

Long-term biogeochemical cycling in agroecosystems inferred from ^{13}C , ^{14}C and ^{15}N

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Abstract

We investigated C and N cycling in long-term agroecological experiments initiated over 50 years ago at a cool, semi-arid site on the North American Great Plains. We used isotopes at natural abundance to trace C and N exchange between soils and plants in contrasting cropping systems. Both ^{13}C and ^{14}C indicated that the soil organic matter was isotopically distinct from current plant inputs, suggesting that recently added plant C was cycling independently of much of the soil C pool. For tracing recent C flows, bomb- ^{14}C was more sensitive than ^{13}C , and increased more in high – than in low – yielding systems. Analysis of ^{15}N in plant tissues, as an index of ^{15}N in actively cycling soil N, suggested that biological and industrial N fixation both tended to decrease plant ^{15}N , whereas livestock manure addition increased ^{15}N abundance. Collectively, the data suggest that soil organic matter is kinetically heterogeneous, so that a majority of soil C and N inputs and outputs exchange with only the small pool of soil organic matter that is actively cycling. Consequently, recently photosynthesized C and deposited N may not readily enter the old, stable fractions of soil organic matter. Practices to retain CO_2 from the atmosphere and prevent leakage of reactive N to non-agricultural systems should therefore focus on management of this active pool.

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1. Introduction

Agroecosystems not only furnish food and fibre but also provide other ecosystem services, including: water cleansing and buffering, biogeochemical recycling and buffering, biodiversity reservoir, and aesthetic retreat (Ellert et al., 1997). They also occupy the largest terrestrial area of the ecosphere that is directly, and often intensively, manipulated by humans. Consequently, agroecosystem management is concerned not only with agricultural output but also with maintaining other ecosystem services and

preventing adverse effects on other ecosystems within the ecosphere. Of particular interest, is enhancing the storage of atmospheric CO_2 and preventing N leakage in agroecosystems (Amundson, 2001; Janzen et al., 2003).

Here we provide an example of how long-term agroecological experiments provide insight to agricultural sustainability, and how isotopic tracing at natural abundance enhances understanding of long-term biogeochemical cycling.

2. Materials and methods

The experimental site is on the North American Great Plains, near Lethbridge Canada (annual precipi-

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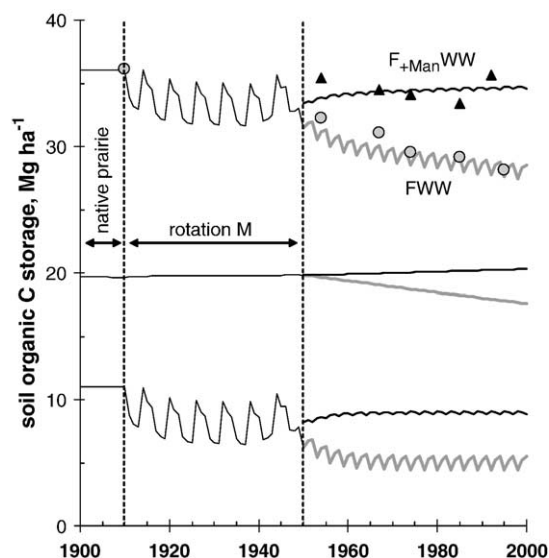


Fig. 1. Long-term changes in SOC storage under contrasting agroecosystems and hypothetical changes after the quasi-steady state under native prairie were perturbed by arable cropping under rotation M (F–W–O–F_{+Man}–H_{OP}–O) from 1910 to 1950. Symbols represent measured SOC for the two most divergent systems since 1950, as well as the pre-cultivation baseline before 1910. Model output plotted at the top represents total SOC in the surface (0 to 15 cm) layer, which is the sum of that in the old (plotted in the middle), young (plotted at the bottom) and inert (fixed at 5.4 Mg ha⁻¹) pools.

tation=403 mm, mean annual temperature=5.1 °C). The site had been under native grasses until just before 1910, when various rain-fed crop rotations were established, shortly after initial cultivation. One of these was a 6-year sequence (designated rotation M) of fallow, cereal crops, and oat and pea hay (H_{OP}), amended with manure at a rate of 27 Mg wet material ha⁻¹ once every 6 years. This sequence remained in place until a cropping systems study (now designated ‘Rotation 120’ or R120) was established in 1951 (Pittman, 1977). Soil samples were collected and stored at 5- to 10-year intervals and yields were recorded annually.

In this analysis, we infer land–atmosphere CO₂ exchange from long-term changes (1951 to 1990) in soil organic C (SOC) stored in four cropping systems from R120: continuous spring wheat (W), fallow–wheat–wheat (FWW), FWW with 11.2 Mg livestock manure (wet) ha⁻¹ in the fallow year (F_{+Man}WW), and a 6-year sequence with 3 years of alfalfa-crested wheatgrass hay (FWWHH). To determine the extent to which recent plant C is retained in soil, we measured the ¹³C and ¹⁴C isotopes in archived soil samples dating back to 1953. Soil organic ¹³C was determined using an automated CN analyzer (NA-1500 series II by Carlo-Erba, Milan, Italy) linked to an isotope ratio mass spectrometer

(Optima by GV Instruments, Manchester, UK). Soil organic ¹⁴C was determined by combusting acidified samples in the CN analyzer, cryogenically trapping the effluent gas, and sealing pure CO₂ in glass ampoules sent to the NSF-Arizona AMS Lab in Tucson, USA, for graphitization and analysis by accelerator mass spectrometry.

3. Results and discussion

The two most contrasting systems established after 1950 are the FWW rotations with and without manure (Fig. 1). Warm, moist conditions during fallow hastened SOC loss by decomposition, but manure inputs replaced this SOC in one of the systems.

We adapted an elementary SOC model (ICBM) developed by Andrén and Kärrer (1997). The model, based on concepts of Hénin and Dupuis (1945), specifies that SOC inputs initially enter a rapidly decomposing ‘young pool’, and a portion is transferred, via humification, to an ‘old pool’ with slower decomposition. The influence of external variables, such as soil moisture, climate and tillage, is imposed using a single rate modifying parameter to adjust rate coefficients for young and old pools. The model output (Fig. 1) described the transition from steady state conditions under native prairie, to arable agriculture under rotation M when SOC was maintained by manure, to changes under contrasting cropping systems since 1950.

A wide array of assumptions could equally well describe the long-term changes observed in soil C storage. To further constrain model structure and parameterization, we used a co-flow construct to simu-

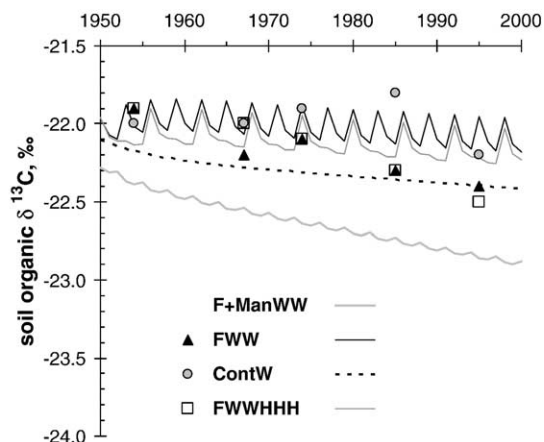


Fig. 2. Measured ¹³C in surface SOC and model predictions for contrasting cropping systems. The ¹³C of contemporary plant C inputs typically were in the range of –26‰ to –28‰.

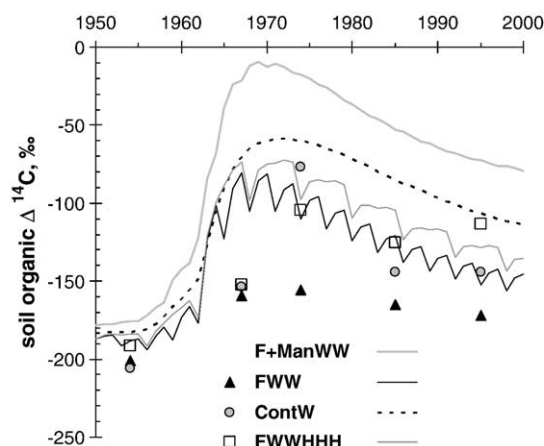


Fig. 3. Measured $\Delta^{14}\text{C}$ in surface SOC and model predictions for contrasting cropping systems.

neously describe SOC and its ^{13}C and ^{14}C isotopic abundances. To account for very low ^{14}C contents of our soils, relative to other surface soils on the North American Great Plains, we assumed a pool of inert C (5.4 Mg ha^{-1} , largely devoid of ^{14}C , -990‰), an assumption similar to that of Jenkinson et al. (1992).

Most of the shift in soil ^{13}C after land use change from prairie to cultivated agriculture occurred during the first few decades of cultivation. Since prairie vegetation included some C4 plants, the $\delta^{13}\text{C}$ of soil C inputs was about -22.5‰ ; and after conversion to arable agriculture with C3 crops, this decreased to about -27‰ . There were no measurable changes in $\delta^{13}\text{C}$ of SOC from 1951 to 2000. Differences among

cropping systems also were undetectable, although we expect the manured treatment, still to be analyzed, to have lower $\delta^{13}\text{C}$ than the others (Fig. 2). Notably, the ^{13}C abundance in SOC remains appreciably greater than that of the plant C inputs entering these soils, even after 90 years. This suggests that C cycling may have been largely confined to a small SOC fraction, such as that represented by the ‘young pool’ of the ICBM model.

The abundance of ^{14}C in SOC reflected the input of ‘bomb C’ during the 1960s and 1970s (McNeely, 1994). Measured $\Delta^{14}\text{C}$ of SOC increased during this period, with larger increases in systems with the greater C inputs and slower decay rates (Fig. 3). ^{14}C was greater under the W and FWWHHH systems compared to FWW, which had slightly smaller C inputs and accelerated decomposition. ICBM predictions of bomb-induced increases in ^{14}C of SOC followed the same patterns as the measured data, but the predicted increases were larger than those measured (Fig. 3). This suggests that C cycling may be confined to a smaller portion of SOC than specified in our ICBM runs.

The $\delta^{15}\text{N}$ of soil N inputs varied with management. Livestock manure applied to rotation M and later R120 is enriched in ^{15}N , presumably due to preferential volatilization of ^{14}N . In contrast, N fixed biologically or industrially from the atmosphere, typically has $\delta^{15}\text{N}$ close to 0‰ . Wheat plants had the greatest ^{15}N in the F+ManWW rotation, and the smallest ^{15}N in rotations with legumes, such as alfalfa of the FWWHHH cropping system (Fig. 4). Within plots,

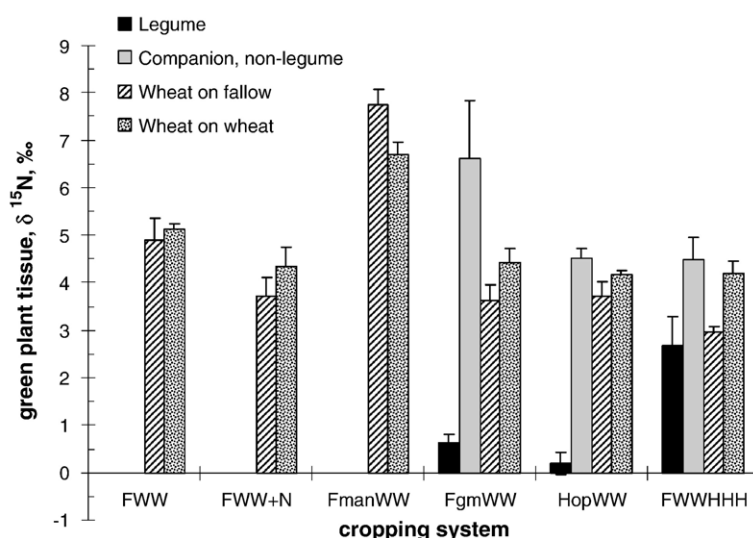


Fig. 4. Natural abundance of ^{15}N in above-ground plant tissue sampled near peak phytomass accumulation in 2004 from selected cropping systems in the R120 study. Error bars represent \pm one standard error. Legume and companion plants were collected within the same plot, whereas the wheat on fallow (FWW) and wheat on wheat (FWW) were collected from separate plots representing contrasting years of the same cropping system.

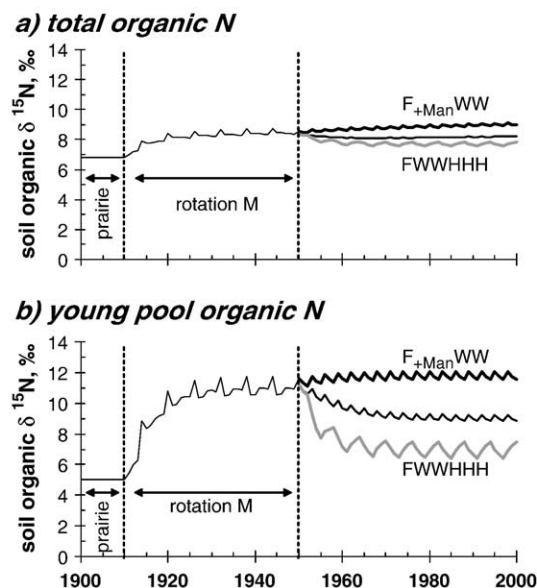


Fig. 5. Natural abundance of ^{15}N predicted by ICBM for organic N a) in the total surface soil pool and b) in the young pool. The thinner line plotted between the lines for the F+ManWW and FWWHHH systems is for the FWW system, which was similar to that for ContW (not plotted).

tissue ^{15}N was smaller in legume than in non-legume plants. Although the FWW rotations with N fertilizer or green manure had only been established in 1985 (H_{OP}WW in 2001), the ^{15}N differences were already evident (Fig. 4). Soil organic N dynamics predicted by ICBM, with some adjustments to the C/N ratios of organic matter inputs, suggested that changes in the ^{15}N of total soil organic N would be difficult to detect, especially in systems established after 1950 (Fig. 5a). But for the young pool, predicted ^{15}N differed among systems, depending on whether N was added as manure, with elevated ^{15}N , or leguminous residues, with small $\delta^{15}\text{N}$ values (Fig. 5b).

4. Conclusions

Natural variations in isotope abundance helped us follow the fate of recent organic matter inputs into the relatively massive pool of soil organic matter. The isotopic data suggested that soil organic matter had to be partitioned among at least three pools with contrasting decay coefficients to describe dynamics. The small differences in SOC storage among contrasting systems

imposed since 1950 can be explained by a large pool of old and stable C that changes only slowly. Despite these small differences, the isotope data enabled us to develop a credible model of C and N dynamics. The ^{15}N abundance in plants from contrasting cropping systems suggest that the crops depend more on the dynamics of the young than the old pool of soil organic matter. Collectively, our results indicate that majority of organic matter inputs enter the young or active fraction and are decomposed without becoming stabilized in the old fraction.

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