Reducing concentrations of carbon dioxide (CO$_2$) and other greenhouse gases (GHG) in Earth’s atmosphere is identified as one of the most pressing modern-day environmental issues (IPCC 2007). As a signatory country to the United Nations Framework Convention on Climate Change (UNFCCC), the United States is actively engaged in a critical international effort to find solutions to the problems posed by climate change. Agriculture, in addition to being affected by the climate, contributes to climate change through its exchanges of GHG with the atmosphere. Thus, the management of agricultural systems to sequester atmospheric CO$_2$ as soil organic carbon (SOC) and to minimize GHG emissions has been proposed as a partial solution to the climate change problem. In this paper, we discuss the potential role of agriculture in the United States to mitigate climate change through sequestration of carbon (C). We also identify critical knowledge gaps where further research is needed.

Carbon enters terrestrial ecosystems, including agriculture, through photosynthesis by green plants that assimilate CO$_2$ and fix it into organic forms (figure 1). Some C eventually enters the soil, where its subsequent cycling and storage among SOC and soil inorganic carbon (SIC) pools determine its residence time and ultimately its return back to the atmosphere. The rate of photosynthetic CO$_2$ assimilation depends on soil fertility, climate, and management, which, in addition to other soil and plant factors, influence rates of C return to the atmosphere. Three major thrusts of GHG mitigation research in agriculture are (1) developing management practices to enhance the assimilation of atmospheric CO$_2$ by vegetation, (2) managing the movement of C from the plants/animals into the soil, and (3) altering the cycling of SOC to increase its residence time. Sequestering C within the soil organic matter (SOM) is among the best options for C storage in terrestrial ecosystems. Besides helping offset CO$_2$ emissions into Earth’s atmosphere, C sequestration into SOM provides multiple benefits, such as improved soil quality through enhanced fertility, soil structure and aggregate stability, water holding capacity, and the capacity to reduce toxic elements.

Two other gases additional to CO$_2$—methane (CH$_4$) and nitrous oxide (N$_2$O)—are important agricultural GHG and deserve mentioning. Agricultural CH$_4$ emissions occur primarily from livestock through enteric fermentation and from
In 2002, harvested and/or development needs for enhancing recommended management practices for briefly review our present knowledge of pools (figure 2). The following sections will continue developing and implementing strategies and technologies are developed. However, even as new—capture, and –sequestration technologies are developed, it will remain important for agriculture to decades to buy time while new, C–saving, and –sequestration technologies are developed. Developed, even as new strategies and technologies are developed, it will remain important for agriculture to continue developing and implementing successful soil C sequestration practices which maintain or enhance SOC and SIC pools (figure 2). The following sections will briefly review our present knowledge of recommended management practices for important US agricultural sectors. At the end of each section, critical research gaps and/or development needs for enhancing US agriculture’s C sequestration capabilities are identified, which are listed together in abbreviated form in table 1.

**CARBON POOLS AND SEQUESTRATION**

Global C can be partitioned into five large pools: oceanic (38,000 Pg C, wherePg = petagram = 10\(^15\) g [42,000 billion t]; geologic (5,000 Pg [5,500 billion t]; pedologic, or soils-based (2,460 Pg [2,710 billion t]—1,500 Pg [1,650 billion t] in SOC and 950 Pg [1,050 billion t] in SIC); atmospheric (800 Pg [887 billion t], increasing at the rate of ~4.1 Pg C yr\(^{-1}\) [4.5 billion t yr\(^{-1}\)] [IPCC 2007]); and biotic C (550 Pg [606 billion t]) (Houghton 2007; Lal 2004, 2006). Approximately 9 Pg (9.9 billion t) of C is presently released to the atmosphere each year from burning fossil fuels and industrial activity, and another ~1.5 Pg (1.7 billion t) is released from deforestation and land use change (Global Carbon Project 2009). Each year, about 60 Pg (66 billion t) C is exchanged in each direction between terrestrial ecosystems and the atmosphere. Although 84% of US net C emissions are from fossil fuel consumption and only 7% from agriculture, the nearly 2,500 Pg (2,800 billion t) C stored in terrestrial soils and the 60 Pg (66 billion t) C exchange with the atmosphere will be important in the next few decades to buy time while new, C-saving, –capture, and –sequestration technologies are developed. Developed, even as new strategies and technologies are developed, it will remain important for agriculture to continue developing and implementing successful soil C sequestration practices which maintain or enhance SOC and SIC pools (figure 2). The following sections will briefly review our present knowledge of recommended management practices for important US agricultural sectors. At the end of each section, critical research gaps and/or development needs for enhancing

**AGRICULTURAL SECTORS**

**Cropping Systems.** In 2002, harvested croplands in the United States covered about 179 Mha (442 million ac), including 138 Mha (340 million ac) used for crops, 16 Mha (40 million ac) as idle cropland, and 25 Mha (62 million ac) as pasture (USDA NASS 2008a; USDA NRCS 2003). Recommended management practices to increase SOC in croplands include increasing cropping frequency and growing high-residue crops. Alternatively, soil C losses can be minimized by reducing soil tillage (effectiveness is soil type and crop dependent), maximizing plant water use efficiency (more efficient rotations and improved irrigation management), and application of surface mulches that shade the soil (Follett 2001). Incorporation of perennial grasses and grass/legume mixtures can be especially effective to allocate a higher percentage of plant biomass C to belowground soil C sequestration, extend the growing season, better utilize soil water, and reduce tillage disturbance compared to annual crops. Improved practices on croplands can increase SOC sequestration rates to 0.1 to 1 Mg (Mg = megagram = 10\(^6\) g) C ha\(^{-1}\) yr\(^{-1}\) (89 to 890 lb C ac\(^{-1}\) yr\(^{-1}\)), with accumulation rates diminishing as soils approach new equilibria (CAST 2004). Higher rates are expected in the conversion of annual croplands to perennial grasses/legumes as conservation set-asides or pastures (Conant et al. 2001; Follett 2001).

Critical research needs for further enhancing C sequestration of cropped systems include (1) clarifying the interactions among tillage, climate, and soil type on C sequestration, (2) quantifying above- and below-ground plant contributions to SOC, and (3) evaluating C sequestration practices for total GHG emissions, since recommended practices like incorporation of legumes or fertilizer additions, which enhance soil C, may enhance the soil release of N\(_2\)O (table 1).

**Grazinglands.** About 37% of the total land area in the US (236 Mha [580 million ac]) was occupied by grazinglands in 2002 (USDA ERS 2007), thereby contributing about 15% to US soil C sequestration potential (Lal et al. 2003). Grazingland

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**Figure 2**

Strategies for carbon sequestration. Strategies for enhancing carbon (C) sequestration may be achieved either through increasing soil organic C (SOC) or soil inorganic C (SIC) pools. For SOC, this encompasses practices which increase the sequestration efficiency of C inputs, improve soil structure, or decrease SOC losses. Increases in the SIC pool result from such management practices as biosolids application, liming, and conservation of water within the root zone.
soil C sequestration is affected by climate (Derner et al. 2006; Jones and Donnelly 2004; Ingram et al. 2008; Svejcar et al. 2008), biome (Conant et al. 2001), and management (grazing, N inputs, restoration) (Derner and Schuman 2007). Rangeland management with proper stocking rates, adaptive management, and destocking during drought can result in sequestration of 11 Tg C yr$^{-1}$ (1 Tg = 10$^{12}$g) (12 million tn C yr$^{-1}$) nationwide. Sequestration rates decline in rangelands over time without added inputs, and the greatest potential gains are on marginal or poorly-managed lands (Conant et al. 2001; Conant and Paustian 2002; Derner and Schuman 2007; Swift 2001). The amount of C stored in improved pasturelands (mostly mesic systems characteristic of the eastern United States) can be double that of cropland and can be enhanced by adjusting stocking rate, plant species, and fertilizer additions; although, the later can reduce the C advantage through increased emissions of N$_2$O (Franzluebbers 2005).

Rates of SOC sequestration under best management practices range from 0.070 to 0.30 Mg C ha$^{-1}$ yr$^{-1}$ (62 to 270 lb C ac$^{-1}$ yr$^{-1}$) for rangelands (Schuman et al. 1999, Derner and Schuman 2007) and from 0.30 to 1.4 Mg C ha$^{-1}$ yr$^{-1}$ (270 to 1200 lb ac$^{-1}$ yr$^{-1}$) for pastures (Schnabel et al. 2001; Franzluebbers 2005).

Critical research needs in grazingland soil C sequestration include (1) quantifying C sequestration in arid shrublands (almost no data presently), (2) evaluating forage species mixtures for optimizing C sequestration and minimizing non-CO$_2$ trace gas emissions, and (3) quantifying interactions of management with climate on C sequestration (table 1).

### Critical research needs for developing and implementing US agricultural carbon sequestration and non-CO$_2$ greenhouse gases mitigation practices.

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Critical research needs in grazingland soil C sequestration include (1) quantifying C sequestration in arid shrublands (almost no data presently), (2) evaluating forage species mixtures for optimizing C sequestration and minimizing non-CO$_2$ trace gas emissions, and (3) quantifying interactions of management with climate on C sequestration (table 1).

**Agroforestry.** Agroforestry is the intentional integration of woody plants into crop and livestock systems to improve soil, water and air quality, and wildlife habitat while supporting sustainable production of food, feed, fiber, and energy (Ruark et al. 2003; Garrett 2009). It represents a significant opportunity for sequestering C on agricultural lands in that a substantial proportion of the C is sequestered in woody biomass, thus creating a system that sequesters a large amount of C per unit area and for a longer duration than many other practices (Montagnini and Nair 2004; Schoeneberger 2009). Since agroforestry is not explicitly inventoried within the two major natural resource inventories in the United States—the USDA Forest Service Forest Inventory Analysis and the USDA Natural Resources Conservation Service (NRCS) Natural Resources Inventory...
Further, cover crops offer many benefits beyond C sequestration, such as increasing soil fertility and enhancing disease control (Delgado et al. 2007).

More research is needed in horticultural systems to (1) evaluate potentially feasible horticultural management practices for storing soil C, (2) quantify C sequestration in promising horticultural systems, and (3) further evaluate benefits of conservation practices beyond C sequestration (table 1).

**Turfgrass.** Although not an agricultural enterprise in the usual sense, turfgrass represents an important feature on the US landscape in regard to C (Jenkins 1994). Many land areas previously used for agriculture have now become part of the urban landscape, including lands that have been converted to C-sequestering turf-grasses. Rates of SOC sequestration under turf have a fairly broad range, from 0.32 to ~1 Mg C ha\(^{-1}\) yr\(^{-1}\) (290 to 890 lb ac\(^{-1}\) yr\(^{-1}\)) (Banarayanake et al. 2003; Huh et al. 2008; Qian et al. 2010; Qian and Follitt 2002). Using the lowest rate of sequestration of about 0.32 Mg C ha\(^{-1}\) yr\(^{-1}\) (290 lb C ac\(^{-1}\) yr\(^{-1}\)) applied to the 16 Mha (40 million ac) of turfgrass reported by Miliesi et al. (2005), we estimate that about 5 Tg (5.5 million tn) C are sequestered by turfgrass systems each year. Critical needs in turfgrass include (1) knowledge to incorporate the combined effects of urbanized land area expansion with agricultural land area losses into national estimates of soil C sequestration, (2) improved quantification of rates and areas for C sequestration under various urban land uses, and (3) obtaining a better understanding of the role that growing turfgrass may have on emissions of other GHGs such as \(\text{N}_2\text{O}\) and \(\text{CH}_4\) (table 1).

**Wetlands and Organic Soils.** Although organic soils and wetland agriculture each constitute ~1% or less of cropped areas in the United States, their high rates of GHG emissions deserve special attention. Organic soils develop under waterlogged conditions, where lack of oxygen inhibits organic matter decomposition. However, with drainage, microbial oxidation of the organic matter causes them to subside and release \(\text{CO}_2\) at high rates. Approximately 7.5% of the 10 Mha (25 million ac) of organic soils in the United States have been drained for agriculture, with about half in Florida and California and the remainder mostly in Minnesota, Michigan, Wisconsin, Indiana, Iowa, Illinois, New York, North Carolina, and South Carolina. Annual \(\text{CO}_2\) emissions from soils in the Everglades Agricultural Area (EAA) in Florida were estimated to release about 25.4 Mg \(\text{CO}_2\)-C ha\(^{-1}\) (11.3 tn \(\text{CO}_2\)-C ac\(^{-1}\)), which is equivalent to 6.93 Mg C ha\(^{-1}\) (3.08 tn C ac\(^{-1}\)) (Allen 2007). However, estimated emissions rates have dropped about 43% (3.95 Mg C ha\(^{-1}\) [1.76 tn C ac\(^{-1}\)]) following declining rates of soil subsidence (Snyder 2005) in more recent years. Recent emissions estimates for 240,000 ha (590,000 ac) of the EAA constitute a loss of 3.46 Tg C yr\(^{-1}\) (3.81 million tn C yr\(^{-1}\)), or nearly half of the total 7.55 Tg C yr\(^{-1}\) (8.31 million tn C yr\(^{-1}\)) of estimated emissions from US organic soils (EPA 2008). An estimate of C annual emissions from about 100,000 ha (247,000 ac) of the Sacramento–San Joaquin Delta is 2.0 Tg C yr\(^{-1}\) (2.2 million tn C yr\(^{-1}\)) (Rojstaczer and Deverel 1993). Although it is not feasible to consider C sequestration in such soils, reducing the emissions of GHG is an important goal. Management to combat GHG emissions includes maintaining high water tables and selection of crops that can tolerate periodic flooding. Unfortunately, high water-table strategies, while reducing organic matter decomposition and reducing \(\text{CO}_2\) emissions, may enhance emissions of both \(\text{CH}_4\) and \(\text{N}_2\text{O}\).

In the United States, wetland agriculture is essentially rice. The 1.4 Mha (3.5 million ac) of rice lands in the United States occur in Arkansas, Louisiana, California, Texas, Mississippi, Missouri, and a minor area in Florida (USDA 2008). The anaerobic conditions of flooded rice fields result in methanogenic bacteria generating \(\text{CH}_4\) as well as \(\text{CO}_2\), formed by oxidation of \(\text{CH}_4\) near plant roots. Water table level, temperature, fertilization, irrigation, organic matter (plant residues), and season can all affect emission rates. Conditions in rice fields that diminish \(\text{CH}_4\) synthesis and release may promote emission of \(\text{N}_2\text{O}\), thus complicating the development of best management practices that can consider both gases. Strategies to reduce \(\text{CH}_4\) (and \(\text{N}_2\text{O}\)) emissions from rice fields include...
timming of midseason drainage, split fertilizer applications, nitrification inhibitors, avoiding incorporation of fresh organic matter and plant residues, and selection of rice cultivars with low gas transport and low rates of root exudation. Research is needed to develop strategies that minimize emissions of both CH$_4$ and N$_2$O for (1) rice cultivation and (2) other major crops grown on organic soils (table 1).

**REGIONAL AND NATIONAL SCALE ANALYSES**

In addition to the needs articulated previously regarding the science and management for enhancing soil C sequestration, regional/national scale analyses of soil C and GHG emissions/removals are needed to construct national inventories (Lokupitiya and Paustian 2006). We discuss two important components of these analyses: (1) measuring and monitoring, and (2) databases.

**Measuring and Monitoring.** Low-cost C and non-CO$_2$ GHG information is needed at multiple levels, from single operators up to regional and national levels (Lokupitiya and Paustian 2006). Measuring networks, such as GRACEnet (Greenhouse gas Reduction through Agricultural Carbon Enhancement network) (GRACEnet 2009; Jawson et al. 2005) and the National Resources Inventory (NRI), can provide opportunities to continuously monitor sites over appropriate time scales. A major challenge in quantifying SOC stocks is in designing an efficient sampling scheme. The spatial variability of SOC across most agricultural fields is typically high (Follett et al. 2009), and the amount of C relative to rate of change can also be high, both of which lead to a low signal-to-noise ratio. Thus, a five- to ten-year period of time between sampling may be required to detect changes (Conant and Paustian 2002; Smith 2004), and evaluating significant changes in soil C across a landscape can require a large number of samples (Garten and Wullschleger 1999). Direct measurements of GHG fluxes can assess the effects of management or climate on C balance (Baldocchi et al. 2001; Svejcar et al. 2008) and can be used in modeling exercises to estimate large-scale (regional or national) C budgets. However, GHG measure-

**Emerging Issues**

Implementation of agricultural C sequestration and non-CO$_2$ GHG mitigation practices must take into account two important emerging issues that US agriculture is only beginning to recognize: (1) biofuels and (2) the potential impact of climate change and rising CO$_2$ on GHG mitigation strategies.

**Biofuels.** About 140 Mha (350 million ac) of agricultural lands in the United States are active croplands, with corn, soybeans, and wheat representing about two-thirds of this area. About 18% of the grain harvested from 35 Mha (86 million ac) of corn in the United States was used for ethanol production in 2007; more than half of harvested corn grain was for animal feed (USDA NASS 2008b; USDA ERS 2008). A keen interest exists to develop sustainable energy technologies from cellulosic biofuels (Robertson et al. 2008). However, a number of concerns have been raised about possible environmental problems arising from intensification of agriculture (e.g., soil erosion, decrease in soil quality and productivity, loss of nitrate and phosphorus, decline in air quality, decline in biodiversity, increased loss of forests to compensate for cropland lost to biofuel production), some of which may compromise the overall goal of enhancing agroecosystem C. There are many gaps in our knowledge about the potential impact of biofuel energy crops on SOC. Top research priorities include (1)
evaluating how SOC responds to annual and perennial biofuel cropping systems, including operations on marginal lands; (2) clarifying relationships among soil C storage and fluxes of non-CO\(_2\) GHGs for biofuel operations; and (3) examining the implications of biofuel production on C storage in Conservation Reserve Program (CRP) lands, grass lands, and forested lands (table 1).

**Climate Change Feedbacks and C Sequestration.** As we become more confident about its trajectory, we are learning that climate change itself may constrain the very processes designed to curb GHG emissions and enhance C sequestration. Rising atmospheric CO\(_2\) generally increases plant production (Brouder and Volenec 2008; Hatfield et al. 2008; Morgan et al. 2004; Runion et al. 2009), which in turn could enhance SOC stocks through greater transfer of plant C into the soil (Allen et al. 2006). However, rising CO\(_2\) often results in higher soil respiration losses (Pendall et al. 2005), which would diminish the benefit of increased plant production on total system C. Rising temperatures in cooler regions may also increase growing-season length, prolong and enhance biological activity, and enhance net C uptake (Luo et al. 2007). However, extension of the growing season at a time of year when daily light fluxes are already low will have limited benefits for C uptake, especially at northerly latitudes, since photosynthesis will become increasingly light limited (Skinner 2007). Furthermore, the fertilization effect of CO\(_2\) on plant productivity observed in short-term experiments may not be sustained because soil nutrients eventually limit plant responses to CO\(_2\) (Luo et al. 2004), especially in native systems without fertilizer additions. Climate change may further constrain, eliminate, and even reverse positive production benefits of higher CO\(_2\) since higher temperatures enhance evaporative demand and lead to desiccation. By itself, warming also leads to higher SOM decomposition rates, which may further increase CO\(_2\) emissions. Thus, while climate change has likely stimulated C sequestration in the recent past, continued warming may reduce terrestrial C sequestration later in this century (Heimann and Reichstein 2008; Pepper et al. 2005). Critical research needs include (1) more process-level research to evaluate how multiple climate change factors affect the functioning of important agroecosystems, (2) modeling exercises that incorporate the latest findings from climate change experiments and project long-term impacts on C sequestration, and (3) observational/monitoring systems for tracking climate change impacts on US agroecosystem attributes (e.g., plant cover, vegetation type) that are likely to be good indicators of C storage potential (table 1).

**CONCLUSIONS**

In agriculture, C sequestration research has tended to focus primarily on productive cropping systems. Too few experiments have specifically addressed best management practices for improving soil C storage, and fewer yet evaluate practices to reduce emissions of non-CO\(_2\) trace gases. Research needs to be expanded to less well-defined components of US agriculture. Despite occupying 37% of total US land area, relatively little research has evaluated the management potential for mitigating GHG emissions in the US horticulture industry and for turfgrass. Organic soils and wetlands present especially complex management challenges since they involve significant emissions of more than one GHG, and practices that reduce emissions of one GHG may stimulate another. Agroforestry contributions to GHG mitigation have not been considered in national inventories. Addressing these research needs, including the challenges presented by biofuels development and climate change feedbacks on agricultural GHG emissions, will be critical for giving US agriculture the necessary tools to mitigate climate change. Continued progress on scaling and monitoring methodologies will be essential to implement regional/national analyses and assessments that climate change policies and protocols will demand.

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**REFERENCES**


Pepper, D.A., S.J. Del Grosso, R.E. McMurrine, and W.J. Parton. 2005. Simulated carbon sink response of shortgrass steppe, tallgrass prairie and forest...