely going to happen in reality. Consequently, the room for increasing carbon sequestration through fire and understory management is pretty small.

Our long-term land use change projections did not include any recent Fort Benning development and future plans to build additional ranges. For example, the construction of a new 730 ha digital multi-purpose range complex (DMPRC) was not considered in this study. This and other additional ranges will likely reduce the capability of carbon sequestration at the base in the future. But the magnitude can only be predicted with detailed information on the location, areal extent, and disturbance intensity of the additional ranges. Because the expanded mission at Fort Benning is highly related to the cuts and reshuffle of other military installations carried out by the DoD under the Base Realignment and Closure program, it is necessary to evaluate carbon sequestration at multiple installations simultaneously to account for all the negative and positive changes (i.e., abandonment and expansion) happened across bases. Our land use change projection was based on the satellite observations from 1992 to 2000 and can be considered as "business as usual". Since 2000, Fort Benning and surrounding areas have experienced significant changes largely because of the mission expansion of Fort Benning. The impacts of such changes on land use and carbon sequestration have not been investigated because of lacking relevant data, but should be studied when data become available in the future. We only quantified carbon storage change in terrestrial ecosystems inside and outside the installation. Future research should strive for a more comprehensive view of the carbon footprint of the installation, including impacts of personnel housing and related activities that partially drive urbanization of surrounding lands.

Our study quantified the differences in carbon sequestration between military installation and surrounding areas under "business as usual" future scenario. The results, generally applicable to other federal lands, suggest that federal lands, which covers approximately 271.9 Mha (30%) of land throughout the United States (http://www.gsa.gov/gsa/ cm_attachments/ GSA_DOCUMENT/ Annual%20Report%20%20FY2003-R4_R2M-n11_0Z5RDZ-i34K-pR.pdf), can continue to play a positive and significant role in sequestering and conserving atmospheric carbon because these lands can adopt proactive management approaches and some anthropogenic disturbances (e.g., urbanization, forest harvesting, and agriculture) can be minimized or prevented on federal lands.

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Supporting Information Available

Additional experimental details and references. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Schimel, D. S.; House, J. I.; Hibbard, K. A.; Bousquet, P.; Ciais, P.; Peylin, P.; Braswell, B. H.; Apps, M. J.; Baker, D.; Bondeau, A.; et al. Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. *Nature* **2001**, *414*, 169–172.

(2) Houghton, R. A., Goodale, C. L. Effects of land-use change on the carbon balance of terrestrial ecosystems. In *Ecosystems and Land Use Change*; DeFries, R. S., Asner, G. P., Houghton, R. A., Eds.; American Geophysical Union: Washington, DC 2004; pp 85−98.

(3) Fang, J. Y.; Chen, A. P.; Peng, C. H.; Zhao, S. Q.; Ci, L. Changes in forest biomass carbon storage in China between 1949 and 1998. *Science* **2001**, *292*, 2320–2322.

(4) Houghton, R. A. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850−2000. *Tellus B* **2003**, *55*, 378–390.

(5) Kauppi, P. E.; Ausubel, J. H.; Fang, J. Y.; Mather, A. S.; Sedjo, R. A.; Waggoner, P. E. Returning forests analyzed with the forest identity. *Proc. Natl. Acad. Sci. U.S.A.* **2006**, *103*, 17574–17579.

(6) Baskaran, L. M.; Dale, V. H.; Efroymson, R. A.; Birkhead., W. Habitat modeling within a regional context: an example using gopher tortoise. *American Midland Nat.* **2006**, *155*, 335–351.

(7) American Forestry Association (AFA). *Enhancing Management of Forests and Vegetation on Department of Defense Lands: Opportunities, Benefits, And Feasibility*, 230-R-005; U.S. EPA Office of Planning and Evaluation: Washington, DC, 1992.

(8) Kress, M. R. *Long-Term Monitoring Program, Fort Benning, GA; Ecosystem Characterization and Monitoring Initiative*, Version 2.1, Technical Report ERDC/EL TR-01- 15; U.S. Army Engineer Research and Development Center: Vicksburg, MS, 2001.

(9) Sohl, T. L.; Sayler, K. L.; Drummond, M. A.; Loveland, T. R. The FORE-SCE model: A practical approach for projecting land use change using scenario-based modeling. *J. Land Use Sci.* **2007**, *1*, 1–24.

(10) Loveland, T. R.; Sohl, T. L.; Stehman, S. V.; Gallant, A. L.; Sayler, K. L.; Napton, D. E. A strategy for estimating the rates of recent United States land-cover changes. *Photogrammetric Eng. Remote Sensing* **2002**, *68*, 1091–1099.

(11) Sohl, T. L.; Sayler, K. L. Using the FORE-SCE model to project land cover change in the southeastern United States. *Ecol. Modell.* **2008**, *219*, 49–65.

(12) Liu, S. G.; Loveland, T. R.; Kurtz, R. M. Contemporary carbon dynamics in terrestrial ecosystems in the Southeastern plains of the United States. *Environ. Manage.* **2004a**, *33*, S442–S456.

(13) Liu, S. G.; Kaire, M.; Wood, E.; Diallo, O.; Tieszen, L. L. Impacts of land use and climate change on carbon dynamics in south-central Senegal. *J. Arid Environ.* **2004b**, *59*, 583–604.

(14) Liu, S. G. Quantifying the spatial details of carbon sequestration potential and performance. In *Science and Technology of Carbon Sequestration*; McPherson, B., Sundquist, E.; American Geophysical Union: Washington, DC (in press).

(15) Tan, Z.; Liu, S. G.; Johnston, C. A.; Loveland, T. R.; Tieszen, L. L.; Liu, J.; Kurtz, R. M. Soil organic carbon dynamics as related to land use history in the Northwestern Great Plains. *Global Biogeochem. Cycles* **2005**, *19*, GB3011, DOI: 10.1029/2005GB002536.

(16) Tan Z.; Liu, S. G.; Johnston, C. A.; Liu, J.; Tieszen, L. L. Analysis of ecosystem controls on soil carbon source-sink relationships in the northwest Great Plains. *Global Biogeochem. Cycles* **2006**, *20*, GB4012, DOI: 10.1029/2005GB002610.

(17) Tan Z.; Liu, S. G.; Li, Z.; Loveland, T. R. Simulated responses of soil organic carbon stock to tillage management scenarios in the Northwest Great Plains. *Carbon Balance Manage.*, **2007**, *2*, 7, DOI: 10.1186/1750-0680-2-7.

(18) Liu, S. G.; Bliss, N.; Sundquist, E.; Huntington, T. G. Modeling carbon dynamics in vegetation and soil under the impact of soil erosion and deposition *Global Biogeochem. Cycles* **2003**, *17*, 1074, DOI: 10.1029/2002GB002010.

(19) Chapin, F. S.; Woodwell, G. M.; Randerson, J. T.; Rastetter, E. B.; Lovett, G. M.; Baldocchi, D. D.; Clark, D. A.; Harmon, M. E.; Schimel, D. S.; Valentini, R.; et al. Reconciling carbon-cycle concepts, terminology, and methods. *Ecosystems* **2006**, *9*, 1041–1050.

(20) Watson R. T.; Noble, I. R.; Bolin, B.; Ravindranath, N. H.; Verardo, D. J.; Dokken, D. J. *Land use, Land-Use Change, And Forestry, A Special Report of the Intergovernmental Panel of Climate Change*; Cambridge University: Cambridge, UK, 2000.

(21) Canadell, J. G. Land use effects on terrestrial carbon sources and sinks. *Sci. China, Ser. C: Life Sci.* **2002**, *45*, 1–9.

(22) Zaehle, S.; Bondeau, A.; Carter, T. R.; Cramer, W.; Erhard, M.; Prentice, I. C.; Reginster, I.; Rounsevell, M. D. A.; Sitch, S.; Smith, B.; et al. Projected changes in terrestrial carbon storage in Europe under climate and land-use change, 1990−2100. *Ecosystems* **2007**, *10*, 380–401.

(23) Schulp, C. J. E.; Nabuurs, G. J.; Verburg, P. H. Future carbon sequestration in Europe—Effects of land use change. *Agric. Ecosyst. Environ.* **2008**, *127*, 251–264.

(24) Kindermann, J.; Würth, G.; Kohlmaier, G. H.; Badeck, F. W. Interannual Variation of Carbon exchange fluxes in terrestrial ecosystems. *Global Biogeochem. Cycles* **1996**, *10* (4), 737–755.

(25) Scholze, M.; Kaplan J. O.; Knorr, W.; Heimann, M. Climate and interannual variability of the atmosphere-biosphere 13CO_2 flux. *Geophys. Res. Lett.* **2003**, *30*(2), 1097, DOI: 10.1029/2002GL015631.

(26) Arnone, J. A.; Verburg, P. S. J.; Johnson, D. W.; Larsen, J. D.; Jasoni, R. L.; Lucchesi, A. J.; Batts, C. M.; von Nagy, C.; Coulombe, W. G.; Schorran, D. E.; et al. Prolonged suppression of ecosystem carbon dioxide uptake after an anomalously warm year. *Nature* **2008**, *455*, 383–386.

(27) Smith, J. E.; Heath, L. S. *A Model of Forest Floor Carbon Mass for United States Forest Types*, Res. Pap. NE-722; U.S. Department of Agriculture, Forest Service, Northeastern Research Station: Newtown Square, PA, 2002.

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