The Effects of Land Use Changes
on Soil Carbon in the Russian Steppe

Abstract of a thesis presented to the Faculty

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Department of Earth and Atmospheric Sciences

Andrew M. Ratigliano
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Abstract

Increasing atmospheric CO_2 levels within the past few centuries have led to many studies about the global carbon cycle. An important aspect in balancing the modern global carbon budget revolves around a missing sink of carbon. It is thought that the carbon accumulation in soil may be a significant component in this loss. As changes in land use under natural conditions have increased over the years, it is not well understood how these changes may affect the soil carbon. A useful technique in determining these changes are with the use of archived samples. Within a Russian steppe preserve that has been protected since 1885, modern samples from three different land use plots (meadow steppe, planted forest, and tilled field) were compared to a 100-year-old archived sample of initial conditions in addition to archived samples from these same plots throughout the past 100 years. It was hypothesized that there would be both increases and decreases in soil carbon in addition to physical changes in the soil. Compared to the initial conditions of the pristine plot, organic carbon concentration decreased in the meadow steppe, remained about the same in the planted forest, and decreased in the tilled field. The conversion to tilling showed the greatest amount of change in organic carbon concentration. The organic carbon stock in the meadow steppe showed little change compared to the pristine stock. The planted forest and tilled field showed a significant decrease in carbon stocks. The bulk density in each land use plot increased in the upper half of the profile and decreased in the lower half compared to the pristine plot. Weathering has increased in each of the land use plots. Overall, the change in land use had varying effects on Russian steppe soil, which was determined by using archived samples starting from initial conditions 100 years ago and at various points throughout that time.

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Introduction

Since the industrial revolution, and especially within the past 100 years, atmospheric CO_2 levels have been increasing more than any other time in history (Lal 2004, Rustad et al. 2000, IPCC 1995). Since 1750, the atmospheric concentration of CO_2 has increased by 31% due to fossil fuel combustion and land use change (IPCC 1995). Over this 100 year time, global emissions of carbon due to land use change and soil cultivation are estimated at 136 ± 55 Pg (Pg = petagram =10^{15} g = 1 billion tones) and 78 ± 12 Pg due to the depletion of soil organic carbon pools (Lal 2004, IPCC 2001). The emission of CO_2 has been a major concern to scientists due to its impact on the climate. This has lead to many studies to gain more knowledge on the global carbon cycle (Lal 2004, Karl and Trenberth 2003, Guo and Gifford 2002, IPCC 2001, Falkowski et al. 2000)

One concern in balancing the modern global carbon budget is a missing sink of carbon that cannot be accounted for (Prentice et al. 2000, Keeling 1997, Kerr 1992). For the 1980’s and 1990’s, 1.9 ± 1.3 Pg C/yr and 2.3 ± 1.3 Pg C/yr, respectively, represented unknown sinks for the global carbon budget (Lal 2004, Prentice 2001). Given that 75% of the terrestrial carbon inventory is contained in soils (Rhoades et al. 2000, Schlesinger 1986, Houghton et al. 1985), it is thought that carbon accumulation in the soil may be a major component in this annual loss. Since much of the world’s soils have been or will be cultivated, being able to quantify changes in soil carbon due to changes in land use could be useful in better understanding the global carbon cycle (Brye et al. 2002, Guo and Gifford 2002, Mikhailova et al. 2000b, Ross et al. 1999). This thesis focuses on one aspect of the global carbon cycle: how changes in land use affect soil carbon over time.

Some of the most fertile soil in the world is the Chernozem (Mollisol) soil of the Russian steppe (Torn et al. 2002, Dokuchaev 1949). This area has in recent time undergone significant changes in land use over most of the area. The effects on soil carbon due to these land use changes are not well understood (Torn et al. 2002, Mikhailova et al. 2000a,b). During the past 100 years, agricultural Chernozems lost about 50 percent of their soil carbon in the top 1 m of soil (Lapenis et al. 2000). Despite this substantial loss of soil carbon from cultivated land, in Russia alone, Chernozems occupy 6,586,470 ha and contain about 130 to 160 t ha^{-1} of organic matter in the top 20 cm of soil (Mikhailova et. al 2000b.). A large reservoir of carbon is contained in the mineral soils throughout the world. Estimates fall between 1115 and 2200 Pg of carbon in the top 1 m of soil (Rustad et al. 2000, Trumbore 1997, Eswaran et al. 1993). This overshadows the biomass of plants by about three fold (Bashkin and Binkley 1998, Houghton et al. 1987), which is estimated between 560 and 835 Pg C (Bernoux et al. 2002, Bouwman 1990).

In the Kamennaya Steppe National Park, near the town of Voronezh, the Dokuchaev Institute has protected an area of land for over 100 years. This area contains pristine steppe, meadow steppe, planted forests and tilled fields. Before the cutting of the meadow steppe, planting of the forests and tilling of the fields, the entire area was covered with natural steppe vegetation. The land use of this area has been known since 1892 (Torn et al. 2002). By assessing these pieces of information together, a better understanding can be made about the effects of land use on weathering and soil carbon over time and more specifically, how total carbon, organic carbon and carbonate concentrations have been affected.

A common way to determine changes in land use over time is to compare modern samples of natural conditions to modern samples of different land uses in the area (Halvorson et al. 2002, Franzluebbers et al. 2000, Mikhailova et al. 2000b, Pulleman et al. 2000, Rodionov et al. 2001, Ross et al. 1999). This is done with the assumption that no change in carbon has occurred in the natural conditions over the period of time that has passed after the change in land use or that natural changes have affected all land uses equally. This assumption could lead to an inaccurate determination of change because it would not be known for certain whether just the change in land use caused the carbon concentrations in each land use plot to increase, decrease, or remain unchanged through time. If the actual initial conditions, representing a baseline for comparison, were known for each of the land use plots, a more accurate determination of change through time can be made (Cerri et al. 2004, Bernoux et al. 2002, Scott et al. 2002). This determination can be made with the use of archived samples. Modern samples can be compared to archived samples taken prior to the change in land use as well as samples taken in times between initial conditions and modern time to determine how much change has occurred. One disadvantage to this method is that archived samples are not that common, or are only a few decades old, which may not be enough time to show clearly the effects of land use change (Shevtsova et al. 2003, Lapenis et al. 2000, Hussain et al. 1999). The turnover time for organic carbon in soil is typically estimated on the order of a decade to a century (Trumbore 1997, Trumbore et al. 1996, Tate et al. 1995, Tate 1992, Jenkinson 1990, O’Brien 1984).

Another problem that is encountered when trying to determine the changes in carbon concentration is that much of the research that has been done only concentrates on the top layers of soil. This could lead to an underestimate of soil carbon (Mikhailova et al. 2000b, Davidson and Ackerman 1993).

A paper by Torn et al. 2002 showed that no change in soil carbon had occurred in the pristine steppe of the Kamennaya Steppe preserve for at least the past 100 years. An archived soil sample taken between 1895 and 1903 was compared to modern samples taken in 1997 to a depth of about 130 cm. The modern samples were taken at the same site as the archived samples by using precise field notes. The concentrations of carbon were similar between the archived and two modern pits. The carbon stock concentrations in the top 20 cm and the total profile varied by less than 6%. The soils contained 32-33 kg C/m^2. One third of that was in the top 20 cm and two thirds below that level. The difference in total nitrogen content or C:N ratio down the profile was not significant. Both the modern and archived soils had C:N ratios of 11 throughout the profile. Also, both ^{13}C and ^{14}C data showed that only the upper layer (10 cm) of soil had fresh organic matter from photosynthesis during the past 40 years. Below 10 cm, the organic matter has the deplete radiocarbon content of older, more recalcitrant material. The increase in ^{13}C/^{12}C ratio with increasing depth of the 100 year-old-soil showed that this pattern was not caused by fossil fuel dilution but by local processes. The shift in ^{13}C from the archived to modern samples showed that little of the currently observed ^{13}C pattern was due to the effect of fossil fuel emissions. The data showed that these soils have a large reservoir of recalcitrant carbon. It also showed that carbon stocks had not changed in the 100 years between sampling.

What makes the present study unique is having archived samples throughout the past 100 years in each of the various land use plots. Since it has been established that the pristine steppe of the Kamennaya Steppe preserve has remained undisturbed in the past 100 years, the change in carbon concentration can be shown in the meadow steppe, planted forest and tilled field using the archived sample from the pristine steppe as the baseline. Secondly, the progression of change in carbon concentration can be seen through time in each of the different land use plots.

The objectives of this study are to observe how these different land uses have affected the soil carbon of this region relative to natural conditions over a period of about 100 years. It is hypothesized that there should be an increase in organic carbon concentration in the meadow steppe and planted forest and a decrease in the tilled field in comparison to the pristine area. An increase in soil organic concentration is expected in the meadow steppe and planted forest because of the addition of new organic matter from the cut hay being left on the ground in the meadow steppe and from the maturing trees in the forest. The organic carbon concentration in the tilled field is expected to decrease because of increased decomposition and leaching. Secondly, compared to each other, the planted forest should have the highest carbon concentration followed by the meadow steppe, then the pristine steppe and finally the tilled field. The planted forest should add more organic matter from litter and roots than the addition of organic matter by the cut hay in the meadow steppe. Without the addition of organic matter as in the planted forest and meadow steppe, the pristine steppe should not change in concentration. The tilled field should have the lowest carbon concentration because of an increase in decomposition and leaching which will decrease the organic carbon concentration compared to the other three plots. The bulk density should increase or remain about the same in the meadow steppe, decrease in the planted forest and increase in the tilled field compared to the pristine area. The meadow steppe could possibly see an increase in bulk density due to changes in the soil from the hay being cut as well as people walking on the land. The roots in the planted forest may lead to a decrease in bulk density because of root growth over time. The roots will cause spaces as the roots move through the soil as well as when the roots die. In the tilled field, compaction is likely because of the soil disturbance and deterioration from the tilling. Carbon stocks (the amount of carbon) are expected to increase in the meadow steppe, increase or remain about the same in the planted forest and decreased in the tilled field compared to the pristine stock. If the carbon concentration and/or the bulk density increase great enough, the carbon stock in the meadow steppe and planted forest should increase. The tilled field will probably be dominated more by the decline in carbon concentration than by an increase in bulk density. Finally, it is expected that the carbonate concentrations, used as an indicator for weathering, will decrease due to an increase in precipitation in combination with natural weathering processes.

Soil Formation

Soil formation is the natural development of horizons in a profile (Donahue et al. 1977). The development is evident as organic matter accumulates, colloids are transported downward in the profile, and zones of clay, carbonate, iron oxide, humus, and/or gypsum accumulation develop. Russian soil scientists proposed that soil formation is the result of climate and living matter acting upon soil material on a given relief over a period of time. There are five factors of soil formation, parent material (passive), climate (active), biosphere (active), topography (passive), and time (neutral).

Rocks on the surface of the earth are weathered until enough of the essential elements become available to support lower forms of plant life. A process is then in place causing a buildup of organic matter, organic acids, and an increase in water retention. This process will cause the weathering of the rock to increase, which will lead to the formation of soil layers. Through time, mobile minerals and organic particles near the surface will be leached downward and some of them will be deposited a few inches below the surface. In a few hundred years, the leached surface soil layers and the accumulation layer in the subsoil may be well developed and contrasting in many characteristics. The kind of soil that develops depends in part upon the kind of rock present. Soils derived from limestone parent rock (half carbonates; half clays, silts, and sands) may develop loams or clay loams of high natural fertility.

Climate is the dominant factor in soil formation. The two main influences are precipitation and temperature. Some direct effects of climate on soil formation include salt accumulation due to insufficient rainfall, acidification due to intense weathering and leaching, and erosion and deposition in unstable landscapes. Moisture is important because a soil is said to be “formed” when it has detectable layers of accumulated clays, organic colloids, carbonates, or soluble salts that have been moved downward by water. An indirect effect of climate is through its action on vegetation. In humid climates forests are the dominant vegetation. The soil profile that develops in a forest has many more horizons than one that develops under grass. Semiarid climates such as the Russian steppe encourage only prairie grasses, and a deep, dark, uniform, surface soil results. Arid climates supply only enough moisture for sparse, short, plains grasses. In areas where temperature is high, weathering is mainly chemical decomposition and occurs most of the time. In contrast, weathering in cold climates can be enhanced by physical disintegration by the formation of ice (frost wedging).

The biosphere influences soil development in many ways. The most direct influence plants and animals have on soil development are the contents and distribution of organic matter, soil acidity, and the bulk density. Variations of this development due to vegetation differences can be seen frequently at the tree-grass boundary in Minnesota, Illinois, and Missouri, as well as most of the regions in the western half of the United States. Forest soils can contain more horizons, which usually include a well developed B horizon, have a more highly leached surface layer, and less decomposed organic matter at the surface compared to soils that were developed under grass vegetation. Grassland soils near the tension zone of forests typically have a deep (30 cm or more), dark A horizon under which are weakly developed subsurface layers. The B horizon can be very thin or absent. In large numbers, burrowing animals such as moles, gophers, earthworms and ants, can have a key part in soil formation. Continuous mixing within the soil profile will lead to the formation of fewer soil horizons. The functions of microorganisms in soil development are the decomposition of organic matter and the production of weak acids that dissolve minerals more readily than water.

Topographic influences on soil formation are closely linked to the water and temperature effects of an area. If the climate and parent materials are similar, a comparison among different topography can be seen. Steep hillsides on average will have thin A and B horizons due to rapid runoff, which doesn’t leave much time for the water to penetrate through the profile, and because of heavy erosion of the surface. A gently sloping hillside usually will display a deeper profile, abundant vegetation, and a higher content of organic matter. These features are primarily the result of differences in water movement through the soil. Depressions can contain soils with a large accretion of organic matter. This is because runoff waters converge from the surrounding elevated areas. This promotes high production of vegetation and high moisture content that can slow decomposition of the biomass. Organic soils like peat are formed when the soil surface is wet for many months of the year. A depression may become a salt marsh if the accumulating waters have dissolved salts from the nearby soils. Depending on the salt concentration, this can cause the growth of unique tolerant vegetation or no vegetation at all.

The length of time that it takes for a soil to develop horizons is associated with varying degrees of contribution from the previous four factors of soil formation. The rate of soil development is the effect of time in addition to parent material, climate, biosphere, and topography. Horizons tend to develop faster under warm, humid, forested conditions where there is enough water to move colloids, allow significant organic matter to decompose, and to weather minerals. A recognizable soil profile may develop within 200 years under ideal conditions, or may be prolonged to several thousand years if conditions are considerably less favorable. The main factors that slow down soil profile development include low rainfall, resistant parent material, very steep slopes, cold temperatures, and mixing by animals and humans.

Organic matter is an active and important portion of soil. Only about 1 to 5 percent organic matter is usually found in the top 25 cm of most cultivated soils. Even that small amount can change the physical, chemical and biological properties of the soil. Organic matter improves soil quality because it increases cation exchange capacity, increases porosity, improves water and air interactions, and reduces erosion by wind and water. Most of the nitrogen in soils comes from organic matter as do large percentages of the phosphorous, sulfur, boron, and molybdenum. To maintain soil productivity, organic matter must be replenished as it mineralizes.

Site Descriptions

The following site description is a summary as interpreted by Torn et al. 2002 due to some references being written in Russian. The area studied was the Central Chernozem Region of Russia, about 200 km east of Voronezh (Figure 1). Soil samples were collected from within the Dokuchaev Institute located in the Kamennaya Steppe National Park (Figure 2). The park is about a 5,000 ha watershed, isolated by the Chigla and Talovaya rivers. Within the preserve, the elevation is 200 m with gradual relief and has a mean annual temperature of 6.4°C. There has been an increase in average annual precipitation in the past 100 years from about 430 mm to 520 mm. The majority of this increase has been due to an increase in winter precipitation. The water table drops from 2 m below the surface in April to 5 m below the surface in mid winter. As with precipitation, the mean annual water table height has also increased over the past 100 years from about 7 m below the surface to about 3 m below. Since 1950 the wind speed has dropped from about 6 m/s to 3 m/s with an average wind speed of 4.5 m/s (Sentsova 2002). The grasslands in the area have been referred to as meadow steppe or Kamennaya steppe. The parent material of the Kamennaya region is brown-yellow carbonate loess and clay thought to have been deposited ~4,500-6,000 years ago during the mid-Holocene. Prior to protection, fields in this region were periodically grazed and burned. Vegetation was not managed (i.e., nothing was seeded) or tilled. Since establishment in 1882-1885, the preserve areas have been protected from tillage, grazing, and other land management changes that are now prevalent in the region. Fire frequency has been reduced in the region and the preserve since 1900. Dokuchaev implemented the planting of forest windbreaks (hedgerows) on the borders of fields in the Dokuchaev Institute area.

The preserve sites are characterized as moist Tipchak (fescue or feathergrass) steppe, analogous to the tall grass prairie of North America. Tipchak steppe was historically widespread in Russia, covering about 1.5 x 10^6 km^2. The vegetation is mainly herbaceous perennials with some encroachment of woody perennials. The dominant species inside the preserved steppe area were *Festuca sulcata* with *Knautia arvensis* (height 45-85 cm), *Veronica spicata* (15-20 cm) and *Sedum acre* (2-5 cm). Above-ground plant biomass is 100-120 g dry wt/m^2. All of the plant species identified from 1970 to 1992 use C_3 photosynthesis and no large changes in relative species abundance have been documented. Pollen analysis of the archived soil confirms that historic plant species also employed C_3 pathways. Therefore, the $\delta^{13}C$ signature of plant inputs is expected to be roughly -27‰, and there is no evidence for historical change in the isotopic content of plant inputs.

Methods

A summary of the methods and data available as described in the proceeding section are shown in Figure 3. Archived monolith HRSC 1900 (historic Russian soil collection 1900) (Figure 4) was taken sometime between 1895 and 1903. For ease, the sample year will be considered to be 1900. This archive is the reference sample representing the pristine, initial conditions of the study region prior to any land conversion. This monolith was labeled 'Kamennaya Steppe, Talovaya preserve.' The preserve is 24 ha in two areas, preserve #1 and #2, located 0.7km apart.

Starting in 1882 within a section of preserve #1, seasonal hay removal had been done yearly until 1912, after which hay was then cut and left on the ground. The other section of preserve #1 where monolith HRSC 1900 was taken as well as most of preserve #2 remained pristine. The land use referred to as the meadow steppe, has continued to undergo seasonal hay cutting that is left on the ground. In 1908, a forest was planted to serve as a windbreak in the preserve #1, by tilling the land and planting acorns. The planted forest measures 116 m wide and is a mix of 50% white oak (*Quercus alba L.*), 30% birch (*Betula bena*), 20% elm (*Ulmus americana*), less than 1% of red maple (*Acer rubrum*) and ash (*Fraxinus L.*). The land use referred to as the tilled field, continued to undergo seasonal hay cutting without hay removal between 1912 and 1920, at which time the field was then tilled for the first time. Since 1920, the field has continued to be tilled. Just prior to the first tilling in 1920, a monolith was collected in this land use plot and archived. Since the tilled field land use plot was still under the same land use as the meadow steppe in 1920, the archived sample taken prior to tilling can be used as an additional archived sample in the meadow steppe. The tilled field was planted with wheat (T*riticum estivum*) which is cut (only about 5-10 cm of stalk remains), collected and then plowed at the end of each growing season. The tilled field is separated from the meadow steppe by the planted forest.

In 1947, a monolith was collected within the planted forest, and archived. In 1970, a monolith was collected within the meadow steppe, and archived. All archived monoliths were stored air dried, in dust proof wooden boxes in a horizontal position (Torn et al. 2002). In 1995, sub samples were taken from each archived monolith by removing a vertical slice (approximately 5 x 2.5 cm) of the profile from the right-hand side of the monolith (Torn et al. 2002, Lapenis et al. 2000).

In 1997, one soil pit was sampled in the pristine area of preserve #1 and one pit in preserve #2. The sample taken in preserve #1 (HRSC 1997) was in the vicinity of archived monolith HRSC 1900 (Torn et al. 2002). In 1998, the meadow steppe, planted forest, and tilled field (Figure 5), were also resampled. Two pits were dug in each of the different land use types. Pits 2 and 3 (Figure 6a), were dug in the meadow steppe, pits 4 and 6 (Figure 6b), were dug in the planted forest, and pits 9 and 10 (Figure 6c), were dug in the tilled field. These samples were also taken in close proximity to the sampling location of their respective archived monoliths. To be as precise as possible when resampling, detailed field notes were used to find the locations where the archived monoliths were taken. Figure 7 and Table I shows the different land use plots and the locations of the modern sampling.

The sampling of the modern soil pits was done by digging down to a depth of 2 m. Beginning at the bottom of the pit, a rectangular channel the entire thickness of the chosen depth interval was collected. Two separate sets of samples were taken; one went to Lawrence Berkeley National Laboratory, Berkeley, CA and the other to The University at Albany, NY.

The samples sent to Lawrence Berkeley National Laboratory were oven dried at 60^oC for 48 hours. Large identifiable plant material was removed from the soil before the sample was passed through a 2 mm sieve. The samples were then ground with metal bards on a roller mill for one week followed by grinding with a mortar and pestle. Carbonate removal for the analysis of organic carbon was done by hydrochloric acid fumigation as described in Harris et al. 2001 with slight modifications to the method. Total carbon and organic carbon concentrations were analyzed using a Carlo Erba NA 1500 Carbon and Nitrogen analyzer interfaced with a Micro Optima Mass Spectrometer.

Both the modern and archived samples sent to The University at Albany were stored in plastic bags and kept cool or refrigerated until being oven dried at 70^oC. They were then passed through a 2 mm sieve. The total carbon concentration of the soil was measured with a Carlo Erba EA1110 CHN Elemental Analyzer. Approximately 25 mg of air dried sample was used in the total carbon analysis. Sample weight did not affect reproducibility. Total carbon concentration had values of 70.38 ± 1.63% for the quality control sample, 1.78 ± 7.57% for the standard reference sample, and an average relative standard deviation of 2.32% for 11 sets of triplicates. The triplicates were three separate analytical runs from the same soil sample that were run in sequence.

Soil core samples of known volume were taken at various depth intervals and dried to calculate the bulk density of the modern pits (Table II). Bulk Density data was not available for the archived samples from each of the different land use plots. The bulk density for HRSC 1900 is assumed to be the same as in the modern samples taken in

1997 due to there being a close match in horizons and carbon concentration (Torn et al. 2002). Carbon stocks were calculated by depth interval using a weighted carbon concentration, interval depth, and bulk density. Volumes were summed to a depth of 20 cm, 50 cm and 100 cm to express carbon contents in kg/m^2 (Table III).

This study utilized two data sets. Data set 1 (Table IV), consisted of total and organic carbon concentrations for the modern samples (pits 2, 3, 4, 6, 9, 10) and organic carbon concentrations only, for HRSC 1900. Organic carbon was measured directly by treating samples with hydrochloric acid to remove carbonates prior to analysis. This data set was obtained from Margaret S. Torn and Asmeret Berhe from Lawrence Berkeley National Laboratory, Berkeley, CA.

Data set 2 (Table V), consisted of total carbon and estimated carbonate concentrations for both modern samples (pits 2, 3, 4, 6, 9, 10) and archived samples collected in the meadow steppe in 1970, the planted forest in 1947, and the tilled field in 1920. Carbonate estimates were obtained from Andrei G. Lapenis from The Department of Geography and Planning, University at Albany, NY. To estimate carbonate concentration a total digest was done on all samples. The samples were digested by microwave-assisted hydrofluoric acid digestion (EPA method 3252). Samples were then analyzed on a Varian Vista ICP. Using the calcium and magnesium (the two primary cations in carbonate loess, the parent material of this soil) concentrations from the total digest, in addition to exchangeable calcium and magnesium, an estimate of carbonate concentration was calculated. This carbonate estimate was then subtracted from the total carbon concentration to give an estimate of organic carbon concentration because organic carbon was not analyzed directly in this data set.

The soil depth of 0 cm corresponds to the top of the mineral layer and increasing depth was indicated positively. The modern samples were collected at depth intervals from the top of the mineral soil down to about 115 cm for data set 1 and down to about 145 cm for data set 2. The archive samples were collected at intervals from the top of the mineral soil down to about 100 cm.

Of the two modern sample pits dug in each of the three land use plots, one of the two pits was chosen to represent that particular land use, pit 2 in the meadow steppe, pit 6 in planted forest, and 10 in the tilled field. One representative pit was chosen because the sampling depths between the two pits did not correspond to each other and therefore were not averaged together. In addition, the variability among the two pits should be consistent therefore choosing one pit should not make a difference when used in comparisons. To assess variability within land use types, data from the two pits were plotted together versus depth for each different land use (Figure 8 and Table VI). To facilitate comparison between the pits, the depth intervals were combined by averaging, to provide the best match.

Data set 2, along with HRSC 1900 from data set 1, were used in the comparisons of the different land use types. The smaller sampling depth intervals in the modern samples in data set 2 (Table V) possibly give a more accurate account of carbon present in the varying sections of the profile compared to the larger sampling depth intervals in data set 1 (Table IV). This is not necessarily the case in all soils. Depending on the variability of the soil, larger depth intervals may also provide the results similar to smaller depth intervals.

Although, directly measured concentrations would be preferred for use in a data set as opposed to using estimated concentrations, in this particular study the measured organic carbon from data set 1 was questionable because the organic carbon concentration was higher than the total carbon concentration, in the upper part of the profile (Figure 9). The main reason for this is due to the method used. The method is moderately accurate in addition to there being compounded experimental error.

To check the similarity between carbon concentrations of the modern samples of data set 1 and data set 2, organic carbon (Figure 10), and total carbon (Figure 11) concentrations were plotted. To make a better comparison between the two data sets, depth intervals from data set 2 were combined to correlate more to the respective depths in data set 1 (Table VII). The organic carbon profiles for data set 2 follow a more typical trend than those for data set 1. In each case, data set 2 has a higher organic carbon concentration than data set 1 in the upper part of the profile and a lower concentration in the bottom part of the profile. The total carbon concentrations of data set 2 are greater than those of data set 1, with the exception of the interval in the meadow steppe from about 62-82 cm depth. The difference is particularly distinct in Figure 11b. The unusual trends with depth in data set 1 further support the use of data set 2.

Results

For each of the three land use plots, samples from the two modern pits yielded similar organic carbon concentrations at most depths (Figure 8). Slight differences were seen in each plot. In the meadow steppe (pits 2 and 3), the largest difference between the two plots was found between the depths of 45-80 cm. In the planted forest (pits 4 and 6), a small difference was seen down the entire profile with a maximum difference at about 10 cm. In the tilled field (pits 9 and 10), the greatest difference was at around 40 cm.

A threshold was identified at the point where the carbonate concentration increased rapidly with increasing depth (Figures 12-17). Above the threshold, the carbonate concentration was around 0.5 % with little variation in both the modern and archived pits. In the modern pits, the thresholds of carbonate concentration were similar to each other and fell between the ranges of 63-73 cm depth with a variation of only a few cm. The exception to this was in the tilled field where the threshold of pit 9 was 88 cm depth. The thresholds in the archived samples were also similar to each other and fell between the ranges of 43-48 cm with a variation of only a few cm (Figures 15, 16, 17). In the archived pits, there were slight variations in carbonate concentration down the profile. In particular around 60 cm where the tilled fields archive decreased rapidly. Over time, all the thresholds moved farther down the profiles and showed a decrease in carbonate concentrations (Figures 18 and 19). The concentration of carbonate in the meadow steppe (pit 2) below the threshold was less than in the planted forest (pit 6) and the tilled field (pit 10).

Above the threshold, the total concentration of carbon is dominated by organic carbon and this feature changes abruptly below the threshold (Figures 12-17). This is shown in both the modern and archived pits. Below the threshold, the organic carbon concentration continues to decrease in contrast to the total carbon concentration which increases greatly due to the increase of carbonate concentration. For the modern pits, the concentration of organic carbon and total carbon plot closer together than for the archived pits. For both the modern and archived pits, the trend of the organic carbon concentration decreases down the profile at a generally consistent rate. The total carbon decreases steadily down the profile until reaching the threshold where is increases rapidly. In the tilled field (pits 9 and 10) this pattern is not followed within the first 40-45 cm. Instead, the carbon concentrations in this interval remain about the same with little variation.

The organic carbon concentration of the three modern pits was plotted along with archived sample HRSC 1900 versus depth (Figure 20). In the first 30 cm of the modern pits, the planted forest (pit 6) had the highest carbon concentration followed by the meadow steppe (pit 2) and the lowest in the tilled field (pit 10). The reference pit, archived sample HRSC 1900, had the highest carbon concentration in the first 10 cm and then plotted close to the planted forest (pit 6) for the majority of the profile. In the tilled field, pit 10 has little variation in the organic carbon concentration to about 35-40 cm before decreasing down the profile. In the planted forest, pit 6 and archived sample HRSC 1900 decreased in organic carbon concentration rapidly in the first 20 cm. In the first 10 cm, the planted forest (pit 6) has about twice the concentration as the tilled field (pit 10). From about 30-40 cm, all the pits converge together before the tilled field (pit 10) decreases more than the others and continued with the lowest concentration down the profile. Below the first 40 cm, the meadow steppe (pit 2),the planted forest (pit 6), and archived sample HRSC 1900 plot close to each other for the remainder of the profile.

With the exception of the upper 40 cm of the tilled field (pit 10), the organic carbon concentration of archived pit HRSC 1900 follows the same general trend as the modern samples as the depth increases down the profile.

To see the changes in organic carbon concentration over time for each land use plot, the archived pits and modern pit were plotted together versus depth (Figures 21, 22, 23). In the meadow steppe (Figure 21), archived sample HRSC 1900 had the highest organic carbon concentration in the first 25-30 cm, followed by modern pit 2, then the archived sample from 1970, and finally the archived sample from 1920. Below 20 cm, pit 2 and archived sample HRSC 1900 plot close to each other and follow the same general trend. Archived samples from 1920 and 1970 also follow this trend, but remain lower in concentration except around 40 cm, where pit 2, the 1970 archived sample, and archived sample HRSC 1900 converge. At around 95 cm, the 1920 archived sample converges with the other plots. Archived sample HRSC 1900 has the greatest decrease in organic carbon concentration in the upper 20 cm. There is not much change between these pits since 1970. There was a very large decrease in organic carbon concentration down to about 25 cm in the 1920 archive compared to the archive HRSC 1900. Below this depth, the 1920 archived sample remains at about half the concentration of archived sample HRSC 1900 until around 80 cm.

In the planted forest (Figure 22), modern pit 6 and archived sample HRSC 1900 plot close together and follow the same trend down the entire profile. Around 30 cm, the 1947 archived sample begins to follow the same trend. The 1947 archived sample has almost half the concentration of organic carbon than the other two pits to about 10 cm, and maintains the lowest concentrations throughout the profile. Pit 6 and archived sample HRSC 1900 decrease in organic carbon concentration at a much faster rate then the 1947 archived sample. At a depth of about 80 cm, all the plots come together for the remainder of the profile.

In the tilled field (Figure 23), archived sample HRSC 1900 has the highest organic concentration in the upper 30 cm, followed by modern pit 10, and then the 1920 archived sample. Archived sample HRSC 1900 has about twice as much organic carbon concentration as the other two pits until about 10 cm. The 1920 archived sample has the lowest concentration until about 90 cm where all three plots converge. The trends are relatively similar after about 40 cm, in particular pit 10 and the 1920 archived sample. For the first 40 cm, modern pit 10 has little variation in organic carbon concentration.

Overall, the modern pits had a greater concentration of organic carbon than the archived samples from their respective land use plots. The planted forest had the greatest difference of organic carbon concentration between its modern pit and corresponding archive. Archived sample HRSC 1900 had the greatest concentration in the uppermost part of the profiles and in some cases farther down the profiles as well. The organic carbon concentrations for all of the pits decreased down the profile and were at low concentration of about 0.5% or less at the bottom of the profile.

The bulk density in the pristine plot steadily increases with depth (Figure 24). The bulk densities of the modern land use plots also increase with depth but more slowly and over a shorter range compared to the pristine plot. In the upper 50 cm, the modern plots have a higher bulk density than the pristine plot. The bulk densities in the top 20 cm fall in the range of 0.5-0.8 (g/cm^3) and 0.8-0.9 (g/cm^3) in the pristine and modern plots respectively. The tilled field has the highest bulk density in the first 10 cm, followed by the meadow steppe, then planted forest and finally the pristine plot. The bulk density for both the meadow steppe and planted forest increase in the first 35-40 cm, whereas the tilled field remains about the same. The meadow steppe and planted forest follow the same general trend down the length of the profile.

The total carbon stocks in the upper 20 cm of the modern plots decreases in order from the meadow steppe (10.50 kg/m^2), to planted forest (10.45 kg/m^2), to tilled field (9.19 kg/m^2) (Figure 25). The organic carbon stocks in the upper 20 cm of the 1900 pristine plot and the modern plots decreases in order from the 1900 pristine plot (10.10 kg/m^2), the meadow steppe (9.75 kg/m^2), planted forest (9.66 kg/m^2), and tilled field (8.27 kg/m^2) (Figure 26). Compared to the pristine organic carbon stock, the meadow steppe, planted forest and tilled field show changes of -3.5%, -4%, and -18% respectively. The organic carbon stocks in the upper 50 cm of the 1900 pristine plot and modern plots range in order from the meadow steppe (21.48 kg/m^2), to the 1900 pristine plot (20.97 kg/m^2), to planted forest (20.54 kg/m^2), and the tilled field (19.82 kg/m^2) (Figure 27). Compared to the pristine organic carbon stock, the meadow steppe, planted forest and tilled field saw changes by +2.5%, -2%, and -5.5% respectively. The total carbon stocks in the modern plots down to 1 m range in order from the highest in the meadow steppe (40.22 kg/m^2), to planted forest (36.64 kg/m^2), and tilled field (34.67 kg/m^2) (Figure 28). The organic carbon stocks in the 1900 pristine plot and modern plots down to 1m, decreased in order of the meadow steppe (31.42 kg/m^2), the 1900 pristine plot (30.99 kg/m^2) planted forest (27.96 kg/m^2), and tilled field (26.88 kg/m^2) (Figure 29). Compared to the pristine organic carbon stock, the meadow steppe, planted forest and tilled field saw changes by +1%, -10%, and -13% respectively. The top 20 cm, contained one third of the organic carbon and about a quarter of the total carbon in the 1 m profiles.

Discussion

Carbon Concentration

The similarity of the replicate modern pits (Figure 8) indicates limited variability within the area of each land use type where the samples were taken, which made it possible to choose one pit to be representative for each land use plot. The variation that is shown could be due to slight natural variability and the association with the location of the pit to the surrounding area (i.e. Pit 2 is closer to the planted forest, Figure 7).

The low concentration of carbonates in the upper part of the profile shows that the majority of carbonates have been weathered away in this part of the profile (Figure 19). The similarity in the carbonate concentrations in the upper 45 cm of the modern and archived samples show that little additional weathering of carbonates has taken place to this depth over time likely because the carbonates were already weathered away prior to the sampling of the archived samples. The downward progression of weathering is shown by a deepening in the carbonate thresholds in the modern profiles compared to the thresholds of the archived profiles. In addition, the concentrations of carbonates have decreased in the modern samples below the thresholds of the archived samples. Weathering processes are responsible for the downward movement of the carbonate threshold (Schlesinger 1997). The rate of downward movement was likely increased by the increase in precipitation of this region. Variations in carbonate concentration may in part be related to the carbonate concentration being estimated using total digest data as well as slight natural variability. The cause of the unusual trend of carbonate concentration in the 1920 archived sample below about 65 cm is not known but may be due to an irregularity in the profile formation in that particular location.

Organic carbon is the primary form of carbon in the upper profile above the carbonate threshold (Figures 12-17). In both the archive and modern plots, there is a general decreasing trend in organic carbon concentration throughout the profile to about 0.5% or less at 1 m depth. The highest concentration of organic carbon is at the top of the profile because that is where most new organic matter is introduced into the soil (Raich and Nadelhoffer 1989). Also, with depth, less and less organic matter is present because of its limited mobility in the soil (Buol et al. 1980). In modern tilled field pits 9 and 10, the decreasing trends in carbon concentration are not seen until below 40-45 cm due to the effect of mixing caused by tilling. Below the carbonate threshold, the organic carbon concentration continues to decrease whereas the carbonate and total carbon concentrations increase. There is a noticeable separation between the organic and total carbon concentrations because of the increase in carbonate concentration. The total and organic carbon concentrations in the modern samples plot closer together compared to the plots of concentrations of the archived samples due to the decrease in carbonate concentration over time. This is further evidence that carbonate has been weathered away throughout the profile. The decrease in total carbon concentration with depth is a combination of both weathering and the decrease in organic carbon concentration.

Meadow Steppe

Twenty years of hay cutting, substantially decreased the organic carbon concentration down to 80 cm. This would be expected because of the removal of aboveground biomass during each growing season up until 1912. Also, the hay removal will allow more precipitation to infiltrate the soil because the biomass will not uptake as much of the precipitation, in addition to more precipitation making it to the ground. This will lead to the leaching of organic matter as well as quicker decay. After 1912, the organic carbon concentration probably began to increase since the hay that was cut was left on the ground. This would allow for some of the biomass to return to the soil. Over the next 50 years, the organic carbon concentration increased and continued to increase slightly for the next additional 18 years after that (Figure 21). One possible reason for this increase in carbon concentration is most likely that the 68 years of leaving the hay on the ground caused an accumulation of carbon throughout the profile. The crop removal resulted in a large decrease in organic carbon concentration that did not fully recover to initial conditions by 1998. The 1970 archived sample and modern pit 2 sample were not taken in the exact same plot as the 1920 archived sample. After 1908, the forest was planted between these sampling areas. There may have been an effect from this causing an accumulation of carbon within the top 70 cm. Finally, it is also possible that because of the distance between sampling sites, there could have been slight variations in the soil that may have added to this increase although this was probably minimal contribution. Below 20 cm, the concentrations were similar to the original conditions of the pristine steppe.

Planted Forest

Prior to the establishment of a new forest plantation, there can be considerable effects on soil carbon due to site preparation (Johnson 1992). Within the first 39 years of being planted, the organic carbon concentration in the forest decreased by about half compared to the pristine plot (Figure 22). The main contributing factors to this decrease were probably the crop removal that started in 1882 up to 1908, followed by tilling, in preparation for the planting of acorns. Smethurst and Nambiar 1990 found about a 40 % decrease in soil carbon over three and a half years with a windrow and plough preparation. As in the meadow steppe, the crop removal prior to 1908 would cause the organic carbon to decrease due to the removal of biomass and increased decomposition and leaching. This decrease would be magnified because of the tilling, which has also been shown, leads to a decrease in organic matter (Cambardella and Elliot 1992, Tiessen and Stewart 1983, Haas et al. 1957, Jenny 1941). As a constantly new supply of organic matter is introduced into the soil from leaf matter, carbon is being decomposed. Turner and Lambert 2000 found that plantation growth does not offset the net decline in soil organic carbon for at least nine years and possibly more than twenty.

Within the next 41 years, the organic carbon concentration increased to a level almost identical to the initial conditions shown by archived sample HRSC 1900. Soil carbon usually increases substantially where former agricultural sites are reverted to forests or where newly developing soil undergoes afforestation (Johnson 1992). Many studies that have taken place over long periods of time (> 50 years) have shown these results (Bashkin and Binkley 1998, Jenkinson 1991, Lugo et al. 1986, Jenkinson 1970, Wilde 1964). An increase is expected once the forest has been established for a long enough period of time, due to the introduction of new organic matter from the decomposition of litter and root matter (Raich and Nadelhoffer 1989). As the trees grow, the belowground root mass will increase. An increase in root mass will increase the uptake of water and hold the soil together which will decrease the amount of leaching and erosion of the soil. As organic carbon inputs from various sources begin to exceed the processes of outputs, soil organic carbon will begin to increase in concentration.

Tilled Field

For 30 years prior to 1912, the tilled field area underwent seasonal hay removal followed by 8 years of seasonal cutting of hay that was left on the ground. The crop removal caused a decrease in organic carbon for reasons previously discussed which can be seen from the archived sample taken in 1920 (Figure 23). The initial decrease was probably slightly larger than what is seen in 1920 because organic carbon was most likely added to the soil between 1912 and 1920. This can not be proven for sure since there are no archived samples between 1900 and 1920. The same year that the 1920 archived sample was taken, annual tilling of the field began for wheat production. Since this area underwent a change in land use prior to tilling, the archived sample taken in 1920 essentially represents the new starting condition to which modern pit 10 can be compared.

Over the next 68 years, the organic carbon concentration increased. From 30-40 cm and below 70 cm, the increase in organic carbon concentration was restored to the conditions of the pristine steppe. Below the tilling depth (40 cm), the organic carbon in modern pit 10 followed the same general trend as the pristine plot. The increase in organic carbon concentration from 1920 to 1998 is somewhat of an anomalous result. Many studies have shown that cultivation of grasslands have led to a loss in soil organic matter (Burke et al. 1995, Cambardella and Elliot 1992, Johnson 1992, Burke et al. 1989, Aguilar et al. 1988, Tiessen and Stewart 1983, Haas et al. 1957, Jenny 1941). In the

Great Plains and Corn Belt regions of the Central United States, conversion of native ecosystems to agricultural lands has significantly reduced the organic matter from soils across these regions (Barnwell et al. 1992, Campbell 1978, Wilson 1978, Haas et al. 1957). Reasons for this loss are plant residue inputs are decreased while outputs such as erosion and decomposition through physical mixing are increased, soil aggregates are degraded, and finally there is enhanced contact of litter and inter-aggregate organic matter with decomposing organisms (Robles and Burke 1997, Burke et al. 1995, Doran and Werner 1990, Tivy 1987, Elliot 1986, Anderson and Coleman 1985, Tiessen et al. 1982, Van Veen and Paul 1981). Based on the land use history in this plot, it should follow that the organic carbon should undergo these same types of processes, leading to a decrease in organic carbon concentration.

The most probable reason that the tilling did not further decrease the organic carbon concentration is the planting of the adjacent forest as a windbreak. Windbreaks have been used for many years because of the benefits that they provide (Kuhns 1998, Kort 1988, Sutherland 1986, Howe 1986, Gade 1978). These benefits include reducing soil erosion, improving moisture by trapping snow, and increasing crop yield (Kuhns 1998, Howe 1986, Russell and Grace 1979, Gade 1978, Bates 1911). In the early 1900's this area was drier and more susceptible to erosion by wind and water (Torn et al. 2002, Ivanov 1991). Erosion removes vast amounts of soil (including organic carbon) each year especially in agricultural land causing a reduction of productivity (Kuhns 1998, Pimentel et al. 1995, Myers 1993, Lal and Stewart 1990). Wind and water erosion will reduce the quality of the soil by decreasing infiltration rates, water-holding capacities, nutrients, organic matter, soil biota and soil depth (Pimentel et al. 1995, Troeh et al.

1991, El-Swaify et al. 1985, Office of Technology Assessment 1982). With the decrease in infiltration rate and water capacity, the amount of runoff will increase leading to a decrease in soil moisture (Kuhns 1998). In this particular case, wind is the main form of erosion. The land in this area is relatively flat so water erosion is less important to the removal of organic carbon. Repeated tilling removes vegetation that can act as a protective cover to help reduce erosion (Pimentel et al. 1995). As the forest windbreak matures and trees grow taller and thicker, the amount of erosion would decrease. This growth would provide protection from wind as well as allow for the trapping of snow.

For the past 100 years, the precipitation in this area has increased, most of which occurred in the form of snow (Torn et al. 2002, Ivanov 1991). In areas that receive a significant portion of precipitation from snowfall, the trapping of snow can be important. The additional moisture from trapped snow, can aid in crop growth during dry years (Agriculture and Agri-Food Canada 2003).

The decrease in soil erosion and the increase in soil moisture resulting from the protection of the windbreak will lead to a higher crop yield. Crop protection can lead to as much as a 44% increase in crop yield (Kuhns 1998). An increase in crop yield would give rise to more organic matter being added to the soil and increasing organic carbon concentrations.

Another consideration besides the crop yield itself is the type of crop. After 1920, the natural grass vegetation was replaced with wheat as the new cover crop. The change from grass vegetation to wheat vegetation may have influenced the crop yield as well as the amount of organic matter that would be added to the soil.

These preceding factors could have overshadowed the effects of tilling, and as a result led to an increase in organic carbon concentration in the tilled field rather than an expected decrease.

In the upper 40 cm of the profile, the organic carbon concentration was relatively constant. This is the result of mixing due to tilling and the depth at which the concentration remains constant is representative of the tilling depth. Below this depth, there is a decrease in organic carbon. This decrease is partially due to the crop removal over time not contributing much new organic carbon to the soil. Also, the increase in precipitation over the past 100 years could be a contributing factor. Although the bulk density has increased over time, the fresh tilling of the soil could lead to a temporary decrease in bulk density. This temporary decrease in bulk density could allow for better infiltration of water which would cause an increase in leaching.

Carbon Stocks

A change in carbon stocks can be influenced by a change in land use or land cover (Guo and Gifford 2002, Bolin and Sukumar 2000). With the additional consideration of time, the effects on carbon stocks of these changes can vary in magnitude (Scott et al. 2002, Jenny 1980, Syers et al. 1970). Many studies have been done investigating the effects of different land use changes on carbon stocks (Guo and Gifford 2002, Scott et al. 2002, Neill and Davidson 1999, Scott et al. 1999, Lal et al. 1998, Johnson 1992). Since there was no total carbon data for the pristine plot, only the total carbon stocks of the modern land use plots could be compared to each other. In the top 20 cm of the profile, the meadow steppe and planted forest had about the same content of total carbon while the tilled field had about 12% less (Figure 25). To a depth of 1 m there was a more distinct difference. Compared to the meadow steppe which had the highest total carbon content, the planted forest and tilled field contained about 9% and 14 % less total carbon respectively (Figure 28). The top 20 cm contained a quarter of the total carbon in the 1 m profiles. This is because there is more carbonate in the lower half of the profile that is being taken into account whereas carbonate is not as big an influence in the top half of the profile. The greater differences between the three land use plots down to 1 m are a result of the differences in total carbon concentration and bulk density.

In the top 20 cm, the organic carbon stock has decreased in each land use plot compared to the pristine plot. The largest decrease was in the tilled field by about 18%. The meadow steppe and planted forest plots decreased by less than 5% (Figure 26). The organic carbon stock down to 1 m gave different results. Compared to the pristine plot, the meadow steppe increased by less than 2% while the planted forest and tilled field decreased by 10% and 13% respectively (Figure 29). Overall, the most significant change in carbon stocks compared to the pristine plot was in the tilled field. The planted forest showed only a slightly significant change in organic carbon stock down to 1 m. Estimates based on ecosystem modeling, have shown that at least half of the organic matter in the top 0-20 cm after disturbance are in fast-cycling carbon pools (Trumbore et al. 1996, Townsend et al. 1995, Schimel et al. 1994, Davidson and Ackerman 1993). Given that the majority of organic matter is added in the upper section of a soil profile, it is understandable that the top 20 cm contained one third of the overall organic carbon in the profile. This agrees with results found in the pristine plot by Torn et al. 2002.

Bulk Density

The bulk density in each land use plot increased compared to the pristine plot. The most likely reason for this increase in the meadow steppe was probably the continued cutting of the hay. Since the area would be traveled on to remove the hay, it would make sense that the ground would become more compact. The planted forest was expected to decrease because of the continued growth of roots leaving spaces in the soil. Increased precipitation and the added weight of the trees as the forest matures could be possible reasons for the bulk density increase. Another consideration could be the type of undergrowth vegetation. The soil may have become more compacted because of smaller root systems and increased precipitation. Although the bulk density in the planted forest did increase, in the top 20 cm, it had the smallest increase in bulk density compared to the other two land use plots. The bulk density in the tilled field was expected to increase. This is mainly due to the temporary decrease in bulk density as a result of tilling causing the soil to be more easily compacted. Over time, the increased precipitation, soil degradation, and the tilling process would cause this compaction.

Meadow Steppe

The meadow steppe showed an increase in organic carbon stock compared to the pristine plot, as well as having a larger stock than the planted forest and tilled field in the first 1 m of soil. Although earlier land use consisted of hay removal from 1882 until 1912, which most likely led to a decrease in organic carbon, after 1912 hay was allowed to remain on the ground after being cut. This most likely led to an accumulation of organic carbon for various reasons. First, by allowing the cut hay to remain on the ground, it will start to decompose and contribute new organic matter to the soil. Another source or organic matter is from the remaining stalks. Once the hay has been cut, the stalks that are still planted in the ground will die and decompose. This will also cause the roots to decompose. Since grasslands have a large root mass, this addition is important to the input of soil organic matter. Finally, the bulk density has increased in the top half of the profile compared to the pristine plot. This, in addition to a rising organic carbon concentration, would result in a greater carbon stock.

Planted Forest

The planted forest had a slightly significant loss in organic carbon stock compared to the pristine plot in the first 1m of soil. It also had a lower concentration than the meadow steppe but a larger concentration than the tilled field. It is commonly thought that afforestation, especially after conversion from degraded soils, will act as a carbon sink (Lal 2004, Perruchoud et al. 2000, Bouma et al. 1998, Dixon et al. 1994, Johnson 1992). Previous studies have shown varying results in the organic carbon stock in planted forests (Kelly and Mays 2005, Hooker and Compton 2003, Guo and Gifford 2002, Johnson 1992). A decrease in soil organic carbon concentrations were found by Knoepp and Swank 1997 and Hamburg 1984. Increases were found by Hooker and Compton 2003, Richter et al. 1999, and Jenkinson 1991, 1970. No Changes were found by Trettin et al. 1999. Johnson et al. 1988 found both no change as well as an increase. Finally, Guo and Gifford 2002 found a decrease and no change in soil organic carbon.

The types of tree species as well as the previous land use are influential in the resulting carbon stock (Turner and Lambert 2000, Turner and Kelly 1977). Pastures converted under pine plantations showed a decrease in soil carbon stocks while under broadleaf or naturally regenerated secondary forests carbon stocks were unaffected (Guo and Gifford 2002). In a forest dominated by mixed oak with previous agricultural land use, soil carbon content increased at a rate of about 0.542 Mg C $ha^{-1}yr^{-1}$ (Hooker and Compton 2003). In 100 red pine plots of varying age planted on former agricultural land showed an increase in soil organic matter (Wilde 1964).

There are several reasons that a decrease in organic carbon stock in the planted forest was seen compared to the pristine plot. Prior to planting, the land underwent hay removal followed by tilling. This disturbance from the establishment of the plantation may have led to a loss in soil organic carbon. Site preparation and tree planting can disturb soil structure, breaking up soil aggregates and can lead to carbon leaching as well as an increase in decomposition (Guo and Gifford 2002, Turner and Lambert 2000). This initial disturbance would only lead to a deficit in carbon stocks, that would increase the amount of carbon needed to be accumulated to return to the original level. After the forest is planted, carbon content will increase due to inputs of organic matter from litter and root turnover (Turner and Lambert 2000) possibly leading to restoration of initial conditions.

The main reason for the overall carbon loss in the planted forest is most likely due to the lower root production in the forest compared to the pristine grassland (Guo and Gifford 2002, Cerri et al. 1991). In tussock grasslands in New Zealand, up to 50% of the carbon input can be from roots (Tate et al. 1995, Meurk 1978). The distribution of soil organic carbon in the top meter of soil is deeper in grasslands than in forests (Guo and Gifford 2002, Jobbagy and Jackson 2000, Tate et al. 1995). Although there may be a higher content of organic matter in the form of litter in forests, it is more susceptible to decomposition and is not distributed far down the soil profile (Guo and Gifford 2002, Tate et al. 1995, Tate et al. 1993). The input of organic matter from tree roots is not as great of an influence as grass roots due to a slower annual turnover of dying tree roots, and could therefore lead to a decrease in soil organic carbon (Guo and Gifford 2002, Post and Kwon 2000).

Since there was a similar concentration of organic carbon in the pristine plot and the modern sample from the planted forest (Figures 20 and 22), bulk density also contributed to the overall decrease in carbon stock in the planted forest. In the top 50 cm of the profile, the bulk density of the planted forest was greater than the pristine plot and thus led to a higher carbon stock (Figure 24). The pristine plot in the lower 50 cm was greater in bulk density than the planted forest and by a greater margin than the difference seen in the upper 50 cm. This led to an overall greater carbon stock in the pristine plot (Figure 27).

Grasslands contain a higher portion of stable organic matter throughout the profile which supplies plant nutrients, increases cation exchange and water holding capacities (Guo and Gifford 2002, Tate and et al. 1995, Anderson 1991, Miller and Donahue 1990). Soil under the snow tussocks in New Zealand was wetter than in the forest which favored organic carbon accumulation (Tate and et al. 1995). The preserve area has over the years increased in precipitation, most of which was in the form of snow (Torn et al. 2002, Ivanov 1991).

Tilled Field

The tilled field had the greatest and most significant loss of organic carbon in the first 1 m of soil compared to the pristine plot, meadow steppe, and planted forest. Many studies have been done showing that cultivation reduces the soil organic matter storage of soils (Miller et al. 2004, Haas et al. 1957, Hide and Metzer 1939, Jenny 1941, 1933, Alway 1909). Schlesinger 1984 estimated that globally 0.8 x 10^{15}g C/yr may be lost from cultivated soils. When tillage occurs it allows for the soil organic matter to become incorporated into conditions that allow for more rapid decomposition (Halvorson et al. 2002, Doran 1980). These include greater moisture content, aeration, leaching of soluble organic carbon, and exposure of stable adsorbed organic matter by the break up of aggregates (Schlesinger and Andrews 2000, Gregorich et al. 1998, Six et al. 1998, Elliot 1986). Halvorson et al. 2002 found that in comparison to other tilling methods, no-till techniques had the greatest amount of accumulation of soil organic matter in the top 15 cm. It has also been shown that the use of no-till techniques used on previously cultivated land could restore soil organic matter (Schlesinger and Andrews 2000, Campbell et al. 1999, Wood et al. 1991, Dick 1983).

An increase in the rate of decomposition is not the only case that can lead to a loss in soil organic carbon. The opposite may also contribute. Tilling soil can lead to erosion, crusting, compaction, reduction in water infiltration capacity and water/air imbalance leading to anaerobiosis. Soil degradation can result in lower biomass productivity by depleting nutrients, increasing soil acidity, and causing a build up of salts in the root zone (Lal 2004).

The disturbance of belowground biomass may also have contributed to the loss in organic carbon. Belowground biomass is an important part of total soil organic carbon and carbon dynamics in grassland soils (Slobodian et al. 2002, Gale and Cambardella 2000, van Ginkel and Gorisson 1998). A study by Slobodian et al. 2002 showed that within prairie grassland, belowground biomass was significantly higher than in a cultivated field. Also the density of plants in the prairie was greater than in the cultivated field. Root systems in prairie grasslands are more developed compared to annual crops due to the perennial nature of grassland species as well as having a longer growing season and not having their roots disturbed by tillage (Slobodian et al. 2002, Acton 1991).

The bulk density and carbon concentration were an important factor in determining the carbon stocks of the meadow steppe and planted forest. Although the bulk density in the tilled field increased from 1900 to 1998 just as the meadow steppe and planted forest did, the carbon concentration was significantly lower in the tilled field than in the other land use plots. The difference in carbon concentration was enough to cause the carbon stock in the tilled field to remain significantly less than the carbon stocks in the other land uses.

Conclusions

Over the time period of 100 years, there was both a gain and a loss of organic carbon concentration in the first 1 m of soil after a pristine steppe underwent three different types of land use conversions that included a meadow steppe, planted forest, and tilled field. Each land use showed an initial decrease in organic carbon concentration followed by an increase through time. Compared to the initial concentration of the pristine plot, the meadow steppe decreased, the planted forest remained about the same, and the tilled field decreased in organic carbon concentration. The conversion to tilling showed the greatest amount of change in organic carbon concentration with lesser change in the meadow steppe and planted forest.

The bulk density in each of the land use plots increased in the upper half of the profile compared to the pristine plot and decreased in the lower half. Overall, each land use plot showed varying degrees of increase and decrease compared to each other.

The organic carbon stocks in the meadow steppe showed little change compared to the pristine stock. The planted forest and tilled field showed a significant decrease in carbon stock.

Throughout the 100 years of land conversion, weathering has increased in each of the different land use plots.

Among the three land use plots, the land use that best sequestered carbon was the planted forest. The organic carbon concentration in the planted forest in 1998 was almost the same as the pristine plot. The concentration in 1998 was about twice the organic carbon concentration in the planted forest in 1947. The least favorable land use for sequestering carbon was the tilled field. Although the organic carbon concentration in the tilled field actually increased after tilling began in 1920, compared to the meadow steppe and planted forest this concentration was much less. As of 1998, the tilled field did not reach organic carbon concentrations that were relatively similar to that of the pristine plot as much as the meadow steppe and tilled field did. For this reason, the tilled field sequestered the least amount of carbon. A land use change that was not directly looked at in this study was the hay removal (1882-1912) on the land use plots prior to their conversion. Although this is a land use change from pristine conditions, this was not a land use conversion that was explicitly investigated. A point to note is that this may have led to the greatest decrease in organic carbon concentration versus the meadow steppe, planted forest, and tilled field. Additional archived samples would be needed in order to show this to be true for certain.

Based on the results of this study, future speculation leads to a continual increase in organic carbon concentration in all the land use plots. The planted forest is expected to show the greatest increase. As the forest matures, more organic matter will be available to be incorporated into the soil. The meadow steppe may continue to increase but on a much slower scale than that of the planted forest. It may take a few decades to a century to return to the initial conditions of the pristine plot if it indeed fully recovers. The tilled field may show an increase in organic carbon concentration but may be limited as to the extent. As the planted forest continues to mature, the influence it has as a windbreak on the tilled field may also increase or at least remain at its current level. Crop yield and soil moisture content may continue to increase as a result. Although an increase in organic carbon concentration may result because of the influence from the maturing of the planted forest, eventually a limit will probably be reached.

Further studies and improvements are needed to be done. In this study, changes in soil carbon were able to be detected, but analyzing for organic carbon directly and sampling at consistent depth intervals could provide for a more refined analysis. Additional types of soil classes and different kinds of land uses need to be incorporated, as well as using deeper profiles in order to get a more complete analysis on the changing global carbon cycle. Also studying different regions of the world may show varying results in the same types of soil and land use combinations. The use of archived samples will greatly aid in this process.

The results of this study did not necessarily directly answer whether or not the sequestration of carbon in soil is a component of the missing carbon sink, it did show that soil carbon plays an important role in the global carbon cycle. The effects on soil carbon will vary in response to land use changes in different parts of the world. This study gives another piece of information about the effects of land use changes on the global carbon cycle in the Central Chernozem Region of Russia.

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Table I Location and coordinates of the modern soil pits sampled in each land use. The locations of the pits are relative to the planted forest. There are no coordinates available for pit 9 (tilled field) and no data available for pit 10 from the tilled field (not included).

Sample Pits	Location	Coordinates	
Pit 2 (Meadow Steppe)	110 m east of planted forest	51 01 55.0 N	40 43 45.0 E
Pit 3 (Meadow Steppe)	115 m east of planted forest	51 01 53.4 N	40 43 46.3 E
Pit 4 (Planted Forest)	25 m inside planted forest, east side	51 01 53.4 N	40 43 46.3 E
Pit 6 (Planted Forest)	25 m inside planted forest, west side	51 01 50.2N	40 43 32.1 E
Pit 9 (Tilled Field)	78 m from planted forest		

Table II Bulk Density of the modern soil pits and the archived pristine soil pit at various sampling depths. Soil cores were taken (used to calculate bulk density) for the modern pits at particular sampling depths within each particular land use. The bulk densities of the pristine pit HRSC 1900 are assumed values from samples taken in 1997.

Sample Depth (cm)	Bulk density (g/cm3)
Pit 2 (Meadow Steppe)	
15	0.87
30	0.98
50	0.92
63	1.00
80	1.10
130	1.14
Pit 3 (Meadow Steppe)	
15	0.77
35	0.95
70	0.93
90	1.03
120	1.05
Pit 4 (Planted Forest)	
15	0.83
40	0.90
60	0.98
85	0.88
110	0.96
Pit 6 (Planted Forest)	
20	0.80
40	0.99
60	0.92
95	1.04
115	1.07
Pit 9 (Tilled Field)	
15	0.98
40	0.98
60	0.89
82	1.05
110	1.10
Pit 10 (Tilled Field)	
15	
35	0.89
55	0.97
80	0.98
110	1.11

Sample Depth (cm)	Bulk density (g/cm3)
HRSC 1900 (Pristine)	
0-5	0.52
5-12	0.68
12-20	0.73
20-36	0.86
36-50	0.85
50-65	1.12
65-78	1.17
78-100	1.23
100-120	1.24
120-134	1.32

Table III Total carbon stocks and organic carbon stocks at various depth intervals from each land use type. Carbon stocks are summed to depth intervals of 0-20 cm, 0-50 cm, and 0-100 cm. There were no total carbon stock values for the archived site HRSC 1900 because data was lacking to calculate the carbon stock.

	Total Carbon (kg/m2)				Organic Carbon (kg/m2)			
Depth interval (cm)	**HRSC 1900**	**Meadow Steppe**	**Planted Forest**	**Tilled Field**	**HRSC 1900**	**Meadow Steppe**	**Planted Forest**	**Tilled Field**
0-20		10.50	10.45	9.19	10.10	9.75	9.66	8.27
0-50		23.78	22.64	22.07	20.97	21.48	20.54	19.82
0-100		40.22	36.64	34.67	30.99	31.42	27.96	26.88

Table IV Data set 1 concentrations of carbonate, total carbon, and organic carbon at various sampling depth intervals from pits in each of the different land uses. The carbonate concentrations in the modern samples (Pits 2, 3, 4, 6, 9, 10) were calculated from the difference of total carbon and organic carbon concentrations. Only organic carbon concentrations were available for the archived pristine site HRSC 1900.

Depth interval (cm)	Carbonate (%)	Total Carbon (%)	Organic Carbon (%)
Pit 2 (Meadow Steppe)			
0-10	-0.61	4.91	5.53
10-25	0.04	5.51	5.47
25-35	0.11	4.11	4.00
36-50	0.27	3.62	3.36
50-70	0.10	2.77	2.67
70-80	2.01	3.71	1.70
80-100	0.06	1.89	1.82
100-120	0.38	2.23	1.85
Pit 3 (Meadow Steppe)			
0-15	-0.65	5.22	5.87
15-30	0.23	5.31	5.08
30-45	-0.11	3.85	3.96
45-55	0.21	3.44	3.23
55-70	0.10	3.00	2.90
70-80	0.27	3.26	2.99
80-90	0.68	2.78	2.10
90-100	0.07	2.39	2.32
100-120	-0.01	1.72	1.72
120-140	-0.21	1.21	1.42
Pit 4 (Planted Forest)			
0-15	-1.06	4.87	5.94
15-35	-0.56	3.63	4.20
35-48	0.04	2.94	2.90
48-73	0.06	2.34	2.28
73-90	-0.80	1.65	2.45
90-110	-1.48	0.75	2.23
Pit 6 (Planted Forest)			
0-20	-1.83	3.14	4.97
20-35	-1.16	3.69	4.85
35-45	0.05	3.74	3.70
45-60	-0.03	2.90	2.93
60-80	0.62	2.83	2.22
80-100	0.93	3.01	2.07
100-115	0.17	2.59	2.41

Depth interval (cm)	Carbonate (%)	Total Carbon (%)	Organic Carbon (%)
Pit 9 (Tilled Field)			
0-10	0.42	4.38	3.96
10-25	0.12	4.37	4.25
20-50	0.17	4.00	3.83
50-70	0.11	2.46	2.35
70-95	-0.06	1.38	1.45
95-110	1.25	2.33	1.08
Pit 10 (Tilled Field)			
0-15	0.25	4.28	4.03
15-28	0.16	4.26	4.10
28-49	0.12	4.18	4.06
47-68	-0.13	2.73	2.87
68-96	1.25	2.50	1.26
96-115	0.95	2.33	1.38
HRSC 1900 (Pristine)			
0-5			10.53
5-12			8.15
12-20			5.97
20-36			4.59
36-50			3.82
50-65			3.17
65-78			1.72
78-100			0.77
100-120			0.47
120-135			0.51

Table V Data set 2 concentrations of carbonate, total carbon, and organic carbon at various sampling depth intervals from pits in each of the different land uses. Carbonate concentrations and organic carbon concentrations are estimated for both the modern soil pits (Pits 2, 3, 4, 6, 9, 10) and archived soil pits (meadow steppe 1970, planted forest 1947, tilled field 1920). Carbonate concentrations were calculated form a total digest and the organic carbon concentrations were the difference of the total carbon concentrations and the carbonate concentrations.

Depth (cm)	Carbonate (%)	Total Carbon (%)	Organic Carbon (%)
Pit 2 (Meadow Steppe)			
0-3	0.52	7.71	7.20
3-6	0.51	7.37	6.86
6-15	0.45	6.92	6.47
15-25	0.47	5.75	5.29
25-30	0.55	5.09	4.54
30-38	0.52	4.60	4.08
38-48	0.58	4.09	3.51
48-58	0.57	3.74	3.17
58-68	0.54	3.24	2.70
68-73	0.61	2.65	2.04
73-78	0.57	2.34	1.77
78-95	1.38	2.43	1.04
95-125	1.86	2.52	0.65
125-145	1.80	2.24	0.44
Pit 3 (Meadow Steppe)			
3-6	0.50	7.50	7.00
6-10	0.51	7.54	7.02
10-20	0.52	6.59	6.06
20-30	0.54	5.39	4.84
30-40	0.53	4.48	3.95
40-50	0.57	4.28	3.71
50-55	0.56	4.04	3.48
55-65	0.56	3.50	2.94
65-75	0.77	3.85	3.08
75-80	1.24	3.52	2.27
80-95	1.97	3.00	1.03
95-105	2.00	2.77	0.77
105-115	2.30	2.55	0.25
115-145	2.22	2.30	0.08

Depth (cm)	Carbonate (%)	Total Carbon (%)	Organic Carbon (%)
Pit 4 (Planted Forest)			
0-3	0.52	8.63	8.10
3-6	0.48	6.98	6.50
6-10	0.51	5.63	5.12
10-20	0.55	4.96	4.41
20-30	0.39	4.65	4.26
30-40	0.53	3.94	3.41
40-47	0.53	3.69	3.16
47-52	0.46	3.19	2.74
52-62	0.50	2.68	2.18
62-67	0.64	2.76	2.12
67-72	0.92	2.36	1.44
72-83	1.75	2.71	0.96
83-93	2.10	2.59	0.49
93-118	2.07	2.34	0.27
118-138	1.91	2.12	0.21
Pit 6 (Planted Forest)			
3-6	0.49	9.42	8.94
6-10	0.50	9.04	8.54
10-20	0.53	7.32	6.79
20-30	0.42	5.34	4.92
30-39	0.49	4.82	4.33
39-43	0.52	4.52	4.00
43-48	0.47	4.34	3.88
48-58	0.53	3.88	3.35
58-67	0.55	3.11	2.57
67-77	1.36	3.05	1.69
77-101	1.94	3.03	1.09
101-115	2.21	2.94	0.74
115-130	2.36	2.64	0.28
Pit 9 (Tilled Field)			
0-3	0.50	5.13	4.63
3-6	0.52	5.13	4.62
6-15	0.46	4.89	4.43
15-26	0.46	4.90	4.44
28-36	0.46	5.30	4.83
36-51	0.46	4.92	4.45
51-63	0.52	3.00	2.48
63-70	0.58	2.60	2.02
70-80	0.61	1.75	1.15
80-95	0.60	1.45	0.85
95-120	2.21	2.60	0.39
120-140	2.34	2.57	0.23

Depth (cm)	Carbonate (%)	Total Carbon (%)	Organic Carbon (%)
Pit 10 (Tilled Field)			
0-3	0.50	5.05	4.55
3-6	0.50	4.72	4.23
6-15	0.56	4.98	4.43
15-25	0.50	4.80	4.30
25-30	0.48	4.96	4.48
30-40	0.50	5.02	4.52
40-46	0.54	3.76	3.23
46-56	0.54	3.06	2.52
56-69	0.53	2.54	2.01
69-85	1.68	2.92	1.24
85-100	2.22	2.85	0.63
100-130	2.34	2.41	0.07
130-140	2.23	2.26	0.03
Meadow Steppe (1970)			
0-5	0.46		
5-10	0.46	6.60	6.14
10-15	0.49	5.83	5.35
15-20	0.56	5.31	4.75
20-25	0.46	4.78	4.31
25-30	0.54	4.93	4.39
30-35	0.44	4.38	3.95
35-40	0.48	4.45	3.97
40-45	0.51	4.15	3.64
45-50	0.55	3.55	3.00
50-60	0.90	3.40	2.50
60-70	2.03	3.52	1.49
70-80	2.49	3.28	0.79
80-90	2.55	3.10	0.55
90-100	2.51	2.95	0.44
Planted Forest (1947)			
0-5	0.63	4.65	4.03
5-10	0.50	4.37	3.86
10-15	0.58	4.30	3.72
15-20	0.56	4.08	3.51
20-25	0.58	4.01	3.43
25-30	0.57	3.71	3.14
30-35	0.56	3.57	3.01
35-40	0.57	3.21	2.65
40-45	0.56	2.86	2.31
45-50	0.69	2.75	2.06
50-60	1.40	3.11	1.71
60-70	1.95	3.10	1.15
70-80	2.56	3.32	0.77
80-90	2.74	3.27	0.52
90-100	2.61	3.24	0.62

Depth (cm)	Carbonate (%)	Total Carbon (%)	Organic Carbon (%)
Tilled Field (1920)			
0-5	0.23		
5-10	0.33	4.17	3.84
10-15	0.31		
15-20	0.29		
20-25	0.30		
25-30	0.27	3.08	2.80
30-35	0.37	3.15	2.78
35-40	0.33	2.72	2.39
40-45	0.48	2.37	1.88
45-50	1.09	2.73	1.65
50-60	1.62	2.58	0.96
60-70	1.97	2.58	0.61
70-80	1.43	1.98	0.55
80-90	1.42	1.60	0.18
90-97	0.95	1.49	0.54

Table VI Averaged organic carbon concentrations in data set 2 at combined depth intervals in the modern pits from each of the different land uses. The organic carbon concentrations shown were combined and averaged from various depth intervals within each pit to best match the corresponding pit from that particular land use.

Depth interval (cm)	Organic Carbon (%)
Pit 2 (Meadow Steppe)	
0-6	7.03
6-30	5.43
30-38	4.08
38-48	3.51
48-73	2.64
73-78	1.77
78-95	1.04
95-145	0.55
Pit 3 (Meadow Steppe)	
3-6	7.00
6-30	5.98
30-40	3.95
40-50	3.71
50-75	3.17
75-80	2.27
80-95	1.03
95-145	0.37
Pit 4 (Planted Forest)	
0-3	8.10
3-6	6.50
6-10	5.12
10-20	4.41
20-30	4.26
30-40	3.41
40-47	3.16
47-67	2.35
67-72	1.44
72-93	0.72
93-118	0.27
118-138	0.21

Depth interval (cm)	Organic Carbon (%)
Pit 6 (Planted Forest)	
3-6	8.94
6-10	8.54
10-20	6.79
20-30	4.92
30-39	4.33
39-48	3.94
48-67	2.96
67-77	1.69
77-101	1.09
101-115	0.74
115-130	0.28
Pit 9 (Tilled Field)	
0-3	4.63
3-6	4.62
6-15	4.43
15-26	4.44
28-36	4.83
36-51	4.45
51-70	2.25
70-95	1.00
95-120	0.39
120-140	0.23
Pit 10 (Tilled Field)	
0-3	4.55
3-6	4.23
6-15	4.43
15-25	4.30
25-30	4.48
30-46	3.88
46-69	2.26
69-100	0.94
100-130	0.07
130-140	0.03

Table VII Averaged total carbon and organic carbon concentrations of the modern representative pits from data set 2 at combined depth intervals from each of the different land uses. The carbon concentrations shown were combined and averaged from various depth intervals within each respective pit.

Depth interval (cm)	Total Carbon (%)	Organic Carbon (%)
Pit 2 (Meadow Steppe)		
0-15	7.34	6.84
15-25	5.75	5.29
25-38	4.85	4.31
38-48	4.09	3.51
48-68	3.49	2.93
68-78	2.50	1.91
78-95	2.43	1.04
95-125	2.52	0.65
125-145	2.24	0.44
Pit 6 (Planted Forest)		
3-20	8.59	8.09
20-30	5.34	4.92
30-43	4.67	4.17
43-58	4.11	3.61
58-77	3.08	2.13
77-101	3.03	1.09
101-115	2.94	0.74
115-130	2.64	0.28
Pit 10 (Tilled Field)		
0-15	4.92	4.40
15-30	4.88	4.39
30-46	4.39	3.88
46-69	2.80	2.26
69-100	2.88	0.94
100-130	2.41	0.07
130-140	2.26	0.03

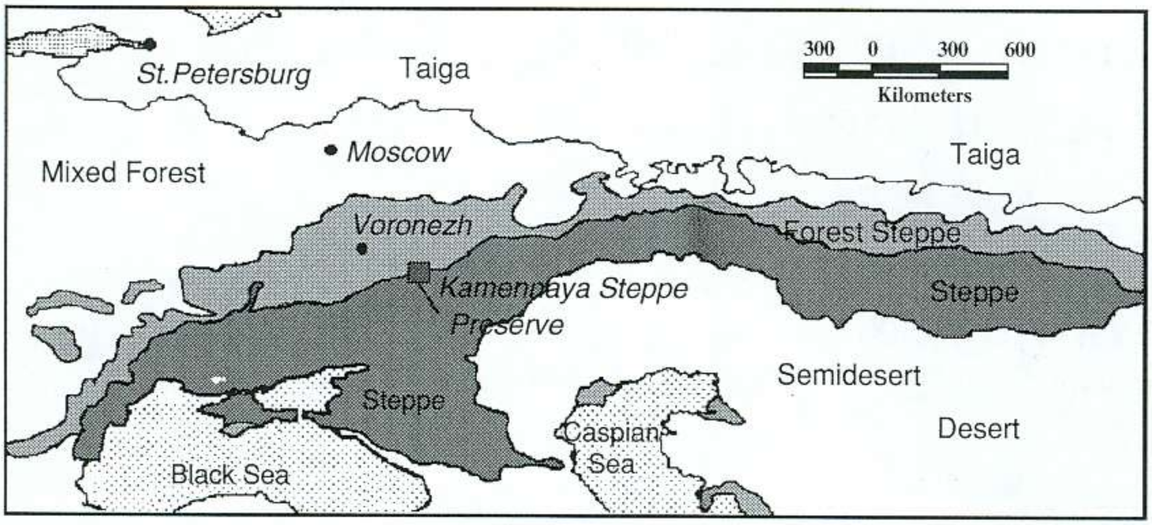


Figure 1 Map of Russia showing the Kamennaya Steppe Preserve where the Dokuchaev Institute is located. The gray shading represents the historic range of steppe. From Torn et al. (2002).

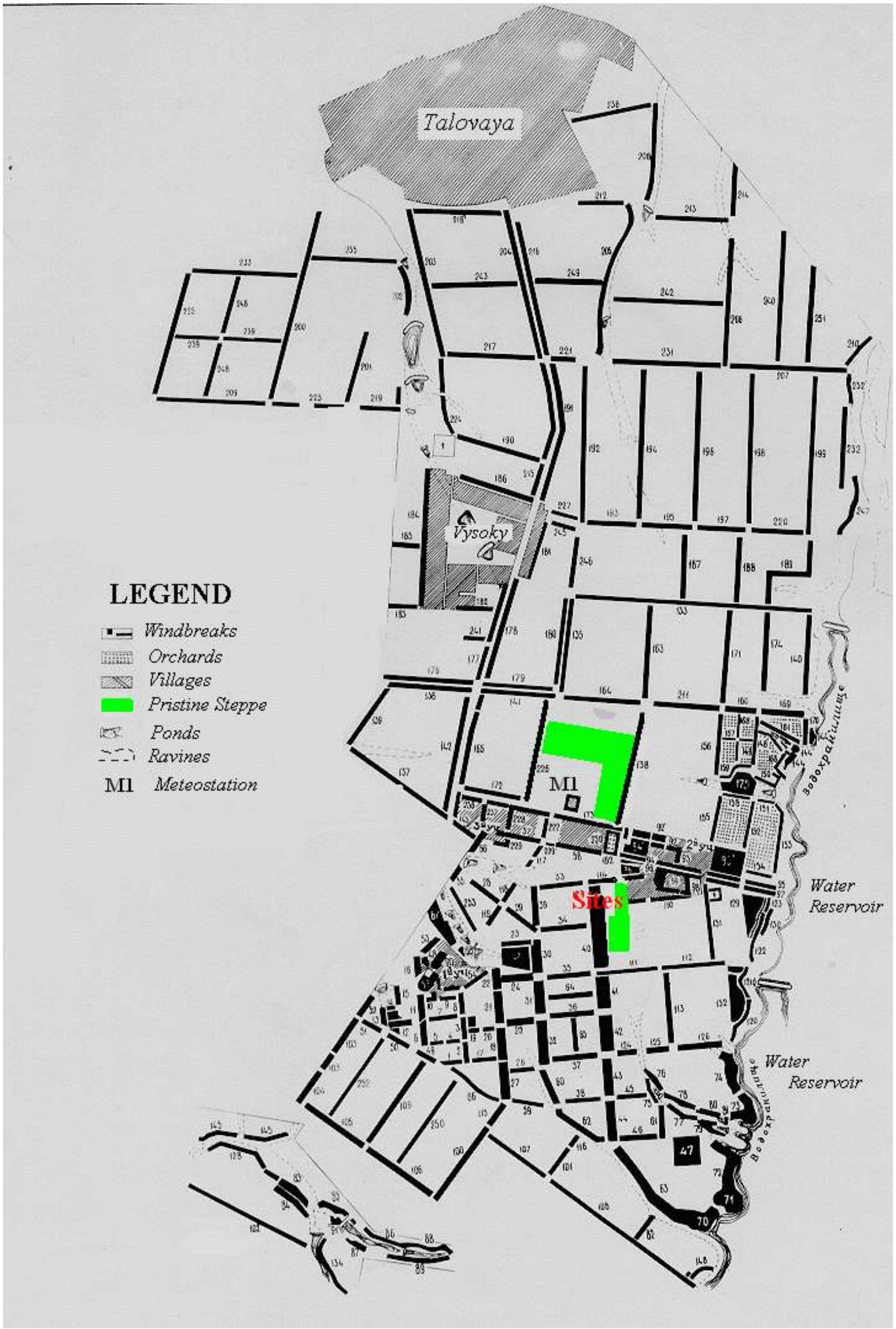
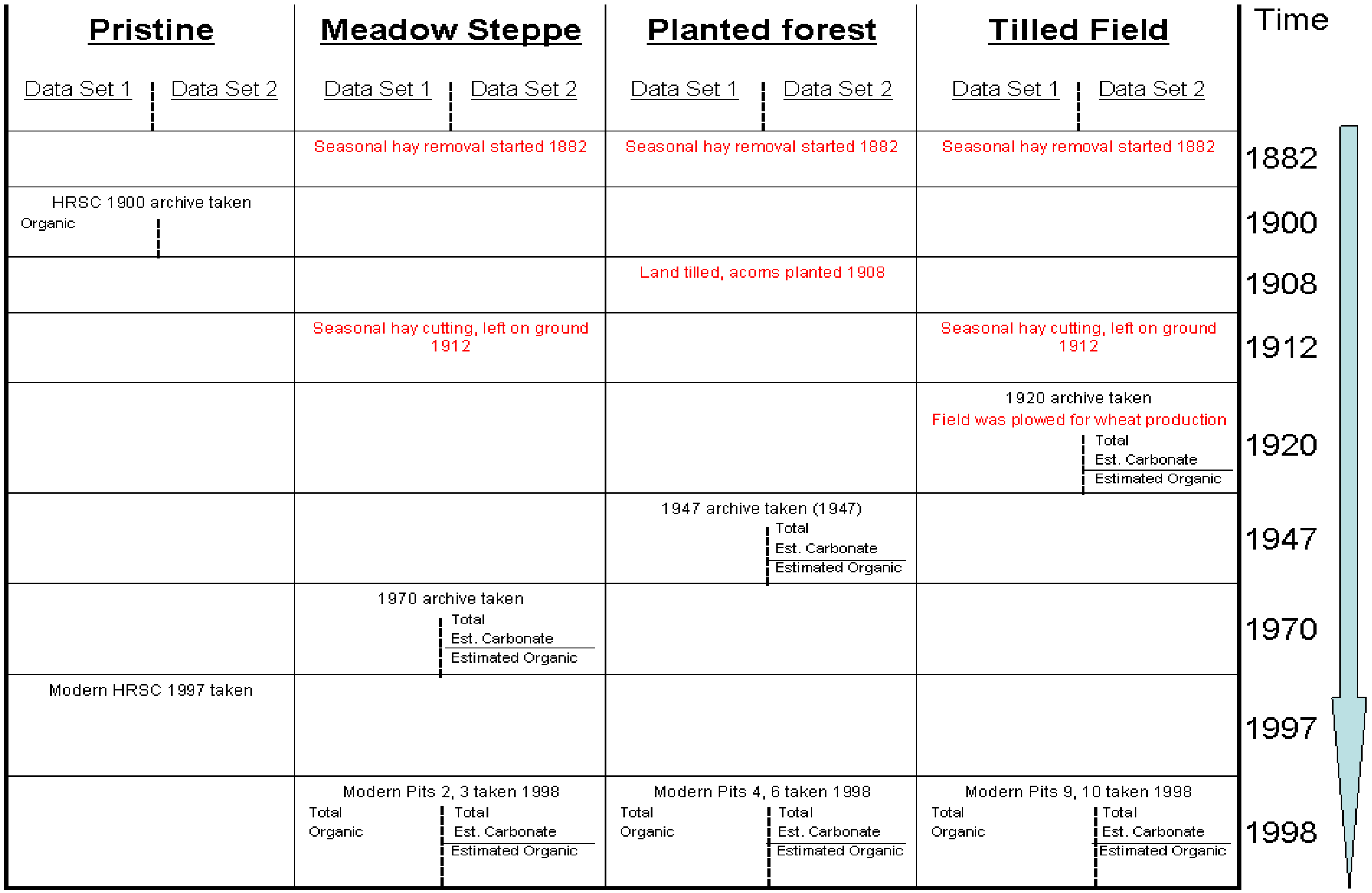


Figure 2 Kamennaya Steppe National Park.



Pristine		Meadow Steppe		Planted forest		Tilled Field		Time
Data Set 1	Data Set 2	Data Set 1	Data Set 2	Data Set 1	Data Set 2	Data Set 1	Data Set 2	
		Seasonal hay removal started 1882		Seasonal hay removal started 1882		Seasonal hay removal started 1882		1882
HRSC 1900 archive taken Organic								1900
				Land tilled, acorns planted 1908				1908
		Seasonal hay cutting, left on ground 1912				Seasonal hay cutting, left on ground 1912		1912
						1920 archive taken Field was plowed for wheat production	Total Est. Carbonate Estimated Organic	1920
				1947 archive taken (1947)	Total Est. Carbonate Estimated Organic			1947
		1970 archive taken	Total Est. Carbonate Estimated Organic					1970
Modern HRSC 1997 taken								1997
		Modern Pits 2, 3 taken 1998 Total Organic	Total Est. Carbonate Estimated Organic	Modern Pits 4, 6 taken 1998 Total Organic	Total Est. Carbonate Estimated Organic	Modern Pits 9, 10 taken 1998 Total Organic	Total Est. Carbonate Estimated Organic	1998

Figure 3 Summary of the types of data available for data set 1 and data set 2 in each land use. Total and organic are analyzed forms of carbon concentration. Est. carbonate is an estimated carbonate concentration based on a total digest analysis. Estimated organic is the difference between total carbon and est. carbonate. The dates are years in which samples were taken or a treatment was done on the land use.

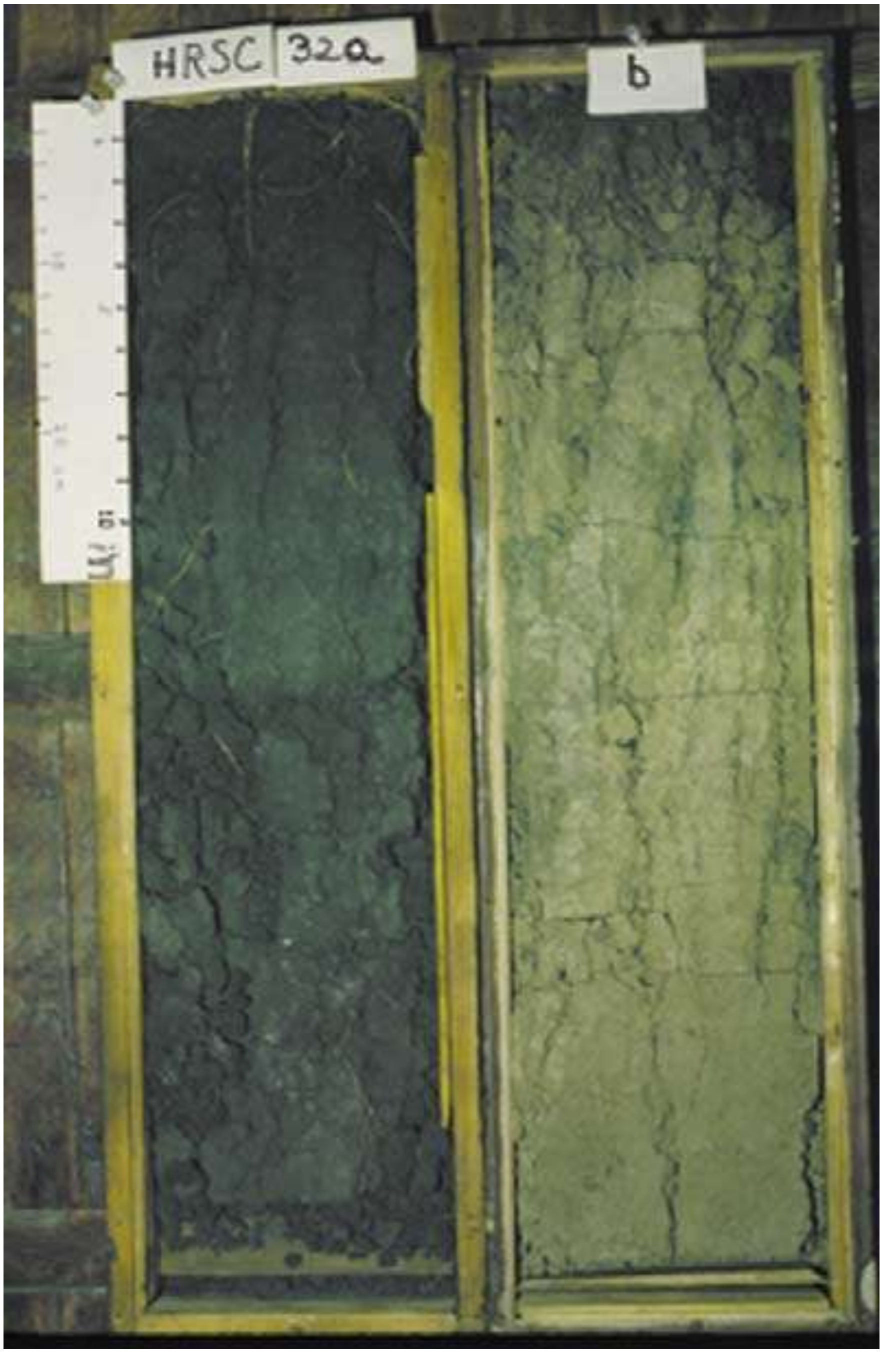


Figure 4 Archived monolith HRSC 1900. The letters a and b indicate the top and bottom half of the monolith, respectively. From Torn et al. (2002).

Figure 5 The meadow steppe (a) planted forest (b) and tilled field (c) in 1998.

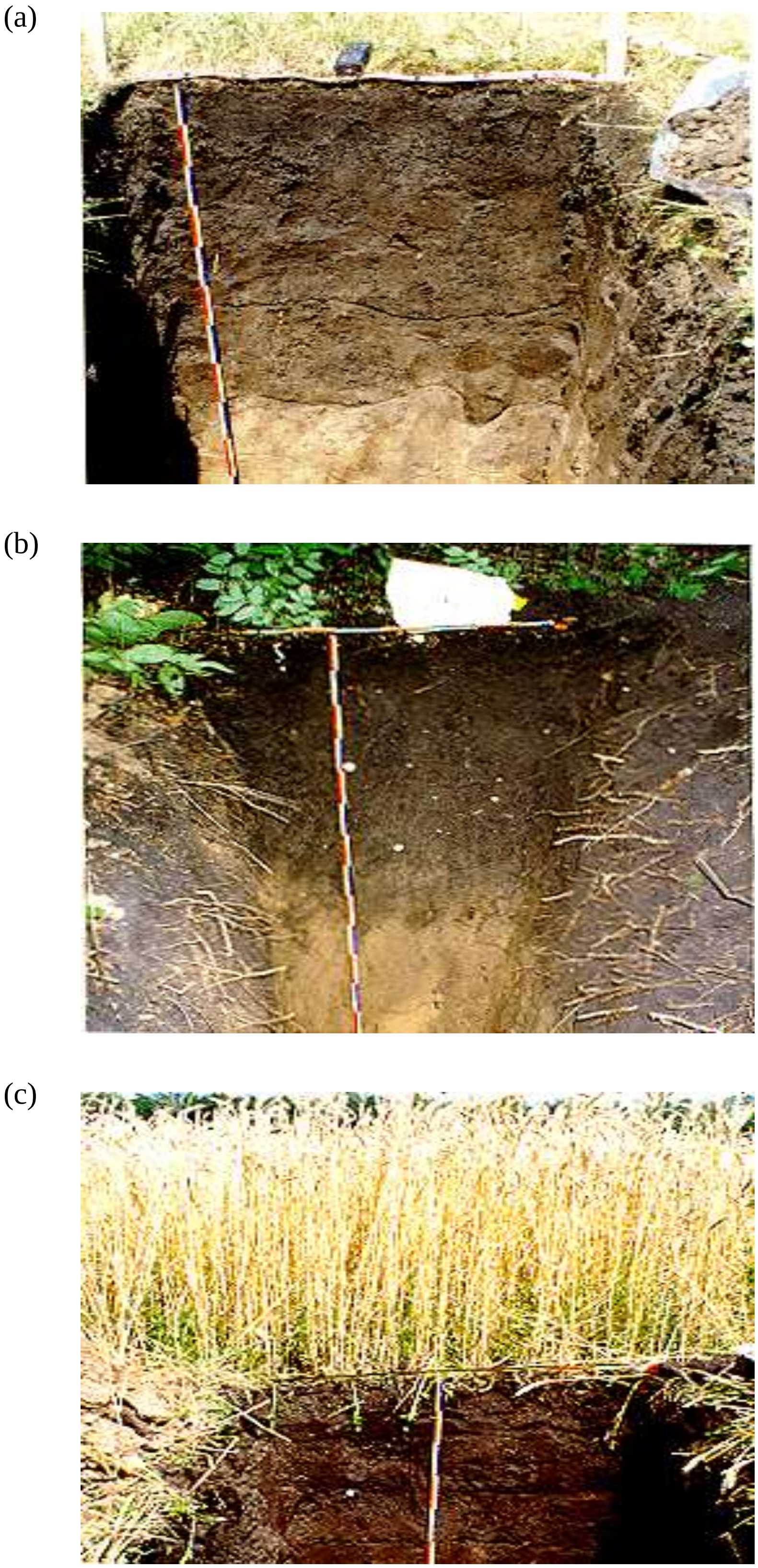


Figure 6 The meadow steppe (a) planted forest (b) and tilled field (c) soil pits in 1998.

Figure 7 The relative locations of the modern (1998) soil pits within each land use. The white represents the meadow steppe. The green represents the planted forest. The yellow represents the tilled field.

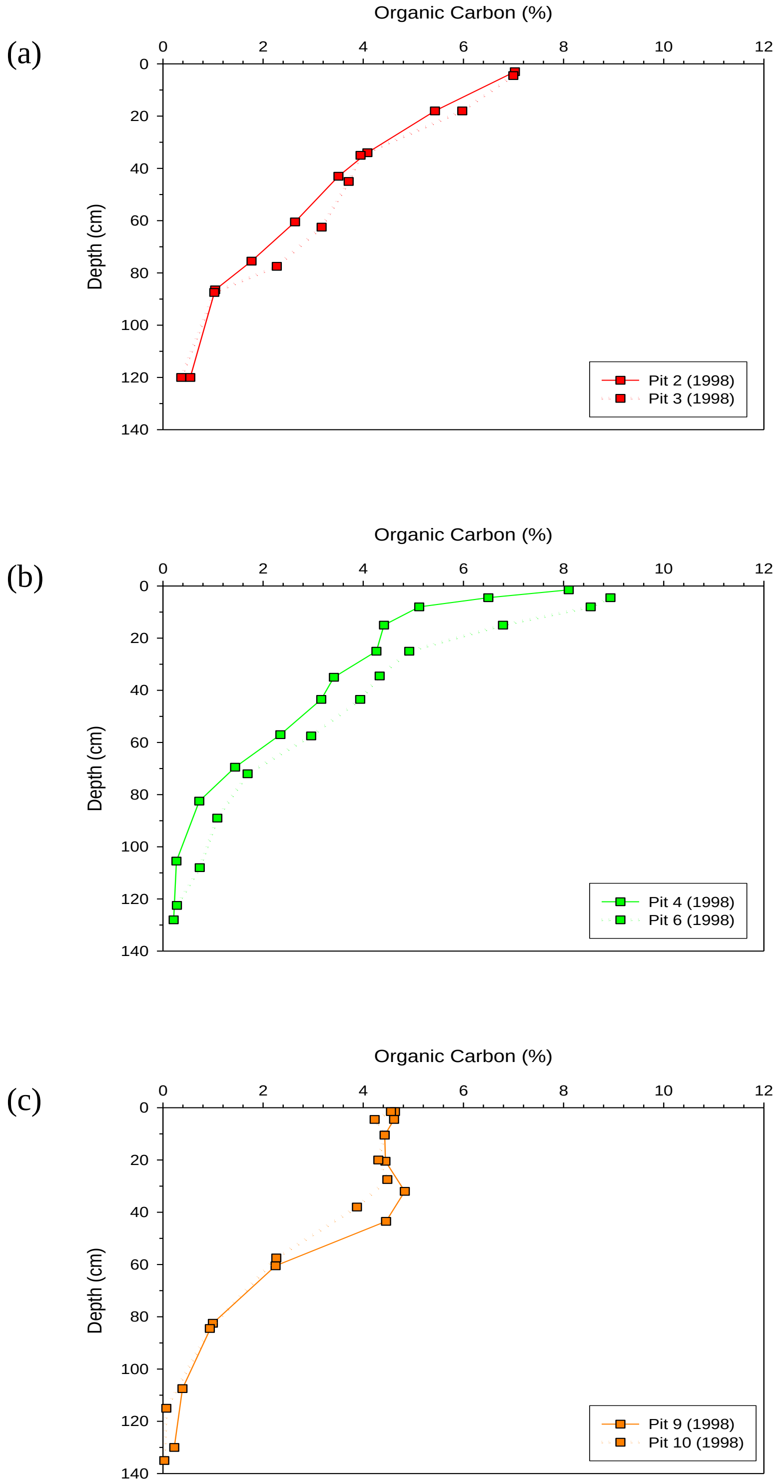


Figure 8 Organic carbon concentrations of two modern samples from the meadow steppe (a) planted forest (b) and tilled field (c) plotted against the midpoint of sample depth.

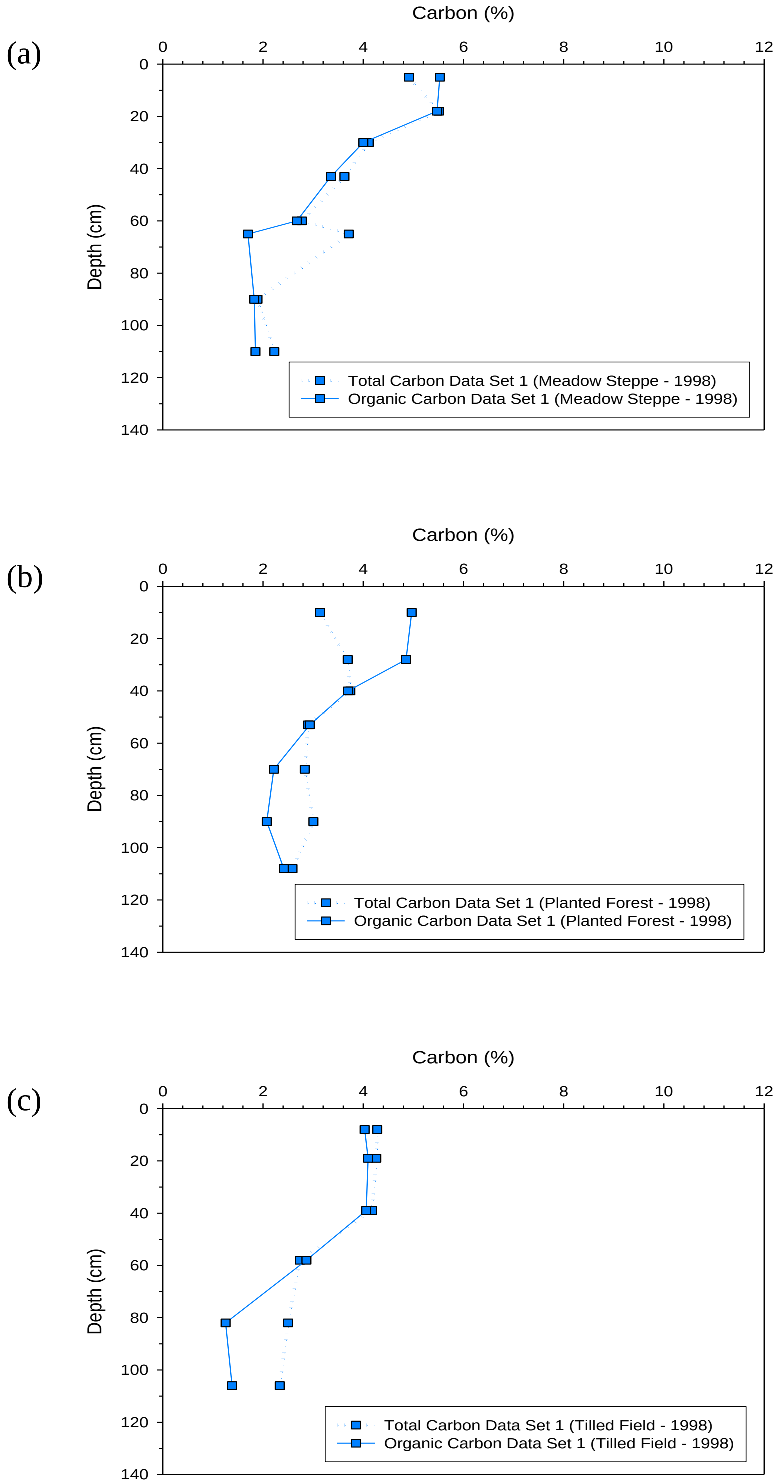


Figure 9 Total and organic carbon concentrations from data set 1 from the meadow steppe (a) planted forest (b) and tilled field (c) plotted together against the midpoint of sample depth.

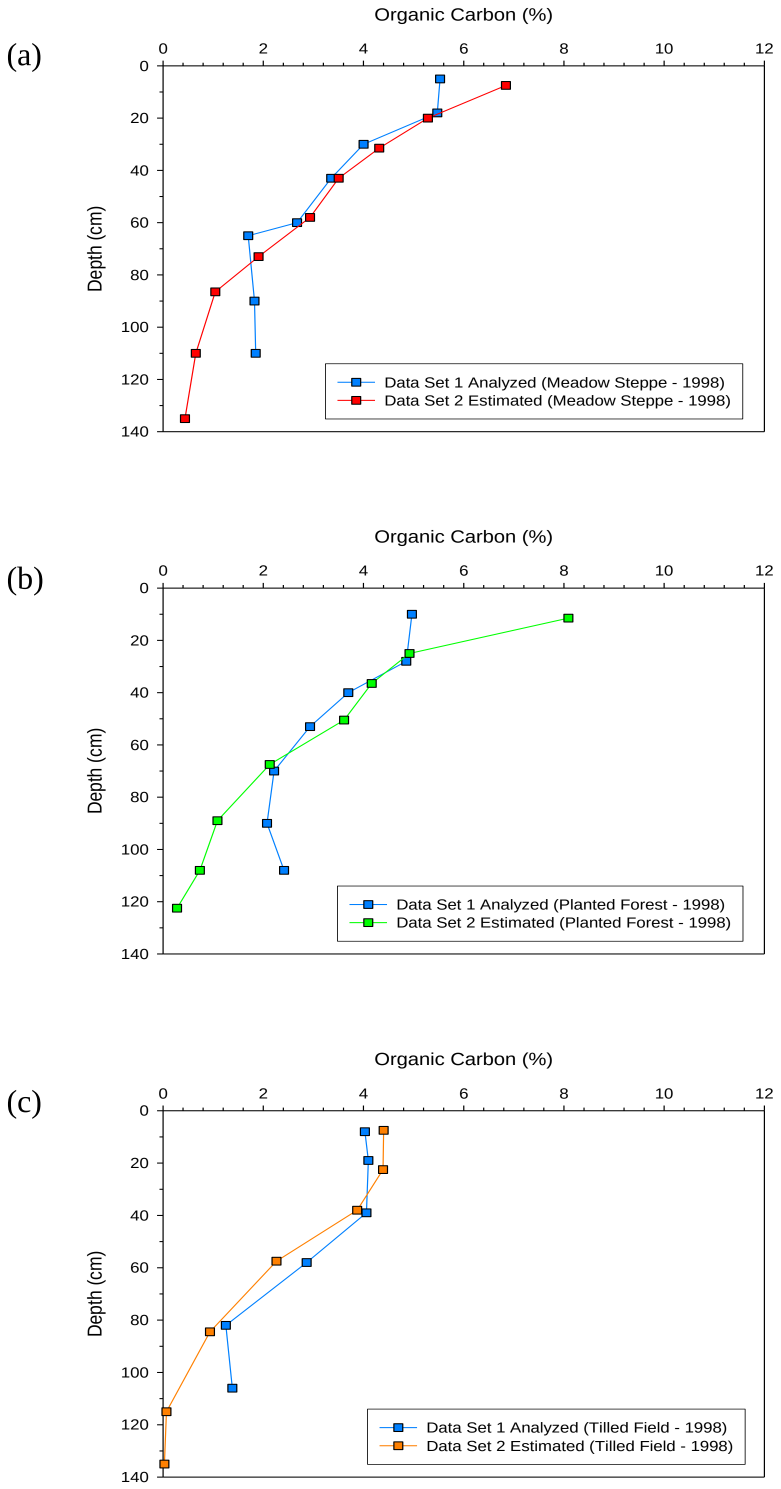


Figure 10 Analyzed and estimated organic carbon concentrations from data sets 1 and 2, respectively from the meadow steppe (a) planted forest (b) and tilled field (c) plotted together against the midpoint of sample depth.

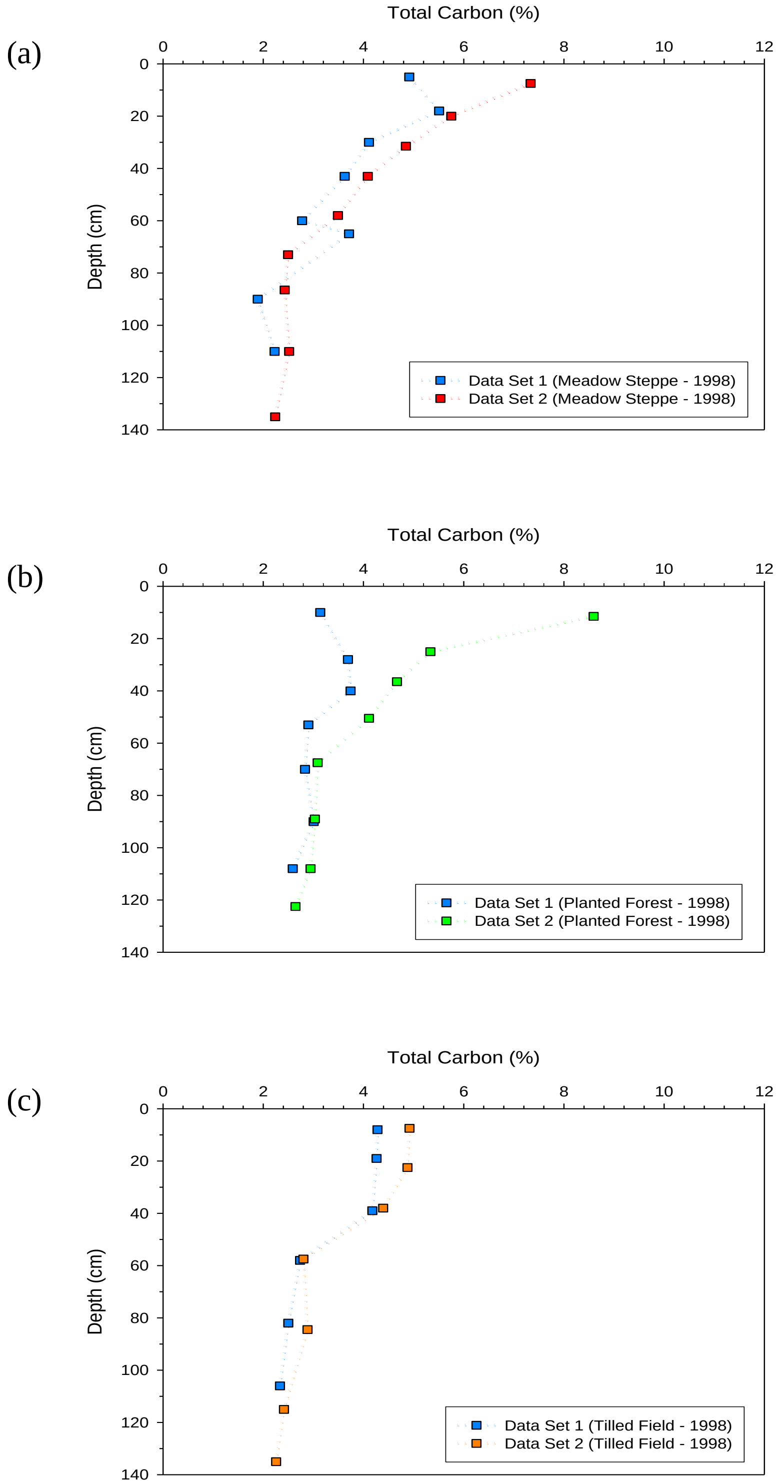


Figure 11 Analyzed total carbon concentrations from data sets 1 and 2, respectively from the meadow steppe (a) planted forest (b) and tilled field (c) plotted together against the midpoint of sample depth.

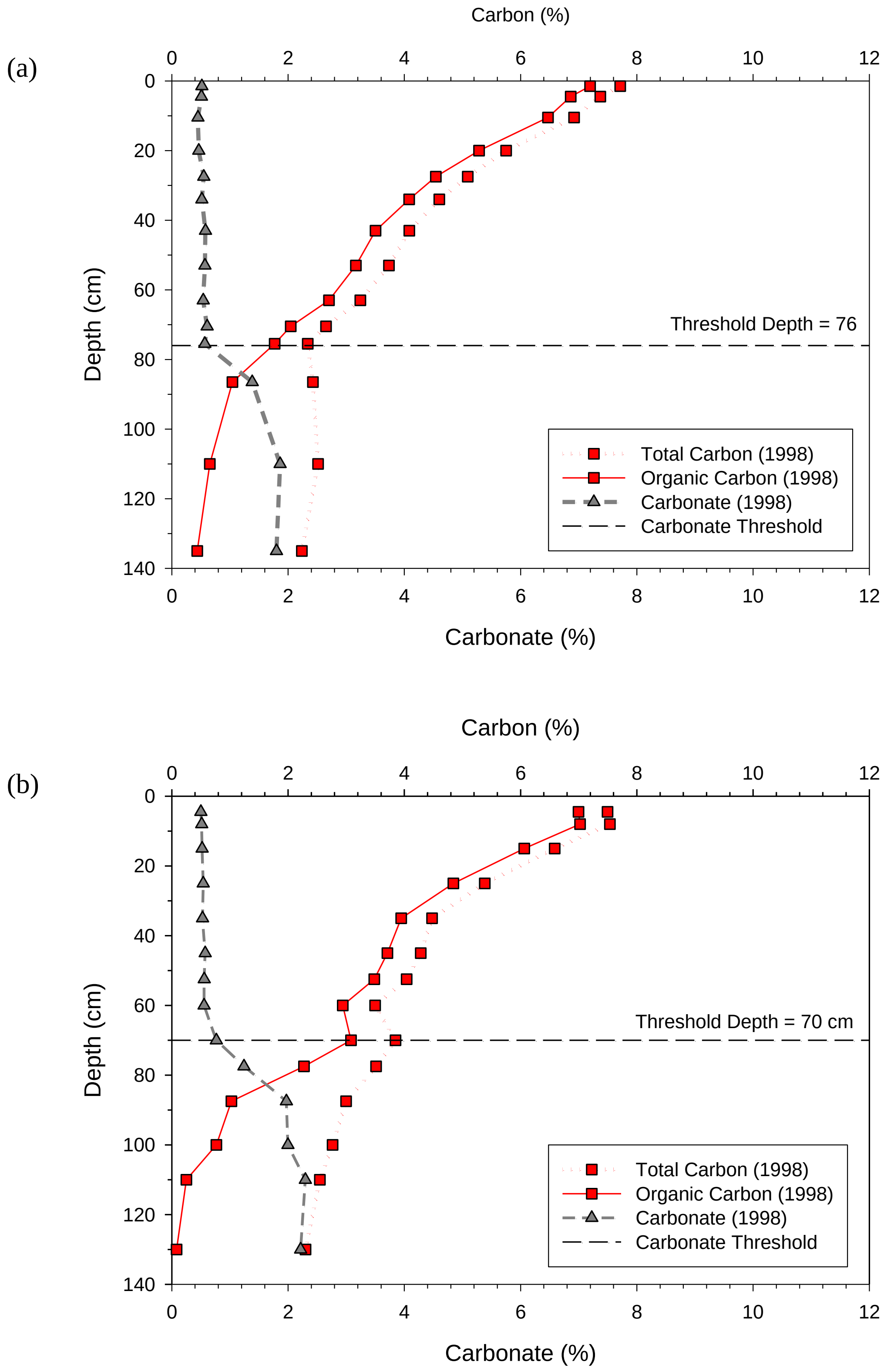


Figure 12 Modern total, organic, and carbonate concentrations from pit 2 (a) and pit 3 (b) in the meadow steppe plotted against the midpoint of sample depth. The carbonate threshold represents the point where the carbonate concentration increases rapidly with increased depth.

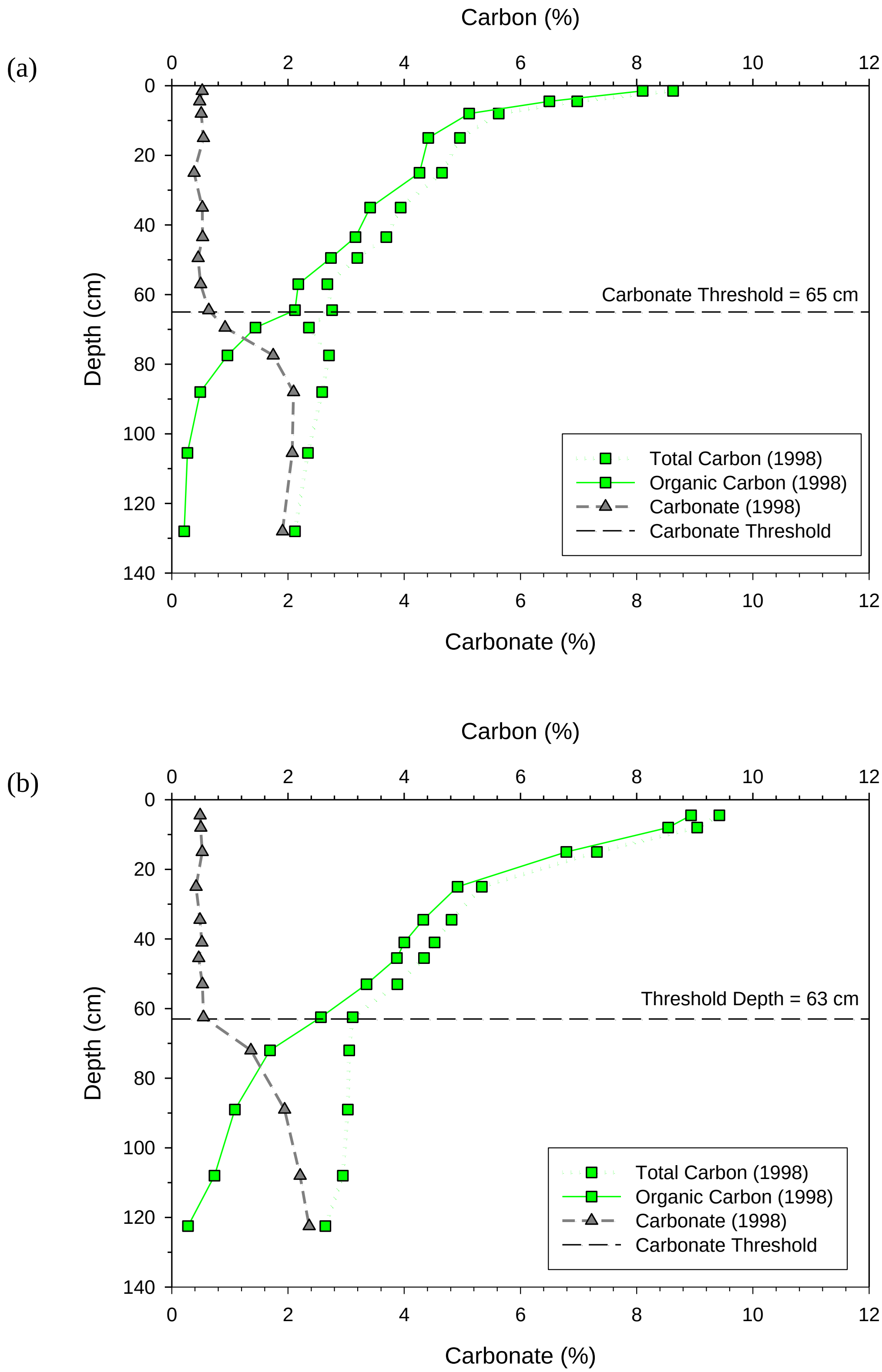


Figure 13 Modern total, organic, and carbonate concentrations from pit 4 (a) and pit 6 (b) in the planted forest plotted against the midpoint of sample depth. The carbonate threshold represents the point where the carbonate concentration increases rapidly with increased depth.

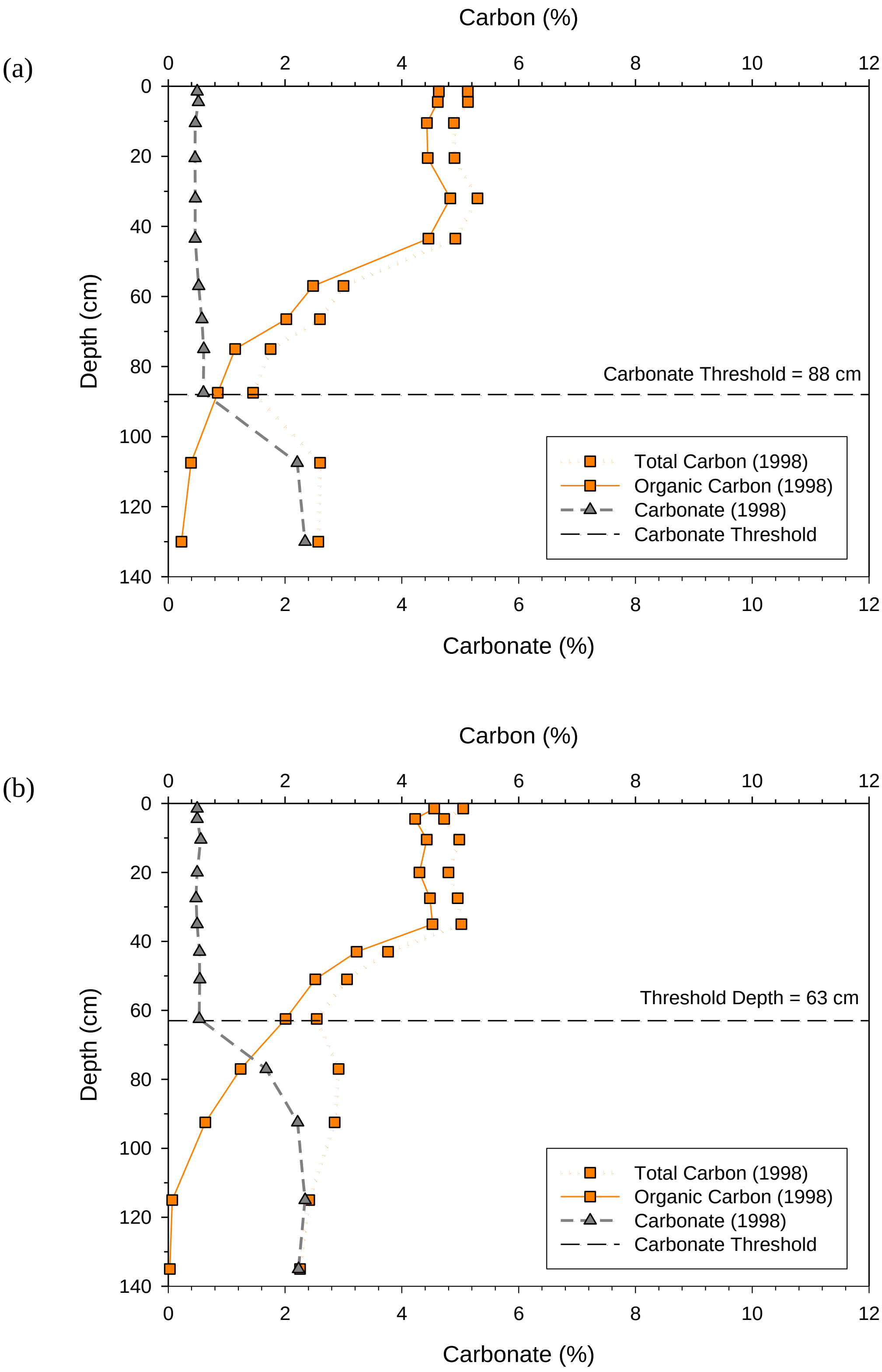


Figure 14 Modern total, organic, and carbonate concentrations from pit 9 (a) and pit 10 (b) in the tilled field plotted against the midpoint of sample depth. The carbonate threshold represents the point where the carbonate concentration increases rapidly with increased depth.

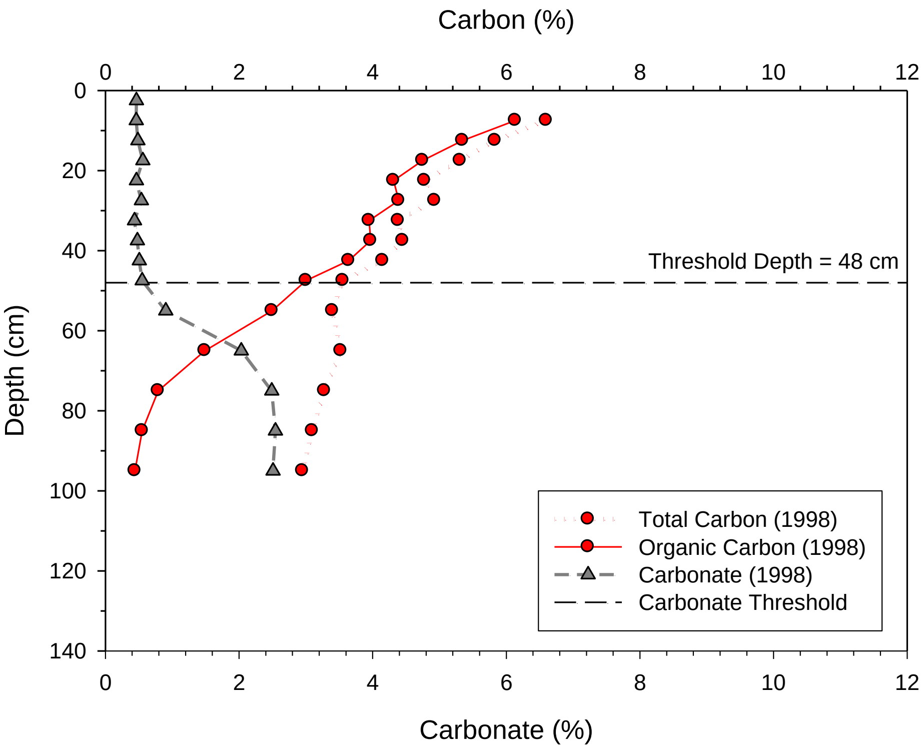


Figure 15 Archived total, organic, and carbonate concentrations from the meadow steppe plotted against the midpoint of sample depth. The carbonate threshold represents the point where the carbonate concentration increases rapidly with increased depth.

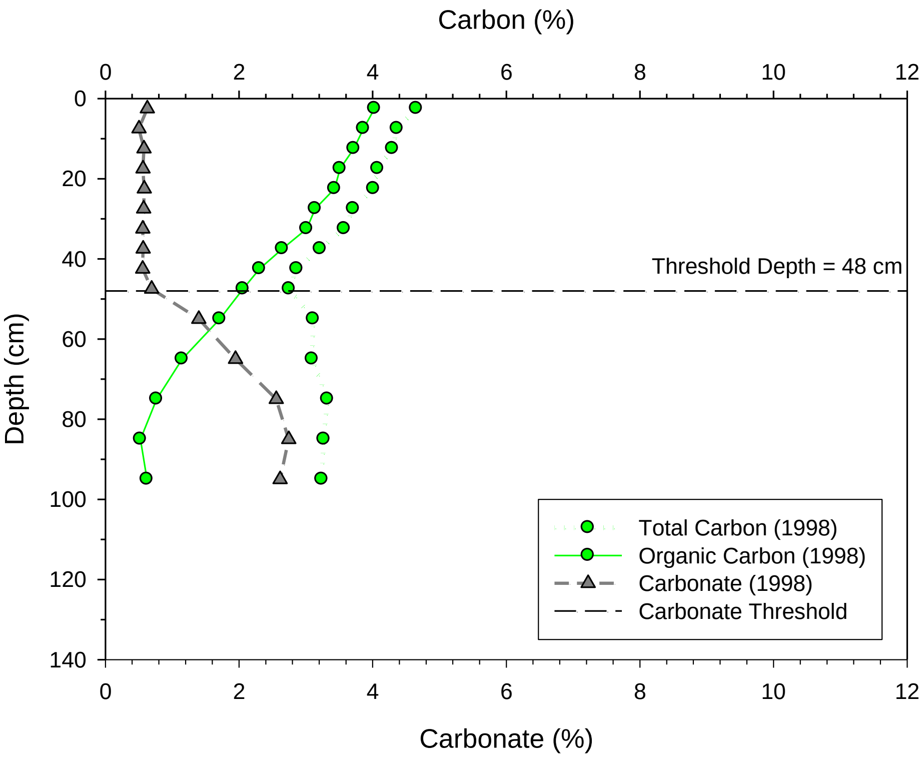


Figure 16 Archived total, organic, and carbonate concentrations from the planted forest plotted against the midpoint of sample depth. The carbonate threshold represents the point where the carbonate concentration increases rapidly with increased depth.

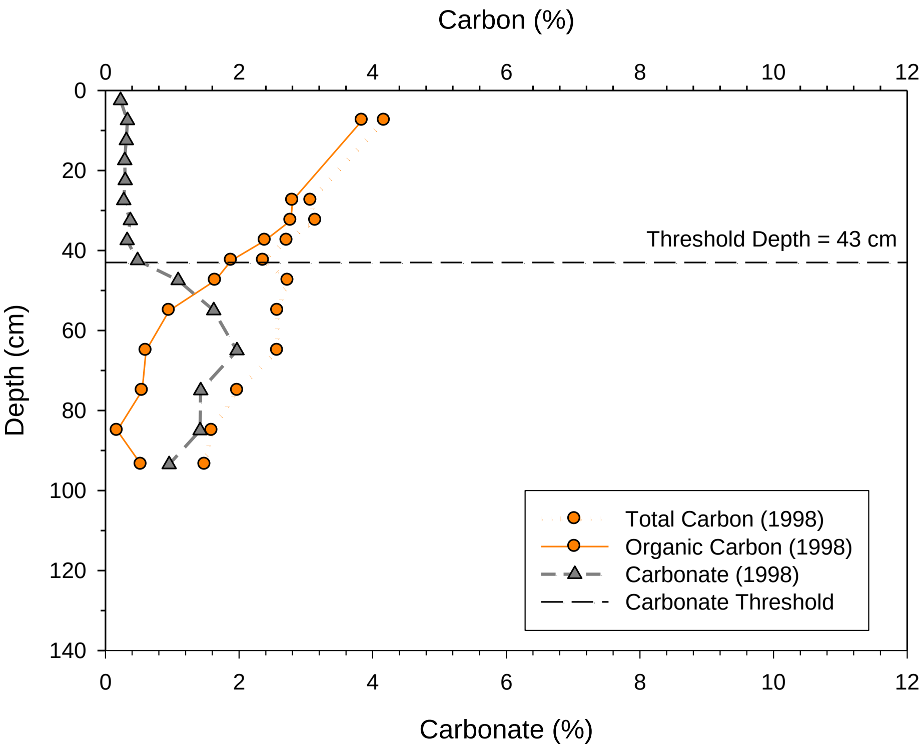


Figure 17 Archived total, organic, and carbonate concentrations from the tilled field plotted against the midpoint of sample depth. The carbonate threshold represents the point where the carbonate concentration increases rapidly with increased depth.

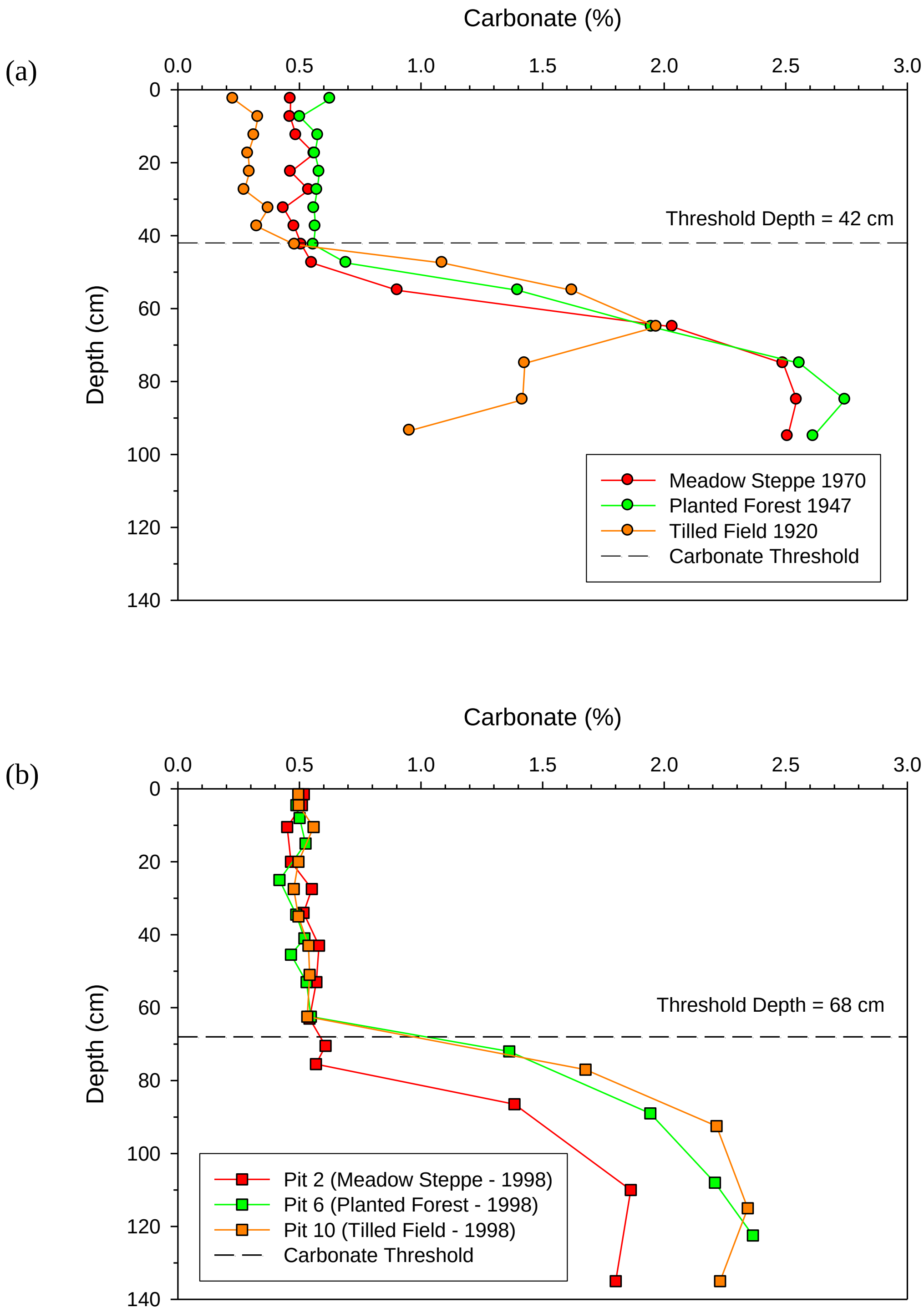


Figure 18 **Archived (a) and modern (b) carbonate concentrations plotted against the midpoint of sample depth. The carbonate threshold represents the point where the carbonate concentration increases rapidly with increased depth.**

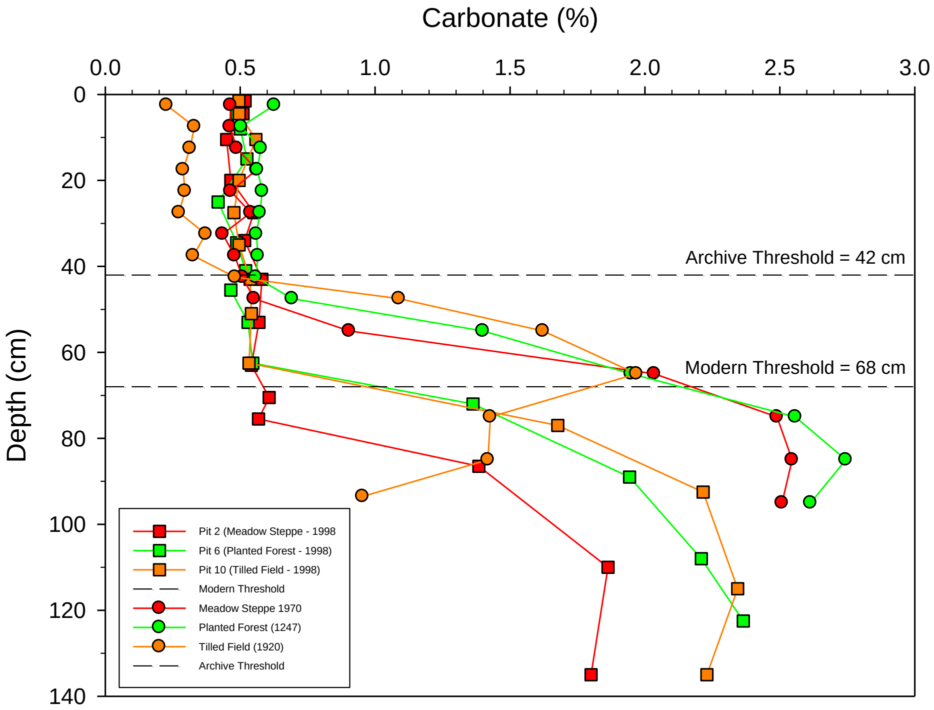


Figure 19 Archived and modern carbonate concentrations plotted against the midpoint of sample depth. The carbonate threshold represents the point where the carbonate concentration increases rapidly with increased depth.

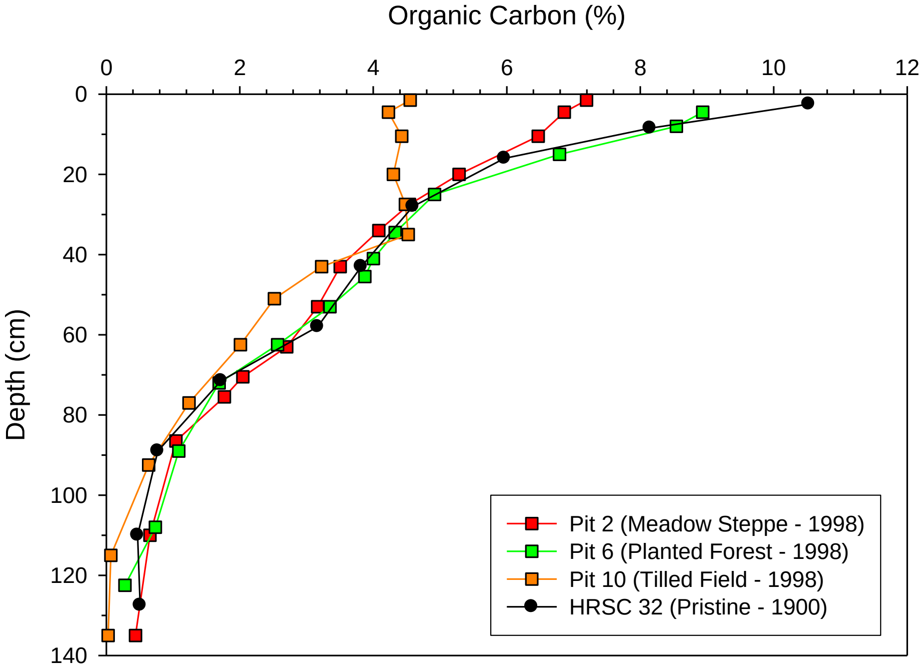


Figure 20 Archived pristine and modern organic carbon concentrations plotted against the midpoint of sample depth.

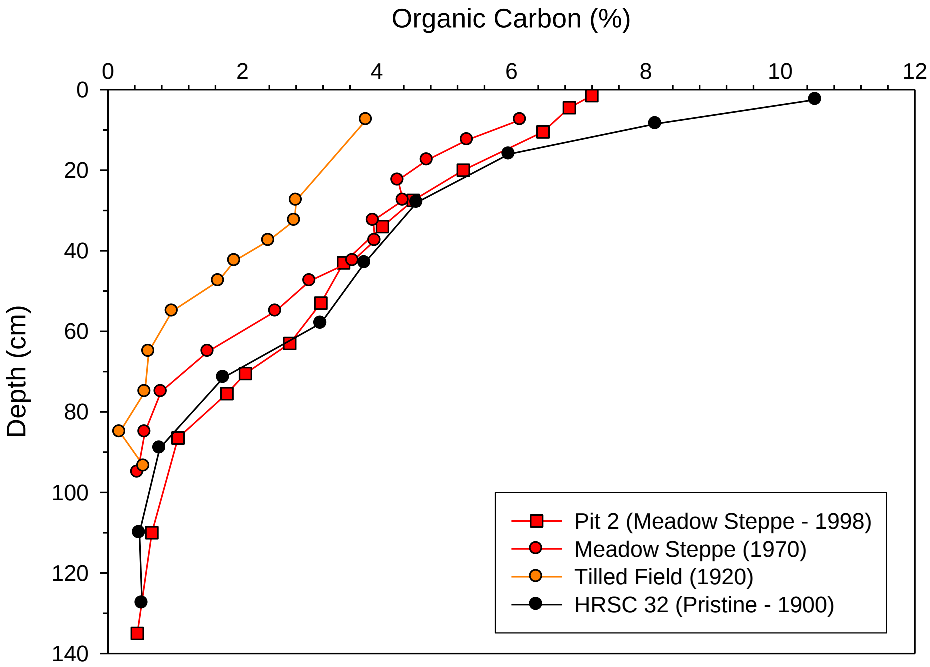


Figure 21 Archived and modern organic carbon concentrations from the meadow steppe plotted against the midpoint of sample depth.

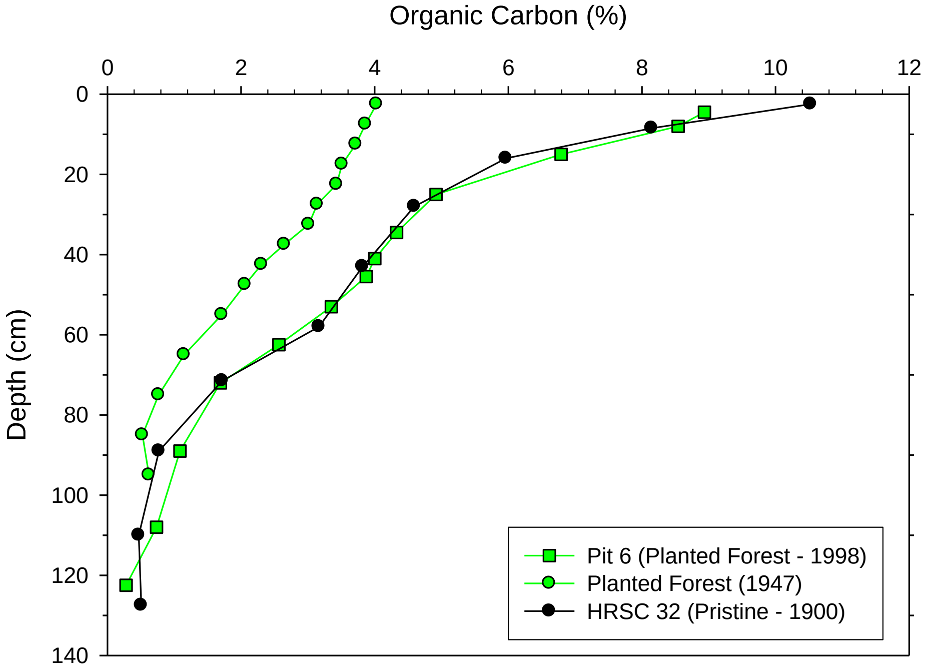


Figure 22 Archived and modern organic carbon concentrations from the planted forest plotted against the midpoint of sample depth.

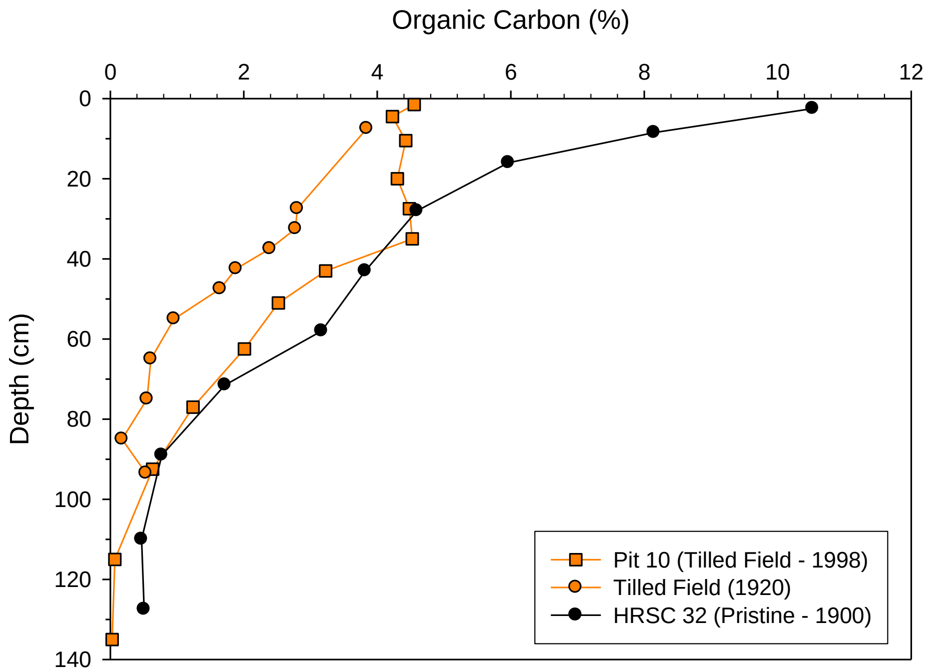


Figure 23 Archived and organic carbon concentrations from the tilled field plotted against the midpoint of sample depth.

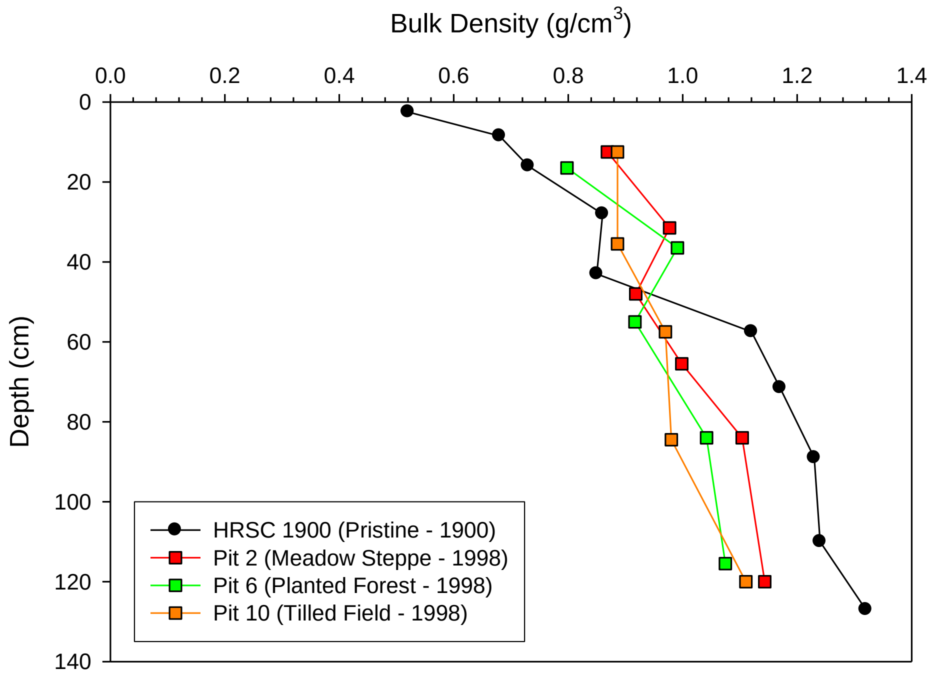


Figure 24 Archived pristine and modern bulk densities plotted against the midpoint of sample depth.

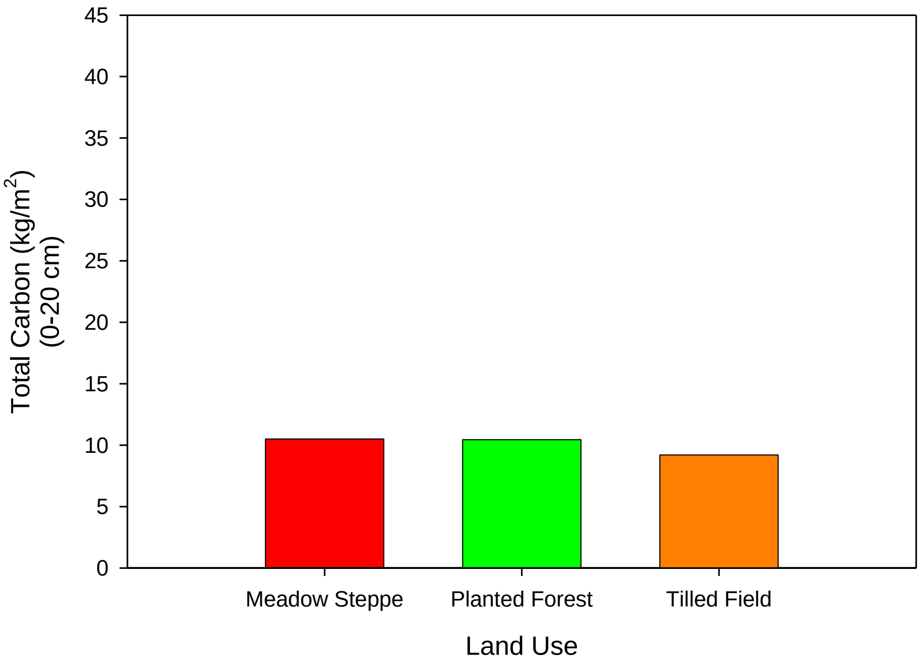


Figure 25 Modern total carbon stocks in the top 20 cm of soil in the different land use types.

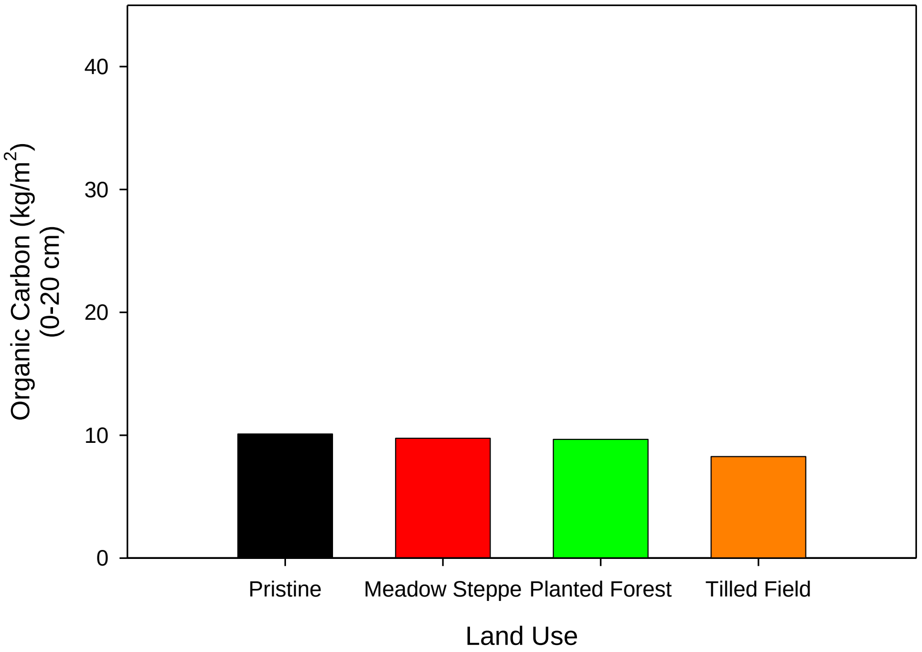


Figure 26 Archived pristine and modern organic carbon stocks in the top 20 cm of soil in the different land use types.

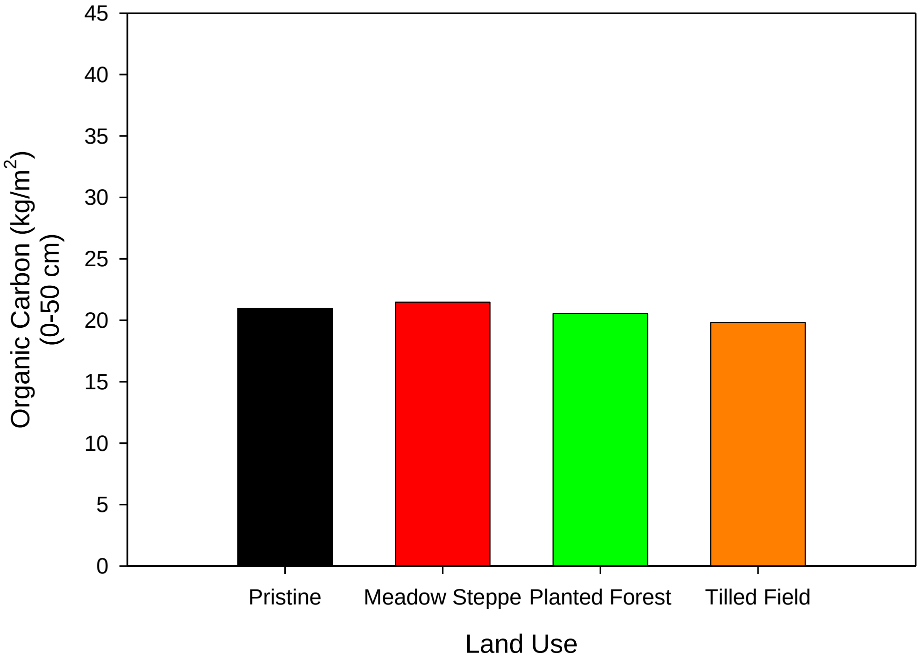


Figure 27 Archived pristine and modern organic carbon stocks in the top 50 cm of soil in the different land use types.

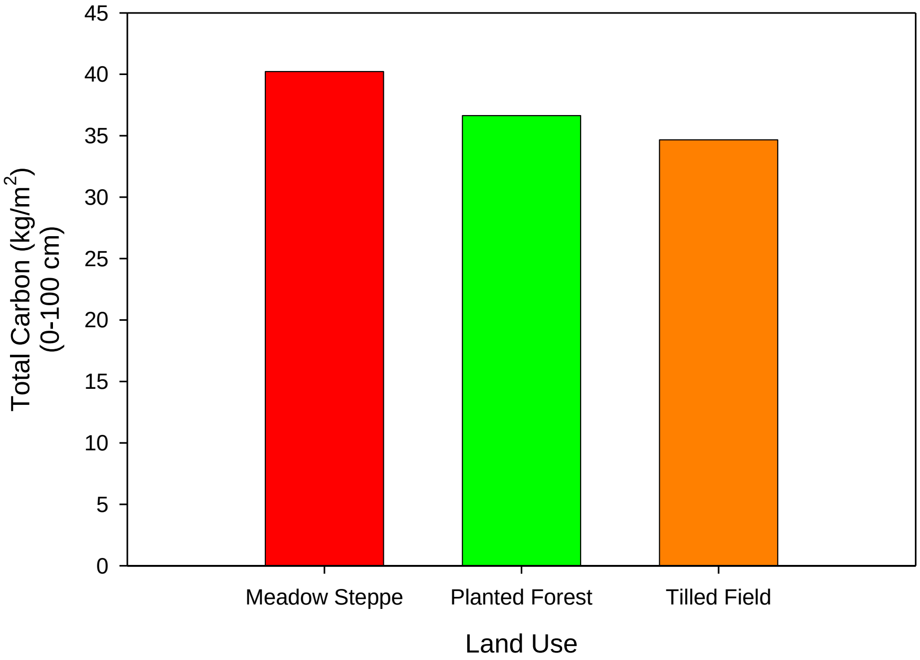


Figure 28 Modern total carbon stocks in the top 100 cm of soil in the different land use types.

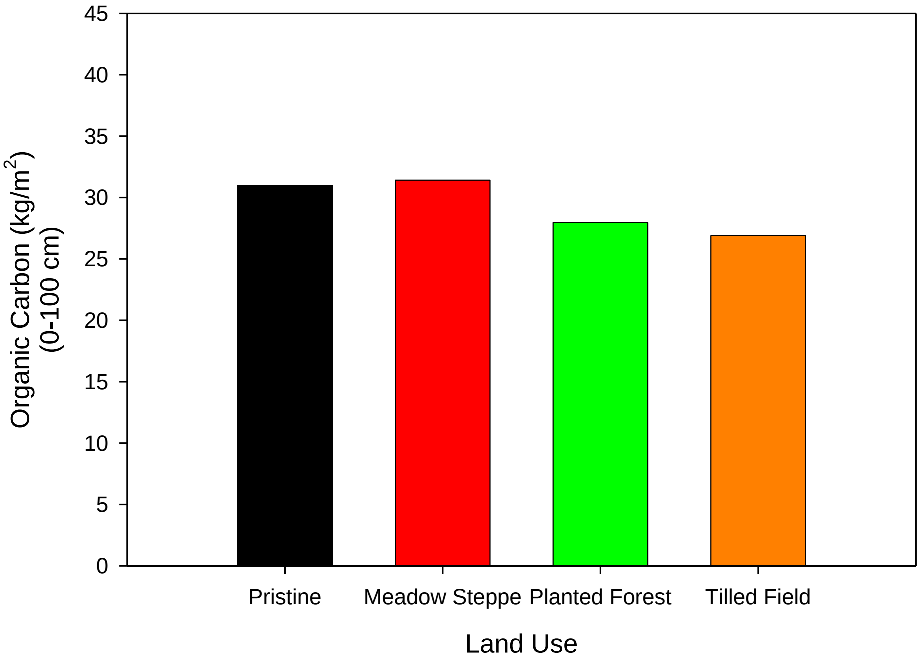


Figure 27 Archived pristine and modern organic carbon stocks in the top 100 cm of soil in the different land use types.