# Prairie ecosystems and the carbon problem

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**There has been great interest in carbon (C) storage in terrestrial landscapes and the potential for trading C released during fossil-fuel combustion for C stored in agricultural landscapes. This is particularly important in the Great Plains of North America, where increased C storage under conservation tillage represents millions of dollars in C credits. However, we contend that the logic behind such trading is imperfect on multiple levels. We suggest that increased C storage in Great Plains soils with conservation tillage can, at best, only partially replenish what was previously emitted by tillage of native prairies. Furthermore, there is disagreement on whether reduced tillage actually does increase C storage in prairie soils. Use of alternative agricultural practices that emulate natural prairie diversity, processes, and function, as well as the establishment of permanent prairie reserves, will aid in recovery of previously lost C and provide for increased biodiversity and resilience in the face of changing climate conditions.**

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The carbon (C) problem that we currently face (too much C in the atmosphere) is not particularly attributable to agriculture – less than 8% of US greenhouse-gas (GHG) emissions are contributed by agricultural practices (USDA 2008) – but rather is associated with consumption. Excess C stems from the unchecked mining and combustion of fossil fuels, which add non-cycled, geological C to the atmosphere. Vegetation, in contrast, fixes C from the atmosphere and temporarily stores this actively cycled, biological C in plant tissue and as soil organic matter. With this in mind, one might question the validity of terrestrial C offset programs. Currently, agricultural fields and forest reserves are considered viable market targets for offsetting the C emitted through the burning of fossil fuels. Improved land management and prairie restoration may well result in increased soil C storage; however, we contend that increased C storage in agricultural landscapes is not an effective means of offsetting fossil-fuel emissions and should not be the driver or objective for shifts in land management. Here, we provide an overview of the potential for C storage in prairie soils, give some perspective on the historical loss of C from these systems, and then use this information to question the validity of addressing the global C problem through terrestrial C storage.

## In a nutshell:

- The current areal extent of North America's Great Plains prairies accounts for only 10% of historical prairie land area before the arrival of Europeans
- Large amounts of carbon (C) were released upon initial tilling of prairie soils
- Carbon sequestered on agricultural lands can only partially replace C released during original tillage of the prairies
- Alternative agricultural systems that emulate natural prairies should be pursued to ensure long-term soil resource sustainability and C neutrality

Terrestrial C offsets for fossil-fuel consumption have been used as a financial incentive to encourage US farmers to use continuous conservation tillage practices on row-crop systems or to place land into the US Department of Agriculture (USDA) Farm Service Agency's Conservation Reserve Program (CRP). The logic behind such offsets is that these management options can increase the storage of C in soil ecosystems (eg National Carbon Offset Coalition, www.ncoc.us/index.htm), countering the GHG emissions generated by other activities, all of which, until recently, could be exchanged as C credits through the Chicago Climate Exchange – which operates North America's cap-and-trade system (www.chicagoclimatex.com/index.jsf). Unfortunately, there are three fundamental problems with this logic: (1) the C stored in soil under alternative management strategies cannot counter the C that is currently being generated, because, at best, C sequestered in agricultural soils only partially replaces the C that was released to the atmosphere through tillage of virgin sod some 80 to 150 years ago (Lal 2004). Given that the half-life of carbon dioxide ($CO_2$) in the atmosphere is between 15 and 90 years (Hansen *et al.* 2005), much of the C added to the atmosphere from tillage by the beginning of the 20th century remains in the atmosphere today. (2) Terrestrial C offsets based on agricultural management ultimately trade the non-cycled (fossil-fuel-derived) C for the temporary storage of actively cycled biological C, which can be released by any number of physical disturbances, including subsequent tillage. (3) There is disagreement as to whether no-till regimes actually serve as a net sink for GHGs (Lal 2004). No-till may result in accumulation of C at shallow depths in the soil, but total C accu-

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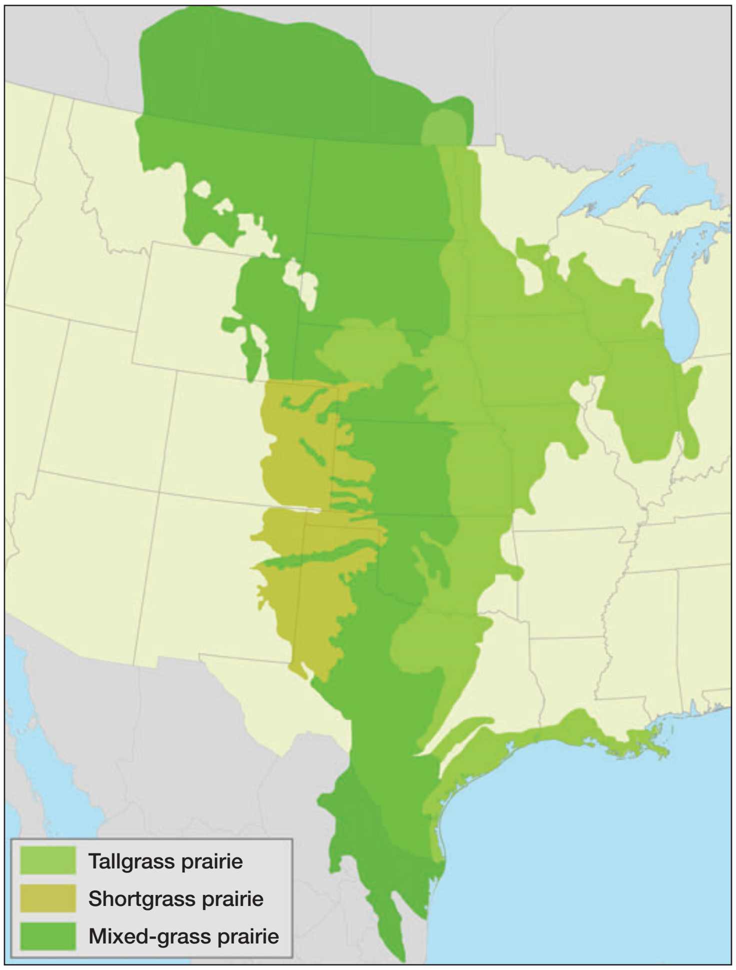

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***Figure 1.** Historical extent of Great Plains prairies of North America, modified from Risser* et al. *(1981).*

mulation in the soil appears to be no different from that in soils exposed to conventional tillage practices (Baker *et al.* 2007; Christopher *et al.* 2009; David *et al.* 2009). No-till may also increase atmospheric nitrous oxide ($N_2O$) emissions under poorly drained soil conditions (Rochette 2008; Govaerts *et al.* 2009). Although no-till greatly reduces soil erosion potential, there may be no net GHG benefit to no-till farming. Failure to recognize these limitations will lead to continued net addition of fossil-fuel-derived C to the atmosphere under the guise of C neutrality (no net addition of C to the atmosphere). Furthermore, if we rely on C sequestration in agricultural soils as a strategy to reduce overall emissions, any future reconversion to conventional agricultural practices will result in release of that stored C, further compounding GHG buildup (van Kooten 2009).

## Carbon storage and loss on the Great Plains

Before the arrival of European settlers, prairie ecosystems of the Great Plains accounted for nearly 1.7 million km$^2$ (about 650 000 square miles) across central North America (Figure 1). Prairie soils in this region were historically deep and black, often storing as much C below ground as temperate hardwood forests store above ground (Schlesinger 1997). This C had accumulated from thousands of years of biomass production, decomposition, and storage as labile and stable soil organic matter. Native tallgrass prairies can produce about 5–10 megagrams (Mg; where 1 Mg = $1 \times 10^6$ g) of shoot biomass ha$^{-1}$ yr$^{-1}$ and about 8–15 Mg of total belowground biomass ha$^{-1}$ yr$^{-1}$ (Sims *et al.* 1978; Guzman and Al-Kaisi 2009). This equates to the annual productivity of about 5–9 Mg C ha$^{-1}$ yr$^{-1}$. Assuming that most of this C is returned to the soil in the absence of crop export, and assuming that 60% is rapidly lost to respiration, then approximately 3–5 Mg C ha$^{-1}$ is temporarily retained in the soil each year as metabolic C – much of which is slowly transformed and eventually respired before the next growing season (Stevenson and Cole 1999). This storage – combined with frequent burning of the prairies, which left behind variable quantities of decay-resistant charcoal (Skjemstad *et al.* 2002) over a 5000–8000-year period – resulted in soils of the Midwestern prairies with a total soil C storage equivalent to about 70–130 Mg C ha$^{-1}$ in the surface 20–30 cm alone (Mann 1985; Davidson and Ackerman 1993; David *et al.* 2009; Jelinski and Kucharik 2009) and 130–357 Mg C ha$^{-1}$ throughout the soil profile (Mann 1985; Kucharik *et al.* 2006; David *et al.* 2009).

## Historical loss of prairie soils

Conversion of native prairie and prairie pothole wetlands to agricultural row-crop production during the late 1800s and early 1900s under US federal legislation such as the Land Act, Homestead Act, and the Swamp Land Act resulted in a rapid and massive release of C to the atmosphere, caused the demise of numerous species, and initiated a historical period of intensive soil erosion. The "settling" of virgin prairies took place at breakneck speeds, averaging about 1.4 million ha yr$^{-1}$ on tallgrass prairies in the mid-1800s (Smith 1992, 1998) and about 500 000 ha yr$^{-1}$ on mixed- and shortgrass prairies in the early 1900s (Eagan 2006). Of the original 66 million ha of tallgrass prairie in the northeastern Great Plains (Sampson and Knopf 1994), less than 3% remain today (Figure 2) and, in the state of Iowa, only 0.1% of the original 12.5 million ha of tallgrass prairie remains uncultivated (Smith 1998). Prairie pothole wetlands were some of the last parts of the landscape to be plowed, but once drained they proved to be highly productive landscapes. European pioneers found about 1 million ha of prime wetlands in Iowa; however, only about 9000 ha remain in the 21st century. In total, about 120 million ha of tall-, mixed-, and shortgrass prairies were plowed across the Great Plains of the US over a period of time measured in decades (Sampson and Knopf 1994). So little native tallgrass prairies remain in the US that it is difficult for most

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people to envision the scale of what has been lost and thus to perceive the role that prairies might play in mitigating the impacts of climate change. The demise of the North American Great Plains prairies occurred at a scale and pace similar to contemporary deforestation in the Amazon. The endless sea of industrial-scale agronomic production in the present-day Great Plains is an iconic symbol of US agricultural prowess, but embedded in this massive conversion from prairie to cropland was a severe loss of biological C to the atmosphere, disturbingly similar to what is happening in the Amazon Basin and other rainforests of the world today.

## Carbon lost from plowing native prairies

Plowing native prairies dramatically reduced the photosynthetic input of C to soils (Sims *et al.* 1978; Huggins *et al.* 1998) and replaced a diverse collection of native perennial grasses and forbs with grain monocultures. Annual net primary productivity of prairie vegetation normally outpaces row-crop production resulting from the far greater belowground biomass production associated with prairie vegetation and because of the sparse and seasonally limited cover associated with some row crops (Huggins *et al.* 1998; Guzman and Al-Kaisi 2009). A good example of this is provided by Guzman and Al-Kaisi (2009); averaged across a corn–soybean rotation, aboveground C inputs associated with a tallgrass prairie remnant in southern Iowa had only 20% greater aboveground net annual C production, but 86% greater net C production belowground. Harvested perennial grasslands in Kansas contained 43 Mg $ha^{-1}$ more soil C than that in adjacent annual wheat fields, with root biomass extending to greater depths (Figure 3) and remaining active over a longer period of the growing season (Glover *et al.* 2010b). Furthermore, it must be emphasized that row crops effectively fix C for a relatively small fraction of the growing season and, because the grain (and in some cases a portion of the residue) is exported, crop plants return to the soil a smaller and relatively uniform, cellulose-rich residue that is rapidly degraded (Huggins *et al.* 1998). Increased biomass production with the irrigation of row crops partially offsets these C losses (Parton *et al.* 2005), but such efforts provide relatively modest increases in total biome C storage.

Breaking the native sod caused the rapid conversion of surface-soil C stocks to $CO_2$ (Voroney *et al.* 1981; David *et al.* 2009) and attainment of a new equilibrium concentration of soil C dominated by stable humic materials (Voroney *et al.* 1981; Huggins *et al.* 1998; Parton *et al.* 2005; David *et al.* 2009). Plowing native lands also caused the rapid decomposition of resident organic matter, with the greatest losses coming from the labile or metabolic soil-C pools (DeLuca and Keeney 1993; Huggins *et al.* 1998). Tillage of native prairie ultimately resulted in a 30–60% decrease in surface-soil total C, with most being lost within the first 5–30 years after tillage (Van Veen and Kuikman 1990; Davidson and Ackerman 1993; Huggins *et al.* 1998; Kucharik *et al.* 2001; Parton *et al.* 2005).

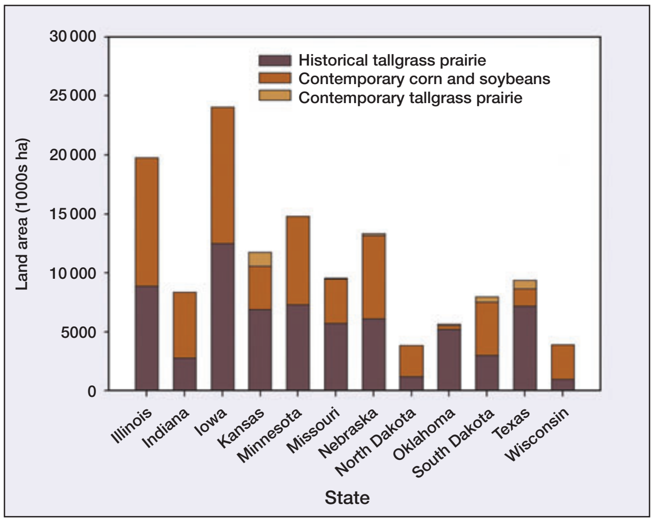

***Figure 2.*** *Major land cover, pre-1850 and contemporary, in the eastern Great Plains (contemporary prairie taken from Sampson and Knopf [1994], contemporary cropland from 2009 agricultural census, USDA National Agricultural Statistics Service [www.nass.usda.gov/Data_and_Statistics/Quick_Stats/]).*

Tillage exposes surface soils to wind and water erosion (Lal 2003). The dramatic rates of wind erosion that occurred during the Dust Bowl of the 1930s remain as an unparalleled environmental catastrophe in US history (Eagan 2006). Rainfall erosion rates on agricultural lands of the Great Plains were also greatly accelerated in this era; water erosion in the Loess Hills region of the northern Great Plains has been estimated at 37.6 Mg soil $ha^{-1}$ $yr^{-1}$ in 1930, as compared with about 15.9 Mg soil $ha^{-1}$ $yr^{-1}$ for this same region in 1992 (Argabright *et al.* 1995). Obviously, both C and nutri-

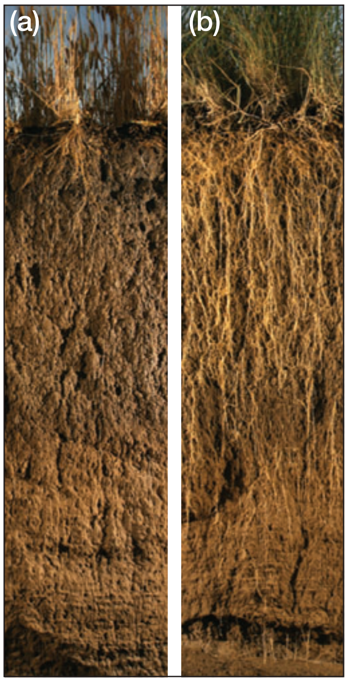

***Figure 3.*** *Belowground biomass from perennial grassland versus that from annual wheat field in Kansas (from Glover* et al. *2010b). (a) Wheat roots grow to a maximum depth of 1 m, whereas (b) perennial grass roots reach a depth of greater than 2 m in these soils. Generally, root biomass averaged across biomes shows that temperate grasslands have almost an order of magnitude more root biomass than that of croplands, in general (1.4 kg $m^{-2}$ standing root biomass for temperate grasslands versus 0.15 kg $m^{-2}$ for croplands; Jackson* et al. *1996).*

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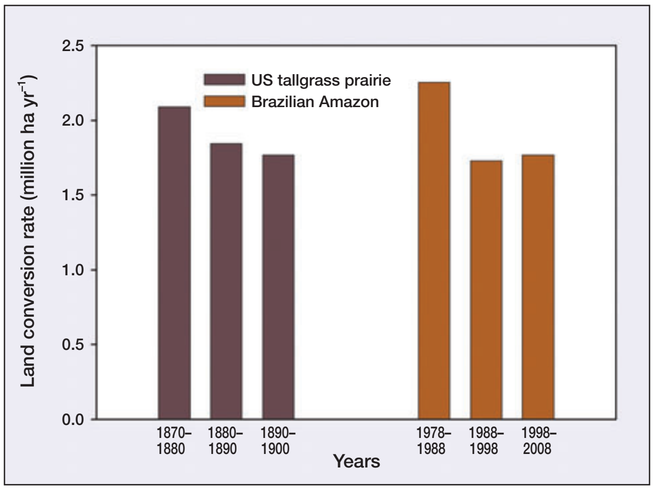

***Figure 4.*** *Rate of land conversion for three decades in the Brazilian Amazon from 1978–2008 (Houghton* et al. *[2000] and www.rainforest.mongabay.com) and Great Plains tallgrass prairie states (estimated from addition of "improved agricultural land" by decade in Illinois, Indiana, Iowa, Kansas, Minnesota, Missouri, Nebraska, North Dakota, Oklahoma, South Dakota, and Wisconsin) from 1870–1900 (USDA historical census data, www.agcensus.usda.gov/index.asp). Average net C emissions for the Amazon have been estimated at 0.1–0.3 Pg yr$^{-1}$ for the period of 1978–1998 (Houghton* et al. *2000); we estimate that the tillage of tallgrass prairie in these states alone yielded an approximate net increase in C emissions of 0.05–0.2 Pg yr$^{-1}$ from 1870–1900 (based on a 47.5% C loss from the surface 20 cm of soil).*

ents are lost with the mineral soil; however, the loss of soil organic C to erosion does not directly equate to evolution of that C as $CO_2$ (Lal 2005). Soil erosion may simply redistribute the C in the landscape or redeposit the C along with sediment in alluvial, lacustrian (lake-associated), or marine bodies (Smith *et al.* 2005), or it may accelerate mineralization of a portion of the total C released (Lal 2005; Polyyakov and Lal 2008). Therefore, rather than attempt to evaluate the percent C evolved that is associated with erosion, we simply present an estimate of total C lost due to mineralization and with limited replenishment in the period shortly after initial plowing of Great Plains prairie soils.

If we assume native tallgrass prairie soils contained 50 g C kg$^{-1}$ in the surface 20 cm of soil (Huggins *et al.* 1998), experienced a net loss of 47.5% of surface soil C (Table 1), and had a surface bulk density of between 0.9 and 1.3 g cm$^3$ (Davidson and Ackerman 1993; David *et al.* 2009), then the conversion of 66 million ha of tallgrass prairie would have resulted in the release of about 3.1 petagrams (Pg; where 1 Pg = 1 × $10^{15}$ g) of C to the atmosphere. The plowing of an additional 60 million ha of mixed- and shortgrass prairies at the turn of the 20th century would have released another 1.7 Pg of C, assuming 25 g C kg$^{-1}$ in the surface 20 cm (Davidson and Ackerman 1993) of these soils, a density of 0.9–1.3 g cm$^3$ in the native soils, and a C loss of 47.5% from surface soils. The combined C losses from tall-, mixed-, and shortgrass prairies likely released nearly 5 Pg of C, a magnitude roughly similar to the C losses associated with the deforestation of the Brazilian Amazon rainforest (Houghton *et al.* 2000). Between 1870 and 1900, land conversion in Great Plains tallgrass prairie states averaged 1.8 to 2.1 million ha yr$^{-1}$ (Figure 4), resulting in emissions of roughly 0.1 Pg C yr$^{-1}$. Similar rates of deforestation in the Brazilian Amazon have taken place over the past 30 years, resulting in the release of 0.1 to 0.3 Pg C yr$^{-1}$ (Figure 4).

Although plowing may redistribute C in the soil profile (specifically moving more C to greater depths), plowing of virgin sod clearly results in a net loss of C from the soil ecosystem. The total C lost from the whole soil profile (1.5 m) resulting from cultivation has been estimated at about 27%, or approximately 49.5 Mg C ha$^{-1}$, based on analysis of 120 cultivated and uncultivated prairie soils

**Table 1. Total organic C concentrations in surface soils of virgin tallgrass prairie remnants as compared with concentrations in cultivated soils planted to grain crops**

| *Comparison of virgin prairie soil to cultivated lands* | *Depth (cm)* | *Prairie (g kg$^{-1}$)* | *Cultivated (g kg$^{-1}$)* | *% change* | *Source* |
|---|---|---|---|---|---|
| One prairie remnant | 0–30 | 20 | 10 | –50 | (Tomko and Hall 1986) |
| | 0–25 | 24 | 15 | –38 | (Buyanovsky *et al.* 1987) |
| | 0–15 | 66 | 23 | –66 | (Russell *et al.* 2005) |
| (Sanborn Field) | 0–20 | 40 | 18 | –55 | (Huggins *et al.* 1998) |
| (Morrow plots) | 0–20 | 55 | 27 | –51 | (Huggins *et al.* 1998) |
| Two prairie remnants | 0–25 | 60 | 33 | –44 | (Jelinski and Kucharik 2009) |
| Three prairie remnants | 0–13 | 57 | 27 | –53 | (Voroney *et al.* 1981) |
| | 0–27 | 51 | 22 | –57 | (Zhang *et al.* 1988) |
| | 0–20 | 55 | 26 | –52 | (David *et al.* 2009) |
| Over 10 prairie remnants | 0–30 | 40 | 29 | –28 | (DeLuca and Keeney 1993) |
| (Aquolls 6 uncultivated) | 0–15 | 77 | 34 | –56 | (Mann 1985) |
| (Udolls 13 uncultivated) | 0–15 | 30 | 24 | –21 | (Mann 1985) |
| **Average** | **0–22** | **48** | **21** | **–47.5** | |

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(Mollisols) across 12 Midwestern states in the US (Mann 1985), which is similar to the total C loss rate calculated by the 47.5% loss rate (Table 1) for the surface 20 cm of C-enriched soil.

Conversion of virgin prairie to agricultural lands resulted in the formation of an "open nitrogen (N) cycle" that experiences greater net and gross nitrification (DeLuca and Keeney 1995). Accordingly, $N_2O$ losses are greater from agricultural soils than from soils under native prairie. Similarly, native prairie soils exhibit net methane ($CH_4$) consumption, whereas highly fertilized agricultural soils tend to function as net $CH_4$ emitters (Chan and Parkin 2001). $CH_4$ emissions could possibly be reduced in drained and plowed prairie soils as compared with emissions under intermittent saturated conditions associated with hydric (wet) prairies, but there is little evidence to support this notion.

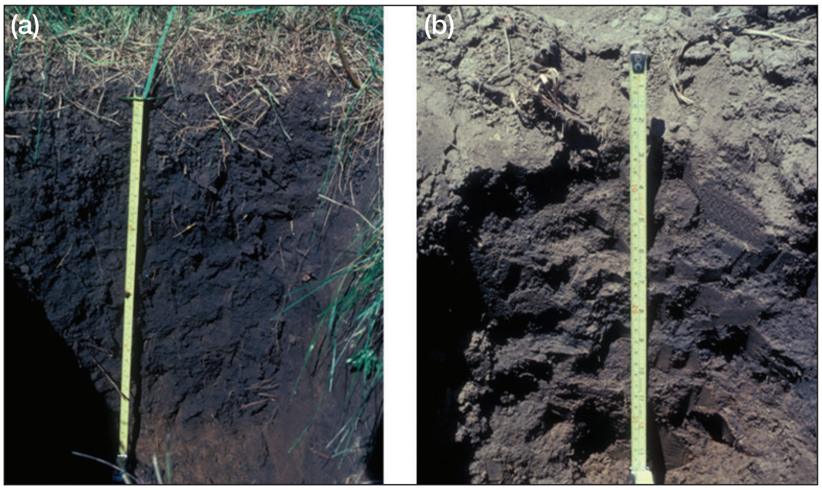

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***Figure 5.*** *Photographic comparison of soil profile (a) under virgin tallgrass prairie and (b) after ~100 years of cultivation. The cultivated soil has a compacted and low organic matter surface horizon, whereas the virgin prairie soil exhibits a darker and thicker A horizon and a noticeable difference in soil structure as compared with the cultivated soil. From this photographic comparison, it is easy to envision a dramatic net loss in soil organic C and noticeable decline in soil quality as a result of 100+ years of cultivation.*

Shifting agricultural lands to no-till agriculture is valuable from the perspective of protecting against erosion; however, it will not effectively accomplish the task of "putting the genie back in the bottle" with regard to C emissions and should not be considered as a sink for newly released fossil-fuel-derived C. Although no-till may store more C in surface soil than conventional tilling regimes, conventional tillage stores more C at depth (David *et al.* 2009) and it is not clear whether net C storage is actually increased with the application of no-till as compared with conventional tillage (Baker *et al.* 2007; Govaerts *et al.* 2009). Grains produced through no-till practices require heavy inputs of synthetic N fertilizers. If we assume a conservative estimate of 120 kg N $ha^{-1}$ applied to 70 million ha (of the 140 million ha currently in production) of agricultural land in the Great Plains and apply an exponential estimate of $N_2O$ emission with increasing N fertilizer application (Millar *et al.* 2010), we arrive at a value of 4.14 kg $N_2O$-N ha $yr^{-1}$. This reflects a value equivalent to 3.45% of N fertilizer application, which is a relatively high estimate for the Midwest. If we assume a more broadly accepted value of 1% N of fertilizer application lost as $N_2O$ (Crutzen *et al.* 2007), we arrive at 84 000 Mg $N_2O$-N annually (132 000 Mg $N_2O$ $yr^{-1}$). Taking into account the nature of $N_2O$ as a GHG (310 times as potent as $CO_2$) and if we incorporate the C costs of N fertilizer production, transport, and use on the site (Cole *et al.* 1993; Russell *et al.* 2005), the limited C-sink potential of no-till soils (Christopher *et al.* 2009) is effectively negated.

Carbon sequesteration in soils that have been placed in the CRP has also been identified as a target for market offsets. Although C storage is generally increased under CRP as compared with that under conventional cropping systems, the incremental increase in total C is not consistent and may slow dramatically with time since initial establishment (Kucharik 2007). Restoration of native prairies is a slow and labor-intensive process; this objective not only would have greater potential for C recovery than reduced tillage strategies or CRP, but also would greatly increase biodiversity. However, only a very small proportion of the Great Plains will likely ever be restored to prairie, and the re-establishment of C stocks in soils under restored prairies would lag considerably behind recovery of aboveground productivity and diversity (Kucharik *et al.* 2006).

## Discussion

Tillage of Great Plains prairies degraded beneficial physical, chemical, and biological properties of the soil (collectively referred to as soil tilth) including dramatic reductions in soil C and an increase in soil bulk density (Figure 5). Improved farming practices that build soil organic matter content and a continuation of the CRP are both desirable practices and will ultimately recapture some of the C released early in this past century and improve the overall condition of these soils (Lal 2004). However, much of what was thought to be increased storage with reduced tillage practices proved to be largely a redistribution of soil C (Balesdent *et al.* 2000; Baker *et al.* 2007; Christopher *et al.* 2009; Govaerts *et al.* 2009; Poirier *et al.* 2009). Further, if farming practices soon revert to tillage-based production, the stored C will be rapidly mineralized, resulting in only a short-term increase in storage. Attempting to mitigate GHG emissions by sequestering C in soils also avoids addressing the real challenge at hand, which is the need for a cultural and technological change to reduce our reliance on fossil-fuel consumption.

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Creation of permanent prairie reserves will accomplish many objectives, including slowly replacing some of the C lost to sod breaking during the previous century, greatly increasing overall ecosystem diversity, and improving habitat for a variety of native species that cannot survive in conventional agricultural landscapes. There are numerous ongoing efforts to conserve existing prairie landscapes and recreate "lost" prairies. The American Prairie Foundation, Ducks Unlimited, The Wilderness Society, WWF, and other organizations are laying the foundation for the preservation and restoration of prairie reserves across the Great Plains. Such efforts should be supported and expanded if we are to retain existing soil C, recapture C emitted through prior land conversion, and resurrect the lost aesthetic and cultural heritage of the Great Plains prairie ecosystems. Paradoxically, however, over the past 10 years, tens of thousands of hectares of native mixed- and shortgrass prairie sod in the Dakotas and eastern Montana have been plowed for small-grain production.

The C problem that we are currently confronted with is not primarily the result of agricultural practices in North America and elsewhere; instead, it stems from excessive consumption of fossil fuels. Although agriculture in temperate regions has been responsible for a substantial net release of C to the atmosphere in the past (and continues to be a noted contributor in the tropics), the accumulation of C in soils with alternative management practices and re-establishment of prairies can only be viewed as a return of C to its "rightful" place – not as a sink for unbridled release of fossil-fuel-derived C to the atmosphere. Carbon storage in prairie soils provides positive physical and biochemical benefits, which will ultimately sustain a diversity of species in prairie ecosystems. However, it must be realized that the conversion of agricultural lands to prairie will result in a slow recovery of soil C stocks (Kucharik *et al.* 2006), and the rate of buildup of soil organic C will be partially regulated by N (Amundson 2001; Knops and Bradley 2009), water (eg Parton *et al.* 2005), or other resource limitations that have developed over the past 100 years of cropping. Furthermore, demands for increasing food production for the burgeoning human population make large-scale conversion of agricultural lands to prairie systems unlikely. This type of argument, however, can be called into question, given that only about 10% of corn production across the Great Plains is used as a direct food resource, while the vast majority is used as livestock feed and to produce ethanol as a transportation fuel (Trostle 2008). Protection of soil resources for future generations must be at the forefront of policy and management decisions. Alternative agricultural production systems that more closely emulate the biodiversity, phenology, and biogeochemical processes associated with native prairie ecosystems (Glover *et al.* 2010a) must be considered in greater detail. To reduce GHG loading of the atmosphere, we must learn to conserve fossil-fuel resources to reduce short-term emissions, and find true alternatives to fossil fuels, in particular coal, soon. Foisting the burden of fossil-fuel-based C-release on soil ecosystems is unrealistic and subverts the need for meaningful strategies that address the cause and mitigation of human-induced climatic change.

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