Estimation of Soil Organic Carbon Changes in Turfgrass Systems Using the CENTURY Model

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ABSTRACT

Soil organic C (SOC) directly affects soil quality by influencing aeration and water retention and serving as a major repository and reserve source of plant nutrients. Limited information is available concerning the long-term SOC changes in turfgrass systems. The CENTURY simulation model offers an opportunity to predict long-term SOC trends based on mathematical representations of C-cycling processes in the soil–plant systems. The objectives of this study were to (i) evaluate the ability and effectiveness of the CENTURY model to simulate the long-term SOC dynamics in highly managed turfgrass ecosystems and (ii) simulate long-term SOC changes for golf course fairway and putting green scenarios with the CENTURY model. The CENTURY model simulations near Denver and Fort Collins, CO, indicate that turfgrass systems can serve as a C sink following establishment. Model estimates are that 23 to 32 Mg ha^{-1} SOC were sequestered in the 0 to 20 cm below the soil surface after about 30 yr. Historic soil-testing data from parts of 16 golf courses with age ranging from 1 to 45 yr were used to compare with the simulated results. Model predictions of organic C accumulation compared reasonably well with observed SOC, with regression coefficients of 0.67 for fairways and 0.83 for putting greens. Our results suggest that the CENTURY model can be used to simulate SOC changes in turfgrass systems and has the potential to compare C sequestration under various turf management conditions. Simulation results also suggest that warming temperatures have greater degree of influence on SOC in turf systems compared with native grasslands.

Understanding long-term SOC changes in various ecosystems is of importance because SOC directly affects soil quality by influencing the air-filled porosity and water retention and serving as a major repository and reserve source of plant nutrients, especially N, P, S, and K.

Recent global concerns over increased atmospheric CO_2, which can potentially alter the earth's climate systems, have resulted in rising interest in studying SOC changes and C sequestration capacity in various ecosystems. Promoting soil C sequestration is an effective strategy for reducing atmospheric CO_2 and improving soil quality (Lal et al., 1998, 1999).

Based on statistics from the 1997 USDA Natural Resource Inventory, urbanized land covers approximately 40.6 million ha in the USA, and the hectarage in this category increased by 25% between 1982 and 1997 (NRCS, 2002). Accompanying urbanization and development is a rapid increase in the area of turfgrass, such as home lawns, commercial landscapes, parks, recreational facilities, and other greenbelts. Turfgrass ecosystems provide excellent soil erosion control, dust stabilization, flood control, and urban heat dissipation. These grasslands may act as C *sinks*, absorbing more CO_2 than they release, resulting in C sequestration.

Previously, we conducted an initial study to assess SOC changes in turfgrass systems using historic soil-testing data collected from 16 golf courses (Qian and Follett, 2002). We found that rapid C sequestration occurred during the first 0 to 25 yr after turfgrass establishment, at average rates approaching 0.9 to 1.0 Mg C ha^{-1} yr^{-1}. These rates are comparable or exceed those recently reported for U.S. land that has been placed in the Conservation Reserve Program (Follett et al., 2001). Further research is needed to compare C sequestration under various turf management conditions. The processes whereby C is sequestered under turf need to be better understood, including the roles of plant species selection, mowing, and irrigation management.

Organic C change in soil is a slow process, and many years and decades of measurements are needed to assess C changes as influenced by management practices. Therefore, evaluation of different management options relative to C sequestration is difficult to accomplish by sampling and measuring SOC content and C fractions over time. Simulation models offer the opportunity to predict long-term trends based on mathematical representations of nutrient-cycling processes in the soil–plant systems. Predictive modeling exercises allow significant insight into the ecosystem dynamics. A number of computer models are available to evaluate SOC dynamics (Powlson et al., 1996). Jenkinson (1990) distinguished four categories of soil organic matter (SOM) turnover models, i.e., single homogenous compartment, two compartment, noncompartmental decay, and multicompartmental. Paustian et al. (1997) suggested that two classes of models are currently being used for analyses at regional scales of C fluxes, ecosystem-level models (designed for local-scale studies), and macroscale models (designed for continental- and global-scale studies). The CENTURY model is a multicompartmental ecosystem model and was developed collaboratively by Colorado State University and the USDA-ARS to evaluate C dynamics in the Great Plains grasslands (Parton et al., 1987). The model has been successfully applied to various ecosystems and various locations in the world. The results show that soil C and N levels can be simulated to within ±25% of the observed values for a diverse set of grassland soils (Parton et al., 1993). The CENTURY model incorporates the most recent improvements in the understanding of SOM dynamics plus interactions among C, N, P, and S. The CENTURY model operates

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Abbreviations: SOC, soil organic carbon; SOM, soil organic matter.

at a monthly time step and is adequate for simulation of medium- to long-term (100 to >1000 yr) changes in SOC and other ecosystem parameters in response to changes in climate, land use, and management.

However, it is unknown whether the CENTURY model provides appropriate simulation for turfgrass systems, which have several unique management characteristics that need to be considered when conducting SOC simulations. First, a portion of the shoots are removed from the site or returned to the soil during regular mowing. Second, although after turf establishment there is no periodic plowing or tilling operations, aerification or soil coring is practiced occasionally to alleviate compaction and improve drainage. Third, due to the great plant density and lack of disturbance, turfgrass usually has a layer of residue C on the soil surface (thatch), which exhibits different properties (such as lignin content) compared with other aboveground tissues. Other operations unique to turf are frequent irrigation and regular N fertilization; these management inputs will reduce the C/N ratio. Incorporation of these management effects into the model is essential for adequate simulations in turfgrass systems. Although the CENTURY model was not developed specially to address these unique conditions, we hypothesize that with proper parameterizations, the model could be used successfully to simulate SOC dynamics of turfgrass systems.

The objectives of this study were to (i) evaluate the ability and effectiveness of the CENTURY model to simulate the long-term SOC dynamics in highly managed turfgrass ecosystems and (ii) simulate long-term SOC changes for golf course fairway and putting green scenarios with the CENTURY model.

METHODS

Model Description

A detailed description of the CENTURY model has been presented by Parton et al. (1987, 1993). Briefly, fresh organic mater, such as plant material, is partitioned into either structural or metabolic pools based on the lignin/N ratio. Soil organic matter is partitioned into three pools: active, slow, and passive organic C pools. The active pool consists of microbes and microbial by-products, having the most rapid turnover rate; the slow SOC pool represents stabilized decomposition products with an intermediate turnover rate; and the passive pool is recalcitrant SOC with a turnover rate of hundreds or thousands of years. The modeled turnover times of these pools are functions of soil temperature, nutrient, water availability, anoxic conditions, etc. A SOM submodel, plant biomass submodel, soil water balance submodel, and N submodel are included in CENTURY to provide driving variables for SOC calculations.

The Version 4.0 (Metherell et al., 1993) of the CENTURY model was used to simulate the long-term changes in SOC content in the surface 20 cm of the soil before and after the establishment of turfgrasses. Simulations were conducted for two management scenarios (golf course fairways and putting greens) in Denver and Fort Collins. To evaluate the precision of the CENTURY model, simulation results were compared with soil-testing data from golf courses around Denver, CO, and near Fort Collins, CO. A detailed description of the soil test results in the study sites was given by Qian and Follett (2002).

Data Input and Model Parameterization

The major input variables for the CENTURY model include (i) soil texture (percentage sand, silt, and clay), (ii) monthly average maximum and minimum air temperatures, (iii) monthly precipitation and irrigation, (iv) lignin content of plant material, (v) plant tissue C and N ratio and initial soil C and N, and (vi) soil N inputs through fertilization and atmospheric deposition (Parton et al., 1987; Parton and Rasmussen, 1994).

In fairway sites, three soil series (Nunn, Renohill, and Fort Collins) were used for simulation because they were the common soil series in the golf courses that we studied (Qian and Follett, 2002). Soil texture and bulk density characteristics were measured in the Soil, Water, and Plant Testing Laboratory at Colorado State University or obtained from the soil survey reports maintained by the U.S. Natural Resources National Soil Survey Laboratory, Lincoln, NE. The Renohill soil series represents a clay loam with 46% clay, 34% sand, and 20% silt. The Nunn soil series is also a clay loam containing 35% clay, 45% sand, and 19% silt. The Fort Collins soil series represents loamy soil with 29% clay, 54% sand, and 17% silt.

Different soil textures were not considered for the putting green simulations. Golf course putting greens are usually established on an artificially created soil profile where the subsoil is overlaid by individual layers of gravel, coarse sand, and a particular root zone on top of which turfgrass is established (Hummel, 1993). The root zone (30 cm) textural class is sand. We used proportions of 92.1% sand, 3.1% silt, and 4.8% clay, which were the average values of six samples from six putting green. Although putting green constitutes only a small area, it is high value and highly uniform and may provide unique conditions for model simulations.

Historic weather data for simulations were obtained from the weather database maintained by the Colorado Climate Center, Department of Atmospheric Science, Colorado State University, Fort Collins, CO. Weather records for Fort Collins were available from a weather station (no. 53005) between 1889 and 2000 (111 yr). Denver weather data were collected by weather stations 52220 and 51547 between 1948 and 2000 (52 yr).

Our survey results from the 16 golf courses indicated that irrigation was provided at 75 to 100% of evapotranspiration since turf establishment. We approximated that turfgrass is irrigated when 25% of available water in the soil is depleted. Our survey indicated that N application rate varies with time and location. We used an average rate of 150 kg N ha^{-1} yr^{-1}, evenly divided in April, June, September, and October, in addition to an approximate 50 kg N ha^{-1} yr^{-1} from atmospheric wet and dry deposit plus N input by symbiosis of free-living, heterotrophic N-fixing bacteria (Epstein et al., 2002; Gijsman et al., 2002)

In this work, we focused on the scenario of converting native grassland to golf course fairways because among the 16 golf courses that we surveyed, 11 were initially constructed on previous native grasslands. To establish the initial SOC pool sizes of the fairways, we conducted a 4500-yr CENTURY model simulation of the undisturbed native grass prairie with low-intensity grazing in Denver and Fort Collins, CO. Because no weather record is available for such a long period, we continuously reused the 52- and 111-yr weather data for Denver and Fort Collins, respectively. The SOC level was at a state of equilibrium toward the end of the simulation, with the active, slow, and passive SOC pool sizes ranging from 0.76

to 1.1, 16.1 to 19.2, and 14.1 to 20.2 Mg/ha, respectively. These values were similar to the findings of Follett et al. (1997) and Paul et al. (1997), who reported active, slow, and passive SOC pool sizes of 1.5, 14.0, and 16.1 Mg/ha, respectively, in a native shortgrass prairie dominated by blue grama (*Bouteloua gracilis* Lag. ex. Steud) near Akron, CO.

Native grassland simulation was followed by simulation of 1 yr of land preparation (that involved break of existing vegetation, strip of the topsoil, the land grading, and replacement of the topsoil) and then 1 yr of turf establishment. The model outputs of C in the active, slow, and passive organic pools were used as starting values of C simulation in turf sites.

Initial SOC value used for putting greens was different. The surface 30-cm root zone mixture used in putting greens is recommended to include about 1% (by weight) reed-sedge peat that primarily consisted of the sedge (*Carex* spp.)-dominated fen peat (Bridgham et al., 1998; Hummel, 1993). However, our previous study of putting greens in 16 golf courses indicated an average SOM of 0.6% after the completion of putting green constructions (Qian and Follett, 2002); this value was considered as the initial SOM in putting greens in the CENTURY simulation. We arrived at proportions of active, slow, and passive SOC pools based on peatland simulation results (Chimner et al., 2002).

Vegetation in the CENTURY model is defined by potential aboveground production, a temperature curve, and C/N ratios and lignin contents of biomass pools. Default vegetation parameterizations are available with the CENTURY model. Based on clipping yield data collected from a 3-yr study in northern Colorado (data not shown), we used a potential aboveground biomass value of 250 g C m^{-2} mo^{-1} for cool-season grasses (default values range from 240–270 g C m^{-2} mo^{-1}) in the simulations. Other primary modifications made to default parameterizations included altering lignin content of tissue samples [6% for clippings and shoots, 20% for thatch, and 12% for roots (Shearman and Beard, 1975; Ledeboer and Skogley, 1967)] and reducing the range of C/N ratio to 20 to 40 to account for the high litter quality in turfgrass resulting from fertilization and irrigation applications and regular mowing.

We simulated mowing activities as numerous harvesting events. We assumed that on monthly basis, about 30% of the aboveground tissue was removed during mowing events in fairways. Our survey results from the 16 golf courses indicated that, on average, 80% of the clippings were returning to the soil in fairways.

In general, no periodic plowing operation is applied after establishment of turfgrass. However, aerification or soil coring is practiced to alleviate compaction and improve drainage. We used the No-Till Drill option in the CENTURY model to simulate aerification applied in turfgrass management.

The CENTURY model computes SOC to a depth of 20 cm and output as grams of C per square meter. Although the CENTURY model has the capacity to provide a monthly output, we choose to only report annual September simulation results to examine the long-term SOC changes. Measured percentage SOM data were available for fairways with Nunn, Renohill, and Fort Collins soil series and for putting greens, with ages ranging from 1 to 45 yr. Soil organic matter contains about 58% of SOC (Follett et al., 1987). For convenience, we converted these percentage SOM values to SOC (Mg ha^{-1}) using average bulk density values measured from three golf courses that participated in the study (1.5 Mg m^{-3} for fairways and 1.7 Mg m^{-3} for putting greens with a standard error of 0.06). For comparison of measured vs. simulated SOC, the CENTURY output was adjusted to correspond to the same soil depth of measured SOC (11.4 cm) by assuming that the distribution of SOC within the 20-cm depth follows the distribution of roots. Our rooting data indicated about 61% of roots were present in the surface 11.0 cm under Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.) fairways (data not shown). Under putting green conditions, about 94% of creeping bentgrass (*Agrostis stolonifera* L.) roots were distributed at the top 11.0 cm of the soil profile (data not shown). Regression analysis was then performed to test the simulation effectiveness by comparing measured vs. simulated SOC.

RESULTS AND DISCUSSION

Simulations under Fairway Conditions

A 4500-yr simulation of native grasslands indicated that SOC ranged from 31.0 to 38.0 Mg ha^{-1} in Fort Collins and 33.0 to 40.5 Mg ha^{-1} in Denver in the state of equilibrium (Fig. 1). The CENTURY model did not predict dramatic changes in total SOC during the 1-yr period of construction and establishment as simulated total SOC levels ranged from 30.0 to 39.0 Mg ha^{-1} at the time of turfgrass establishment. This has likely occurred because we only simulated the scenario of land conversion from shortgrass prairie to fairways with topsoil being stripped before grading and replaced after grading. Results would be very different for situations where a great extent of grading occurs and topsoil and subsoil are mixed, which creates new soil profiles.

The CENTURY model simulation strongly suggested that significant C sequestration occurred after conversion of shortgrass prairie to turfgrass (Fig. 1). Total SOC at 0 to 20 cm in the fairway soil profiles increased to 56 to 75 Mg ha^{-1} over approximately 30 yr. Thereafter, SOC increased very slowly in both Denver and Fort Collins. The average rates of accumulation over the 30-yr period were 1.2 and 0.9 Mg ha^{-1} yr^{-1} for Fort Collins and Denver, respectively. These simulated SOC changes during the first 30 yr after turfgrass establishment showed close agreement with the measured C sequestration rate of 0.9 to 1.0 Mg ha^{-1} yr^{-1} presented by Qian and Follett (2002). Simulated time to reach a relatively steady state ranged from about 30 to 40 yr, depending on soil texture and locations. Again, this compared very favorably with the 31 yr generated from nonlinear regression analysis of compiled historic soil-testing data (Qian and Follett, 2002). Soil organic C differences among the three soils indicated that the CENTURY model is sensitive to soil texture; clay particles provide greater protection to SOM than do sand and silt.

Gebhart et al. (1994) reported that the C sequestration rate was 1.1 Mg ha^{-1} yr^{-1} after temperate cultivated land was converted to perennial grasslands. Bruce et al. (1999) estimated a gain of 0.6 Mg C ha^{-1} yr^{-1} for previously cultivated lands that have been reseeded to grass. Post and Kwon (2000) compiled literature data for soil C in areas where grasslands have been allowed to develop on previously disturbed lands and reported that the average rates of C accumulation were 0.33 Mg ha^{-1} yr^{-1} during the early aggrading state of grassland establishment. The greater C accumulation found in our

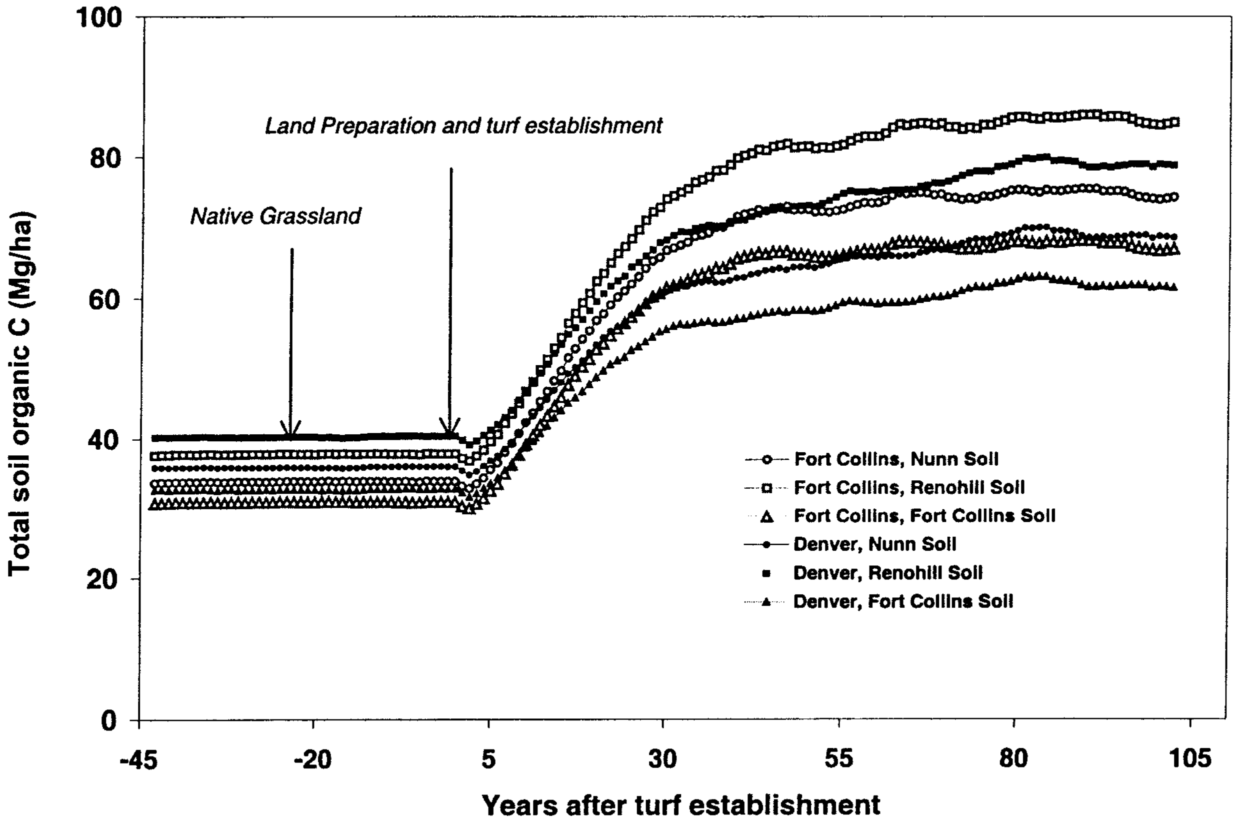

Fig. 1. CENTURY-simulated soil organic C before and after establishment of fairway turfgrass in Fort Collins and Denver in three different soils.

study likely resulted from fertilization and irrigation inputs for these highly managed turfgrass systems.

The first 45 yr of simulated results were compared with the compiled soil-testing results (Fig. 2). A significant linear relationship (R^2 = 0.67) resulted between observed and simulated total SOC content, despite the large variations present in the measured data. The large variations in observed SOC are expected, considering that samples were collected from different fairways in 11 different golf courses. Different fairways likely varied with the initial degree of soil disturbance during land preparations and had been subjected to different microclimates and management.

Simulated SOC accumulations in fairways were different between Fort Collins and Denver (Fig. 1). In all soils, the CENTURY model predicted that the Fort Collins location would exhibit a higher rate of SOC accumulation after turf establishment, despite the fact that, under native grass conditions, simulated SOC was higher in Denver than Fort Collins. Thirty years after turfgrass establishment, the simulated SOC was 62 to 75 Mg ha^{-1} in Fort Collins and 56 to 69 Mg ha^{-1} in Denver. The different model outputs between Denver and Fort Collins may be related to weather differences; the mean maximum and minimum temperatures were 1.35 and 0.95°C warmer in Denver than Fort Collins, respectively. In nonirrigated, moisture-limited and warm-season grass–dominated native grassland, the 0.95 to 1.35°C warmer temperature resulted in higher SOC, probably due to higher production. By contrast, the warmer temperature in Denver (compared with Fort Collins) resulted in lower SOC in a well-irrigated, cool-season grass–dominated turfgrass system. The different responses of SOC to temperature between native grass and turfgrass ecosystems also suggested the important role of soil moisture in controlling how SOC decomposition responds to temperature. Wang et al. (2000) showed that higher temperature accelerates decomposition of

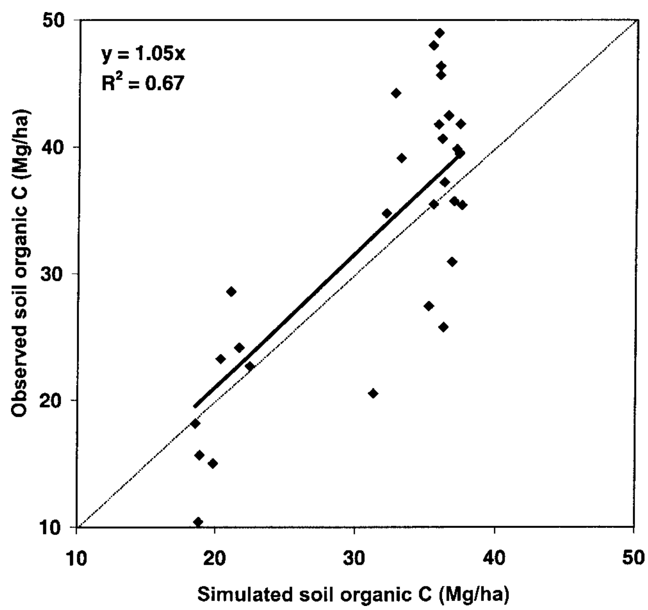

Fig. 2. Comparison of observed and simulated soil organic C in fairways in golf courses near Denver and Fort Collins.

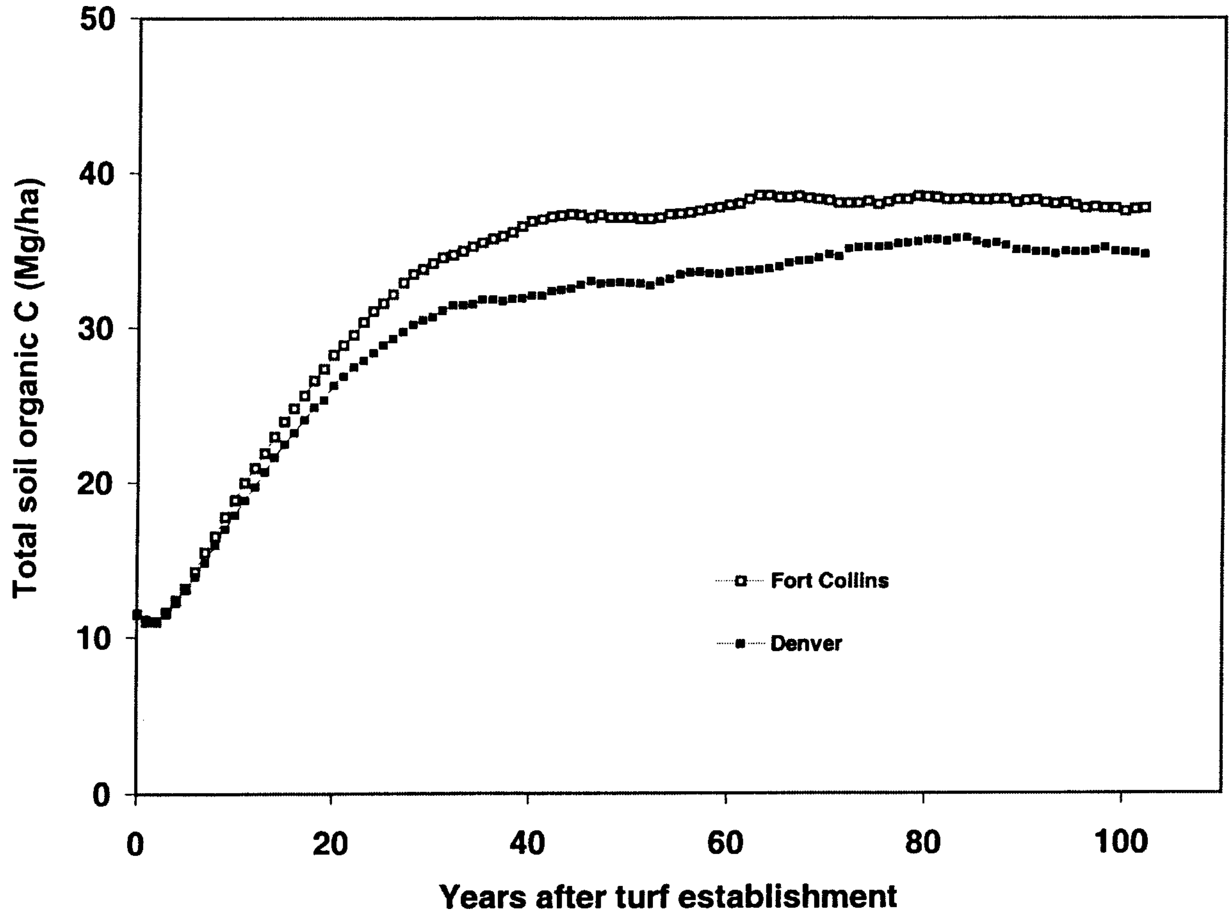

Fig. 3. CENTURY-simulated soil organic C after establishment of putting green turfgrass in Fort Collins and Denver.

SOC only when soil moisture is adequate and inhibits decomposition when soil moisture becomes limited.

As reported by the Intergovernmental Panel on Climate Change (IPCC, 1996), the global average temperature has increased by 0.7 to 1.5°C since 1860 due to increasing greenhouse gases. It is predicted that by 2050, atmospheric CO_2 will be 550 mg kg^{-1}, and the average temperature will be about 1.0°C higher. There is great current interest in the question of whether soil C pools will increase or decrease as global warming occurs. The CENTURY model simulation suggested that temperature has a greater degree of influence on SOC in turf systems compared with native grasslands (Fig. 1). However, to evaluate the impact of global warming on soil C pools in turfgrass systems, more research is needed to evaluate the influences of both increasing atmospheric CO_2 and temperature on soil C storage and decomposition.

Simulations under Putting Green Conditions

Simulation results indicated a SOC of 11.4 Mg ha^{-1} in putting greens in the first years of turf establishment in both Fort Collins and Denver (Fig. 3). Total SOC at 0 to 20 cm in putting greens are predicted to gradually increase over time, reaching 31.5 Mg ha^{-1} in Denver at 34 yr after putting green establishment and 37.4 Mg ha^{-1} in Fort Collins 44 yr after turf establishment. The average C sequestration rates were about 0.60 Mg ha^{-1} yr^{-1} for 34 to 44 yr. The predicted lower SOC accumulation in Denver than Fort Collins may have been attributed to the higher maximum and minimum temperatures as indicated by the historic weather data.

Simulated SOC accumulation in putting greens correlated very well with observed results ($R^2 = 0.83$) (Fig. 4). The simulated time to reach a relatively steady state of SOC was shorter than the 49 yr generated by regression analysis of compiled historical data (Qian and Follett, 2002). The longer time to reach equilibrium in the observed data may be due to the regular soil aeration and sand topdressing that add new sand into the existing soil profile and prolong the time required for SOM to reach equilibrium.

CONCLUSION

The CENTURY model simulations in scenarios of this research indicate that turfgrass systems serve as a sink for atmospheric C for approximately 30 to 40 yr after establishment at approximately 0.9 to 1.2 Mg ha^{-1} yr^{-1}. However, to consider the net impact of urban grassland on the atmosphere's greenhouse effect, we need to consider fuel expenses in maintaining turfgrass and the fluxes of other greenhouse gases (mainly N_2O and CH_4) in addition to soil C sequestration. Additional

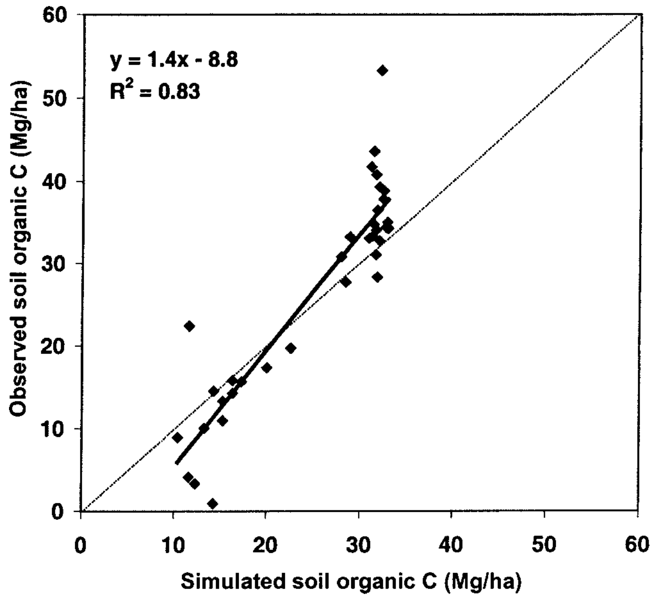

Fig. 4. Comparison of observed and simulated soil organic C on putting greens in golf courses near Denver and Fort Collins.

work is needed to evaluate fluxes of the other greenhouse gases in turfgrass systems.

Model predictions of organic C accumulation compared reasonably well with compiled historical SOC data, suggesting that the CENTURY model is able to simulate SOC changes and C sequestration in managed turfgrass scenarios. This result is not surprising, given that the CENTURY model was developed in, and widely tested for, temperate grasslands. Our results suggested that the CENTURY model is sensitive to both location and soil texture and can be used effectively as a tool to predict SOC dynamics in turfgrass systems. It may be further used to predict how management, climates, soils, and species selection influence soil C dynamics. Information on these aspects is needed so that turfgrass managers can choose the management options for increasing C sequestration. Furthermore, understanding SOC dynamics in turfgrass systems may lead to improved management practices.

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