

Changing Soil Characteristics during Succession in the Alaskan Boreal Forest

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Repeated sampling and chronosequence approaches can be used to develop an understanding of successional dynamics in forest ecosystems. The chronosequence approach enables a relatively rapid and consistent assessment of key variables, but relies on an assumption that spatial variability is a good substitute for temporal dynamics. Repeated sampling gives a more direct measure of temporal dynamics, but by definition requires much more time and is vulnerable to changes in investigators and methodologies. In this study, we compared these techniques in two well-studied Alaska boreal forest landscape positions—upland (UP) and floodplain (FP)—and found a number of contrasting trends. In UP stands, soil C concentration increased with stand age across the chronosequence, but declined in individual stands over time. Conversely, soil P concentration declined across the UP chronosequence, but increased in individual stands. Both approaches yielded consistent trends for several variables, including N, pH, CEC (UP and FP), and K (UP). No changes were observed for 5 factors (upland C quantity, floodplain C concentration and quantity, and total P and Ca quantity on the floodplain) between sampling years that displayed either a positive or negative chronosequence trend. Changes in the one meter depth profile chemistry between sample time periods were investigated and showed the same differences that were found for the total profile average values of the soil property. Differences observed between these two values were tied to the depth structure of the observed soil characteristic.

The state factors as defined by Jenny (1980) have been used to describe soil development in interior Alaska (Van Cleve et al., 1993) based on chronosequence studies in the 1980s. On floodplain (FP) sites along the Tanana River, soil development occurs on sand and silt deposited from glacial outwash that accumulates on terraces during high water events. Site moisture regimes are strongly related to river levels resulting from both precipitation events and glacial melting during the summer, resulting in high river levels. Soil seasonal degree-day accumulation declines from early to late successional sites and is related to both the development of the forest floor organic layer and silt deposition during flooding events (Van Cleve et al., 1993). Soil chemistry in this chronosequence exhibits major changes tied to terrace elevation related to flooding events and vegetation development in the primary successional sequence (Van Cleve et al., 1983, 1993). Carbon chemistry plays a major role in the C dynamics from inorganic ($\text{CO}_3\text{-C}$) in early succession to organic C in late successional stages (Marion et al., 1993). These factors are easily related to temporal variation in soil properties described by Tugel et al. (2005) or the dynamic soil properties described by Arnold et al. (1990).

The upland's soil development is strongly related to loess deposition from glacial outwash deposited north of the Alaska Range during the last ice age (Pewe, 1975). Site moisture regimes are coupled to precipitation events with bedrock often deeper than 2 m below the mineral soil surface. Soil temperature shows a general decline in seasonal degree-day accumulation from early succession to late

Core Ideas

- Repeated sampling compared to a chronosequence can display changes due to climate change.
- Carbon quantities increased across the floodplain chronosequence, upland sites displayed no change.
- Nitrogen displayed a chronosequence increase in both concentration and quantity on the floodplain sites.

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successional sites (Van Cleve and Yarie, 1986). The soil chemistry in the upland chronosequence displays very little change. For example, N content ranged from 290 to 312 g m⁻² for a 60-cm profile depth (Van Cleve et al., 1996) from early to late successional sites. Fire has a greater influence on the forest floor structure and chemistry than on the mineral soil chemistry. Mineral soil temperatures are assumed to be relatively cool during fires (Van Cleve et al., 1996).

A chronosequence across several locations can be used to identify potential changes that might occur if repeated sampling over a long time frame at a single location was used. We studied two successional chronosequences utilizing three major turning points in an upland secondary successional sequence and four turning points in a floodplain primary successional sequence (Yarie et al., 1988; Van Cleve et al., 1996). Turning points are defined as “relatively short time intervals (less than 50 yr) when critical changes in ecosystem structure are accompanied by functional changes that have far-reaching effects on ecosystem development” (Van Cleve et al., 1991). The upland sequence starts with recently burned stands and moves through mid-successional hardwood stands to mature white spruce stands. The floodplain sequence represents an early shrub stage, an alder/balsam poplar stage, a balsam poplar/white spruce stage and a mature white spruce stage (Table 1). Soils are thought to be stable over long time periods. However a number of recent studies have shown short-term changes in both physical and chemical properties in soil profiles (Tugel et al., 2005; Lawrence et al., 2013).

This project represents a first step in comparing well-developed patterns of soil and forest dynamics developed from two chronosequences within the Bonanza Creek Long-Term Ecological Research program (Chapin et al., 2006b) to time series patterns in soil characteristics within the sites comprising the upland and floodplain chronosequences (this study). Van Cleve et al. (1996) has described the initial soil data sampled in 1988 and 1989.

METHODS

The Bonanza Creek Long-Term Ecological Research program was designed to analyze a number of factors tied to primary succession on floodplains and secondary succession in upland forested ecosystems in interior Alaska. The set of research sites represented a chronosequence of successional stages in upland and floodplain landscape positions. Repeated sampling of a

number of ecosystem characteristics has been performed at various time intervals since the start (1986) of the program to document various ecosystem dynamics on specific successional stages. The soils at the research sites represented one of these ecosystem characteristics. The repeated measures technique represents the start of long-term monitoring of changes in soil profile characteristics. The sampling procedure was a closely tied measurement chain as suggested by Desautels (2012). The repeated sampling represents a subsample at various time intervals on individual sites within the two established successional chronosequences (Viereck et al., 1983; Chapin et al., 2006a).

Field Methods

The floodplain research sites portrayed four distinct stages in a primary successional sequence that occurs along floodplain landscape positions (Table 1). The sites were selected to represent an early successional willow-alder site (FP1) typical within 5 yr after establishment on a bare silt bar on the river floodplain, a young mid successional balsam poplar/alder site (FP2) that has developed about 25 yr after site establishment, an old growth balsam poplar with a young white spruce understory (FP3) approximately 110 yr old, and a set of mature white spruce sites (FP4) developing 200 yr after initial establishment of the silt bar. All ages were estimated at the start of the study in 1988.

The upland research sites represented three distinct stages in a post-fire secondary successional sequence (Table 1). The sites were selected in 1988 as an early successional site (UP1) typical within 5 yr of a fire disturbance, a mid-successional site typical of a hardwood stand (UP2) that has developed 75 yr after fire and third a set of mature white spruce [*Picea glauca* (Moench) Voss] sites developing 200 yr after fire (UP3). A detailed description of all sites at both landscape locations can be found at <http://www.lter.uaf.edu/research/study-sites-bcef>.

In 1987 and 1988, soil pits were excavated outside all four boundaries of the replicated ($n = 3$) control plots at all sites (Fig. 1). In 2010 and 2011, an additional set of pits close to (within 3 m) the original pits on the four sides of the control plots were installed. Soil profiles were described using standard soil sampling procedures (Schoeneberger et al., 2012). The sampling technique used for both time periods represented a profile face (Lawrence et al., 2013) and follow methods suggested by Lawrence et al. (2016). Bulk density at both sample

Table 1. Site age at both sampling periods and vegetation type at the time of sampling in 1988 for the upland (UP) and floodplain (FP) sites.

Site	Age (years) at site establishment and second sampling	Vegetation type in 1988†
Upland		
UP1	6, 33	Open young shrub
UP2	75, 102	Mixed hardwood with white spruce understory
UP3	201, 237	Mature even-aged white spruce
Floodplain		
FP1	2, 29	Open young willow shrub
FP2	30, 57	Open balsam poplar with dense alder understory
FP3	100 balsam poplar with 45-yr old white spruce, second sampling 127 and 72	Mixed balsam poplar and white spruce
FP4	150 to 250; 177 to 277	Open white spruce forest

† From Viereck et al., 1983.

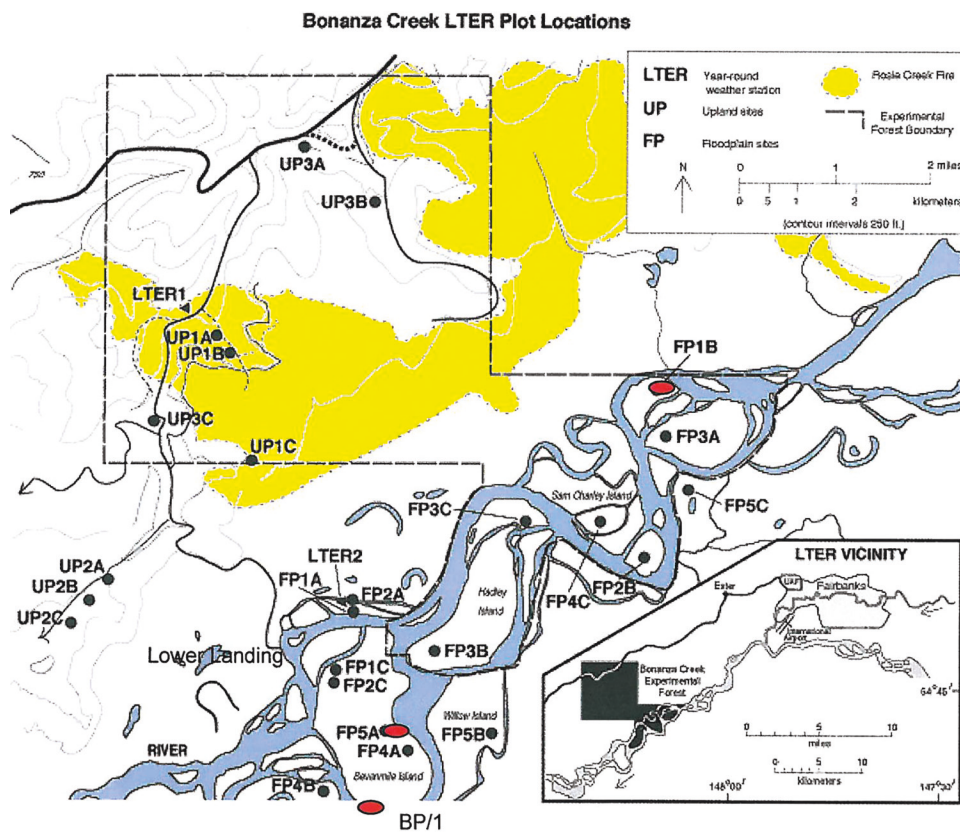


Fig. 1. Bonanza Creek Long-Term Ecological Research (LTER) site locations (Adams, 1999) in upland and floodplain forested ecosystems of interior Alaska.

times was determined using techniques described by Blake and Hartge (1986). The major difference between the two sample times was in the orientation of the sampling tube. It was used in a vertical direction in 1988/1989 and a horizontal direction in 2010/2011. As a result the sample volume varied due to horizon depth in 1988/1989 and sample volume was consistent in 2010/2011. The horizon colors were determined using the standard Munsell soil-color charts (Munsell Color, 2009).

Laboratory Methods

Soil samples were obtained from each genetic horizon of the soil profiles at each site. Air-dried samples were passed through a 2-mm mesh sieve prior to chemical analysis. Exchangeable base status and cation exchange capacity (CEC) were determined by the ammonium acetate method at pH 7 (Black et al., 1965). The concentration of exchangeable cations was determined on aliquots of the ammonium acetate extract using an Agilent Technologies Microwave Plasma-Atomic Emission spectrometer. Soil CEC was determined colorimetrically on aliquots of the NaCl extract. Total C and N were determined using a LECO TruSpec CN determinator. Soil particle size was determined by the hydrometer method (Black et al., 1965). Total P was determined colorimetrically using the molybdenum blue method with an amino-napththol-sulfonic acid reducing agent (Jackson, 1958) on an aliquot of a perchloric acid digest. Kjeldahl N was determined using a sulfuric acid digest. Percent organic matter was determined by ignition at low temperature. Available

P was determined by a dilute acid fluoride extraction (Jackson, 1958). Floodplain soil carbonate was determined by a manometric method (Nelson, 1982).

Personnel and Soil Profile Descriptions

Because of the time period between the fieldwork campaigns, different sets of scientists were engaged in developing the soil descriptions. Even though there is a clear-cut method for describing soils (Schoeneberger et al., 2012), it is common to find two general groups (lumpers and splitters) of people. So differences in soil descriptions can result from more than a physical change in the soil profile that would be due to time between sampling and actual location of the sampled profiles. For example, UP1A Pit 2 was described with 5 horizons in 1988 and with 9 horizons in 2010, although other pits at the same site were very similar. The question becomes: How much of these differences are due to the true variability in the soil profile or to the overall experience of the scientist that describes the soil profile?

Profile Changes

The temporal comparison of mineral soil characteristics through a depth profile for the individual successional stages was performed using a bootstrapped LOESS regression (BLR) technique (Keith et al., 2016). This technique was applied to the concentration data sets for C, N, Ca, Mg, K, and P. We also analyzed the depth distribution for bulk density, pH, and cation exchange capacity. The technique is non-parametric and useful with non-independent data. The BLR approach develops an overall depth confidence interval for the entire data set (both time periods) and then develops a mean depth distribution for the second time period. If the mean depth model for the second time period falls outside the range for the entire data set there is a significant difference between the two sample times. If the depth model for the second time period falls within the entire data set confidence interval then the two time periods show no significant difference for the measured property (Keith et al., 2016). An example is described below is the results regarding profile changes.

A simple two-sample *t* test was used to investigate changes in total profile average nutrient concentration and total quantity for C, N, total P, Ca, Mg and K between the two sampling periods at each successional stage. The same *t* test was used to show changes in the profile average values of bulk density, pH, and CEC.

The successional trajectory in each (1988/1989 and 2010/2011) chronosequence was displayed using the R “geom_smooth” and “geom_boxplot” routines (Wickham 2009, 2011). The boxes displayed at each successional stage and time period represent the two central quartiles of the range of the data; the vertical lines represent the data range that is less than 1.5-fold the interquartile range of the data set. The horizontal line in the box is the median and the data mean is the diamond shape. The successional trends for each chronosequence are depicted with a shaded bar across the chronosequence time frame. The darkened shading represents a zone of similarity between the two chronosequences. The black line represents the time trajectory across all six (upland) or eight (floodplain) data sets.

All soil descriptions from both sampling periods have been submitted to the Bonanza Creek program database and are available as Excel files. In addition, the soil chemistry data sets are available through the same site. All data are publically available the Bonanza Creek program website (www.lter.uaf.edu). Examples of the figures that describe the results of the chemical characteristics

will be presented in the paper. The full set of figures are available in the supplemental material.

RESULTS

Floodplain Soil Profiles

Physical Soil Characteristics

The floodplain soil profiles were highly variable over both space and time as a result of patterns of fluvial deposition and erosion, up through the 2010/2011 sampling period. This complicates direct comparisons of soil profiles over time, due to sand and silt deposition during flooding events.

The subgroup classification changed for the floodplain soils from Pergelic Cryaquepts or Histic Pergelic Cryaquepts (Van Cleve et al., 1996) to nonacid Aquic Cryofluvents (Soil Survey Staff, 2016). Specific differences between the characteristic pedon descriptions for the sample years at the FP1 sites were tied to the number of horizons described, 5 horizons in 1989 and 7 horizons in 2011 (Fig. 2). Soil color and texture were very similar during both sampling periods. The FP2 sites showed two ad-

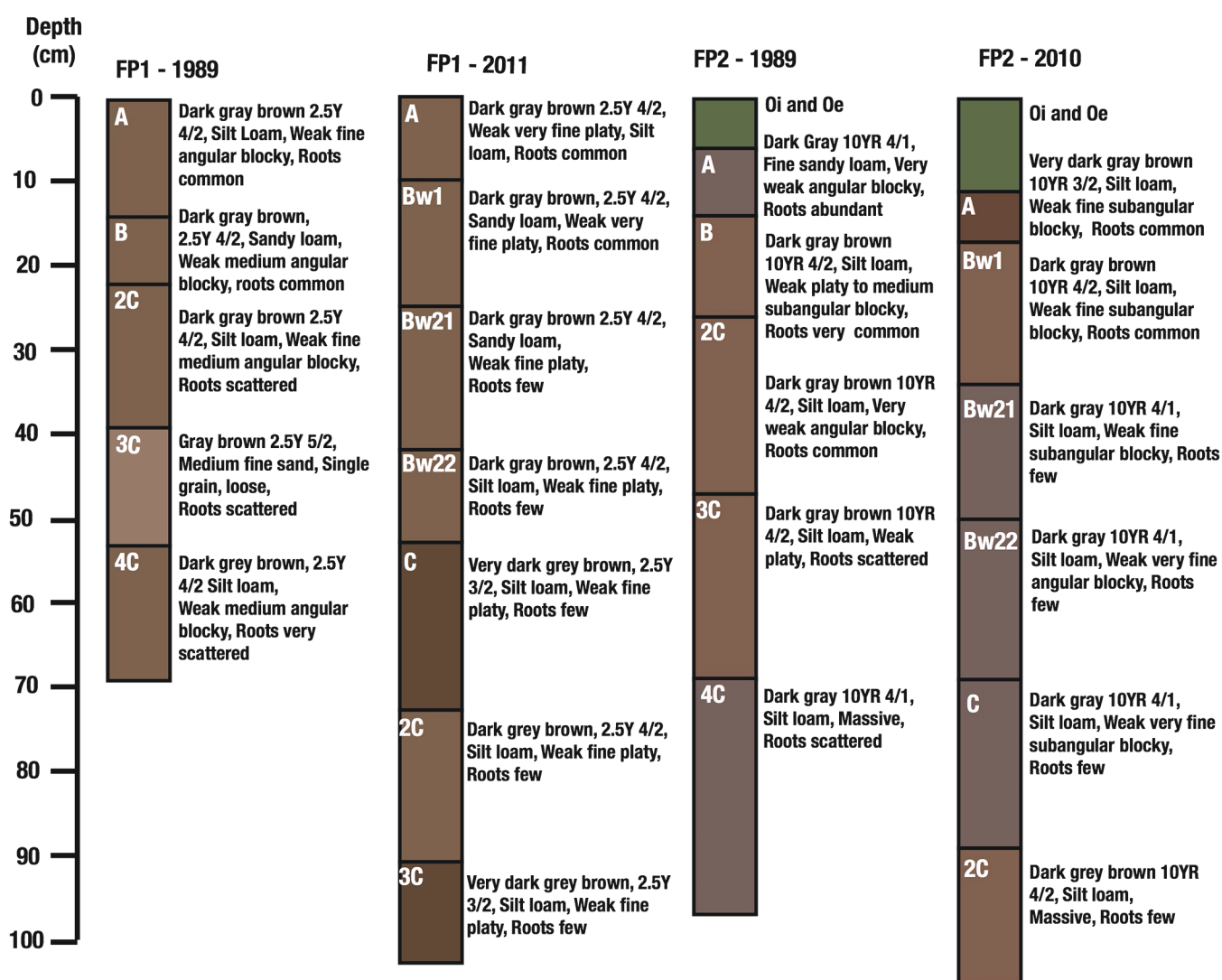


Fig. 2. Soil profile comparison between 1989 and 2011 for the floodplain sites FP1 and FP2. The 1989 profiles were developed by Van Cleve et al. (1996). The profiles are now classified as nonacid Aquic Cryofluvents, Fairbanks Soil Series (Soil Survey Staff, 2016). The soil colors were derived using the conversion from Munsell colors to a sRGB format (Centore, 2013).

ditional mineral horizons in 2011 compared to 1988, but the soil texture and color were very similar for both sample periods (Fig. 2). The FP3 sites showed three more horizons in the second sample period. Horizon colors showed some minor variability (Fig. 3) and the texture included significantly more fine sand in the 1988 sample compared to the silt loam texture in the 2010 sample (Fig. 3). The FP4 sites displayed an equal number of horizons and a buried organic horizon below the A-horizon (Fig. 3). The texture was the same through each of the horizons. All of these descriptions are within the range of characteristics presented for the taxonomic units (Swanson and Mungoven, 2006).

Bulk density varied little between sampling periods. The FP1, FP2 and FP4 sites displayed only minor differences (Table 2). There was a small decrease at 10 and 20 cm for FP1, an increase from 0 to 40 cm for FP2 and no change for the FP3 sites. The FP4 sites showed an increase from 30 cm to 95 cm (Table 2; Supplement S1). It is possible that these differences were due to a change in the measurement techniques that could have resulted in deviations in estimation of sample volume between the

1988/1989 and 2010/2011 sample periods. As a result the average bulk density values for both sampling periods were used to calculate the quantity of nutrients in the mineral soil.

Profile Chemical Characteristics

Both the 1-m depth profile and the depth weighted average value for the entire profile for pH significantly decreased in the FP1, FP2 and FP3 sites, but no changes were observed on the FP4 sites (Table 2; Supplement S1). This was consistent with the observed pattern across the longer time span associated with the chronosequence. The cation exchange capacity depth distribution displayed an increase on the FP1, FP2 and FP3 sites and an increase from the surface to 30 cm on the FP4 sites (Table 2). The C concentration showed no change on the FP3, and FP4 sites, an increase in the top 30 cm on the FP1 sites and a decrease on the FP2 sites but the quantity was equal on the FP1, FP3 and FP4 sites and higher on the FP2 sites (Fig. 4; Table 2). Nitrogen showed significant increases in concentration and quantity through the profile on the FP1 and FP3 sites, an increase from 60 to 100

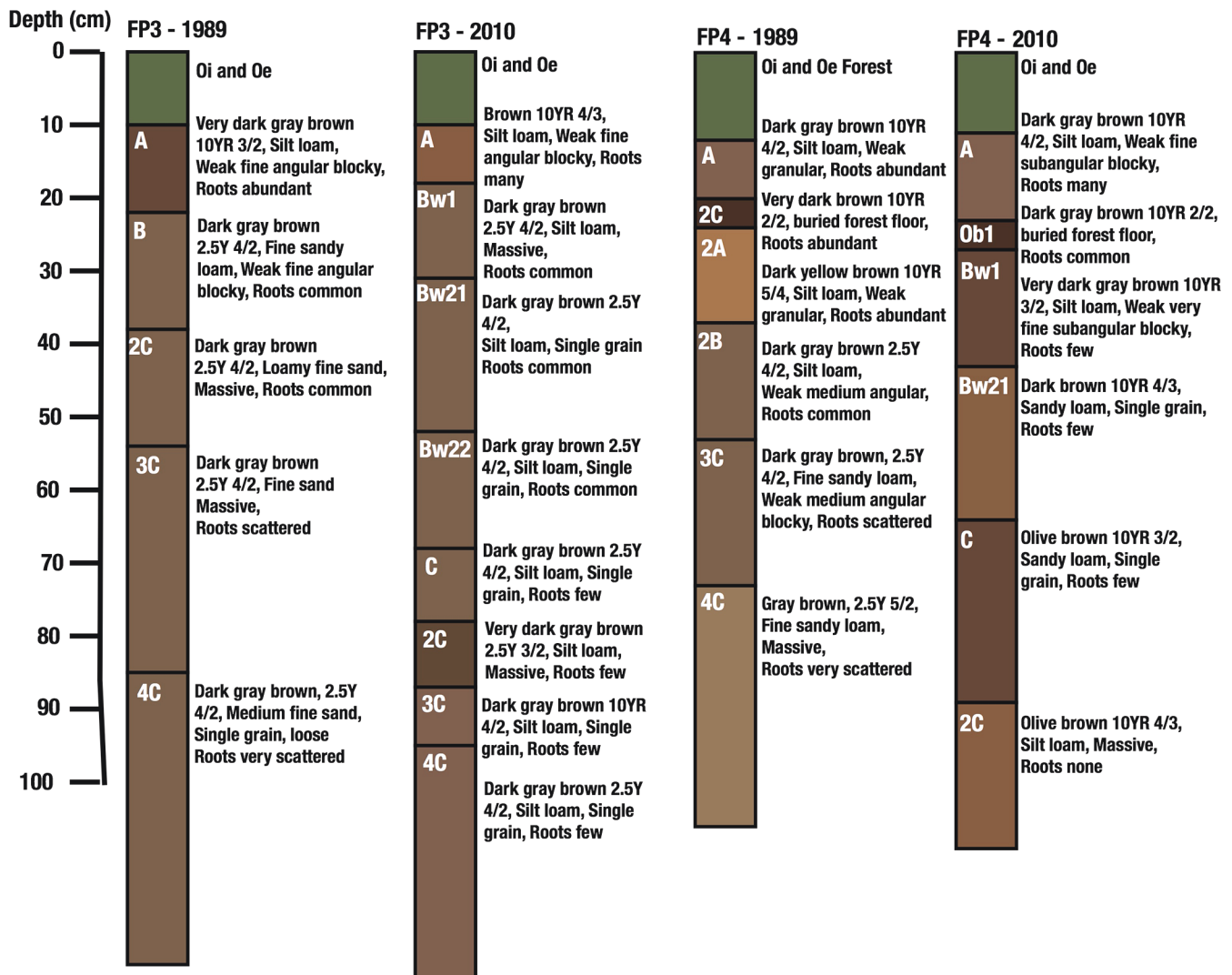


Fig. 3. Soil profile comparison between 1989 and 2011 for the floodplain sites FP3 and FP4. The 1988 profiles were developed by Van Cleve et al. (1996). These profiles are now classified as nonacid Aquic Cryofluvents, Fairbanks Soil Series (Soil Survey Staff, 2016). The soil colors were derived using the conversion from Munsell colors to a sRGB format (Centore, 2013).

Table 2. Significant increase (+) or decrease (–) within the floodplain (FP) soil profile at 10-cm depth increments for concentration between sampling dates (1988/1989 and 2010/2011) and for the total 1-m profile value, or quantity and average concentration. Standards units are used for bulk density, pH and cation exchange capacity (CEC).

Mineral soil property	Individual site							
	FP1		FP2		FP3		FP4	
	10-cm layer†	1-m profile‡	10-cm layer†	1-m profile‡	10-cm layer†	1-m profile‡	10-cm layer†	1-m profile‡
Bulk density	(–) 10, 20 cm	No change	(–) 0-40 cm	(+)	No change	No change	(+) 30-95 cm	(+)
pH	(–)	(–)	(–)	(–)	(–)	(–)	No change	No change
CEC	(+)	(+)	(+)	(+)	(+)	(+)	(+) top 30 cm	No change
C	(+) to 30 cm	(+) in concentration; No change in quantity	No change	No change in concentration; (+) in quantity	No change	No change in concentration or quantity	No change	No change in concentration or quantity
N	(+)	(+) in both concentration and quantity	No change	(+) in both concentration and quantity	(+)	(+) in both concentration and quantity	No change	No change in concentration or quantity
Total P	(+)	No change in concentration or quantity	(–)	(+) in concentration; No change in quantity	No change	No change in concentration or quantity	(–) 0-70 cm	No change in concentration or quantity
Ca	No change	No change in concentration or quantity	No change	No change in concentration or quantity	(–)	(–) in concentration; (–) in quantity	No change	No change in concentration or quantity
Mg	(+) 0 to 60 cm	No change in concentration or quantity	No change	No change in concentration or quantity	No change	(+) in both concentration and quantity	(–) 30-100 cm	(–) in concentration; (–) in quantity
K	(–) 70-100 cm	No change in concentration or quantity	(–) 0-80 cm	(–) in concentration; No change in quantity	No change	No change in concentration; (–) in quantity	(–)	(–) in concentration; No change in quantity

† Indicates change in soil property values for a mineral soil property between 1988/1989 compared to 2010/2011.

‡ Indicates an increase or decrease in the total value for a mineral soil property between 1988/1989 value compared to the 2010/2011 value.

cm on the FP2 sites, and no change on the FP4 sites (Table 2). Total P displayed varying differences in the concentration depth distribution. There was an increase in concentration for the whole profile on the FP1 site, a decrease on the FP2 site, no change on

FP3 site, and a decrease in concentration in the upper 60 cm on the FP4 sites (Table 2). Calcium displayed no change on the FP1, FP2 and FP4 sites, and a decrease in concentration on the FP3 sites (Table 2). Magnesium showed an increase in concentration down to 60 cm on the FP1 sites, no change in concentration on the FP2 sites, an increase in concentration below 50 on the FP3 sites and a decrease in concentration below 30 cm on the FP4 sites (Table 2). Potassium displayed a decrease in concentration below 70 cm for FP1 sites, a decrease down to 80 cm for the FP2 sites, small decrease down to 20 cm on the FP3 sites and a decrease in the entire profile on the FP4 sites (Table 2).

Floodplain Successional Characteristics

Soil characteristics across the floodplain primary successional sequence showed a combination of site, chronosequence and time series changes. The pH chronosequences tended to show a decrease between sample periods with significant site differences for the first three floodplain sites (FP1 to FP3). The time series displayed an overall decrease in pH with no difference between sample periods at the FP4 stage (Table 3). Cation exchange capacity displayed site increases for the FP1, FP2 and FP3 sites. Both chronosequences had a similar shape and were different during the first 125 yr of the chronosequence. The overall trend was positive increasing from 5.4 to 16.1 cmol_c kg^{–1}. The C concentration increased between sample years at the FP1 stage and the total profile quantity was greater at the FP2 stage (Fig. 5). The C concentration and quantity chronosequences were equal across the entire time frame and the

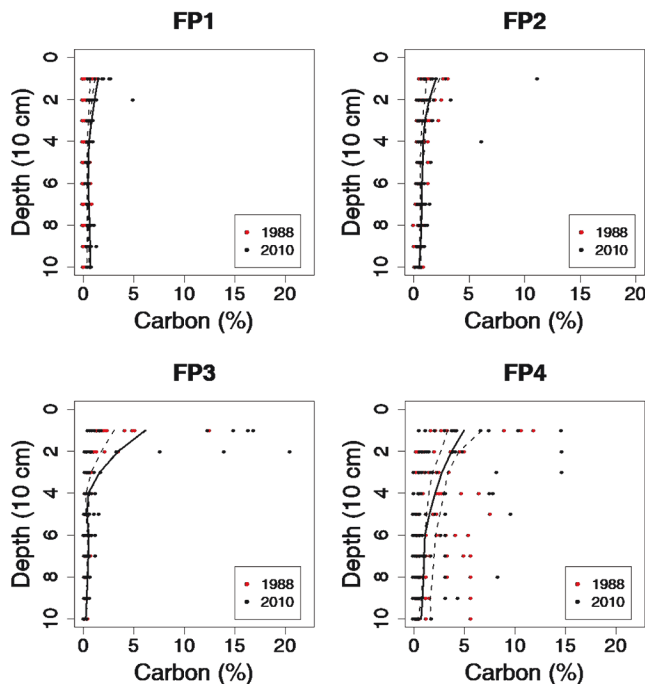


Fig. 4. Changing depth distribution of carbon concentrations between the two sampling periods for the floodplain (FP) soil profiles across the successional sequence.

Table 3. Significant property value, or concentration and quantity trend differences between the two chronosequences (2010/2011 compared to 1988/1989 sampling dates), and overall direction of change within the eight sample combined time series for floodplain (FP) sites.

Mineral soil property	Chronosequence difference†	Time series‡
Bulk density	FP1 to FP3 equal; FP4 higher	Decreasing trend from young to old sites
pH	FP1 to FP3 higher, FP4 equal	Decreasing trend from young to old sites
CEC	FP1 to FP3 higher, FP4 equal	Increasing trend from young to old sites
C	Concentration and quantity are equal	Increasing trend from young to old sites for both concentration and quantity
N	Concentration higher at FP3 site; quantity trend is higher from FP1 to FP3 equal at FP4	Increasing trend from young to old sites for both concentration and quantity
Total P	2010 chronosequence tends to be lower than 1988; both quantity chronosequence are equal	Very little change in concentration and quantity across the entire time period
Ca	Concentration is equal for the first 125 yr then 2010 is lower; quantity chronosequences are equal	Concentration shows a linear decrease across succession; quantity has a curved trend with a maximum at 80 and a minimum at Year 225
Mg	Concentration equal for first 170 yr then 2010 values lower; quantity trend is equal to Year 80 and then results in a crossing pattern through Year 225	Overall concentration trend is increasing; the quantity trend is increasing until Year 150 and then constant
K	Chronosequence is lower until Year 75 and after Year 175; Small difference in quantity chronosequence from ages 130 to 175 due to the variability in the 2010 data set	Concentration trend is increasing until Year 125 and then no change; the quantity trend is decreasing until Year 125 and then a slight increase to Year 225
K	Concentration chronosequence is lower until Year 75 and after Year 175; Small difference in quantity chronosequence from ages 130 to 175 due to the variability in the 2010 data set	Concentration trend is increasing until Year 125 and then no change; the quantity trend is decreasing until Year 125 and then a slight increase to Year 225

† Indicates the difference between the 2010/2011 and 1988/1989 chronosequences.

‡ Indicates the overall trend across all six samples (3 chronosequence sites × 2 sample periods).

total times series tended to show an increase across the successional sequence (Table 3; Fig. 5). The quantities of C increased from 5.8 to 16.5 kg m⁻³ from age 5 to 225 yr. The concentration and quantity of N displayed site increases from 1988 to 2010 for the first three sites in the successional sequence (Table 3). Both chronosequences displayed an increasing trend with significant differences between ages of 80 to 140 for concentration and 35 to 170 for quantity (Fig. 6). Overall the general time series is showing an increase in both the concentration and quantity of N across the successional sequence (Fig. 6). The concentration of total P was significantly lower in 2010/2011 than in 1988/1989 on the FP2 site (Table 3). However both chronosequences were equal and the total time series was relatively flat (i.e., no change in the 200-yr time frame). Site Ca concentration and quantity were equal across the floodplain successional sequence except for the FP3 stage, where a significant decrease was found between 1988/1989 and 2010/2011. Both chronosequences tended to be equal and the total time series indicated a decrease in concentration from 18% at Year 5 to 12.5% at Year 125 and back to 15.2% at Year 220. Calcium quantity displayed a linear drop through the entire time frame.

Magnesium concentrations and quantities were equal for the FP1 and FP2 stages but were significantly higher in the FP3 stage and lower in the FP4 stage between sample time periods. The concentrations and quantity chronosequences showed different trends between the 1988/1989 and 2010/2011 sample periods. The total quantity time series tended to show a distinct increase in early succession leading to an asymptote later in succession for the 2010/2011 sample. The Mg concentration and quantity trend was increasing from FP1 to FP4 sites in a linear fashion.

Potassium displayed different location concentrations at the FP2 and FP4 sites and higher quantities for the 1988/1989 samples at FP2 and FP4 sites. The chronosequences for concentration and quantity overlapped for the FP3 site but were generally different for the FP1, FP2 and FP4 times. The overall time series tended to show an upward trend for concentration and quantity until Year 125 and a slight downward trend to Year 225.

Upland Soil Profiles

Physical Soil Characteristics

Due to changes in US Soil Taxonomy (Soil Survey Staff, 2014), the subgroup classification changed for the upland soils from Alfic Cryochrepts (Van Cleve et al., 1996) to Typic Eutrocryepts (Soil Survey Staff, 2016). Specific differences between the characteristic pedon descriptions for the sample years at the UP1 sites were tied to the number of horizons described, 5 mineral horizons in 1988 and 6 mineral horizons in 2010, and the color of mineral horizon 4 between the two sample periods (Fig. 7). The UP2 sites showed the same number of horizons for both sample periods with only a minor difference for color of the C1 horizon (Fig. 7). The UP3 sites showed one more mineral horizon in the second sample period and colors displayed minor variability except for the A and C1 horizons (Fig. 7). All of these descriptions are within the range of characteristics presented for the taxonomic units (Swanson and Mungoven, 2006).

The soil texture was predominately silt loam in both measurement periods (1988/1989 and 2010/2011). Bulk density displayed increases between the initial and second measurement

periods below 10 cm for the UP1 and UP2 (Table 4) sites and an increase from 10 cm to 80 cm except at 50 cm for the UP3 sites. The profile differences resulted in an overall increase in depth weighted average bulk density for each of the three sites used in the chronosequences. To be consistent with the floodplain sites the average bulk density for the upland sites was used in the calculation of total nutrient quantities.

Profile Chemical Characteristics

Both soil pH and CEC displayed significant profile changes in all three successional stages (Table 4). Soil pH decreased significantly below 50 cm in the UP1 sites, throughout the entire profile on the UP2 sites and down to 80 cm on the UP3 sites (Table 4), consistent with a generally decreasing soil pH with time across the chronosequence. All three stages displayed a significant increase in cation exchange capacity over the 23-yr period (Table 4). The concentration of C showed no change throughout the profile between the two sample periods (Table 4). Nitrogen concentrations increased significantly on all three sites at or below 20 cm (Table 4).

Total P displayed an increase in concentration below 10 cm on the UP1 sites, below 20 cm on the UP2 sites, and below 50 cm on the UP3 sites (Table 4). The base cations (Ca, Mg and K) showed different trends through the profiles. Calcium concentrations decreased throughout the UP1 profile, increased below 30 cm in the UP2 site and did not change on the UP3 site (Table 4). Magnesium showed no changes in concentration on all three sites between sample years. Potassium displayed a decrease in concentration for the UP1 site, a small decrease below 50 cm on the UP2 site, and inconsistent concentration decreases on the UP3 site (Table 4) between sample times.

Upland Successional Characteristics

The successional soil characteristics showed a combination of site, chronosequence and time series changes. The overall average site bulk density displayed a nonsignificant downward trend across the chronosequence from 1.265 g cm^{-3} in the UP1 sites to 1.22 g cm^{-3} on the UP3 sites. The time series based on all six values displayed a flat line at an overall value of 1.25 g cm^{-3} . The average soil pH on the UP2 and UP3 sites showed a significant decrease with no change on the UP1 sites (Table 5). Both the chronosequences (1988, 2010) tended to show a decrease in mineral soil pH from early to late successional stages

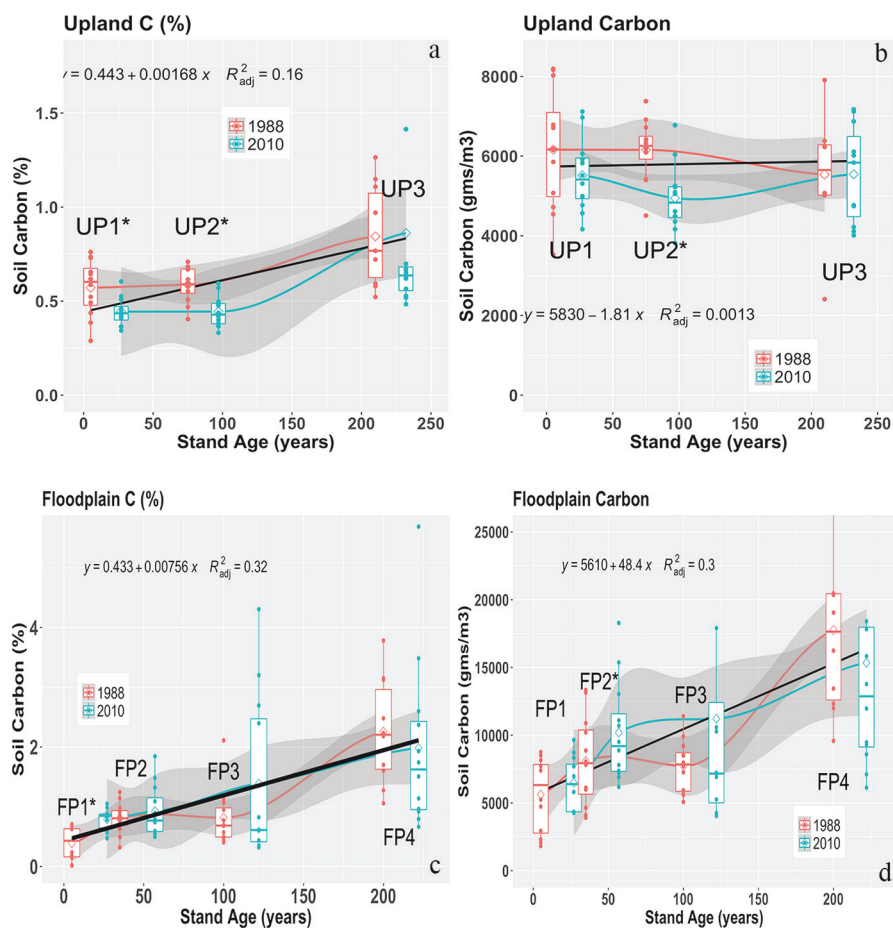


Fig. 5. Site, chronosequence, and time series trends for upland (UP; a-b) and floodplain (FP; c-d) mineral soil carbon concentrations and total quantity in the mineral soil to 1 m. Site significant differences indicated with an asterisk (*) with site name. Chronosequence differences shown with separation between the gray loess confidence regions for the first (1988, red line) and second (2010, blue line) trend lines. The overall time series direction for all six data sets displayed with the black line and regression equation.

and the six value time series tended to show the same decreasing trend. Cation exchange capacity showed a significant increase between the 1988 and 2010 sample periods at each site, a large increase across the successional sequence in 2010 compared to a small increase in 1988, and a large amount of time series variability if all six sites were used in a single time sequence. Average values of CEC at the UP1, UP2 and UP3 sites were 13.1 , 12.0 and $22.4 \text{ cmol}_c \text{ kg}^{-1}$, respectively. The overall site averages for C concentration on the UP1 and UP2 sites were significantly higher in the 1988/1989 samples (Fig. 5; Table 5). The overlapping confidence bands indicate a nonsignificant difference between the chronosequence trend lines, which would result in an overall upward trend across the successional sequence (Fig. 5). The total quantity of C in the profile showed a significant decrease on the UP2 sites (Fig. 5) and no change between time periods on the UP1 and UP3 sites. The confidence bands around both chronosequences displayed marginal overlap up till Year 140 and overlapped through the UP3 sites (Fig. 5). So the overall trend line was nonsignificant, no change in C quantity across the successional time frame. Nitrogen displayed an increase in concentration and quantity for all three

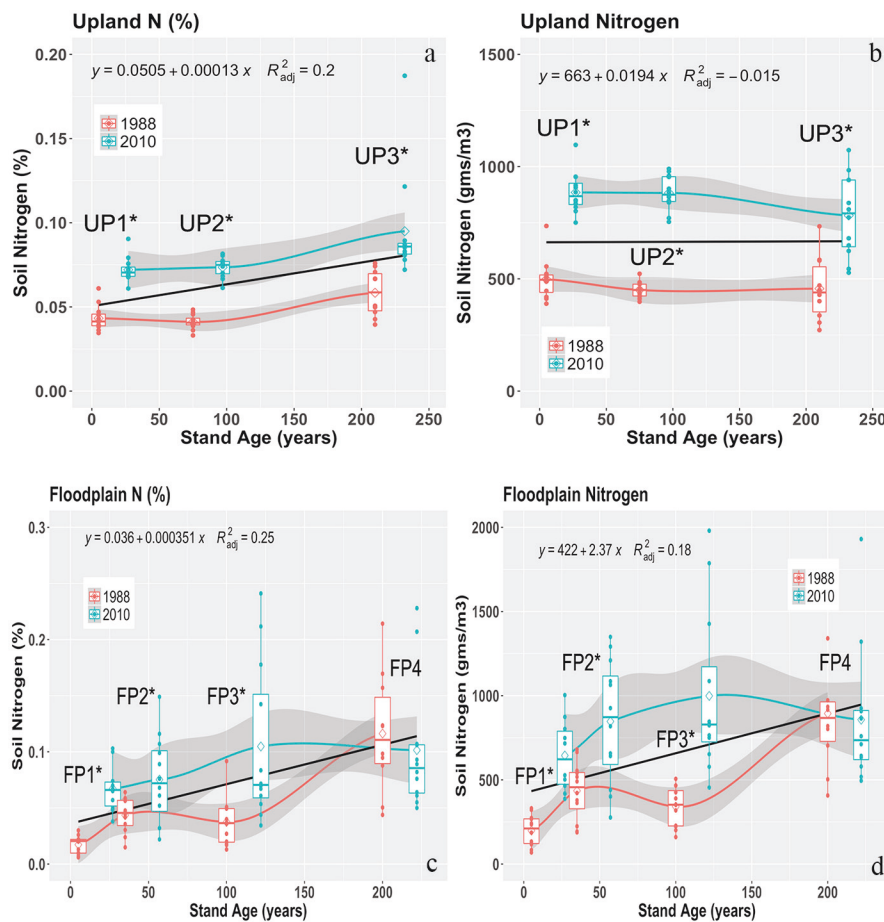


Fig. 6. Site, chronosequence, and time series trends for upland (UP; a-b) and floodplain (FP; c-d) mineral soil nitrogen concentrations and total quantity in the mineral soil to 1 m. Site significant differences indicated with an asterisk (*) with site name. Chronosequence differences shown with separation between the gray loess confidence regions for the first (1988, red line) and second (2010, blue line) trend lines. The overall time series direction for all six data sets displayed with the black line and regression equation.

successional sites (Fig. 6; Table 5). Both chronosequences tended to display an increase in concentration from young to old stands and this resulted in an average line that has a positive slope (Fig. 6). However the overall quantity of N showed no change due to decreasing bulk density across the chronosequence. The average quantity of mineral soil nitrogen is 5830 g m^{-3} . Once this is tied to the decreasing bulk density values a consistent quantity of N across the 230-yr chronosequence is present. The average N quantity is 663 kg m^{-3} . Total P concentration and quantity significantly increased on the UP1 and UP2 sites (Table 5). However there was a decreasing trend in concentration in both chronosequences and the overall time series for both concentration and total quantity of P in the soil profile (Table 5). Changes in the Ca dynamics were a little more complex. Calcium concentration for the total profile decreased for the UP1 sites and there was no change on the UP2 and UP3 sites. The total quantity was lower in 2010 for the UP1 site, higher in 2010 on the UP2 sites and no change on the UP3 sites (Table 5). Overall both the concentration and total quantity trends are decreasing for the successional time sequence. Magnesium did not show any site differences in concentration and total quantity across

all three sites (Table 5). The concentration chronosequences and overall time series showed an increase across the successional time frame. Potassium showed lower profile concentrations in 2010 for the UP1 and UP2 sites and no change on the UP3 sites. Both the concentration and quantity displayed a decreasing trend across both chronosequences, which produced a decreasing trend across the entire time series (Table 5). The total quantity of K in the mineral soil decreased from 72.6 to 29.0 g m^{-3} over a 225-yr time period.

DISCUSSION

A combination of spatial, temporal, and investigator factors play a role in the changes observed for soil profile descriptions; and the physical and chemical characteristics of the sampled soils. The overall design of the sampling procedures have to be effective so the quantification of temporal changes is not masked by the spatial variability of the measured soil traits (Lawrence et al., 2013). The measurement instability described by Desaulles (2012) was well controlled in the structure of the sampling design and the consistency of methods used for the chemical analysis. The statistical analysis then allows us to develop interpretations concerning four groupings of the data set: (1) profile differences at individual

sites, (2) summary values for the total mineral soil profile depth weighted average value mean between sampling periods, (3) repeated sampling of a primary and secondary chronosequence, and (4) an overall total sample chronosequence. So a primary question to answer is: Were the temporal changes suggested by the initial chronosequence sampling verified by the second round of repeated sampling?

Floodplain Soils

Descriptions of the floodplain soil profiles were related to the observer, and the flooding dynamics in the intervening two decades between the soil descriptions and sampling. The lowest terrace (FP1) was under water during floods in 1986, 2008, and 2009 and as a result a number of surface horizons (Fig. 2) were added. At least one of the surface horizons in the FP2 sites described in 2010 was the result of flooding but differences in deeper horizons are related to soil and observer variability (Fig. 2). The third horizon from 1989 and the fourth horizon from 2010 on the FP3 sites (Fig. 3) are very similar; indicating that one of the flooding events did make it to the FP3 terrace height. The oldest, highest terrace (FP4) was very similar in the number

of soil layers present and the position of a major organic layer that was buried in a major flood in 1967 (Fig. 3). Considering the flooding dynamics on these sites, the consistency of the soil profile descriptions is very good and changes viewed in the profiles can be related to natural environmental events in the past 23 to 24 yr.

The dynamics of the soil chemical environment reported for the second chronosequence sampling of the floodplain soils does support the results presented by Marion et al. (1993) and

Van Cleve et al. (1993). However the ecosystem successional dynamics did produce differences between the two sample sets at the same location. Of all potential differences between the first and second profile depth distribution across the floodplain successional stages (Table 2) we observed 11 positive changes (the value for the item measured in 2010 to 2011 was higher than the overall average). Cation exchange capacity was the only characteristic that displayed a positive change in all four successional stages (Table 2) but only in the top 30 cm on the

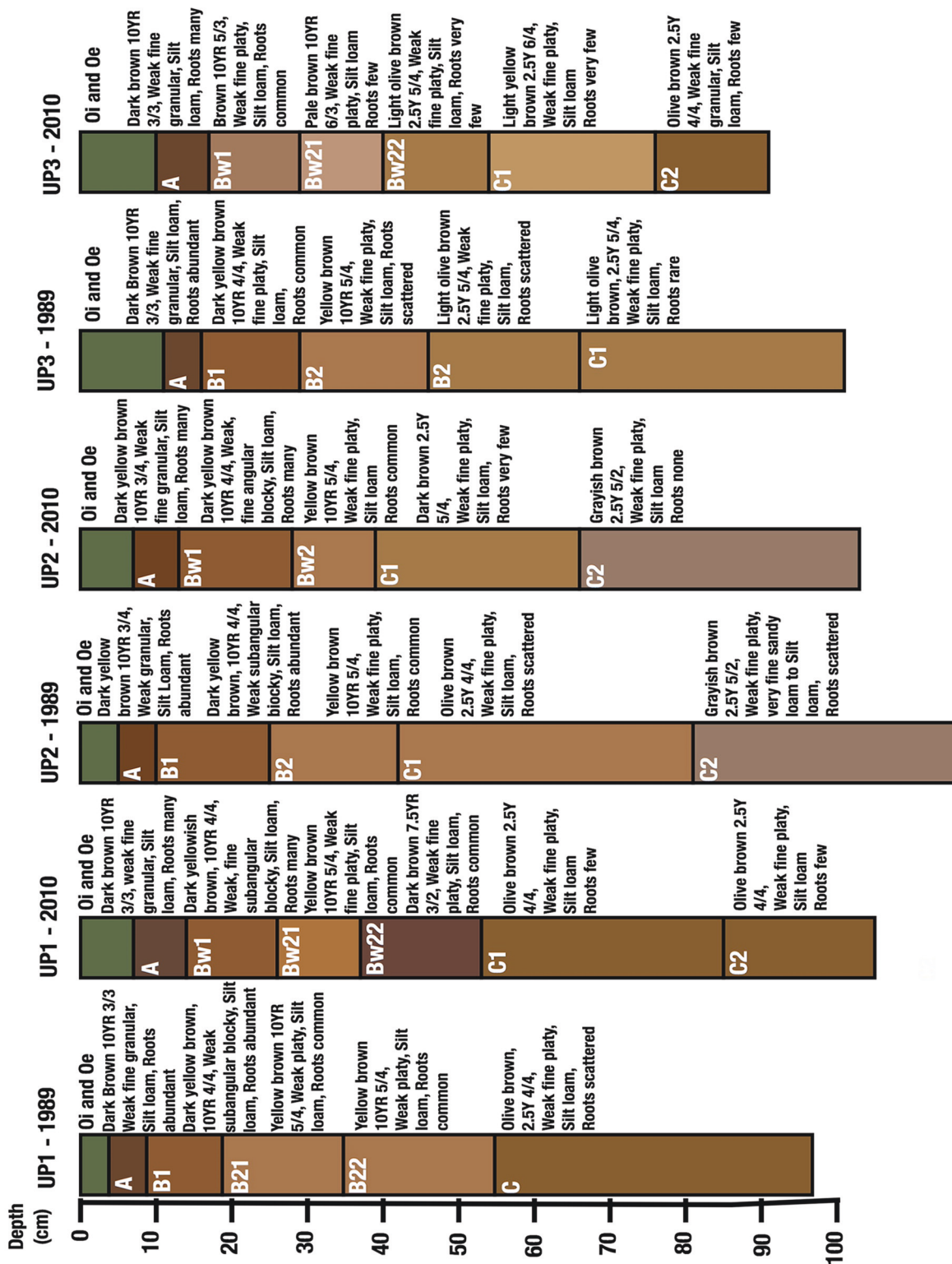


Fig. 7. Soil profile comparison between 1988 and 2010 for the three upland sites UP1, UP2, and UP3. The 1988 profiles were developed by Van Cleve et al. (1996). The profiles are now classified as a Typic Eutrocept, Fairbanks Soil Series (Soil Survey Staff, 2016). The soil colors were derived using the conversion from Munsell colors to a sRGB format (Centore, 2013).

Table 4. Significant increase (+) or decrease (–) within the upland (UP) soil profile at 10-cm depth increments for concentration between sampling dates (1988/1989 and 2010/2011) and for the total 1-m profile value, or quantity and average concentration. Standards units are used for bulk density, pH and cation exchange capacity (CEC).

Mineral soil property	Individual site					
	UP1		UP2		UP3	
	10-cm layers†	1-m profile‡	10-cm layers†	1-m profile‡	10-cm layers†	1-m profile‡
Bulk density	(+) below 10 cm	(+)	(+) below 10 cm	(+)	(+) 20 to 80 cm	(+)
pH	(–) below 50 cm	No change	(–) entire profile	(–)	(–) above 80 cm	(–)
CEC	(+) entire profile	(+)	(+) entire profile	(+)	(+) entire profile	(+)
C	No change	(+) in concentration; no change in quantity	No change	(+) in concentration; no change in quantity	No change	No change in concentration or quantity
N	(+) below 10 cm	(+) in both concentration and quantity	(+) below 20 cm	(+) in both concentration and quantity	(+) below 20 cm	(+) in both concentration and quantity
P	(+) below 10 cm	(+) in both concentration and quantity	(+) below 20 cm	(+) in both concentration and quantity	(+) below 50 cm	No change in concentration or quantity
Ca	(–)	(–) in concentration; (+) in quantity	(+) below 30 cm	No change in concentration; (+) in quantity	No change	No change in concentration or quantity
Mg	No change	No change in concentration; (+) in quantity	No change	No change in concentration; (+) in quantity	No change	No change in concentration or quantity
K	(+)	(–) in both concentration and quantity	(–) below 50 cm	(–) in concentration; no change in quantity	Inconsistent decreases in the profile	No change in concentration; (–) in quantity

† Indicates change in value for a mineral soil property between 1988/1989 compared to 2010/2011.

‡ Indicates an increase or decrease in the total value for a mineral soil property between 1988/1989 compared to 2010/2011.

FP4 sites with no change in the total profile average. Bulk density showed significant increases in stages FP2 (0 to 40 cm) and FP4 (30 to 95 cm), N and Mg concentrations in sites FP1 and FP3, and total P on stage FP1 (Table 2). Decreases were observed for 33% (12 profiles) of the measured features: pH across stages FP1, FP2 and FP3 (Table 2); C in the FP2 sites; total P in sites FP2 and FP4; Ca concentration on the FP3 stage; Mg concentration on the FP4 stage; and K concentration on stages FP1, FP2, and FP4 (Table 2). Thirty-three percent of the measured properties within a profile showed no changes. The changes in bulk density may be related to the different measurement techniques but also

to flooding events and an increase in organic matter content of the soil during progression of the primary succession.

Total C is showing an increase in concentration in the average values for the top 30 cm of the FP1 sites with no concentration change in the three older sites (Fig. 4). The two chronosequences (1988/1989 and 2010/2011) followed the same trends and overall there was a significant change in the total quantity of C present from the youngest to oldest successional stage (8.4 kg m^{-3}) over a 220-yr time frame (Fig. 5). Primary successional dynamics play a major role (Van Cleve et al., 1993). The early successional soils on the floodplains will contain a

Table 5. Significant property value, or concentration and quantity trend differences between the two chronosequences (2010/2011 compared to 1988/1989 sampling dates), and overall direction of change within the six sample combined time series for upland (UP) sites. Standards units are used for bulk density, pH and cation exchange capacity (CEC).

Mineral soil property	Chronosequence comparison†	Time series‡
Bulk density	2010 higher than 1988	No change from young to old sites
pH	2010 lower than 1988	Increasing trend from young to old sites
CEC	2010 higher than 1988	Increasing trend from young to old sites
C	Concentration at UP1 to UP2 lower, UP3 equal; no difference for quantity	Increasing trend from young to old sites for both concentration and quantity
N	Concentration and quantity higher	Increasing trend from young to old sites for concentration; no change for quantity
P	Concentration and quantity higher	Decreasing trend from young to old sites for concentration and total P quantity
Ca	Concentration and quantity lower at UP1, equal UP2 to UP3	Decreasing trend from young to old sites for concentration and quantity
Mg	No difference for concentration and quantity	Increasing trend from young to old sites for concentration; no change in quantity
K	Concentration and quantity decreasing from 1988 to 2010	Decreasing trend from young to old sites for concentration and quantity

† Indicates the difference between the 2010/2011 and 1988/1989 chronosequences.

‡ Indicates the overall trend across all six samples (3 chronosequence sites × 2 sample periods).

substantial amount of carbonate C, which will slowly dissolve over time and be reflected in changes in the pH in the first three successional stages. In addition organic carbon will be added due to the primary successional vegetation dynamics from both an aboveground and belowground perspective.

Alder plays a significant role in the successional dynamics on the floodplains (Van Cleve et al., 1971, 1993; Klingensmith and Van Cleve 1993). As a result of the alder presence N concentration and quantity (Fig. 6) show significant increases in the individual profiles of the FP1, FP2, and FP3 sites (Table 2). And as a result of the profile differences the average concentration and total quantity for the total profiles show significant increases between the two sampling periods (Table 2; Fig. 5). There were no differences found in the late successional white spruce sites (FP4).

Total P concentration showed a significant decrease on the FP2 sites (Table 2). Both chronosequences displayed some variability across the successional stages for both the concentration and total P but displayed no trend across the entire successional sequence. The concentration across all sites was 0.0534% and the total quantity was 625 g m⁻³.

Upland Soils

The soil descriptions for the three upland successional sites between sample years showed a great deal of similarity (Fig. 7). The major soil subgroup was a Typic Eutrochrypt (Soil Survey Staff, 2016). Each of the three representative soil descriptions was developed from 12 profiles for each successional stage. The average profiles (Fig. 7) comprised either 6 or 7 horizons, and the color, structure and texture were very similar between sample years. This is a good indication of consistency in the soil descriptions between scientists in the different sample years. The depth variability observed can easily be a result of location differences between the measured soil profiles despite their close proximity and the ability of the scientist to determine the boundary between profile layers.

Of all potential differences within the depth distribution of a factor across all upland successional stages (Table 4) we observed 13 positive changes (the 2010/2011 profiles were higher than the 1988/1989 profiles). These changes were seen in all successional stages for bulk density, CEC, N concentration and total P concentration. Calcium concentration increased on stage UP2 (Table 4). Decreases were observed for 18% (5 profiles) of the measured features, pH across all stages (Table 4), Ca concentration on the UP1 stage, and K concentrations on the UP1 and UP2 stages. Thirty-three percent of the measured properties showed no changes. The increases in bulk density may be related to the different measurement techniques. In both cases the values are typical for the soils that were measured. The time series changes for bulk density show a significant increase between the 1988/1989 and 2010/2011 sample sets. The variability around the means was relatively small but there was a distinct difference between the means for both chronosequences (Table 5). This is an indication that differences in measurement techniques may be an influence. The overall trend through all six datasets was flat indicating no change in bulk density. Acidity also showed a decrease in average

profile pH values for all three sites (Table 4). The overall trend was expected when going from an early succession hardwood site to a late successional conifer site.

Carbon shows a decrease in the average profile concentration values for the UP1 and UP2 sites (Fig. 4) but there was no difference between the two chronosequences and the overall concentration increase through the successional sequence. The total quantity present in the mineral soil displayed a small increase of 339 g m⁻³ over a 220-yr time frame (Fig. 4). These changes could be related to climate change dynamics that would affect the surface soil layers below a shallow organic matt and increased temperature dynamics after disturbance on the UP1 sites. However there were no differences found in the profile distribution of C in all three of the sampled sites (Table 4). The changes present in the concentration data were masked in the calculation of the total quantity data due to the differences in the bulk density data series.

Nitrogen concentration and quantity (Fig. 5) show significant increases throughout the profile in all three successional stages. The alder vegetation component probably is the reason in the UP1 and UP3 sites and the retention of throughfall N could be a major input on all three upland sites. Overall the concentration of N in the soils appears to be increasing (Fig. 5) while the total quantity is showing very little change through the entire successional progression (Table 5). Total P concentrations and quantities showed significant increases on the UP1 and UP2 sites (Table 4). However both chronosequences displayed a decreasing trend from the early to the late successional stands (Table 5) and the time series is a decreasing linear trend for concentration and a curved decreasing trend for P content (Table 5).

The chronosequence approach combined with repeated sampling occurring over a sufficiently long time frame can result in a sound method for describing changing soil characteristics during succession (Walker et al., 2010). The key factors that need to be considered in this process are:

1. Time should be the major varying state factor. However spatial variability will need to be handled with careful site selection. Climate and vegetation change dynamics also play a major role tied to the time period between sampling dates.
2. Selection of field and laboratory methods that do not change within a single chronosequence and between chronosequence sampling times.
3. Well-trained field personnel for description and sampling of visually measured soil properties (i.e., soil color, structure, etc.)
4. Current vegetation and climatic dynamics do not necessarily match historic patterns, which means that modern repeated measurements may not match patterns observed on historic chronosequences. These differences could be a source of important insights into the role of climate change in governing forest soil dynamics.

CONCLUSIONS

Based on the results of the reported observations we can develop a number of conclusions related to the soil profile changes

between sampling time periods at individual successional stages and total profile changes across the primary successional on floodplain ecosystems and secondary successional on upland ecosystems after fire. We can suggest that:

1. Soil texture, color and structure were comparable between the two sampling periods for both the upland and floodplain ecosystems. However there were a number of new horizons present in the 2010/2011 sample periods due to flooding dynamics on the floodplain sites.
2. Soil pH across all upland sites decreased from a range of 6.4 to 5.6 in 1988/1989 to 5.8 to 5.2 in 2010/2011. Across all the floodplain sites pH decreased from a range of 7.8 to 7.0 in 1988/1989 to 7.2 to 6.7 in 2010/2011.
3. Cation exchange capacity displayed an increase across the successional chronosequence in both upland and floodplain sequences. Individual sites displayed a significant increase between the 1988/1989 and 2010/2011 sample periods.
4. Bulk density upland profiles increased, showed a significant increase between the 1988/1989 and 2010/2011 chronosequence but the long term six site average show no successional change. Floodplain profiles showed small profile changes, significant decreases in the FP2 and FP4 sites with an overall decrease in bulk density across all eight data sets.
5. Carbon concentrations increased from early to late succession on the floodplain and upland series. The overall C quantity did not show an increase over the sample time period on the upland sites. The floodplain (primary succession) C concentrations increased starting at 0.39% on the FP1 sites in 1988/1989 to a maximum value of 2.26% in the FP4 sites again in 1988/1989. The quantity of C showed an increase from 4.8 kg m^{-3} on the FP1 sites in 1988/1989 to 15.1 kg m^{-3} on the FP4 sites in 2010/2011.
6. Nitrogen concentration showed an increase across both chronosequences and an overall increase across all six sample sites and time periods but showed no change in overall quantity on the upland sites. On the floodplain sites N concentrations and quantity displayed an increase across the entire time sequence.
7. Total P both concentration and total quantity showed a decrease across the chronosequences and the total time period on the upland sites. However on floodplain sites P concentrations and total quantity were unchanged across the whole time sequence. The concentration averaged 0.06% and the quantity averaged 622 g m^{-3} .
8. On upland sites Ca and K concentrations and quantity tended to show a decrease while the Mg concentrations and quantity increased. On the floodplain sites Ca concentrations tended to display a decrease while Mg and K concentrations displayed an increase through succession. The total quantity of Ca and K tended to decrease while Mg increased to an asymptote at about 150 yr.

At this point in time it is difficult to tie any observed changes to climate dynamics. We could hypothesize that the dynamics of C quantity should be tied to change in vegetation growth and soil organic matter dynamics. Based on the upland sites it could be suggested that the balance between growth and decomposition has not changed which resulted in relatively no change in soil C content. However both chronosequences (1988 and 2010) showed an upward trend for concentration data while the individual sites displayed a decrease between the two sample periods (Fig. 5). The two quantity chronosequences displayed no change over the 250-yr time frame, but the site data exhibited a downward trend for the UP1 and UP2 sites. A carbon-capture structure tied to the primary successional dynamics was present on the floodplain for both concentration and quantity. It will be interesting to see what changes have occurred in a subsequent sample of these research sites in 2030.

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SUPPLEMENTAL MATERIAL

Supplemental material is available with the online version of this article. Supplement 1 contains profile depth differences for floodplain mineral soil chemical characteristics derived from a bootstrapped loess regression approach. Supplement 2 contains profile depth differences for upland mineral soil chemical characteristics derived from a bootstrapped loess regression approach. Supplement 3 contains site differences for upland and floodplain mineral soil chemical characteristics. Each supplemental document contains color figures and is 10 pages in length.

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