Management Strategies/Practices for Increasing Storage of Organic C and N in Soil in Cropping Systems in the Northern Great Plains of North America

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Background

- Soils lost substantial original organic C and N reserves in last 100 or more years.
- Range from 16.2 to 62.1%, or 4.2 to 51.4 Mg C ha^{-1}, or 0.105 to 0.734 Mg C ha^{-1} yr^{-1}.
- Mainly due to tilled summer fallow.
- Currently, many soils represent a potential sink for atmospheric CO_2.

Objective

- In this report, we summarized research information on the impacts of tillage, crop residue management, balanced fertilization, manure, crop rotation/diversity and frequency of summer fallow on cultivated cropland, and conversion of cultivated land to perennial grassland on storage of organic C and N in soil.

Inherent Factors Affecting Changes in Soil C and N

Climate - Temperature and Precipitation

- Affect OM production (mainly via plant growth) and loss (mainly via microbial decomposition).
- Climosequence.

Soil Texture and Topography

- Soils with greater clay retain more water/nutrients for production (i.e., increasing C and N input to soil), while complexing of OM with clay slows the decomposition of OM via aerobic microbial activity, thereby decreasing C and N loss.
- Less evaporative water loss from steep slopes facing away from the equator than slopes facing the equator, and as a result, generally possess greater soil C and N.

- Effects of landscape position on soil C and N closely follow trends in soil texture and drainage across variable terrain, but tend to be more pronounced under arable agriculture than native vegetation due to redistribution of topsoil.

Vegetation Attributes

- Plant type, growth stage and nutritional status, all affect rate of decomposition.
- The C:N ratio of plant residues - a useful guide to determine the potential for release of available N during decomposition.
- A C:N ratio of approximately 25:1 is used as a threshold for this potential. Values below the threshold resulting in net N mineralization, and values above the threshold resulting in net N immobilization.
- Plant residue C:N can range from 10:1 (legumes and young green leaves) to 80:1 (wheat straw), with the former decomposing rapidly in soil.
- Carbohydrate and lignin content of plant residues are also useful parameters for estimating C and N dynamics in soil. The residue decomposition rate could be described by the general equation [(C:N) (% lignin)] (% carbohydrate$^{-1/2}$).
- In addition to C:N ratio, the chemical composition of plant residues provide insight regarding potential impacts on soil C and N dynamics.

Effects of Management Practices on C and N Storage in Soil

- Crop Residue Management and Tillage
- Fertilizer Rate and Balanced Crop Nutrition
    - Annual Crops
    - Grassland for Hay
- Manure Applications
- Integrated Use of Fertilizers and Manure
- Crop Rotation/Diversity, Cropping Frequency and Fallow
    - Summer Fallow Frequency
    - Cropping Systems
- Conversion of Cultivated Land to Perennial Grassland

Crop Residue Management and Tillage

Crop Residue Effects

- Crop residues are a source of OM in soil; therefore, the accumulation of organic C in soil can be greatly influenced by the input of crop residue.
- Significant positive correlations between SOC, SON, light fraction organic matter (LFOM), light fraction organic C (LFOC), mineralizable C (C_{min}), mineralizable N (N_{min}) or water stable aggregates (WSA), and input of crop residue, residue C, or residue N.
- Straw removal from the land at harvest, or burning it to facilitate seeding, tends to deplete SOC and LFOC.
- Burning also causes considerable immediate loss of crop residues, and organic C, N and other nutrients from straw by volatilization to the atmosphere, plus soil desiccation and poor soil tilth, decreasing potential for snow trapping or conservation, and increasing water runoff and potential for soil erosion.
- Long-term continuous straw burning can result in a reduction in SOC and SON, and may impart detrimental effects on soil physical, chemical and biological properties.

Tillage Effects

- The intensity of tillage influences the degree and magnitude of organic C loss or build-up in soil.

- Tillage increases SOM decomposition by making it more susceptible to microbial attack through the physical disruption of soil aggregates.
- No-tillage reduces C oxidation due to less incorporation of crop residue and changes in physical, chemical or biological microenvironment and microbial populations within the soil.
- Adoption of no-tillage increased SOC and LFOC; the amount of organic C stored in soil, however, varied with location, climatic conditions, inherent level of organic C in soil, and the duration of the experiment.

Summary

- Organic C in soil can be stored by minimizing the loss of C from soil, accomplished through the elimination of tillage (with appropriate attention to fertility management), and/or by increasing C input through returned crop residue.
- The return of crop residues increases the input of organic C, but its effect on increasing C storage depends on the method of managing straw or crop residues and also varies with the fraction of OM being considered.
- The LFOC and C_{min} are early indicators of change in OM, and are also more sensitive to straw management practices than total SOC.

Fertilizer Rate and Balanced Crop Nutrition

Annual Crops

- "Fertilization effect" is most likely due to an increase in both above-ground and below-ground plant residue input.
- Fertilization increased SOC and LFOC, but the magnitude of increase varied with the inherent level of OM and fertility of soil, crop yield response to applied nutrients and climatic conditions. In Alberta, SOC increased on a Gray Luvisol (low in OM) but not on a Black Chernozem (rich in OM). In Saskatchewan, SOC increased due to N and P fertilization on a Brown Chernozem soil.
- In a few cases, there was no gain in SOC due to N fertilizer application, but LFOC increased with proper fertilization compared to no-N control. For example, in central North Dakota, no effect of fertilization on SOC storage.
- Greater increases accompanied higher cropping frequencies, or less summer fallow. However, detected no measurable effect of fertilizer on SOC in a Black Chernozem soil rich in OM at Melfort, Saskatchewan.

Grassland for Hay

- On a thin Black Chernozem at Crossfield, Alberta, where AN at 0 to 336 kg N ha^{-1} was applied for 27 years (from 1968 to 1994), mass of SOC in the 0-30 cm soil increased by 16.6 Mg C ha^{-1} with 56 kg N ha^{-1}, and by 24.0 Mg C ha^{-1} with 112 kg N ha^{-1}.
- Annual average hay yield increased from 1.41 Mg ha^{-1} in the no-N control to 5.82 Mg ha^{-1} with 224 kg N ha^{-1}.
- In northern Saskatchewan, annual addition of 112 kg N ha^{-1} and 11 kg S ha^{-1} for 11 years to native grass forage substantially increased DMY (dry matter yield), SOC, and LFOC when compared to the no-N control.
- Forage DMY, NUE (N use efficiency), SOC, SON, LFOC and LFON all increased with N + S treatment after 21 years, but decreased in the N only treatment due to nutrient imbalance.

- Because most of the aboveground portion of bromegrass was removed as hay, the increase in SOC and LFOC was mainly associated with increased root biomass and rhizodeposition of forage grasses in response to N fertilization and possibly biomass of fallen dead leaves and harvest losses.
- The findings also suggest that N fertilization is more effective on grasslands managed as hay than in cereal cropping systems. This outcome is most likely due to greater production of root biomass by forage grasses.

Summary

- Adequate and balanced fertilization produces higher yields and increases SOC content. The increase can be influenced by N fertilization rate, N source, application timing, and placement method.
- The majority of the C storage in soil occurs in the surface layers; increasing the duration of time under NT management increases C storage in deeper soil horizons.
- Total organic C may be less sensitive or insensitive for assessing the quality of SOM or soil quality. The change in LFOC, a potential soil quality indicator, is usually more responsive and sensitive to N application than SOC.
- Perennial forages can sequester more C in soil than cultivated annual crops because of a greater increase in root biomass and rhizodeposition induced by fertilization and possibly from increased above-ground crop residue production with fertilization (stubble and falling leaves).
- Increased below-ground and above-ground biomass production acts as a C input to the soil, thereby sustaining or improving fertility, quality and health of the soil.
- It appears that adoption of NT management, increased use of balanced fertilization from inorganic and organic sources, and retention of crop residue can all potentially contribute to increased SOC storage in agricultural lands.

Manure Applications

- Commercial fertilizers are inorganic compounds targeted to supply specific nutrients, usually N, P, K, and S; they do not offer any direct contribution to SOM content.
- On the other hand, OM from manure, in addition to supplying multiple nutrients to the soil, adds directly to SOM.
- Application of solid manure with high OM content, such as solid cattle manure (SCM, ~ 50% solids), adds considerable organic C directly to the soil due to the C and N content of feces and bedding materials.
- Application of liquid manures, such as liquid swine manure (LSM, ~ 2% solids), adds much less C directly to the soil. However, crop plants utilize nutrients such as N, P and micronutrients contained in both solid and liquid manures leading to greater production of biomass thereby indirectly adding C and N to the soil.
- In a long-term study on a Gray Luvisol soil near Breton, Alberta, pronounced increases in SOC and microbial biomass N with the application of manure and commercial fertilizers when compared to un-amended soil.
- At Melfort, Saskatchewan, the application of LSM increased LFOC compared to the control. The increase was attributed to stimulation of plant growth from the nutrients in the manure and subsequent residue input.
- Manure was also found to be the best amendment to restore eroded soils containing low OM content to agricultural production.

Integrated Use of Fertilizers and Manure

- In short-term experiments in Alberta, combined applications of inorganic fertilizers and farmyard manure resulted in the highest gain in both SOC and LFOC when compared to the application of fertilizer or manure alone; this effect was particularly pronounced in eroded soils.
- The integrated management of fertilizer and manure (i.e., applying manure according to requirements for P and then topping-up the N requirements with inorganic fertilizers) was also helpful in improving other soil quality attributes or properties and produced the highest grain yield and quality.
- The limited research suggests integrated application of inorganic fertilizers and organic manures/amendments may be an important strategy for maintaining/increasing soil organic C and N, improving soil fertility/quality, and minimizing damage to the environment, while simultaneously sustaining high crop production.

Crop Rotation/Diversity, Cropping Frequency and Fallow

Summer Fallow Frequency

- In many areas of the Northern Great Plains, available water is the most limiting factor for sustainable crop production. Consequently, cropland is often summer fallowed to replenish water and control weed populations.
- Mechanical tillage during summer fallow eliminates vegetation growth but intensifies C loss because it enhances decomposition of existing SOC due to better contact of crop residues with soil microorganisms and favourable soil moisture during the fallow year.
- Cultivation of crops in rotations with tilled summer fallow resulted in lower SOC, LFOC and C_{min} when compared to those in a continuous cropping system.
- The magnitude of decrease in SOC varied generally with the frequency and duration of tilled summer fallow, soil-climatic zone and soil texture. This was attributed to a smaller return of both above and below-ground crop residue and the increased loss of organic C as CO_2, which escapes to the atmosphere from enhanced mineralization and potentially from accelerated erosion on tilled summer fallow lands.

Cropping Systems

- The adoption of diversified cropping systems, with mixed crop rotations of annual grains and perennial forage crops, provides another option for C sequestration in soil.
- The mass or concentration of SOC, LFOC or C_{min} varied with crop type in the rotation.
- The increases were usually higher when perennial forage crops and/or green manure were included in the rotation.
- Management options such as inclusion of perennial forage crops in the rotation, and decreasing frequency of fallow can be used to enhance organic C in soil, which may offset the negative effect of residue removal.

Conversion of Cultivated Land to Perennial Grassland

- Higher amounts of organic C in soils seeded to perennial grasses (5 to 12 years) than in the adjoining annually cultivated soils, in east-central and north-east Saskatchewan.
- In another study in Saskatchewan, a substantially higher SOC and LFOC in soil converted to perennial forage (30 or 60 years ago) compared to annually cultivated soils.

- In southern Alberta, an increase in SOC, SON, LFOC, LFON, C_{min} and N_{min} following conversion of cultivated land to perennial forage after 8 years.
- In another study in southern Alberta, an increase in organic C levels of previously cultivated soils which had reverted to perennial vegetation.
- In east-central Saskatchewan, in Black and Gray-Black soil zones, grassland restoration was found to sequester 0.6 to 1.2 Mg C ha^{-1} yr^{-1} over a period of approximately 10 years.
- Carbon sequestration rates were greater on sites that had lower SOC (usually because tillage and fallow had been included), depending upon the landscape position.
- Summary: The mass of LFOC and the proportion of SOC comprised of LFOC were higher in the restored grassland, which is reflective of higher recent C input. The findings indicate that a switch to permanent grass cover on these soils is likely to increase SOC.

Constraints to C Sequestration

Straw Handling Problems

- Heavy straw residue on soil surface in some areas can still hinder seeding/other field operations, even with improved seeding and harvesting equipment in recent years.

Incorporation

- Options: (1) straw can be chopped by the combine, (2) straw can be uniformly distributed during harvest by straw spreaders on combine, (3) stubble can be cut short at harvest, or (4) straw can be baled and removed.
- Additional field operation and greater energy requirement.
- Incorporating straw into the soil decreases effect of residue to capture snow and to protect soil from erosion, and increases loss of moisture and CO_2 from soil.

Burning

- Burning of straw and stubble often practiced when extremely heavy residue or diseases a problem (burning not effective in reducing plant pathogens).
- Smoke also causes air quality problems and can be a health hazard.
- Burning also causes nutrient loss (up to 90% of C, 98 to 100 % of N, 24 % of P, 35 % of K and 75 % of S).

Removal

- Straw for feed and bedding in livestock operations, and manure generated from it can replace a portion of the fertilizer nutrients.
- However, manure is rarely applied to all of the land from which straw removed.
- Recently, increasing amounts of straw removed and baled for industrial use (paper or fiberboard, power generation or ethanol production, or construction of homes).
- To maximize straw yield, crop cut short, requiring greater harvester capacity (additional equipment neede for baling/handling bales).
- Straw removal also depletes C, N, P, K and S (although lower than burning).

Cost of Manure Transport and Application

- Manure used as a nutrient source, but increasing fuel costs for transportation can partially offset the fertilizer value of the manure.
- Nutrient values of manure may vary by manure source. Chicken manure application costs 18-37% of commercial fertilizer cost. Cow manure 125-137%.
- Nutrient management guidelines may limit over-application of manure, increasing handling/transportation/application costs, and major constraints to application.

Cost of Green Manure (Losing Crop Year)

- Green manure crops may minimize soil erosion during fallow periods, provide N for subsequent crops and increase SOC.
- Green manure becoming economic alternative, as costs of N fertilizer increase.
- In semi-arid areas, GM crops utilize soil water, leaving less for subsequent crops.
- Green manure crops may need to be terminated early to limit depletion of stored water, but this reduces N fixation and makes it impractical to use for hay or silage.
- Overall, these benefits are not without cost. GM crop can deplete soil water, resulting in lower subsequent crop yield while providing little or no economic return to the land during the fallow (green-manure crop) period.

Duration, Magnitude and Permanence of C Sequestration

- Carbon sequestration duration depends upon crop residue C inputs, and rates of C loss by decomposition of both added residues and SOM.
- Sequestration is enhanced when OM is resistant to decomposition.
- Decomposition of SOM slowed by physical/biochemical protection.

Saturation

- Soils with initially high SOC are relatively un/less responsine to C input.
- C saturation - maximum quantity of C that can be stored in a particular soil under a specific set of conditions.
- Estimating C saturation point is uncertain and many soils may be sufficiently below saturation levels so that C sequestration rates are not affected over decades.

Duration of C Change

- Carbon sequestration will not continue indefinitely, where total decomposition increases with total SOC, as is expected under first-order kinetics or saturation.
- The duration of significant C sequestration from management changes (elimination of fallow and adoption of no-till) is generally about one to two decades.
- Twenty years is the default value for C change proposed by IPCC.
- In contrast, other research (Janzen) suggested for at least 50 years.
- For land-use change from cultivated to grassland/forest can be 50 to 100 years.

Magnitude

- Magnitude of C change depends on initial soil C, degree of management change in terms of C inputs and/or decomposition rates, and climate and production potential.
- Change in C increases as degree of C input increases and greater for tillage than other changes in management.
- Conversion of cropland to perennial provides greatest magnitude of C change.
- Manure addition also provides for high C sequestration rates, but the benefit is perhaps small when considering the C balance of the land producing the feed and bedding which is the source of the C within the manure.

Permanence

- Discontinuing the management practices that sequester C may cause sequestered SOC to be mineralized and lost to atmosphere.
- Although the immediate loss of all sequestered C has been reported from single tillage of no-till, this is an exceptional situation.
- An occasional inverted tillage could actually increase C sequestration for no-till.
- The effect of return to tillage on SOC after long-term no-till depends on soil texture (with

little loss on medium/fine-textured soils but large loss on coarse-textured soils).
- Much of SOC loss related to disruption of aggregates (physical protection POM).
- Losses of C following conversion of grasslands to arable cropping increased with the frequency of bare fallow and intensity of tillage.
- Losses of SOC after land-use change were minimal with MT/NT without fallow.

Potential Negative Effects of C Sequestration on Emission of N_2O and CH_4 Gases
- There is an unavoidable increase in soil-emitted N_2O associated with organic or inorganic forms of N applied as fertilizer.
- Because N_2O is such a powerful GHG. It would require about 130 kg C ha^{-1} to be sequestered each year to offset a yearly increase in N_2O emissions of 1.0 kg N ha^{-1}.
- Moreover, rate of C sequestration will diminish over time as new equilibrium in SOC is approached, but N_2O emissions will continue for as long as N application.
- Therefore, application of organic/inorganic fertilizer N to increase soil C sequestration exclusively for GHG mitigation cannot be justified in the long-term.
- However, replacing the N removed from the soil when crops are harvested is critical for the continued productivity of that soil.
- The appropriate compromise is to strive for the lowest N_2O intensity (units of N_2O per unit of crop production) possible.
- This means that N inputs must match crop needs and uptake patterns as closely as possible to optimize crop yield, while minimizing N_2O additions.
- In the cool semiarid and subhumid regions, similar or lower N_2O emissions on NT compared to CT soils, but results variable and reversals.
- On the Canadian prairies, N_2O emissions are 20% lower from NT than CT.
- Influence of tillage on CH_4 uptake by soil is not always consistent. Based on limited research, estimated that CH_4 consumption would be 20% greater in NT than CT.
- No CH_4 consumption data has been reported for agricultural soils on the Northern Great Plains, but would be similar or higher on soils under NT compared CT soils.
- We conclude that reducing tillage intensity will result in reduced GHG emissions for cropping systems on the Northern Great Plains.
- On the semiarid prairies, improved moisture conservation by NT practices, have allowed farmers to reduce fallow frequency or even eliminate it entirely.
- Nitrogen application requirements will increase in proportion to the reduction in fallow frequency, raising a concern about increased N_2O emissions associated with those N inputs.
- However, in western Canada, annual N_2O emissions from fallow plots are often similar or higher than those from fertilized cereal plots.
- Extending and diversifying crop rotations appear to be beneficial in terms of SOC levels and general soil quality attributes.
- Emissions from pulse phase of crop rotations tend to be lower than emissions from their fertilized cereal counterparts. Emissions do not appear to be increased by the presence of pulse residues in the following crop year, thus net GHG emissions tend to be lower from rotations that include pulse crops compared to those that do not.
- Considering that the soil profile tends to be dryer, NT occurs, and, if the forage is a legume, no fertilizer is applied during the years under forage; we may speculate that emissions would be lower from established forages compared to their fertilized annual

crop counterparts.

- However, in other regions, increased N_2O emissions have been measured after forage legume stands are returned to annual cropping.

Energy Input Cost of C Sequestration

Tillage (No Till/Direct Seeding versus Conventional Tillage)

- In general, the non-renewable energy inputs associated with fuel and machinery repair are reduced as tillage intensity is reduced. The magnitude of this change is proportional to the magnitude of the change in tillage intensity.
- However, fertilizer N requirements usually increase when reduced tillage systems are adopted. The energy intensity of manufacturing and transporting N fertilizer is very high, and represents 60 to 70% of the energy inputs for cropping systems in the Northern Great Plains.
- If fertilizer N requirements increase with the adoption of reduced tillage systems, overall energy inputs can be higher compared to their more intensively tilled counterparts.
- Total energy inputs that were 8% higher for NT compared to CT for a study in south-western Saskatchewan, but total energy inputs were similar for several 4-year rotations under NT and CT in south-eastern Saskatchewan.
- Conversely, lower total energy inputs for NT compared to CT in north-eastern Saskatchewan, but in these studies fertilizer N applications were equivalent on CT and the reduced tillage systems.

Fertilizer Rate and Balanced Crop Nutrition

- Benefit of storage of C and N in soil attributed to fertilizer use must be weighed against the non-renewable energy costs of the fertilizer.
- Further, soils will reach a new equilibrium for soil C and N and no further sequestration will occur without other changes to the system.
- However, in order to maintain soil C and N at the new level, the fertilizer application rates will need to be maintained on an ongoing basis.
- Thus, increasing fertilizer inputs for the sole purpose of storing more C and N in soil cannot be justified. However, soil C and N storage is only one of many important benefits of the judicious use of fertilizers.

Crop Rotation/Diversity (Diversified Annual Grains and Perennial Forages)

- Varying nutritional needs (fertilizer inputs) and pesticide requirements associated with different crop types can have a considerable influence on the overall energy input cost of crop rotations.
- Pulse crops have lower energy inputs compared to cereals or oilseeds due to their reduced requirement for N fertilizer.
- Canola tends to have higher input energy costs compared to cereals, while flax tends to have somewhat lower energy inputs compared to cereals.
- Forage crops also reduce energy inputs compared to annual crops. This is particularly true if the forage is a legume or a legume-grass mix where N fertilizer requirements are minimized.

Increased Cropping Frequency

- Non-renewable energy inputs increase as cropping intensity increases (frequency of fallow decreases), primarily because higher amounts of fertilizer N are required.

- Total energy inputs of 7100, 4470 and 3482 MJ ha^{-1} for continuous wheat, fallow-wheat-wheat, and fallow-wheat systems under CT management.
- The increased energy requirement for more continuously cropped systems can be mitigated somewhat if fallow is replaced with an annual grain legume.
- Total energy inputs were 210% higher on the continuous wheat, and 160% higher on the wheat-lentil compared to the fallow-wheat.
- Similarly, at a site in eastern Saskatchewan energy inputs for a wheat-wheat-flax-winter wheat rotation managed as CT were 130% higher than a wheat-wheat-winter wheat-fallow rotation, while a wheat-flax-winter wheat-field pea rotation was only 14% higher than the fallow containing rotation.
- Clearly, there is a trade-off between the C sequestration benefit of reducing fallow frequency and the increase in non-renewable energy costs. However, considering the many important ancillary benefits associated with reducing the frequency of summer fallow, it remains a highly desirable objective.

Manure Application

- The high energy inputs associated with fertilizer applications can also be offset with judicious use of animal manures.
- However, considerable non-renewable energy is required to haul animal manures, thus at some point the energy benefit of the avoided fertilizer use will be counterbalanced by the energy invested in transport and application of manure.
- The hauling distance at which this occurs will be determined largely by the nutrient density of the material and the energy efficiency of the manure handling system.
- Composting of the animal manures will effectively increase the nutrient density of the material to be land applied, but the composting process also requires some investment in non-renewable energy.

Quantifying C Sequestration and C Trading

- There are three general methods of determining how land use and land management affect SOC. 1. To measure SOC to compare land uses and management practices of interest, 2. To use models that simulate C dynamics to estimate changes in SOC, and 3. To measure the balance between CO_2 taken up during net primary production and crop harvest plus net CO_2 emissions from decomposition.
- Practical problem of determining SOC change through measurement is that SOC is highly variable horizontally and vertically, so great care and expense is needed in sampling and analytical strategy to obtain representative SOC values.
- Further, the differences in SOC between land uses and/or managements are often relatively small compared to total SOC, so again the sampling and analytical strategy are critical to successfully detecting these differences against the inherent variability.
- The strategy not only has to consider number of samples, but also the method used to measure soil bulk density and the procedure of handling of larger (>2 mm) pieces of organic materials within the soil. Finally, translocation of soil by erosion from tillage, water, or wind will affect amounts of SOC. This also needs to be included when comparing land uses or managements that could have different erosion rates.

C Trading

- An increase in SOC derived from plant residues corresponds to a removal of atmospheric CO_2. In this way, SOC increases offset CO_2 emissions.

- Importantly, the offset results only from the increase in SOC and is not from the entire stock of SOC itself.
- A CO_2 emitter which seeks to reduce emissions, either by regulation or voluntarily, may be willing to purchase these offsets from increased SOC to reduce the emitter's net CO_2 emissions, providing these offsets are at lower cost than other means available to the emitter to reduce net CO_2 emissions.
- The market for SOC provides an incentive for the adoption of management practices or land use that will increase SOC to help meet this market demand.

Summary of Findings

- Adoption of no-tillage (NT) increases C sequestration by up to 1.170 Mg C ha^{-1} yr^{-1} compared to conventional tillage (CT) and up to 0.227 Mg C ha^{-1} yr^{-1} when compared to minimum tillage (MT).
- Retaining straw added an additional 1.068 Mg C ha^{-1} yr^{-1} or 0.400 g C kg^{-1} soil yr^{-1} over straw burning and up to 0.695 Mg C ha^{-1} yr^{-1} or 0.405 g C kg^{-1} soil yr^{-1} compared to straw removal practices.
- Annual application of N, P, or other nutrients increased C sequestration by 0.906 Mg C ha^{-1} yr^{-1} at 56 kg N ha^{-1} under NT and by 1.620 Mg C ha^{-1} yr^{-1} at 150 kg N ha^{-1} under CT.
- On a perennial grassland for hay production where soil was deficient in both N and sulfur (S), annual application of S fertilizer in a combination with N was required to store additional soil organic C (SOC - by up to 1.275 Mg C ha^{-1} yr^{-1} with 120 kg N plus 11 kg S ha^{-1} yr^{-1}), demonstrating the importance of balanced fertilization.
- Compared to fertilized cropping systems, the addition of manure had greater improvement in SOC, which was maintained at a higher level in the long-term (e.g., 33.7 Mg C ha^{-1} for NPKS fertilized vs. 43.2 Mg C ha^{-1} for manure after 60 yr).
- Integrated or combined use of manure and fertilizers resulted in much higher SOC (3.888 Mg C ha^{-1} yr^{-1}) compared to the application of manure (3.140 Mg C ha^{-1} yr^{-1}) or fertilizers alone (1.534 Mg C ha^{-1} yr^{-1}); this effect was particularly notable in eroded soils.
- The adoption of continuous annual cropping systems, or mixed crop rotations of annual grain and perennial forage crops, usually resulted in higher SOC than crop rotations with summer fallow.
- Compared to total organic matter in soil, young or labile fractions (i.e., light fraction organic C [LFOC] or light fraction organic N [LFON]) were much more responsive to changes in management practices.
- The conversion of annually cultivated lands to perennial grassland resulted in substantial increases in SOC when compared to cultivated soils.
- The gains and losses in SOC due to changes in management practices will not occur indefinitely.
- The economic and energy input costs of C sequestration in agroecosystems, along with the negative impacts, if any, of C sequestration on total greenhouse gas (i.e., CO_2, N_2O and CH_4) emissions should be considered in the calculation of net C change.

Conclusions

- Storage of organic C and N can be increased in cultivated soils by implementing proper soil (elimination of tillage and minimizing summer fallow frequency), crop residue (returning residue), nutrient management (balanced fertilization, and combined use of organic amendments and mineral fertilizers) and land use (conversion of marginal cultivated lands to perennial grassland) practices that prevent loss of C from soil and/or increase C input.

- The findings suggest that reduction of summerfallow frequency and adoption of no-till may be the most effective techniques/practices to increase storage of C and N in soil, as long as crop residues are returned to soil and nutrient deficiencies in crops are properly prevented.
- The findings also suggest that these soils can be used as a short-term CO_2 sink.
- Furthermore, it would appear C and N storage in soil provides the accompanying benefits of more sustainable crop production (due to an improvement in soil quality and nutrient supplying power), and reducing the potential for greenhouse gas emissions.

Research Gaps and Future Needs

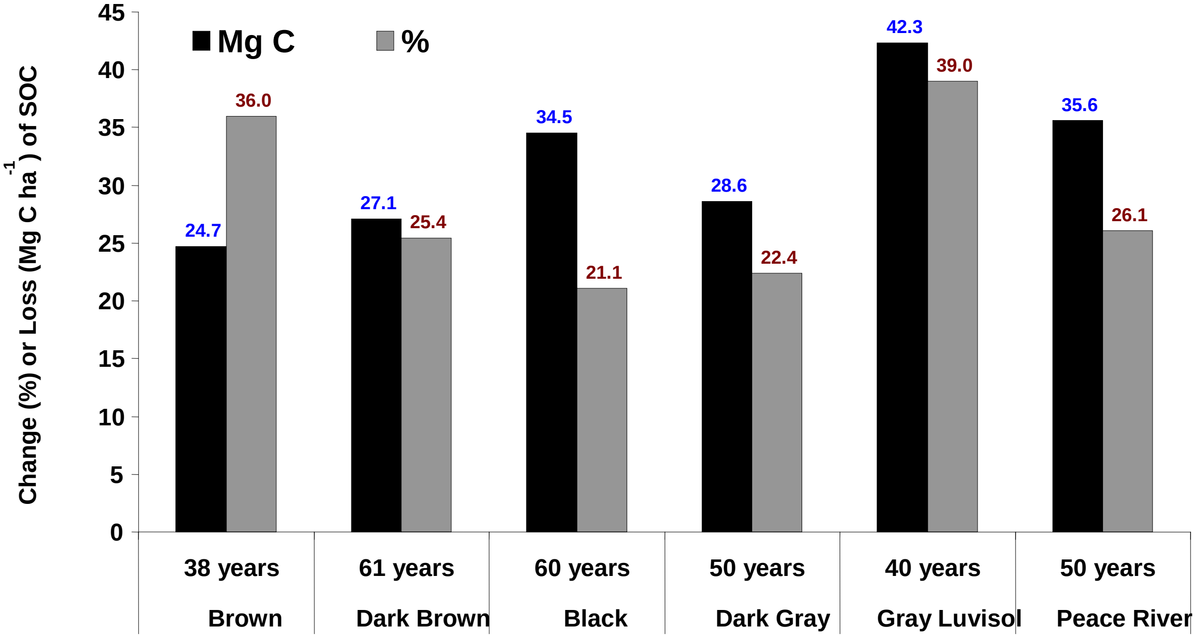
- Quantitative research information is needed on the actual contribution of erosion in the loss of C from cultivated fields, especially during summer fallow.
- There is also a need for research related to various mechanisms of organic C decline in soil, as it is important to distinguish the fate of C lost through various methods (erosion, CO_2, leaching). For example, biologically oxidized C is presumed to be emitted to the atmosphere, while eroded C may be buried deep in soil where further decomposition and turnover of C can be much slower.
- Because young/dynamic fractions in organic matter are much more sensitive to management practices, soil samples should also be analyzed for LFOC, LFON, C_{min}, N_{min} and microbial biomass C.
- Future research is needed on the fate of sequestered C in soil over the long term after the management practices are altered. Research information is also needed regarding the mechanisms involved in the sequestration of C into more stable organic C pools.
- There is little research information on the contribution of roots and stubble in increasing the storage of organic C in soil, and future research should concentrate on the contribution of roots and stubble in increasing SOC storage.
- This is also suggested that existing long-term experiments must be continued, and more new long-term experiments should be established, as long-term experiments provide vital information to evaluate management effects on OM, validate models to predict OM dynamics, and calculate C sequestration efficiency.
- Few studies have reported the C sequestration efficiency (defined as: Mass of C sequestered in soil/Mass of C input to soil x 100) of management practices.
- There has been no report on the economic benefits (Net $ returns = Added $ returns from increased crop yield due to C – Additional input costs of C sequestration) from sequestered C in soil.
- Future reports/research should include calculations of C sequestration efficiency (Mass of C sequestered in soil/Mass of C input to soil x 100)) and economic benefits/return ratio (Net $ returns = Added $ returns from increased crop yield due to C – Additional input costs of C sequestration) for various C enhancing management practices under various cropping systems.
- Because the majority of C is sequestered in the surface soil layers, soil samples are rarely collected below 30 cm. Future C sequestration studies should also address changes in organic C below 30 cm, especially in cropping systems that include perennial forages in the rotation.

Acknowledgements

- The authors would like to thank Darwin Leach for preparing the colored slides.

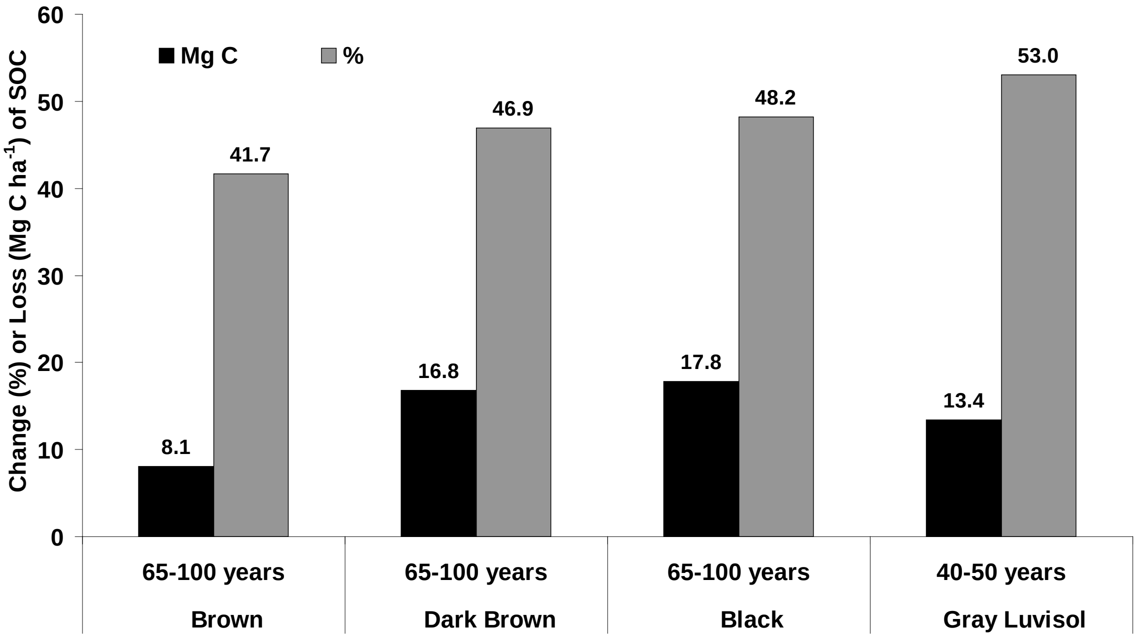
Loss in SOC due to cultivation

Alberta - Loss in SOC due to cultivation soil profile - Reinl 1984



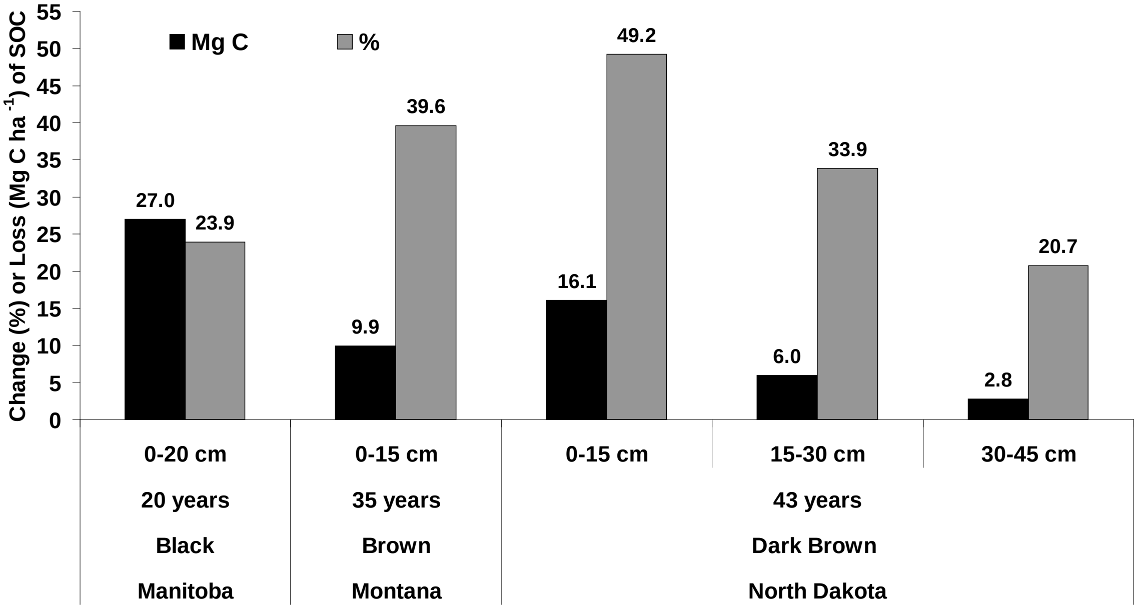
Saskatchewan - Loss in SOC due to cultivation 0-15 cm soil depth

Campbell and Souster 1982

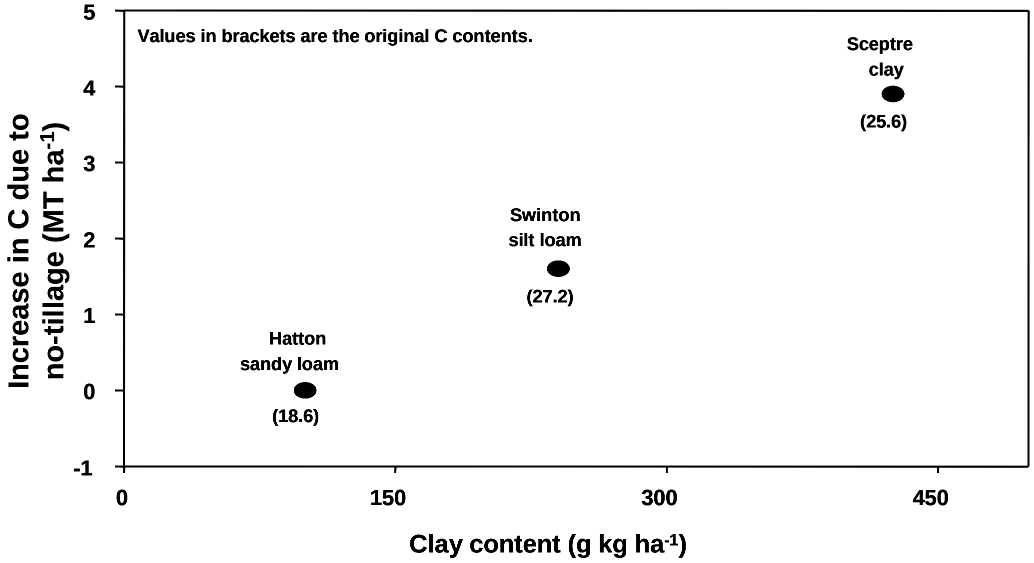


Manitoba, Montana and North Dakota

Manitoba (Shutt 1925)
USA sites (Haas et al.)

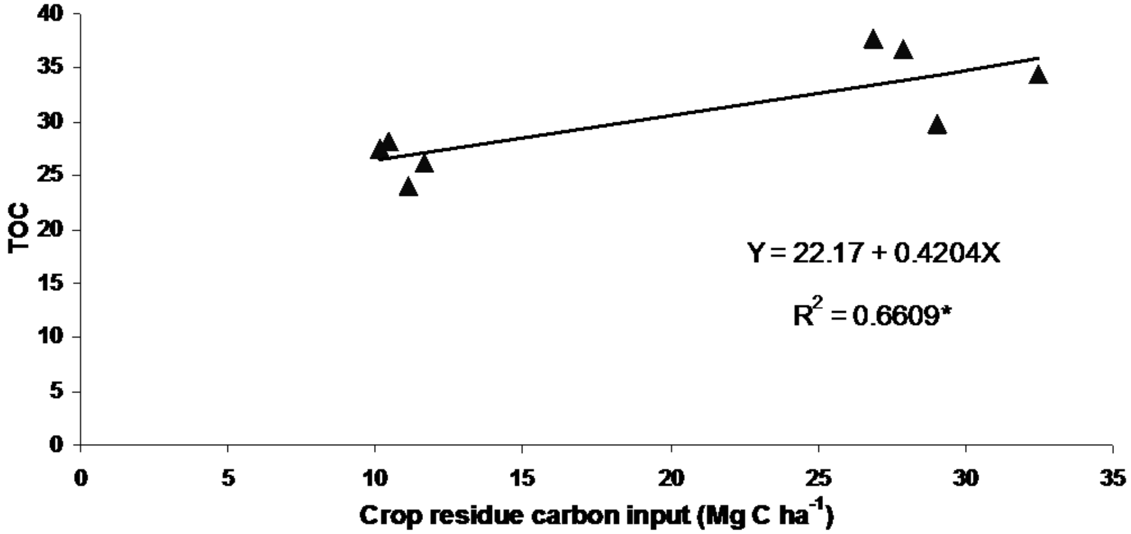


Effect of soil texture on SOC storage

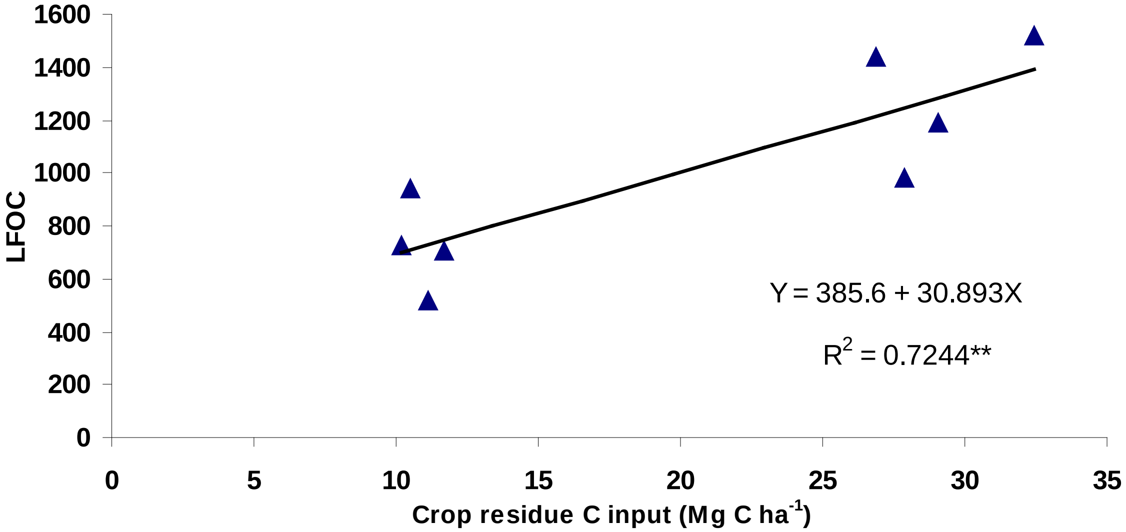


Soil texture influence on SOC gain in the 0 to 15 cm depth 11-12 yr after adopting no-tillage management in the Brown soil zone (adapted from Campbell et al. 1996).

Relationship of soil organic C (SOC), soil organic N (SON), light fraction organic matter (LFOM), light fraction organic C (LFOC), mineralizable C (Cmin), mineralizable N (Nmin) or water stable aggregates (WSA), with input of crop residue, residue C, residue N, LFOC or clay content in various annual grain crop field experiments conducted in the Northern Great Plains of North America.



Linear regression for relationship between crop residue C input and soil TOC stored in soil from 1980 to 1998, sampled in autumn 1998 at Breton, Alberta, Canada (Gray Luvisol soil, experiment established in autumn, 1979).

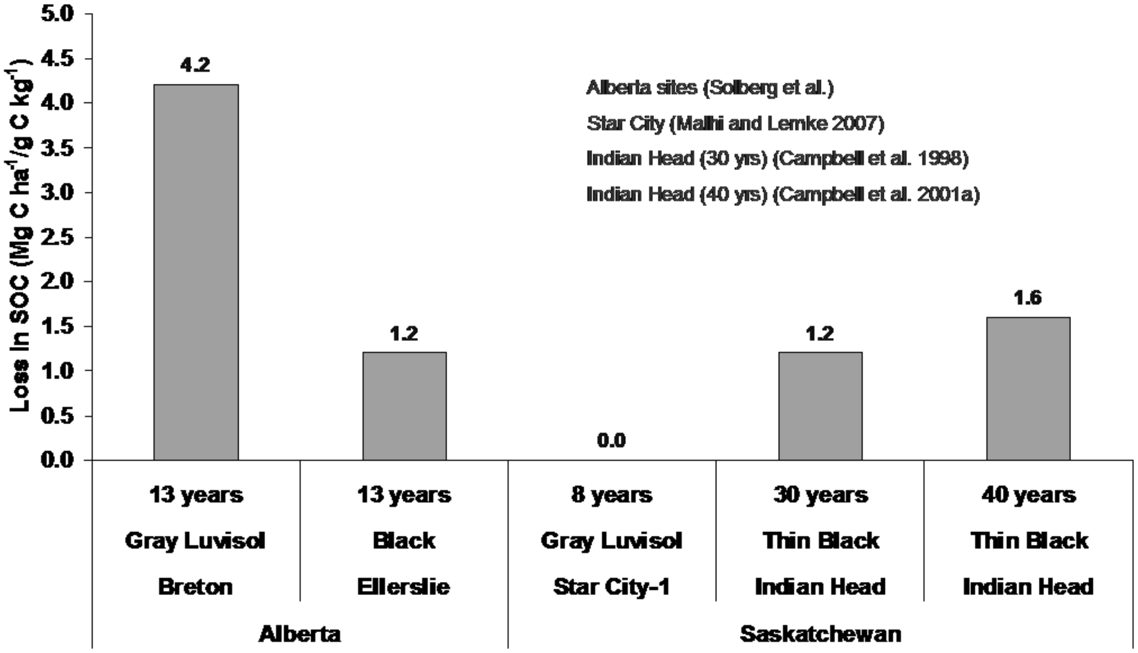


Linear regression for relationship between crop residue C input and soil LFOC stored in soil from 1980 to 1998, sampled in autumn 1998 at Breton, Alberta, Canada (Gray Luvisol soil, experiment established in autumn, 1979).

Decrease in soil organic C (SOC) and light fraction organic C (LFOC) due to removing straw compared to its retention or return to land in various annual grain crop field experiments conducted in the Northern Great Plains of North America

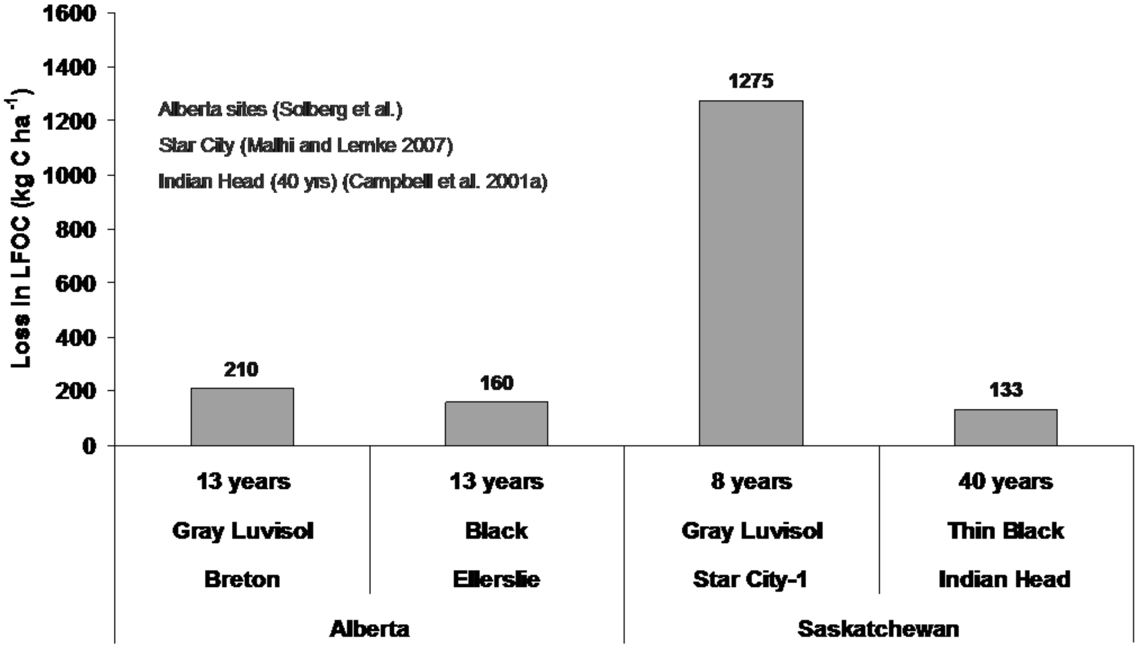
Decrease in SOC due to straw removal

Breton and Ellerslie Alberta (Straw Retained vs. Straw Removed) (CT) (0-30 cm, 0-15cm soil depth)
Star City and Indian Head Saskatchewan (Straw Retained vs. Straw Removed)) (Average of NT and CT treatments) (0-15 cm soil depth)



Decrease in LFOC due to straw removal

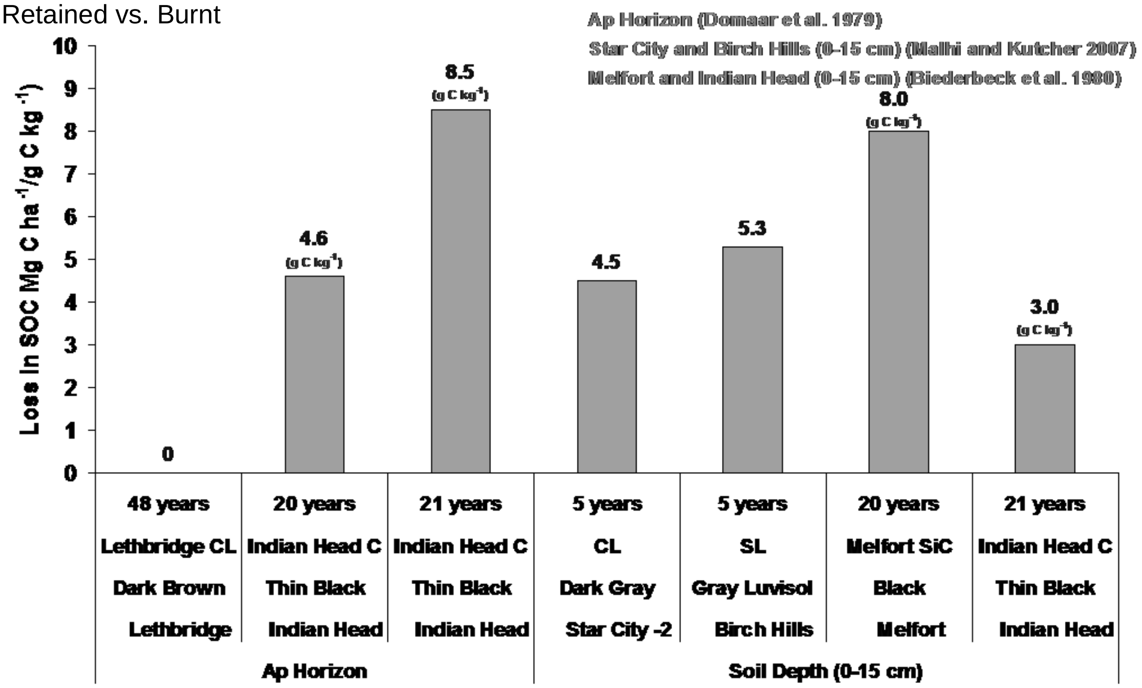
Breton and Ellerslie Alberta (Straw Retained vs. Straw Removed) (CT) (0-30 cm, 0-15cm soil depth)
Star City and Indian Head Saskatchewan (Straw Retained vs. Straw Removed)) (Average of NT and CT treatments) (0-15 cm soil depth)



Decrease in soil organic C (SOC) and light fraction organic C (LFOC) due to burning straw compared to its retention or return to land in various annual grain crop field experiments conducted in the Northern Great Plains of North America

Decrease in SOC due to burning

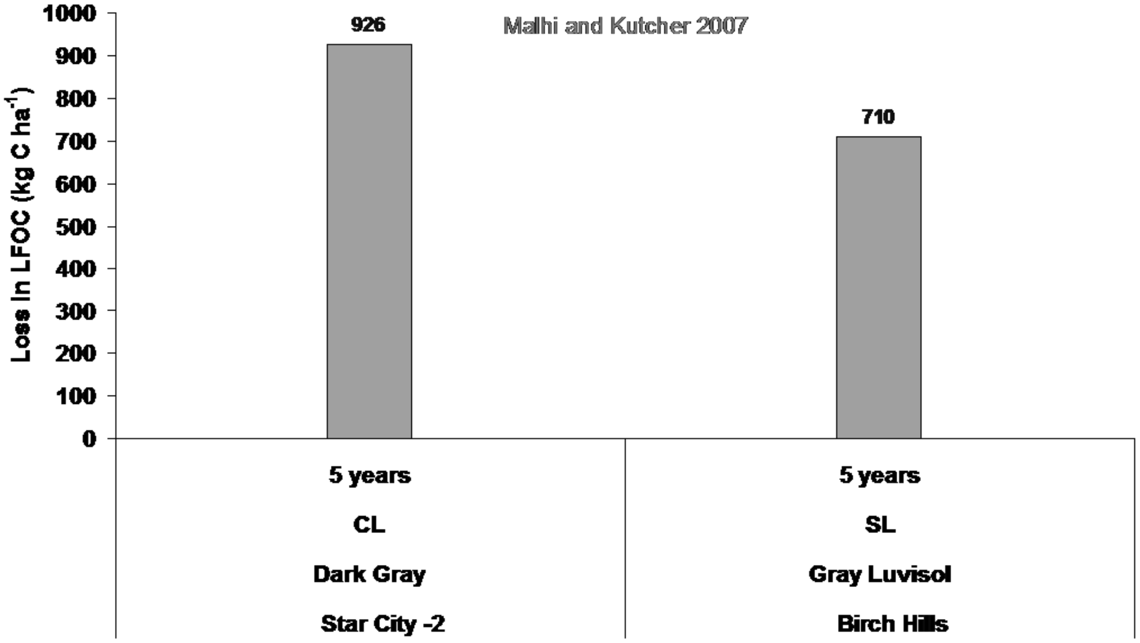
Retained vs. Burnt



Decrease in LFOC due to burning

Retained vs. Burnt

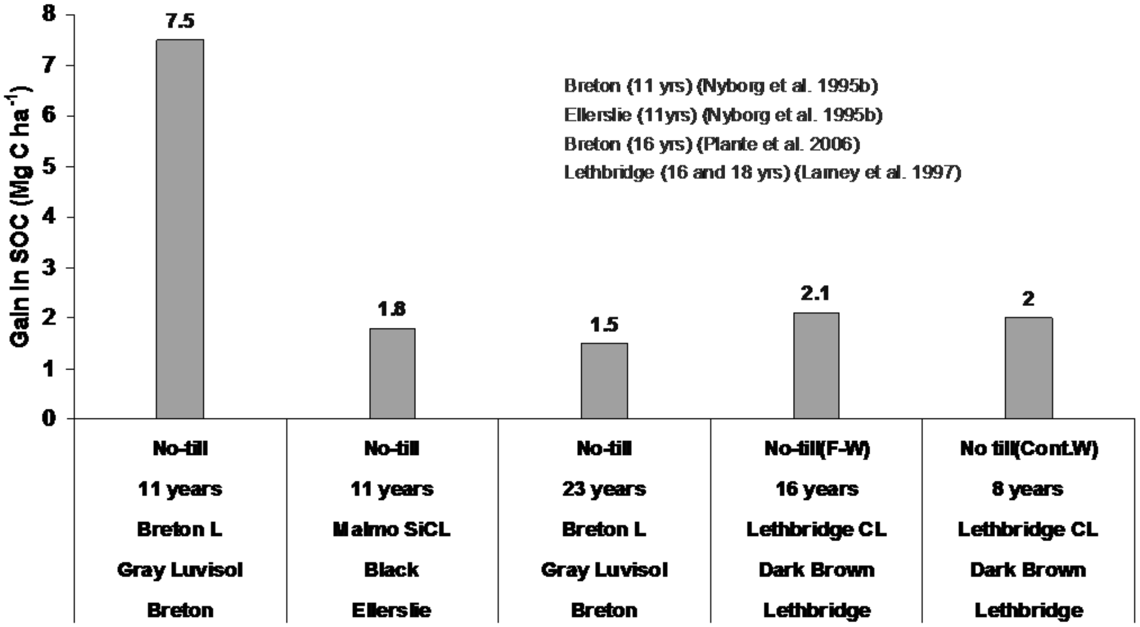
Soil Depth (0-15 cm)



Increase in soil organic C (SOC) and light fraction organic C (LFOC) due to adoption of no-till or minimum tillage (MT), compared to corresponding conventional tillage (CT) in various field experiments conducted in the Northern Great Plains of North America

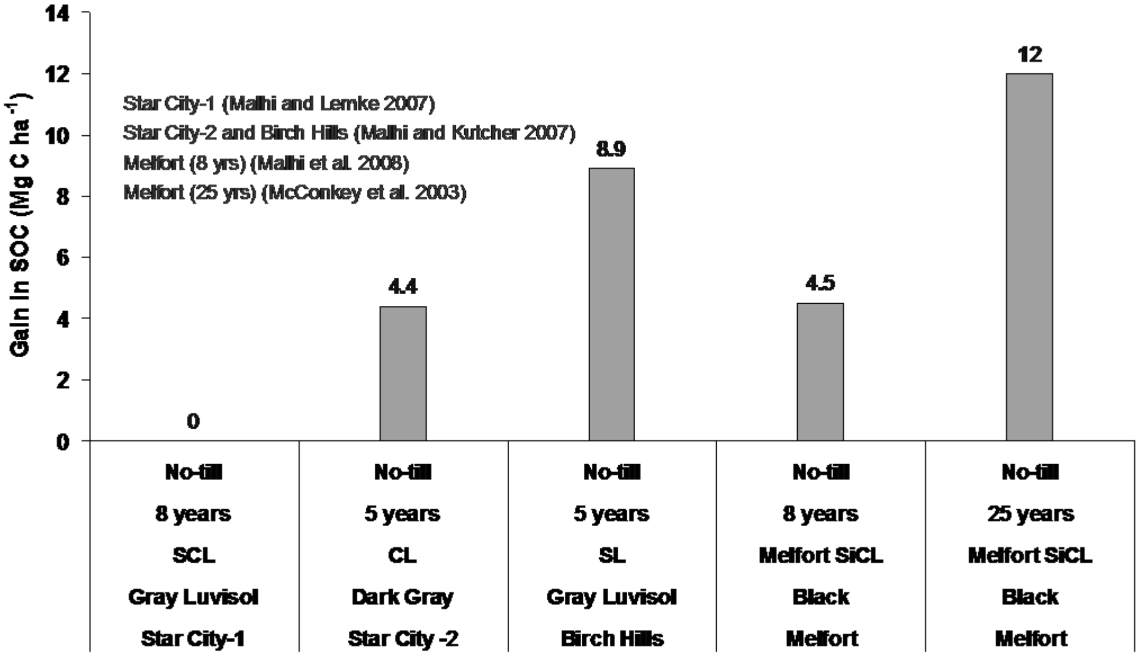
Alberta – Gain in SOC due to NT

Depth = 0-15 cm for all sites except Breton (23 years) is 0-20 cm soil depth



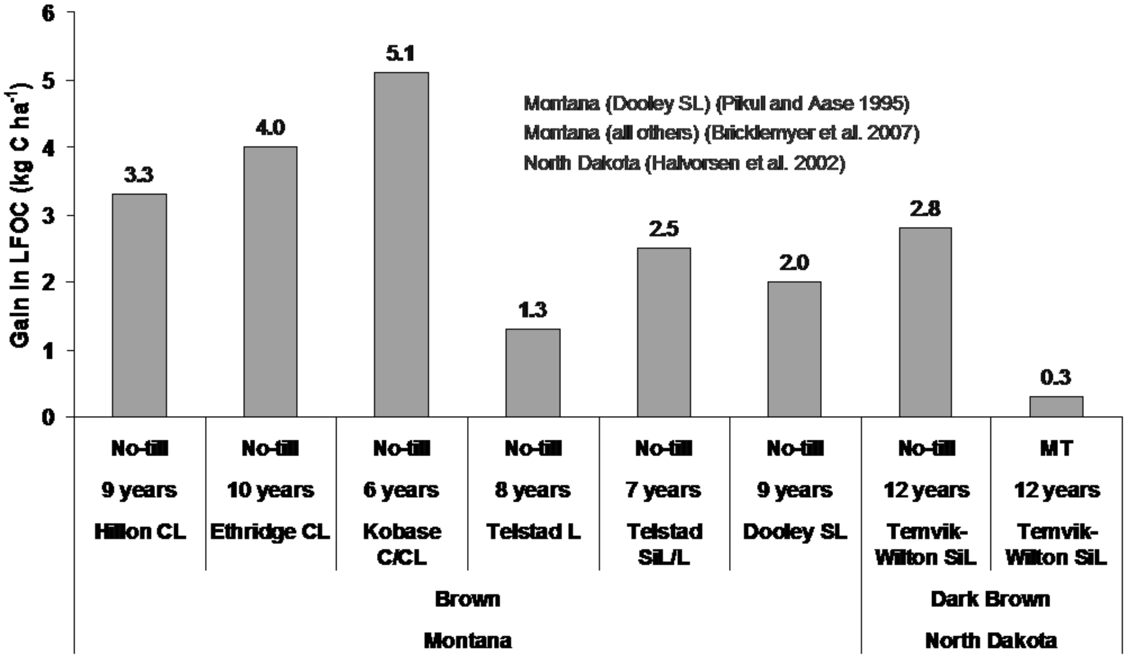
Saskatchewan – Gain in SOC due to NT - Black and Gray soils

0-15 cm soil depth



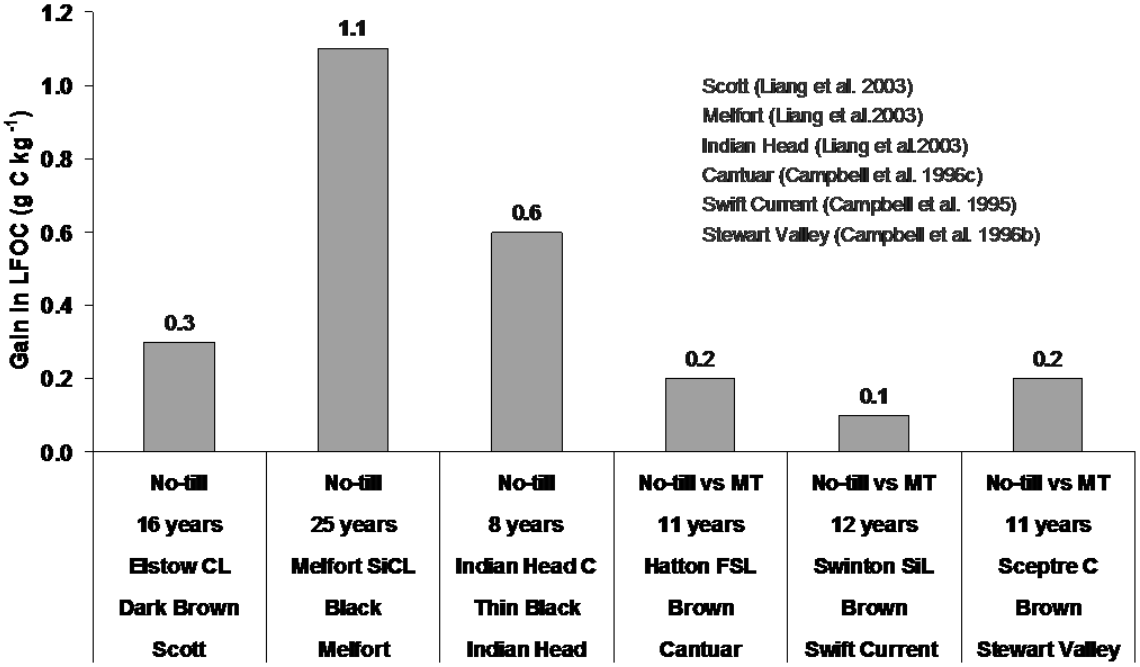
Montana and North Dakota – Gain in LFOC due to NT or MT

Depth = 0-20 cm for all sites except Montana Dooley SL is (0-9 cm) and North Dakota site is (0-15 cm) soil depths



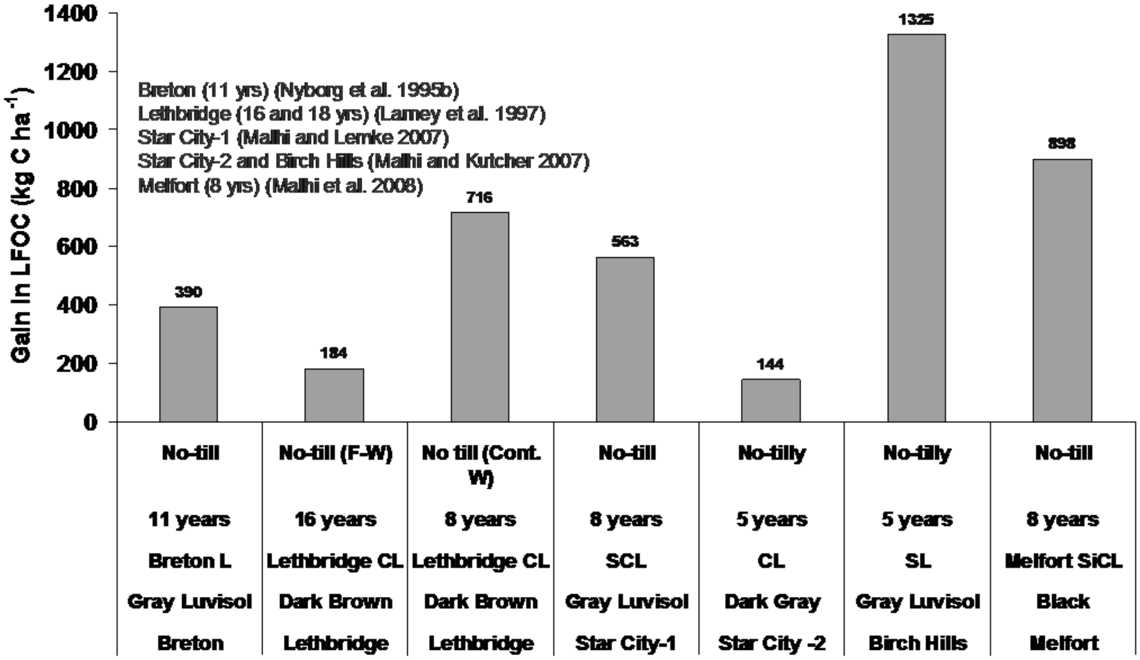
Concentration LFOC – Gain due to NT or MT

Depth = 0-15 cm



Mass LFOC Gain due to NT

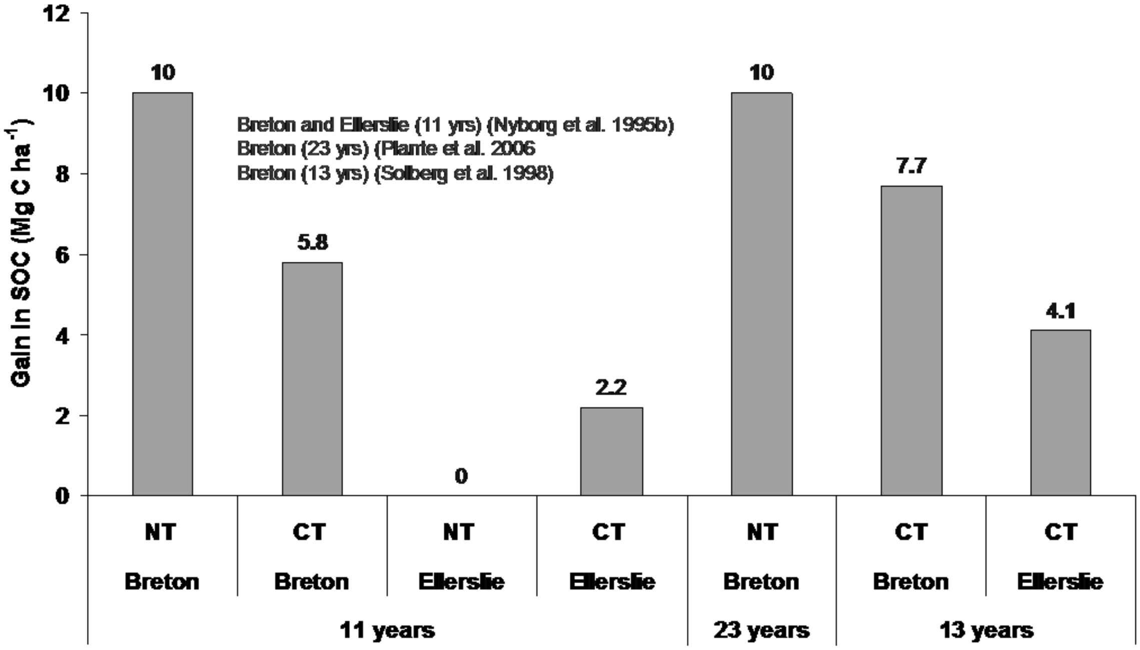
Depth = 0-15 cm



Increase in soil organic C (SOC) and light fraction organic C (LFOC) as affected by fertilizers in various annual grain crop field experiments conducted in the Northern Great Plains of North America

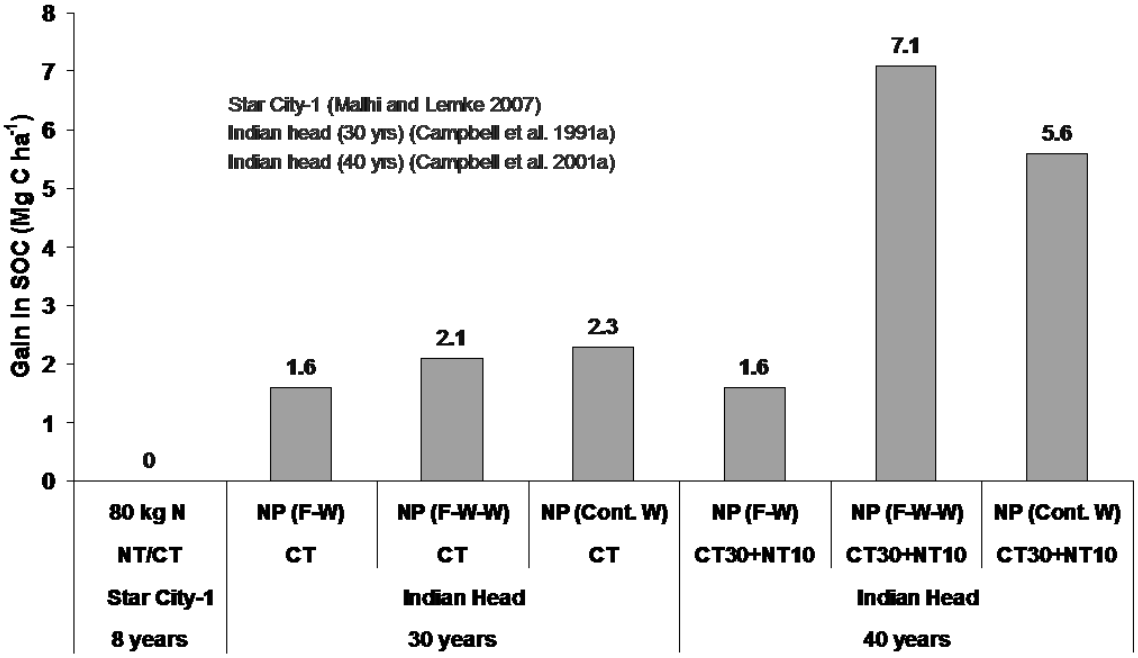
Alberta – Gain in SOC due to N fertilizer

0-15 cm soil depth except Breton 23 years (0-20 cm) and Breton 13 years (0-30 cm)



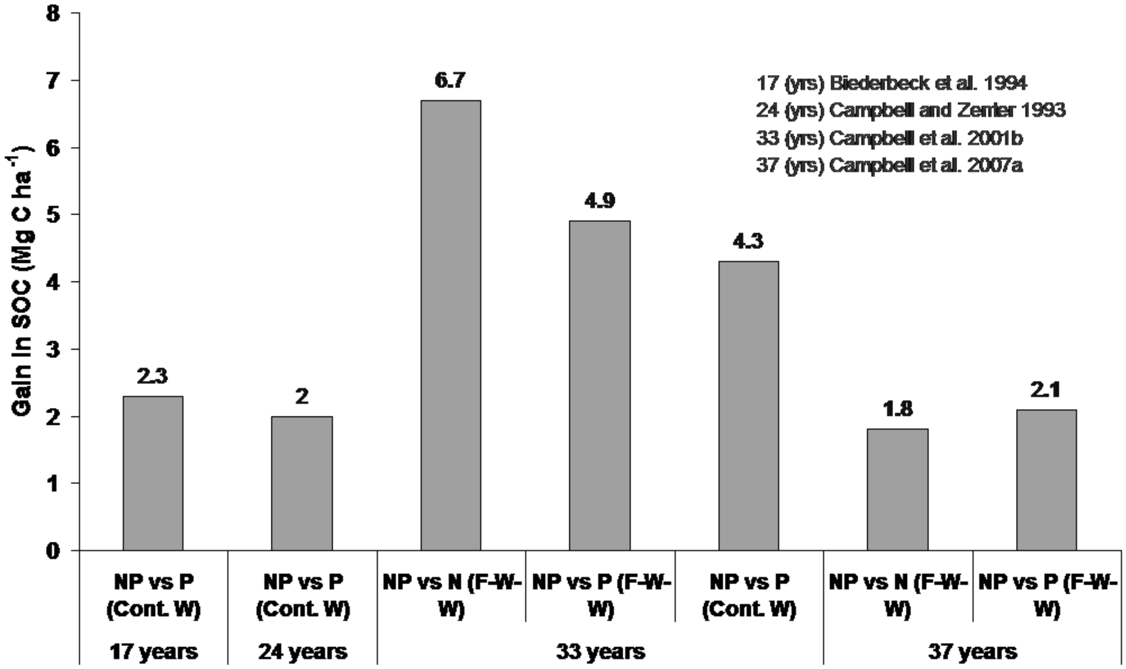
Star City and Indian Head – Gain in SOC due to fertilizers or cropping

0-15 cm soil depth



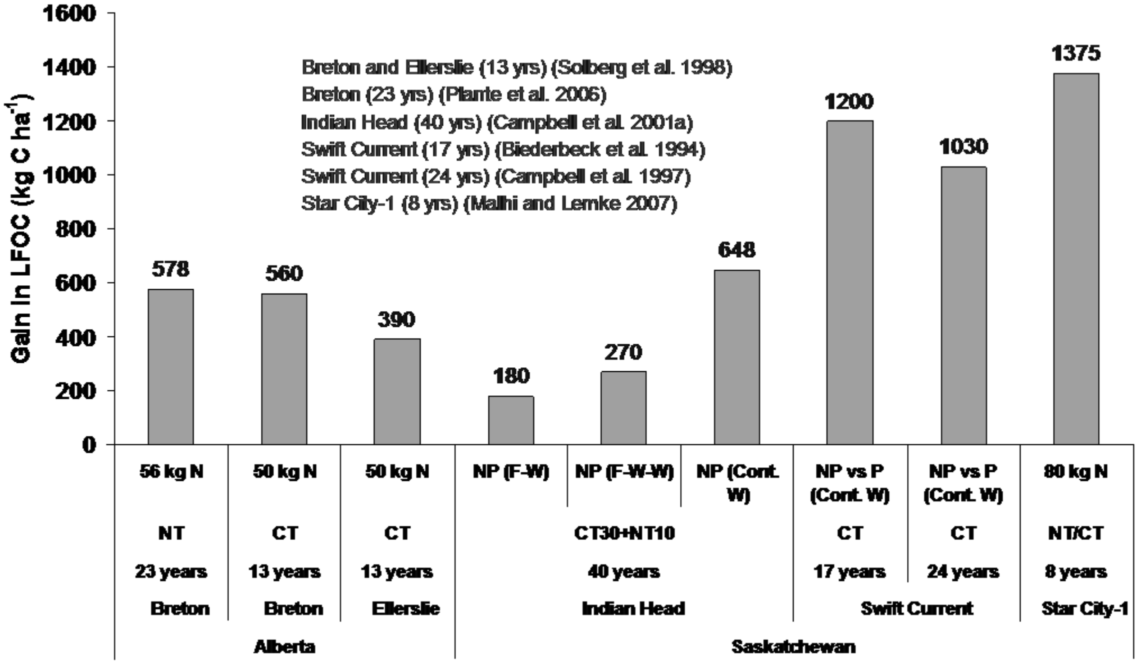
Swift Current – Gain in SOC due to fertilizers

0-15 cm soil depth for Swift Current 17 years (0-7.5 cm) and Swift Current 24 years (0-7.5 cm)



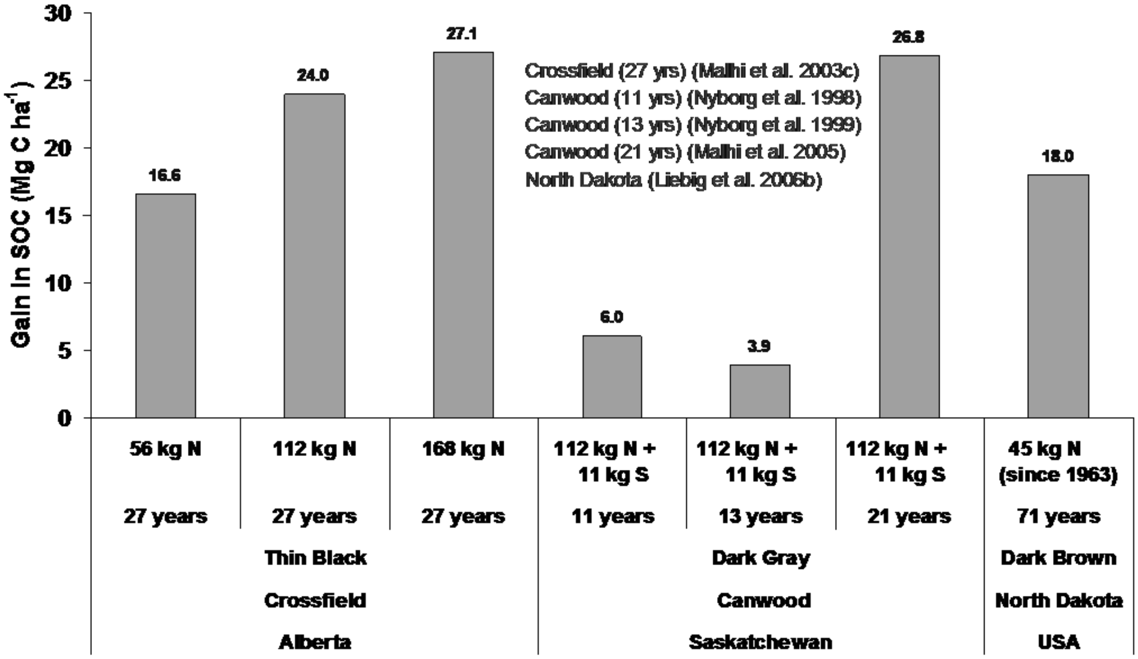
Gain in LFOC due to fertilizers

0-15 cm soil depth except Breton 23 years (0-20 cm), Breton 13 years (0-30 cm), Swift Current 17 years (0-7.5 cm) and Swift Current 24 years (0-7.5 cm)

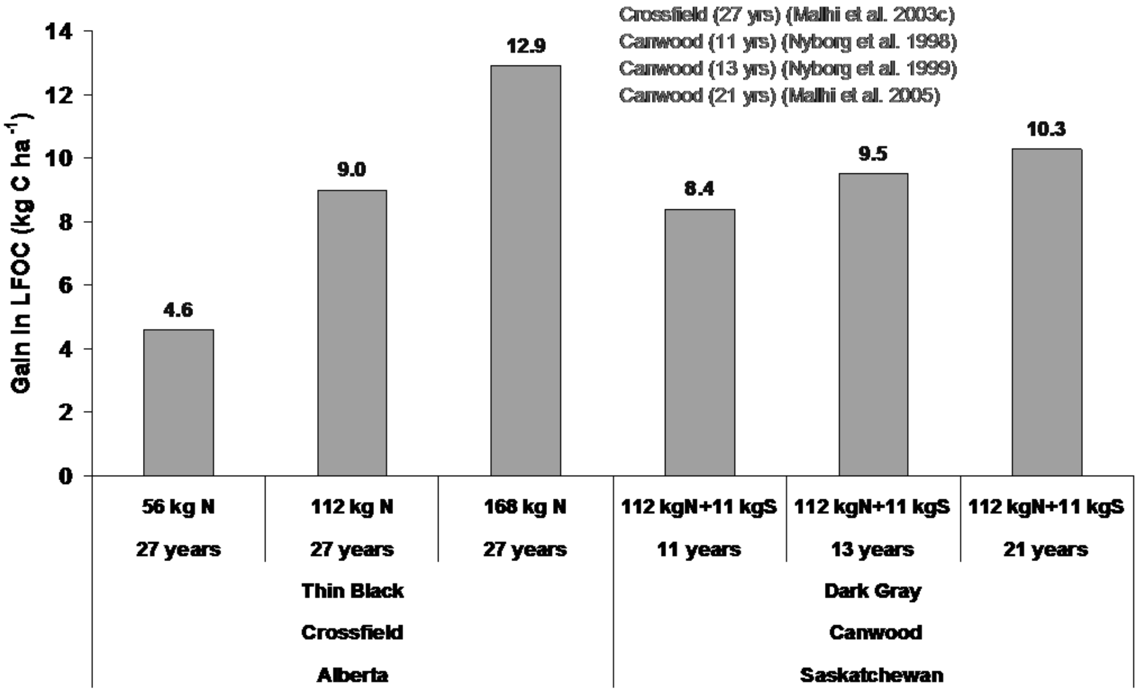


Increase in soil organic C (SOC) and light fraction organic C (LFOC) as affected by fertilizers in various grasslands field experiments conducted in the Northern Great Plains of North America

Gain in SOC due to N or balanced fertilization in grassland



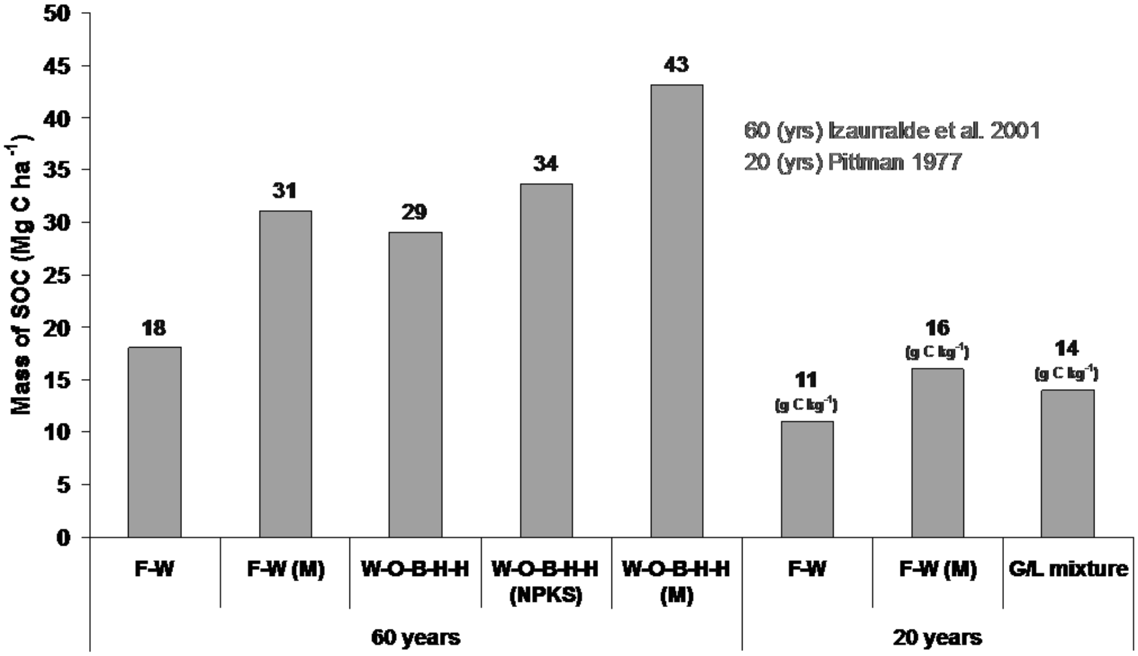
Gain in LFOC due to N or balanced fertilization in grassland



Effect of manure addition on soil organic C (SOC), light fraction organic C (LFOC) and mineralizable C (Cmin) in various field experiments in the Northern Great Plains of North America

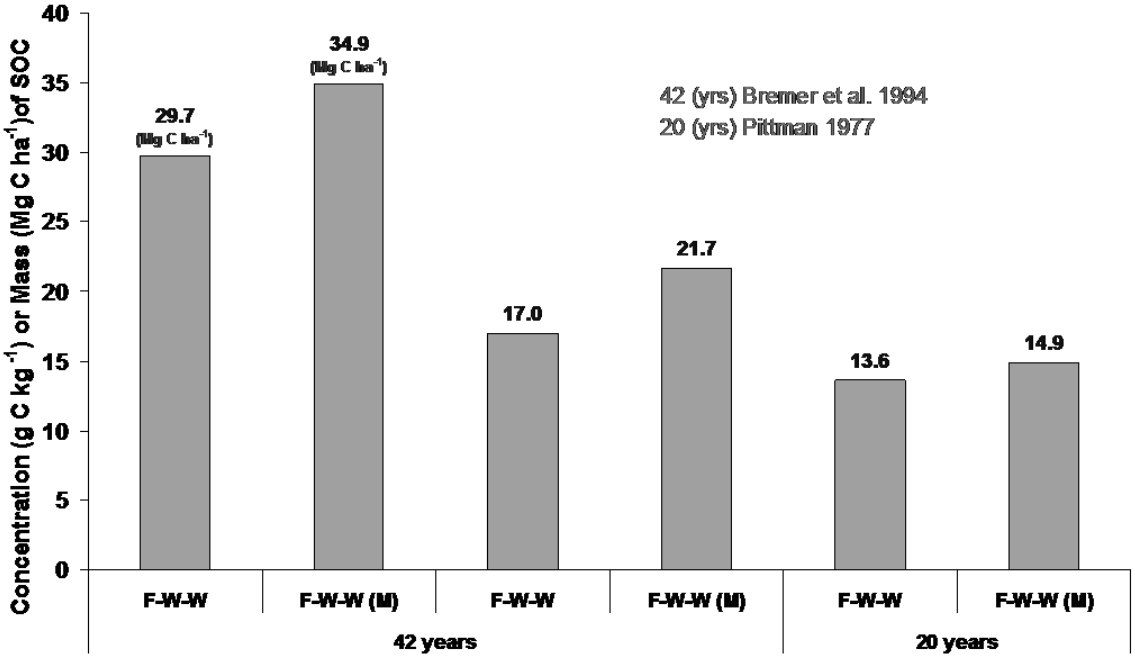
Breton - Concentration or mass of SOC – Manure

Gray Luvisol



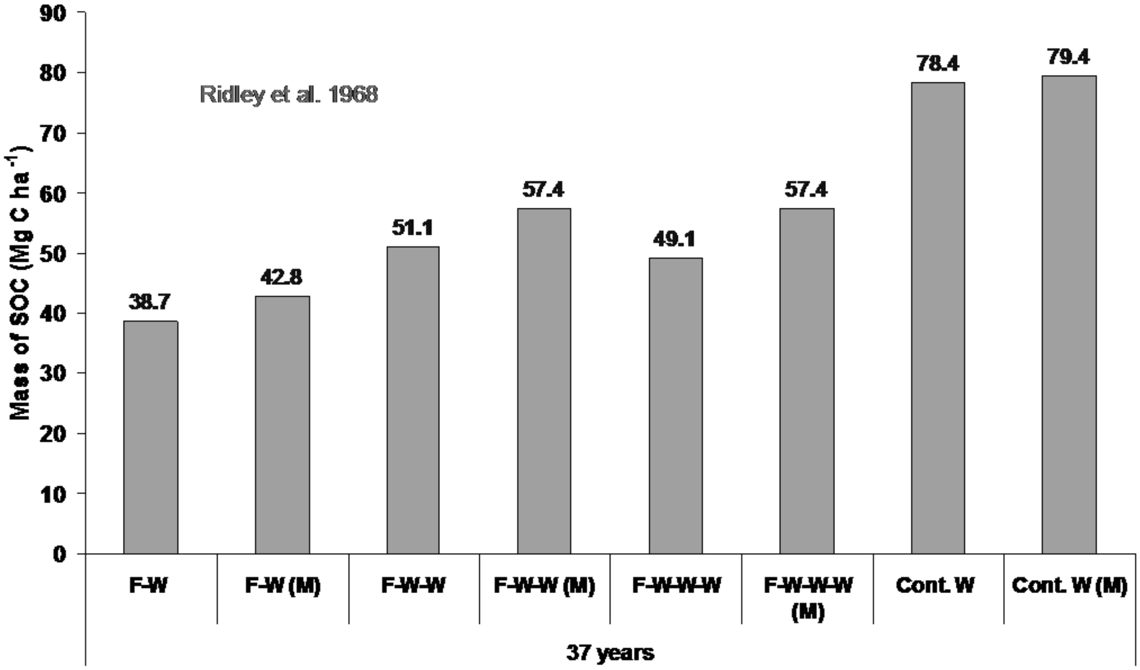
Lethbridge - Concentration or Mass SOC - Manure

Dark Brown Lethbridge CL



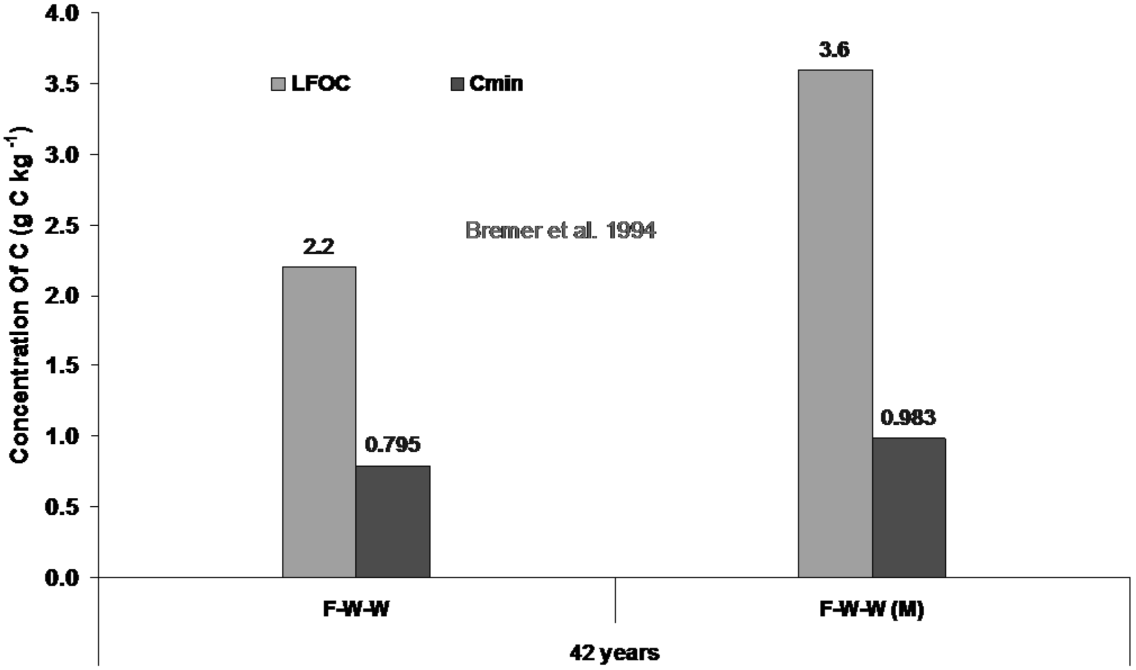
Winnipeg – Mass in SOC – Manure

Black Red River C

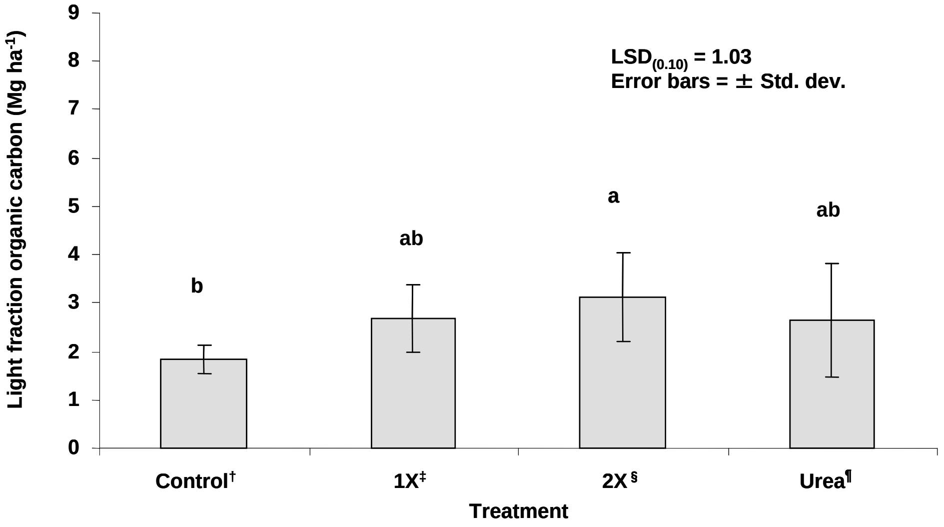


Lethbridge - Concentration in LFOC and C_{min} - Manure

Dark Brown Lethbridge CL



Swine Manure

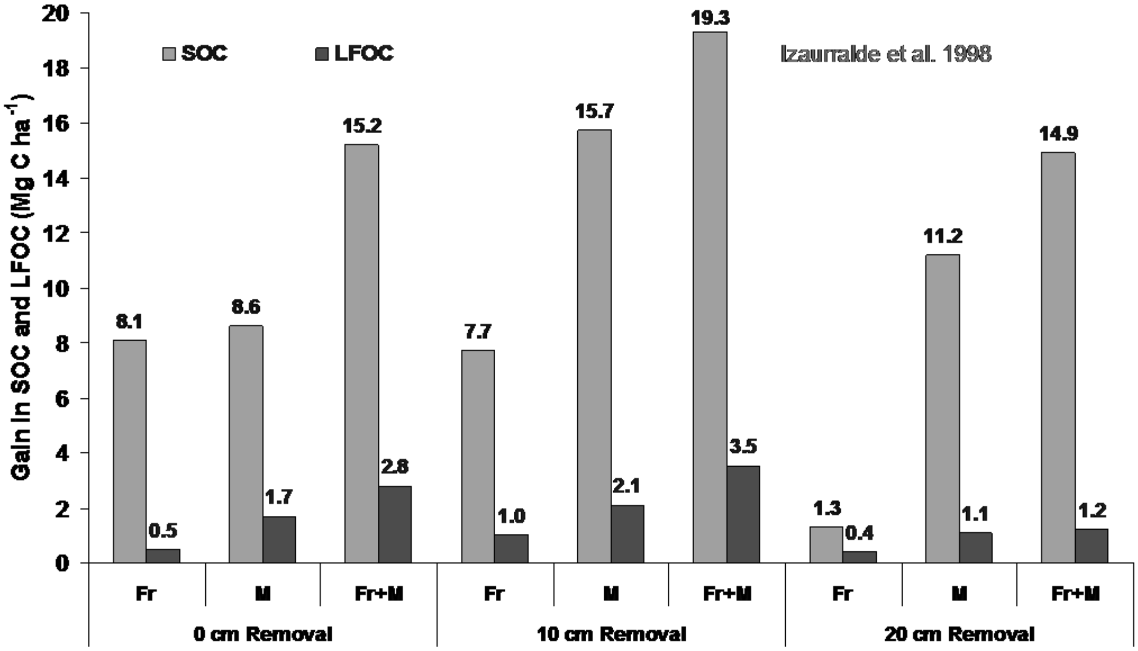


Light fraction organic C in the 0-15 cm soil depth under various liquid swine manure (LSM) and fertilizer treatments at Melfort, Saskatchewan. Bars followed by the same letter are not significantly different at $p \leq 0.10$ (†Control - no LSM or fertilizer applied; ‡LSM applied at 37,000 L ha^{-1} annually; § LSM applied at 74,000 L ha^{-1} every second year; ¶Urea applied at 80 kg N ha^{-1}) (adapted from King 2007).

Increase in soil organic C (SOC) and/or light fraction organic C (LFOC) from the integrated use of chemical fertilizers (Fr) and manure (M) on eroded and non-eroded soils in field experiments at two locations in Alberta, Canada

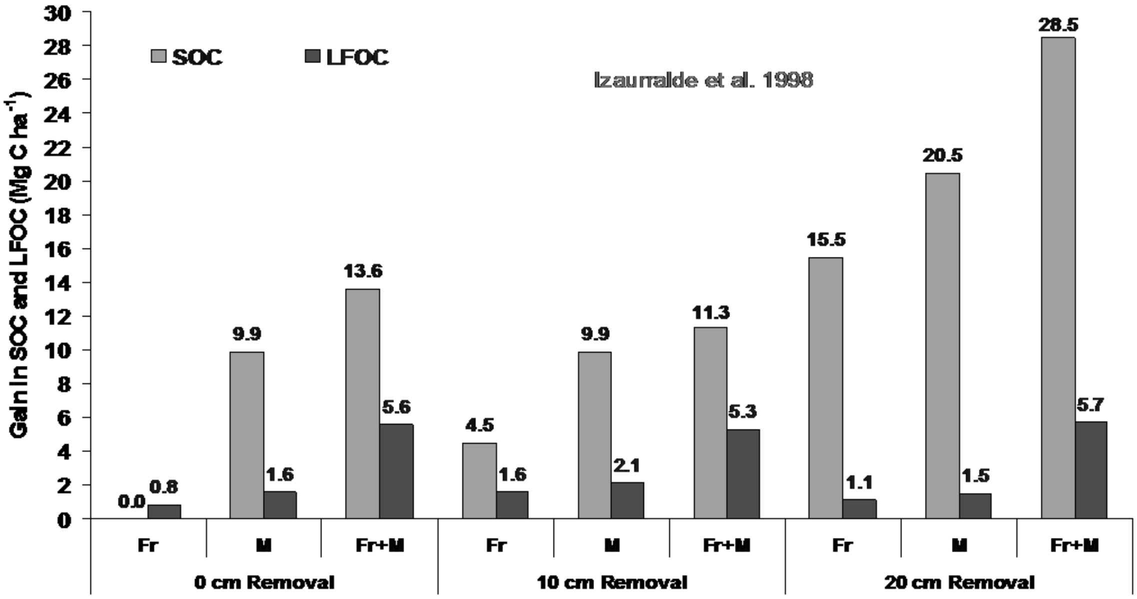
Cooking Lake – Gain in SOC and LFOC – Manure + Fertilizer

Black - Cooking Lake L – - 5 years – (CT)
Chemical fertilizers (Fr) and manure (M)



Josephburg – Gain in SOC and LFOC – Manure + Fertilizer

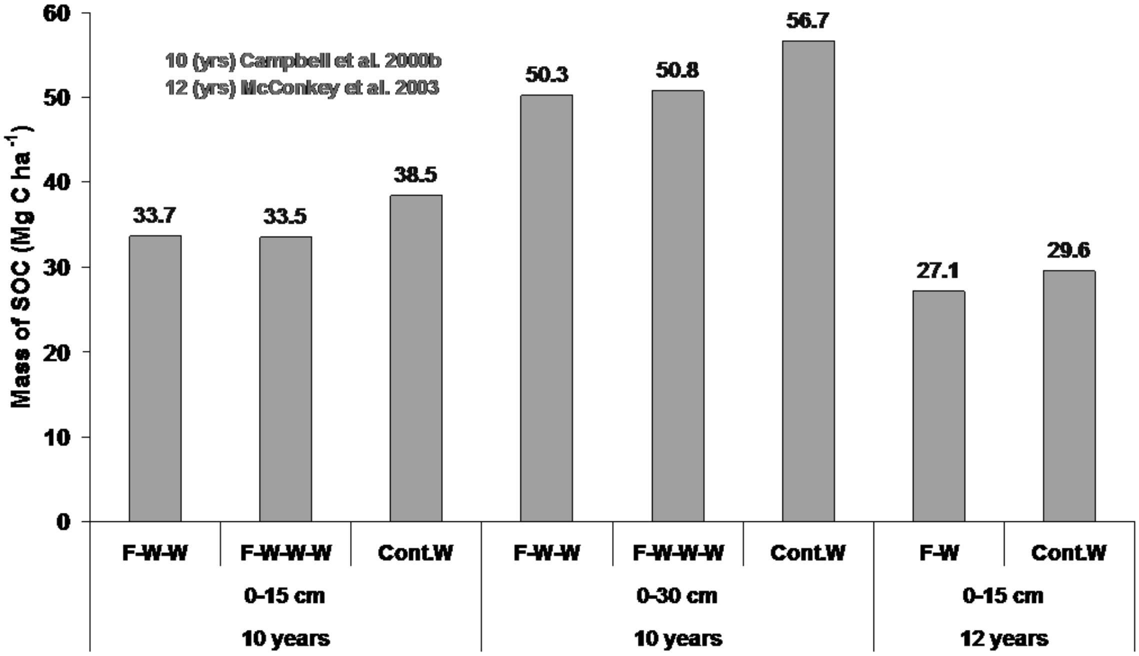
Gray Luvisol - Angus Ridge SiCL - 5 years – (CT)
Chemical fertilizer (Fr) and Manure (M)



Effect of cropping frequency (CF) or summer fallow frequency (SFF) in a crop rotation on soil organic C (SOC), light fraction organic C (LFOC) and mineralizable C (Cmin) in various field experiments conducted in the Northern Great Plains of North America (Swift Current, Saskatchewan)

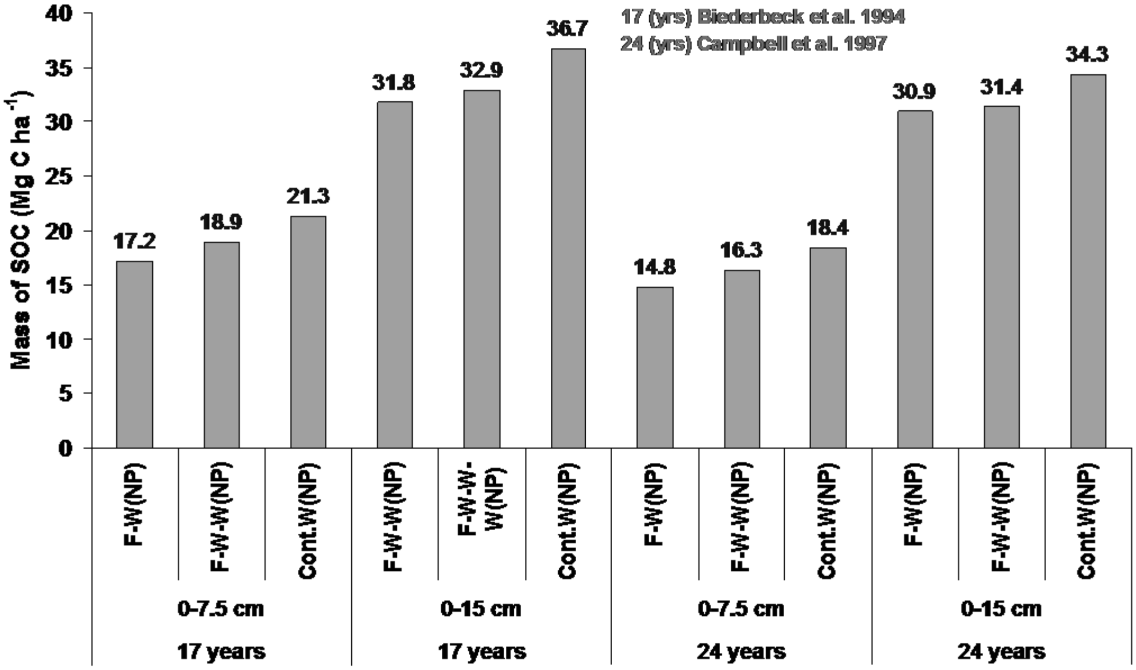
Swift Current – Mass of SOC – Summer fallow or cropping frequency

Brown - Switon L and Switon SiL
10 and 12 years

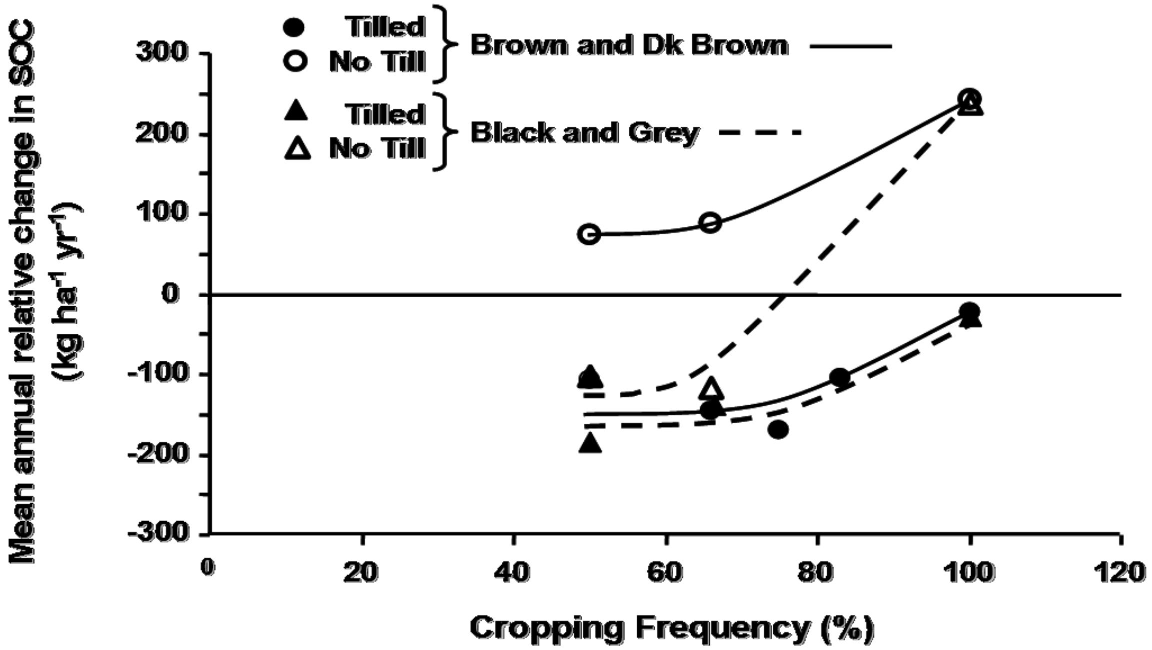


Swift Current – Mass of SOC – Summer fallow or cropping frequency

Brown - Switon L and Switon SiL
17 and 24 years



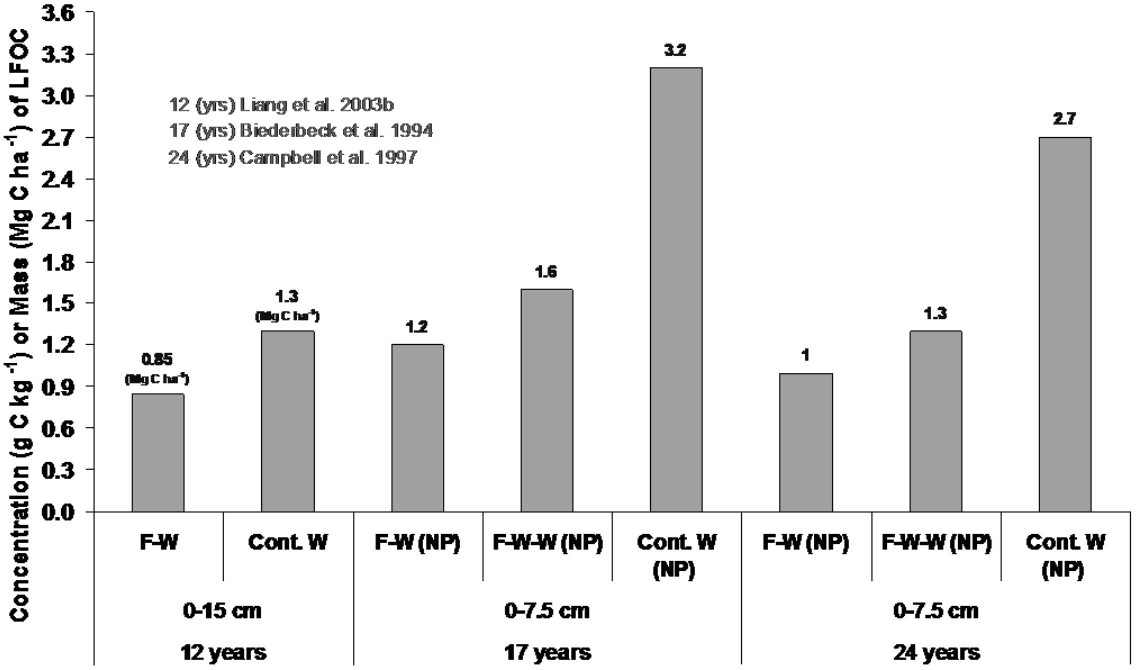
Crop Rotation/Diversity, Cropping Frequency and Fallow



Effect of cropping frequency on mean annual rate of change in soil organic C (SOC) in the Canadian Prairie studies (adapted from Campbell et al. 2005).

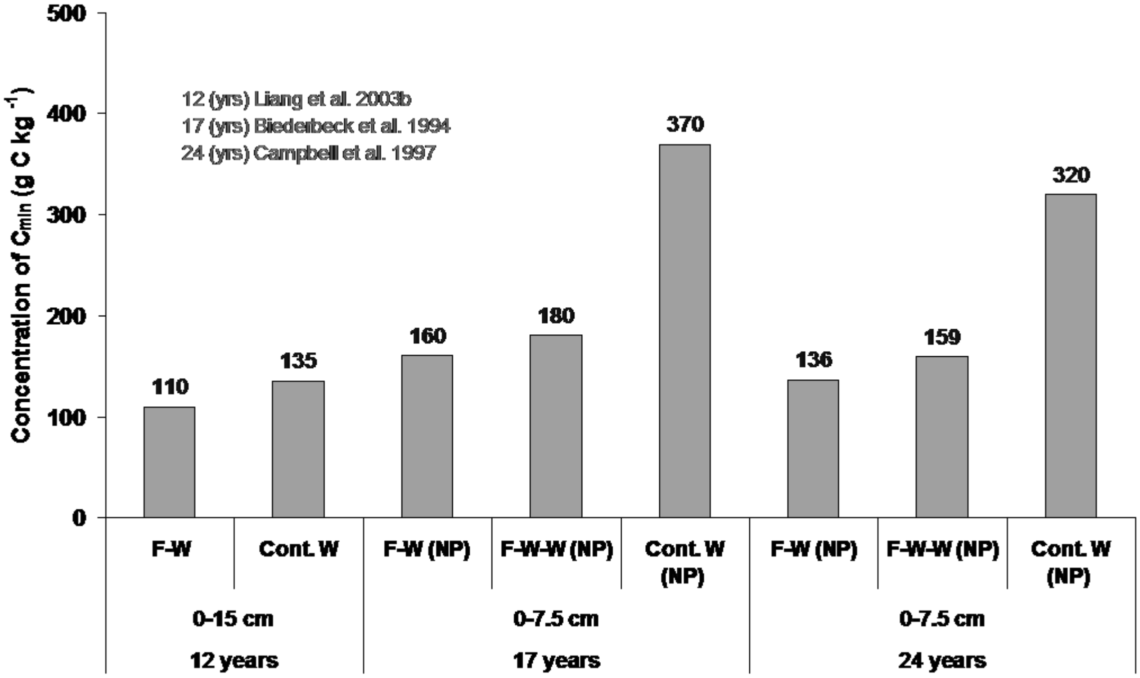
Swift Current – Concentration or Mass of LFOC

Brown - Switon L and Switon SiL – Summerfallow or cropping frequency



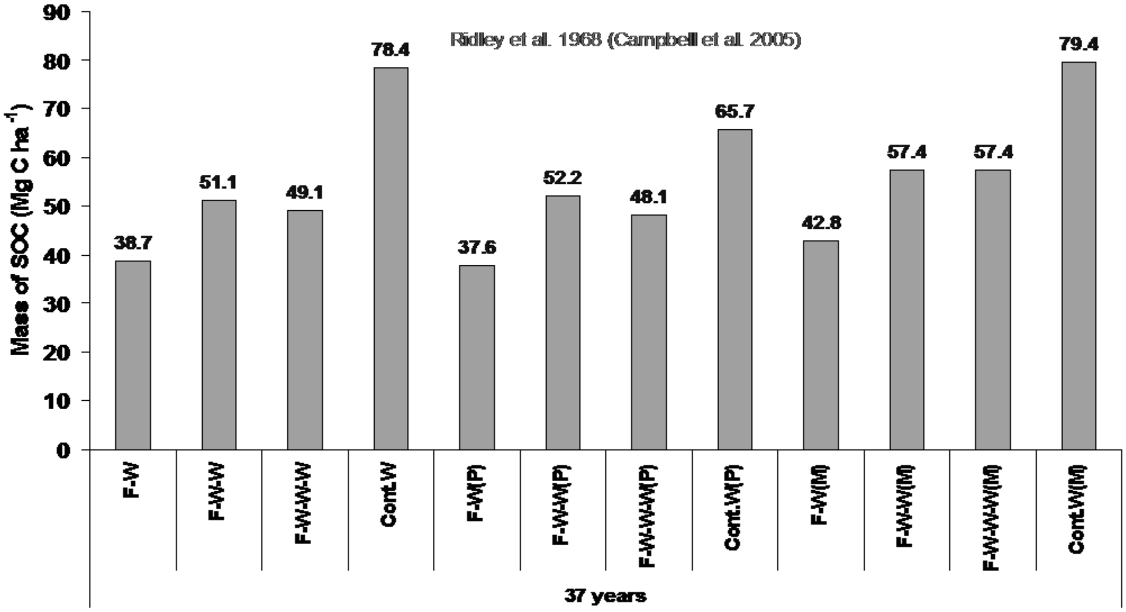
Swift Current – Concentration of Cmin

Brown - Switon L and Switon SiL – Summer fallow or cropping frequency



Winnipeg – Mass of SOC – Summer fallow or cropping frequency

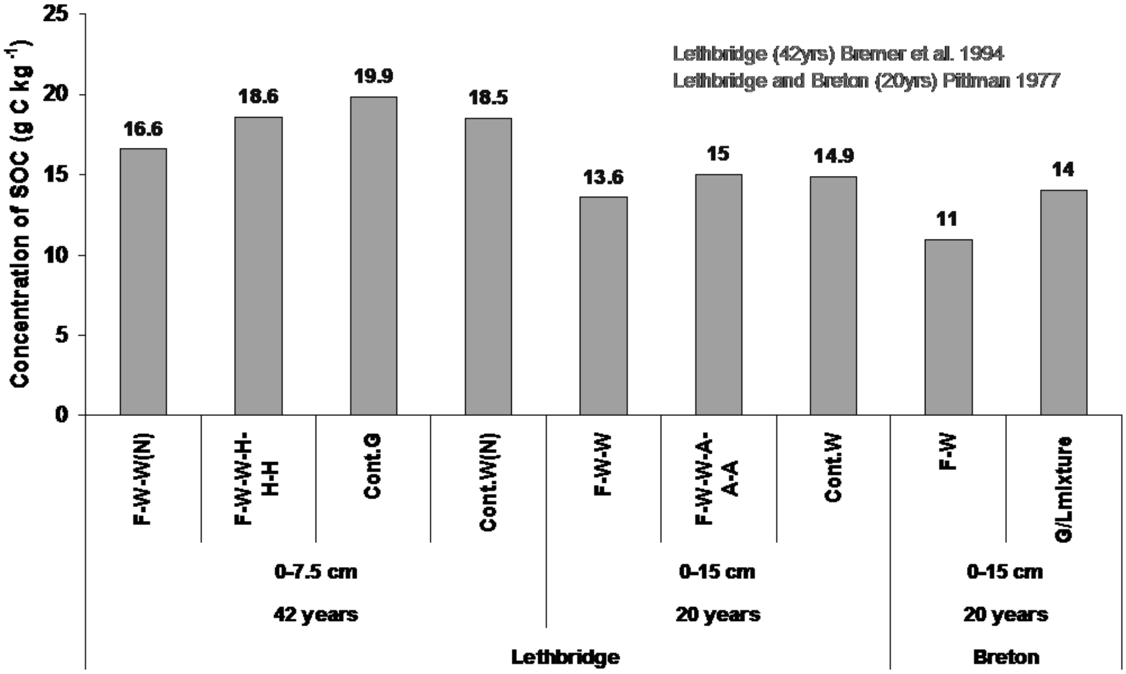
Red River C 0-15 (cm) depth



Effect of crop type (including forages), green manure, and other crop management practices in a crop rotation on soil organic C (SOC), light fraction organic C (LFOC) and mineralizable C (Cmin) in various field experiments conducted in the Northern Great Plains of North America

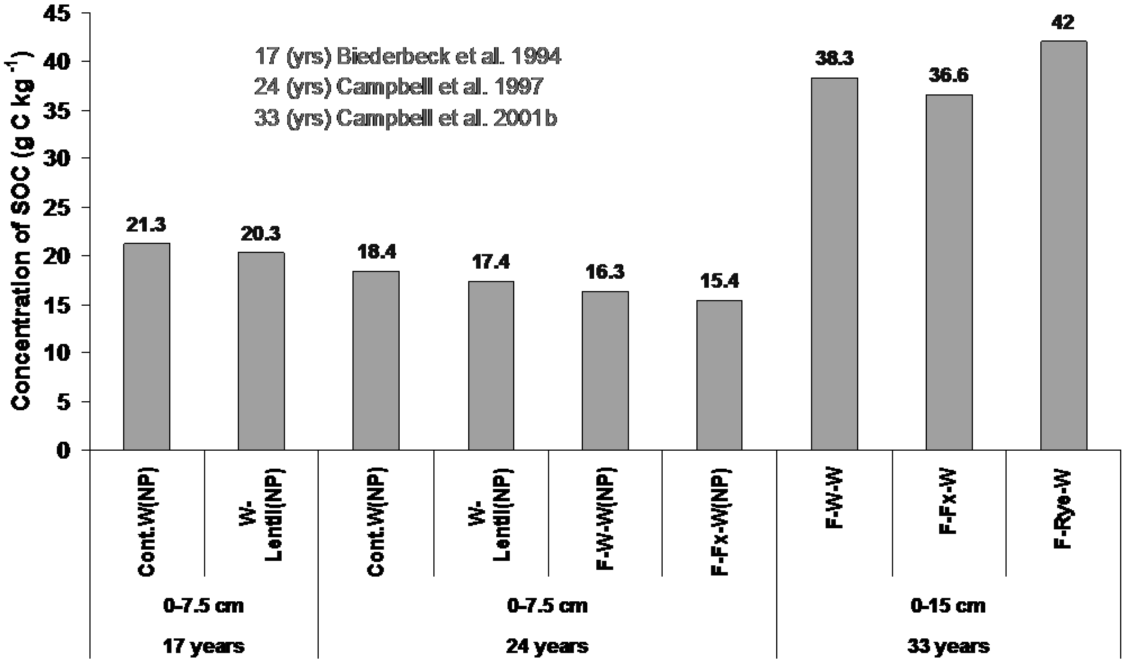
Concentration of SOC – Crop management

Lethbridge - Dark Brown Lethbridge CL
Breton - Gray Luvisol Breton L



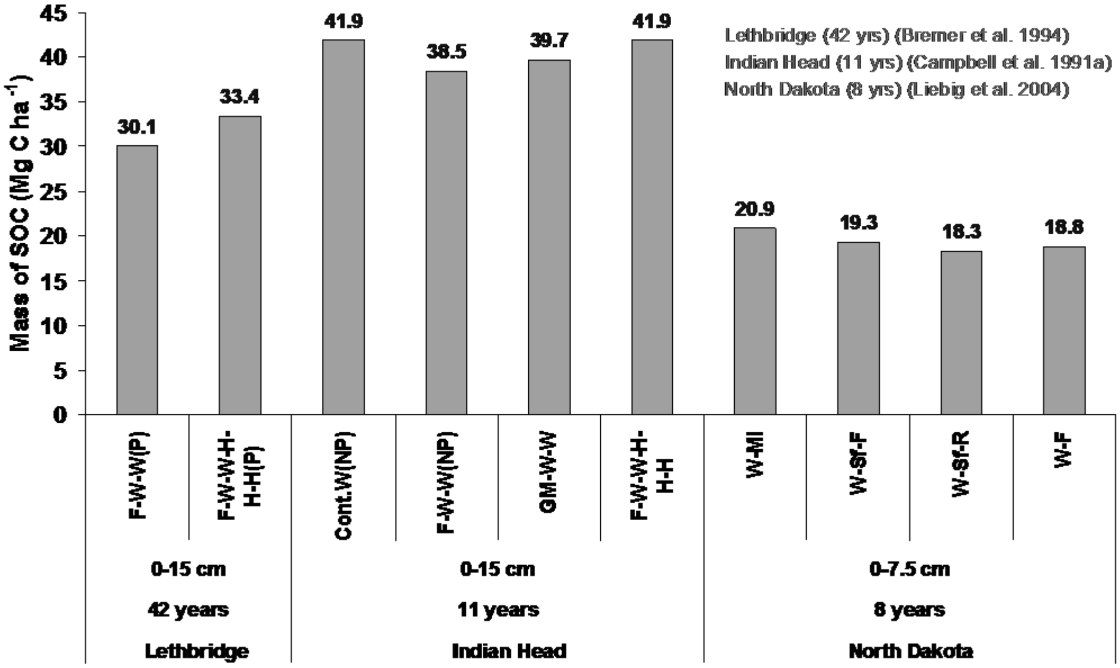
Swift Current – Concentration of SOC

Brown Swinton L – Crop management



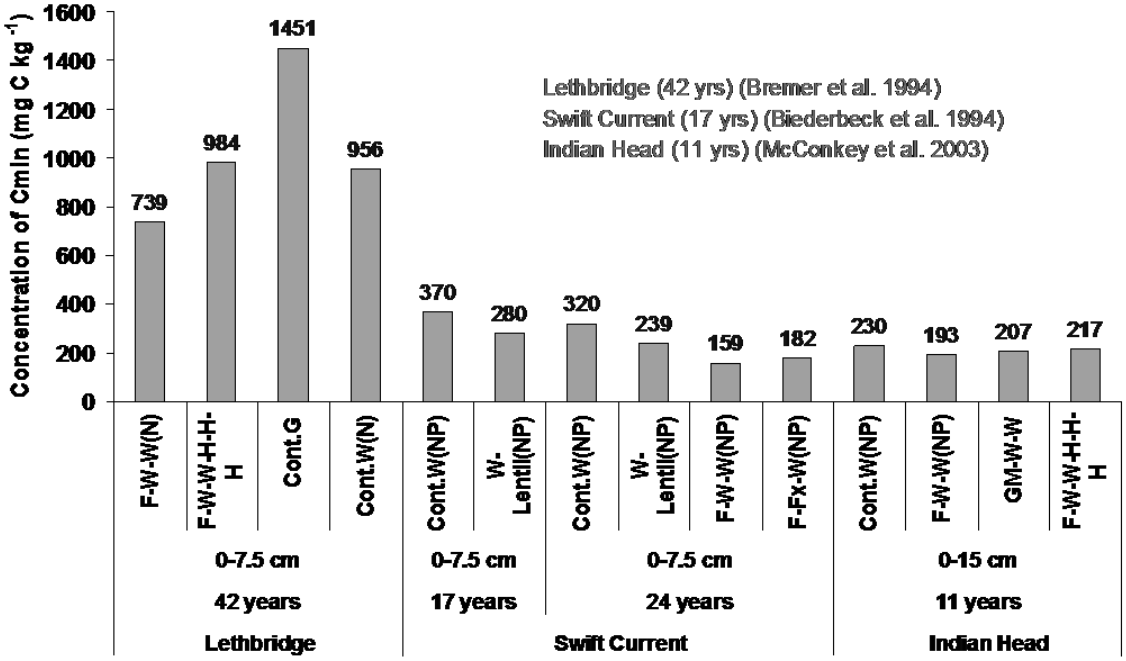
Mass of SOC – Crop management

Lethbridge Dark Brown Lethbridge CL
Indian Head Thin Black Indian Head C
North Dakota Dark Brown Temvik-Wilton SiL



Concentration of SOC – Crop management

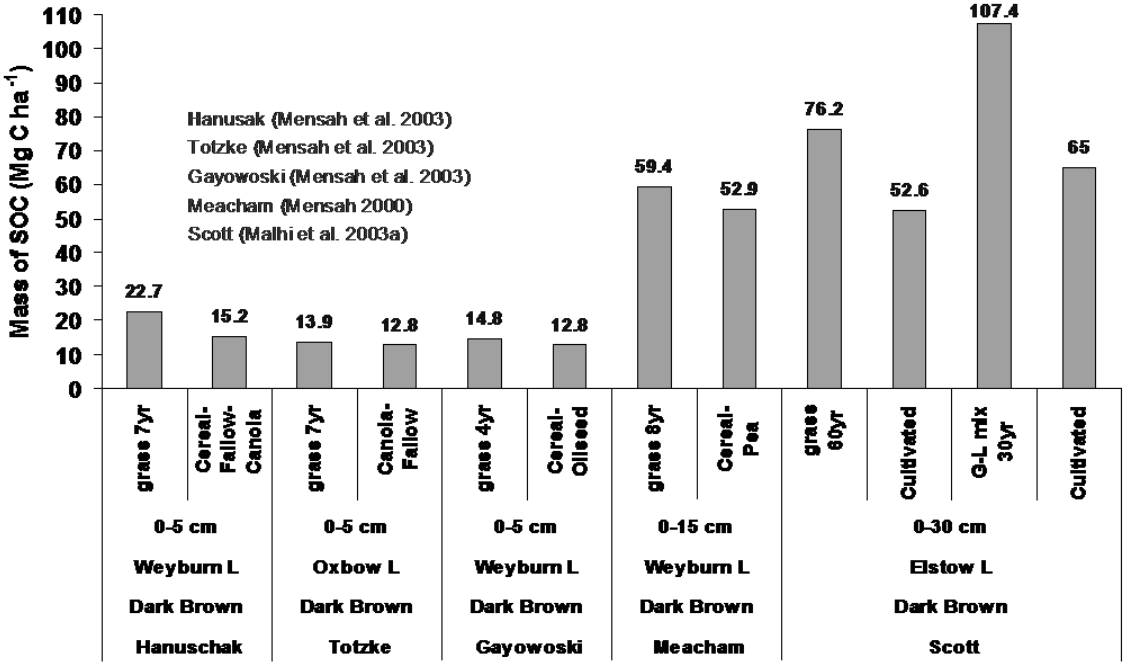
Lethbridge Dark Brown Lethbridge CL
Swift Current Brown Swinton L
Indian Head Thin Black Indian Head C



Soil organic C (SOC) and light fraction organic C (LFOC) as affected by land use (conversion to grassland versus cultivated land) at various locations in Saskatchewan, Canada

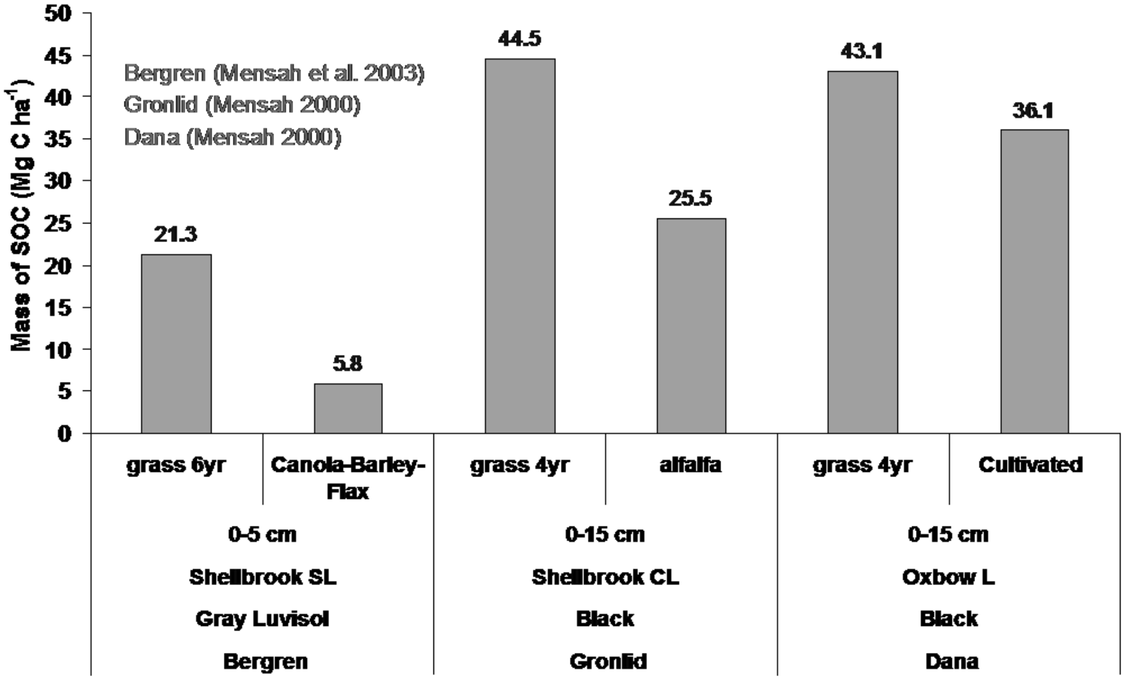
Saskatchewan - Mass of SOC - Land use effect

Dark Brown sites



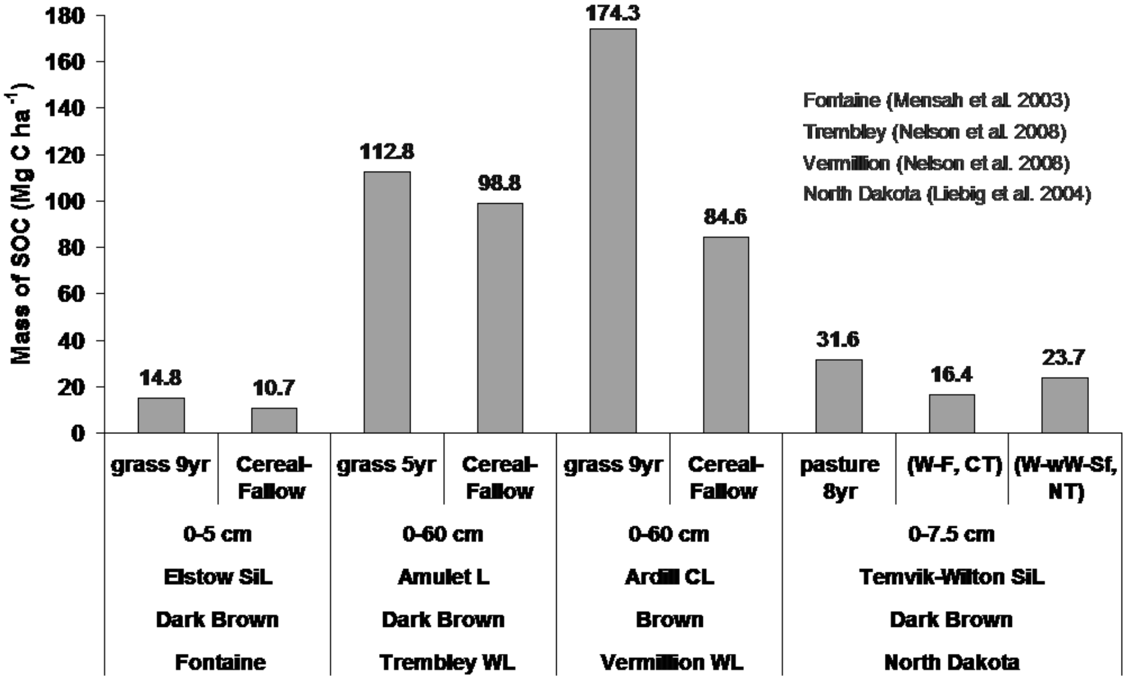
Saskatchewan - Mass of SOC - Land use effect

Black and Gray sites



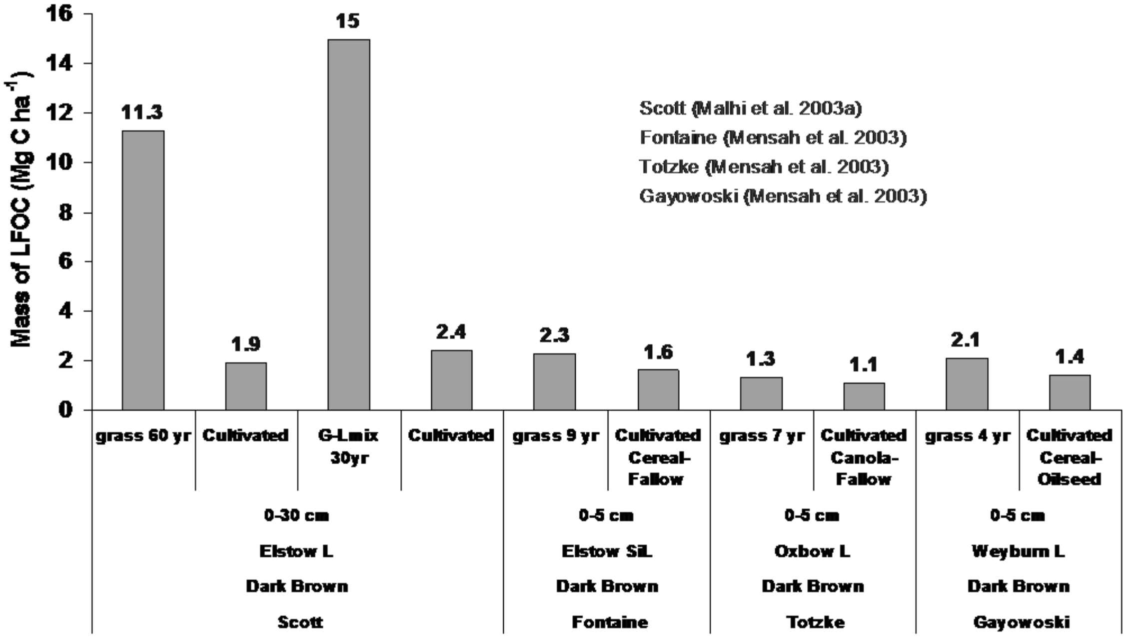
Alberta and USA – Mass of SOC - Land use effect

Brown and Dark Brown



Mass of LFOC - Land use effect

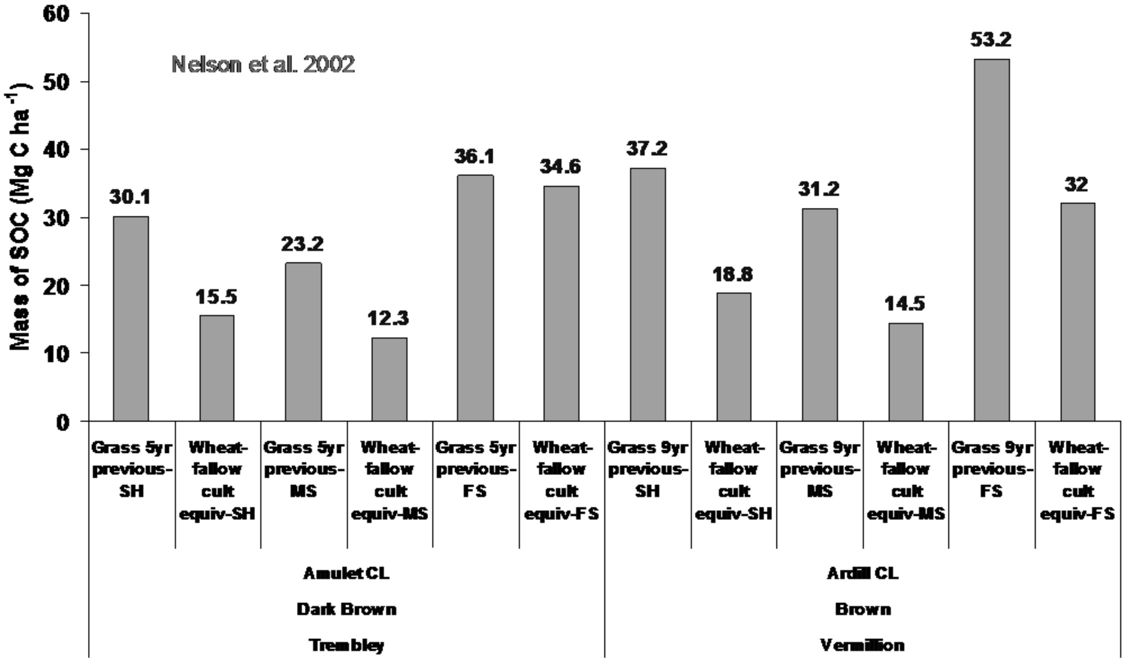
Dark Brown



Soil organic C (SOC) and light fraction organic C (LFOC) as affected by conversion of land use from cultivated land to grassland on different landscape position (SH – shoulder, MS – middle slope, and FS – foot slope) at various locations in Saskatchewan, Canada

Mass SOC – Conversion to grassland

Tremblay and Vermillion



Mass LFOC – Conversion to grassland

Tremblay and Vermillion