Prairie Soils; A Sink for Atmospheric CO_2?

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Introduction

The soils of western Canada were first cultivated about a century ago. Almost from the outset, there was concern about organic matter loss from these soils. Already in 1922, one researcher worried about "... the rapid destruction of the soil fibre where a bare fallow is maintained..." (Fairfield, 1922. Experimental Station Interim Report, Lethbridge). And, indeed, the concern was justified: within a few decades of their initial cultivation, soils on the prairies often lost about 25% of the organic matter originally present in the surface layer.

The rate of C loss abated, however, and the organic C content of most prairie soils is now almost stable. With improvements in cropping practices, furthermore, there is now the prospect for partially reversing previous losses. Interest in such soil C gains has intensified recently with anxiety over increasing atmospheric C02, a condition linked to global warming.

Canada has made a commitment to reduce by about 2010 emissions of greenhouse gases (including C02) to 94% of levels in 1990. One proposed strategy is to store excessive atmospheric CO2 in soils as organic matter. Agricultural soils on the prairies are an attractive repository because they contain large amounts of organic C: roughly 3 Pg C in the surface 30 cm. This amount is more than 20 times the CO_2-C emitted annually from fossil fuel combustion in Canada. Consequently, a small incremental increase in the C content of agricultural soils could, in theory, offset a significant portion of CO2 emissions.

Our objective is to consider the potential role of Canadian prairie soils as a sink for atmospheric C. We address this objective by posing four questions: 1. How can we elicit soil C gain?; 2. What is the pattern and amount of that C gain?; 3. Can we measure the C gain if it occurs?; and 4. What are the secondary effects of any C gain?

Methods of increasing soil C

The methods of increasing soil C can perhaps be deduced most easily from the C cycle itself. Crop plants, using solar energy, convert atmospheric CO2 to organic molecules; a portion of this organic material is returned to CO2 via plant respiration, a portion is exported from the ecosystem as harvested product, and the remainder enters the soil as plant litter and becomes organic matter. The organic matter, in turn, is gradually oxidized back to CO_2 by microbial activity in the soil, thereby completing the cycle. Thus the pool of C in the soil is dynamic; always decomposing and continually being replenished.

From this simple view of the C cycle it is clear that any strategy to increase stored C in soil must either: 1. increase the rate of C addition in the form of plant litter; or 2. suppress the rate of soil C decomposition.

Enhanced C inputs can be achieved by increasing photosynthetic activity (i.e., increasing net primary production) or by increasing the proportion of the total plant biomass returned to the soil. Examples of strategies to increase C input include: fertilization (which increases photosynthesis), elimination of summer fallow (resulting in greater total net primary production), use of perennial forages (which extend the duration of photosynthetic activity and allocate higher amounts of C below-ground), and use of livestock-based cropping systems (which return higher amounts of plant C to the soil in the form of manures).

The rate of decomposition can be slowed in several ways. One approach is to suppress the rate of microbial activity by creating less favorable conditions in the soil. For example, soils under continuous cropping tend to be drier and cooler than those under fallow, resulting in slowed decomposition in the former. Another approach is to reduce accessibility of the decomposable C to microbial activity either by protecting it inside aggregates or physically isolating the residue from the soil. For example, reduced tillage tends to slow decomposition by promoting aggregation and also by retaining residues on the surface where conditions are often less favorable for decomposition.

This overview, therefore, suggests numerous possibilities for revision of cropping systems to promote soil C gain. It also implies that C gain is not a function of adopting any specific practice but managing the entire agroecosystem to enhance C input and reduce decomposition.

Amount and pattern of C accumulation

Soils cannot accumulate C indefinitely. At some point after adoption of an improved practice, soil C reaches a new equilibrium beyond which additional gains can be achieved only by further alterations to the system. This upper limit is enforced by two constraints: 1. The limit on total productivity, imposed by climatic, soil, and economic conditions; and 2. The tendency for organic matter decomposition to follow first-order kinetics; that is, the rate of CO_2 production increases as organic matter accumulates. After adoption of a new practice, therefore, organic C may initially increase but, as decomposable C accumulates, the rate of CO_2 release also increases, so that the net gain of soil C diminishes with time and eventually approaches 0. At this point, soil C is at a new steady-state level, and additional increases can be achieved only by further changes to enhance C input or slow decomposition rate.

One potential way of circumventing the latter limitation would be to shunt a significant proportion of new soil organic matter into a comparatively inert pool. Analysis of soil organic matter using isotopic techniques indicates that a large proportion of organic matter, perhaps 50% or more, is virtually resistant to decomposition, with turnover times measured in centuries or even millennia. If a sizeable fraction of incoming plant C could be diverted into this pool, increases in soil C could continue almost indefinitely. Unfortunately, though it may be possible to build inert C, the rate of accumulation is likely too slow to be of consequence over periods of less than a century. A rough estimate of the rate of inert C gain can be derived from historical accumulations. Assume, for example, that a soil has 60 Mg C ha^{-1} that half of this C is in inert form, and that it accumulated at a constant rate over the 10,000 years since the retreat of the glaciers. From these (admittedly crude) assumptions, we can estimate an annual inert C gain of about 3 kg C $ha^{-1}yr^{-1}$, a negligible rate from the standpoint of atmospheric C withdrawal.

Given the constraints, what is the potential amount of C gain in prairie soils? Prediction of future gains, clearly, is risky. But some estimate of potential gains can be obtained by looking at data from long-term experiments that have compared various cropping practices. For example, the potential gain of soil C in response to adoption of no-till can be estimated from long-term comparisons of no-till and conventional-till treatments. A review of such sites reveals high variability among sites; the difference in stored C between tilled and un-tilled treatments may range from about 0 to as high as 5 Mg C ha^{-1} or more. This variability can probably be attributed to a number of factors, including: 1. Other agronomic factors (for example, the response of C to no-tillage may be greater under continuous cropping than under a fallow-based system); 2. Soil properties (for example, some research suggests a positive link between soil clay content and C gains under no-till); 3. The initial soil C content (soils which have been depleted of C by previous management usually have higher potential for C gain than soils with high initial C); and 4. The potential productivity of a soil, given climatic constraints (potential gains maybe much higher in areas where precipitation supports high yields than in arid regions). Based on these criteria, the soils in western Canada with the highest potential capacity for C gain may be the Luvisolic soils, because of their relatively low initial C content and high productivity owing to favorable moisture regimes.

Our understanding of soil C dynamics is still insufficient to predict future C gains with certainty. Suppose, however, that all of the currently cultivated land on the Canadian prairies were to be shifted to the 'best-possible' management practices (including optimum tillage, crop sequence, nutrient management regimes, and, in marginal lands, reversion to grassland). Assume, further, that these practices elicit a C gain of 3 Mg C ha^{-1} over a period of several decades, an increase in accord with observations from long-term sites. The total C gain, then, would amount to about 0.1 Pg C (0.1×10^{15} g), roughly the amount of C released annually into the atmosphere by fossil fuel combustion in Canada. This gain, of course, would occur over several decades. Furthermore, this estimate assumes full adoption of most-favorable practices on all cultivated lands and is probably, therefore, best viewed as a potential value rather than as a predicted gain.

From this rough approximation it is clear that prairie soils can probably offset only a relatively small proportion of the CO_2 released into the atmosphere by fossil fuel combustion in Canada. Nevertheless, reductions in greenhouse gas emissions will almost certainly occur through the combined effect of numerous measures, each making a small, incremental contribution. From that standpoint, the potential role of prairie soils as a sink for atmospheric CO_2 cannot be ignored.

Measurement of soil C gain

If we do increase soil C on the Canadian prairies, can we quantify it? Indeed, will we even know it has occurred?

These questions are not trivial: accurately quantifying a C gain is not easy because of the large amount of C already present. For example, a soil may contain about 60 Mg C ha^{-1} in the surface 20 cm. A gain of 3 Mg C ha^{-1} therefore represents just a 5% increase, an increment not much larger than typical analytical variation alone. When we consider, further, the high spatial variability of organic C on the landscape, accurate measurement of soil C change seems even more troublesome.

Several recent developments have improved the accuracy of measuring soil C change. One is the improvement in analytical instruments themselves; automated C analyzers based on dry combustion of soils now permit highly reproducible analysis of C concentration in large sample numbers. Another is the adoption of methods of sampling soils and of calculating their C content, based on an 'equivalent mass' of soil among sampling points. These and other innovations now permit precise measurement of soil C at specific locations. Such advances, however, they still do not address the issue of spatial variability; for now, the best approach for estimating soil C change may be to perform repeated measurement of C at the same locations on a landscape over time. Regional estimates of C gain can them be derived using simulation models calibrated against these site-specific measurements.

Despite the improvements in techniques, uncertainties about the reliability of quantifying soil C change remains an impediment to the recognition of soils as an important sink for C.

Secondary effects of soil C gain

The decision to adopt C-conserving practices depends not only on the amount of their potential C gain but also on other, broader considerations.

One important consideration is their impact on energy use. Most agroecosystems are dependent on supplementary energy from fossil fuel, and the amount of CO_2 release from this source may amount to about 0.1 Mg C ha^{-1} yr^{-1} (including C from energy used to manufacture and transport farm inputs). The net removal of atmospheric CO_2, then, is the difference between soil C gain and cumulative CO_2-C release from fossil fuel use. Maximizing the net removal of CO_2 from the atmosphere therefore depends both on increasing soil C and also reducing energy use. Practices that reduce energy use, like reduced tillage or more efficient fertilizer use, may therefore have benefits on atmospheric CO_2 beyond the soil C gain. Conversely, if a new practice requires higher energy input, the net benefit will be less than amount of soil C gain.

Another important consideration is the potential impact of any C-conserving practice on the emission of other greenhouse gases. Both N_2O and CH_4 are much more potent than CO_2 in terms of radiative forcing. For example, the global warming potential of N_2O is 3 10 times that of CO_2 (kg/kg) when their effects are calculated over a **100** year period. Consequently, a small increase in the emission of N_2O can negate any gain in soil C. If the intent of the soil C gain is to reduce agriculture's contribution to global warming, then the overall impact of all the gases must be considered.

Finally, soil C gain may have other effects quite apart from the net emission of greenhouse gases. Foremost among these is the effect on soil productivity. Because of the relationship between soil organic matter and soil quality, increases in soil C may also improve productivity or reduce costs of production. Furthermore, many of the practices which elicit soil C gain may also reduce erosion, increased net economic returns, and minimize environmental impact. In the end, these factors may play a decisive role in motivating the adoption of practices that favor soil C storage.

Conclusion

The prairies of western Canada can be a significant sink for carbon if there is widespread adoption of improved management practices including reduced tillage, reduction in fallow use, greater use of forages, improved crop nutrition, use of other agronomic practices that promote yield, and conversion of marginal cultivated lands to grassland. The increases in carbon, while perhaps offsetting only a small fraction of Canadian greenhouse gas emissions, may nevertheless play a significant role as part of a larger effort involving numerous mitigation strategies, each making an incremental contribution. Furthermore, many of the practices that promote soil C can already be advocated because of their other benefits, and any removal of atmospheric CO_2 therefore is almost a supplementary advantage.

The eventual change in C storage on the Canadian prairie is subject to numerous uncertainties. These include potential changes in agronomic practices: cropping systems which are now innovative may be obsolete several decades from now, and shifts in economic factors may accelerate the transition from wheat-based production systems to livestock-based systems. Aside from changes within agroecosystems, there may also be changes in the global environment: possible changes in climate and increases in atmospheric CO_2. All of these have a strong bearing on processes within the C cycle and inject additional uncertainty into predictions of future C reserves. Consequently, though the C cycles within prairie agroecosystems has been studied now for almost a 100 years, this area of study will likely remain a research priority well into the next century.