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The University of Alberta Breton Plots

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Summary

The Breton Plots were established by the Department of Soils at the University of Alberta in 1929. Within the Breton Plots research site, numerous long-term plot experiments have been conducted over the years. This paper summarizes results from the Breton Classical Plots (est. 1930), the Breton Hendrigan Plots (est. 1980), the Breton Tillage Straw Nitrogen plots (est. 1979) and the Breton Nitrogen Immobilization Plots (est. 1982). The experiments were established to find suitable cropping rotations and fertilizer management strategies appropriate for the Gray Wooded soils developed on glacial till in the Breton area of Alberta. Long-term results from the plots show that production challenges on these soils can be addressed with proper nutrient (fertilizer, manure) and residue management and the incorporation of perennial legume forage crops into annual crop rotations.

Introduction

As with so many stories, the details have faded with time. The gist of the story of the establishment of the Breton Plots remains, but exactly how the conversation went isn't clear. In the early 1920s the fledgling Department of Soils (as it was) at the University of Alberta was conducting fertilizer tests on Black and Gray soils in central Alberta. Soil surveyors out in the country were asked to be on the lookout for suitable fields. Tom Mather noted a site near Breton, in an area where there was yet little breaking, and he reported this to Dr. F. A. Wyatt who was Head of the Department. Dr. Wyatt approached the owner, Ben Flesher, about placing a test on his oat crop in one of his fields. Flesher mentioned that the selected field had been seeded to legumes and he was not planning to seed oats there. As they walked the field, Wyatt [awkwardly] observed that there weren't any legumes growing in the field, after which Flesher [exasperated] agreed to the lease and the fertilizer, saying that nothing was working anyways![22]

A conversation followed by a simple handshake marked the beginning of the Breton Plots. A preliminary test was done in 1929 and 1930 and the first fertilizer experiments were established (the "Classical Plots"). The agreement was terminated in 1946, when the University of Alberta purchased Flesher's land. For years, Ben Flesher assisted with the plots and the Fleshers remain friendly neighbors of the Plots to this very day. This article is intended to distill lessons learned from the long-term experiments executed at Breton over the last 80 or so plus years.

Characteristics of the Gray Wooded (Gray Luvisol) Soils

Unique challenges are involved in farming gray soils and so some information about their characteristics and formation is warranted. Soils in the gray soil zone in Alberta were originally called Gray Wooded, but the current name is Gray Luvisol. The old, Gray Wooded name lingers perhaps because it is such a good adjective of these soils: they are gray and they developed under forests. Thus it is not surprising to see that the gray soil zone in Alberta coincides with forested regions within and east of the foothills of the Rocky Mountains, the Peace River, and the Boreal forest.

Gray Wooded (Luvisolic) soils in the Breton area are developed on glacial till material. Glacial till is a mixture of sand, silt and clay (generally 20 to 30% clay) deposited by advancing or retreating glaciers. The most obvious characteristic of these soils is the gray colour of the topsoil. This gray colour is the result of two processes that occur in forested ecosystems: 1) organic acids released into the soils from leaf litter bleach the natural colour of the soil minerals creating a gray surface horizon 5 to 15 cm thick; and 2) above ground organic plant material (leaves, deadfall, etc) is not mixed into the surface soil horizons because, over the course of soil formation, there were no organisms such as earthworms to mix it in and tree and shrub roots are coarse and sparsely distributed in the soil. Many of the Gray Wooded soils in the Peace River areas in north-western Alberta were developed on much different water-lain sediments associated with glacial lakes and generally have higher amounts of clay. Best management practices for these soils may be different from the till soils at the Breton Plots.

Also, during soil formation under forests, clay is mobilized in the topsoil (A horizon) and transported into the subsoil (B horizon). The exact mechanism for this process is not entirely understood, but it is thought that the organic acids released from the leaf litter mobilize the clay in the A horizon which is transported deeper in the soil profile with the percolating waters under the wetter conditions in the forest. At a certain depth, the clay eventually gets stuck and accumulates in the B horizon where it clogs the larger soil pores.

Thus the surface horizon of the gray soils is much lower in organic matter compared to brown, dark brown and black soils. Breaking of the land resulted in burying of the light, bulky leaf litter, which then decomposed rapidly, leaving the soil low in organic matter. The low clay and organic matter levels in the surface horizon of Gray Wooded soils translates into poor soil structure and aggregation often referred to as soil tilth. These soils are susceptible to crusting, compaction, wind and water erosion under certain conditions. Further, the acidic pH (around 5.5 to 6) inherited from their forest heritage is prone to become even more acidic with long-term application of ammonium-based fertilizers like urea. Clay and organic matter are able to moderate added acidity.

The second characteristic of these soils is a dense subsoil horizon (i.e., B horizon). This dense subsoil horizon is an inherent property of the glacial till and the way it was deposited. Many Brown, Dark Brown and Black soils also have till as a parent material, but the dense, deep and fine root systems of their prairie grassland vegetation did much to alleviate this density. This dense B horizon generally has low water permeability which can cause extended periods of water logging in wet years. During these periods, oxygen can't reach plant roots causing poor root development and crop growth. These slowly drained soils are also be susceptible to compaction if worked when too wet.

With these challenges in mind, the experiments established at the Breton Plots were intended to develop a "…system of farming suitable for the wooded soil belt…" (F. A. Wyatt[30]). The remaining pages of this article are devoted to reviewing the lessons learned from the Breton Plots.

Descriptions of Long-term Agricultural Experiments at the Breton Plots

Within the Breton Plots site, a number of long-term agricultural experiments have been established over the years. The word "plots" is used in the names of the experiments, as well as the whole site, which may cause some confusion. In this section the Classical Plots, Hendrigan Plots, Tillage Straw Nitrogen (TSN) Plots and Immobilization Plots – all experiments run at the Breton Plots – are described.

The Classical Plots (1930 – Present)

The Classical Plots are the flagship of the Breton Plots and represents the longest on-going experiment at the site, set up to address some of the challenges faced by producers like Ben Flesher located on these soils. In 1930, the nutrient status of the soils at Breton was unknown. The original treatments of the Classical Plots were intended to test which nutrients were deficient in these gray soils. Another objective was to gain better understanding of which rotations would perform better on these soils. A schematic layout of the Classical Plots is presented in Figure 1 and treatment descriptions are presented in Table 1. The 11 treatments described in Table 1 are applied to two rotations: a five-year wheat-oats-barley-hay-hay (WOBHH) rotation and a 2-year wheat-fallow (WF) rotation. The five-year rotation is implemented on the north-south oriented "series" A, B, C, D and F (Fig. 1) and the wheat-fallow rotation is implemented on series E. Fertility treatments are oriented east-west across the rotations series.

The rotations and fertility treatment descriptions come with a few caveats and management notes:

1) The two rotations were originally a four-year rotation (3 years of cereals and 1 year of legumes) and continuous wheat between the years of 1930 – 1938/1941. In 1941, the continuous wheat rotation was changed to the wheat-fallow system that remains to this day. In 1938, the four-year rotation was converted to the five-year WOBHH rotation that remains to this day. The forage crops have varied over the years, but have always included a legume. Since 1967 the forage/hay crops have been alfalfa-brome mixtures.

2) Starting in 1980, the fertility treatments were updated to reflect higher nutrient application rates commonly used for modern cereal varieties and to better test the crop responses to individual nutrients.

3) Fertilizer application and placement varied during the period of the original treatments (1930 -1979). Fertilizers were broadcast initially. From 1946-1964, fertilizers were applied every other year. Starting in 1964, annual applications were resumed and phosphorus was seed-placed. For the manure treatment, manure was applied every five years to achieve the annual rates listed in Table 1.

4) Lime was applied to plots 6 and 7 several times between 1930 and 1948 totaling 6.6 t ha^{-1}. Starting in 1972, lime was added to the east half of plots in the WOBHH rotation and to full plots in the WF rotation all whenever the measured soil pH measured was less than 6.0. Currently, lime rates are calculated so that soil pH can be restored to 6.5. Using these guidelines, the resulting frequency of lime application is about every 10 years or so.

5) When binders were still in use, harvest involved the removal of straw from the Plots and this continued to 2000. Since then, straw has been retained on the plots with the use of combine harvesters. Tillage and weed control has varied over the years. Herbicides have been used on the Plots since 1964.

Grain, straw, hay and silage yields are available for almost all of the growing seasons since 1930 (barley was cut for silage a few times since the start of the Classical Plots). While there have been crop and management changes over time, great efforts have been made to quantify additions of nutrients to the soil, and removals of nutrients from the soil. For example, from 1933 – 1944, legumes were ploughed down as green manure on one half of the plots and cut for hay on the other half. Since 2000, barley under-seeded with alfalfa and brome has been removed as silage rather than harvested just for barley grain. An electronic database is a work in progress to fully quantify these additions and removals. Currently, detailed soil sampling of the Plots is carried out every five years.

The Hendrigan Plots (1980 – Present)

The Hendrigan Plots were established in 1980 to compare 3 different rotations: 1) continuous grain (CG; barley) with N, P, K, and S fertilization and straw returned to the Plots; 2) continuous forage with N, P, and S fertilization (CF fescue and white "Dutch" clover) and 3) an 8-year "agro-ecological" rotation of barley, faba beans and grass-legume forages. The CG and CF rotations are meant to represent two extreme cropping systems that could be implemented on gray wooded soils.

The continuous forage system consists of a creeping red fescue, tall fescue and white "Dutch" clover. This was conceived by a farmer from Winfield, AB, Mr. Lou Hendrigan. Mr. Hendrigan was an advocate of growing perennial forages on Gray Wooded soils and was quoted as telling farmers in the area: "Don't spend money on expensive equipment – put power *in* the soil not *on* it[31]." The system is based on nitrogen supply through N-fixing legumes (white clover) and low amounts of added P and S fertilizers.

The 8-year agro-ecological crop sequence was designed as a mixed farming rotation that is self-sufficient for nitrogen fertility. Nitrogen is supplied to this cropping system by a combination of manure and biological fixation (faba beans, alfalfa and red clover). The plots themselves are too small to be grazed so grazing is "simulated" by removing hay and returning manure. The manure rates are calculated using the assumption that grazing animals would return 70% of the nitrogen they consume in the forage as manure. Therefore, in year 1 of the rotation, manure is applied to offset the N removals from the previous 3 years of hay. Nitrogen for the barley crops in subsequent years of the rotation is supplied from manure (assuming the grain was used as feed) and from a green manure crop using faba bean. A summary of the rotation and management of the 8-year agro-ecological rotation is presented in Table 2.

The CF and CG rotations are meant to simulate strict cropping systems that aren't grazed and no manure is introduced into the soil. Thus, nitrogen fertilizer is used as the primary N source for these rotations. A complete nitrogen balance of the three rotations included in the Hendrigan Plots is presented later in this article along with the fertilizer N rates used.

Tillage Straw Nitrogen (TSN) and Immobilization Plots

These plots were established by Dr. Marvin Nyborg of the Department of Soil Science, later changed to Department of Renewable Resources, and his graduate student Sukhdev Malhi (currently working at

Agriculture and Agri-Food Canada, Melfort, SK). The main objective of these plots was to assess the influence of tillage (conventional, minimum, zero), N fertilizer, and straw (retained vs. removed) management on annual crop production (barley, wheat, canola, peas) and soil organic matter.

The TSN Plots were established in the autumn of 1979 and will be decommissioned in 2012. These plots consist of 10 treatments replicated four times. The treatments are summarized in Table 3.

Fertilizer is banded in all treatment except for treatment 9 where it is broadcasted on the soil surface and subsequently incorporated with tillage. Phosphorus, potassium and sulfur are applied according to soil test recommendations.

The Immobilization Plots were established in the fall of 1982 and were intended to discover the influence of straw management (removed or retained on the plots), fertilizer N source and application rate on crop yield, crop N uptake and total soil carbon and nitrogen using a conventional tillage system. These plots consist of 14 treatments replicated four times. The treatments for the immobilization plots are summarized in Table 4.

The N fertilizer was broadcast and incorporated for all treatments. On both the TSN and Immobilization Plots, the primary crop grown was Barley with wheat, canola and peas grown less frequently.

Major Findings from Long-term Experiments at the Breton Plots

Each of the experiments described above were designed to address unique questions. The article will focus on what answers the plots have provided to these questions to date and what new questions could be answered with these studies.

Responses to Nitrogen, Phosphorus, Sulfur and Potassium Fertilizers

The earliest publications described crop responses to fertilizers. The first sentence of a paper from 1934, authored by R. E. McAllister, states: “The podsolic wooded [gray wooded] soils of Alberta have failed to produce satisfactory yields, especially with the grain crops[18].” Thus Ben Flesher’s experience with freshly broken gray wooded soils (as described above) was very different from the experience of farmers in the Black, Dark Brown and Brown Soil zones.

Results from the Classical Plots[35,18,36] and Breton soil in the greenhouse[34] showed strong response by clover and wheat to added nitrogen (N) and Phosphorus (P) fertilizers. As a result of the early treatment design, however, N and sulfur (S) were applied together as ammonium sulfate and the contribution of S was overlooked. The deduction of the response of crops to S came later.[25,26,27,28,3] Current recommended fertilization practices in these soils call for N, P and S application for grains and P and S application for legumes. In addition to yield responses, adequate N, P and S fertilization resulted in higher protein in grains especially in the five-year rotation,[29,1] and added P and S resulted in a higher nutritional feed quality for forages.[2,33]

Although McAllister[18] recommended addition of potassium (K) fertilizers in addition to N and P fertilizers, long-term crop responses to added K at Breton have been small. Determining how much additional crop yield can be produced when a nutrient is added to the soil can assess soil nutrient deficiencies. Summaries of the long-term average yields for each fertility treatment and each crop over the 1930 – 1979 and 1980 – 2009 periods are presented in Figures 2 and 3 for annual crops and Figures 4 for hay. The yields are presented over two time periods because the treatments were modified starting in 1980. The new treatments also make it easier to assess nutrient deficiencies because of the systematic elimination of macronutrients.

For the 1980 – 2009 period (Fig. 3), long-term average yields for the annual crops (barley, oats and wheat) are generally highest in the NPKS, NPS (-K) or manure treatments followed by NPK(-S), then NKS (-P), PKS(-N) and control treatments. In general then, the annual crop yields in both rotations of the Classical Plots respond the most to added N and P, followed by S and there is generally very little response to added K. First and second cut hay (legume-grasses, currently alfalfa-brome) yields (Fig. 4) do not show a response to added N (because legumes fix their own N), but show strong responses to added P and S and a weak response to added K. The observed response to S in the forage crops is greater than for the annual crops. It is interesting to note that yields in the manure treatment are usually close to the yields on the NPKS treatments. From the 1980 to 2009 period, manure rates were calculated to supply nitrogen at equal rates to the fertilizers, but manure also contains P and S. Very little historical data for the nutrient content of the manure is available. The most recent manure addition was in 2008. This manure had an average total N, P and S content of 2.7%, 0.3% and 0.35%, respectively. Therefore, the 175 kg N ha^{-1} manure application in 2008 to the 5-year rotation series also resulted in the application of 18 kg P ha^{-1} and 20 kg S ha^{-1}.

Another soil amendment that warrants discussion is lime. Lime (calcium carbonate, $CaCO_3$) is generally not added as a nutrient amendment even though calcium is a macronutrient. Lime is added to adjust the soil pH or acidity of the soil. Early response of clover to added lime was noted by Wyatt and Newton[35] and the importance of moderating soil acidity with added lime, especially in legume forages, was recommended by Bentley et al.[2] and McCoy and Webster.[19] As mentioned earlier, lime was added at irregular intervals until 1972, but since then has been added to the east half of the treatments in the 5-year rotation series and to the entire area of the wheat-fallow rotation series whenever soil pH drops to 6.0 or below. Therefore, yields for the five-year rotation series can be split further according to whether lime is added or not. The yield summaries presented in Fig. 2, 3 and 4, are averaged by combining the lime and no lime subplots. Table 5 summarizes the long-term average yields for the control, NPKS and manure treatments for the five-year rotation series according to lime application.

Small yield differences in annual grain crops between the lime and no lime subplots are noticeable in the control treatment, but these differences seem to disappear when nutrient deficiencies have been removed with either N, P, K, or S fertilizers and with manure treatments. The forage legumes have a stronger response to lime additions, especially in the second cut. It is also interesting to note that the forage yield differences between the lime and no lime subplots in the manure treatment are smaller than with the NPKS treatments. Manure not only contains various N, P, K or S nutrients but, unlike chemical fertilizers, also contains organic matter that can buffer soil acidity and various basic compounds that can also neutralize the acid-producing N transformations.

In terms of basic crop nutrition, results from the Classical Plots suggest N, P and S additions for annual crops in the form of fertilizers or manures regardless of rotation. Nutrient application rates will vary according to soil nutrient levels, the nutrient demands of the crop and its place in the rotation. Forage crops require P and S for sure, but N is not required for N-fixing forages such as alfalfa if they are adequately nodulated. The addition of P and S fertilizers to forage fields is especially beneficial for the second cut. On top of the nutrient requirements, the pH should be monitored in these soils, especially for pH sensitive crops like alfalfa. Manure and lime are amendments that have ameliorating effects on soil acidity. To date, K has had little beneficial effect and other possible beneficial micronutrients effects have not been identified.

The Crops Will Use the N no Matter Where it's From

The 8-year Agro-ecological Rotation within the Hendrigan Plots is designed to not require any fertilizer N additions. Based on a nitrogen balance analysis by Ross et al.[31], it appears that the 8-year agro-ecological rotation is indeed N self-sufficient. A summary of the 1980-2005 nitrogen balance for the three different cropping systems and their average yields are presented in Table 6.

The Hendrigan Plots are a great example of how an integrated crop-livestock system can be designed to be nitrogen self-sufficient. No fertilizer N is required in the 8-year agroecological rotation and even without N fertilizer, there is an estimated 73.8 kg N ha^{-1} yr^{-1} that is added to the soil N pool. Excess N is added to the N pool in the CG and CF rotations as well, but the amounts are not as great. Despite these gains in soil N, leaching of nitrogen below the root zone in the 8-year rotation is less than the CG rotation[6].

In general, comparison of the Hendrigan Plot rotations and Classical Plot rotations show the utility of perennial legume forages in off-setting fertilizer N inputs[37,38,39]. The long-term average yields of barley under-seeded to forage on the Classical Plots (NPKS and manure treatments) is around 3220 kg ha^{-1}, comparable to the CG and 8-year rotation barley yields from the Hendrigan Plots. The barley in the Classical Plots receives 50 kg N ha^{-1} as fertilizer compared to 90 kg N ha^{-1} for the CG and no N for the 8-year rotation on the Hendrigan Plots. The wheat yields in the 5-year rotation in the Classical Plots (fertilizer N rate = 50 kg

N ha^{-1}) are also very similar to the wheat yields in the wheat fallow rotation (fertilizer N rate = 90 kg N ha^{-1}) for the NPKS and manure treatments. In all cases fertilizer N rates for annual grains in rotations that include perennial legume forages are lower than continuous grain rotations. The crops don't care where the N comes from. Incorporating forages into the rotation may mean fewer cash crop years, but reduced fertilizer additions also translates into lower input costs and may also mean reduced costs associated with other inputs such as lime, especially if manure is used in place of fertilizer. The long-term data also shows that incorporation of perennial legume forages into rotations also benefits soil quality.

Rotation Contributions to Soil Quality: A Long-term Investment

The rotations featured in the Classical Plots (WF and WOBHH) and the Hendrigan Plots (CG, CF and 8-year agro-ecological) have had significant influence on soil stocks of carbon, nitrogen, phosphorus and sulfur. Detailed studies into various soil carbon (C) and N fractions have also been published from the Breton Plots. The primary themes of these publications are the influence of rotation on amounts, quality and fractions of soil C and N. Figure 5 compares soil levels of total C, N, P and S for selected treatments from the WF and WOBHH rotations of the Classical Plots and the three rotations from within the Hendrigan Plots (data from 2008). Note that total levels of the nutrient elements (i.e., total N, P, S) are not representative of the plant-available nutrient pool, but are the total stocks of each element. They include organic, inorganic and microbial components of which available nutrients are a very small component. The total C, N, P and S levels are correlated to the organic C, N, P and S levels in the soil. Organic C, N, P and S are important components of the entire soil organic matter pool. Soil organic matter is very important for the development and maintenance of soil tilth and soil nutrient cycling. On average, a soil with higher levels of organic matter is better for crop production than a soil with lower levels of organic matter.

The total soil stocks of these elements can be viewed like an investment portfolio. At any one time in an investment portfolio, there is a certain amount of liquidity/cash (i.e., available nutrients) and a much larger amount tied up in investments (i.e., organic matter). In this case, however, the soil is much more stable than the markets over the long-term so farmers can be assured that their soil investments will not be easily lost. The return on the investment is higher long-term average yields (see the yield summaries from the previous two sections) and potentially higher land values. The following conclusions can be made from this data:

1) Addition of nutrients in the form of fertilizers and manure has increased soil stocks of C, N, P and S in all rotations. The control treatments in the Classical Plots have the lowest total C, N, P and S stocks compared to the treatments with added fertilizer or manure and the Hendrigan Plot rotations, which also have added nutrients.

2) When comparing rotations with similar nutrient sources (i.e., fertilizer or manure), rotations with perennial legume forages (WOBHH, CF and 8-year) show equal or greater soil C, N, P and S stocks in the surface 15 cm compared to annual grain only crop rotations (CG, WF).

3) The increased carbon in the soil as a result of fertilizer and manure additions shows that these soils can be carbon sinks with careful management. Currently, carbon credits are available to farmers in Alberta for no-till practices, but the data from the Breton Plots may be useful for other carbon credit programs in the future.[4,5,7,8,11]

Conclusions from past investigations into soil C and N stocks, fractions and dynamics are as follows:

1) In the Classical Plots, there is a significant rotation effect on the amounts and types of soil organic carbon, nitrogen, and phosphorus namely:

a. The higher levels of soil organic C in the five-year WOBHH rotation are reflected in higher levels of soil carbohydrates and humic acids compared to the WF rotation.[13,14,4] Carbohydrates and humic acids are the more active and reactive components of soil organic carbon. Higher levels of these forms of C may enhance soil nutrient cycling, microbial biomass, and soil aggregate formation and stability.

b. The higher levels of soil N in the five-year WOBHH rotation are in the forms of hydrolyzable N, amino acids and amino sugars.[15,4] While these forms of N are not directly available to plants, they are easily mineralized into available forms that plants can take up Thus there are greater levels of potentially available N in the WOBHH rotation compared to the WF rotation.

c. The five-year WOBHH rotation showed significantly higher levels of soil microbial biomass C and N.[20,4] Microbes (or bacteria) are essential for cycling nutrients and the creation and maintenance of soil structure in agricultural soils. Microbial biomass also acts as a temporary storage pool for nutrients. The higher microbial biomass in the five-year rotation indicates greater nutrient retention in the soil.

d. Fertilization resulted in greater increases in various P fractions in the five-year rotation than the WF rotation.[21,4]

e. The average organic matter content in the five-year rotation was 20% greater than the WF rotation after 50 years.[9,10,12]

2) In the Classical Plots, there is an important rotation effect on soil structure and soil erosion, namely

a. Toogood and Lynch[32] and McGill et al[20] observed that the average diameter of soil aggregates in the 5-year WOBHH rotation was twice that of the WF rotation.

b. More soil has been lost from all forms of erosion (wind, water and tillage erosion) in the WF rotation compared to the WOBHH rotation when comparing like treatments.[23] The WF control treatment soil loss estimates were 3.1 mm of topsoil per year, compared to 1.4 mm/year for the control treatment of the WOBHH rotation. On the WF NPKS treatment, the estimated soil loss estimate was 2.2 mm/year compared to 0.7 mm/year for the WOBHH NPKS treatment. The manure WF treatment soil loss estimate was 1.65 mm/year compared to 0.33 mm/year for the WOBHH-manure treatment

c. Regular use of fertilizers and manure also reduced erosion susceptibility within the two rotations. However, the incorporation of legume perennial forages into rotations enhances soil structure (which enhances aeration and water infiltration) and reduces susceptibility to soil erosion compared to the WF rotation. These erosion-reducing practices also reduce losses of organic matter via eroding soils.[24]

Crop's Trash is Soil's Gold

Farmers may have a number of reasons for removing straw from their fields such as livestock bedding or because it is plugging seeding equipment. The development of cellulose-based biofuels may result in an economic incentive for farmers to remove crop residues from their fields in the future. Results from the Tillage-Straw-Nitrogen (TSN) and Immobilization Plots at Breton, however, show that returning straw to the soil has beneficial effects on the soil organic carbon and nitrogen levels in cereal-based rotations (Table 7,[16,17]). Long-term barley yields, soil organic carbon and soil organic nitrogen levels for the TSN and immobilization Plots are summarized in Table 7. The results are organized according to N rate, tillage management and straw management. The expected increases in long-term yields as a result of N rates are observed, but tillage and straw management showed little difference. Further, tillage management doesn't appear to have a strong effect on organic carbon and organic nitrogen levels in the soil. The results in Table 7, however, indicate that fertilizer and straw management have a more significant influence on soil organic carbon and organic nitrogen. As mentioned earlier, the increased levels of organic carbon enhance soil structure and soil tilth, and organic nitrogen enhances nitrogen cycling. Therefore, farmers might want to think twice before removing or burning crop residues on a long-term regular basis. The data from these experiments indicate that, occasionally, incorporating excess straw into the soil with tillage is perhaps better than straw removal.

The Future of the Plots

With respect to future investigations, The Classical Plots and the Hendrigan Plots are still maintained and will be indefinitely. The Immobilization Plots were decommissioned in 2010 and the TSN Plots will be decommissioned in 2012. The University of Alberta owns the Breton Plots. Primary responsibility for day-to-day operations lies with the Department of Renewable Resources (Faculty of Agriculture, Life and Environmental Sciences). The "Breton Plots Management Team" consisting of University of Alberta employees and faculty members makes management decisions for the Breton Plots, and their associated long-term experiments. Mr. Dick Puurveen is the current on-the-ground manager at the Plots and has been with the University since 1992. Funding for maintaining the Breton Plots is provided by an endowment established through the efforts of Dr. J. A. Robertson (Jim) in 1983 and strongly supported by Dr. C. F. Bentley (Fred) throughout the 1990s. If not for the endowment, it is unclear whether the Breton Plots would still exist today.

The Breton Plots Management Team reviews the treatments and rotations of the Classical Plots and Hendrigan Plots on a regular basis. No significant changes to the Classical Plots treatments or rotations have been made since 1980 with the exception of straw retention in 2000 (Table 1). The last significant changes made to the Hendrigan Plots were in 2000 (Table 2). The Breton Plots Management Team just recently decided to replace Barley with Triticale in the CG rotation and in year 2 of the 8-year agroecological rotation of the Hendrigan Plots because of disease concerns. Detailed soil samples are taken every 5 years and plant samples on an annual basis. These samples are analyzed for a limited number of parameters after they are collected and archived for later investigations.

After 80-plus years of research, one might think there are no more questions that could possibly be answered with information from the Plots. However, there are many more questions and investigations that will hopefully be pursued in the future:

1. Many agronomic and soil fertility questions have been answered using the data from the Plots over the years. Less analysis has been done on the economics of the rotations in the Classical and Hendrigan Plots. In addition to economics, the database from the Classical and Hendrigan Plots is extensive enough to do lifecycle analysis comparison of the carbon and/or energy footprint of these rotations.
2. As mentioned earlier, total soil C, N, P and S shed light on the long-term effects of the rotations on soil quality, but new analytical methods are available to find out what kind of compounds are found in these C, N, P and S pools, how they are created and how they are cycled by soil microorganisms. The long-term experiments at the Breton Plots will hopefully be the subject of more detailed soil C, N, P and S cycling investigations in the future.
3. Most of the investigations to date have concentrated on treatment and rotation responses to macronutrients (N,P,K,S). Are there micronutrient deficiencies in the Breton soil or have any micronutrient (boron, molybdenum, copper, selenium) deficiencies arisen over time?
4. Does long-term addition of lime, increase carbon dioxide emissions from these soils or influence the soil organic carbon pool?
5. Rotations including perennial legume forages appear to increase soil quality. Do these increases in soil quality result in better soil moisture holding, infiltration or aeration characteristics and to what depth in the soil profile?

One criticism frequently leveled against long-term research plots is that their management practices and treatments are often not representative of contemporary management practices and so it is difficult to practically apply the results. Perhaps this is a fair criticism. It is not likely that today's farmer would implement exactly the rotations at the Breton Plots. However, the results of these long-term experiments might inspire a farmer to diversify their cropping rotations. The primary take-home message from these plots is that more cropping diversity in rotations results in improved soil quality and can help reduce fertilizer inputs. It is up to the farmer to apply these results to their operation in an economically feasible way if they are so inspired. Further, long-term research is complementary to short-term work. Long-term research allows for extrapolation of short-term results. Because of the inherent variability and heterogeneity of the soil, long-term experiments are required to identify changes in soil quality as a result of different management systems.

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Table 1. Treatment Descriptions in the Breton Classical Plot Study.

	treatments 1930 – 1979 inclusive[+]					treatments, 1980 onward				
		kg ha^{-1}					kg ha^{-1}			
Plot	Treatment	N	P	K	S	Treatment	N	P	K	S
1	Control	0	0	0	0	Control	0	0	0	0
2	Manure(M)	76	42	91	20	Manure	#			
3	NPKS	10	6	16	10	NPKS	*	22	46	5.5
4	NS	11	0	0	11	NSK(-P)	*	0	46	5.5
5	Control	0	0	0	0	Control	0	0	0	0
6	Lime(L)	0	0	0	0	Lime	0	0	0	0
7	NPKSL‡	11	6	16	9	NPK(-S)	*	22	46	0
8	P	0	9	0	0	PKS(-N)	0	22	46	5.5
9	MNPS	86	48	91	28	NPKS†	*	22	0	5.5
10	NPS	10	6	0	8	NPS(-K)	*	22	0	5.5
11	Control	0	0	0	0	Control	0	0	0	0

[+] fertilizer application rates of the original treatments varied (see text in article); manure was applied every 5 years to achieve the annual rates listed

*N amounts depend on the crop and its place in the rotation:
- wheat on fallow: 90 kg N ha^{-1}
- wheat after forage: 50 kg N ha^{-1}
- oats or barley after wheat: 75 kg N ha^{-1}
- barley underseeded to hay: 50 kg N ha^{-1}
- legume-grass forages: 0 kg N ha^{-1}

N application via manure depends on the rotation.
- wheat-fallow: 90 kg N ha^{-1} during cropped years
- cereal crops in WOBHH rotation: 175 kg N ha^{-1} every 5 years applied in two equal applications

† subsoiled in 1983

‡ lime plus P (LP) from 1930 – 1963. NPKSL from 1964-1979. This has a major effect on yields and the added S had residual effects for years after modification in 1980 to NPK (-S).

Table 2. Management summary of the 8-year agroecological rotation in the Hendrigan Plot Study[31]

Years		Year of rotation							
		1	2	3	4	5	6	7	8
1980-1999	Crop	barley	fababean	barley	fababean	barley under-seeded to forage	brome-red clover	brome-red clover	brome-red clover hay
	Management	grain harvest	plough-down	grain harvest	plough-down	grain harvest	2 cuts of hay	2 cuts of hay	1 cut of hay, fall plough-down
2000-present	Crop	barley	barley	fababean	barley	barley under-seeded to forage	brome-alfalfa hay	brome-alfalfa hay	brome-alfalfa hay
	Management	grain harvest	grain harvest	plough-down or silage	grain harvest	silage	2 cuts of hay	2 cuts of hay	1 cut of hay, fall plough-down

Table 3. Treatment Descriptions in the Tillage-Straw-Nitrogen (TSN) Plot Study

Treatment number	Tillage management	Straw management	N rate (kg ha^{-1})
1	no-till	removed	0
4	no-till	retained	0
3	no-till	retained	50
6	no-till	retained	100
5	conventional	retained	0
8	conventional	retained	50
7	conventional	retained	100
2	conventional	removed	0
10	conventional	removed	50
9	conventional	removed	50

Table 4. Treatment Description in the Immobilization Plot Study

Treatment number	Straw management	N rate	N source
13	removed	0	none
1	removed	25	ESN*
7	removed	25	Urea
3	removed	50	ESN
9	removed	50	Urea
5	removed	75	ESN
11	removed	75	Urea
14	retained	0	none
2	retained	25	ESN
8	retained	25	Urea
4	retained	50	ESN
10	retained	50	Urea
6	retained	75	ESN
12	retained	75	Urea

* slow release, environmentally sensitive (ESN) fertlizer

Table 5. The effect of lime from selected treatments on the long-term average crop yields (period 1980 – 2009) from the Breton Classical Plot Study.

	Crop Yield					
	Control (average of plots 1, 5 and 11)		NPKS		Manure	
	Lime	no Lime	Lime	no Lime	Lime	no Lime
wheat (kg/ha)	1750	1548	2894	2827	2692	2827
oats (kg/ha)	2746	2556	4119	4233	3928	3928
barley underseeded to forage (kg/ha)	1669	1400	3554	3446	3069	2800
alfalfa-brome, 1st cut (kg/ha)	1977	1869	3634	3021	4040	3739
alfalf-brome, 2nd cut (kg/ha)	725	651	1766	1463	1969	1939

Table 6: Rotation nitrogen balance and long-term crop yields from the Breton Hendrigan Plot Study[31]

	Cropping system		
	8-year agro-ecological	continuous forage (CF)	continuous grains (CG)
N inputs (kg ha^{-1} yr^{-1})			
atmospheric deposition	5.0	5.0	5.0
above cutting height legume N fixation			
Fababeans	33.3		
Forage legumes (clover and alfalfa)	36.5	14.6	
below cutting height legume N fixation			
Fababeans	17.2		
Red clover and alfalfa	24.4		
white clover		11.9	
non-legume N fixation	5.0	5.0	5.0
manure	47.6	0	0
fertilizer	0	17.5	91.1
seed	2.8	0	1.7
total inputs	**171.8**	**53.9**	**102.8**
% of total inputs from fertilizer	**0**	**32**	**89**
N outputs (kg ha^{-1} yr^{-1})			
N exported in crop (seed or forage)	70.2	30.8	58.2
gaseous losses			
denitrification from manure or fertilizer	4.8	1.7	9.1
volatilization from manure or fertilizer	2.4	0.9	4.6
gaseous losses of legume-fixed N	7.5	1.2	
leaching losses			
leaching from manure or fertilizer	4.8	0	9.1
leaching losses from legume-fixed N	2.4	0	
surface runoff losses	1	0	1.5
total outputs	**98.0**	**34.6**	**82.5**
Totals (kg ha^{-1} yr^{-1})			
N balance: inputs-outputs	73.8	19.3	20.3
increase in total soil N (0-30 cm)	75.9	65.0	23.6
unaccounted for N	-2.1	-45.7	-3.3
Long-term average crop yields (1980 – 2009)			
barley (kg ha^{-1})	3500		3284
barley underseeded to hay (kg ha^{-1})	3123		
fababeans			
grain yield (kg ha^{-1})	2288		
silage (kg ha^{-1})	6200		
alfalfa-brome (kg ha^{-1})			
1st cut	3700		
2nd cut	2200		
silage	3900		
red clover-brome (kg ha^{-1})			
1st cut	4800		
2nd cut	1700		
cr. r. fescue-tall fescue-w. clover (kg ha^{-1})			
1st cut		2000	
2nd cut		1200	

Table 7. Summary of long-term barley yields and soil organic carbon and nitrogen levels (from soil samples taken in 2008) from the Immobilization and TSN Plot Studies at Breton. The results in bold-face are from the TSN plots and the results from the Immobilization plots are in non-bold-face.

			Nitrogen rate (kg ha^{-1})				
	Tillage	Straw management	0	25	50	75	100
Long-term barley yield (kg/ha)	CT	Straw retained	1023	1777	2315	2800	**2423**
			862		**2154**		
		Straw removed	915	1777	2369	2746	
			862		**2207**		
	ZT	Straw retained	**808**		**1992**		**2100**
		Straw removed	**754**				
Organic carbon (kg/ha 0-15 cm)	CT	Straw retained	21240	22140	26740	28.38	**30570**
			21090		**25440**		
		Straw removed	19940	21630	25060	27.74	**n/a**
			20110		**n/a**		
	ZT	Straw retained	**25490**		**31800**		**32470**
		Straw removed	**16220**		**n/a**		**n/a**
Organic nitrogen (kg/ha 0-15 cm)	CT	Straw retained	1863	1990	2414	2.468	**1854**
			2582		**2804**		
		Straw removed	1846	1921	2294	2.487	**n/a**
			2390		**n/a**		
	ZT	Straw retained	**2799**		**3229**		**3352**
		Straw removed	**2476**		**n/a**		**n/a**

N↑

F WOBHH	E W-F	D WOBHH	C WOBHH	B WOBHH	A WOBHH	Series Rotation
Control	Control	Control	Control	Control	Control	1
Manure (M)	Manure (M)	Manure (M)	Manure (M)	Manure (M)	Manure (M)	2
NPKS	NPKS	NPKS	NPKS	NPKS	NPKS	3
NS [NSK(-P)]	NS [NSK(-P)]	NS [NSK(-P)]	NS [NSK(-P)]	NS [NSK(-P)]	NS [NSK(-P)]	4
Control	Control	Control	Control	Control	Control	5
Lime(L)	Lime(L)	Lime(L)	Lime(L)	Lime(L)	Lime(L)	6
LP / NPKSL [NPK(-S)]	LP / NPKSL [NPK(-S)]	LP / NPKSL [NPK(-S)]	LP / NPKSL [NPK(-S)]	LP / NPKSL [NPK(-S)]	LP / NPKSL [NPK(-S)]	7
P [PKS(-N)]	P [PKS(-N)]	P [PKS(-N)]	P [PKS(-N)]	P [PKS(-N)]	P [PKS(-N)]	8
MNPS[NPKS]	MNPS[NPKS]	MNPS[NPKS]	MNPS[NPKS]	MNPS[NPKS]	MNPS[NPKS]	9
NPS [NPS(-K)]	NPS [NPS(-K)]	NPS [NPS(-K)]	NPS [NPS(-K)]	NPS [NPS(-K)]	NPS [NPS(-K)]	10
Control	Control	Control	Control	Control	Control	11

Plot/Treatment

Figure 1. Layout of the Breton Classical Plot Study. See Table 1 for a complete description of the treatments.

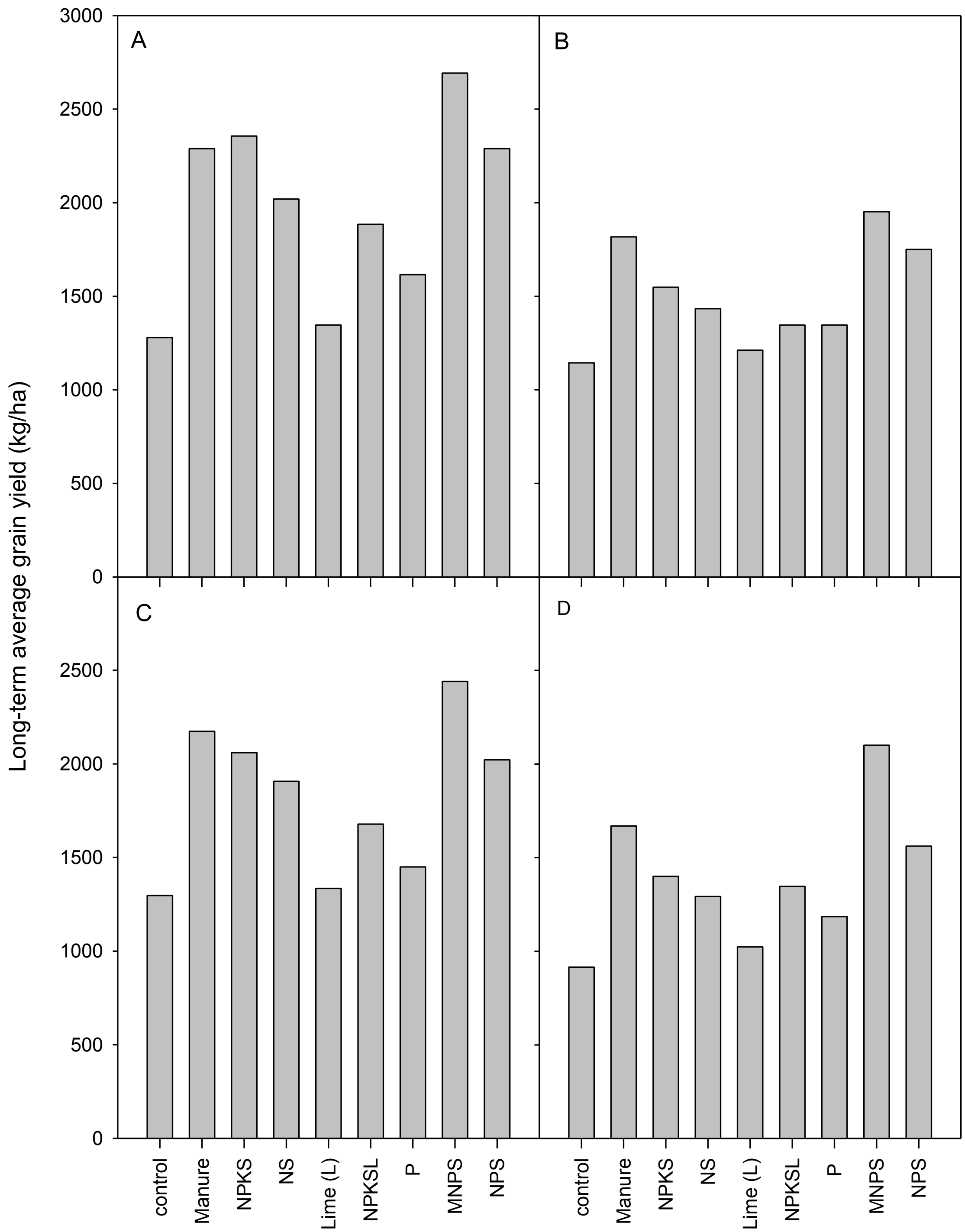

Figure 2. Summary of long-term average grain yields from the Breton Classical Plot Study, 1930 – 1979. A) wheat (WOBHH); B) wheat (WF); C) oats (WOBHH); D) barley underseeded to hay (WOBHH). Control yield is average of plots 1,5 and 11 (Figure 1). Yields are averaged over limed and non-limed treatments.

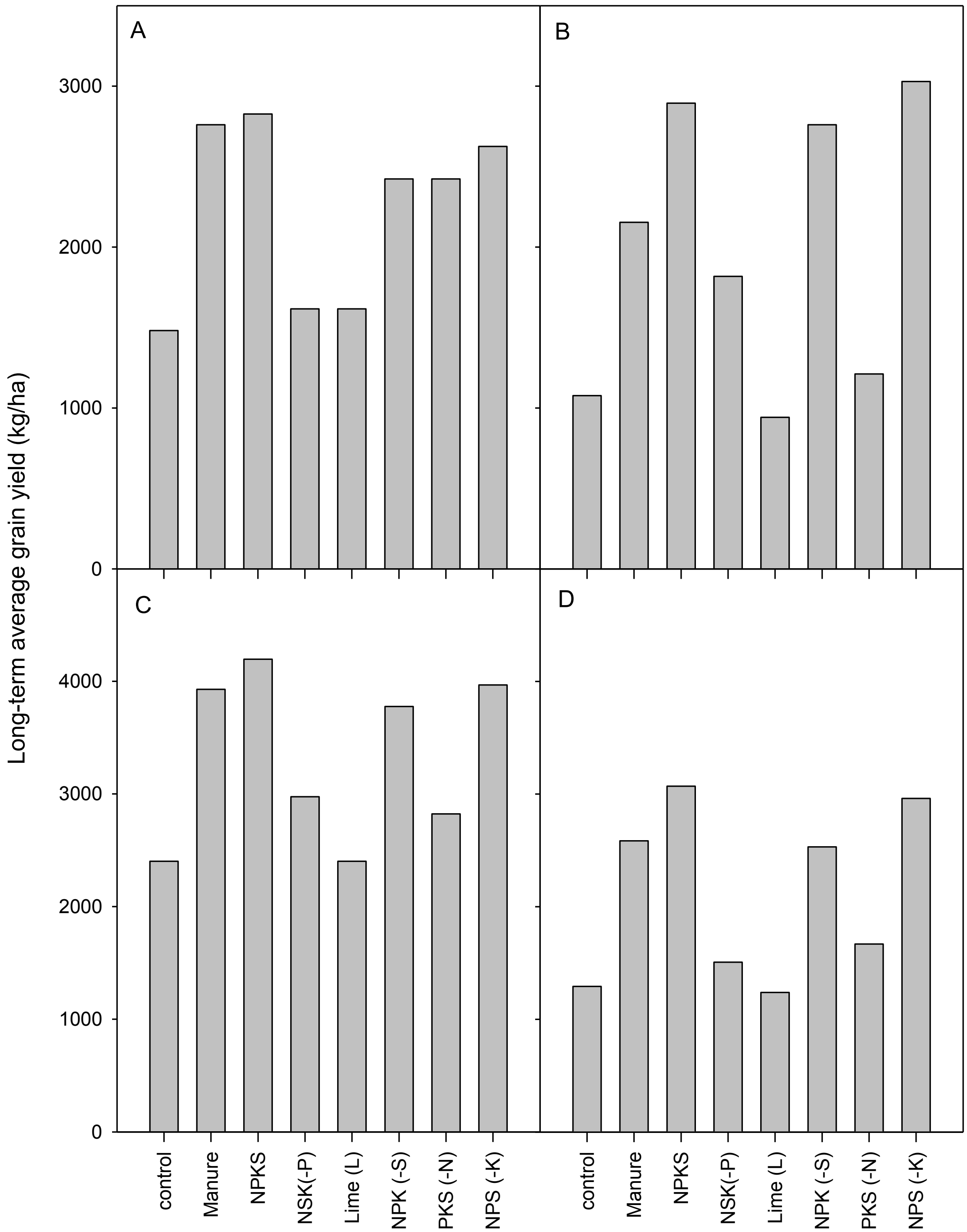

Figure 3. Summary of long-term average grain yields from the Breton Classical Plot Study, 1980 – 2009. A) wheat (WOBHH); B) wheat (WF); C) oats (WOBHH); D) barley underseeded to hay (WOBHH). Control yield is average of plots 1,5 and 11 (Figure 1). Yields are averaged over limed and non-limed treatments

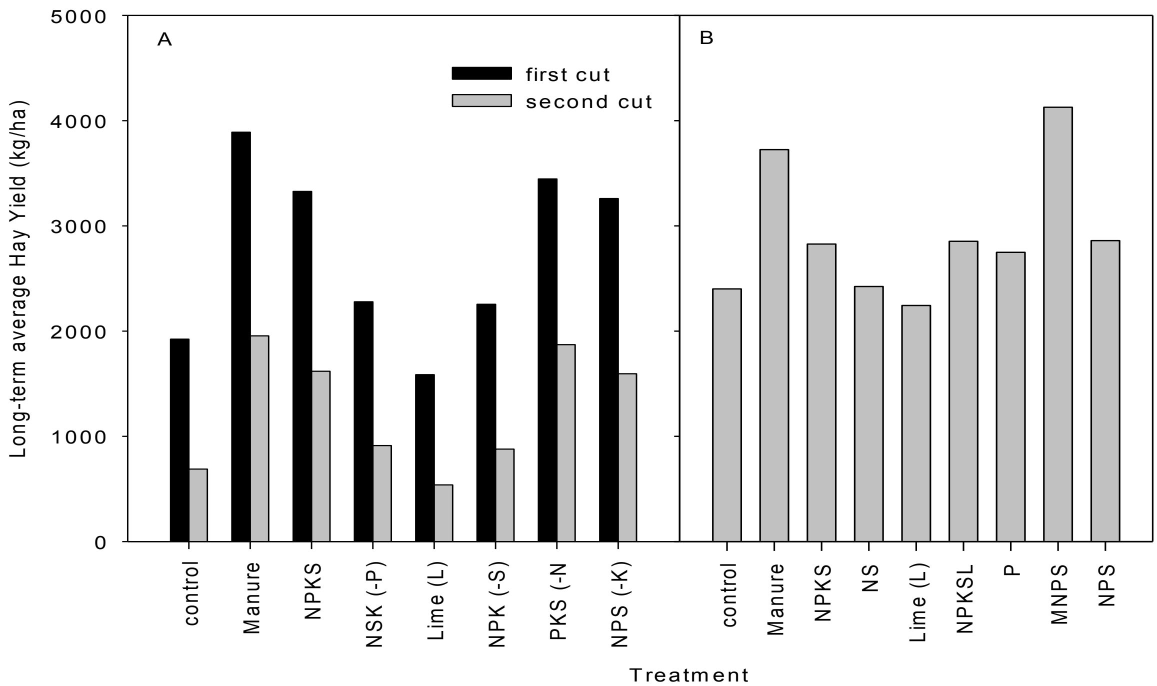

Figure 4. Summary of legume-grass hay yields for the Breton Classical Plot Study. A) 1980 – 2009, first and second cuts. B) 1930 – 1979, first cut only. Yields are averaged over limed and non-limed treatments.

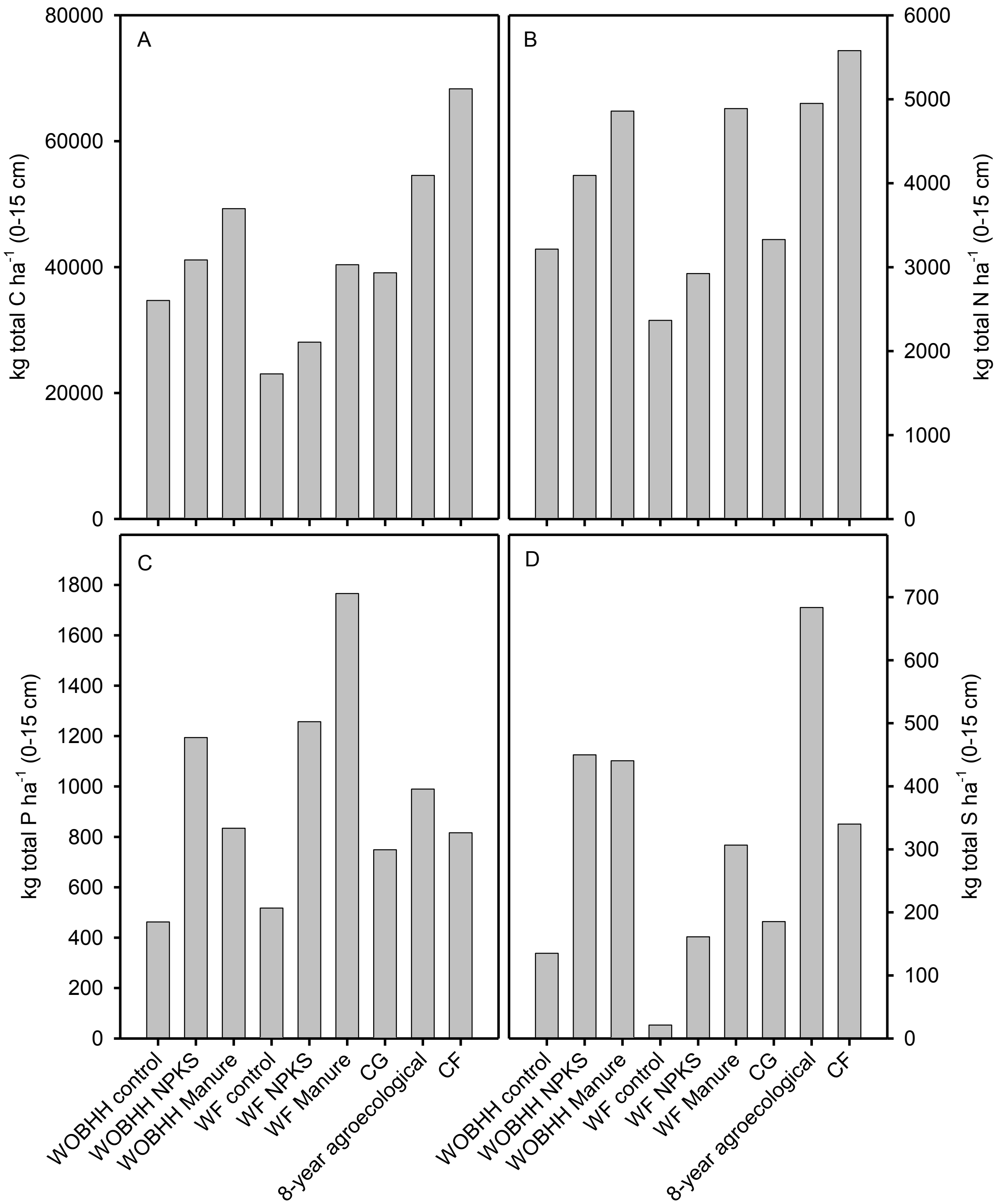

Figure 5. Total C, N, P and S soil levels (0 – 15cm) measured in 2008 from selected treatments in the Breton Classical Plot Study and all three rotations from the Breton Hendrigan Plot Study.

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