VEGETATION SUCCESSION AND PEDOGENESIS ON THE YUKON-KUSKOKWIM DELTA NEAR ST. MARY'S, ALASKA

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Abstract

Arctic lowlands of Alaska are known to contain large stores of soil organic carbon (SOC) in organic-rich wetland systems and in the permafrost. Vegetation succession that follows floodplain and wetland development strongly affects the organic carbon stores and distribution of permafrost. Due to recent climate warming there has been losses of permafrost, and much of the SOC stored in Arctic lowlands is at risk for transfer within the global carbon budget. The vast Arctic lowland system in western Alaska is within the zone of discontinuous permafrost. It is anticipated to lose most of the permafrost within this century, yet it is inadequately studied due to the lack of road system connecting the region. This study is the first designed to explore the relationships between vegetation succession and soil development at different stages of sediment deposition. The study area is near St. Mary's at the north part of the Yukon-Kuskokwim Coastal Plain in western Alaska. Soil development is weak due to frequent flooding events and prolonged saturation. The irregular distribution of organic carbon and detritus, silt dominated particle size distribution, and nearly uniform composition of clay minerals with depth attest the alluvial deposition due to flooding events. Cryaquents were found in poor to very-poorly drained raised alluvial bars, Cryaquepts were found on somewhat poorly drained levees, Historthels were found on an abandoned floodplain, and Cryofibrists in very poorly drained depressions. Carbon stores range from 27.7 kg C m^{-2} on raised alluvial bars and levees and 40.9 to 45.3 kg C m^{-2} on oxbow depressions and the abandoned floodplain. It is crucial to have reliable measurements of SOC stores in order to estimate the potential impact of climate change on the global carbon budget. Soil development and nutrient level in response to vegetation succession are also reported for the area near St. Mary's, Alaska to add to the current understanding of soils in the region and the global carbon budget.

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1. Introduction

1.1 Introduction and Background

The Arctic has experienced some of the greatest increases in surface temperatures in the past century, which has resulted in a decrease in permafrost stability throughout much of this region (IPCC, 2007; Vaughan et al., 2013). Recent observations of climatic warming and associated increases in atmospheric CO_2 concentrations have raised urgency in understanding the impact occurring in response to this effect on the Arctic ecosystem and permafrost. Permafrost has been established as an important reservoir of terrestrial carbon that has a tremendous potential impact on global CO_2 dynamics. Schuur et al. (2008) estimated carbon stores in permafrost are nearly double the amount that is present in the atmosphere. The thawing and loss of permafrost has a great potential to contribute to even greater carbon fluxes. Additional factors confounding the issue of climate warming in arctic regions have been linked to changes in sea ice extent that contributes to warmer transfers of energy to terrestrial systems that impacts the stability and persistence of permafrost (Post et al., 2013). Changes in the density and abundance of shrub vegetation in tundra regions due to warming climate conditions can also impact permafrost by changing soil environmental conditions (Lawrence & Swenson, 2011). Some regions are at high risk for accelerated losses of permafrost due to warming climate trends, such as Arctic lowlands, which could greatly influence the global carbon budget.

Arctic lowlands have been recognized to contain some of the world's largest stores of soil organic carbon (SOC) (Ping et al., 2008a). Arctic lowlands are dominated by wetlands and floodplains that have different state factors influencing soil development and SOC stores in the region. The wetlands of Arctic lowlands are characterized by water saturated and reducing soil conditions and tundra vegetation communities that favor organic matter accumulations (Ping et al., 2008b). Floodplains are characterized by highly productive ecosystems with vegetation succession occurring in response to soil development (Viereck et al., 1993; Yarie et al., 1998). Arctic lowlands are favorable for permafrost development, such as in depressions covered by wet, thick organic layers and in more stable, developed soils on fluvial terraces (Shur and Jorgenson, 2007). Additionally, vegetation succession occurring in response to soil development on floodplains and wetland systems in Arctic lowlands plays a major role in the distribution of permafrost, soil organic matter accumulation, hence SOC stores in the region (Shur and Jorgenson, 1998). The soil clay mineralogy is another factor that has been recognized to play an important role in the stabilization of SOC in soils (Baldock and Skjemstad, 2000) with implications of how this may impact Arctic lowland systems.

In the Arctic lowland system in western Alaska, floodplain dynamics are common with cryogenic processes strongly influenced by floodplain development, vegetation succession, peat accumulations, and permafrost aggradation. Common features associated with floodplain development include the effect of meandering streams and subsequent soil development of inactive stream channels through formation of stream terraces, levees, oxbow lakes, sloughs, and islands (Péwé, 1948). These features associated with floodplain development play an important role in vegetative succession (Péwé, 1948; Drury, 1956; Viereck et al., 1993). Organic matter accumulations and permafrost development were observed to increase with soil development on stream terraces in the Tanana floodplain of interior Alaska, much associated with vegetation succession (Viereck et al., 1993).

The Yukon-Kuskokwim Coastal Plain contains actively braiding and anastomosing rivers that have left much evidence of changes in stream paths by the vegetation succession stages that mark the streams prior path along the floodplain. In active-floodplain deposits, raised alluvial bars form where stream materials accumulate to heights that eventually exceed the stream stage. The alluvial bars continue to build up as more sediment is deposited during periodic flooding events. Vegetation aids in stabilizing alluvial bars, such as willow (*Salix* spp.) with their elaborate rooting system that also provides surface roughness allowing for collection of sediment during floods (Bliss and Cantlon, 1957). Over time in inactive-floodplain deposits, surfaces can reach heights that rarely encounter floods and are fairly stable and form levees. These levees act as barriers to prevent flood waters from reaching regions beyond these surfaces that are rarely flooded and surfaces develop in abandoned-floodplain deposits. Floodplain systems are dynamic and as a stream courses change over time, stable floodplain deposits can be eroded away as new alluvial bars form.

For interior Alaska floodplain systems, patterns of vegetation communities are found in response to phase of floodplain development and subsequent soil development after stream abandonment (Péwé, 1948; Drury, 1956; Viereck et al., 1993). Péwé (1948) and Drury (1956) observed that the initial geomorphic processes in floodplain development progress from the presence of bare alluvium bars (Phase I) that are frequently flooded to later stage processes in floodplain development characterized by stable stream terraces that have only rare flooding events (Phase III and IV). These stable stream terraces are older surfaces and high in elevation (>3m) (Van Cleve et al., 1993) that consist of floodplain deposits no longer within the current flooding regime, left from the river down cutting. The different stages in floodplain development are attributed by changes in deposition and erosion of materials from flooding events that influence soil chemical and physical properties. These factors influence the ability for vegetation communities to persist and the formation of permafrost in later phases of floodplain development. Poorly drained soils developing in Phases I-IV have common occurrence of wet meadow vegetation or willow (*Salix* spp.) - alder (*Alnus* spp.) dominated vegetation communities. Thick organic layers accumulate following the succession and gradually insulate the ground, which can lead to the development of permafrost and formation of Gelisols (Ping et al., 2004). In moderately well to well-drained soils, the base-rich Haplocryepts form when dominantly willow and cottonwood (*Populus balsamifera* var. *tricocarpa*) vegetation communities change to white spruce (*Picea glauca*) mixed forests (Shaw et al., 2001; Van Cleve et al., 1993). These conditions can eventually lead to permafrost development when the forest canopy provides shade that favor moss growth. Final stages in stream terrace development are dominated by mixed white spruce and black spruce (*P. mariana*) forests with common wetland species such as sedges and mosses in relic oxbow lake surfaces and thermokarst depression environments (Péwé, 1948; Drury, 1956; Viereck et al., 1993). Thus in the final stages of floodplain development the environment becomes increasingly more favorable for organic matter accumulation, and portions of the surface accumulated organic matter will end up in permafrost due to permafrost aggradation and/or cryoturbation resulting in high SOC stores in this ecosystem (Ping et al., 2008a).

The changes in clay mineralogy with depth in soils on the floodplain can represent changes in mineral composition from types of deposition events characteristic of spring flooding or summer flash floods. Additionally, chemical weathering of primary minerals to secondary minerals have the potential to occur due to optimal moisture levels for chemical alterations that can be found in soils on the floodplain (Johnsson and Meade, 1990).

The impact of the floodplain system on soil clay mineralogy could have a variety of effects. In some locations there is reduced stability of the environment when soils are eroded away before chemical alterations could occur. The older developed soils on the floodplain are anticipated to contain permafrost in shallower regions of the soil, which would reduce the temperature of the active layer in soil and reducing the speed of chemical alterations in clay mineralogy.

Wetlands dominate the Yukon-Kuskokwim Coastal Plain region with cryogenic properties affected much by restricted drainage systems. Peat plateaus, palsas, depressions and shallow basins, connected by subsurface/surface stream networks, and numerous thermokarst lakes of various sizes characterize much of Arctic lowland systems. Palsas are common in bogs of discontinuous permafrost regions. They form as mosses, especially *Sphagnum* moss accumulate and build-up, which provide insulation resulting in segregation-ice core development that pushes up the land as the core grows (Zoltai, 1972). Palsas generally grow no larger than 100 m in diameter and up to 10 m in heights and occur in groups (Gurney, 2001). Soils on palsas are typically better drained with shallow active layers than the surrounding soils but are susceptible to decay if ice core is weakened from increased snow pack or warmer environmental conditions (Worsley et al., 1995; Gurney, 2001). An interesting feature of palsas includes the potential cyclic pathway where after a palsa destabilizes, the soils will typically return to a peat bog that may eventually reform another palsa within close proximity to the original location (Zoltai, 1972; Gurney, 2001) and is an example of a system that favors permafrost persistence in a climate not necessarily favorable for permafrost to occur (Shur and Jorgenson, 2007).

Thermokarst, common in arctic and subarctic lowland regions, develop from thawing of permafrost with extensive ground-ice, and change the hydrology and topography features that can initiate changes in vegetative communities, soil chemistry, and over-all system dynamics (Schuur et al., 2007; Osterkamp et al., 2009). Thermokarst development can lead to subsidence of the land due to thawing of permafrost, and can expose stored carbon to decomposition or transfer to some other carbon pool (Schuur et al., 2008). In the Arctic, fine-textured soils are commonly associated with high ice contents and are increasingly more susceptible to thermokarst development depending on soil temperature and moisture conditions. Changes influenced by thermokarst development have a great propensity to affect SOC stores.

The response of permafrost to rising temperatures is not straightforward but a variety of factors indicate much about permafrost stability/instability during current climate trends. Shallow active layers can sustain permafrost presence in discontinuous permafrost zones through greater exposure to winter weather conditions. In soils actively experiencing permafrost degradation, the active layer is generally increasing in thickness as the upper region of the permafrost thaws (Kane et al., 1991). Jorgenson et al. (2010) recognized that vegetation succession can provide a negative feedback effect by protecting permafrost to some increases in surface temperatures, while surface water can act as a positive feedback reducing permafrost stability, a response indifferent to warmer temperatures.

On the Yukon-Kuskokwim Coastal Plain, a region located on the fringe of the discontinuous permafrost zone, earlier studies show there is much variation in permafrost distribution associated with only slight differences in climate (Péwé, 1948; Drury, 1956; Mungoven, 2008). The permafrost in the Yukon-Kuskokwim Coastal Plain is believed to be "warm" with surface temperatures of the permafrost to be of the range -0.5 to 0 °C and future forecasts expects the vast majority of the permafrost to be actively degrading or gone by the end of this century (Romanovsky et al., 2007). Currently little is known about the soils or permafrost in this region because the Yukon-Kuskokwim Coastal Plain is scarcely populated and inaccessible due to the lack of resource exploration. The thawing of permafrost with consequent changes in soils and hydrology will have significant impact on SOC and nutrient dynamics in addition to vegetation community and wildlife habitat changes. Thus it is imperative to study the permafrost-soil-vegetation relationships to understand the carbon and nutrient dynamics in such a fragile and sensitive region.

The objectives of this thesis research are to describe and characterize soils on the floodplain near St. Mary's Alaska and to explore the soil formation and SOC distribution following vegetation succession.

1.2 Study Area Description

The Yukon-Kuskokwim Coastal Plain, a major portion of the Arctic lowland (Walker et al., 2005), is geographically located in western Alaska extending from the Yukon River Delta south to the Kuskokwim River Delta (Figure 1). The climate is maritime with an increase in continental influence in more interior locations. The study site is located south of the remote city of St. Mary's, Alaska near the confluence of the Andreafsky and Yukon Rivers. The mean July and February temperatures for St. Mary's between 1976 and 2000 were 18 and -22 °C, respectively with average annual precipitation at 48 cm of rain and 172 cm of snow. The Yukon-Kuskokwim Coastal Plain lies entirely within the Yukon Delta National Wildlife Refuge and provides an important habitat to waterfowl and other wildlife populations. The Yukon and Kuskokwim Rivers host two of the largest salmon fisheries in the world. Additionally, the area is an important resource for subsistence living of the native/local populations.

The Yukon River at St. Mary's is 160 rkm (river kilometers) from the mouth at the Bering Sea. The Yukon River is the primary drainage of the Yukon River Basin, geographically located between the Brooks Range and the Alaska Range. At Pilot Station, Alaska, 40 rkm upstream from St. Mary's, a yearly average of 54,500,000 metric tons of suspended sediment is carried at this reach of the river (Brabets et al., 2000). The Andreafsky River is the 3rd largest

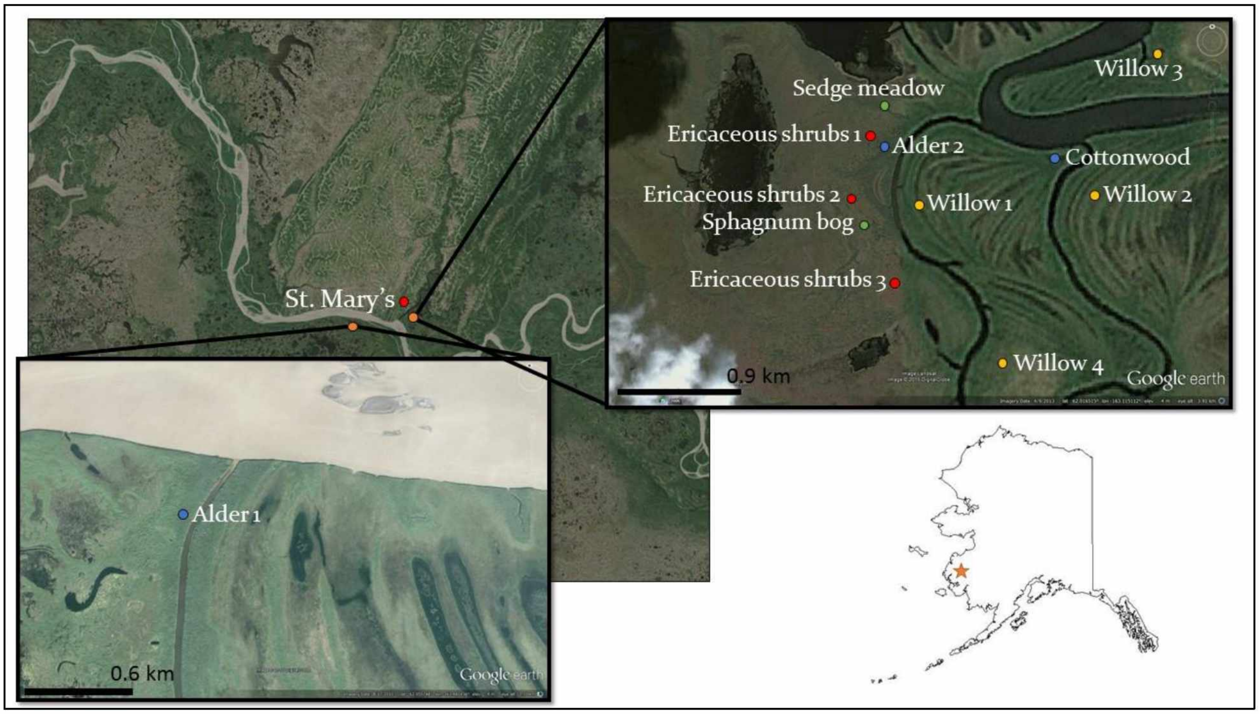

Figure 1. The region with study sites near St. Mary's in western Alaska.

drainage within the Yukon River Basin and it collects drainage from a large region dominated by tundra and wetland systems. Flooding of the Andreafsky and Yukon Rivers occurs during spring break-up in May or early June for the study region. Periods of intense rainfall temporarily increase the stream stage levels in the region.

The location is transitional for major changes in vegetation where the western edge of the distribution of white spruce is recognized to be near Mountain Village (approx 40 rkm down the Yukon River from St. Mary's) with the vegetation changing to mostly deciduous trees and shrub species. Vegetation communities associated with wetlands in the Yukon-Kuskokwim Coastal Plain are broadly classified by Walker et al. (2005). Common species found include horsetail (*Equisetum* spp.), sedges (*Carex* spp.), mosses (*Sphagnum* spp., *Hylocomin* spp. etc.), and ericaceous shrubs such as blueberry and cranberry (*Vaccinium* spp.). These species are tolerant to the cold and wet conditions of the environment and are significant contributors to the large soil organic matter accumulations and corresponding large stores of SOC in the region. Other vegetation communities associated with floodplain processes that dominate in this region include willow along the stream edges and alder and cottonwood in better drained soils on higher terraces and spruce on older terraces. The physiographic environments of each study sites are presented in Table 1.

Soil formation on the floodplain does not occur over uniform parent materials due to the periodic flooding events that contribute to new sediment deposits over soils. The bedrock source materials for the Yukon River Basin are extremely diverse and reflect a complex history of collisions of the earth's crust to eventually form the bulk of Alaska (Brabets et al., 2000). The Nulato Hills region drains into the Andreafsky River and hosts Mesozoic sedimentary rocks such as shale, siltstone and sandstone while the Yukon delta region consists of Cenozoic unconsolidated deposits of alluvium, eolian, and glacial in origin (Brabets et al., 2000). The older surficial geology units of the Yukon-Kuskokwim delta correspond with former coastal deposits with stratified alluvium with low elevation surfaces (<3 m). Sedimentary deposits on floodplain soils in the region near St. Mary's will be influenced by not only local stream inputs (Andreafsky River) but other tributary inputs into the Yukon River that are influenced by dilution or transformation during transport downstream.

Table 1. General site description of soils studied near St. Mary's, Alaska.

Site	Lat.° N Long.° W	Landform	Sedimentation process	Microrelief
Willow 1 Stage 2	62.002 163.102	Raised alluvial bar	Modern, Active	Undulating
Willow 2 Stage 2	62.025 163.084	Recent oxbow fill	Modern, Active	Slightly undulating
Willow 3 Stage 2	62.034 163.090	Raised alluvial bar	Modern, Active	Hummocky
Willow 4 Stage 3	62.009 163.105	Raised alluvial bar	Modern, Active	Slightly undulating
Alder 1 Stage 4	61.576 149.040	Natural levee	Modern, Inactive	Slightly undulating
Alder 2 Stage 4	62.014 163.118	Natural levee	Modern, Inactive	Slightly undulating
Cottonwood Stage 4	62.021 163.097	Natural levee	Modern, Inactive	Slightly concave
Sedge meadow Stage 5a	62.014 163.119	Abandoned river channel	Older, Abandoned	Low sedge mound

Water table (m)	Drainage Class	Slope (%)	Vegetation Community
-0.2 to 0.1	Poor	0	*Salix* spp., *Alnus* spp., *Carex* spp., *Calamagrostis canadensis, Equisetum arvense, Rubus chamaemorus, Pyrola virens*
-0.2 to 0.1	Very poor	0	*Salix* spp., *Carex* spp., *Calamagrostis canadensis, Equisetum arvense, Rosa acicularis, Ribes hudsonianum, Alnus spp., Chamerion angustáfolium, Rubus chamaemorus, Mertensia paniculata*, ferns
-0.2 to 0.1	Very poor	0	*Salix* spp., *Alnus* spp., *Carex* spp., *Equisetum arvense, Calamagrostis canadensis, Mertensia paniculata, Rubus chamaemorus, Ribes hudsonianum*
0.25	Poor	0	*Salix* spp., *Alnus* spp., *Carex* spp., *Equisetum arvense, Calamagrostis canadensis, Iris setosa, Rubus chamaemorus, Chamerion angustifolium, Picea glauca*
0.95	Somewhat poor	0	*Alnus* spp., *Salix* spp., Carex spp., *Ribes hudsonianum, Equisetum arvense, Calamagrostis canadensis, Rubus chamaemorus, Heracleum maximum*
1	Somewhat poor	0	*Alnus* spp., *Salix* spp., *Carex* spp., *Ribes hudsonianum, Equisetum arvense, Calamagrostis canadensis, Rubus chamaemorus, Heracleum maximum, Mertensia paniculata,* ferns
1.15	Somewhat poor	4	*Populas balsamifera var. tricocarpa, Alnus* spp., *Salix* spp., *Carex* spp., *Ribes hudsonianum, Equisetum arvense, Calamagrostis canadensis, Rubus chamaemorus, Heracleum maximum,* ferns
*-0.2 to 0.1	Very poor	0	*Carex* spp., *Sphagnum* spp., *Pleurozium schreberi, Alnus* spp., *Calamagrostis canadensis, Betula nana*

Table 1 (cont.). General site description of soils studied near St. Mary's, Alaska.

Site	Lat.° N Long.° W	Landform	Sedimentation process	Microrelief	Water table (m)	Drainage Class	Slope (%)	Vegetation Community
Sphagnum bog Stage 5a	62.014 163.118	Oxbow depression	Older, Abandoned	Undulating to hummocky	*-0.2 to 0.1	Very poor	0	*Sphagnum* spp., *Equisetum arvense, Potentilla gracilis, Salix* spp. (dwarf)
Ericaceous shrubs 1 Stage 5c	62.017 163.119	Abandoned floodplain	Older, Abandoned	Undulating to hummocky	*seasonal frost	Somewhat poor	0	*Sphagnum* spp., *Pleurozium schreberi, Carex* spp., *Vaccinium uliginosum, Rubus chamaemorus, Betula nana, Ledum decumbens, Pyrola virens, Iris setosa, Potentilla gracilis, Alnus* spp., *Salix* spp., *Picea glauca*
Ericaceous shrubs 2 Stage 5c	62.014 163.119	Abandoned floodplain	Older, Abandoned	Undulating to hummocky	*seasonal frost	Somewhat poor	0	*Sphagnum* spp., *Pleurozium schreberi, Carex* spp., *Vaccinium uliginosum, Vaccinium vitis-idaea, Ledum decumbens, Rubus chamaemorous, Petasites frigidus, Alnus* spp., *Salix* spp., *Picea glauca*
Ericaceous shrubs 3 Stage 5c	62.0144 163.12	Abandoned floodplain	Older, Abandoned	Nearly level depression	*seasonal frost	Somewhat poor	0	*Sphagnum* spp., *Pleurozium schreberi, Carex* spp., *Vaccinium uliginosum, Vaccinium vitus-idaea, Ledum decumbens, Rubus chamaemorus, Petasites frigidus, Alnus* spp., *Salix* spp., *Picea glauca*

*Reflects the conditions influenced by the presence of seasonal frost during sampling.

2. Methods

Field work was performed in late June, 2012. In the study area, twelve sites were sampled with replicates of the four dominating stages of vegetation succession and floodplain development that occur on the floodplain near St. Mary's, Alaska (Table 1). A general ecological survey was performed at each location where the presence of particular species was recorded, but detailed information on specific alder, willow, moss, and sedge species were not identified nor was the specific percentage of abundance compared to other species recorded in this survey. The associated vegetation with each site was assessed as dominating species (i.e. willow, alder, etc.) with other species listed as present at the site in varying abundances. Soils at each site were described and sampled by genetic horizons according to the USDA-NRCS field description and sampling procedures (Schoeneberger et al., 2002) and classified according to *Soil Taxonomy* (Soil Survey Staff, 2014). Soils that had a seasonal frost layer during time of sampling were re-visited in September of 2012. These sites were then assessed with a permafrost probe to re-evaluate the active layer depth in each one. Samples were taken from each horizon and analyzed in the Forest Soils Laboratory at the University of Alaska Fairbanks (UAF) and the UAF Palmer Research Center laboratory in Palmer, AK.

Soil pH and electrical conductivity (EC) were determined by saturation extract. A 600 mL beaker was filled 2/3 full and water was slowly added and mixed into the soil until a glossy sheen was observed and then let sit overnight and then pH and EC were measured with pH and EC electrode. Total soil carbon and nitrogen content was determined by combustion on a CHN analyzer (LECO Corp., St. Joseph, MI). The percent organic matter (% OM) was determined by loss on ignition method with a muffle furnace (400 °C). Particle size distribution was determined by hydrometer according to Soil Survey Staff (2011).

Pedon organic C and TN storage were calculated using the equation of Michaelson et al. (2013): OC Storage (kg/m^2) = T* BD* (%OC/100) *(%volume <2mm/100)*10, (T = horizon thickness (cm) and BD = bulk density (Mg/m^3)). Because of the water saturated soil conditions and the presence of seasonal frost a complete set of bulk density measurements were not obtained. Bulk density was estimated from % OM, % clay and % silt using equations developed by Michaelson et al. (2013). For soil horizons with >10% OM, the function used was

$$y = -0.414\ln(x) + 1.832 \ (R^2 = 0.93, P<0.01)$$

where x is the % OM. For mineral soil horizons with bulk density between 1.1 - 1.4 Mg m^{-3} and <10% OM, the function used was

$$y = -0.043x + 0.020w - 0.007z + 1.684 \ (R^2 = 0.62, P<0.05)$$

where x is % OM, w is % clay and z is % silt.

Cation exchange capacity (CEC) and extractable base cations were determined by using 1M ammonium acetate (NH_4OAc) at pH 7 extraction. CEC and extractable base cations calcium (Ca), potassium (K), magnesium (Mg), and sodium (Na) were determined by inductively coupled plasma optical emission spectrometer (ICP-OES). The percent base saturation was determined by the sum of cations divided by CEC and then multiplied by 100.

Secondary iron (Fe) and aluminum (Al) were selectively extracted with buffered dithionite-citrate (Mehra and Jackson, 1960; McKeague and Day, 1966); ammonium oxalate [pH 3.5 for poorly crystalline and organically-bound Fe and Al, and amorphous silica (Si)] (Blume and Schwertmann, 1969; Parfitt and Henmi, 1982); and sodium-pyrophosphate solution pH 10 [for organically bound Fe and Al] (Bascomb, 1968; McKeague et al., 1971) and extracts were analyzed by ICP-OES. The ratios of these amounts serve as proxy indices of the intensity of alteration, thus pedogenesis (Blume and Schwertmann, 1969; Parfitt and Henmi, 1982).

Clay mineralogy of selected samples was determined by X-ray diffraction method. Soil samples were sieved to collect materials <2 mm and treated with 10 mol hydrogen peroxide to remove organic matter. The soil materials were then ultra-sonicated to separate the coarser fractions from the fine earth fraction and the latter was poured into 500 mL settling columns. The settled materials from sonication was dried and considered to be the sand sized fraction. The supernatant in separating columns were shaken and allowed to sit for approximately 24 hours for the >2 µm fraction to settle at the bottom of the column. The supernatant in the columns was pipetted to containers and centrifuged and the sediment collected was dried and considered to be 2-0.2 µm clay fraction used for analyses. The <0.2 µm portion of the clay fraction was not collected because of the low percentages of clays present in the soils of this study.

Separate samples of the clays were treated with 2M $MgCl_2$, 2M KCl, and 0.5M $CaCl_2$. Samples were shaken in solution and set over night then rinsed with DI water then 91% isopropyl alcohol and then rinsed again with DI water. Samples were then filtered and preferentially mounted on petrographic microscope slides using the Millipore filter transfer method (Moore and Reynolds, 1997).

Oriented mounted samples were analyzed by XRD at room temperature and were subsequently treated by the specified treatments. The Mg^{2+}, K^+, and Ca^{2+} samples were treated with ethylene glycol overnight and rescanned by XRD. The K^+ and Ca^{2+} treated samples were heated to 100 °C and rescanned by XRD. The Mg^{2+}, K^+, and Ca^{2+} samples were then subsequently heated to 300 °C overnight and were rescanned by XRD. The Mg^{2+}, K^+, and Ca^{2+} samples were heated to 550 °C for overnight and were rescanned by XRD.

Treated samples were analyzed using a PANalytical X'PERT PRO Materials Research Diffractometer using a Cu-Kα source (45 kV and 40 mA) with Ni filter. Each sample was scanned between 2° and 42° 2θ and analyzed using PANalytical X'pert HighScore Plus (PANalytical Inc., Westborough, MA). Results are discussed in terms of the associated d spacing that were calculated by using the formula d spacing = 1.542/(2*SIN(RADIANS(θ/2))). The clay minerals in the soils sampled were assessed using diffractograms for the major clay families including kaolinite, smectite, vermiculite, illite and chlorite.

Semi-quantitative analyses were performed to determine the relative amounts of clay minerals in soils using the 100% approach (Biscaye, 1965; Naidu and Mowatt, 1983; Kahle et al., 2002). The relative amounts of clay minerals in soils were estimated using diffractrograms for the major clay families including kaolinite, expanding minerals (smectite+mixed layer smectites and vermiculites (HIV+HIS)), illite and chlorite. The weight percentages of kaolinite, expanding minerals, illite, and chlorite were calculated by determining the intensity area for low angle reflections (001) after subtracting the background and using intensity height times the full width at half maximum (FWHM) and then normalizing with a mineral intensity factor (MIF) for each clay mineral identified. The ratio of kaolinite and chlorite was determined from 3.54Å and 3.57Å peaks and then subtracted from areas under the 7Å peak for kaolinite and chlorite determination. The information for all the minerals identified is summed and then the weight percentage of each mineral was determined.

3. Results

3.1 Floodplain Geomorphology and Vegetation

Land surfaces develop on the floodplain near St. Mary's, Alaska through deposition events of materials by the river. Figure 2 illustrates the dominating process on the floodplain: alluvial bar build-up due to fluvial processes. This feature contributes to changes in surface elevation in relation to the river and associated changes in dominant vegetation communities.

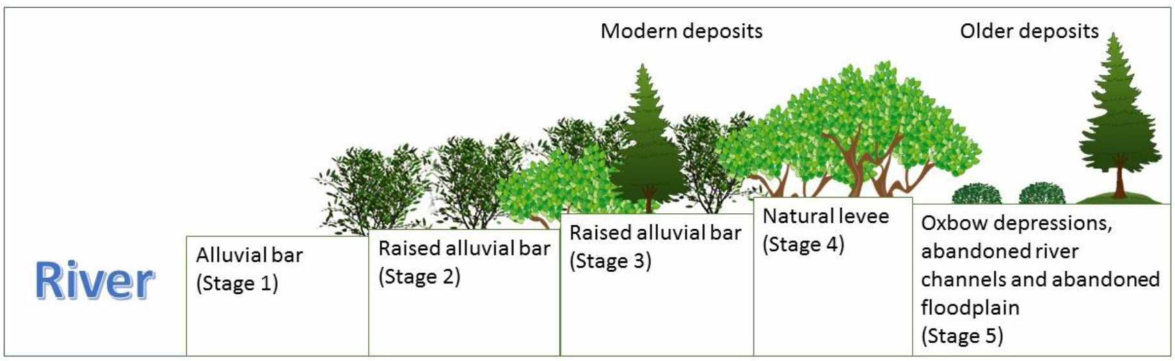

Figure 2. Illustration of alluvial bar build-up on the floodplain near St. Mary's, Alaska.

The early stage of floodplain development was found on alluvial bars of Stage 1 (Figure 3, sites not sampled in this study). These surfaces are slightly higher but nearly level with the stream and are dominated by *Equisetum arvense* and *Salix* spp. These surfaces are forming in active-floodplain deposits and are frequently flooded and inundated with stream waters.

Stage 2 (Figure 4) corresponds with raised alluvial bars and recent oxbow fill sites (sites Willow 1, Willow 2, and Willow 3, Table 1) that experience extensive annual flooding due to spring thaw and break-up of the Andreafsky and Yukon Rivers. These sites are in active-floodplain deposits and are in close proximity to the river. Surfaces have a low relief (elevations <1 m) which characterizes the hydrology with high water tables (0 cm) in much of these landforms in the region. Willow 2 was located on recent oxbow fill near a bend in the stream.

Figure 3. Example of Stage 1 of floodplain development, alluvial bars.


Figure 4. A Stage 2 site, Willow 1, that is dominated by willow.

The Stage 2 sites are dominated by willow and bluejoint grass (*Calmagrostis canadensis*), species tolerant to frequent flooding and saturated conditions. Other vegetation species found include *Alnus* spp., *Equisetum arvense*, *Mertensia paniculata*, *Rubus chamaemorus, Ribes hudsonianum, Chamerion angustafolium, Rosa acicularis,* and *Pyrola virens.*

Surfaces of Stage 3 (the Willow 4 site) are slightly higher in elevation (1-2 m) and the water table is deeper than Stage 2 (Table 1). Surfaces are low enough in elevation to be impacted by the river during annual spring break-up and are considered to be a more mature feature of active-floodplain deposits. The Stage 3 site (Figure 5) vegetation communities were similar to Stage 2 communities except for the presence of white spruce scattered across the site.

Figure 5. The Willow 4 site, Stage 3, a more mature surface on active-floodplain deposits.

Over time as stratification of materials continues through flooding events, the heights of the raised alluvial bars increase to the degree that they are above the high water level and inhibit the extent of overbank deposits, thus forming natural levees. The levees are found on inactive-floodplain deposits that are not necessarily flooded annually or not inundated as long as surfaces lower in elevation. Stage 4 (Figure 6, Alder 1, Alder 2, and Cottonwood sites) surfaces are higher in elevation (2-3 m) with much lower water table depths than earlier stages (Table 1). Besides alder and cottonwood, other common vegetation species found include *Salix* spp., *Carex* spp., *Ribes hudsonianum*, *Equisetum arvense*, *Calamagrostis canadensis*, *Rubus chamaemorus, Heracleum maximum,* and ferns.

Figure 6. Stage 4, the Cottonwood site on natural levees dominated by cottonwood trees.

Stage 5 represents floodplain surfaces beyond the levees of Stage 4 are rarely flooded or impacted by the river. These stable surfaces developing in abandoned-floodplain deposits support wetland vegetation communities in abandoned river channels and oxbow depressions and ericaceous shrub communities on the abandoned floodplain. The abandoned floodplain is a surface with peat accumulations that contains permafrost that has elevated these surfaces in relation to the depressions creating a “jacked-up” feature. Seasonal frost was present at all of the older floodplain sites when sampled in late June impacting the water table depth measurements and soil drainage class (Table 1).

Stage 5a is the *Sphagnum* bogs found in oxbow depressions (Figure 7, the Sphagnum bog site, Table 1) that are within and adjacent to surfaces dominated by ericaceous shrub communities and correspond with former oxbow lake fill of fine sediment. Stage 5a also includes the sedge meadows found in abandoned river channels (the Sedge meadow site, Table 1). Thick organic layers are present within the depressions with standing water and saturated soil conditions. Vegetation found of the *Sphagnum* bog site consisted mostly of *Sphagnum* spp., with few *Equisetum arvense*, *Potentilla gracilis*, and dwarf willow (*Salix* spp.) scattered about the depression. Vegetation of Sedge meadow site includes *Carex* spp., *Sphagnum* spp., *Alnus* spp., *Calamagrostis canadensis*, *Betula nana,* and *Pleurozium schreberi.*

Figure 7. Oxbow depressions in abandoned-floodplain deposits, Stage 5a.

Stage 5b (Figure 8, sites not sampled in this study) is the palsas found in locations outside the perimeter of the depressions on the abandoned floodplain. Palsa formation is scattered with spruce trees growing from the top of these elevated, frosted-cored mound formations. Vegetation on the palsas included *Sphagnum* spp., *Carex* spp., *Pleurozium schreberi, Vaccinium uliginosum, Vaccinium vitis-idaea*, *Ledum decumbens*, *Rubus chamaemorous*, *Petasites frigidus*, and few *Alnus* spp., and *Salix* spp.

Figure 8. Palsa in Stage 5b on the abandoned floodplain.

Stage 5c represents the sites dominated by mosses and ericaceous shrubs communities with scattered white spruce trees in abandoned-floodplain deposits (Figure 9, sites Ericaceous shrubs 1, Ericaceous shrubs 2 and Ericaceous shrubs 3, Table 1). There is an "elevated" effect of the surface that is likely attributed to the buckling-up of the surface through freeze-thaw actions as permafrost aggrades due to increased insulation following vegetation succession and colonization of mosses on the forest floor and the stability in environmental conditions.

Vegetation of Stage 5c includes scattered white spruce and *Alnus* spp., *Salix* spp., with *Sphagnum* spp., *Pleurozium schreberi Carex* spp., and ericaceous species such as *Vaccinium uliginosum*, *Vaccinium vitis-idaea*, *Ledum decumbens*, *Rubus chamaemorous*, and *Petasites frigidus*.

Figure 9. Ericaceous shrubs of Stage 5c on the abandoned floodplain.

3.2 Soil Morphological and Physical Properties

Selected soil morphological and physical properties are provided in Table 2. The Stage 2 and Stage 3 sites (Willow 1-4 sites) had thin organic layers (mean depth 9 cm) with silt loam substrates. Willow 2, the recent oxbow fill site, had loamy sand materials at the base of the soil profile. Below the organic horizon at these sites there is layer of organic rich mineral soil that have some structure and are recognized to be A horizons. The subsurface soils have greyish hues (2.5Y) with the presence of iron concentrations reflect the reducing environment. Soils impart a platy structure between 9-30 cm and maximum rooting depths occur at 17-47 cm at Stages 2-3.

Table 2. Physical properties of soils studied near St. Mary's, Alaska.

Site	Depth	Horizon	Color (matrix)	Redoximorphic Features^	Sand (%)	Silt (%)	Clay (%)	Field texture‡
Willow 1 Stage 2	0-8	Oi/Oe	10YR 2/1	--	--	--	--	PT, MPT
	8-13	Oa/A	10YR 3/1	--	25	65	10	MSiL
	13-30	Cg1	2.5Y 4/1	FE3 (7.5YR4/4; 7.5YR4/6); FED-RPO	12	70	18	SiL
	30-47	Cg2	2.5Y 4/1	20% FE3-APF, FE3-LPO (7.5YR4/6)	7	73	20	SiL
	47-60	Cg3	2.5Y4/1	--	8	71	21	SiL
	60-75	Cg4	2.5Y4/1	--	8	70	22	SiL
	75-100	Cg5	2.5Y4/1	--	12	68	20	SiL
Willow 2 Stage 2	0-4	Oe	10YR 3/1	--	--	--	--	PTMK
	4-17	A	10YR 3/1	--	28	62	10	MSiL
	17-33	Cg1	2.5Y 4/1	40% FE3, FE3-LPO (7.5YR4/4); 5% FED-RPO (5Y4/1)	34	58	8	SiL
	33-58	Cg2	2.5Y 4/1	25% FE3-LPO (7.5YR4/4); 5% FED-RPO (5Y4/1)	23	64	13	SiL
	58-80	Cg3	2.5Y 5/1	25% FE3 (10YR3/3), FE3-LPO (7.5YR4/2)	9	76	15	SiL
	80-100	Cg4	2.5Y 4/2	--	76	30	4	LS
Willow 3 Stage 2	0-9	Oi	5YR 2.5/1	--	--	--	--	PTMK
	9-18	Ag	2.5Y 4/1, 2.5Y 4/2	20-25% FE3 (10YR4/4)	30	62	8	SiL

Detrital Material (%)	Structure†	Consistence		Roots#	Horizon Boundary⁺	B.D.
		moist§	wet¶			(Mg/m³)
--	--	--	--	3f3m1c	as	0.2
--	1fsbk	vfr	so, po	3f2m	cs	0.5
--	--	--	--	2f2m	--	0.8
2 to 20	2cpl	fi	s, p	1f1m	--	1.0
--	--	--	--	--	--	1.3*
--	--	--	--	--	--	1.3*
--	--	--	--	--	--	1.4*
--	--	--	--	3f2m1c	cs	0.2
--	2fgr	fr	so, po	3f2m	as	0.8
--	1cpl	fr	so, sp	--	cs	1.1
--	1cpl	fr	so, sp	--	as	1.3*
--	ma	fr	s, p	--	as	1.2*
--	ma	fr	so, po	--	--	1.5*
--	--	--	--	--	as	0.1
--	1mpl	fr	so, sp	3f2m	cs	0.7

Table 2 (continued). Physical properties of soils studied near St. Mary's, Alaska.

Site	Depth	Horizon	Color (matrix)	Redoximorphic Features^	Sand (%)	Silt (%)	Clay (%)	Field texture‡
Willow 3 Stage 2 (cont.)	18-24	Cg1	5Y4/1, 2.5Y 4/2	40% FE3-LPO (7.5YR4/6), FE3 (10YR5/4)	23	64	13	SiL
	24-41	Cg2	5Y 4/1	15% FE3 (10YR3/2), 5% FE3-LPO (7.5YR3/2)	16	72	12	SiL
	41-65	Cg3	2.5Y 4/1	FE3, FE3-LPO (10YR4/4) diffuse boundary LPO	19	65	16	SiL
	65-82	Cg4	2.5Y 4/2	20% FE3, FE3-LPO (7.5YR4/4) diffuse boundary LPO	7	76	17	SiL
	82-96	Cg5	5Y 4/1, 2.5Y 4/1	20% FE3, FE3-LPO (7.5YR4/6; 7.5YR4/4) diffuse boundary LPO	10	74	16	SiL
	96-110	Cg6	2.5Y 4/1	FE3, FE3-LPO (7.5YR4/6) diffuse boundary LPO	5	74	21	SiL
Willow 4 Stage 3	0-12	Oi/Oa	10YR 2/2, 7.5YR 2.5/2	--	--	--	--	PTMK
	12-24	Ag	2.5Y 4/2	FE3 (10YR3/3)	27	61	12	SiL
	24-37	Cg1	2.5Y 4/1	30% FE3, FE3-APF (7.5YR4/4); FED,	7	71	22	SiL
	37-63	Cg2	2.5Y 4/1	FE3, FE3-APF (10YR4/2)	27	57	16	SiL
	63-100	Cg3	2.5Y 4/2	50% FE3, FE3-APF (10YR4/2)	28	60	12	SiL
	100-135	Cg4	2.5Y 4/2	40% FE3, FE3-APF (7.5YR4/4)	22	66	12	SiL

Detrital Material (%)	Structure†	Consistence moist§	Consistence wet¶	Roots#	Horizon Boundary+	B.D. (Mg/m³)
--	1mpl	fr	so, sp	3vf3f1m	as	1.1*
10	fsbk	fi	ss, sp	--	as	1.1*
2	ma	fi	ss, p	--	--	1.2*
5	ma	fi	ss, sp	--	--	1.2*
1	ma	fi	ss, p	--	--	1.2*
5	ma	fi	ss, p	--	--	1.3*
--	--	vfr	ss, sp	3f3m3c	cs	0.4
>20	1mpl	fr	ss, sp	2vf2f2m1c	cs	0.6
--	2fpl	fi	ss, p	2m1c	as	0.7
<2	1mpl	fi	s, p	--	cs	1.4*
--	ma	fi	ss, p	--	cs	1.4*
--	ma	fi	ss, p	--	--	1.3*

Table 2 (continued). Physical properties of soils studied near St. Mary's, Alaska.

Site	Depth	Horizon	Color (matrix)	Redoximorphic Features^	Sand (%)	Silt (%)	Clay (%)	Field texture‡
Alder 1 Stage 4	0-8	Oe/Oi	7.5YR 2.5/2	--	--	--	--	PT, MPT
	8-20	Bw	10YR 3/3	15% FE3, LPO	26	67	7	SiL
	20-43	Ab	10YR 3/2	8% FE3-LPO	37	57	6	SiL
	43-67	Cg1	2.5YR 4/1	30% FE3 (7.5YR3/3), FE3-	42	54	4	SiL
	67-85	Cg2	2.5YR 4/1	15% FE3-LPO (7.5YR4/6), FE3 (10YR4/4)	48	48	4	SiL
	85-130	Cg3	2.5YR 4/1	15% FE3 (7.5YR4/4), FE3-LPO (10YR3/3)	32	61	7	SiL
Alder 2 Stage 4	0-13	Oe	7.5YR 2.5/2	--	--	--	--	PT
	13-27	A	7.5YR 3/2	--	--	--	--	SiL
	27-48	Bg	2.5Y 4/1	50% FE3 (7.5YR4/4)	5	71	24	SiL
	48-60	Cg1	2.5Y 4/1	30% FE3-APF (7.5YR3/4); FED-LPO (2.5Y4/1)	35	51	14	SiL
	60-75	Cg2	5Y 4/3	20% FE3, FE3-LPO (10YR4/3); FED	47	47	6	SL
	75-105	Cg3	2.5Y 4/1	30% FE3 (7.5YR4/4), 2% FE3-LPO (5YR4/3)	24	65	11	SiL
	105-120	Cg4	5Y 5/1	5% FE3-LPO (7.5YR4/6)	24	64	12	SiL

Detrital Material (%)	Structure†	Consistence		Roots#	Horizon Boundary⁺	B.D.
		moist§	wet¶			(Mg/m³)
--	--	--	ss, sp	3f3m1c	cs	0.1
--	1msbk	fr	so, sp	3vf3f2m	as	0.8
--	1mpl	fr	so, sp	2f1m	as	1.1
--	2cpl	fr	so, sp	1f3d	as	1.2
>20	2cpl	fr	so, sp	--	as	1.2
2 to 20	2cpl	fr	so, sp	2d	--	1.2
--	--	--	--	3f2m1c	as	0.1
--	1fgr	vfr	so, sp	3vf3f2m1c	cs	0.5
--	1msbk	fr	so, sp	2f1m	cs	0.9
--	2cpl	fr	so, sp	--	cs	1.4
--	ma	fr	so, sp	--	as	1.4
--	ma	fr	so, sp	--	cs	1.4
2 to 20	ma	fr	ss, sp	--	cs	1.2

Table 2 (continued). Physical properties of soils studied near St. Mary's, Alaska.

Site	Depth	Horizon	Color (matrix)	Redoximorphic Features^	Sand %	Silt %	Clay %	Field texture‡
Alder 2 Stage 4 (cont.)	120-135	Cg5	2.5Y 3/1, 7.5YR 2.5/2	--	18	68	14	SiL
	135-155	Cg6	5Y 4/1	10% FE3 (10YR4/3); strong positive alpha,	1	73	26	SiL
Cottonwood Stage 4	0-12	Oa	10YR 2/1	--	--	--	--	MK
	12-18	A	7.5YR 3/3, 10YR 4/2	--	26	67	7	SiL
	18-41	Bw	2.5Y 4/1	20% FE3, FE3-LPO (5YR3/4)	18	74	8	SiL
	41-67	C	10YR 4/2, 2.5Y 4/2	40% FED (2.5Y4/2)	16	72	12	SiL
	67-105	Cg1	2.5Y 4/2	50% FE3, FE3-APF, (10YR4/2)	4	78	18	SiL
	105-150	Cg2	2.5Y 4/2	40% FE3, FE3-APF (7.5YR4/4)	24	64	12	SiL
Sedge Meadow Stage 5a	0-20	Oi	7.5YR 4/3	--	--	--	--	PT
	20-22	Oe	10YR 2/2	--	--	--	--	PTMK
	22-30	Oa1	7.5YR 3/1	--	--	--	--	MK
	30-38	Oa2	10YR 3/1	--	--	--	--	MK
	38-51	Bg1	2.5YR 3/1	--	12	75	13	MSiL
	51-65	Bg2	2.5YR 3/1, 10YR 3/1	--	10	75	15	SiL
	65-71	Cg1	2.5Y 3/1, G14/N	--	17	67	16	SiL

Detrital Material (%)	Structure†	Consistence		Roots#	Horizon Boundary+	B.D.
		moist§	wet¶			(Mg/m³)
2 to 20	ma	fi	ss, p	--	as	1.3*
--	ma	fi	ss, p	--	--	1.3*
--	--	vfr	so, po	3f3m3c	--	0.1
--	1fsbk	fr	ss, sp	3vf3f3m2c	aw	0.7
--	1msbk	fr	ss, sp	3f3m	cs	0.9
--	1cpl	fr	ss, sp	1f2m	cs	1.1
--	2cpl	fr	so, sp	1f1m	cs	1.2
--	2mpl	fr	ss, po	--	--	1.4
--	--	--	--	3f2m1c	cs	0.1
--	--	--	--	3vf3f	as	0.2
--	--	vfr	so, po	3f2m	as	0.3*
--	--	--	--	--	aw	0.5*
--	--	--	--	--	--	0.6*
--	1msbk	fr	ss, sp	3f3m	--	0.6*
--	ma	fi	ss, sp	3f3m	--	1.2*

Table 2 (continued). Physical properties of soils studied near St. Mary's, Alaska.

Site	Depth	Horizon	Color (matrix)	Redoximorphic Features^	Sand (%)	Silt (%)	Clay (%)	Field texture‡
Sedge Meadow Stage 5a (cont.)	71-84	Cg2	G2, 4/5PB	--	8	78	14	SiL
	84-110	Cg3	G14/N, 5Y 4/1	--	5	75	20	SiL
Sphagnum bog Stage 5a	0-25	Oi1	10YR 4/3, 7.5YR 4/6	--	--	--	--	PT
	25-38	Oi2	7.5YR 3/1	--	--	--	--	PT
	38-53	Oa1	10YR 2/1	--	--	--	--	MK
	53-60	Oa2/Bg1	10YR 3/1	--	3	75	22	MK, SiL
	60-80	Bg2	2.5Y 3/1, 2.5Y 3/2	--	4	75	21	SiL
	80-100	Bg3	G14/N	--	5	76	19	SiL
Ericaceous shrubs 1 Stage 5c	0-12	Oe	7.5YR 2.5/2	--	--	--	--	PTMK
	12-25	Oa	10YR 2/1	--	--	--	--	MK
	25-58	Oe/Bg	7.5YR 2.5/3, 2.5Y 4/2	--	5	74	21	PTMK, SiL
	58-94	Cg	2.5Y 4/1	--	1	80	19	SiL
Ericaceous shrubs 2 Stage 5c	0-17	Oi/Oe	10YR 2/1	--	--	--	--	MPT
	17-25	Oa	10YR 2/1, 10YR 2/2	--	--	--	--	MK
	25-47	Bg/Oe	2.5Y 4/2, 7.5YR 3/2	--	4	74	22	SiL

Detrital Material (%)	Structure†	Consistence moist§	wet¶	Roots#	Horizon Boundary⁺	B.D. (Mg/m³)
1	ma	fi	ss, sp	1d	--	1.2*
--	ma	fi	ss, sp	--	--	1.3*
30		fi	so, sp	3f	as	0.04
--	--	--	--	--	--	0.03*
--	--	--	--	--	--	0.2*
25	--	--	--	--	--	0.6*
--	--	--	--	--	--	0.6*
8	ma	fi	ss, sp	--	--	1.3*
--	--	vfr	so, po	3f2m2c	as	0.1
--	--	vfr	so, po	3f2m	as	0.4
40	2fpl	fr	so, sp	3f1m	--	0.6*
30	1fpl	fi	s, p	--	--	1.1*
--	--	--	--	1f2m1c	as	0.1
--	--	--	--	3f3m	as	0.4
2 to 20	1mpl	vfr	so, sp	3f2m	as	0.6

Table 2 (continued). Physical properties of soils studied near St. Mary's, Alaska.

Site	Depth	Horizon	Color (matrix)	Redoximorphic Features^	Sand (%)	Silt (%)	Clay (%)	Field texture‡	Detrital Material (%)	Structure†	Consistence moist§	Consistence wet¶	Roots#	Horizon Boundary[+]	B.D. (Mg/m³)
Ericaceous shrubs 2 Stage 5c (cont.)	47-60	Cg1	--	--	11	74	15	SiL	--	--	--	--	--	--	1.2
	60-92	Cg2	5Y 4/1, 7.5YR 3/3	--	9	74	17	SiL	30	--	fi	so, sp	--	as	0.9*
Ericaceous shrubs 3 Stage 5c	0-12	Oi	--	--	--	--	--	PT	--	--	--	--	3f3m1c	cs	0.03
	12-17	Oe	7.5YR 3/2	--	--	--	--	MPT	--	--	--	--	3f3m1c	as	0.1
	17-26	Oa/A	7.5YR 2.5/1, 5Y 2.5/1	--	--	--	--	MK	--	1mpl	fr	so, po	3f3m	as	0.4
	26-50	Cg1	2.5Y 4/1	--	8	76	16	SiL	--	--	--	so, sp	--	--	0.7
	50-65	Cg2	2.5Y 3/2	--	17	67	16	SiL	30	--	--	--	--	--	1.2*
	65-80	Cg3	5Y 4/1	--	3	77	20	SiL	20	ma	fi	s. sp	--	--	1.2*
	80-88	Cg4	--	--	7	75	18	SiL	40	ma	fi	ss, p	--	--	0.5*
	95+	Cf	--	--	--	--	--	--	--	--	--	--	--	--	--

^ Redoximorphic features abbreviations: FE3, iron concentrations/ masses; LPO, pore lining; APF, ped faces; FED, iron depletions/ masses; RPO, root channels.

‡ Texture abbreviations: SiL, silt loam; LS, loamy sand; PT, peat; MPT, mucky peat; PTMK, peaty muck; MK, mucky; MSiL, mucky silt loam.

† Structure abbreviations: 1, weak; 2, moderate; 3 strong. Soil structure size: f, fine; m, medium; c, coarse. Soil structure type: gr, granular; pl, platy; abk, angular blocky; sbk, subangular blocky; l, lenticular; rt, reticular; ma, massive.

§ Consistence abbreviations (moist): vfr, very friable; fr, friable; fi, firm; vfi, very firm.

¶ Consistence abbreviations (wet): so, nonsticky; ss, slightly sticky; s, sticky; vs, very sticky; po, nonplastic; sp, slightly plastic; p, plastic; vp, very plastic; sat, saturated.

Roots abbreviations: 1, few; 2, common; 3, many; vf, very fine; f, fine; m, medium; c, coarse; d, dead.

[+] Horizon boundary abbreviations: a, abrupt; c, clear; d, diffuse. Soil horizon boundary: s, smooth; w, wavy; i, irregular; b, broken.

* Bulk density measurements estimated using pedotransfer functions.

Buried soil organic matter (SOM) appears in discreet zones like broken horizons and is recorded as percentages of the soil matrix. In some instances individual root remains or detritus materials were observed and were estimated in a quantitative range for the observations. At the Willow 1 site, common detritus materials were observed in the Cg2 horizon. The Willow 3 site had various percentages of buried organic material starting with the Cg2 horizon (24-41 cm) with the highest percentage (10%) and there is an irregular decrease in the percent of buried organic debris with depth.

Soils slightly more mature than the Stages 2 and 3 sites are observed on inactive-floodplain deposits of Stage 4 (Alder 1-2, and Cottonwood sites). These soils had thicker organic horizons than the Stage 2 and 3 sites (mean thickness 11 cm). Soil texture is dominantly silt loam with horizontal lenses of organic material at random depths within the profiles. Soil drainage is moderately well at the Stage 4 sites allowing for some altercation of materials and development of cambic (Bw) horizons.

Redoximorphic features including reduced matrix with iron concentrations and depletions are abundant within the mineral soil horizons of levee sites and correspond with ground water fluctuation (Table 2). Soils at Alder 1 are strongly influenced by seasonal flooding that is characterized by the buried surface horizon (Ab). At the Alder sites, the buried detritus appears as discreet zones and as individual root remains or detritus material.

Soils in the abandoned floodplain deposits including abandoned river channels and oxbow depressions (Stages 5a-5c) had seasonal frost at 30-50 cm during the field sampling. The soils observed on these older and stable floodplain deposits feature thick surface organic horizons (+30 cm, Table 2). Lenses of organic debris (containing large percentages up to 40%) with depth can be found in the soils of the ericaceous shrub sites of the abandoned floodplain. In

September, after the seasonal frost had thawed, the surfaces of the abandoned floodplain were probed to determine if permafrost was present within 2 meters of the soil surface. The surface characterization and depth to permafrost probed along a 65 meter transect for the sites at Stages 5a and 5c are provided in Table 3. Permafrost was observed at depths 70-125 cm in soils of the abandoned floodplain of Stage 5c and no permafrost was found in soils of the oxbow depressions and abandoned river channels of Stage 5a (Table 3). The depth to permafrost was more shallow on the palsas (40-60 cm) compared to the abandoned floodplain (Table 3). The ages of three trees were measured by tree rings from increment boring (Table 3).

Table 3. Results from permafrost probing of the abandoned floodplain to 2 m in depth for 65 m transect and Stage 5a and 5c sites and ages of trees on the palsas.

Surface characterization	Site information	Permafrost depth (cm)
Palsa	top	50
Abandoned floodplain	--	110
Palsa	top	55
Abandoned floodplain	--	115
Abandoned floodplain	--	90
Abandoned floodplain	--	85
Abandoned floodplain	in shade of alder	70
Abandoned floodplain	marshy willow	120
Abandoned floodplain	standing water	110
Abandoned floodplain	standing water	125
Sedge meadow	standing water	none
Palsa	side	60
Palsa	top	40
Sedge meadow	site	none
Sphagnum bog	site	none
Ericaceous shrubs 1	site	120
Ericaceous shrubs 2	site	110
Ericaceous shrubs 3	site	95
Tree #1 (on top of palsa)	Circumference 114 cm, Relative age 77 y	50
Tree #2 (on top of palsa)	Circumference 46 cm, Relative age 48 y	28
Tree #3 (on top of palsa)	Circumference 53 cm, Relative age 58 y	53

Soils at the oxbow depression sites have thick surface organic horizons (38-60 cm, Table 2) with water tables maintaining at the surface (Table 1). A silt loam substratum underlies the thick organic horizon at both oxbow depression sites. At the Sedge meadow and *Sphagnum* bog sites there is a small percentage of buried organic debris sandwiched in the mineral matrix at 71-84 cm and 80-100 cm (Table 2).

The mineral soils in this study are dominated by silt with lesser amounts of sand and clay, and a shift in the percentage make-up of the mineral soils across the landforms (Table 2, Figure 10). When soils are grouped by stage of development there are recognizable similarities or differences in the percentages of sand, silt and clay (Figure 10). Soils of the youngest surfaces including the sites in active-floodplain deposits of Stage 2 and 3 and sites in inactive-floodplain deposits Stage 4 sites had the highest sand weight percentages of the studied sites. Soils on the abandoned floodplain including the oxbow depressions and abandoned river channels of Stages 5a and 5c had higher silt contents compared to the other sites (Figure 10). There were no significant differences in clay percentages across the sites of this study (Figure 10). There are large fluctuations in the percentages of sand and silt that extend across the studied sites (Table 2). Mineral soils to a depth of 60 cm were included in Figure 2 to illustrate the major differences across the landforms.

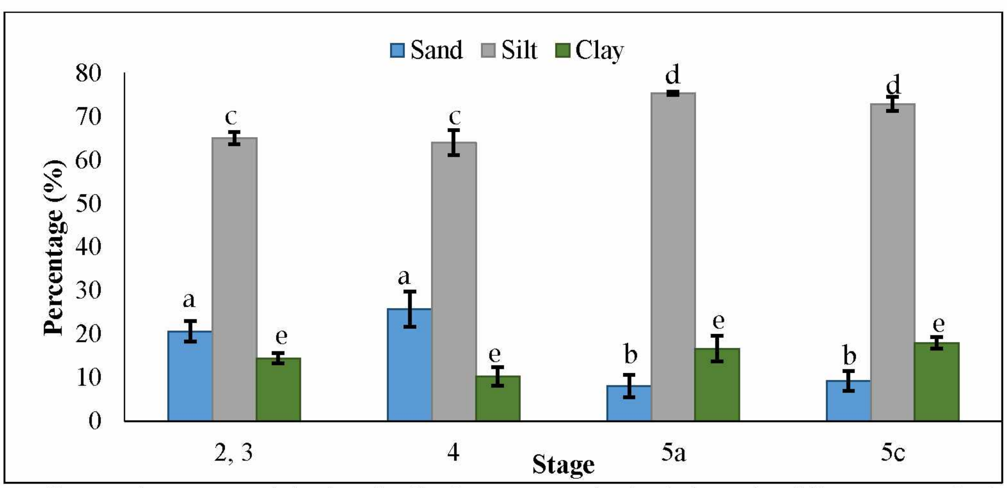

Figure 10. Changes in mean particle size distribution to 60 cm in depth from the different stages in the study. Different letters indicate values that are significantly different (ANOVA, P<0.05): sand (a, b), silt (c, d) or clay (e).

3.3 Soil Chemical and Mineralogical Properties

3.3.1 Soil pH and Nutrients

Soil chemical properties including pH, soil organic carbon and nitrogen, and macronutrients are provided in Table 4.

Measured soil pH values varied little across sites (Table 4). Soils at Stages 2 (Willow 1-3 sites) are strongly to moderately acid (pH 5.1-5.9) in surface horizons with slight increases with depth. Soils at Stage 3 (Willow 4) have slightly lower pH values than Stage 2 (pH 4.3-5.4). The soils on the levees of Stage 4 (Alder 1 and 2, and Cottonwood sites) sites are very strongly to strongly acid (pH 4.8-5.2) in surface horizons. In subsurface horizons there are slight increases of pH with depth at Alder 1 and 2 sites and irregular increases in soil pH with depth at the Cottonwood site. Soils at the Stage 5a (Sedge meadow and *Sphagnum* bog sites) are very strongly acid (pH 4.8) with slight increases with depth. The soils at Stage 5c (Ericaceous shrubs sites) are very strongly acid (pH 4.6-4.9) with slight decreases in soil pH with depth.

Highest values of CEC were measured in surface organic horizons and decreased with depth, often irregularly as with organic matter contents. The highest measured CEC values were measured in the Oi/Oe at the Ericaceous shrubs 3 site of Stage 5c (268 cmol kg^{-1} soil, Table 4). The lowest soil CEC values in surface organic horizons were found in soils at the Ericaceous shrub 1 site (74 cmol kg^{-1} soil, Table 4).

The extractable base cations followed similar patterns as CEC across landforms. The highest extractable base is Ca at all sites with highest values in surface organic horizons that decrease irregularly with depth (Table 4). Ca concentrations are similar across the sites, except for the Stage 4 sites where generally lower values of Ca occur with depth when compared to other sites (Table 4). Mg had the next highest extractable concentrations in soils following a

Table 4. Chemical properties of soils formed on the Yukon-Kuskokwim River floodplain near St. Mary's, Alaska.

Site	Horizon	pH (1:1)	EC (dS/m)	SOC (%)	TN (%)	C/N (ratio)	SOM (%)	CEC ($cmol\ kg^{-1}$)	K	Ca	Mg	Na
										($cmol\ kg^{-1}$)		
Willow 1 Stage 2	Oi/Oe	5.1	1.0	22.7	1.6	14.5	39.9	259.4	0.6	26.4	5.5	0.2
	Oa/A	5.1	0.9	8.9	0.8	11.7	23.4	56.6	0.2	17.2	3.2	0.2
	Cg1	5.2	0.5	3.9	0.4	10.5	10.6	39.4	0.1	8.5	1.5	0.2
	Cg2	5.3	0.4	3.0	0.3	10.8	8.4	41.6	0.1	11.2	1.9	0.1
	Cg3	5.4	0.4	2.8	0.3	9.5	8.4	39.7	0.1	12.7	2.2	0.2
	Cg4	5.2	0.3	2.5	0.3	10.0	7.7	44.3	0.1	12.2	2.1	0.2
	Cg5	5.5	0.3	1.3	0.1	9.8	5.1	30.9	0.1	10.0	2.0	0.2
Willow 2 Stage 2	Oe	5.6	1.0	17.0	1.1	16.1	29.3	132.2	0.7	29.1	5.9	0.1
	A	5.7	0.6	4.8	0.4	12.0	11.6	31.4	0.2	16.7	2.7	0.1
	Cg1	5.4	0.3	1.5	0.2	9.5	5.6	25.7	0.1	7.6	1.8	0.1
	Cg2	5.4	0.3	1.5	0.2	9.1	5.8	31.4	0.1	8.3	1.9	0.1
	Cg3	5.3	0.3	1.3	0.2	8.4	5.4	29.3	0.1	7.5	1.9	0.1
	Cg4	5.3	0.2	0.5	0.1	5.6	2.6	14.9	0.1	3.6	0.9	0.1
Willow 3 Stage 2	Oi	5.9	1.1	25.0	1.4	18.4	41.9	99.4	1.8	27.7	6.7	0.2
	Ag	5.1	0.4	5.4	0.5	10.9	12.5	43.7	0.1	9.8	2.3	0.1
	Cg1	5.3	0.4	3.6	0.3	10.6	9.2	39.4	0.1	10.4	2.4	0.1
	Cg2	5.1	0.4	3.2	0.3	11.3	8.3	26.6	0.1	10.4	2.3	0.1
	Cg3	5.7	0.4	2.5	0.2	10.6	7.7	38.0	0.1	12.2	2.9	0.1
	Cg4	5.7	0.3	2.5	0.2	10.8	7	29.9	0.1	11.3	2.6	0.1
	Cg5	5.7	0.3	1.8	0.2	10.4	5.9	33.1	0.1	10.6	2.5	0.1
	Cg6	6.1	0.2	2.1	0.2	10.0	6.7	36.6	0.1	12.1	2.8	0.1
Willow 4 Stage 3	Oi/Oa	5.2	1.4	15.7	1.1	14.1	38.3	73.9	0.4	20.4	4.5	0.2
	Ag	4.3	0.6	8.0	0.7	12.2	16.8	41.3	0.1	8.0	1.5	0.2
	Cg1	4.5	0.9	7.0	0.6	11.2	15	50.5	0.1	9.4	1.4	0.2
	Cg2	5.0	0.3	2.3	0.2	9.3	7.4	29.6	0.1	8.1	1.5	0.1
	Cg3	5.1	0.2	0.5	0.1	6.4	3.3	23.0	0.1	6.5	1.3	0.1
	Cg4	5.4	0.1	0.4	0.1	6.3	3.5	24.3	0.1	6.4	1.5	0.1
Alder 1 Stage 4	Oe/Oi	4.8	1.7	26.8	1.8	15.0	51.7	127.3	1.2	20.7	6.3	0.5
	Bw	4.1	0.6	7.5	0.7	11.3	13.7	54.3	0.1	6.4	1.3	0.2
	Ab	4.9	1.3	2.8	0.3	10.2	6.6	31.3	0.0	6.0	1.1	0.2
	Cg1	4.6	0.4	1.9	0.2	10.2	5.4	30.7	0.0	6.9	1.1	0.1
	Cg2	4.7	0.5	1.8	0.2	9.9	5	29.2	0.0	7.5	1.1	0.1
	Cg3	4.6	0.8	1.1	0.1	9.5	3.8	24.3	0.1	4.9	1.4	0.1
Alder 2 Stage 4	Oe	4.7	1.2	45.1	4.5	10.0	66.3	223.3	1.2	50.1	10.6	0.2
	A	--	--	14.0	1.2	11.9	28.6	69.0	0.1	13.7	2.2	0.2
	Bg	4.6	0.4	4.5	0.4	10.3	11.3	48.0	0.1	10.9	1.5	0.2
	Cg1	5.0	0.2	1.3	0.1	8.9	5.1	27.7	0.0	7.0	1.1	0.1
	Cg2	5.1	0.2	0.6	0.1	7.1	3	57.5	0.1	5.6	0.8	0.1
	Cg3	5.2	0.2	0.7	0.1	7.4	2.8	19.7	0.1	6.9	1.2	0.1
	Cg4	5.0	0.5	1.4	0.2	9.0	5.1	28.6	0.1	6.9	2.2	0.1

Table 4 (continued). Chemical properties of soils formed on the Yukon-Kuskokwim River floodplain near St. Mary's, Alaska.

Site	Horizon	pH (1:1)	EC (dS/m)	SOC (%)	TN (%)	C/N (ratio)	SOM (%)	CEC (cmol kg^{-1})	K	Ca	Mg	Na
										(cmol kg^{-1})		
Alder 2 Stage 4 (cont.)	Cg5	5.0	0.2	1.6	0.2	9.1	5.5	30.7	0.1	7.5	2.5	0.1
	Cg6	4.2	0.7	3.8	0.3	11.2	9	38.0	0.1	7.9	2.4	0.1
Cottonwood Stage 4	Oa	5.2	1.4	32.7	2.0	16.1	59.3	121.2	1.6	37.3	9.9	0.1
	A	4.5	0.8	8.3	0.7	11.7	18.1	59.1	0.1	16.0	2.9	0.2
	Bw	4.2	0.6	4.0	0.4	10.0	10.4	42.6	0.1	8.2	1.5	0.2
	C	4.7	0.6	1.7	0.2	8.9	5.7	28.6	0.0	4.6	0.8	0.1
	Cg1	4.8	0.3	1.1	0.1	8.8	4.8	29.6	0.1	7.5	1.3	0.2
	Cg2	5.2	0.2	0.5	0.1	6.6	3.2	21.2	0.1	6.2	1.2	0.1
Sedge meadow Stage 5a	Oi	4.8	0.9	42.0	2.0	20.5	80.4	145.9	1.4	20.8	4.8	0.4
	Oe	4.0	0.7	17.7	1.3	14.0	34.2	78.4	0.0	14.9	1.5	0.1
	Oa1	4.1	0.7	19.6	1.4	14.5	39.4	97.2	0.1	15.6	2.0	0.2
	Oa2	4.3	0.8	12.7	1.1	11.9	26.2	79.6	0.0	11.1	1.1	0.1
	Bg1	4.2	0.7	10.7	0.9	12.0	22.3	59.3	0.0	12.2	1.3	0.1
	Bg2	4.2	0.6	10.6	0.9	12.0	21.8	54.1	0.0	12.5	1.3	0.1
	Cg1	4.0	0.7	3.6	0.3	10.9	8.9	19.6	0.0	6.6	0.9	0.1
	Cg2	3.8	0.6	1.6	0.2	10.3	5.4	25.3	0.0	4.4	0.7	0.1
	Cg3	4.0	0.6	2.7	0.2	12.7	7.4	78.4	0.1	5.6	0.8	0.0
Sphagnum bog Stage 5a	Oi1	4.8	0.3	48.9	1.2	40.4	94.7	135.8	1.8	56.4	14.4	1.0
	Oi2	4.1	0.5	46.1	1.3	34.4	84.7	68.8	0.3	13.6	3.6	0.3
	Oa1	3.9	0.6	29.5	1.4	21.2	52.9	97.1	0.1	15.4	2.3	0.3
	Oa2/Bg1	3.9	--	9.5	0.8	12.6	20.7	55.0	0.1	10.2	1.0	0.2
	Bg2	4.3	0.5	7.9	0.5	14.9	21	25.6	0.1	11.6	1.1	0.1
	Bg3	4.0	0.7	3.9	0.3	14.1	5.9	38.8	0.1	7.6	0.9	0.1
Ericaceous shrubs 1 Stage 5c	Oe	4.8	1.0	38.5	1.9	20.2	61.5	256.0	1.6	26.6	6.9	0.4
	Oa	4.8	1.0	15.3	1.1	13.7	30.8	87.1	0.1	19.9	2.9	0.2
	Oe/Bg	4.6	0.8	8.5	0.7	12.8	17.9	40.8	0.1	11.4	2.1	0.1
	Cg	4.5	0.5	4.9	0.3	16.2	9.7	40.7	0.1	9.3	2.1	0.1
Ericaceous shrubs 2 Stage 5c	Oi/Oe	4.9	1.1	41.5	1.8	23.1	73.9	267.7	1.9	32.9	7.3	0.4
	Oa	4.6	0.7	20.8	1.4	15.3	33.9	106.4	0.5	35.3	6.0	0.3
	Bg/Oe	4.6	0.6	10.3	0.7	13.7	21.5	54.1	0.1	11.9	2.1	0.2
	Cg1	4.6	0.6	3.0	0.3	12.2	8.2	40.0	0.1	8.8	1.9	0.2
	Cg2	4.5	0.7	4.5	0.3	14.4	10.8	44.1	0.1	10.0	2.4	0.1
Ericaceous shrubs 3 Stage 5c	Oi	4.6	1.0	45.8	1.5	29.9	81.2	154.4	2.1	31.2	7.6	0.1
	Oe	4.8	0.9	42.0	1.7	24.7	76	103.5	1.1	38.9	7.4	0.2
	Oa/A	4.7	0.7	19.3	1.2	15.4	37.5	83.9	0.2	25.3	3.9	0.2
	Cg1	4.3	0.6	6.6	0.5	12.7	15	53.0	0.1	9.7	1.8	0.2
	Cg2	4.2	0.6	2.7	0.2	12.2	7.1	32.5	0.1	7.3	1.9	0.2
	Cg3	4.4	0.6	3.0	0.2	13.7	7.6	40.3	0.1	5.9	1.4	0.1
	Cg4	4.3	0.9	10.5	0.9	12.4	23	64.0	0.1	11.4	2.0	0.2
	Cf	--	--	--	--	--	--	--	--	--	--	--

similar pattern as Ca. Highest values of Ca and Mg were both found in surface horizons at the *Sphagnum* site. The concentration of extractable K were low (1.6-2.1 cmol kg^{-1} soil, Table 4) with highest values in the surface horizons of the Stage 5c soils. The concentration of extractable Na was very low (0.1-1.0 cmol kg^{-1} soil, Table 4).

The measured electrical conductivity (EC) values were highest in organic horizons of Stage 4 sites (1.2-1.7 dS/m, Table 4) compared to surface organic horizons at the other sites. Measured EC values in surface organic horizons were lowest at the 5a sites (0.3-0.9 dS/m, Table 4). Measured EC values decreased with depth at all sites (Table 4).

Among the three extractants, ammonium oxalate measured the highest values of extractable iron (as Fe_o) and aluminum (as Al_o) across all sites (Table 5). In many cases Fe measured by ammonium oxalate are higher than that by dithionite-citrate (Fe_d) which indicates the presence of magnetite in the sediments of the Yukon River (Walker, 1983). Lowest values of Fe and Al were measured from the Na pyrophosphate extraction (Fe_p, Al_p) and the ratio of Al_p/Al_o is low indicating that less than 30% of Al is organically bound (Table 5). The ratio of both Fe_p/Fe_d shows a slight increase over time as soils develop showing a shift to organically bound Fe in soils. Most of the free or secondary iron is in poorly crystalline forms, most likely ferrihydrite, a product of rapid oxidation of ferrous iron (Schwertmann and Taylor, 1989). There are few changes in the Fe measurements for ammonium oxalate and dithionite extractions across sites. There was a slight increase in the Fe_p from the Stage 2 sites to the Stage 3 site (Table 5). There are minor changes in Fe measurements with depth, but no trends identified. The total iron values measured in sediment of Yukon River stream samples from Pilot Station (30 km upriver from the study area) were high (7,620 µg/L Fe) (Brabets et al., 2000) and suggests how soils frequently inundated with stream water would be impacted.

Table 5. Extractable Fe and Al in soils of selected sites in Yukon-Kuskokwim River floodplain, near St. Mary's, Alaska.

Site	Horizon	Na Pyrophosphate		Ammonium Oxalate			Dithionite-Citrate			Al_p/Al_o*	Fe_p/Fe_d °
		Fe	Al	Fe	Al	Si	Fe	Al	Mn		
		%								(ratio)	(ratio)
Willow 2	Oe	--	--	--	--	--	--	--	--	--	--
Stage 2	A	0.5	0.1	1.4	0.3	0.3	1.1	0.1	0.0	0.2	0.4
	Cg1	0.3	0.1	1.3	0.3	0.2	1.0	0.1	0.0	0.2	0.3
	Cg2	0.3	0.1	1.5	0.3	0.2	1.1	0.1	0.0	0.2	0.3
	Cg3	0.3	0.1	1.4	0.3	0.2	1.1	0.1	0.0	0.2	0.2
	Cg4	0.1	0.0	0.8	0.2	0.1	0.7	0.1	0.0	0.2	0.2
Willow 3	Oi	--	--	--	--	--	--	--	--	--	--
Stage 2	Ag	0.4	0.1	1.0	0.3	0.3	0.7	0.1	0.0	0.3	0.5
	Cg1	0.5	0.1	1.6	0.3	0.3	1.1	0.1	0.0	0.2	0.4
	Cg2	0.3	0.1	1.4	0.3	0.2	1.1	0.1	0.0	0.2	0.3
	Cg3	0.3	0.1	1.4	0.3	0.2	1.2	0.1	0.0	0.2	0.2
	Cg4	0.2	0.0	1.4	0.3	0.3	1.1	0.1	0.0	0.1	0.2
	Cg5	0.2	0.0	1.4	0.3	0.3	1.1	0.1	0.0	0.2	0.2
	Cg6	0.3	0.1	1.5	0.3	0.3	1.2	0.1	0.0	0.2	0.3
Willow 4	Oi/Oa	--	--	--	--	--	--	--	--	--	--
Stage 3	Ag	0.7	0.2	1.4	0.4	0.3	1.1	0.2	<0.01	0.4	0.7
	Cg1	1.1	0.2	2.3	0.4	0.3	1.8	0.2	0.0	0.3	0.6
	Cg2	0.6	0.1	1.9	0.4	0.3	1.6	0.2	0.0	0.3	0.4
	Cg3	0.1	0.0	1.3	0.3	0.3	1.2	0.1	0.0	0.1	0.1
	Cg4	0.1	0.0	1.2	0.3	0.3	1.1	0.1	0.0	0.1	0.1
Alder 2	Oe	--	--	--	--	--	--	--	--	--	--
Stage 4	A	--	--	--	--	--	--	--	--	--	--
	Bg	0.8	0.2	2.0	0.5	0.3	1.5	0.3	0.0	0.3	0.5
	Cg1	0.4	0.1	1.4	0.3	0.3	1.2	0.1	0.0	0.3	0.4
	Cg2	0.2	0.0	1.1	0.2	0.2	1.0	0.1	0.0	0.1	0.2
	Cg3	0.2	0.0	1.1	0.2	0.2	1.0	0.1	0.0	0.1	0.2
	Cg4	0.1	0.1	0.7	0.3	0.2	0.4	0.1	<0.01	0.2	0.4
	Cg5	0.3	0.1	1.0	0.2	0.3	0.8	0.1	<0.01	0.2	0.4
	Cg6	0.2	0.1	0.7	0.3	0.3	0.4	0.1	0.0	0.2	0.6
Cottonwoo	Oa	--	--	--	--	--	--	--	--	--	--
d	A	0.9	0.1	1.5	0.4	0.3	1.2	0.2	0.0	0.3	0.8
Stage 4	Bw	0.7	0.1	1.6	0.4	0.3	1.2	0.2	0.0	0.3	0.6
	C	0.5	0.1	1.5	0.3	0.3	1.2	0.2	0.0	0.3	0.4
	Cg1	0.4	0.1	1.6	0.3	0.3	1.3	0.1	0.0	0.2	0.3
	Cg2	0.2	0.0	1.4	0.3	0.3	1.1	0.1	0.0	0.1	0.1
Ericaceous	Oi	--	--	--	--	--	--	--	--	--	--
shrubs 3	Oe	--	--	--	--	--	--	--	--	--	--
Stage 5c	Oa/A	--	--	--	--	--	--	--	--	--	--
	Cg1	1.0	0.2	1.7	0.5	0.3	1.1	0.2	0.0	0.3	0.9
	Cg2	0.5	0.1	1.4	0.3	0.3	1.0	0.1	0.0	0.2	0.5
	Cg3	0.4	0.1	1.1	0.3	0.3	0.8	0.1	0.0	0.2	0.5
	Cg4	0.9	0.2	1.5	0.4	0.3	1.0	0.2	0.0	0.4	0.9
	Cf	--	--	--	--	--	--	--	--	--	--

*Al_p/Al_o represents ratio of Na pyrophosphate extractable Al to Ammonium oxalate extractable Al.

°Fe_p/Fe_d represents ratio of Na pyrophosphate extractable Fe to Dithionite citrate extractable Fe.

3.3.2 Soil Organic Carbon Stores

Total carbon content was assessed to be comparable to the values of organic carbon content because of low pH values (<5.2) for most soils sampled which implies the absence or insignificant inorganic carbon content. In addition, the assumption that organic matter is approximately 58% organic carbon was assessed conventionally (Soil Survey Staff, 2011). The percent total carbon values were much lower than 58% in this study even though the total organic carbon measurements have a linear relationship with soil organic matter; %SOC = 0.493 (%SOM), ($R^2 = 0.9855$, $P < 0.001$). Ping et al. (2010) found the conversion factor of 0.493 of converting %SOM to %SOC for other Alaskan soils. For these reasons values for LOI can be used for estimating the SOC content in this region.

Measured values for SOC and SOM are reported in Table 4. There is a large increase in SOM and SOC contents (%) in subsurface horizons from soils in modern-floodplain deposits of Stages 2, 3 and 4 sites, compared to the soils of the abandoned floodplain of Stages 5a and 5c (Table 4). In general, there are irregular decreases in SOM and SOC contents with depth in soils at all studied sites (Table 4). The SOM and SOC contents are greatest in the surface horizon of the *Sphagnum* site and lowest at the Willow 2 site (Table 4). The soils of the Stage 5c sites have the greatest SOM and SOC content throughout the soil profiles (Table 4).

Other soil chemical properties appear to be connected to SOM, including CEC, TN, and extractable cations (Ca, Mg and K) (Table 4). Highest concentrations of Ca, Mg, and K coincide with highest SOM contents that peak in the surface organic horizons (Table 4). The changes in CEC closely corresponded to the changes in SOM contents and are plotted in Figure 11. Soils of the Stage 5a and 5c sites have some of the highest SOM contents and CEC values compared to soils of Stages 2, 3, and 4 (Figure 11). Changes in CEC values do not correspond with the changes in the clay mineral content (Figure 12). There is more variability in clay mineral content and associated CEC value in Stages 2, 3, and 4 compared to Stages 5a and 5c but there is still a poor relationship (Figure 12).

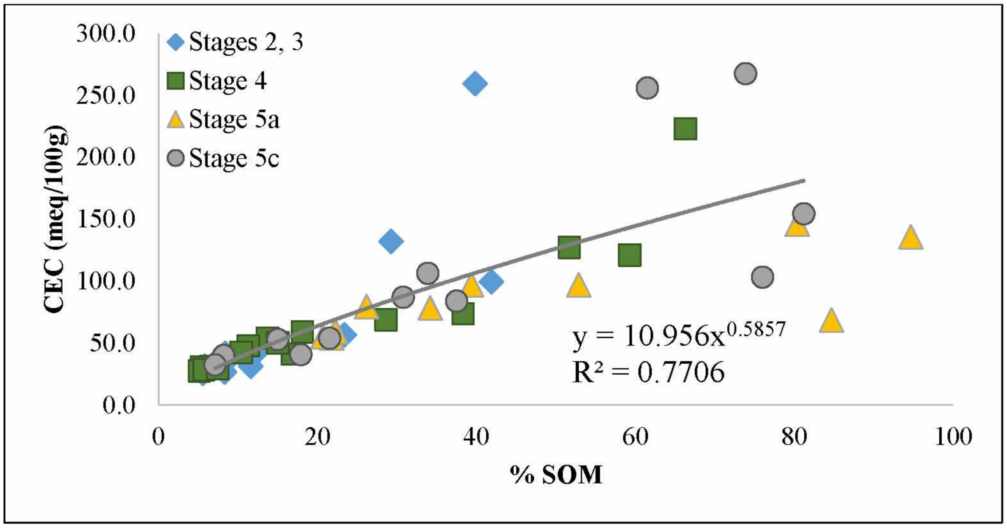

Figure 11. The relationship between cation exchange capacity (CEC) and soil organic matter (SOM) contents for different Stages to 60 cm in depth.

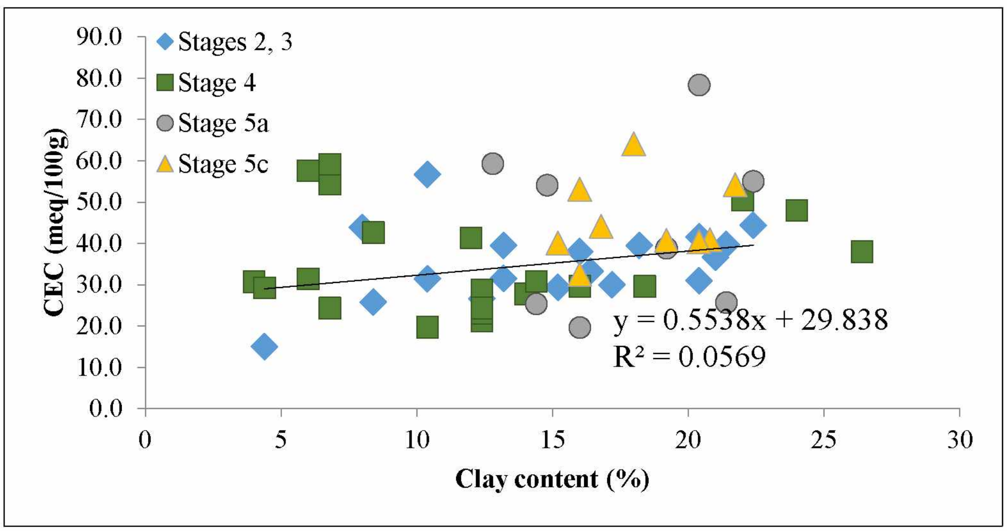

Figure 12. The relationship between cation exchange capacity (CEC) and clay contents in mineral horizons of different Stages to 60 cm in depth.

Information on SOC and TN content and storage for the stages of floodplain development is provided in Table 6. Mean values represent the soils to 100 cm in depth of the soil profiles for associated landforms. There is a large increase SOC and TN content from soils in Stages 2, 3, and 4 to the soils in Stages 5a and 5c (Table 6). Both SOC and TN contents peaked in soils in Stage 5c and followed by soils in Stage 5a (Table 6). The SOC contents in soils of the raised alluvial bars and natural levees have similar SOC contents that are significantly lower than the soils of the abandoned floodplain including the abandoned river channels and oxbow depression sites.

Table 6. Mean values (standard error) of SOC and TN contents (%), and C and N storage in different stages of succession. Different letters indicate values that are significantly different (ANOVA, $P<0.05$).

Stage	Sedimentation process	Dominant vegetation	SOC (%)	TN (%)	Carbon storage (Kg C m^{-2})	Nitrogen storage (Kg C m^{-2})	C:N (ratio)
2, 3	Modern, Active	Willow	5.8 (1.3)a	0.5 (0.1)a	27.7 (2.9)a	1.7 (0.7)a	10.9
4	Modern, Inactive	Alder and Cottonwood	9.2 (3.2)a	0.8 (0.3)ab	27.7 (2.6)a	2.7 (0.3)a	10.4
5a	Older, Abandoned	Grasses and Mosses	17.8 (4.2)b	0.9 (0.1)b	40.9 (2.5)b	2.8 (0.6)a	17.1
5c	Older, Abandoned	Ericaceous shrubs	17.3 (3.9)b	0.9 (0.2)b	45.3 (1.4)b	3.2 (0.1)a	16.4

There is a large increase in the C storage from the modern floodplain deposits (Stages 2, 3, and 4) to the older floodplain deposits (Stages 5a and 5c) (Table 6). C storage is greatest in soils of Stage 5c closely followed by soils of Stage 5a. C storage is similar for soils of Stages 2, 3 and 4 but values are much lower than for soils of Stage 5a and 5c (Table 6).

The nitrogen (TN) content increases from soils in active-floodplain deposits of Stages 2 and 3, to the soils in abandoned-floodplain deposits of Stages 5a and 5c (Table 6). For N storage, there are no significant differences between stages of floodplain development in this study (Table 6). The lowest C/N ratio occurs in soils in inactive-floodplain deposits with vegetation communities dominated by alder and cottonwood (Table 6).

The changes in SOC contents and C storage with depth at the Alder 2 site are highlighted in Figure 13. The SOC content peaked in the surface O horizon and decreased drastically with depth to the Cg2 horizon then SOC contents increased through to the Cg6 horizon; reflecting the fluvial processes and deposition of organic debris within the soil profile. But when the SOC contents expressed on a weight basis changed to a volume basis as C stores, the distribution pattern changed due to correction with bulk density. The highest C store is highest in the A horizon followed by the substratum at 135 cm.

The changes in C storage generally follow the perturbations in SOC contents but peak C storage values are offset to the horizon at depths 13-27 cm (Figure 13). The C storage values decline with depth until depth 60-75 cm and then increase to peak at depths 135-155 cm. The changes in SOC contents and C storage with depth illustrate the heterogeneity of a typical floodplain soil that formed from the build-up of mineral and organic materials deposited from stream waters.

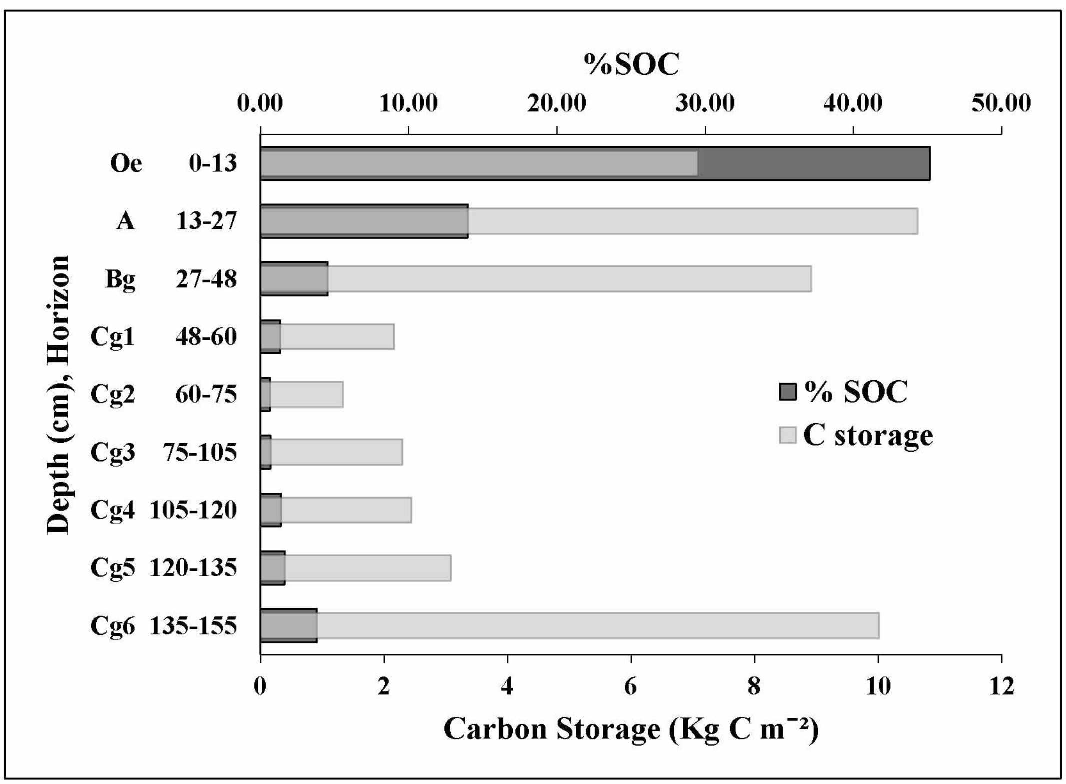

Figure 13. Changes in soil organic carbon (% SOC) distribution with depth and the relative changes in C storage (Kg C m^{-2}) with depth at the Alder 2 site in modern, inactive-floodplain deposits.

3.3.3 Clay Mineralogy

The soils classified as Inceptisols show some development, and are only inundated by stream waters during the more major flooding events on the floodplain. Any changes with depth in clay mineralogy can give insight to the degree of weathering or stability of the mineralogy in soils forming on the floodplain. In the older surfaces on the floodplain, there is a potential for permafrost aggradation and as soil temperatures decrease, the degree of clay weathering decreases. The site chosen for the clay mineral analysis is the Cottonwood site, dominated by *Populas balsamifera* var. *Tricocarpa* with *Alnus spp*. as co-dominant species. The site is located on a levee in modern, inactive-floodplain deposits and is classified as a coarse-silty, mixed, acid Fluvaquentic Cryaquept. Samples from the A, Bw, C and Cg1 horizons were used to see if there were any changes in the clay mineral composition with depth in the soil profile. There is a shift in the texture with depth of this soil profile where the percent clay drops greatly from the A to the Cg1 horizon from 26% to 4% accompanied by percent sand increase from 7% to 18% (Table 2). This shift in soil texture likely is attributed to the different flooding depositional events that commonly occur on the floodplain, but give insight into the potential explanation for the clay mineral type and distribution within the soil. Because the clay mineralogy was only assessed for one soil profile, information revealed in this analysis have limited extrapolation power and represent a restricted picture of what soils in this region may contain. Nonetheless, these results provide data in a region void of soil clay mineralogy information.

Soil clay minerals can either be inherited from the soil parent materials, form as products of transformation from other clay minerals, or form as precipitates from the soil solution. Laboratory saturation of prepared clays with Mg^{2+}, Ca^{2+}, or K^{+} and then subsequently treated with ethylene glycol (EG) and heated to various temperatures and scanned via XRD analysis is a diagnostic tool used to identify specific clay minerals and can additionally give insight into the relative changes in abundances that may hint at transformation of clay minerals in soils (Pipkin, 1965).

Dominant clay minerals found through the XRD qualitative analysis in this study were illite, smectite, kaolinite, and chlorite with lesser amounts of vermiculite. There are only slight changes with the clay mineral composition with depth (Figure 14, Table 2) which suggests the clay mineralogy of the soils reflecting the primary composition of the parent materials which is stratified alluvium.

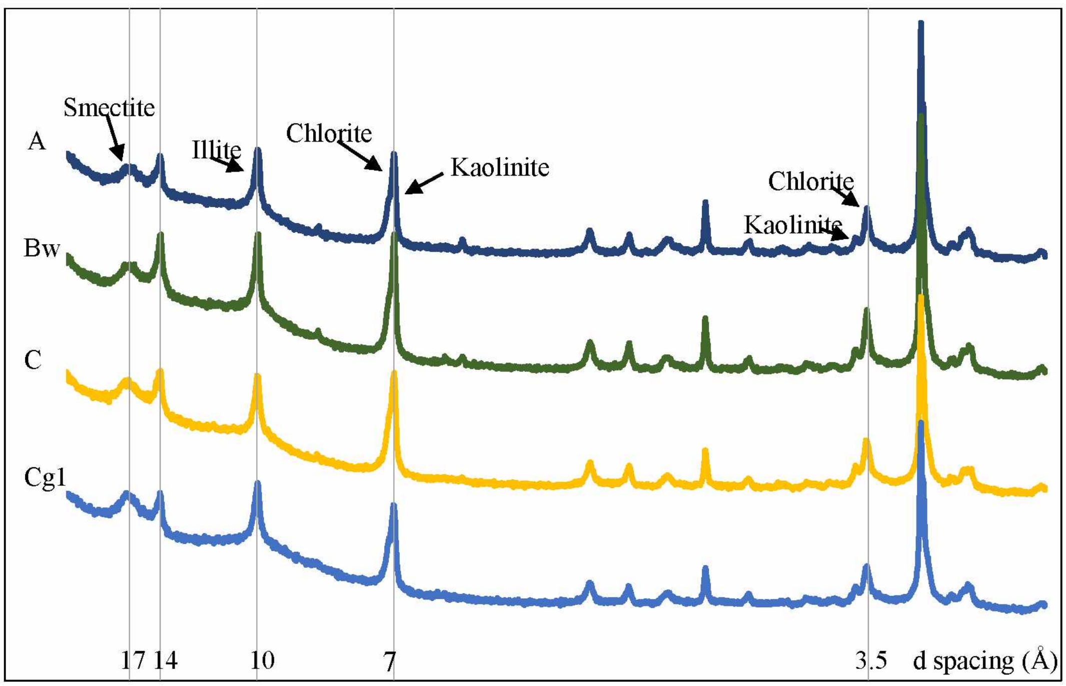

Figure 14. Diffractograms of Ca- ethelene glycolated (EG) treated samples of different horizons sampled. Units represent d-spacing for diagnostic peaks of major clay groups.

The diffractograms in Figure 14 represent the relative changes in depth of the major clay mineral groups in the soil profile explored. The diffractograms from the calcium saturated, ethylene glycolated treated samples (Ca-EG) represent the major clay mineral components in the soils of this study with few changes in intensity of the major peaks with depth in the soil profile. Smectite is distinguished by the expansion of a 17 Å peak after glycolation of Ca or Mg saturated clays (Figure 14 and 15). In Mg treated samples there was partial collapse of the 14Å peak that expanded to 17Å (Figure 15). In Ca treated samples there was no loss of the 14Å peak after glycolation, but there is a 12Å peak present in the Ca-25°C samples that shifts to 17Å after glycolation (Figure 16). This curious 12Å peak is not present in the Mg saturated clays (Figure 15), but corresponds with the diagnostic peaks of Na-montmorillonite as a form of the smectite present (Chen, 1977). The differences between Mg and Ca treated samples may reflect the impact of low humidity (in the lab) on the different cation saturation of clay samples and more analyses of this effect are required to understand this effect, but relative humidity has been reported to effect peak heights (Gosh and Tomar, 1974). After heat treatment of the Ca-EG or Mg-EG treated samples, the 17Å peak collapses to 10Å (Figure 15 and 16).

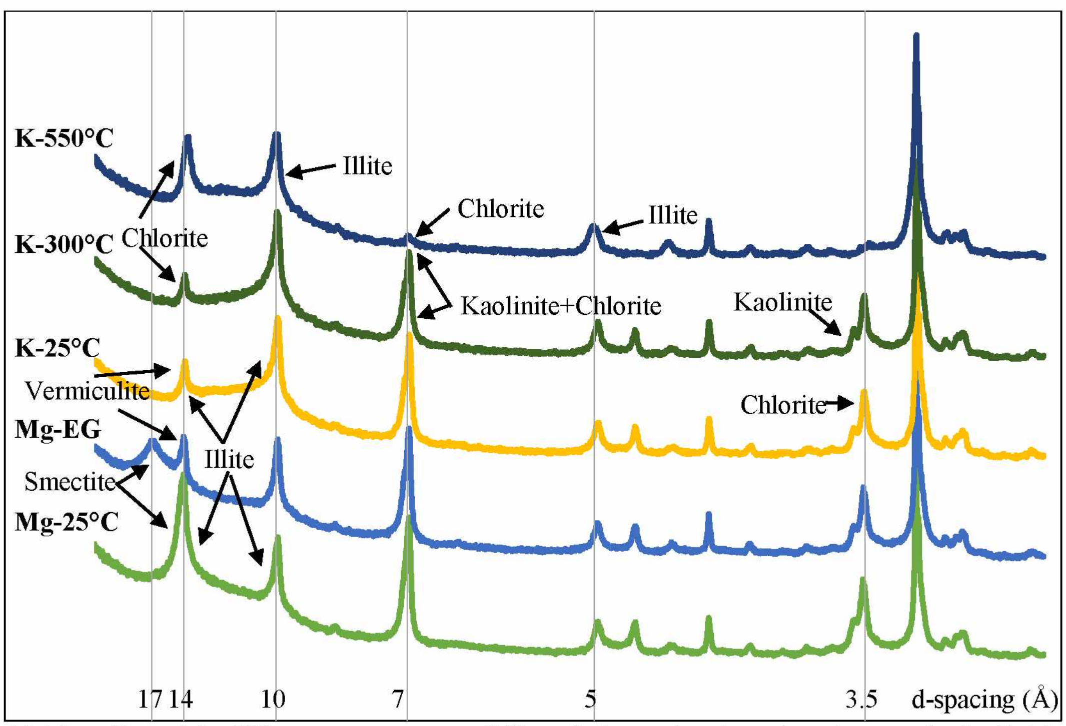

Figure 15. The effect of the different treatments on differentiating major clay mineral groups in the Cg1 horizon.

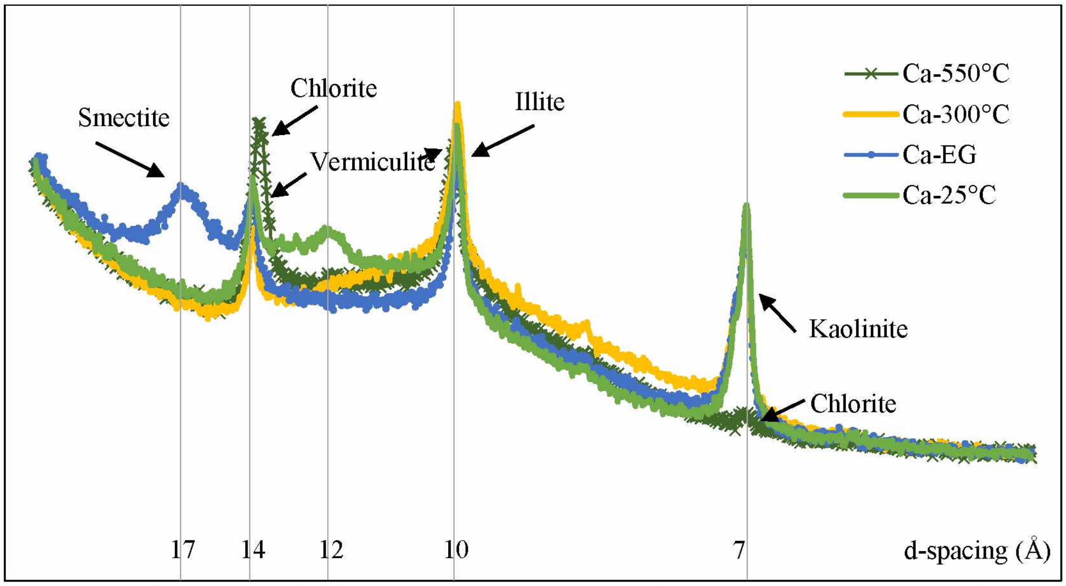

Figure 16. Diffractogram of different clay minerals found in Ca treated samples of the Cg1 horizon.

Vermiculite is evident through observations of the 14 Å peak and changes from Ca-EG or Mg-EG samples to K treated samples, from which after K saturation the vermiculite peak collapses to 10 Å. This feature is evident through small changes observable in Figure 15. Additionally, an increase in the intensity of the 10 Å peak from the Ca-EG or Mg-EG to the Ca-300°C or Mg-300 °C treated samples (Figure 15 and 16) also signify the presence of vermiculite and hydroxyl-interlayer vermiculites. Though vermiculite is qualitatively more challenging to identify through diffractograms because the prominent peaks associated with vermiculite share basal reflections with other clay minerals, the efforts to identify the presence of vermiculite is even more challenging because of its suspected minor appearance in the soils of this study. Nonetheless, there was indication of slight changes with the diagnostic peaks intensities associated with vermiculite in the soils of this study and suggests small concentrations of vermiculite (Figure 15 and 16). Kaolinite is present in the sampled horizons as is evident by the 7Å peak that collapses after heat treatment to 550°C in Ca, Mg, and K treated samples (Figure 15 and 16). The 7Å peak persists at a similar intensity throughout the samples, showing little changes in the concentration with depth in the soil. Collapse of the 3.5Å peak after heating to 550°C in Ca, Mg, and K treated samples is another indicator of kaolinite (Figure 15).

Chlorite was found in all soils with no distinct changes with depth. Chlorite is identified through the 001 (1^{st} order) peak at 14Å peak that grew and sharpened in intensity from Ca-300°C or Mg-300°C treated samples to Ca-550°C or Mg-550°C treated samples (Figure 15 and 16), a characteristics of Fe-rich chlorite. Additionally, looking at the 14Å peak and observing the portion of the 14Å peak that expanded to 17Å in the Ca-EG and Mg-EG treated samples due to the presence of smectite and in the K saturated samples an additional portion of the 14Å peak collapsed to 10Å due to the presence of vermiculite, the persisting 14Å peak after treatments is due to the presence of chlorite (Figure 15). To distinguish chlorite from kaolinite, in the K-550°C treated samples there is a slight peak that remains at 7Å and is characteristic of chlorite while the loss of the 7Å peak is characteristic of kaolinite (Figure 15). The resolution of the 002 peak (2^{nd} order peak) of kaolinite at 3.59Å and the 004 peak (4^{th} order peak) for chlorite at 3.55Å in all the samples distinguishes chlorite from kaolinite after collapse of the 3.59Å after heating to 550°C (Figure 15 and 16).

Illite was identified in all soils sampled with a prominent 10 Å peak that persisted in K treated sampled that were heated to 550 °C (Figure 15). There is a relative shift in peak intensity for peaks at 14 Å and 10 Å in Mg treated samples to K treated samples (Figure 15). This shift corresponds with the affinity illite has for fixing K. Furthermore, the persistence of a 5 Å peak after the 550 °C heating suggests that this is dioctahedral (aluminous) mica, such as illite (Figure 15).

The relative changes in the abundance of clay minerals were semi-quantitatively determined using a 100% approach method developed by Biscaye (1965) and results are provided in Table 7. This method assessed the amounts of illite, expandable materials (smectite+HIV+HIS), kaolinite, and chlorite based on normalized peak intensity areas. Naidu and Mowatt (1983) used Biscaye's (1965) method to determine relative amounts of clay minerals on the continental shelf of Alaska, the terminal depositional region of the Yukon River. Employing the methods used by Naidu and Mowat (1983) can give insight into any changes between the clay mineralogy of the soils of the study area and the sediment deposited by the Yukon River. Peak intensity areas were determined from Ca-EG treated samples to use in the analysis.

Table 7. Relative weight percentages of major clay minerals for soils at the Cottonwood site in modern, inactive-floodplain deposits on the Yukon-Kuskokwim River floodplain near St. Mary's, Alaska.

Depth (cm)	Soil horizon	Kaolinite (%)	Expandable materials (%)	Illite (%)	Chlorite (%)	Expandable materials/ Illite (ratio)
12-18	A	14	21	47	18	0.4
18-41	Bw	14	23	44	19	0.5
41-67	C	14	25	41	20	0.6
67-105	Cg1	13	30	39	18	0.8

Illite was found to have the greatest percentages by weight (39-47%) of the clay minerals in the soils of this study with lesser amounts of expandable materials (21-30%) and chlorite (18-20%), with lowest percentages of kaolinite (13-14%). There were only minor differences between horizons in the relative abundances of any of the clay minerals and is apparent by the consistency between diffractograms in Figure 14. The weight percentages of illite were assessed as the intensity areas under the 10Å peak. Illite made up the largest weight percentages of the clays with highest percentages in horizons closest to the surface (A horizon) that decrease with depth (Table 7).

Weight percentages for expandable materials came from the measured intensity area of the 17Å peak. There were slight increases in the weight percentages with depth of the expandable materials where percentages are the highest in the Cg1 horizon (Table 7). Lowest weight percentages for expandable materials occur in the A horizon.

Chlorite weight percentages were found by using the intensity area under the 7Å peak and subtracting the kaolinite portion determined from the kaolinite/chlorite intensity area ratio under the resolved 3.58Å/3.54Å peaks. The relative weight percentages are fairly consistent for chlorite throughout the soil profile (Table 7).

The weight percentages for kaolinite were determined by using the kaolinite/chlorite ratio from the resolved 3.58Å/3.54Å peaks and applying that portion to the intensity area under the 7Å peak. Kaolinite had lowest weight percentages compared to other clays with essentially no changes in kaolinite with depth, similar to chlorite (Table 7).

The changes in illite and expandable materials with depth are reflected in the increase in the ratio of the percent expandable materials / illite with depth (Table 7). This ratio doubles from the A horizon (0.4) to the Cg1 horizon (0.8) (Table 7).

3.4 Soil Classification

The soils of this study are classified based on *Soil Taxonomy* (Soil Survey Staff, 2014) and listed in Table 7. *Soil Taxonomy* is hierarchical in organization with specific properties in soils that are distinguished as diagnostic features that key soils into Orders, Suborders, Great Groups, Subgroups, and Families. The soils of this study are keyed into the Entisol, Inceptisol, Histosol, and Gelisol Orders, which denotes the degree of flooding disturbance, weak weathering, large accumulations of organic matter, and the presence of permafrost (depths <1 m without cryoturbation, depths <2 m with cryoturbation) , respectively observed in these floodplain soils. All the mineral soils in this study have aquic conditions based on redoximorphic features within 50 cm of the mineral soil surface that place these soils in aquic Suborders or Great Groups. The organic soils are in the Histosol order based on the presence of histic epipedon that is more than 40 cm thick and saturated for more than 30 days during the growing season.

Table 8. Classification of soils studied on the floodplain near St. Mary's, Alaska.

Site	Sedimentation process	Landform	Soil family
Willow 1 Stage 2	Modern, Active	Raised alluvial bar	Coarse-silty, mixed, nonacid Typic Cryaquents
Willow 2 Stage 2	Modern, Active	Oxbow fill	Coarse-silty over sandy, mixed nonacid Typic Cryaquents
Willow 3 Stage 2	Modern, Active	Raised alluvial bar	Fine-silty, mixed, nonacid Typic Cryaquents
Willow 4 Stage 3	Modern, Active	Raised alluvial bar	Coarse-silty, mixed, acid Typic Cryaquents
Alder 1 Stage 4	Modern, Inactive	Levee	Coarse-silty, mixed, acid Fluvaquentic Cryaquepts
Alder 2 Stage 4	Modern, Inactive	Levee	Coarse-silty, mixed, acid Fluvaquentic Cryaquepts
Cottonwood Stage 4	Modern, Inactive	Levee	Coarse-silty, mixed, acid Fluvaquentic Cryaquepts
Sedge meadow Stage 5a	Older, Abandoned	Abandoned river channel	Coarse-silty, mixed, acid Histic Cryaquepts
Sphagnum bog Stage 5a	Older, Abandoned	Oxbow depression	Coarse-silty, mixed, euic Terric Cryofibrists
Ericaceous shrubs 1 Stage 5c	Older, Abandoned	Abandoned floodplain	Loamy, mixed, euic, subgelic Terric Haplohemists
Ericaceous shrubs 2 Stage 5c	Older, Abandoned	Abandoned floodplain	Coarse-silty, mixed, acid Histic Gelaquepts
Ericaceous shrubs 3 Stage 5c	Older, Abandoned	Abandoned floodplain	Coarse-silty, mixed, acid, subgelic Fluvaquentic Historthels

The soils formed in modern, active- and inactive-floodplain deposits (Willow 1-4, Alder 1-2, and Cottonwood sites) are keyed into Aquents and Aquepts suborders due to hydromorphic features associated with prolonged saturation due to a high water table. These soils have a cryic soil temperature regime (MAST between 0 and 8°C, estimated from regional climate data) which keys these soils in the great groups as Cryaquents or Cryaquepts. The soils on the raised alluvial bars in active-floodplain deposits (Willow 1-4 sites) have not developed observable structure in the subsurface horizons to qualify for cambic horizon (B horizon designation) and no evidence of material translocation or any other important distinguishing features. Thus they key into the subgroup of Typic Cryaquents. Soils at the Alder 1 and 2, and Cottonwood sites (Stage 4) that formed on levees classify as Cryaquepts because of the development of a cambic horizons, a result due to soils being less inundated thus allowing the upper horizons to have the opportunity to develop weak structures and experience the oxidation-reduction cycles due to fluctuating water-tables. Soils at the Stage 4 sites have better drainage than soils of the lower elevation alluvial bars with water table depths at 45-50 cm. Redoximorphic features including reduced matrix with iron concentrations and depletions are abundant within the mineral soil horizons and correspond with ground water hydromorphology (Table 2). Evidence of buried organic debris was observed with depth in the profile at sites Alder 1 and 2 that contributes to an irregular decrease in soil organic carbon with depth (Figure 13) which keys the soils as Fluvaquentic Cryaquepts.

All the observed soils developing in abandoned-floodplain deposits (Stages 5a and 5c) had a layer of seasonal frost present during the field observations. This feature can contribute to aquic conditions by restricting the draining of surface waters (Soil Survey Staff, 2014). Many of the soils observed at Stages 5a and 5c feature thick layers of organic matter which meet the criteria of either histic epipedon (20-40 cm of surface organic material saturated ≥30 days during the growing season) or Histosol Order (Table 1 and 2). In fall after thawing of the seasonal frost, permafrost was observed with depth (<2 m) in soils on the abandoned floodplain but not in soils of the abandoned river channels and oxbow depressions.

Depressions of Stage 5a have contributed to restricted drainage in fine-grained oxbow fill with vegetation dominated by *Carex* spp. and *Sphagnum* moss which help sustain the wet and reduced conditions in the soils and form histic epipedons. These sites had seasonal frost at 30-51 cm for the seadge meadow and at 38-53 cm in the *Shagnum* bog during sampling with MAST 0°C. Because these sites were saturated at the surface and had no permafrost <2 m (Table 3), these sites were considered to be in the cryic soil temperature regime (MAST between 0 and 8°C). The soils formed at the Sedge meadow site show progression in development of subsurface materials with a Bg horizon under a histic epipedon <40 cm which makes this soil a Histic Cryaquept. At the *Sphagnum* bog site, thick layers (≥40 cm) of slightly decomposed moss (Oi) (Table 2) have accumulated in the wet and cold conditions which classify these soils in the great group Cryofibrist. These soils can be further evaluated to be in the subgroup of Terric Cryofibrist, because of a mineral soil layer >30 cm thick (Bg1, Bg2) that are directly beneath the organic horizons (Table 2).

Soils formed on the abandoned floodplain of Stage 5c (Ericaceous shrubs 1-3 sites) have a thick organic layer (+30 cm) with histic epipedons (Table 2). These sites had seasonal frost at 25-60 cm for the Ericaceous shrubs 1 site, 25-56 cm at the Ericaceous shrubs 2 site, and at 26-50 cm in the Ericaceous shrub 3 during sampling with MAST 0°C. The Ericaceous shrub 1 and 2 sites have permafrost at depths >1 m (i.e. these are not Gelisols) with subgelic soil temperature class (MAST between +1.0 to -4°C). The Ericaceous shrubs 1 site has >40 cm of sapric or hemic materials in surface and near surface horizons with mineral soil >30 cm thick directly below the control section (organic horizons) and classifies as subgelic Terric Haplohemist. The Ericaceous shrubs 2 site met the requirements for gelic soil temperature regime (MAST ≤0°C) that is estimated due to the presence of permafrost at 120 cm with a thick surface organic layer (>25 cm) to insulate subsurface temperature conditions. Soils feature aquic conditions (Table 2) and a Bg horizon designates this soil into the Gelaquept great group, and with a histic epipedon this soil classifies as a Histic Gelaquept. At the Ericaceous shrubs 3 site, permafrost occurs within 1 m of the soil surface without cryoturbation which keys in the suborder Orthels and because this soil has a histic epipedon this soil further keys in the Historthel great group. Once again, there is an irregular decrease in soil organic carbon with depth in the profile due to stratification of organic debris from prior flooding events, which makes this soil a Fluvaquentic Haplorthel.

4. Discussion

Soil formation on the floodplain near St. Mary's, Alaska is influenced by the frequency of flooding events, height of the water table and the presence or absence of permafrost. The effect of water table fluctuation, fluvial sedimentation, and duration of saturation impacts soil chemical and biochemical processes. The particular stage of floodplain development reflects this impact through changes in vegetation community and organic material accumulation. Alluvial bars represent the floodplain landform that is experiencing the gradual building-up of sediments from deposition by the stream during flooding events that are characteristic of meandering stream processes.

The changes in the physical properties of the soils formed on the floodplain near St. Mary's reflect changes associated with proximity to river, periodicity of flooding events, and accumulation of organic materials. The dominantly silt loam texture, reflects the particle size distribution of the sediments and their sources; from upstream where the Yukon Basin has wide spread loess deposits (Péwé, 1975). The weakly developed structure and moist friable consistence is related to the weak soil development on lower elevation alluvial bars of Stages 2 and 3. The greater abundance of clay in soils sampled contributes to moderately plastic consistence, otherwise soils are slightly plastic. The abrupt and smooth boundaries are characteristic of the fluvial deposit or water laid sediment.

Soils formed on raised alluvial bars (Stage 2) at the Willow 1 and Willow 3 sites are similar in texture and matrix colors due to similar depositional environments and water saturated conditions (Table 2). The loamy sand material at the base of the profile at the Willow 2 site (Table 2) is characteristic of coarse materials that are deposited at the point bar side of a meander that contributed to the alluvial bar aggradation process to close off the oxbow lake.

The Spruce 1 site (Stage 3), a higher elevation, raised alluvial bar has a high water table thus reducing conditions are present. These soils are likely impacted by the river because they are close in proximity to the river and are not high enough in elevation to avoid impact by the river during seasonal flooding events. This site has wetland features with abundant grasses and water logged soils. The soils reflect a high degree of hydromorphism (Table 2) and are more similar in characteristics to the Willow sites than the levee sites.

Soils formed on the levees at Stage 4 (Alder 1-2, Cottonwood sites) reflect changes due to improved drainage that has allowed for periodical aeration of the soils. Water table depths are much lower in the profile than at the Willow sites. These soils show signs of hydromorphism from redoximorphic features that are abundant (Table 2) likely caused from snow melt in the spring and perched water tables due to spring flooding.

The persistence of seasonal frost in soils formed on the abandoned floodplain including Stages 5a and 5c can contribute to aquic conditions by restricting the draining of surface waters producing redoximorphic features observable in the subsurface soil horizons (Ping et al., 1993). In the oxbow depression and abandoned channel deposits sites (Sedge meadow and *Sphagnum* bog), water accumulates in these slightly concave features and sustains the aquic conditions while the fine-textured oxbow fill restricts the drainage. These conditions favor the hydrophilic vegetation such as *Carex* spp. and *Sphagnum* spp. thus resulting in thick organic matter horizons at these sites.

The sand and silt contents change from “younger” surfaces of raised alluvial bars and levees (Stages 2, 3 and 4) to the older surfaces of the abandoned floodplain including the abandoned river channels and oxbow depressions (Stages 5a and 5c). This change reflects the effect of the building-up of the land surfaces over time to distances away from the main river channel where only fine sediment is deposited (Figure 10). This distinction reflects the difference between lateral accretion of coarser materials closest in proximity to the main river channel and vertical accretion of finer materials that are deposited on the surfaces in the slower moving flood waters that extend out farther and take longer to recede to the main river channel (Bloom, 1998

). These changes are similar to what was observed on the Tanana River floodplain, where soil development was noted to be greatly impacted depending on the proximity of the river and the position of the soil location is in relation to the stream (Marion et al., 1993).

Many of the changes in soil chemistry reflect changes in response to reducing conditions due to saturation, soil organic matter accumulation, buried layers of organic debris, or improved drainage resulting in increased weathering of soils of the study area (Tables 2 and 4). The CEC in soils of this study largely reflects the concentration and degree of humification of the soil organic matter and the depth of materials within the profile. The changes in CEC were found to be closely correlated to the changes in SOM contents when plotted based on landform groups (R^2 = 0.7706, P < 0.001, Figure 11) and the changes in concentrations of base cations follow similarly (Table 4). The CEC has a poor relationship with the clay content in soils of this study (R^2 = 0.0569, Figure 12) where changes in CEC values are controlled by the large SOM content in the soils of this study.

The measured EC values are generally high in surface organic horizons likely corresponding to extractable cations and degree of humification. The measured EC values are positively correlated with measured CEC values (R^2 = 0.44, P < 0.001) suggesting the bulk of the cations make up the available nutrient load (Table 4). Higher C/N values in surface organic horizons were negatively correlated with measured EC values (R^2 = 0.56, P < 0.001) suggesting less available nutrients in soils of the abandoned floodplain including the abandoned river channels and oxbow depression (Stages 5a and 5c, Table 3).

Soils at the willow sites (Stages 2 and 3) are in closest proximity to the river and soil reactions are influenced by river water and reflect features specific to each site. All the willow sites have alder co-dominating the land cover type (Table 1), which has shown to contribute to lowering of soil pH in Alaska floodplains systems while increasing the amount of N available in soils (Van Cleve et al., 1993). The Willow 3 site was closest to the stream and had the lowest elevation compared to other willow sites and showed a slightly higher pH (Table 4) with soils more directly influenced by the river. In the soils of this study soil pH does not necessarily increase with soil depth. Because of the relationship between soil pH and the organic matter content, the irregular decrease in the soil organic matter likely is a major factor that produces the irregular decrease in soil pH with soil depth (Table 4). Soils on the abandoned floodplain including the oxbow depression sites with ericaceous vegetation had lowest pH values (Table 4) reflecting the high percentages of organic acids produced by mosses in these systems. Mosses, especially *Sphagnum* moss, are proton donors that initiate paludification in a tundra environment (Clymo, 1964).

The Willow 4 site appears to be a more mature stage of vegetation succession on raised alluvial bars. Based on the model of Viereck et al. (1993), permafrost is expected to be developing at sites dominated with mature spruce. At the Willow 4 site, there is only a scattered spruce distribution and there was no permafrost found within 2 m and no colonization of mosses. Curiously, there was a large bulge at the base of the individual spruce trees at this site which may be the result of root growth that was previously limited to shallower depths. The plausible explanation for this is that there was subsidence of the land due to permafrost degradation in recent times. Additionally, the area was very wet and there were no spruce saplings and the forest appeared “mature”. This may represent a shift to the final stage of vegetation succession that eventually progresses to wetland vegetation.

In Drury’s report (1956) for the upper Kuskokwim region, an area approximately 400 km west of St. Mary’s, the transformation of forest to wetland was observed to occur in response to changing hydrology, but depending on the conditions these systems may progress to a sedge meadow or *Sphagnum* bog or may return to forest coverage (p. 24). For floodplain soils not impacted by sedimentation processes by the river, Drury describes how additions of wind-blown loess to soils and the impact of erosion along on the shores of open water where ice is blown against the edges can allow for mineral soil to build-up for more upland vegetation to persist versus hydrophilic vegetation. This process can allow for the eventual progression back to spruce forests with thick mosses in the understory that is favorable for permafrost aggradation again on the floodplain. The potential for this cyclic trajectory in this particular environment to occur in soils near St. Mary’s is unclear with current warming climate trends and further investigations would be necessary to understand how this ecosystem might respond.

Péwé (1948) related the presence of low relief surfaces near streams with willow or alder coverage to lack permafrost, or if present, the permafrost is generally much deeper in the profile (1.5-6 m) and where there are steep cut-banks overlain by spruce forests the permafrost is generally found in shallow depths in the profile (30-100 cm). This feature is common for interior Alaska floodplain systems, where the older, higher in elevation floodplain surfaces (>3 m) or terraces are dominated by spruce forests that progress to tundra vegetation communities with shallow active layers and permafrost (Péwé, 1948; Drury, 1956; Van Cleve et al., 1993). In the study area near St. Mary’s there were no steep cut-banks dominated by spruce canopy, but mostly low to moderately elevated surfaces (<3 m) with willow, alder or cottonwood dominating canopies, which may reflect the age of the landscape or hints at the difference in characteristics of the terrain in the study area. For these reasons the older floodplain surfaces are not classified as terraces like interior Alaska, because these surfaces do not feature the height or stage of development that correspond with interior Alaskan terraces. Potentially the effect of warming climate conditions are reflected in the soils of this study compared to what Péwé experienced more than sixty years ago. The geographic differences in the study areas and the slight differences in climates of these regions may also explain some of the differences as was hinted to explain the differences between Péwé's work published in 1948 and Drury's work where Péwé observed more permafrost than Drury in Galena just 200 km north of the upper Kuskokwim region.

From observations of the floodplain near St. Mary's there appears to be two trajectories of vegetation succession and soil development. The first, in modern-floodplain deposits is the building-up of alluvial bars to form natural levees over time with vegetation communities that shift from willow to alder and cottonwood with some spruce. Sedge meadows with willows and some alder occupy the poorly-drained sites. This scenario may or may not involve the aggradation of permafrost in modern-floodplain depositional environments. For interior Alaska floodplain systems, vegetation succession includes spruce canopy coverage that contributes to moss accumulation providing a potential for permafrost formation. In some areas on the floodplain near St. Mary's there may be enough spruce coverage, but otherwise permafrost may not be part of the soil forming process of modern-depositional environments in this region because the lower part of the soil profile that is still influenced by the thermal regime of the river system which prevents permafrost formation. The older floodplain environment, the abandoned floodplain, is the other potential trajectory that represents an environment stable enough for permafrost aggradation. On the abandoned floodplain, ericaceous shrubs dominate with moss communities and thick peat accumulations that provide insulation favoring for permafrost aggradation. Amid the concerns of permafrost degradation due to a warming climate, this feature of the abandoned floodplain provides evidence of permafrost aggradation following vegetation succession on the Yukon River Delta. The lack of spruce near St. Mary's highlights a major difference between vegetation succession and factors contributing to permafrost presence or formation on the floodplain compared to interior Alaska floodplain systems.

Features such as palsas may provide continued stability of permafrost even in warming climate trends. Sollid and Sørbel (1998) observed palsas continuing to persist in regions with mean annual air temperatures at 0.0 °C, even after the surrounding peat plateau had degraded, but new formation of palsas was thought to be hindered by warming air temperatures. The current mean annual air temperature for St. Mary's is -2 °C and with the anticipated increase in air temperatures for the region to be around 5 °C (USGCRP, 2009), permafrost may persist in this region longer than expected because of palsas formation.

In the soils formed on the floodplain near St. Mary's, Alaska, SOC sequestration occurs through three major processes. The first process occurs in response to active-floodplain processes where soil organic matter is carried by fluvial sediments and then buried through subsequent fluvial processes and then sequestered following permafrost aggradation (Viereck et al., 1993; Shur and Jorgenson, 1998). Cold temperatures combined with the wet and reducing soil conditions reduce the rate of organic matter decomposition thus contributing to large organic matter accumulations. The second process is soil organic matter accumulation through litterfalls on uplands or higher terraces where deciduous trees and shrubs dominate, or through bryophytes in poorly drained sites. Thus the thickness of surface organic horizons is controlled by drainage. The third process involves cryoturbation that is more common on older floodplains and uplands (Furbush and Schoephorster, 1977; Ping et al., 1998) where the surface organic matter is frost-churned to the lower active layers and upper permafrost, thus sequestered (Ping et al., 2008b). However this process is not verified in this study but expected in older peat plateaus, such as the area further west (Mungoven, 2008). The whole region of the Yukon-Kuskokwim Delta is experiencing active vegetation succession in response to floodplain development and subsequent soil development. As part of this region, the floodplain near St. Mary's, exemplified the effect of soil-vegetation interaction and carbon distribution associated with sedimentation processes, permafrost aggradation and cryogenesis, and wetland development which dominates the mechanisms for SOC accumulation/sequestration.

There are large increases in the SOC content from soils on raised alluvial bars and natural levees of Stages 2, 3 and 4 compared to the soils of the abandoned floodplain including the abandoned river channel and oxbow depression of Stages 5a and 5c on the floodplain near St. Mary's (Table 6). On terrain in a floodplain, the intermittent burial of debris and stream bank aggradations attribute to irregular concentrations of carbon with depth in the soil profile that was well represented in the soils near St. Mary's (Figure 13). For soils more frequently flooded, the stream can influence SOC stores by flushing soils of organic matter reducing concentrations of SOC within the soils profile (Gervais-Beaulac et al., 2013). The presence of SOC with depth increases over time as soils stabilize and are less frequently impacted by the river and more SOC is preserved in the subsurface horizons leading to greater storage with depth in subsurface soils on the abandoned floodplain including the abandoned river channels and oxbow depressions. Hydrophilic vegetation such as *Sphagnum* mosses are more recalcitrant and resist decomposition more than the willow, alder and cottonwood leaf litter (Hobbie, 1996). In addition the presence of permafrost with depth and the cold temperatures reduce decomposition rates that support the build-up of organic materials on this landscape

The carbon storage in Arctic lowland soils of the region near St. Mary's fit within the estimated SOC values of Ping et al. (2008a). The average SOC storage across all sites of this study (34.3 kg C m^{-2}) is slightly higher than the average for this ecoregion (Johnson et al. 2011). In the same publication, reported values for the Arctic Tundra ecoregion, which serves as the region with the largest SOC stores in Alaska, comparable to the SOC stores for the abandoned floodplain of this study (Table 6). When comparing soil type and associated SOC stocks, the soils in this study classified as Entisols and Inceptisols found on raised alluvial bars and natural levees, have much higher SOC stocks than soils of the same soil orders from northern circumpolar permafrost regions (Hugelius et al., 2014) because of the fluvaquentic nature of these soils. Soils on the abandoned floodplain including the abandoned stream channels and oxbow depressions (Stage 5a and 5c) have soils classified as Inceptisols, Histosols and Gelisols that collectively have large SOC stores when compared to works in the same study (Hugelius et al., 2014). The values for SOC storage at all sites in this study are high comparable to other geographic regions in the arctic and subarctic (Ping et. al, 2008a; Johnson et al., 2011; Hugelius et al., 2014) and excite the need for even more data collection across this large region to improve the accuracy of the SOC estimates in Alaska.

The SOC and nitrogen (N) storage at the abandoned floodplain sites including the abandoned stream channels and oxbow depressions sites (Stage 5a and 5c) represent the amount of SOC and N that is at risk to accelerated decomposition due to warming climate trends in permafrost terrain and areas in western Alaska including the Yukon-Kuskokwim Delta that is projected to lose all permafrost in the next 50 years (Romanovsky et al., 2007). Recent observations of the changes in arctic treeline of this region were assessed where shrub-tundra ecosystems are recognized to be emerging into forests in western Alaska (Lloyd et al., 2002; Beck and Goetz, 2011). This effect will trigger impacts on soil properties such as SOC and N content and storage and the presence/absence of permafrost that occur in response to vegetation succession. In addition, the SOC and N storage in soils near St. Mary's reflect the increases in SOC and N contents that occur as soils develop and stabilize on the floodplain (Table 6). It is of great concern that the sequestered carbon in this lowland system may be released faster than the rest of Alaska and affecting the global carbon budget following permafrost degradation and thermokarst development.

The soil clay mineralogy in soils formed on a natural levee (the Cottonwood site) was analyzed to assess the weathering potential and depositional pattern of clays in the study area. Soils in subarctic regions are thought to show little evidence of pedogenic weathering of clay minerals due to cold temperatures that slow reactions. In any soil, temperature and moisture are recognized to host the major controls over weathering rates of materials (Pope et al., 1995), such as clay mineral composition, abundance and transformation. In sub-arctic regions where temperatures are below freezing for much of the year, weathering of mineral materials in soils is anticipated to be greatly reduced (Jenny, 1941) and the presence of clay minerals in soils are thought to occur mostly as a product of mechanical weathering of geologic materials and the depositional environment, though it has been reported minor weathering of clay minerals in acid soils of northern Alaska (Borden et al., 2010). The a poor relationship between CEC and clay content (Figure 12) reflects the low activity of the clay minerals seen though there are 2:1 or expandable layered silicates. The reason is that both these clays are inherited from the parent material instead of pedogenic, as Borden et al. (2010) and Dement, (1962) found in the arctic and subarctic soils, respectively.

The impact of floodplain systems could have a variety of effects on soil clay mineralogy. In some locations there is reduced stability of the environment when soils are eroded away before chemical alterations could occur. The older developed soils on the floodplain are anticipated to contain permafrost in shallower sections of the soil, which would reduce the temperature of the active layer in soils thereby reducing the rate of chemical alterations in clay mineralogy.

Eberl (2004) observed large changes in the clay mineral concentration and composition between the summers of 2001-2003 at three different reaches of the Yukon River. This suggests there are changes in sediment source contributions from year to year in the main stream channel along with changes in dilution scenarios of the river. Early summer when flooding or high water is widespread along the active braiding zone of the river due to river break-up and the rapid melting of snow on the landscape; little sediment is deposited to soils during this period. Flash floods that occur in response to high rainfall events in the summer contribute to the greatest amount of sediment deposited onto soils on floodplains (Mason and Begét, 1991). The clay minerals found in the soils on the floodplain near St. Mary's reflect the materials deposited from both of these types of flooding events. The soils at the Cottonwood site are formed on a natural levee and are not inundated every year during spring flooding or high water events. These soils are impacted in more major spring flooding events and during major summer floods. The depositional patterns are consistent with maintaining similar clay mineral compositions with depth.

Primary micas are generally found in greater abundances with depth in soils of uniform parent materials because weathering is more intense in near-surface soils and at depth the micas are generally more preserved. In these conditions, secondary minerals such as vermiculite, smectite, and kaolinite would have a greater abundance in surface regions than at greater depths. The results from this study show an opposite trend, where there are decreases with relative weight percentages of illite with depth and increases in the percentages of expandable materials with depth (Table 7). These relative changes in the weight percentages of expandable materials with depth are likely attributed to depositional events associated with major flooding events of the Tanana River, a major upstream tributary of the Yukon River (Eberl, 2004). The Tanana River likely plays the biggest role in major depositional events because it carries the largest suspended sediment load and largest smectite contributions to the Yukon River of all the major tributaries (Eberl, 2004). In addition, variations in the sand, silt and clay component are reflected by the position of the site in respect to the river due to changes in the level of flooding intensity that will impact the site, where more coarse sediment is typically found in closer proximities to high energy portions of a main river channel (Marion et al., 1993). In addition, Yukon River loess contains large concentrations of micas (Muhs and Budahn, 2006) which likely contribute to the large concentrations of illite in soils of this study.

In subarctic floodplains where there are periodic additions of new materials, most of the changes in the presence and abundance of clay minerals are attributed to the material deposition events rather than degree of weathering, which is supported through data provided in Table 7 and diffractograms in Figure 14. The structure of chlorite is less stable which lends to chlorite generally thought to be a high latitude clay mineral with lower concentrations in mid to lower latitude soils, especially in acid soils, where there is increased tendency to weather into secondary minerals; while kaolinite is commonly referred to as the end product of weathering and is common in "older" soils of lower latitude regions (Biscaye, 1965). Because there are such minor changes in the relative weight percentages of kaolinite and chlorite this suggests that the source of these constituents may be different than the source of illite and smectite that have more variations in the relative weight percentages.

The results of this study correspond with the clay mineralogy of the suspended sediment in the Yukon River sampled near the river's terminus into the Bering Sea (Naidu and Mowatt, 1983). The proximity of the study area to the study region in the works of Naidu and Mowatt (1983) suggest that any changes in the relative concentrations of clay minerals of Yukon River suspended materials occur upriver of the study region. Because the suspended sediment of the Yukon River has a diverse composition depending on reach and season (Eberl, 2004), the soil clay mineral concentration and composition of soils formed along the floodplain likely mirror these changes along the river. This gives reason of the need for more clay mineralogy studies along the Yukon River floodplain to assess the changes in the depositional record of the soils in this region.

On floodplain soils in interior Alaska, Van Cleve et al. (1993) and Shaw et al. (2001) found low clay contents (3-12% and 4.7% mean, respectively) in floodplain soils formed on stream terraces dominated by cottonwood with only minor changes with depth in the profile and suggested any changes in clay mineralogy were attributed to depositional events rather than weathering. These clay percentages along with the understanding of the factors influencing changes in clay mineralogy correspond with the findings in this study and reflect the similarity in fluvial processes that contribute to floodplain development for Alaskan floodplain systems.

5. Conclusion

Soil formation on the floodplain in the Arctic lowland region near St. Mary's, Alaska is dynamic with some major distinct differences in the soils and vegetation of this study compared to soil studies of more interior locations in Alaska. The gradual building-up processes of raised alluvial bars and natural levees dominated by willows, alders and cottonwood accumulate SOM throughout the profile that eventually stabilize on the abandoned floodplains and in palsas under ericaceous shrubs and *Sphagnum* mosses due to permafrost aggradation. Wetlands dominated by sedges and *Sphagnum* mosses on the floodplain also are regions of major SOM accumulations. The soil clay mineralogy reflects the material additions from flooding events in the region with high relative weight concentrations of illite and expanding materials, with lesser amounts of chlorite and kaolinite. The observed changes in the SOC distribution in soils formed on the floodplain near St. Mary's, Alaska show an increase in the carbon partition into subsurface soils as soils develop. Based on research on arctic tundra soils in northern Alaska the stability of SOC is enhanced through sequestration due to cryoturbation that translocates soil organic matter from the surface to the lower active layer and the upper permafrost. The stability of SOC in the studied area is likely to be enhanced with the permafrost aggradation on the abandoned floodplain. However, the stability of soil carbon stores as soil develops likely has a close connection between the state of permafrost and other cryogenic processes in this region. The state of permafrost in this region is not well understood even though abundant features observed on the landscape are characteristic of permafrost terrain including palsas, permafrost under ericaceous shrub communities with thick peat accumulations on the abandoned floodplain, and the potential subsidence of the land at the Willow 4 site. Based on aerial imagery of the area south of St. Mary's, there are large abandoned floodplain regions that are speculated to contain permafrost, thus more organic carbon. Investigations involving long-term monitoring of the terrain would provide more information on the presence and stability of permafrost in this region to elucidate how changing climate patterns may influence such a dynamic environment as the Arctic lowland of the Yukon-Kuskokwim Delta.

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