Long-Term Effects of Clipping and Nitrogen Management in Turfgrass on Soil Organic Carbon and Nitrogen Dynamics: The CENTURY Model Simulation

Y. L. Qian,* W. Bandaranayake, W. J. Parton, B. Mecham, M. A. Harivandi, and A. R. Mosier

ABSTRACT

Experiments to document the long-term effects of clipping management on N requirements, soil organic carbon (SOC), and soil organic nitrogen (SON) are difficult and costly and therefore few. The CENTURY ecosystem model offers an opportunity to study long-term effects of turfgrass clipping management on biomass production, N requirements, SOC and SON, and N leaching through computer simulation. In this study, the model was verified by comparing CENTURY-predicted Kentucky bluegrass (Poa pratensis L.) clipping yields with field-measured clipping yields. Long-term simulations were run for Kentucky bluegrass grown under home lawn conditions on a clay loam soil in Colorado. The model predicted that compared with clipping-removed management, returning clippings for 10 to 50 yr would increase soil C sequestration by 11 to 25% and nitrogen sequestration by 12 to 28% under a high (150 kg N ha\(^{-1}\) yr\(^{-1}\)) nitrogen (N) fertilization regime, and increase soil carbon sequestration by 11 to 59% and N sequestration by 14 to 78% under a low (75 kg N ha\(^{-1}\) yr\(^{-1}\)) N fertilization regime. The CENTURY model was further used as a management supporting system to generate optimal N fertilization rates as a function of turfgrass age. Returning grass clippings to the turf–soil ecosystem can reduce N requirements by 25% from 1 to 10 yr after turf establishment, by 33% 11 to 25 yr after establishment, by 50% 25 to 50 yr after establishment, and by 60% thereafter. The CENTURY model shows potential for use as a decision-supporting tool for maintaining turf quality and minimizing negative environmental impacts.

Fertilization is one of the major management components in maintaining aesthetically appealing turfgrass in our urban and suburban landscapes. Urban landscapes account for approximately 10% of all fertilizer N used in the USA (Food and Agricultural Organization, 2002; USEPA, 1999). Improper N fertilization may lead to negative environmental impacts, including nitrate leaching and gaseous loss of nitrogen as \(\text{N}_2\text{O}\), \(\text{NO}_x\), and \(\text{NH}_3\). Nitrate leaching directly affects ground water quality. Nitrous oxide (\(\text{N}_2\text{O}\)) is a greenhouse gas with 310 times greater global warming potential than \(\text{CO}_2\) on a per molecular basis over a 100-yr time frame (Intergovernmental Panel on Climate Change, 1997). The current IPCC national inventory methodology for estimating \(\text{N}_2\text{O}\) emissions from soils relates \(\text{N}_2\text{O}\) emissions to fertilizer input, that is, about 2% of \(\text{N}_2\text{O}\) loss for nitrogen added as fertilizer (Intergovernmental Panel on Climate Change, 1997; Mosier et al., 1998). Nitric oxide (NO) and nitrogen dioxide (\(\text{NO}_2\)) (\(\text{NO} = \text{NO} + \text{NO}_2\)) emissions contribute to acidification of precipitation and local air quality problems while ammonia (\(\text{NH}_3\)) volatilization is an N loss mechanism that distributes N across the landscape. To meet the demand for environmentally friendly urban landscapes, turf scientists have been challenged to provide management strategies that reduce the use of synthetic fertilizer, while providing aesthetically appealing turf.

Turfgrass produces a large amount of clippings every year (Harivandi et al., 2001). Clipping removal from turf represents a major N loss. However, clippings are often removed from lawns because clippings can be unsightly and may contribute to disease and thatch build up (Harivandi et al., 2001). With increasing landfill restrictions on yard waste and efforts to minimize resource input to turfgrass systems, recycling clippings via a mulching mower is becoming a common practice. Several studies have been conducted to determine the impact of clipping management on turf quality and N requirements. Heckman et al. (2000) demonstrated that the amount of applied N could be cut in half (from 195 to 98 kg N ha\(^{-1}\) yr\(^{-1}\)) when clippings were recycled. Starr and DeRoo (1981) observed that 30% of the total N applied could be saved via clipping return. Recently, Kopp and Guillard (2002) reported that turf plots receiving 0 to 98 kg N ha\(^{-1}\) yr\(^{-1}\) with clippings returned produced a comparable quality and clipping yields to plots that received 390 kg N ha\(^{-1}\) yr\(^{-1}\) with clippings removed, suggesting that returning clippings could reduce N fertilization by 75% or more without reducing turf quality. The discrepancies in the degree of reduced N requirements when clippings are returned may have resulted because of the duration of the experiments, site conditions, and initial SOM levels. Although the above studies have examined the effects of clipping return on turfgrass growth, N requirements, and turf quality, no research has documented the effects of clipping management on ecosystem consequences including changes in soil organic carbon (SOC), soil organic nitrogen (SON), and N leaching.

Nitrogen availability in the soil is a dynamic process. Nitrogen in clippings returned to a turf system is not available to turfgrass until it is incorporated into SOM.
and released via mineralization. Mineralized N can be tied up by soil microorganisms (immobilization). The mineralization and immobilization are both controlled by C to N ratio. Therefore, dynamics of N are controlled by C transformation. The effect of clipping management on N and C interrelation is complicated by other management components, such as irrigation and fertilization. This makes it difficult to capture the intertemporal interactions and carryover effects with single-period static analysis. The long-term experiments necessary to fully assess the influence of clipping management on SOC and SON content are difficult and costly. Computer simulation modeling is therefore a useful means of studying potential impacts of alternative clipping management on N requirements and SOC and SON content.

**CENTURY** is a multicompartmental ecosystem model developed to simulate long-term changes in soil organic carbon and nitrogen, nutrient cycling, and plant production for the soil–plant ecosystem of U.S. Great Plains grasslands (Parton et al., 1987). The model has been well validated and successfully applied to various ecosystems (including pasture, agriculture, and other native systems) in various locations around the world (including tropical and temperate regions) (Kelly et al., 1997; Parton et al., 1993; Parton and Rasmussen, 1994; Carter et al., 1993). CENTURY operates on a monthly time step and is adequate for simulation of medium to long-term (10 to 10000 yr) changes in SOC and other ecosystem parameters in response to changes in climate, land use, and management.

Previously, we used CENTURY to simulate SOC changes in response to turfgrass management in golf courses and found that the model is sensitive to both location and soil texture (Bandaranayake et al., 2003). Predictions of SOC accumulation by the CENTURY model compared very well with compiled historical SOC data ($R^2$ ranged from 0.67–0.83), suggesting that CENTURY is able to simulate SOC changes in managed turfgrass scenarios.

The CENTURY model has not yet been used to simulate the impacts of turfgrass clipping management on fertilization requirements and SOC and SON dynamics. The objectives of this work were to (i) fit the CENTURY model to turfgrass systems and to compare the CENTURY-predicted clipping yields with measured clipping yields from a 3-yr field experiment in northern Colorado; (ii) predict the long-term impacts of clipping management (clippings returned vs. clippings removed) and N fertilization rates on biomass production, SOC and SON content, and N leaching; and (iii) use the CENTURY model as a supporting tool for generating N requirements as a function of turfgrass standing age under clippings returned vs. clippings removed management scenarios.

**MATERIALS AND METHODS**

**Field Experiment**

From 1993 to 1995, a study was conducted on 8-yr-old Kentucky bluegrass plots at the Northern Colorado Water Conser-
The CENTURY Model Simulation for Turfgrass Systems

The major input variables for the CENTURY model include: (i) soil texture (% sand, clay, and silt); (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 (vi) soil N inputs through fertilization and atmospheric deposition (Parton et al., 1987; Parton and Rasmussen, 1994).

The initial soil organic carbon (0.46, 14.7, and 7.8 Mg C ha\(^{-1}\)) in active, slow, and passive SOC pools, respectively) was provided by the CENTURY model for cultivated agricultural land in the region.

As the first step, we ran a short-term simulation (15 yr) using the site-specific soil texture, weather data, and management regime (mowing, fertilization, and irrigation) employed in the field experiment. Simulated annual and seasonal clipping yields were compared with measured clipping yields to evaluate the performance of the CENTURY model.

Long-term (100 yr) CENTURY simulations were then conducted using the average precipitation and average minimum and maximum temperatures of a 100-yr weather station record. To generate the best N fertilization regime as functions of the age of turf stand and clipping management, we ran numerous simulations with variable nitrogen rates. We compared model outputs of aboveground biomass, SOC, SON, C to N ratio of SOM, and nitrate leaching under various fertilization rates with clippings removed or returned. Our aim was to select the fertilization regimes that produced a maximum production under the constraint of minimal N leaching. We used aboveground biomass as an indicator of turf quality. As such, the best fertilization rates for different periods after turf establishment under clippings returned or removed scenarios were selected.

RESULTS AND DISCUSSION

Comparison of Measured and Simulated Clipping Yield

Mowing turf to 5.1 cm weekly removed an average of 4.7% of the standing aboveground biomass at each mowing (Table 1). This percentage is higher than that reported in California by Madison (1971), who found that 3% of the aboveground standing biomass was removed at each mowing event.

Simulated clipping yields were compared with the measured clipping yields (Fig. 1). The model correctly simulated the annual clipping yield in 1994, but slightly underestimated annual clipping yields in 1993 and 1995 (Fig. 1A). Model-simulated monthly clipping yields mis-timed the seasonal trend, overestimating yields later in the season and underestimating yields early in the season (Fig. 1B). This mistiming trend resulted in a negative EF value (−1.25), a CD value of less than 1 (0.44), and a relatively large M (101.6). The correlation coefficient for the observed vs. simulated clipping yield was −0.32. The mistiming by the CENTURY model may occur because Version 4.0 of CENTURY does not have the ability to simulate photoperiod-induced growth pattern changes. In response to daylength change, bluegrass exhibits more upright growth during the spring (which results in high clipping yields) and more lateral growth during the fall (which results in low clipping yields). Improvement in model performance requires additional information about the seasonal photoperiod effects on C allocation to verdure and clippings. Nevertheless, the CENTURY model simulated annual accumulative clipping yield within 21% of the observed values (Fig. 1A). Previously, we demonstrated that predictions of SOC accumulation by CENTURY compared very well with measured historical SOC data from highly managed turfgrass systems (r = 0.82 to 0.91; EF = 0.67 to 0.57;
Fig. 1. Comparison of measured and CENTURY-simulated (A) annual accumulative clipping yields and (B) monthly clipping yields collected from a field study in Colorado. Kentucky bluegrass was managed under typical home lawn conditions.

CD = 2.3 to 3.0; M = −0.019 to 6.0) (Bandaranayake et al., 2003). These results suggested that even though monthly variability in clipping biomass was often not well represented, CENTURY is able to simulate different clipping management (clippings retained vs. clippings removed) effects on long-term soil C and N dynamics.

Long-Term Simulation

Long-term simulations were run to examine the effects of different N fertilizer application rates and clipping management regimes on aboveground biomass, SOC, SON, and nitrate leaching for the experimental site. We present the simulation results of four representative management scenarios: the factorial combination of clipping management (removed vs. returned) and two N fertilization levels (150 vs. 75 kg N ha⁻¹ yr⁻¹).

Aboveground Biomass

The model predicted that nitrogen availability was very important in ecosystem aboveground productivity. A combination of high fertilization (150 kg N ha⁻¹ yr⁻¹) and clipping return would be essential for optimal biomass production (and therefore high turf quality; Fig. 2A). Compared with high fertilization (150 kg N ha⁻¹ yr⁻¹) and clipping return management regime, aboveground biomass is predicted to be lower when fertilized at 150 kg N ha⁻¹ yr⁻¹ N with clippings removed or fertilized at 75 kg N ha⁻¹ yr⁻¹ N with clippings removed, especially for young turf stands. A low N fertilization coupled with clipping removal would result in a rapid decline of biomass.
Soil Organic Carbon

Our simulated results indicated that SOC increased with all management scenarios except that of low N fertilization with clippings removal, in which case SOC did not increase after land use was changed to turf. Compared with the clippings removed scenario, returning clippings for 10 to 50 yr would increase soil C sequestration by 11 to 25% under high (150 kg N ha\(^{-1}\) yr\(^{-1}\)) N fertilization regime and by 11 to 59% under low (75 kg N ha\(^{-1}\) yr\(^{-1}\)) N fertilization regime. Returning clippings increases carbon sequestration capacity by 14 to 21 Mg ha\(^{-1}\) 50 yr after establishment of turf.

With N fertilization at 150 kg ha\(^{-1}\) yr\(^{-1}\) and the clippings returned scenario, total SOC increased from 34 Mg ha\(^{-1}\) at the turf establishment to 65 Mg ha\(^{-1}\) about 50 yr after turf establishment. The average rate of accumulation over the 50-yr-period was 0.62 Mg ha\(^{-1}\) yr\(^{-1}\). Thereafter, SOC increased very slowly. With N fertilization at 75 kg ha\(^{-1}\) yr\(^{-1}\) and clippings returned, SOC increased from 34 Mg ha\(^{-1}\) at the turf establishment to 65 Mg ha\(^{-1}\) within 75 yr after turfgrass establishment. Simulated SOC dynamics showed that high N availability leads to more rapid increases in SOC after turf establishment and faster arrival at the relatively steady state than low N management. Qian and Follett (2002) reported a rapid C sequestration at 0.9 to 1.0 Mg C ha\(^{-1}\) yr\(^{-1}\) during the first 0 to 25 yr after turfgrass establishment, suggesting the high N availability on the highly managed golf courses.

Soil Organic Nitrogen

Simulated SON exhibited a pattern similar to SOC, with high N application rates leading to more rapid increases in SON after the establishment of turf while returning clippings increased soil N sequestration capacity. The SON increase is slightly and proportionally higher than that of SOC, a reflection of the increase in relative nitrogen content in SOM and a reduction of C to N ratio of SOM over time (Fig. 2B,C). The decreasing soil C to N ratio indicates that the turf ecosystem becomes a more nutrient-rich ecosystem as standing age increases. The CENTURY model predicts that the turf–soil system serves as a strong sink of mineral N. However, the N sink strength gradually decreased with prolonged N or high N application. With best management practices, SOM in the turf ecosystem serves as an important sink of N for several decades. With a 150 kg ha\(^{-1}\) yr\(^{-1}\) N fertilization rate and clippings returned management scenario, soil N sequestration is approximately 66, 27, and 14 kg N ha\(^{-1}\) yr\(^{-1}\) during 1 to 30, 31 to 60, and 61 to 100 yr after turfgrass establishment, respectively. Although the N sink strength gradually declines over time, our predictions suggest that turfgrass can maintain sink strength much longer than that reported by Porter et al. (1980), who concluded that SON reached plateau about 10 to 12 yr after turf establishment. A complete vanishing of soil N sink strength within the first decade following establishment of turf was a key assumption made in a model simulation by Valiela et al. (1997), who concluded that 39% of applied fertilizer N would be lost via gaseous forms and 61% would reach the subsoil, resulting in significant leaching.

Nitrate Leaching

The CENTURY model predicted that N leaching would be minimal (close to nonexistent) under the management scenarios of low N fertilization or high N rate with clippings removed (Fig. 3). With a 150 kg ha\(^{-1}\) yr\(^{-1}\) nitrate leaching...
N fertilization rate and clippings returned scenario, N leaching is minimal (close to nonexistent) 20 to 30 yr after turf establishment. These results are consistent with the research findings of many studies conducted on newly established turf plots (<10 yr old; Petrovic, 1990). The model predictions indicate that minimal nitrate leaching occurred during the period of rapid carbon sequestration. This suggests that SOC accumulation would tie up soil mineral N and result in a rapid accumulation of SON. As the rate of carbon sequestration declined, less applied N was tied up in the SOC. Therefore, with time, an increasing amount of applied mineral N (NO₃⁻) is available for gaseous loss and/or leaching, if the fertilization regime is unchanged. Continuously high fertilization and clipping return would result in increased nitrate leaching, reaching 50 to 60 kg ha⁻¹ yr⁻¹ when turf reaches 100 yr. Fertilization rates higher than 150 kg ha⁻¹ yr⁻¹ can lead to significant N leaching that occurs earlier. These simulation results suggest that following a period of clipping return, N fertilization should be reduced, otherwise N loss would increase over time.

**Optimal Nitrogen Fertilization Rates as a Function of Turf Ecosystem Age and Clipping Management**

We examined opportunities for reducing N fertilization by comparing simulated biomass and N leaching at various fertilization rates with clippings removed or returned. The CENTURY model predicted that, as the age of a turf ecosystem increases, N application rates should be reduced to balance the greater amounts of N mineralized from SOM. At a loam soil site and under a clipping-returned scenario, the CENTURY model predicts that optimal productivity and low N leaching (<2 kg N ha⁻¹ yr⁻¹) are obtained at annual N fertilization rates of 150, 100, 75, and 60 kg N ha⁻¹ during 1 to 10, 11 to 25, 26 to 50, and 51 to 100 yr after turfgrass establishment, respectively (Fig. 4A,B). In contrast, under the clippings removed scenario the model suggests that N fertilization at 200, 150, and 140 kg N ha⁻¹ yr⁻¹ would be required for the periods of 1 to 15, 16 to 50, and 51 to 100 yr after turfgrass establishment, respectively, to achieve a comparable productivity and turf quality (Fig. 4B). Fertilization below these rates would be insufficient for maximum biomass production and desired turf quality.

Our simulation results suggest that N application to turfgrass systems can be reduced over time and the reduction should be greater where clippings are returned. In addition, returning grass clippings to the turf-soil ecosystem can reduce N requirements by 25% between 1 to 10 yr after turf establishment, 33% between 11 to 25 yr after establishment, 50% between 25 to 50 yr after establishment, and 60% thereafter (Fig. 4A). These amounts of reduction in N fertilization, along with clipping return, could result in a substantial reduction of nitrate leaching and gaseous loss of nitrogen.

**CONCLUSIONS**

The CENTURY simulation model offers an opportunity to couple C and N processes and study long-term effects of turfgrass clipping management on biomass production, N requirements, SOC and SON content, and N leaching. The CENTURY model predicted that, following establishment, turf–soil systems have great potential to sequester C. Rapid carbon sequestration retains mineral N as SON in a young turf stand. Thus, the turf–soil systems serve as a strong N sink. However, the N sink strength gradually decreased with a prolonged or high rate of N application.

Clipping input plays an important role in C and N sequestration, and consequently, in ecosystem sustainability. Net carbon and nitrogen sequestration can be increased by returning clippings to turfgrass ecosystems. Returning clippings offers opportunities for reducing N fertilization requirements by 25 to 60%, depending on the duration of the practice, without a loss of turf quality as indicated by aboveground biomass. In addition to 25 to 60% fertilization reduction, long-term return of clippings increased SOC and SON pools. The CENTURY model simulation suggests that, by reducing N fertilization as the age of turf stand increases, it is possible to maintain desired turf quality with minimal long-term N leaching (<2 kg N ha⁻¹ yr⁻¹). Further field research is needed to test the model with long-term measurements of SON, SOC, and nitrate leaching as affected by clipping and fertilization management.
REFERENCES


