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Cultivated Gray Luvisol Soils of the Prairie Region

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Summary

Gray Luvisol or Gray Wooded soils occur in the cool and moist forest regions of Western Canada, from southeastern Manitoba, across the northern plains to the foothills of the mountains on the west. They have grayish coloured, leached surface (Ae) horizons and clayey subsoil (Bt) horizons where the main soil-forming process is the downwards movement or translocation of clay minerals. When cultivated, the generally silty, low organic matter surface horizons are of poor tilth and generally deficient in nitrogen, phosphorus and sulphur. The clayey Bt horizons are slowly permeable to water and difficult for roots to grow into. Despite these limitations, and the cool climate that limits the range of crops, Gray Luvisols can be improved with good farming. Appropriate fertilizer management, returning organic residues and manure to the soil, and forage cropping all lead to better and more productive soils.

Introduction

The principal (zonal) soils in the subhumid Boreal Forest region of the northern Great Plains and the Foothills of the Rocky Mountains are Gray Luvisols. These are forest soils with leached surface horizons that have formed mainly in medium and fine textured, calcareous materials. The principal processes have been the movement of soluble salts, carbonates and then clay downward. The result is an ashy, platy structured Ae horizon and a more clayey, usually blocky Bt horizon at 20 to 80 cm[11,16]. Gray Luvisols were originally called Gray Wooded soils because of the gray Ae horizons and general occurrence under forest. Indeed Canada was the first country to recognize and name these soils as being fundamentally different from the acidic Podzols of Europe and eastern North America[9].

Gray Luvisols are typical for nearly all the forested lands in western Canada. However, much of the more northern and higher elevation areas have climates that have been too cool for grain farming. Arable agriculture is confined to the southern Boreal - the mixed wood forests dominated by aspen. This covers two main ecoregions, the Boreal Transition of southern Manitoba, central Saskatchewan and Alberta and the Peace Lowland of northwestern Alberta and adjacent British Columbia[7].

Agriculture is limited mainly by the cool and relatively short growing seasons, and by soil characteristics. Ap horizons derived mostly from Ae horizons are gray with low organic matter contents and often silty texture, resulting in poor structure. Bt horizons are clayey, often limiting the percolation of water and root growth. Gray Luvisols, however, are responsive to good management, and are productive with appropriate use of fertilizer, manures and legume cropping to build soil organic matter (sequester carbon) and improve tilth. The following discussion will be confined to those soils that fall within the agricultural zone.

Gray Luvisol Characteristics and Classification

A typical non-cultivated profile (Fig. 1) has 5-15 cm of leaf litter (LFH); a thin, 2-5 cm dark grey, granular surface mineral horizon (Ah); 5-15 cm grey, platy Ae; a 5-10 cm, often dull grey-brown, loamy to clayey, granular to blocky horizon (AB); a thick, 20-50 cm, strong brown, blocky, usually heavy clay loam horizon (Bt); grading into the parent material (Ck) containing lime carbonate.

A typical cultivated profile (Fig. 1) usually has a 10-20 cm mixed, silty or loamy Ap horizon. With incorporation of organic residues the organic matter content increases and the classification may change to Dark Gray Luvisol even Dark Gray Chernozem as the horizon gets darker. The Gray Luvisol Great Group includes intergrades to other orders with the main variants being thicker Ah horizons (Dark Gray Luvisols), tough, clayey, columnar Bt horizons (Solonetzic Gray Luvisols) and imperfectly drained (Gleyed) subgroups.

Gray Luvisols are classified generally in the Alfisol Order, the Cryalf Suborder, and the Haplocryalf Great Group of the USDA Soil Taxonomy [18]. Because most Gray Luvisols are not strongly acidic they are Eutric Haplocryalfs, or Mollic Haplocryalfs where thick relatively dark Ap horizons are present.

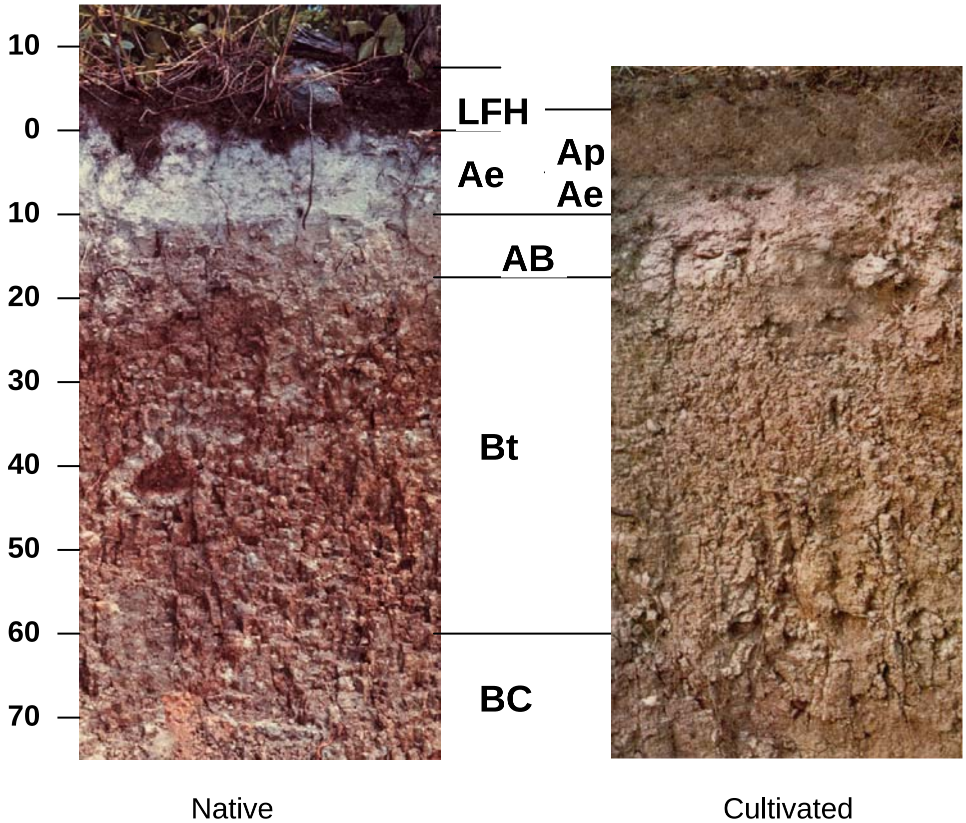


Figure 1. Native and cultivated Orthic Gray Luvisol profiles.

Factors of Soil Formation (the ecological setting)

There are six factors of soil formation of importance to Gray Luvisols: climate, parent material, vegetation and other biotic components, topography and drainage, time, and the influence of humans, as discussed on a Prairie-wide basis in a companion paper[2].

Climate: Gray Luvisols develop under cool and moist climates and forest vegetation. At the time of agricultural development, the Frost Free Period was about 100 days (80-110), with an effective growing season heat accumulation of about 1150 Growing Degree Days (1000-1250), and annual precipitation of about 450 mm (350-550), a growing season precipitation of about 300 mm and a moisture deficit index of about 200 mm[8]. In general it is warmer in the east and cooler in the western and northern reaches of the area. Recent data indicate a warmer and longer growing season[1].

Surficial Geologic Materials: In the Manitoba Lowlands, the cultivated Luvisols occur mainly on glaciolacustrine clays in the southeast area around Pinawa, and medium textured glaciofluvial deposits along the Manitoba escarpment. The Interlake area is dominated by very stony, very high carbonate till[15].

The Saskatchewan and Alberta Plains are dominated by medium-textured glacial till. Clay content generally increases and stoniness decreases from east to west. Carbonate contents also decrease along this transect from about 20% in the east to 5% in the west[2]. These trends reflect the movement of the glaciers away from the granitic Canadian Shield and the adjacent carbonate bedrocks onto the shales and sandstones of the central plains. There are small areas of glaciofluvial sands and glaciolacustrine silts and clays[17].

The Peace Lowlands have mainly clayey glaciolacustrine deposits. Fine-textured tills are common around the lake margins. Medium- and coarse- textured deposits occur where flowing water carried sediments into the glacial lakes, forming deltas. The northernmost (Fort Vermilion) area has medium and coarse textured materials[13,17].

Vegetation: Forest vegetation is a key factor in the formation of Gray Luvisols. Aspen forests are most common on uplands within the Aspen Parkland and in southern parts of the Boreal Forest, grading to mixedwood (mainly aspen with white spruce) stands as the climate becomes cooler and more moist further north. Grasses, forbs and shrubs are more common in the understory of the aspen forests in the south.

Topography and Drainage: Most of the northern Great Plains has undulating to hummocky glacial landscapes with about 80% of the area draining to local depressions with wetlands[17]. The proportion of poorly drained soils increases with increasing latitude and elevations concomitant with a cooling climate. Gleysolic soils are discussed more completely in a companion article[3].

There is often an additional concern related to near-surface perched water tables associated with the slowly permeable Bt horizons. Problems in agriculture occur where clayey, slightly saline glaciolacustrine subsoils may be almost impermeable, leading to saturated surface conditions.

Time: Gray Luvisols occur generally on deposits exposed after the last glaciation that are about 10,000 years old[2]. The present climate and vegetation were more or less established about 3000 years ago.

Humankind: The most obvious effect of humans on Gray Luvisols has been the clearing of the forest and the cultivation of the soil. This profoundly affects the upper horizons, mixing the organic LFH horizon with the Ae to form an Ap horizon. Where a high proportion of the organic materials, and perhaps some Ah horizon, have been worked in, the Ap horizon is darker, the soil is classified as a Dark Gray Luvisol when remnant Ae remains, or as a Dark Gray Chernozem where the Ae has been completely mixed in.

Humans may have influenced the nature of some prairie soils by preventing forest invasion of grassland by burning the prairie. Fire, whether natural from lightning or set by Indigenous peoples, appears to have kept the boundary between aspen forest and grassland further north than climate alone would dictate, or at least fluctuating[5]. This is supported by the rapid increase is aspen forests with the reduction in fires after settlement and may account for the many Chernozem-Luvisol intergrades (eluviated Chernozems, Dark Gray Luvisols) along the prairie-forest boundary.

Horizon,Depth,cm	pH	Org C, %	CaCO3%	Sand,%	Silt,%	Clay,%	F.Clay, %
LFH, 1-0	5.9	32.9	0				
Ae, 0-18	6.2	0.30	0	61	34	4	0
Bt, 18-45	6.6	0.37	0	48	26	26	17
Cca, 45-60	7.8		13	56	27	16	8
Ck1, 60-90	7.9		10	57	27	16	8
Ck2, 90-120	7.9		10	57	27	15	8

Figure 2. An Orthic Gray Luvisol developed from sandy loam, calcareous glacial till in the Boreal Forest of Saskatchewan. The soil is acidic only in the LFH and Ae horizons, with a very low organic C content in Ae and Bt horizons. The low clay content of the Ae and marked gain in clay, particularly fine clay, in the Bt indicates the strong translocation of clay.

Processes of Soil Formation

There are two aspects to this discussion, the processes leading to the formation of Gray Luvisol soils and other significant soil forming processes that occur in the “Luvisolic Zone”.

Processes associated with Gray Luvisol: Under forest vegetation, leaf and other organic litter accumulate mainly on the mineral surface. Microorganisms gradually decompose the litter, and soil fauna mix it into the upper few centimetres of mineral soil, resulting in a mixture of discrete organic and mineral particles and organo-mineral complexes in aggregates[21]. Organic acids produced during decomposition in the LFH increase the acidity and weathering intensity[11].

Where forests develop there is enough moisture in parts of most years to have water moving from the surface to the water table. The most apparent soil processes are eluviation or leaching of clay, organic matter and sesquioxides from the surface horizons and illuviation (washing in) or accumulation of those materials in the subsoil[11]. This leads to the ashy coloured, often silty surface (Ae) horizons and the dark brown, clayey subsurface (Bt) horizons that are the hallmark of Gray Luvisol soils. However, before that can happen the surface horizons have to be conditioned by the removal of calcium carbonates (and more soluble salts) to create the slightly acid environment that is conducive to the solution of amorphous materials and the dispersion of clay[11]. Lower carbonate contents, coarser textures and higher precipitation all lead to stronger leaching and deeper horizons with more pronounced differences in colour, structure and clay contents.

Another feature of well-developed Gray Luvisol soils is temporary saturation of the surface horizon due to the clayey, slowly permeable Bt horizons. This results in several related processes. Ice lenses that form during freeze-thaw cycles cause the development of the typical platy structure of the Ae horizon[21]. Oxidation and reduction are associated with temporary saturation, leading to accelerated weathering of minerals, and the mobilization of iron (and aluminum). Interestingly, chemical weathering forms pits and fissures within sand particles, as observed on electron micrographs[12]. When the cracks are filled with water and freeze the sand particles break apart, resulting in the physical weathering of sand to silt observed in the Ae of Gray Luvisols[20]. Reddish mottles and small dark concretions in the Ae just above the Bt horizon are additional indicators of alternating oxidized and reduced conditions. Hydrolysis is also involved leading to increased acidification such that the lower part of the Ae and upper part of the Bt are typically the most acidic horizons in the profile. These temporary, saturated conditions have management implications that are discussed later in the Agricultural Characteristics section.

Where grasses and forbs increase in the understory because of fire or clearing, the greater accumulation of organic residues results the development of a deeper (5-10 cm) dark grey or even black Ah horizons, and Dark Gray Luvisol soils.

In more humid regions, high water tables in the lower landscape positions leads to reduced conditions (dull colours) or reddish mottling in a fluctuating water zone. The imperfectly drained soils are considered an intergrade to the Gleysolic Order, classified as Gleyed Gray Luvisols.

A less common process associated with Luvisols is solodization – the dispersion of clays to form extremely dense, very slowly permeable subsoils, similar to but not as strongly developed as the Bnt horizons of Solonetzic soils[11]. Solodization is normally associated with the dispersion of clay by sodium ions, an unusual process in strong leaching regimes. However, the glacial lake deposits of western Canada are all weakly saline and while not necessarily high in sodium do have a high proportion of exchangeable magnesium. This factor and the associated clayey textures results in solodic features. These soils are classified Solonetzic Gray Luvisols and are particularly common in the Peace Region of Alberta and B.C.

Other Soil Forming Processes in the Luvisolic Zone: Gleization or reducing conditions associated with high water tables is a principal process in the forested zone. High and often fluctuating water tables are associated with all depressional and many level areas as well. When the water table is close enough to the surface to keep it saturated for much of the year, the native vegetation becomes dominated by hydrophytic plants. Under these poor and very poor drainage conditions, gleization becomes the dominant process and are classified as Gleysolic soils[3].

In very sandy (almost no clay) or high carbonate parent materials, profile development is often weak. There may be some mellowing and oxidation with a resultant formation of a reddish brown Bm horizon, not the Bt of Gray Luvisols. These soils are classified in the Brunisolic Order[14].

Gleysols and Brunisols have quite severe limitations for agricultural production. With improved drainage, some Gleysols have been successfully cultivated but they often have continuing wetness, coldness and chemical limitations[3].

Typical Soil Landscapes

Introduction: The previous discussions have identified a range of climatic and drainage or moisture conditions as well as a variety of soil forming processes that occur in the zone of cultivated Gray Luvisol soils. The regional, climate related, controls are latitude and elevation while landforms provide the control for local soil distribution. Slope steepness and curvature are the key to distribution of water in the landscape which in turn controls the relative dominance of the various soil forming processes[6].

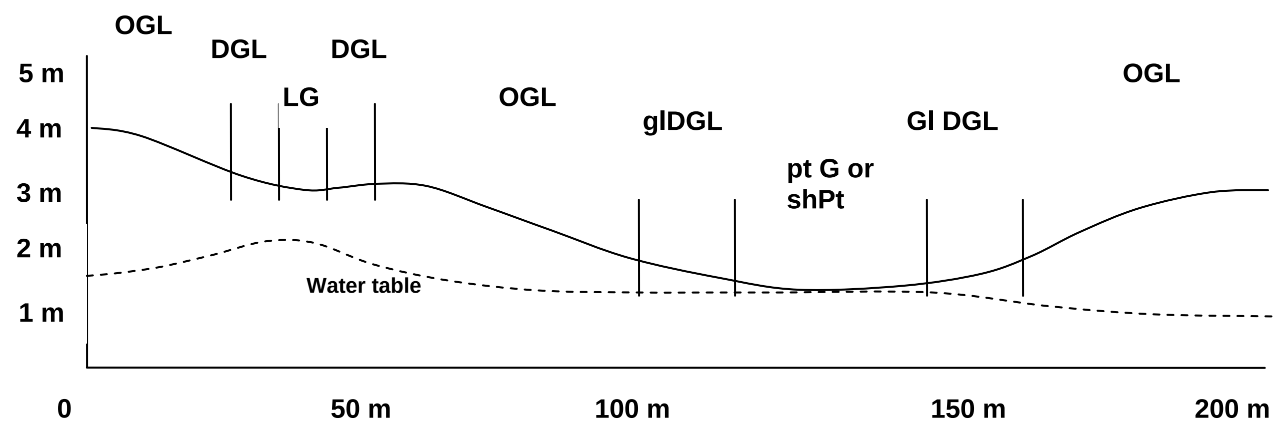
The combination of all the above forces results in typical combinations of soil characteristics – often referred to as “soil landscapes”[17].

Figure 3. A landscape with cultivated Gray Luvisol soils, and aspen forest in the background. Note the gray colour of the surface horizon, particularly on the slightly higher land with Orthic Gray Luvisols. The darker soils in lower areas are probably Dark Gray Luvisols and may be imperfectly drained.

Soil Landscapes of the Boreal Transition of the Alberta and Saskatchewan Plains: The glacial plains are dominated by undulating to hummocky landforms characterized by the occurrence of undrained depressions. In the cultivated areas the slopes are generally less than 5% and surface runoff is generally not overly rapid with time for infiltration. An exception can be during spring melt while the soil may still be frozen.

In the usual scenario, the well drained upper slopes have Orthic Gray Luvisol soils (Fig. 3). The slightly more humid, imperfectly drained lower slopes have thicker surface organic (LFH) horizons and faint mottles within 50 to 75 cm of the surface, and Gleyed Dark Gray Luvisols (Fig. 4). The lowest parts of the landscape, which accumulate water will usually have water tables near or at the surface for much of the year and will have accumulations of peat (peaty Humic Gleysols and Organic soils)[3].

However, the depth to the seasonal water table is critical with respect to the characteristics of the depressions. When deeper than about 50 cm in the summer, the increased water flow through the depressions results in quite strong leaching and the formation of Luvic Gleysols or Gleyed Gray Luvisols (Fig. 4).



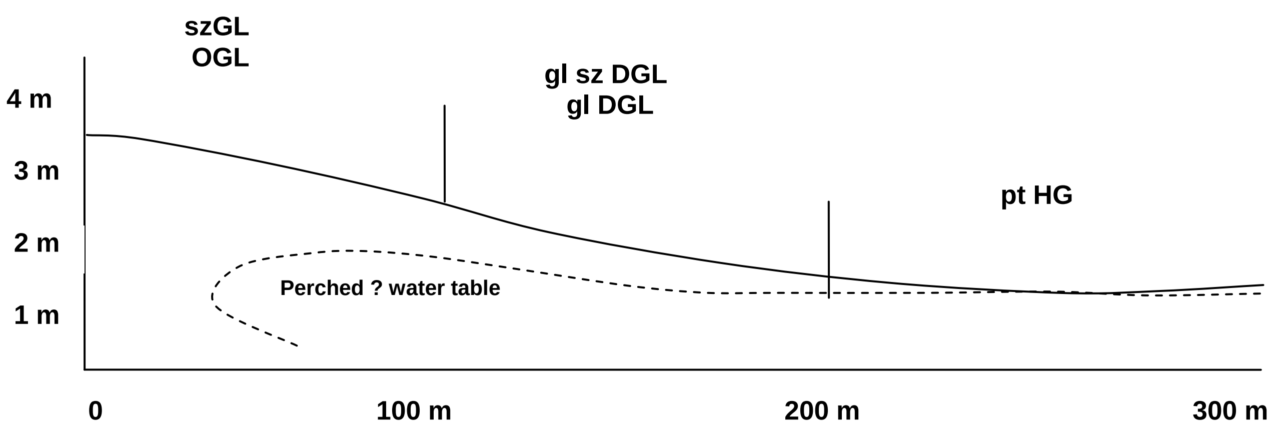
OGL = Orthic Gray Luvisol; DGL = Dark Gray Luvisol; gl DGL = gleyed Dark Gray Luvisol;
LG = Luvic Gleysol; pt G = Peaty Gleysol; shPt = shallow peat

Figure 4. Typical Gray Luvisol soil landscape in undulating glacial terrain.

Variations to the above model are common and predictable. Gently undulating landforms with slopes of about 2% usually will have more of the darker, imperfectly drained component and generally thinner peat accumulations[22]. On the other hand, the strongly undulating or hummocky landforms will have more contrasting soils, that is more Orthic Gray Luvisols on well-drained uplands and wetter depressions. The other major variation relates to the regional climate. In the warmer (more southerly or lower elevation) areas of the Gray Luvisol zone, as one approaches the Aspen Parkland, the original vegetation contained more grasses and forbs and less dense forests, probably due to more frequent fires. The result is an increase in Dark Gray soils in the upland and thinner peat accumulations in the depressions. Indeed there are often significant differences even in southern vs northern aspects, particularly noticeable on large hills or ridges, in this quite sensitive ecotone. In the warmer situation there will even be small areas of Chernozemic soils in the landscape. At the other cooler extreme there will be a decrease in the Dark Gray Luvisol component and an increase in the proportion of Organic (deep peat) soils.

Soil Landscapes in the Boreal Transition of the Peace Lowland: The same general considerations identified previously apply to the Peace Lowland. However, there are some differences in emphasis related to the finer textured materials and the generally smoother slopes[13].

The clayey glaciolacustrine parent materials are only slowly permeable and this is exacerbated by the formation of the dense, illuvial, B horizons (subsoils) which is often augmented by solonetzic-like dispersion of the clay materials. Combined with the long gentle slopes of the area, the result is a dominance of imperfectly drained or gleyed soils (Fig. 5). With long gentle slopes, there are fewer depressions in the region, compared to the undulating till plains, but, where they occur, there are often quite extensive.



sz GL = Solonetzic Gray Luvisol; gl sz DGL = Gleyed SolonetzicDark Gray Luvisol;
pt HG = Peaty Humic Gleysol

Figure 5. Typical Gray Luvisol soil landscape in gently undulating glaciolacustrine terrain.

For a significant portion of the Peace region, the cultivated Luvisols are located toward the edge of the glaciolacustrine basin. With increased elevations and local relief, there are more Orthic Gray Luvisols in the sloping areas and more Organic soils in the level or depressional portions of the landscape.

Other Considerations: In nearly all instances, agriculture development has been accompanied by improved surface drainage (often associated with the road network). This has resulted in lowering of water tables and gradually decreasing the depth and extent of peat accumulations.

The landscape considerations described for the Alberta and Saskatchewan Plains and Peace Lowlands can be extrapolated to other boreal areas. For example, the points made on Peace Lowland apply to the clayey soils of eastern Manitoba or the smaller glaciolacustrine inclusions of the glacial plains areas.

Agricultural Characteristics

Gray Luvisols present agricultural management problems that confronted the first settlers in the forested areas and remain as challenges today. These are discussed under the headings physical properties, chemical properties, and nutrient supplies.

Physical Properties: The two diagnostic horizons of Gray Luvisols, the sandy to silty, OM-deficient Ae, and the clayey Bt often have undesirable physical properties (tilth) for agricultural use[4]. The Ap horizons, composed largely of the former Ae horizons, are weakly aggregated, prone to pulverization when cultivated dry, and to puddling when wet. These reduce infiltration of water and increase runoff. Strong crusts that inhibit seedling emergence may form when puddled soil dries. There is a narrow range of soil moisture during which tillage should be done. Forage crops in rotation are especially beneficial. Returning crop residues (including green manures) and applying manure help to protect the soil surface and to maintain an actively decomposing pool of organic matter strengthens aggregates.

The subsoil horizons (Bt) have high bulk densities and low porosities, particularly in fine-textured Gray Luvisols. Slow movement of water through the Bt causes temporary saturation and puddling of Ap horizons and therefore increased runoff. Bt horizons can also restrict root growth and therefore the volume of soil from which water and nutrients can be extracted. Deep taproots of crops such as alfalfa may penetrate Bt horizons and open channels for air, water, and other roots.

Chemical Properties: Many Gray Luvisols, particularly in the western portion of the area, have acidic (low pH) Ap and upper Bt horizons. Low pH inhibits the nodulation of alfalfa and sweet clover roots by rhizobacteria, and thus their ability to use atmospheric nitrogen. Low pH often results in toxic levels of aluminum and manganese[4]. There is only a small portion of the Luvisol area with pH values acidic enough (< 5.5) to limit most crops but a much larger area has values of 5.6 to 6.0, which severely restrict alfalfa and sweet clover. Further, NH_4-based fertilizers and pollution from the atmosphere will eventually make soils more acidic. Growing acid-tolerant crops is currently the only practical management practice for acidic soils in the Prairie Provinces. Grasses are generally more tolerant than legumes. Alfalfa and sweet clover are very sensitive to acidity whereas red and alsike clovers are somewhat more tolerant. For cereal crops oats are most tolerant followed by wheat, then barley. Canola is similar to wheat. Application of lime (calcium carbonate or calcium/magnesium carbonate, **not gypsum**), as used elsewhere, is not economically practical in this area.

Nutrient Supply

Introduction: Plants require at least 16 to 18 nutrient elements to complete their life cycles. Most of these come from the soil. Nitrogen (N), phosphorus (P), and sulphur (S) are commonly deficient in Gray Luvisols, while potassium (K) and copper (Cu) are sometimes. Other micronutrients are rarely deficient now. Nutrients exist in soil in different inorganic and organic forms, they are released for plant use by different processes, and plants need different amounts. Thus they will be discussed separately.

Nitrogen (N): The total amount of N in Gray Luvisol profiles (to 1 m) is in the range of 4000 to 12,000 kg ha^{-1} and most came originally from the atmosphere by biological fixation during soil formation. Almost all of this is contained in soil organic matter and not available for plant use. Organic N is released as ammonium (NH_4^+) when soil organisms decompose the organic matter, and other organisms convert some of it to nitrate (NO_3^-). Plants use both nitrate and ammonium, the forms that soil testing labs measure. Nitrate is vulnerable to losses through leaching, or loss to the atmosphere when the soil is saturated.

The seeds of cereal crops and oilseeds remove 50 to 100 kg ha^{-1} and the straw contains 20 to 50 kg ha^{-1}. Forage crops remove 100 to 300 kg ha^{-1}. Inoculated legumes, grains or forages, obtain most of their N from the atmosphere, thus sparing the soil's supply and leaving some for subsequent crops. Nitrogen deficiency can be managed by growing legumes, returning manure, or applying fertilizers[4]. Common N fertilizers are urea (46-0-0) and anhydrous ammonia (82-0-0).

Phosphorus (P): Total P in Gray Luvisol profiles (to 1 m) ranges 4000 to 7000 kg ha^{-1} and unlike N it came originally from minerals in the parent material. Due to biological processes during soil formation up to one half of the P, especially in surface horizons, is now in the organic matter. Also, unlike Chernozems, there was considerable loss of P from upper horizons during soil formation, and that P has not accumulated in the subsoil, a unique situation among Canadian soil ecosystems[11,19,23]. The concentration of P in the soil solution is very low at any time and must be renewed many times during the growing season to supply plants adequately. This is accomplished by soil organisms decomposing organic matter, and by release of P from mineral (inorganic) surfaces. Phosphorus exists in soil solution as inorganic anions ($H_2PO_4^-$, $HPO_4^=$), the forms that plants take up. Common soil tests measure P in soil solution plus some held on mineral surfaces; potentially available P in organic forms is usually not included.

Crops remove some 10 to 20 kg ha^{-1} in the harvested parts. Most cultivated Gray Luvisols are low in plant-available (soil test) P so addition from manure or fertilizers is generally required. The usual fertilizer is mono-ammonium phosphate (11-55-0). Phosphate anions are not easily mobile in soils but large applications of manure can lead to excess P in soils and loss, especially of organic P, to leaching and runoff.

Potassium (K): Total K in Gray Luvisol profiles (to 1 m) ranges from 150 000 to 300 000 kg ha^{-1}, occurring in several minerals. It is not a constituent of soil organic matter. Generally soils developed from calcareous or coarse-textured parent materials have lower K than soils derived from materials higher in shale content. Eluviation of clay during soil formation has resulted in higher K concentrations in Bt and C horizons than in Ap horizons. Most of the K is unavailable to plants; some 10 percent is slowly available, releasing small amounts annually. Very small amounts of K are present in the soil solution or weakly attached to clays and organic matter. These are the forms that soil test labs measure and from which plants obtain their supply. Most Prairie Province soils, including Gray Luvisols, were originally able to supply crops with adequate K, but coarser-textured and more strongly leached soils are now often deficient[10].

The amount of K exported from the land is 15 to 20 kg ha^{-1} in the seeds of cereal and oilseed crops, but is 70 to 90 kg ha^{-1} if the straw is removed as well. Potato tubers and forage crops may remove as much as 125 to 150 kg ha^{-1}. Potassium can be added to deficient soils by fertilizers, usually potassium chloride (KCl, 0-0-60).

Sulphur (S): Total sulphur (S) in Gray Luvisol profile (to 1 m) ranges 500 to 2500 kg ha^{-1}, about one tenth that of N. Unlike N, but similar to P and K, the S was derived mainly from the soil parent materials, with a minor contribution from S gases in the atmosphere. Sulphur minerals in most parent materials were relatively soluble sulphate ($SO_4^=$) salts, so most surface horizons contain low amounts of S due to leaching. There is an area of the Peace River region of Alberta, however, where the underlying shale contains the mineral pyrite (FeS_2), mixed into the parent materials during glaciation. With improved aeration in the soil the pyrite is oxidized to soluble sulphates.

Sulphur occurs in both inorganic and organic forms with organic forms comprising over 90% in A and B horizons, and over 70% in C horizons. The inorganic portion consists of sulphate salts ($SO_4^=$) and small amounts of $SO_4^=$ held on mineral surfaces, and these low concentrations are maintained by decomposition of organic matter. In a general way N deficient soils are likely to be S deficient as well. Solonetzic Gray Luvisols often contain accumulations of sulphate salts in lower horizons. Also some S, ranging from a few kg ha^{-1} in remote areas to tens of kg ha^{-1} in industrial areas, is added from the atmosphere. Soil testing labs usually measure soluble $SO_4^=$, often to 30 or 60 cm, in a manner similar to NO_3^- for N.

Export of S in crops ranges from 7 to 10 kg ha^{-1} for cereal grains, 12 to 15 kg ha^{-1} for canola seed, and 20 to 40 kg ha^{-1} for legume forages. Sulphur deficiencies can be corrected by addition of fertilizers, either sulphate salts such as $(NH_4)_2SO_4$ and $CaSO_4$, or elemental S. The latter is insoluble and therefore slow release, but it is quite suitable if used on a rotation rather than an annual basis.

Micronutrients: Plants are now known to require at least seven micronutrients: boron, chlorine, copper, iron, manganese, molybdenum, and zinc. They are all derived from minerals in the parent material and are released slowly as they weather. Amounts removed annually from soils by harvested crops are generally less than one kg ha^{-1}. To date most Prairie Province soils, Luvisols included, have supplied sufficient amounts of micronutrients[10]. Indeed, manganese (Mn) often occurs in toxic amounts in more acidic Gray Luvisols. Copper (Cu) deficiency has received the greatest attention. Deficiency is commonest on coarser (sandier) soils, especially those with higher organic matter, as well as on Organic (peat) soils, generally not on Gray Luvisols. High soil pH reduces availability of copper. Deficiencies have been observed most frequently on cereal crops, particularly some cultivars of wheat. Soil tests have not been very satisfactory in predicting deficiencies.

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