Soil C change over 14 years in grasslands sown into a highly disturbed soil

Jackson, R.D.*; Stier, J.†

* Department of Agronomy, University of Wisconsin-Madison; † Herbert College of Agriculture, Department of Plant Sciences, University of Tennessee-Knoxville

Key words: turfgrass, prairie, reed canarygrass

Abstract. Perennial grasslands are thought to sequester C, so restoring them is touted as part of the solution for mitigating climate change. Moreover, there is growing interest among managed grassland stakeholders in selling C credits on nascent C markets. Former agricultural and municipal sites are often considered viable areas for conversion to grasslands, with types ranging from unmanaged prairies with diverse plant communities to monocultures in highly managed urban environments. We sowed five perennial plant communities into an area that had undergone massive soil disturbance five years previous during conversion from row crop agriculture to C3 turf. We found that soils lost an average of 461 g C m^{-2} over the initial 3-y period, irrespective of mowing, fertilizer addition, or plant community type, with a similar magnitude of soil C loss occurring in the adjacent undisturbed turf. However, by the fourth year of sampling, soil C had returned to pre-treatment levels for most treatments. When sampled 14 years after disturbance and sowing, many soils had gained SOC relative to 2004 (~300 g C m^{-2}). Exceptions included control-prairie grasses, fertilized-Kentucky bluegrass, mowed-fine fescue and mowed-prairie forbs, which had gained enough SOC to return to 2004 levels, but not enough for SOC gain in 2018. Soil-disturbing renovation or restoration of non-irrigated grasslands in the upper Midwest results in a short-term, but highly significant loss of soil C, but after 14 years SOC can sometimes, but not always recover and exceed pre-establishment SOC.

Introduction. The relative ability of turf grasses, forage grasses, native prairie grasses, and commercially popular (forb-dominated) prairie mixtures to sequester atmospheric C have received scant attention (but see Ammann et al. 2007, Qian et al. 2003, Kaye et al. 2005), even though all are candidates for restoration or rehabilitation of plots in in urban, suburban, and rural settings. Agricultural sites usually provide relatively large contiguous areas for renovation, compared to urban sites. Individual restoration sites in urban areas are often quite small (0.02 to 0.1 ha), but collectively represent significant land area.

We implemented a 14-year experiment, beginning in fall 2004, to compare changes in soil C of temperate grassland plant communities under typical management regimes, first during a four-year (managed) establishment phase, followed by a ten-year unmanaged phase. Plots were sown in 2004 and managed through 2008; all plots were sampled three times during this period. Plots were then left unmanaged for 10 years, and all plots were sampled again in 2018. We hypothesized that communities dominated by perennial grasses would sequester more soil C than forb-dominated systems, and that mowing and N addition to would enhance C storage.

Methods and Study Site. We established field plots at the O.J. Noer Agricultural Research Station in Verona, WI. The soil was a Troxel silt loam (12.0±0.6% clay, 69.7±0.5% silt, and 18.3±0.3% sand; mean±s.e., n=25) on virtually flat land. The soil had pH ~7.8 and was classified as a fine-silty, mixed, superactive, mesic Pachic Argiudoll. The site had been used for row crop production but was converted to turf in 1999. During this conversion, the field was recontoured by removing the surface 20-cm of topsoil, leveling the subsurface with heavy equipment, then returning the topsoil. A Kentucky bluegrass (*Poa pratensis* L.) turf was established by seeding, and the sward mowed quasi-weekly during the 7-month growing season to a residual height of 7.5-cm from 1999 through 2004 with clippings returned. Turf was fertilized annually with two to three applications of 48 kg N ha^{-1}. A 75×50-m plot of this turf was killed with glyphosate in October 2004. One month later, the dead sod was disked and in December 2004, five species mixes were broadcast seeded onto bare soil in a 5×5 Latin square experimental design (Fig. 1).

The five sown plant communities were: 1) Pasture - reed canarygrass (*Phalaris arundinacea* L.), 2) Pasture/turf - Kentucky bluegrass, 3) Turf - Fine fescue mixture (*Festuca rubra* L.), 4) Prairie grasses - big bluestem (*Andropogon gerardii* Vitman), Canada wild rye (*Elymus canadensis* L.), switchgrass (*Panicum virgatum* L.), indiangrass (*Sorghastrum nutans* (L.) Nash), and 5) Prairie forbs - nodding pink onion (*Allium cernuum* Roth), smooth aster (*Symphyotrichum laeve* L.), New England aster (*Symphyotrichum novae-angliae* (L.) G.L. Nesom), lanceleaf coreopsis (*Coreopsis lanceolata* L.), pale purple coneflower (*Echinacea* *purpurea* (L.) Moench), rattlesnake master (*Eryngium yuccifolium* Michx.), ox eye sunflower (*Heliopsis helianthoides* (L.) Sweet), prairie blazingstar (*Liatris pycnostachya* Michx.), bergamot (*Monarda fistulosa* L.), wild quinine (*Parthenium integrifolium* L.), smooth penstemon (*Penstemon digitalis* Nutt. ex Sims), yellow coneflower (*Ratibida pinnata* (Vent.) Barnhart), black eyed susan (*Rudbeckia hirta* L.), sweet black eyed susan (*R. subtomentosa* Pursh), brown eyed susan (*R. triloba* L.), compassplant (*Silphium laciniatum* L.), stiff goldenrod (*Oligoneuron rigida* L.), Canada milk vetch (*Astragalus canadensis* L.), blue false indigo (*Baptisia australis* (L.) R. Br.), white false indigo (*B. alba* (L.) Vent.), wild senna (*Senna hebecarpa* (Fernald) Irwin & Barneby), purple prairie clover (*Dalea purpurea* Vent.), plus the four grasses listed under treatment 4.

Starter fertilizer (Spring Valley 15-11-7 [%N-%P_2O_5-%K_2O]) was applied at a rate equivalent to 4.8 g P m^{-2}. Seeding rates for each treatment were 1.7, 1.1, 0.79, 19.54, and 7.33 g seed m^{-2} for treatments 1 through 5, respectively. Seed was applied by hand using a shaker jar and seed was mixed with sand to ensure uniform coverage across the entire plot. Following seeding, plots were covered in biodegradable Futerra® erosion control blankets (Profile Products LLC, Buffalo Grove, IL). No irrigation was applied to the study during establishment or at any time thereafter.

Spring/summer 2005 was an establishment period for the study. All plots were mowed to 5 cm early in the spring to help control annual weeds before prairie plants had emerged from the soil. Turf plots (treatments 2 and 3) were mowed at 7.5 cm throughout the summer until sufficient ground cover (≥70%) was achieved. All turf plots were fertilized in mid-June with 25-1-3 (%N-%P_2O_5-%K_2O) at a rate equivalent to 4.8 g N m^{-2}. In September of 2005 main plots were split into sub-plots (0.66 m wide × 2 m long), which were randomly assigned to one of 3 treatments: mowed, mowed + fertilized, or control. Fertilized plots received 4.8 g N m^{-2} of 25-1-3 (%N-%P_2O_5-%K_2O) fertilizer in spring, summer and fall. Mowed prairie grass and forbs plots were mowed to 10 cm one time in April. Mowed reed canarygrass and fine fescue plots were mowed monthly during the growing season to a height of 7.5 cm. Mowed Kentucky bluegrass plots were mowed to a height of 5 cm every week throughout the growing season. Clippings were always left on the plots. These treatments were in place through the end of the 2008 growing season, at which point they were stopped. Plots were left undisturbed from 2009 through 2018.

Immediately following disking in November 2004, we collected 24 soil cores (5 cm dia × 15 cm deep) from 6 evenly spaced transects across the entire experimental site. A 2-mm sieve was used to remove gravel, roots and other plant material before samples were ground with mortar and pestle and analyzed for total C concentration on a Carlo Erba NA 1500 series 2 elemental analyzer (CE Elantech, Inc; Lakewood, NJ). This process was repeated in September 2006, but only on soils from the 25 control plots (which had vegetation treatments established by June 2005), and again in July 2007 and August 2008 from all 75 experimental units. In July 2007, we measured soil bulk density to 15-cm depth on the 25 control plots using one 5-cm diameter core per plot. Soil C pools on a mass per unit area basis (15-cm depth) were calculated as the soil C concentration at a given time point multiplied by our 2007 determination of bulk density for each control plot (Table 1). In addition, we removed 12 soil cores from the surface 15-cm under the matrix turfgrass in areas within one meter of our experiment that were not disturbed during the 2004 sowing. We determined bulk density and soil C content for these 12 cores and used the grand mean of the bulk density estimate for the site to calculate soil C on a mass basis. In June 2018, we collected 24 soil cores, following the same process from previous years and multiplied soil C concentration by our earlier bulk density estimate.

In July 2007 we estimated plant cover by placing a 20 × 50-cm quadrat in three locations within each control plot and visually estimating the percentage of the quadrat covered by C3 grasses, C4 grasses, prairie forbs, and weeds. Belowground biomass was estimated in July 2007 by removing two 5-cm diameter × 15-cm depth soil cores from each control plot. Soil and gravel were rinsed from roots, which were dried at 65 °C for 2 d before being weighed and recorded. Species cover sampling was repeated in August 2008 on all 75 experimental units.

Our response of interest was each plot's calculated change in grams C m^{-2} (to 15 cm) since 2004. To determine whether there were any significant spatial effects on C sequestration in the experiment, results were analyzed according to a replicated Latin Square design, where blocking variables remained fixed across replications. Statistical significance was determined at the $p < 0.05$ level, and results were interpreted with Tukey correction for multiple comparisons.

Results. The absolute cover of four plant guilds in June 2007 and August 2008 indicated that productive stands of the sown plant communities had established. Significant bare ground (20 to 30%) was found in the Kentucky bluegrass and prairie grass treatments, however, mowing increased plant density of Kentucky bluegrass compared to unmown plots. Broadleaf weeds were abundant in all but the prairie forb treatment. Root biomass in the upper 15 cm soil profile varied dramatically among the communities.

Two years after vegetation establishment, the total soil C pool of control plots had decreased by 154 g C m^{-2} ($P=0.01$, $t=2.79$, $df=24$; Fig. 1A). Subsequent sampling in July 2007 of control, mowed, and mowed + fertilized plots indicated that these soils had lost another 307 g C m^{-2}, averaged across all management treatments ($P<0.001$, $t=12.04$, $df=72$; Fig. 1B). The difference in soil C between 2006 and 2007 control plots was also highly significant ($P<0.0001$, $n=25$). Suspecting that much of this soil C loss stemmed from the herbicide application, disking, and sowing of these plant communities during establishment, we also sampled soils under the surrounding turfgrass matrix that was established five years earlier into former agricultural fields (maize-soybean rotation). Soil C in the matrix turfgrass surrounding the experimental site was 1.76%, within the range of soil C detected among treatments. By August 2008, average soil C across all treatments was no longer significantly different from 2004 ($P=0.18$, $t=1.36$, $df=72$; Fig. 1C). No significant differences were found among vegetation or management treatments for any of the three periods.

By June 2018, soils had gained ~300 g C m^{-2} (Fig. 2), but exceptions included control-prairie grasses, fertilized-Kentucky bluegrass, mowed-fine fescue and mowed-prairie forbs, which had gained enough SOC to return to 2004 levels, but not enough for SOC gain in 2018 (Fig. 2).

Discussion. The process of perennial grassland renovation, where massive soil disturbance occurs, is likely to result in at least a short-term loss of SOC irrespective of vegetation type, fertilization, or cutting. Irrespective of the mechanism, the patterns of short-term SOC loss under this kind of soil disturbance are important for land managers to understand–whether the land is being managed for pasture, turf, or prairie–that breaking up the soil will result in loss of soil C that may continue for many years after the vegetation has been replaced.

In particular, sales of C credits may be based on erroneous assumptions when less intensive but periodic soil disturbance is

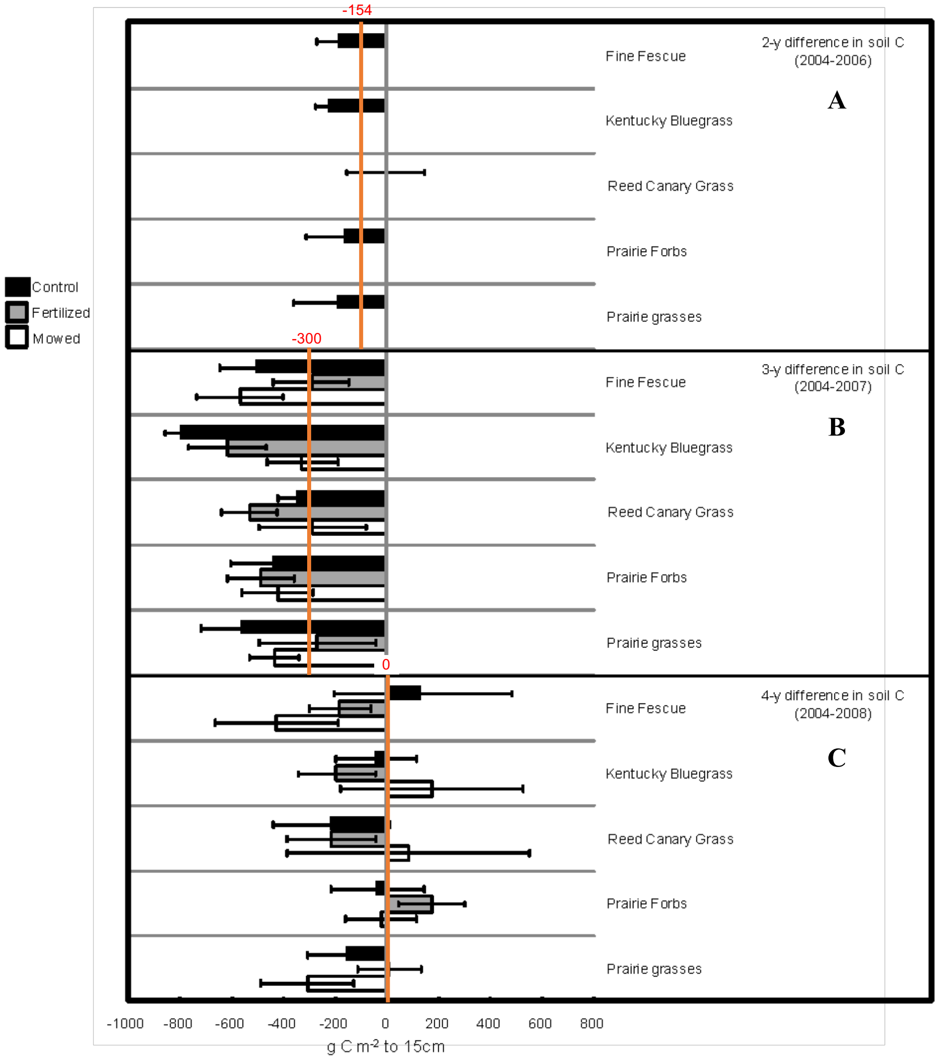

Figure 1. Mean soil C differences (±s.e.) for A) the period October 2004 to September 2006, B) the period October 2004 to July 2007, and C) the period October 2004 to August 2008. Differences were significantly different than zero for the first two periods (P=0.01, P<0.001, and P=0.18; respectively). No significant differences were found with Latin square ANOVA amongst vegetation or management treatments for any period.

part of the site management. Examples include sod growers and graziers who are each represented by groups keen to sell their C-sequestration capacity. Sod growers till and/or scrape the upper horizons from the system at 6 to 12-mo intervals, while many graziers managing 'perennial pastures' periodically renovate their pastures by killing the existing sod, disking or lightly tilling, and replacing it with improved forage varieties. In both cases, most gains in surface soil C during the undisturbed period are likely lost in the periodic disturbance event that is considered typical of their management. Municipalities and urban developers are even more likely to encounter difficulties showing C credits on developed or renovated land. Topsoil is typically moved from one site to another for road construction, housing developments, and industrial and municipal areas.

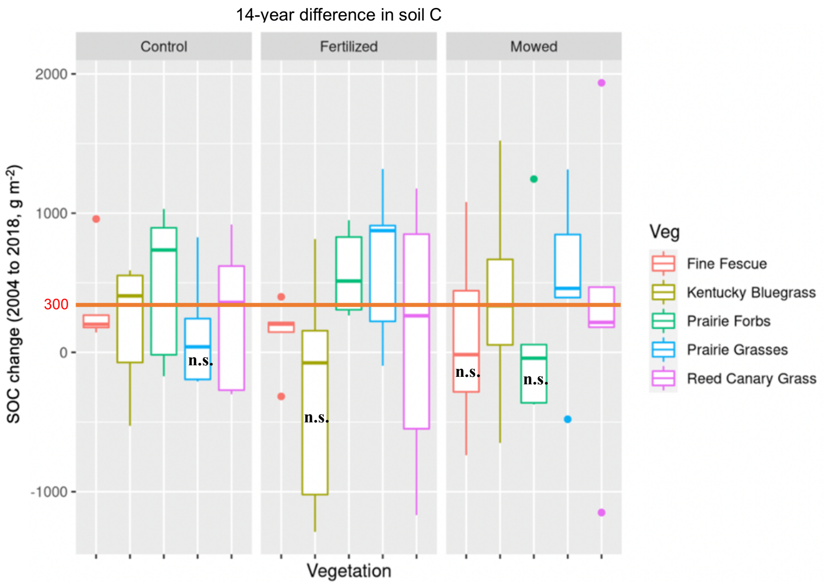

Figure 2. Boxplots of differences in SOC from October 2004 to July 2018 (medians, 75% of data within boxes, 95% of data within whiskers, >95% indicated by asterisks). All treatment combinations gained SOC except control-prairie grasses, fertilized-Kentucky bluegrass, mowed-fine fescue and mowed-prairie forbs, which had gained enough SOC to return to 2004 levels, but not enough for SOC gain in 2018.

Conclusions. Massive soil disturbance and translocation of the soil, which is characteristic of urban development, sod farming, and pasture renovation, will cause a substantial loss of soil C to the atmosphere for at least several years irrespective of vegetation type or management. Mowing and fertilizer management are not likely to mitigate these losses. Carbon credit policy should be based on long-term grassland cover and not new plantings.

Acknowledgments. We would like to thank Eric Koeritz for plot management and John Albright, Andy Jakubowski, Armand Krueger, L. Gary Oates, Abigail Jackson, Priya Mathur, Emily Groves, and Maggie Phillips for sample collection and processing. Early versions of this manuscript were greatly improved by the comments of Karen Haubensak, Rebecca McCulley, and Troy Baisden. Partial support for this research was provided by the College of Agricultural and Life Sciences at the University of Wisconsin-Madison (Hatch #WIS05238) including the Agricultural Research Stations division.

References

Ammann, C., C. R. Flechard, J. Leifeld, A. Neftel, and J. Fuhrer 2007. The carbon budget of newly established temperate grassland depends on management intensity. Agriculture Ecosystems & Environment **121:**5-20.

Kaye, J. P., R. L. McCulley, and I. C. Burke 2005. Carbon fluxes, nitrogen cycling, and soil microbial communities in adjacent urban, native and agricultural ecosystems. Global Change Biology **11:**575-587.

Qian, Y. L., W. Bandaranayake, W. J. Parton, B. Mecham, M. A. Harivandi, and A. R. Mosier 2003. Long-term effects of clipping and nitrogen management in turfgrass on soil organic carbon and nitrogen dynamics: The CENTURY model simulation. Journal of Environmental Quality **32:**1694-1700.

Qian, Y. L., and R. F. Follett 2002. Assessing soil carbon sequestration in turfgrass systems using long-term soil testing data. Agronomy Journal **94:**930-935.