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Soil Formation in the Canadian Prairie Region

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Summary

The Canadian Prairies is a vast region with a cool and generally dry climate, strongly influenced by the mountains on the west and the northern latitude. Regular variation in climate influences the kind of natural vegetation, in turn resulting in regular or zonal changes in soil. Soils range from Brown Chernozems in the dry Mixed Grassland to Black Chernozems in the moister Aspen Parkland and Gray Luvisols in forested regions. Within soil zones, regular differences in the kind of soil depend upon other soil-forming factors, particularly the kind of geological deposit (parent material), topography, time, the influence of ground water, and the impact of humans on soil. Soil is part of nature and its properties and occurrence can be related to those natural and human factors influencing both its formation and present-day processes.

Introduction

The Canadian Prairies, part of the Interior Plains, lie within the continental interior of North America[1]. The Cordilleran (Rocky) Mountains are to the west and the Canadian Shield to the north and east. The southern boundary is a political boundary, the USA-Canada border at 49^{O} North. The Great Plains extend as far south as Texas. The Prairies have a cool and generally dry climate, strongly influenced by the mountains to the west and their northern latitude. It has been said that no other agricultural region has a similar combination of both aridity and cold temperatures, making the success of agriculture all the more satisfying. The Prairies do have fertile soils, and is a vast agricultural region. Depending upon one's perspective, it is either a breadbasket for the world or one of the world's most 'disturbed' ecological systems because of the high proportion of land converted to agriculture[9]. The Prairies are a special region from the perspective of soil formation. Gradual and consistent changes in climate and native vegetation have resulted in distinct soil zones. The subject of this article is a description of the factors that determine the kinds of soil (the soil-forming factors) and the processes that have and are forming soils.

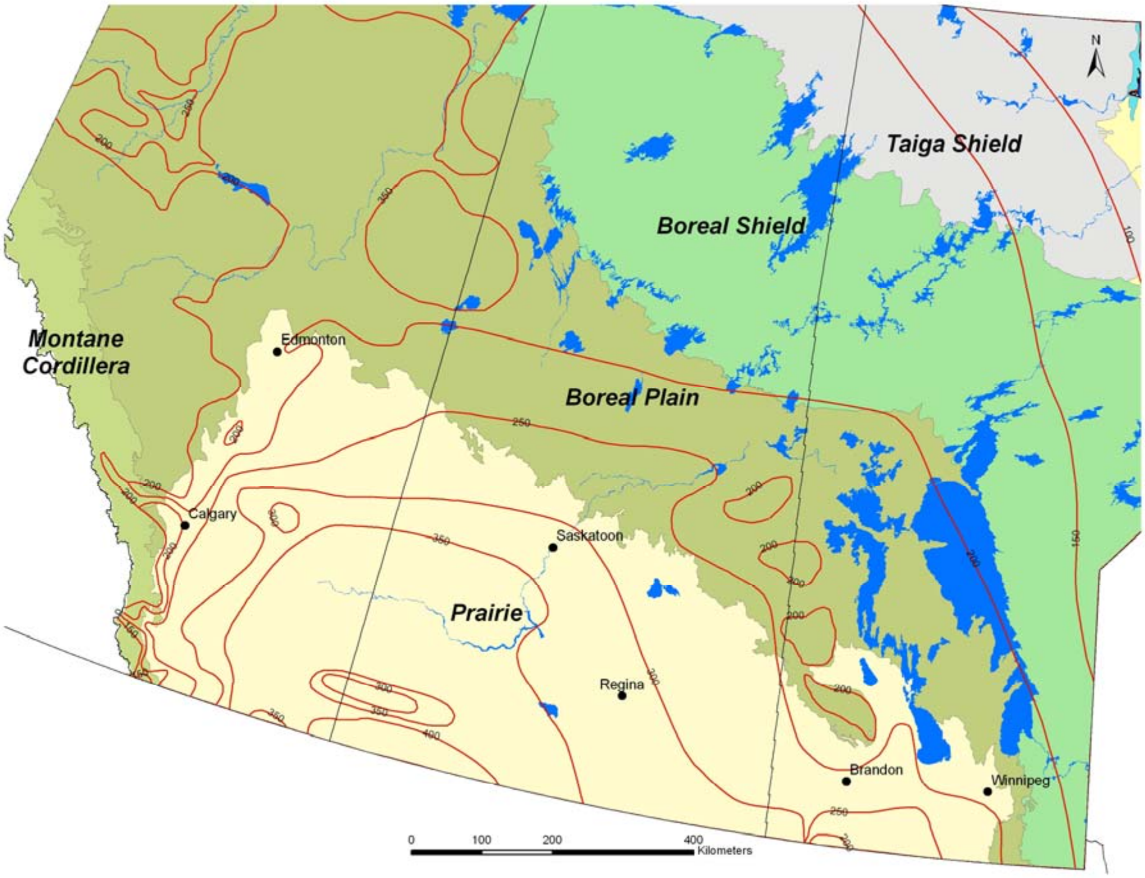
Factors of Soil Formation

Professor J.H. Ellis, in his 1938 book, The Soils of Manitoba, was among the first to list seven factors of soil formation[7]. In addition to the usual list of five (climate, parent material, vegetation and other biota, topography and time) he included the impact of humans and groundwater as soil-forming factors.

Climate

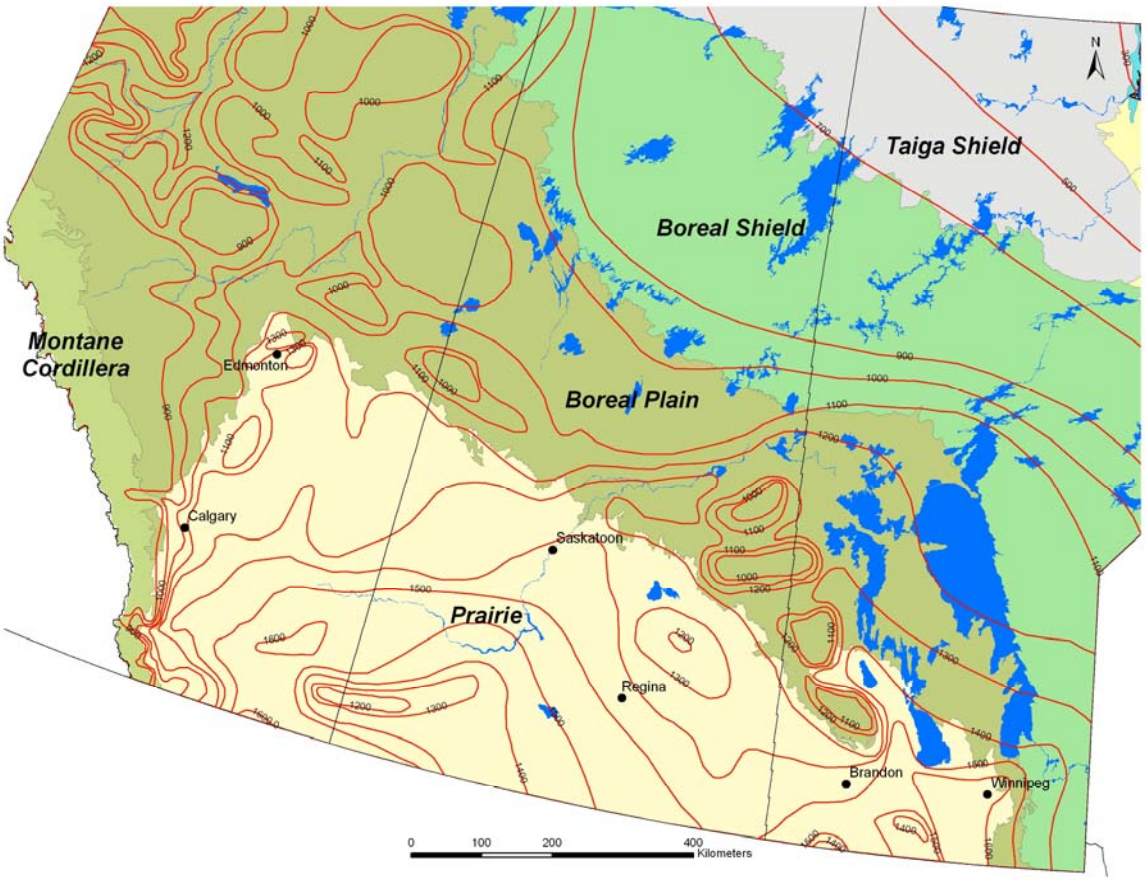
The Prairie region is cold and dry, but with considerable variation that strongly influences both soil formation and agriculture today. The driest area, occurring in southwestern Saskatchewan and southeastern Alberta, is well within the rain shadow of the western mountains. The area is known locally as the Palliser Triangle, and also as the Mixed Grassland Ecoregion, but commonly referred to as the Brown Soil Zone. Precipitation is just under 400 mm per year and droughts are frequent. The low precipitation coupled with a high demand for water by plants due to the warm, sunny and windy conditions result in a considerable water deficit. The climatic moisture index (CMI), calculated by subtracting the potential evapotranspiration from annual precipitation shows a water deficit of 400 mm in extreme SW Saskatchewan- SE Alberta (Fig. 1)[13]. Moving out from the Brown Soil Zone, west towards the mountains and northeast, the climate becomes gradually more moist, not so much from an increase in precipitation as from decreased evaporative demand due to the cooler, less windy conditions generally. The CMI is 350 mm at the boundary of the Dark Brown Soil Zone or Moist Mixed Grassland, marking the margin of the Palliser Triangle. The transition to Aspen Parkland Ecoregion or Black Soil Zone occurs at a CMI of 300 mm. Uplands of higher elevation within all zones are cooler and effectively moister than the plains. The Aspen Parkland gradually changes to more continuous aspen forest and then Boreal Forest, as the climate becomes more moist, now described as sub-humid, with precipitation of 400 to perhaps 500 mm in Manitoba and the Foothills, on average, each year) and the CMI in the range of 200 to 250mm.

Figure 1. The climatic moisture index for the Prairie Region. The CMI increases with increasing moisture deficit.



The climatic temperature index (TMI) is a measure of temperature, described as effective growing season degree days (EGDD). It is the cumulative number of days that the temperature is above 5°C.[13] For example, ten days of 25°C weather would be 10 times 25°C-5°C, or 200 EGDD. South-central Manitoba is warmer than other regions with EGDDs of 1600 in the Red River Valley (Fig. 2). The native vegetation of this warm and moist area was Tall Grass Prairie, marking the northern-most extension of this grassland type.[14] Southern Alberta near Lethbridge also has 1600 EGDD. Most of the Prairies has between about 1400 and 1500 EGDD, a range suitable for most cereals, oilseeds and pulse crops. The native vegetation is Mixed Prairie becoming Aspen Parkland in cooler areas. The number of EGDD decreases as one moves north or up in elevation, with uplands such as Riding Mountain in Manitoba and the Porcupine Hills in Saskatchewan having as few as 1000 EGDD. EGDD also decrease markedly in the Foothills region. The areas with cool temperatures and short growing seasons are generally forested, and have Gray Luvisol soils.

Figure 2. Effective growing season days (EGDD) for the Prairie region. EGDDs increase as growing seasons are warmer and longer.

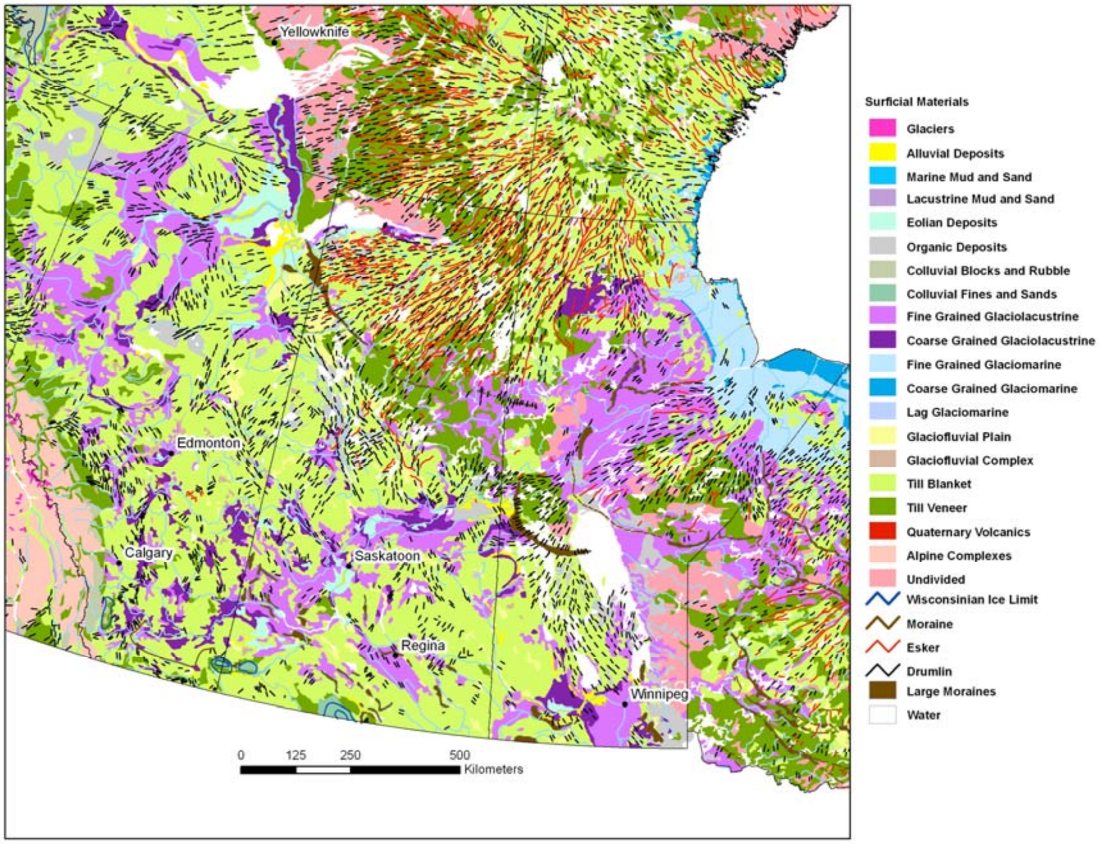


There are two aspects of the climate that are important to both soil formation and agriculture. One is that snow accumulates over the winter, resulting in large amounts of water at snowmelt, and the possibility of water being stored in the soil or moving through the soil to recharge the groundwater. The strong downward movement of water through the soil (leaching) occurs mainly when extra water is available from snowmelt, with the ponding of runoff from adjacent slopes, or after unusually heavy rains. The second important aspect is that about two-thirds of the annual precipitation is received in the early growing season, in May, June and July making its use in producing crops (or natural vegetation for that matter) all the more effective.

Parent Material

The geological deposit upon which soils form is called the parent material. The accumulation of the parent material may be considered the first step in soil formation[15]. Virtually all the soils of the Prairies are on unconsolidated, transported parent materials. The soils and landscapes of the region except for a few uplands such as the Cypress Hills show the impact of glaciation[16]. Continental glaciers (the Laurentide glacier) originating to the west of Hudson Bay moved south across the region at least four times in the past two million years. Cordilleran glaciers from the western mountains deposited glacial till in the Foothills region of Alberta. Parent material deposited directly by the melting glaciers is called glacial till, and covers nearly 2/3 of the region (Fig. 3)[8]. Glacial tills reflect the characteristics of the bedrock surfaces that the glaciers have passed over, and also may contain materials transported in the ice for hundreds of kilometers. The influence of limestone bedrock is evident in Manitoba, particularly in the Interlake region where the till contains 40% and more calcium carbonate and many limestone pebbles and cobbles (Fig. 4)[17]. The till becomes lower in carbonate as one moves west, particularly in northwestern Alberta. Interestingly, the higher carbonate of till in the Foothills near Calgary is a probable consequence of the origin of the till in the mountains.

Figure 3. Surficial geological materials in the Prairie Region[8].



Generally across western Manitoba and through much of Saskatchewan and Alberta, shale bedrock of the Bearpaw Formation underlie the till, resulting in clay loam textures and relatively low stone contents[16]. Even in those regions, the influence of materials of distant source are important to the composition of the glacial till. The geologist, FH Edmunds, in a chapter entitled Geology and its Relationship to Soils in Saskatchewan, in Saskatchewan's Soil Survey Report 12[12] wrote, "*It is considered that glaciation was of considerable economic benefit not only because the present topography is more favourable than the pre-glacial topography, but also because the physical and chemical composition of the surface material was improved.*" Edmonds mentions the unfavourable growth characteristics of the shale bedrock and its containing acid-forming pyrite minerals, and continues, "*Glaciation was effective at stirring up the bedrock material which lay at the pre-glacial surface. It incorporated with this material, fresh mineral matter, containing a good supply of potash and phosphorus from the Precambrian rocks and lime from the Paleozoic limestones".* In the western regions, particularly the Peace River Valley, there is little limestone to be mixed into the glacial till. The soils of the level lands within the Valley are developed from weakly calcareous, glaciolacustrine deposits, with thin glacial till deposits over pyrite-containing shale on uplands. The pyrite or iron sulphide oxidizes naturally to result in acidic soils, and the need for using lime to counteract the acidity.

Because the natural slope of the land and drainage is to the northeast, large glacial lakes often formed in front of the glaciers as they melted[16]. Water running into these proglacial lakes carried in sediments, with silty and especially clayey textured, glaciolacustrine deposits in the quiet waters of the lakes. Four huge areas with level landscapes and clayey soils are the Red River Valley of Manitoba, deposited in Lake Agassiz, the Regina Plains in Saskatchewan, formed by glacial Lake Regina, and the Peace River Lowland (Fig. 3). Many of the region's most fertile soils are of glaciolacustrine origin. Those that contain smectite or expanding clays have special characteristics. They shrink and form wide and deep cracks as they dry and swell as they re-moisten. The 'cracking clay' or gumbo soils are in the Vertisolic Order.

Fast-flowing waters in streams running from and through the melting glaciers result in sandy to gravelly glaciofluvial parent materials. Sandy materials, especially those deposited in deltas where streams entered glacial lakes (coarse-grained glaciolacustrine on Fig. 3) often have been further impacted by wind, forming aeolian landscapes with sand dunes, such as the Upper Assiniboine Delta east of Brandon in Manitoba. Wind-blown silty deposits or loess occur on the Swift Current Plateau and Cypress Hills of southwestern Saskatchewan and across southern Alberta.

Vegetation and Other Biota

Vegetation is important to soil formation. The carbon fixed by photosynthesis in plants becomes soil organic matter. Roots and organic substances bind soil particles together to form aggregates, making the soil more porous and enhancing the entry and storage of water in the soil. Plants shade the soil making it more moist and less subject to extremes in moisture and temperature. Microorganisms recycle nutrients as they decompose added residues, returning some of the carbon to the atmosphere as carbon dioxide, making humus in the process. Other microorganisms are able to use nitrogen from the atmosphere, adding it to the soil when they die.

Grasslands occurred across the drier parts of the Prairies at time of settlement with forest in more moist areas[14]. The kind of grass varied with climate and soil, but all add organic residues as roots decay, resulting in the build-up of organic matter in the soil. Forests, on the other hand add proportionately more residues above ground as leaf litter, resulting in a build-up of organic matter on the soil surface. Within the grasslands, the amount of vegetative growth increases with available moisture, increasing the feed stocks for organic matter production.

Archaeologists describe interesting connections among vegetation, animals and humans over the past few thousand years prior to settlement. The native peoples appear to have used fire to manage the vegetation, in order to attract bison to the fresh new grass. Fires kept the grassland-forest boundary further north and east of where it might have been without fire, in turn, influencing the nature of the soil.

Topography Elevation in the Prairies ranges from about 250 metres above sea level in the east, and slope upwards to the west, from the Manitoba Lowlands, to the Saskatchewan Plains in central regions, and the Alberta High Plains to the west of the Missouri Coteau, reaching about 1000 m at the Foothills of the Rocky Mountains[1]. The elevation decreases from north to south across the whole region. Fort Vermillion near the northern boundary of Alberta, for example, is at 250 m elevation. The land is reasonably level, particularly those parts with glaciolacustrine parent materials, such as those lands within the Manitoba Lowlands that were once inundated by glacial Lake Agassiz. As noted earlier, areas of low elevation generally have warmer and longer growing seasons, although the land in southern Alberta is an exception to this general rule, being both of relatively high elevation and warm.

About 60% of the Prairie region has an undulating (< 5% slopes) to hilly (up to 30% slopes) landscape known as hummocky moraine. This is a landscape formed as large areas of glacier simply melted at the time of deglaciation. This 'local' topography and its role in the redistribution of water and determining microclimate has a strong impact on soil formation, resulting in the systematic variation in soil profiles termed a soil catena. Uplands within the Prairie Ecozone or grassland region, even those only 100 or 150 metres above the grassy plain, have forests and Gray Luvisol soils.

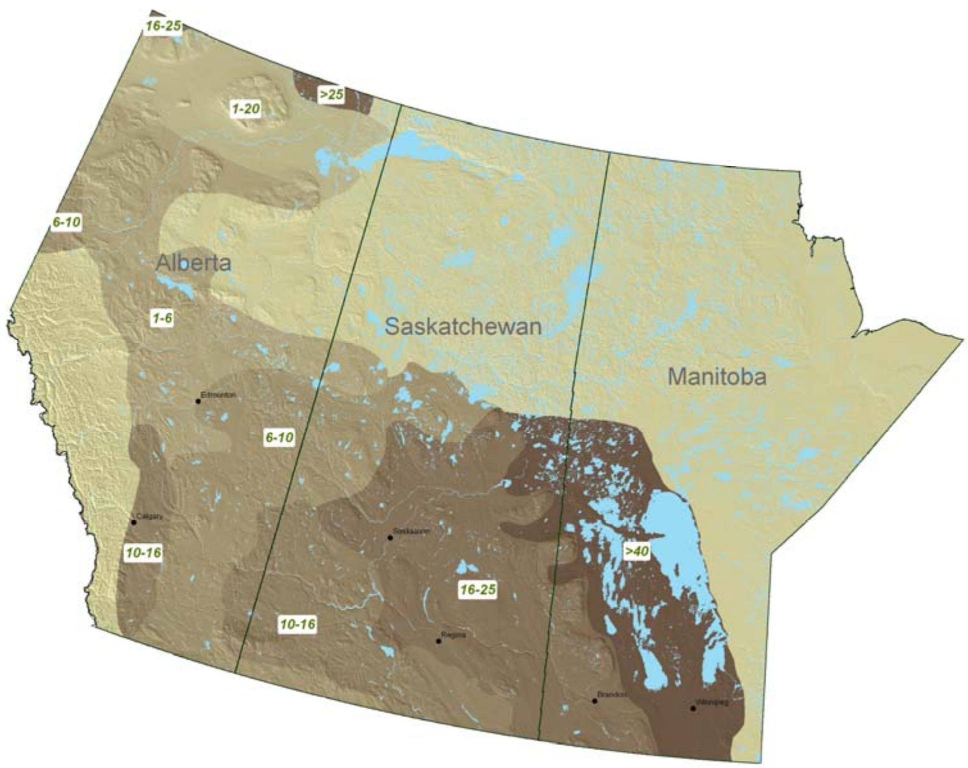
Time: Soil formation began as the glaciers melted, with the first land in southern Saskatchewan becoming ice-free about 17,500 years ago[6]. Deglaciation was complete in central parts about 12,500 years ago, and about 8,000 years ago in northern areas. Other geologists question some of Christiansen's radiocarbon dates and suggest that deglaciation started about 2500 years later[18]. An ice-free corridor developed as the mountain and continental glaciers receded about

13,000 years ago, with a cold desert vegetation[2]. Although ten or fifteen thousand years seems to be a long time, the soils of the Prairie region are young in comparison to those in many parts of the world and comparatively fertile because of the fresh minerals present. The youngest soils, perhaps only decades or centuries old, occur on the alluvial flood plains of present-day streams.

Groundwater Soils within the Central Interior Plains are influenced strongly by hydrogeology, particularly the depth to, and the direction of flow of groundwater. Uplands with deep water tables and a general movement to the water downwards to the water table (recharge) generally have more strongly leached or eluvial soils, especially Gray Luvisols. Lowland areas often have shallower water tables, and artesian pressure moving water toward the soil surface. Soils in eluvial landscapes tend to be deep and more strongly leached, whereas those in lowlands with shallow water tables are less strongly leached with soluble salts present. Strongly calcareous, Solonetzic and saline soils occur where water moves upward from shallow water tables carrying along dissolved salts.

Human Influences on Soil Many soil landscapes are influenced by human activities. As suggested earlier, man's influence on the soils of the Plains may have been first through the use of fire to control vegetation. Burning kept the forest-grassland further north, maintaining grassland and Chernozem soils on lands that became Gray Luvisol soils as fires were controlled by settlers and forest invaded the grassland[5]. The plowing of the grasslands that began about 125 years ago removed the protective cover of vegetation and increased soil erosion in many areas. The former practice of leaving land in fallow every second or third year while controlling weeds with cultivation, resulted in a considerable decline in soil organic matter, often about 20 to 30 % of the initial store[11]. Many tillage machines move soil down slope by the process termed tillage erosion, resulting in thinner soils on convex upper slopes and over-thickened soils on concave, lower slopes.

Figure 4. Lime content (% calcium carbonate equivalent) of glacial tills in the Prairie Region, modified from St. Arnaud[17].



Processes of Soil Formation

Early soil scientists thought of soil as basically disintegrated rock with some organic matter present. That first idea was replaced with the concept that soils were more than weathered rock. Soil profiles are made up of genetically related horizons that result from a particular combination of soil-forming factors at a particular location. The changes that transform the initial parent material into a soil profile with distinctive horizons are, collectively, called soil formation, sometimes soil genesis and, in a more technical way, pedogenesis. The early ideas about soil formation talked about those processes that resulted in a particular kind of soil and, despite descriptive terms such as podzolization, solodization and so on, were poorly understood. Roy Simonson (1958), a famous American soil scientist proposed that soil formation could be regarded as consisting of two major steps.[3,15]

1. The accumulation of the parent material
2. The differentiation of the horizons within the soil profile by processes of:

Additions: Materials not present in the parent material are added to the soil. The most obvious addition to prairie soils is organic matter, added as plants containing carbon fixed by photosynthesis are added to the soil as the plants die[3]. Also added in the organic matter is nitrogen obtained from the atmosphere and fixed by microorganisms, often in cooperative relationship with plants known as legumes. The nitrogen becomes part of the soil organic matter, building a store that is critical to nitrogen supplies to non-leguminous plants. The addition of organic matter results in the formation of the dark-coloured surface (Ah) horizons so typical of prairie soils, and makes the soil a better place for plants to grow by its action to form aggregates and a structure with pores of varying size, important to water retention and to drainage of the soil, aeration, providing channels for roots to grow through and the living space for microorganisms.[10]

Removals: The downward movement of water from rain or snowmelt through the soil is able to dissolve soluble components, moving the soluble constituents to greater depths. Where soluble materials, particularly the more soluble salts, are moved right out of the soil and to the deep subsoil or water table, the process is termed ‘removals’ or leaching. Removals are important in that a build-up of soluble salts results in saline soils, although strong leaching as occurs in high rainfall areas results also in a loss of nutrients and the development of soil acidity. Interestingly, soils are able to retain finite but often adequate amounts of nutrients and important elements against the forces of leaching as cations (potassium, calcium and ammonium, for example) adsorbed to negatively charged clay minerals, and as part of the organic matter (nitrogen and phosphorus and many trace elements)[4]. Soils are complex and elegant systems.

Transfers or translocations of materials: Some soil components are moved but not lost from the soil profile. Calcium carbonate, for example, may be dissolved by the slightly acidic rainwater moving through the upper horizons but precipitate again in a lower horizon where chemical conditions are different. Clay minerals are the smallest particles in soil, less than 0.002 mm in diameter. Fine clays are even smaller, less than 0.0002mm. When fine clays exist as individual particles, they can be washed downward by water moving through the pores of the soil. This results in the translocation or transfer of the clay from an upper eluvial (Ae) horizon to a lower, illuvial (Bt) horizon. Clay translocation, also known by the more technical term, lessivage, is the main process in Gray Luvisol soil. The process by which clays exist as individual particles rather than in the clumps known as aggregates is called dispersion. Dispersion in most soils results from the loss of cations such as calcium that favour aggregation, and increased presence of H^+ cations that favour dispersion. Interestingly, and related to their formation, in Solonetzic soils the dispersion of the clay particles and the solubilization of organic matter results from the presence of moderate amounts of sodium cations.[3]

Transformations: Changes in the characteristics of a soil component are known as transformations. The gradual changes in the composition and chemical structures of organic matter added as plant residues and gradually forming the complex, dark-coloured material known as humus is an example of a transformation. Minerals present in the parent material are transformed to new forms in the soil. For example, most of phosphorus in the parent material occurs as the mineral apatite. Apatite is the initial source of the phosphate ions that plants and animal require for their growth, and is thereby transformed into organic phosphorus form. Some of the phosphate ions released into the soil solution by weathering form complexes with calcium (especially in calcareous soils) and become calcium phosphates, whereas in more weathered and acidic soils, iron or aluminum phosphates form.[4]

Simonson considered that all four basic processes are active to some degree in all soils. It is the balance within the combination of changes (processes) that determines the ultimate nature of the soil horizons and the soil profile. The main process in the Chernozem soils of the grasslands is the addition of organic matter, but the transformation of the plant and microbial residues to humus is important as well[4]. Clay translocation is the dominant process in the Gray Luvisol soils, but organic matter additions although less than in the Chernozems are still significant. Similarly clay translocation occurs in many grassland soils, becoming a more significant process in those more moist soils with stronger weathering and leaching known as 'eluviated' Chernozems.

Concluding Discussion

The foregoing discussion has stressed those factors that determine the kinds of processes that form soil. One intention of the discussion is to stress that soils are part of nature. The soils within a region have particular characteristics for a combination of reasons. Those reasons, the processes and the characteristics of the soils, and their capability for agriculture are discussed more fully in the following chapters.

References

1. Acton, D.F., revised by A. Bedard-Haughn. 2011. The Interior Plains, Physiographic Regions. www.thecanadianencyclopedia.com
2. Adams, Jonathan (not dated) North America during the last 150,000 years. Accessed 30-04-2010 at http://www.esd.ornl.gov./projects/nercNORTHAMERICA.html
3. Anderson, D.W. 1987. Pedogenesis in the grassland and adjacent soils of the Great Plains. Adv. Soil Science 7:53-97.
4. Anderson, D.W. 1988. The effect of parent material and soil development on nutrient cycling in temperate ecosystems. Biogeochemistry 5:71-97.
5. Campbell, C., Campbell, I.D., Blythe, C.B., McAndrews, J.H. 1994. Bison extirpation may have caused aspen expansion in Western Canada. Ecography 17: 360–362
6. Christiansen, E. A, 1979. The Wisconsinan deglaciation of southern Saskatchewan and adjacent areas. Can. J. Earth Sci. 16:913-938.
7. Ellis, J.H. 1938. The soils of Manitoba. The Dep. Agriculture and Immigration, Province of Manitoba, Winnipeg, MB.
8. Fulton, R. J. 1995. Surficial materials of Canada, "A" Series map 1880A.
9. Gauthier, David A. and J. David Henry. 1989. Misunderstanding the Prairies. In Monte Hummel (ed), Endangered Spaces, Key Porter Books. pp183-193.
10. Greenland, Dennis L. 2006. Soil: the essence of life and its interaction with other natural resources. Encyc. of Soil Science: 1642-1643.
11. Gregorich, E.G. and D.W. Anderson. 1984. Effects of cultivation and erosion on soils of four toposequences in the Canadian Prairies. Geoderma 36:343-354.
12. Mitchell, J., H.C. Moss and J.S. Clayton.1944. Soil Survey Report No. 12. University of Saskatchewan, Saskatoon, SK.
13. Pettapiece, W.W. 1995. Land suitability rating system for agricultural crops. Technical Bulletin 1995-6E, Centre for Biological Resources Research, Research Branch, Agriculture and Agri-Food Canada.
14. Rowe, J. Stan. and Robert T. Coupland. 1984. Vegetation of the Canadian Prairies. Prairie Forum 9:231-248.
15. Simonson, Roy W. 1958. Outline of a generalized theory of soil formation. Soil Sci. Soc. Am. Proc. 23:152-156.
16. Simpson, Mark. 1999. Quaternary geology. In Fung, Ka-Iu (ed) Atlas of Saskatchewan. University of Saskatchewan, Saskatoon, SK. pp 84-87.
17. St. Arnaud, R.J. 1977. Pedological aspects of glacial till. In Robert F. Leggett (ed), Glacial till, an interdisciplinary study. Royal Society of Canada. Ottawa, ON. 133-155.
18. Teller, James T., Stephen R. Moran and Lee Clayton. 1980. The Wisconsinan deglaciation of southern Saskatchewan and adjacent areas: Discussion. Can. J. Earth Sci. 17:539-541.