Published March 13, 2015

Hydromorphic Soil Development in the Coastal Temperate Rainforest of Alaska

David V. D'Amore*
USDA Forest Service
Pacific Northwest Research Station
11175 Auke Lake Way
Juneau, AK 99801

Chien-Lu Ping
Agricultural and Forestry Experiment Station
Palmer Research Center
Univ. of Alaska–Fairbanks
Palmer, AK 99645

Paul A. Herendeen
Graduate Degree Program in Ecology
Colorado State Univ.
Fort Collins, CO 80523

Predictive relationships between soil drainage and soil morphological features are essential for understanding hydromorphic processes in soils. The linkage between patterns of soil saturation, reduction, and reductimorphic soil properties has not been extensively studied in mountainous forested terrain. We measured soil saturation and reduction during a 4-yr period in three catenas of the perhumid coastal temperate rainforest of Alaska and compared these measurements to soil morphological features of Spodosols and Histosols. Soil saturation and anaerobic conditions indicated by redox potential corresponded to low-chroma colors, Fe concentrations, and accumulation of organic matter. Hue changes from 7.5YR to 10YR, 2.5Y, and 5GY were observed, at depths corresponding to water table position and Fe depletion, in Spodosol B horizons of backslope landscape positions. The depth to the features was dependent on the distance from the top of the catena, with a consistent pattern of near-surface soil saturation evident below the topographic break of 10% slope. The mean annual water table position was 34 cm below the surface in upper slope positions and 14 cm below the surface in lower slope positions. The association of color changes confirms the influence of saturation and reduction on the soil morphology of Spodosols. The consistent patterns in soil saturation, reduction, and soil morphological features offers guidance for hydric soil identification, wetland delineation, and ecological processes related to near-surface soil saturation.

Abbreviations: BS, backslope; Fe_d, dithionite-extractable iron; Fe_o, oxalate-extractable iron; FS, footslope; JUN, Juneau; LBS, lower backslope; PCTR, perhumid coastal temperate rainforest; THB, Thorne Bay; TS, toeslope; WRG, Wrangell.

Research linkages between soil hydrology and pedogenic processes have been investigated in natural topographic hydrosequences across several ecosystem types (Veneman and Bodine, 1982; Pickering and Veneman, 1984; Thompson and Bell, 1998; Reuter and Bell, 2001). The hydrosequence is essential for evaluating the hydromorphic soil properties associated with patterns of saturation and associated anaerobic conditions. However, soil morphology can only be reliably used as an indicator of soil drainage patterns and determination of hydric soil status after calibration with local conditions from long-term observations (Zobeck and Ritchie, 1984; Lin et al., 2006). Observations in regional hydrosequences were used as a common framework to determine soil saturation patterns associated with soil morphology in the National Wet-Soil Monitoring Program (Lynn et al., 1996). This program maintained several regional observatories to provide calibration of soil morphological features with patterns of soil saturation. One of these observatories was established in Alaska to investigate Spodosols and Histosols in mountainous terrain. These soils are common to

Soil Sci. Soc. Am. J. 79:698–709
doi:10.2136/sssaj2014.08.0322
Received 12 Aug. 2014.
Accepted 5 Jan. 2015.
*Corresponding author (ddamore@fs.fed.us).

the northeastern and northwestern regions of the contiguous United States and Alaska.

Soil formation in the perhumid coastal temperate rainforest (PCTR) of Southeast Alaska is influenced mainly by topography and a perhumid climate with abundant precipitation that exceeds evapotranspiration most of the year (Patric and Black, 1968). These environmental conditions lead to relatively rapid soil development, with Spodosols emerging after ∼200 yr (Chandler, 1943). In addition, the intensive hydromorphic soil development and extensive Histosols are caused by aquic moisture regimes in the region (Alexander, 1990). In this complex forested terrain, however, it is difficult to determine the duration and distribution of soil saturation due to the variability of the surface relief and complexity of the soil morphology caused by the interaction of bioturbation and slope processes (Bowers, 1987; Bormann et al., 1995). Spodosol colors related to hydromorphic soil development are often confounded with colors developed during podzolization (Veneman and Bodine, 1982; Mokma, 1983). The movement of Al– and Fe–organic matter complexes during the spodic process creates variegated colors and strong reddish-brown colors in Spodosols. There is often a subtle change in the colors within a profile subject to spodic horizon formation. The process of redox depletion, where Fe is reduced, mobilized, and redistributed as concentrations of Fe, often appears similar to the spodic colors. In addition, the presence of a depleted matrix, where Fe has been diminished due to reductive dissolution, can also be subject to ongoing podsolization, creating a difficult interpretive condition for determining the presence of anaerobic conditions through soil morphology. For example, the link between soil saturation and color changes in seasonally saturated Spodosols was elusive in Michigan (Evans and Mokma, 1996; Mokma and Sprecher, 1994a, 1994b). The PCTR offers a setting where the soil-forming factors such as parent material, organisms, and climate are relatively constant but the slope and influence of water varies with landscape position (Amundson and Jenny, 1997).

There have been few studies in coastal temperate forests that directly measure soil hydrology and the association with soil morphology. Soil formation studies in the region have concentrated on well-drained toposequences (McKeague, 1965), lithology (Heilman and Gass, 1974; Alexander, 1990), vegetation succession (Klinger, 1996), and windthrow (Bormann et al., 1995). Many notable investigations have focused on time as the major soil-forming factor in the context of glacial chronosequences (Chandler, 1943; Crocker and Major, 1955; Crocker and Dickson, 1957; Ugolini and Mann, 1979; Alexander and Burt, 1996; Burt and Alexander, 1996), but numerous soil hydrologic and chemical processes are of concern in areas of forest and wetland management as well (Kahklen and Moll, 1999; Creed et al., 2003; Julin and D'Amore, 2003; Dudley and Rochette, 2005; Caouette and DeGayner, 2005). Hydromorphic soil properties and processes within the region have recently been explored as an important factor in explaining soil landscape relationships (Hartshorn et al., 2003; D'Amore et al., 2012); however, there are no quantitative data available on soil hydrologic fluctuations and associated patterns of anaerobic conditions across soil types in the region. Therefore, determining the boundaries between saturated and unsaturated soils in the PCTR has been difficult.

This study was designed to more clearly articulate the patterns of hydromorphic properties with measurements of soil saturation and reduction in Spodosols and Histosols of the PCTR. Our goals were to: (i) establish relationships between soil saturation, reduction, and patterns of hydromorphic soil development in forested Spodosols and Histosols; and (ii) improve the understanding and prediction of hydromorphic soil development to confirm the assignment of soil drainage classes in the PCTR.

MATERIALS AND METHODS

Setting

The study was conducted in the PCTR of Southeast Alaska (Alaback, 1996). This part of the Pacific Mountain system (Wahrhaftig, 1965) covers approximately 8.5 million ha and extends 800 km from Dixon Entrance in the south to Yakutat Bay in the north (Fig. 1). Precipitation occurs year-round and ranges from 1500 to 5000 mm annually, with the greatest accumulation of rainfall during September and October (Helmers, 1974). Several episodes of extensive glaciation during the Pleistocene initiated the most recent major transformation of the landscape (Mann and Hamilton, 1995). The Wisconsin glaciation has masked the earlier glacial features and had the most prominent influence on the surface stratigraphy and soils of the area. The soils in the region have all formed from coarse-textured post-glacial Holocene deposits or a combination of glacial drift, colluvium, and weathered bedrock (Krosse, 1993). Topography also exerts a

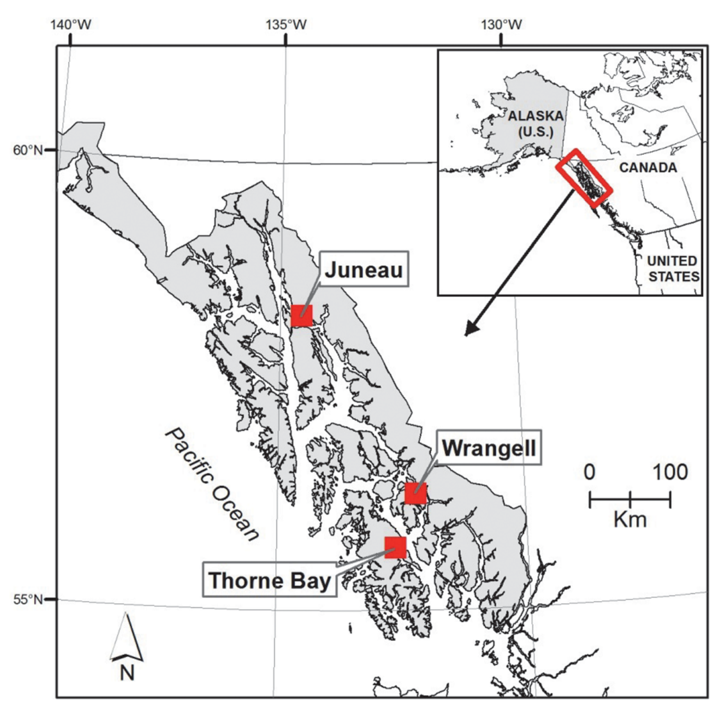

Fig. 1. Location of the perhumid coastal temperate rainforest in Alaska (box) and locations of hillslope catenas in Southeast Alaska.

strong influence on the landscape, with dramatic changes in elevation across short distances from sea level to alpine summits.

Site Selection and Experimental Design

The study locations were selected along a regional climate gradient of increasing precipitation and temperature from north to south (Fig. 1; Farr and Hard, 1987). These areas are located in three different subsections of Southeast Alaska: Douglas Island Volcanics (Juneau, JUN), Zimovia Strait Complex (Wrangell, WRG), and central Prince of Wales till lowlands (Thorne Bay, THB) (Table 1; Nowacki et al., 2001). The locations of the three sites fall into the Glacial Topography (THB) or Rolling Hills (JUN and WRG) classes in the local landform guide (US Forest Service, 1996). The Glacial Topography class consists of drumlins, while the Rolling Hills have moderate relief and are moderately incised by streams. We established catenas and identified soils at four hillslope positions at each location (Fig. 2). Each catena had specific landscape position designations along the hillslope sequence but varied in certain geologic and geomorphic attributes. Our approach relied on the strong influence of topography on the flow and routing of water through the landscape positions in each catena. Many landscape models rely on topography as a primary driving variable (Moore et al., 1993; McBratney et al., 2000). Therefore, although there were subtle variations in soils, the landscape position served as a replicate for the presence of water in a soil.

We further accounted for the geographic and spatial variability by selecting catenas that were located on hydrologically isolated hillslopes spanning the transition between potential hydric and non-hydric soils (Fig. 2). The catenas were all located on hillslope sequences that had well-defined areas of precipitation accumulation starting at an identified summit and were constrained so that drainage was limited to the sequence of soils along the slope gradient. Therefore, all water flow originated at the summit of the catena and accumulated downslope. The catenas varied in slope length and associated contributing area, but they were all similar drainage sequences with replicate landscape positions instrumented within each catena. Each catena sequence contained four observation points at different topographic positions from well-drained soils at the top of the catena to poorly drained organic soils at the bottom of the hillslope.

Table 1. Locations and physical environments of three catena sites located in the perhumid coastal temperate rainforest of Southeast Alaska.

Transect	Location	Elevation range	Aspect	MAP†	MAAT‡
		m	°	cm	°C
Juneau	58°17.515′ N 134°32.552′ W	240–275	90	141	4.7
Wrangell	56°18.074′ N 132°12.575′ W	120–180	270	200	6.0
Thorne Bay	55°42.077′ N 132°37.763′ W	59–75	270	300	9.0

† Mean annual precipitation.

‡ Mean annual air temperature.

Soil Characterization and Laboratory Analyses

Soil pits were excavated at each observation point to a depth of 2 m or impermeable glacial till. Soil genetic horizons were determined, described, and sampled following the protocol of Soil Survey Division Staff (1993) and modified by Schoeneberger

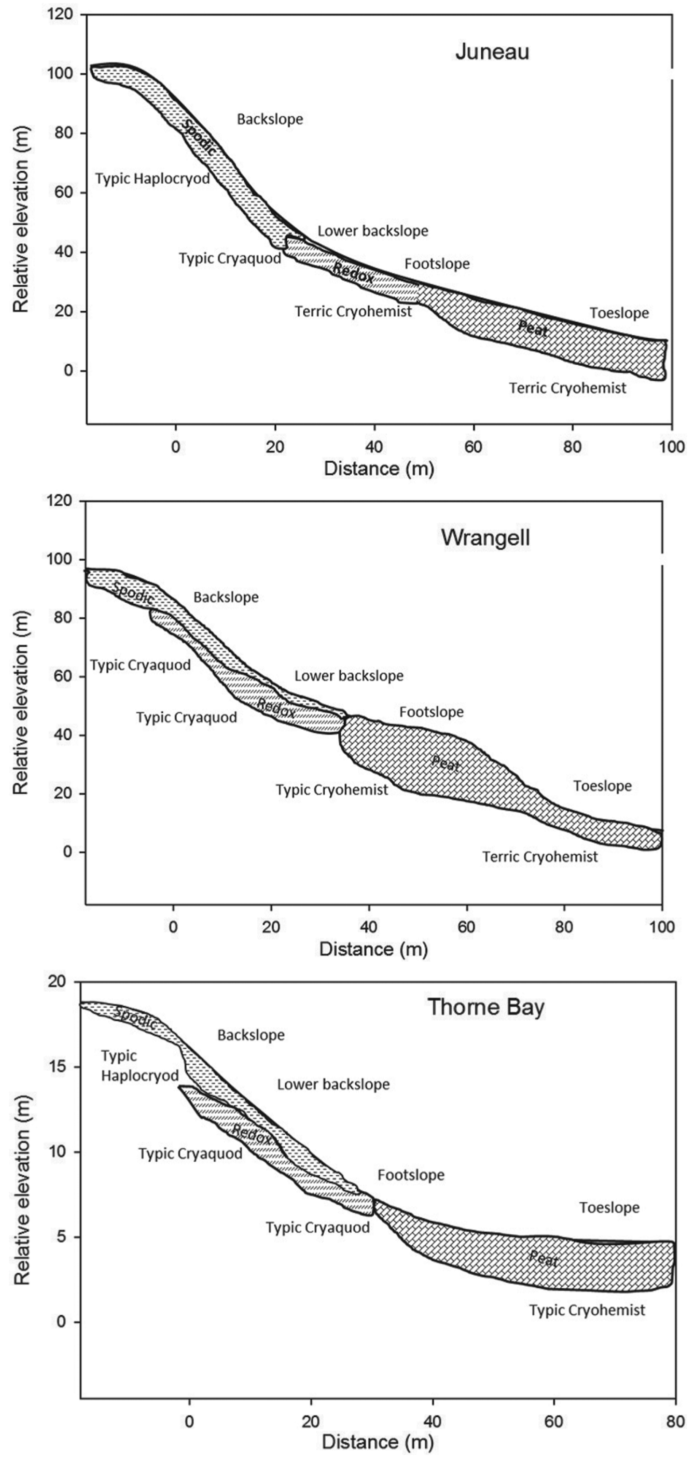

Fig. 2. Soil observation locations and associated landscape positions at the Juneau, Wrangell, and Thorne Bay sites in Southeast Alaska. Generalized horizon features are noted according to the dominant soil-forming process including podzolization (spodic), reductimorphic (redox), and organic accumulation (peat). The elevation measurements are relative to the bottom of the catenas for comparison of observation location along the slope. The clear color change occurs at the top intersection of the area indicated as redox in the figure.

et al. (2002) to change the terminology from *mottles* to *redoximorphic features*. Soil pedons were classified on site using soil descriptions and then correlated with laboratory data (Table 2; Soil Survey Staff, 1999). Soil characterization analysis was performed according to standard methods (Soil Survey Laboratory Staff, 1996), unless otherwise specified. Bulk density for mineral soils was determined by the resin method. Organic soil field samples were taken in triplicate 125-cm^3 cubes, weighed, dried and reported as dry weight per unit volume (g cm^{-3}). Soil particle size was determined by the pipet method. Total C and N contents were determined on pulverized samples in a Leco CHN analyzer. Soil pH was measured in 0.01 mol L^{-1} $CaCl_2$. Sequential extractions of Fe and Al were completed by sodium pyrophosphate, ammonium oxalate, and Fe by dithionite–citrate.

Climate

Long-term average rainfall and temperature at the sites was determined from regional weather stations located near the catena locations (Table 1). The Juneau data are from the Juneau airport, approximately 5 km north of the Juneau catena. The Wrangell weather data are from a US Forest Service Remote Automated Weather Station located 75 km northwest of the study site. The Thorne Bay data are from the Ketchikan airport, which is the closest long-term record and approximately 115 km southeast of the Thorne Bay catena.

Hydrology

Water table wells and piezometers were installed in each pedon sampling site at each catena location (Sprecher, 2008). Two piezometers and one well were installed at each landscape position at depths ranging from 30 to 70 cm depending on the location of the impermeable contact. Piezometers were constructed of 3.2-cm schedule 40 polyvinyl chloride (PVC) pipe, slotted for a 10-cm length at the bottom of the pipe. Piezometers and water table wells were installed by excavating a hole with a 2.54-cm auger and then driving the piezometer tube into the hole with a post driver. Each piezometer pipe was equipped with a pressure transducer wired to a datalogger (Unidata America) for measurement of water depth relative to the soil surface compiled as hourly measurements. Piezometers were the primary measurement device used to detect water levels in the soil. Water table wells were perforated along the entire length of the PVC pipe and measured manually during site visits from May to November for additional data.

Redox Potential

Five platinum microelectrodes were installed at approximately 25 cm below the surface (Faulkner et al., 1989; Vepraskas and Sprecher, 1997). Field voltages were measured hourly through a datalogger (Unidata America), and a Ag–AgCl reference electrode (Jensen Instruments) was dedicated exclusively to redox potential measurements. The dataloggers were tested for interference with the soil redox potential voltage and found to place a minimum load on the signal due to the brief interruption of the circuit during measurements. Dataloggers can detect weak signals because they do not erode the signal due to their high impedance (van Bochove et al., 2002; Rabenhorst et al., 2009). The Pt microelectrodes were modified from the design of Patrick et al. (1996) by enclosing the soldered Cu–Pt connection in heat-shrink tubing and then coating the outside in epoxy to ensure a watertight seal. Redox electrodes were replaced and reconditioned on a regular basis due to the potential for failure of probes placed in the field for long periods of time (Austin and Huddleston, 1999; Owens et al., 2005). Field voltages were corrected to the standard H^+ electrode by adding 199 mV to the raw field voltage. The average pH at each depth and site was calculated from pH measurements taken during site maintenance visits. The potential Fe reduction threshold was determined to be approximately 400 to 500 mV using the pH-corrected equilibrium relationship for $Fe(OH)_3$ (Vepraskas and Faulkner, 2001).The

Table 2. Site location, landscape position, local soil series, and soil classification along with measured slope and drainage class of pedons in each catena sequence.

Site	Landscape position	Soil series†	Taxonomic classification‡	Slope class	Drainage class§
				%	
Juneau	backslope	ND	Typic Haplocryod	25–35	well drained
	lower backslope	Mitkof	Typic Cryaquod	15–25	moderately well-drained
	footslope	Maybeso	Terric Cryohemist	5–10	poorly drained
	toeslope	Maybeso	Terric Cryohemist	0–5	very poorly drained
Wrangell	backslope	Mitkof	Typic Cryaquod	25–35	moderately well-drained
	lower backslope	Wadleigh	Typic Cryaquod	15–25	moderately well-drained
	footslope	Kina	Typic Cryohemist	5–10	somewhat poorly drained
	toeslope	Maybeso	Terric Cryosaprist	5–10	very poorly drained
Thorne Bay	backslope	Karta	Typic Haplocryod	15–25	moderately well-drained
	lower backslope	Karta	Typic Cryaquod	15–25	moderately well-drained
	footslope	Wadleigh	Typic Cryaquod	0–5	somewhat poorly drained
	toeslope	Kina	Typic Cryohemist	0–5	very poorly drained

† The series listed are the most closely associated soil series expected in these areas, while actual soils sampled are variants of the series; ND, not determined.

‡ Taxonomic classification represents the field and laboratory interpretation for the site, not the official series description.

§ Drainage class was determined by field observations.

relationship of actual field redox–pH conditions to the linear slope correction factor is uncertain. Therefore, gradients of reduction are noted as occurring between 400 and 500 mV rather than at a defined threshold. Soil temperature was measured at the 50-cm depth. Duplicate temperature probes were installed and the average of these two measurements is reported as the final temperature (in °C).

Statistical Analysis

The influence of landscape position (backslope, lower backslope, footslope, and toeslope) and time on average monthly soil water table depth and redox potential was tested using a linear mixed-effects model (Proc Mixed procedure in SAS, Version 9.3). The model was modified to also test the influence of the water table level, along with landscape position, and time vs. average monthly redox potential. Correlation between replicated measurements was accounted for by using a linear mixed model analysis (SAS Proc Mixed procedure). The SLICE option (SAS, Version 9.3) was used as a means separation test for the average monthly depth to water table across landscape positions. This procedure was not applied to the redox data due to the presence of a continuous variable (depth to water table) in the model.

RESULTS

Climate

The precipitation recorded during the study period is consistent with the general patterns of the regional climate records (Fig. 3). The measurement interval falls at the end of a period of the Pacific decadal oscillation that shifted Pacific weather patterns toward warmer and wetter conditions (Mantua and Hare, 2002). Precipitation measured at stations near the sites had values slightly above long-term averages. The fall of 2001 was slightly drier at all sites than the long-term averages, but there were not any extreme departures from normal conditions of precipitation. There was a latitudinal trend of decreasing precipitation from the south in the Ketchikan region (THB site) to Kake (WRG) and Juneau (JUN) in the northern part of Southeast Alaska. The average annual rainfall was close to 500 cm in Ketchikan compared with approximately 200 cm in Juneau. Soil temperatures at a depth of 50 cm ranged between 5 and 11°C during the year.

Soil Development Related to Hydromorphic Properties along the Catenas

Clear color changes and Fe concentrations present in the Spodosol profiles indicate the presence of sustained soil saturation and reduction. The color changes include hue shifts from red to yellowish-brown (5YR to 7.5 or 10YR) and yellowish-brown to yellow (2.5Y to 5Y) within the B horizons. Chromas also decrease one to two units across the same horizons, indicating a loss of bright colors associated with stripping of Fe from the soil matrix. We use the term *clear* to define a change that occurs over 2 to 5 cm between horizons consistent with the terminology for clear boundary designations as described by Soil Survey Division Staff (1993). The clear color boundary is most

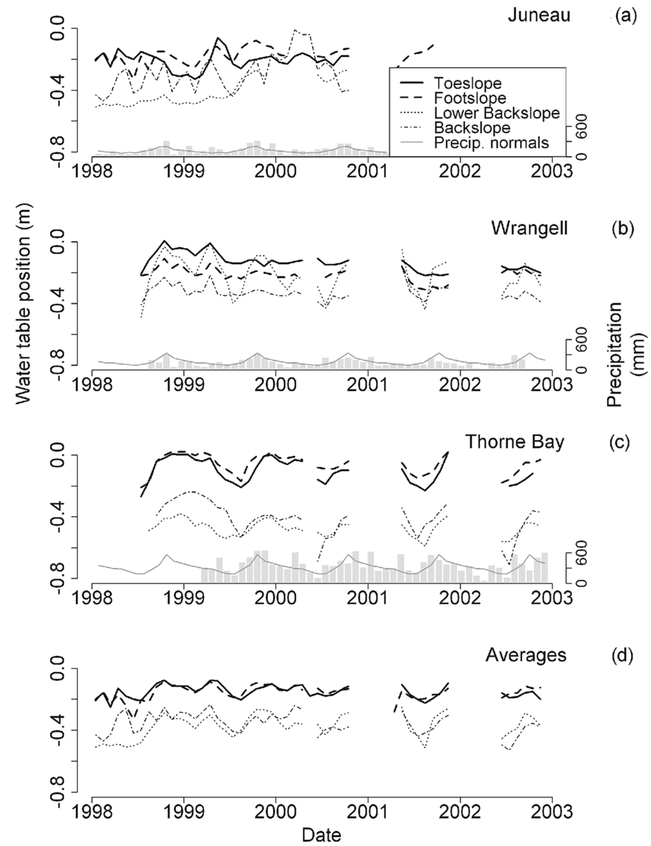

Fig. 3. Precipitation and water table position from 1998 to 2003 at the Juneau, Wrangell, and Thorne Bay catenas in Southeast Alaska. Landscape positions are noted by line type. Precipitation normals are 1981 to 2010 averages.

conspicuous in the lower backslope (LBS) landscape positions. The JUN LBS hue changes from 7.5YR to 10YR from the Bs to the Bg horizon at the 27-cm depth (Table 3). This is not a substantial matrix color change, but the value and chroma colors change dramatically from bright 5/6 colors to dull 4/1 colors. There are also common, distinct concentrations of Fe within the Bg horizon (Table 3). The WRG LBS has a hue change from 7.5YR to 5Y between the Bhs2 and Bg horizons at the 40-cm depth (Table 3). Common, prominent concentrations of Fe are also present in the Bg horizon, similar to the JUN LBS site. The THB LBS has a dramatic change from 7.5YR to 2.5Y between the Bhs2 and Bg horizons at the 49-cm depth (Table 3). The hue change is accompanied by no value change but does show a change in chroma from 6 to 1, indicating a drastic depletion of Fe in the horizon. This horizon has many distinct Fe concentrations, consistent with the redistribution of Fe from the matrix to the concentrations.

Clear color changes did not occur in the upper part of the B horizons within the profiles of the backslope (BS) soils. The clear color change was evident in the lower part of the profile at the transition from the B horizons to the C horizons. The JUN BS has a hue change from 5YR to 2.5Y between the Bs and C horizons at 39 cm depth (Table 3). The C horizon also has common, prominent iron concentrations. The WRG BS also has a clear color change associated with the transition from the Bs2 hori-

Table 3. Selected physical and chemical properties of the soils from the three transects in Southeast Alaska.

Landscape position	Depth	Horizon	Matrix color	Redoximorphic features†	pH‡	Organic C
	cm					%
			Juneau			
Toeslope	0–16	Oe1	10YR 5/4		3.4	50.09
	16–33	Oe2	10YR 3/3		3.3	50.60
	33–60	Oe3	5YR 2/1		3.2	56.11
	60–84	Oe4/Oe5	5YR 2/2		3.3	56.39
	84–102	Oe6	5YR 2/2		3.7	27.82
	102–115	2Bwb	10YR 5/3		4.2	3.21
	115–140	2Cg	5G 5/1		4.9	0.53
Footslope	0–10	Oe1	5YR 3/1		4.4	43.2
	10–23	Oe2	5YR 3/2		4.2	27.33
	23–31	Oe3	5YR 3/2		4.1	29.84
	31–51	Oe4	5YR 3/2		4.2	12.71
	51–75	2C	5Y 4/3		4.5	2.73
	75–110	2Cg	5Y 5/2		4.8	1.09
	110–150	3C2	5Y 4/3, 2.5YR 5/1	2md 5YR 4/6	4.9	0.22
Lower backslope	0–16	Oi	10YR 2/2		3.3	46.21
	16–27	Bs	7.5YR 5/6	2cf 7.5YR 5/6 1cd 5YR 5/6	4.7	2.12
	27–42	Bg	10YR 4/1	2cd 5YR 4/4	5.1	2.24
	42–59	2C1	7.5YR 4/2	2fd 5YR 5/4	5.3	0.76
	59–71	2Cg1	5GY 5/1	2md 7.5YR 4/4	5.4	0.33
	71–100	2Cg2	5GY 5/1	2md 7.5YR 4/4	5.7	0.17
Backslope	0–7	Oe	7.5YR 2/2		3.8	44.75
	7–11	E	10YR 5/3		3.3.	11.05
	11–15	Bh	10YR 2/2		3.6	12.02
	15–20	Bs1	7.5YR 4/6		3.9	5.28
	20–39	Bs2	5YR 3/3		4.1	3.62
	39–72	C	2.5Y 5/4	2cp 5YR 3/2	4.1	0.4
			Wrangell			
Toeslope	0–11	Oi	2.5YR 3/2		3.5	47.5
	11–26	Oa1	10YR 2/1		3.1	46.02
	26–53	Oa2	10YR 2/2		3.1	55.71
	53–70	Oa3	5YR 2/2		3.5	35.56
	70–78	Ab	10YR 3/2		4.2	5.18
	78—103	Bg	5GY 4/1		4.4	2.16
	103–118	Cg1	5B 4/1		4.2	0.41
	118–130	Cg2	5B 5/1		4.2	0.28
Footslope	0–7	Oi	5YR 3/2		3.0	48.69
	7–15	Oa	5YR 3/2		3.0	50.15
	15–22	Oe1	7.5YR 2/2		2.9	52.19
	22–45	Oe2	10YR 2/1		2.9	53.6
	45–90	Oe3	10YR 4/4		3.1	52.66
	90–130	Oe4	10YR 3/3		3.2	54.92
Lower backslope	0–7	Oi	5YR 3/2		3.3	49.72
	7–25	Oa	5YR 2/1		3.8	33.31
	25–33	Bhs1	5YR 3/2		4.6	7.25
	33–40	Bhs2	7.5YR 3/2		5	3.35
	40–53	Bg	5Y 4/3	2fp 7.5YR 5/6	5.1	2.45
	53–80	C1	5Y 4/2	2mf 5Y 5/3	5.1	0.37
	80–100	C2	5Y 5/2	2ff 5Y 5/3 1fp 7.5YR 4/4	5	0.48

Continued on next page.

zon to the C horizon at the 66-cm depth (Table 3). The hue changes from 7.5YR to 2.5Y, with increases in value from 3 and 4 to 5. Chroma differences are noted in the secondary chroma of 2 compared with Bs2 chromas of 4. The THB BS has varying colors within the Bhs and Bs horizons but no clear color change until the transition from the Bs to the Cd horizon at the 87-cm depth (Table 3). This color change is accompanied by abundant prominent Fe concentrations in the Cd horizon.

The Spodosols from the catenas fall into either the Haplocryod or Cryaquod Great Groups depending on the interpretation of soil saturation (Table 2). The relationship between the dithionate-extractable Fe (Fe_d) and the oxalate-extractable Fe (Fe_o) was used as an indicator of the intensity of Fe transformations in the soils compared with expressions of soil color (Fig. 4). A wide oxalate/dithionate-extractable Fe ratio (Fe_o/Fe_d) is an indicator of aerobic weathering processes, while a narrow ratio is characteristic of a saturated anaerobic soil environment (Schwertmann and Taylor, 1989). Larger extractable quantities of Fe_d than Fe_o in the Haplocryods are consistent with the presence of fine crystalline Fe oxides such as goethite and poorly crystalline (ferrihydrite) and amorphous Fe compounds that persist in the soil under sustained aerobic weathering (Fig. 4). The low Fe_d values in the Cryaquods are due to the long-term saturation and reduction that leads to the reduction of Fe(III) to Fe(II) and the subsequent transformation or loss of Fe in the soil. This Fe_o to Fe_d relationship is present at depth in each soil, indicating that saturation and removal of secondary Fe compounds occurred across the spectrum of soils observed in the study area. Fine crystalline Fe contents decrease with depth and occur at abrupt changes from aerobic, Fe-rich environments to zones of Fe depletion associated with color changes (Fig. 4).

Soil Saturation along the Catenas

Long-term water table measurements revealed distinctions in the duration of saturation among landscape positions. The overall pattern of soil saturation was significantly related to landscape position ($F_{(3,6)} = 5.23, P = 0.041$; Fig. 3). An analysis of water table depth among the landscape positions revealed significantly different depths to water table during each month of measurement between the upland (BS and LBS) and lowland footslope and toeslope (FS and TS) landscape positions (least square means test of landscape position by month interaction with SLICE option, $F_{(3,88)} = 3.08–6.07, P < 0.05$). The statistical results can be interpreted visually by examining the patterns of average water table depths among the two lower landscape positions (TS and FS) compared with the upper landscape positions (BS and LBS; Fig. 3d).

There is a landscape distinction between "wet" and "dry" conditions related to the aquic–non-aquic moisture regime at the sites. The range of water table position was greater in the upper slope positions than the lower slope positions throughout the measurement period (Fig. 3d). The variability among the landscape positions across the catenas included large fluctuations in the JUN BS and the WRG LBS (Fig. 3a and 3b). The majority of water table position observations were below the 30-cm depth in both the BS and LBS landscape positions. A notable exception to this trend was the WRG LBS (Fig. 3b), where the water table position was observed above the 30-cm depth 79% of the observation period. This site is subject to large seasonal fluctuations in the depth to water table compared with the other sites (Fig. 3b). The seasonal drawdown and subsequent rise in water table position within the soil profile is dramatic and much more variable than the BS position above it along the catena. Similarly, the JUN BS has a similarly large fluctuation in the water table position seasonally (Fig. 3a).

The presence and duration of soil saturation in the landscape positions was consistent with the presence of the clear color changes and the occurrence of redoximorphic features. The mean water table position in the BS and LBS landscape positions was similar at 34 and 36 cm below the soil surface (Table 4). The water table position corresponds closely to the redoximorphic features noted in the LBS landscape positions at THB and JUN (Table 4). There is a bit more variability in the WRG LBS, where the mean water table position is located above the redox features noted in the profile (Table 4). The variability in the WRG LBS can be seen in the fluctuations of the water table position in the detail for the site in Fig. 3b. The water table position persists in the upper part of the soil at the WRG LBS (79% of observations; Table 4) compared with the TBH and JUN sites; however, the redox potential was dominated by the aerobic range during 80% of the time at all three sites (Table 4). All three LBS sites showed redoximorphic features distributed across several horizons, attesting to the fluctuation of the water table position. The BS sites are all well drained and thus have no perched water table and accompanying redoximorphic features.

The lower bound of the FS and TS soil water table position was 27 cm below the soil surface. The upper bounds of the BS and LBS soil water table positions were 21 and 24 cm below the soil surface, respectively. Therefore, a demarcation between the depth to long-term water table position between the upper and lower landscape positions was 21 to 27 cm below the soil surface. Average water table positions were somewhat lower than these ranges due to the seasonal depression of the groundwater due to evapotranspiration and lower rainfall in early summer (Table 4). The amount of time the water table positions were observed in the upper part of the soil (top 30 cm) in the BS and LBS landscape positions was 32% of the observation period. Therefore,

Table 3. continued.

Landscape position	Depth	Horizon	Matrix color	Redoximorphic features†	pH‡	Organic C
Backslope	0–7	Oi	5YR 3/2		3	50.37
	7–14	Oa	10YR 2/1		3.2	40.41
	14–19	Eh	10YR 5/2		3.7	12.64
	19–26	Bh	7.5YR 3/2		3.7	4.16
	26–43	Bs1	7.5YR 4/1 5YR 3/4		4.3	2.93
	43–66	Bs2	10YR 4/4 7.5YR 3/4		4.6	2.74
	66–100	C	2.5Y 5/4 2.5Y 5/2	2mp 7.5YR 4/6	4.8	0.84
			Thorne Bay			
Toeslope	0–8	Oi	2.5YR 2/1		3.2	48.92
	8–33	Oa	7.5YR 2/1		2.8	52.64
	33–63	Oe	5YR 3/3		3.1	55.0
	63–85	Oe2	5YR 3/2		3.5	54.82
	85–125	Oe3	5YR 3/1		4.1	53.51
	125–150	Oe4	7.5YR 2/1		4.3	52.45
Footslope	0–7	Oi	5YR 2/1		3.9	46.74
	7–16	Oe	7.5YR 2/1		3.8	49.72
	16–21	E	7.5YR 4/2		4.4	3.87
	21–47	Bhs	2.5Y 4/2 2.5YR 2/1	2mf 7.5YR 3/3	4.4	4.93
	47–65	Bg	7.5YR 4/2		5	3.07
	65–72	2C	2.5Y 4/2		5.1	1.34
	72–90	3Cd	2.5Y 5/1		5.4	0.37
Lower backslope	0–7	Oe	2.5YR 2/1		3.5	50.47
	7–28	Oa	2.5YR 2/2		2.9	50.48
	28–32	E	10YR 3/1		3.6	9.17
	32–42	Bhs1	7.5YR 4/6 5YR 3/4		3.9	6.25
	42–49	Bhs2	7.5YR 4/6		4.4	4.71
	49–76	Bg	2.5Y 4/1	3md 10YR 4/6	4.9	2.41
	76–88	C	2.5Y 4/4	1fp 7.5YR 3/4	5.1	1.03
	88–103	Cd	2.5YR 5/3	1fmp 7.5YR 4/6	5.2	0.45
Backslope	0–7	Oi	2.5YR 2/1		3.3	49.98
	7–22	Oe1	7.5YR 2/1		2.8	52.67
	22–46	Oe2	10YR 2/2		2.8	49.02
	46–63	E	2.5Y 3/1 10YR 3/2		4.4	1.76
	63–73	Bhs	7.5YR 2/2 10YR 3/4		4.6	4.82
	73–87	Bs	10YR 3/4		4.9	1.24
	87–130	Cd	2.5Y 4/4	3mp 7.5YR 5/6	5.1	0.69

† 1, few; 2, common; 3, many; f, fine; m, medium; c, coarse; fa, faint; d, distinct; p, prominent.

‡ Determined in 0.01 mol L^{-1} $CaCl_2$.

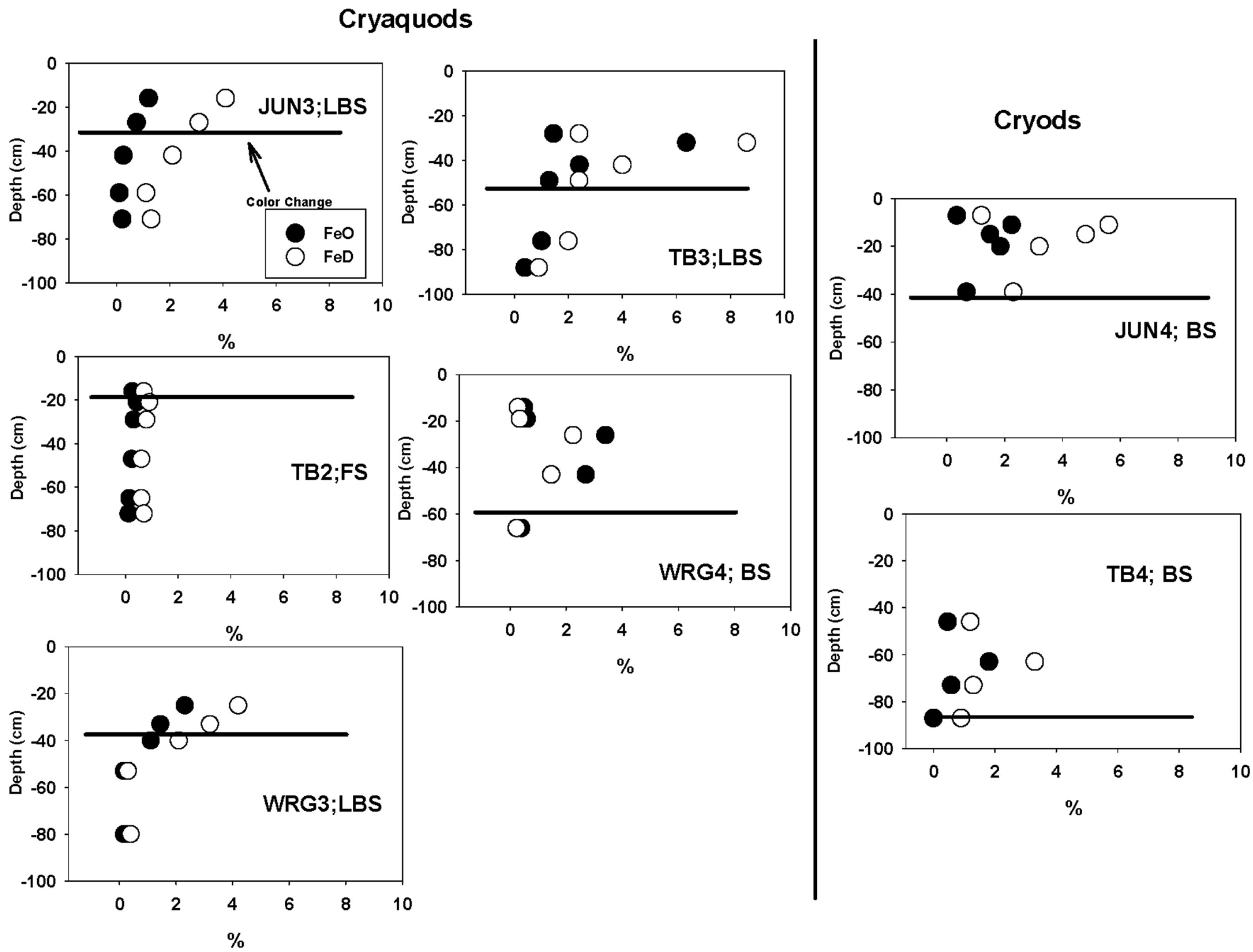

Fig. 4. Oxalate- (FeO) and dithionate-extractable (FeD) Fe in Spodosol mineral horizons, soil taxonomic distinction, and hydric status for seven pedons at the Juneau (JUN), Wrangell (WRG), and Thorne Bay (TB) catenas. The solid line indicates the location of the clear color change and depth of average soil saturation. The decreases and convergence between the concentration of the two extractable forms of Fe have a clear relationship to anaerobic zones in the soil indicated by the location of the clear color change and the long-term soil saturation indicated by the solid line. The corresponding landscape positions for each location are noted along with the site name: BS, backslope; LBS, lower backslope; FS, footslope.

water levels reaching into the upper part of the soil occurred only for approximately one-third of the time of observation at this position, which is consistent with the prediction of a limit of approximately 24 cm, on average, to the water table position in the soil profile. However, soil saturation in these landscape positions is more consistently located below the 30-cm depth in the soil profile. By contrast, soil saturation in the upper 30 cm was present during 96% of the observation period in the FS and TS landscape positions.

Patterns of soil saturation in the upper 30 cm of the soil profiles change substantially at slope inflection points between approximately 5 and 10% (Table 2). This slope break occurred at the location of the footslope to toeslope transition, where the dominant groundwater pathway changed from recharge and throughflow to discharge. This change in water table position corresponds to the functional boundary of soil development between well to moderately well drained mineral soils in recharge zones (Spodosols) and the somewhat poorly drained mineral soils in throughflow zones (Aquods) and poorly drained organic soils in discharge zones (Histosols; Table 2). This relationship is well reflected in the color change as well as the distribution of redoximorphic features. The general water table position can be visualized as the top of the redox designation in the profiles in Fig. 2. The recharge, flow-through, and discharge locations can be traced across the upper boundary of the redox zone.

The soil saturation patterns among all sites were synchronous but varied in depth throughout the time of data collection (Fig. 3). The seasonal variation in water table depths among the landscape positions was consistent during the monitoring period (test for interaction $F_{(33, 88)} = 0.61$, $P = 0.947$). The within-site variability can be seen in the patterns of water table depth in Fig. 3. The significant influence of the time of measurement ($F_{(11,88)} = 6.95$, $P < 0.001$) on water table depth was related to the seasonal precipitation (Fig. 3) and temperature patterns. The water tables lowered in June and July each year (Fig. 3) due to declining precipitation and increased evapotranspiration associated with

Table 4. Soil water table and redox characteristics for sites in Southeast Alaska. Water table depth range is the calculated prediction interval between the 5th and 95th percentile observations. Percentages are for daily averages during the period of record for water table observations and redox readings. Summaries for each landscape position are provided in bold.

Site	Water table			Redox		
	Mean	Range	Above −0.30 m	Above 400 mV	Depth to redox feature	Hydric soil indicator†
	m		% of record		m	
			Backslope			
Juneau	−0.30 (0.10)‡	−0.48 to 0.05	39	99	−0.39	NIM
Thorne Bay	−0.41 (0.07)	−0.67 to −0.24	19	97	−0.87	NIM
Wrangell	−0.32 (0.04)	−0.44 to −0.21	37	100	−0.66	NIM
	−0.34 (0.05)	**−0.47 to −0.21**	**32**	**98**		
			Lower backslope			
Juneau	−0.42 (0.05)	−0.52 to −0.26	18	92	−0.42	NIM
Thorne Bay	−0.47 (0.04)	−0.59 to −0.37	0	94	−0.49	NIM
Wrangell	−0.21 (0.07)	−0.46 to −0.02	79	88	−0.40	NIM
	−0.36 (0.05)	**−0.49 to −0.24**	**32**	**91**		
			Footslope			
Juneau	−0.18 (0.04)	−0.3 to −0.09	95	3	−0.40	A1
Thorne Bay	−0.06 (0.04)	−0.19 to 0.04	99	1	−0.21	A2
Wrangell	−0.21 (0.03)	−0.32 to −0.13	93	94	−0.40	A1
	−0.14 (0.05)	**−0.27 to −0.16**	**96**	**33**		
			Toeslope			
Juneau	−0.21 (0.04)	−0.35 to −0.11	88	0	−0.40	A1
Thorne Bay	−0.10 (0.05)	−0.22 to 0.03	100	17	−0.40	A1
Wrangell	−0.13 (0.04)	−0.22 to −0.01	100	7	−0.40	A1
	−0.14 (0.05)	**−0.27 to −0.01**	**96**	**8**		

† NIM, no indicator met; A1, Histosol; A2, histic epipedon (source: NRCS, 2010).

‡ Standard error in parentheses.

increased temperatures. Increased precipitation and low evapotranspiration rates recharge soil water at all sites, and water tables rise in the fall. These seasonal climate patterns are notable and consistent aspects of the measurement record (Fig. 3).

Redox Potential Patterns along the Catenas

The presence of hydromorphic conditions is supported by the soil saturation and redox potential data. The zones of redoximorphic features and low-chroma matrices are saturated and have redox potentials that are in the range of potential Fe reduction (Fig. 5). There was a clear distinction in the redox potential measurements between the upper and lower landscape positions consistent with the depth to water table at each site. Redox potential measurements were significantly related to the measured depth to water table ($F_{(11,322)} = 7.34$, $P = 0.007$; Fig. 5) and landscape position ($F_{(3,8)} = 4.82$, $P = 0.033$; Fig. 5). There was also a significant influence of the time at which the measurement was taken during the year ($F_{(11,97)} = 13.64$, $P < 0.001$) on the redox potential measurements (Fig. 5). There was no statistically significant interaction between redox potential and water table depth or redox potential and landscape position, as the overall patterns among the landscape positions were synchronous throughout the measurement period. There was a consistent pattern of increasing redox potential associated with the water table drawdown period in June and July (Fig. 5). This pattern appeared to be more pronounced at the backslope and lower backslope. These landscape positions have fluctuations in water table position due to the abundant throughflow of water (Fig. 3). The redox potentials were lowest during the periods of sustained soil saturation (Fig. 5) and coincide with the range of temperatures from approximately 5 to 10°C, which are conducive to microbial activity.

DISCUSSION

Visual Indicators of Biogeochemical Transformations Associated with Saturation and Reduction

The presence of low-chroma colors and Fe concentrations are used as indicators of saturated and reduced conditions; however, distinguishing color changes associated with saturation and reduction from parent material color in coarse-textured, postglacial soils continues to be a source of uncertainty (Pickering and Veneman, 1984). We have provided evidence that soil saturation is closely associated with anaerobic conditions and transformations of electro-active metal species, primarily Fe. The resulting soil morphological features were clearly associated with measured soil saturation and reduction in the catenas. These findings address the need for criteria to distinguish spodic horizons formed in poorly drained soils from better drained, strongly mottled spodic and cambic horizons that are high in Fe (Reiger, 1983). In addition, our data support the observation that low-chroma colors may form below the seasonal high water table (Humphrey and O'Driscoll, 2011). The low-chroma colors in the PCTR Spodosols are a conservative estimate of soil saturation and reduction, alleviating the possibility that low-chroma

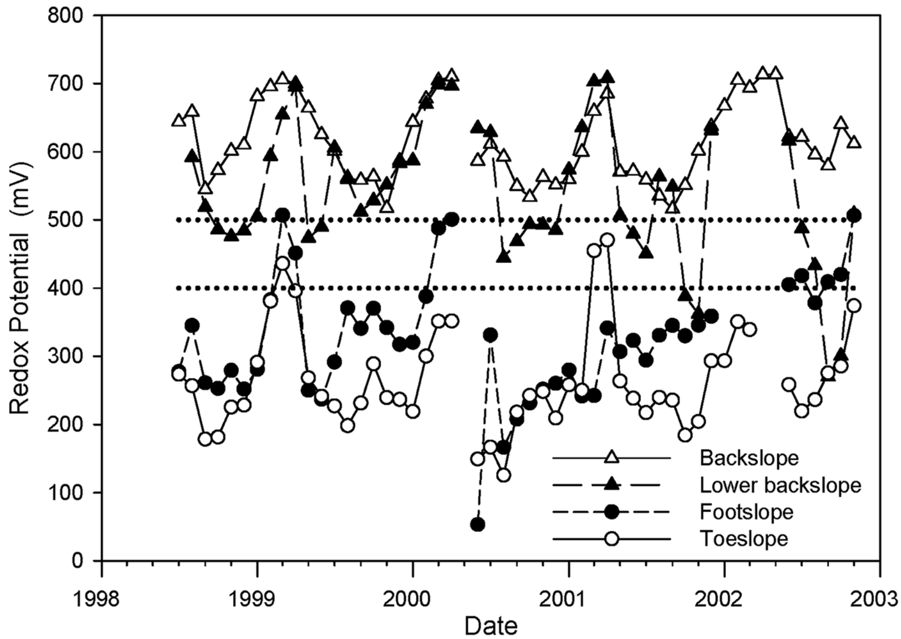

Fig. 5. Redox potential measurements in the upper part of soils averaged monthly at four landscape positions in catenas of Southeast Alaska. Monthly averages are means of three landscape positions at different locations. Dotted lines represent the Fe reduction threshold calculated for pH 4 to 5.

colors may overestimate the degree of soil saturation (Vepraskas and Wilding, 1983).

Spodic horizons were believed to be resistant to color changes due to saturation in Michigan soils (Evans and Mokma, 1996), but our results confirm that saturation and reduction can alter the color and Fe distribution in Spodosols. Profile color changes associated with transformations of Fe have been replicated in experimental podzolization studies (Harris and Hollien, 2000), and now the presence of a clear color change from red-brown to yellow hues and high to low chroma identified in the soil profiles along our catenas has identified this change under natural conditions. The close association between the depth to water table, anaerobic conditions, and changes in color patterns in the soils of our study reduces the risk of misinterpreting the influence of soil saturation, rather than parent material, on soil color patterns. We believe that our study provides the most robust evidence of color changes associated with saturation and reduction available for Spodosols in the field.

Hydric soil identification from soil morphological indicators is a key tool in wetland identification (NRCS, 2010). The use of hydric soil indicators for wetland mapping in Southeast Alaska has been limited by uncertainties associated with soil morphological features across landscape positions and soil types. Wetland plants were not always associated with wet soils in plant association establishment (DeMeo and Loggy, 1989) making wetland determinations in the PCTR difficult. Soil drainage classes were originally inferred from indications of water table depth through observations of soil morphology during the Tongass National Forest soil survey. However, these drainage-class field observations were not supported with measurements of soil saturation and reduction. Our data provide an opportunity to calibrate soil drainage classes with measurements of the depth to the water table and association of redox potentials among the landscape positions. Topography is a useful tool to limit potential wetland assessment areas in mountainous terrain and facilitate the identification of aquic conditions in soils. Landscape position provides a reliable guideline for discriminating between aquic and non-aquic soils in the PCTR. The patterns of saturation and reduction among the soils in the catenas confirm the influence of the slope transition on soil morphological features. Our analysis of soil saturation and the development of anaerobic conditions in hillslope soils constrain aquic and non-aquic soils between the lower backslope and footslope across several soil geomorphic settings. The threshold for aquic conditions is located at a slope break of approximately 10%.

The soils observed in this study can be identified as hydric or non-hydric given the duration of saturation in the upper part of the soil (<30 cm) along with the presence of anaerobic conditions (NRCS, 2010; Table 4). Redoximorphic features, including low-chroma matrices and Fe concentrations, were located at depths associated with measurements of soil saturation and redox potentials below the Fe reduction threshold. Our anaerobic threshold was established as a zone between 400 and 500 mV (Fig. 5) based on the pH (Table 3) and the assumed Fe minerals active in the redox reactions. While the anaerobic threshold is uncertain due to the mixed potentials in the soil, it does provide a guideline for determining the presence of anaerobic conditions in the soil profile.

Iron chemistry is not utilized in hydric soil field indicators but does play an important role in the verification process for redoximorphic features (Reuter and Bell, 2001). The chemical depletion of Fe is closely associated with the color changes from brownish to olive and gray colors in each horizon, providing evidence of hydromorphic soil development in specific locations in each soil profile (Fig. 4). The measured distribution of Fe_o and Fe_d provides additional evidence that color changes are related to Fe transformations in the soil profiles. It is clear from our results that the spodic process in the Haplocryods resulted in high Fe contents in the Bs horizons, while the Cryaquods were depleted in Fe at similar depths (Fig. 4).

Location and Duration of Soil Saturation as a Predictive Landscape Factor

Depth to the water table is an important first-order factor for predicting the response of plant communities and biogeochemical functions in PCTR soils. The link between plant distribution and patterns of soil saturation is widely accepted and documented by regional surveys (Neiland, 1971) and plant ordination (Hennon et al., 1990). However, the specific soil water regime has not been previously documented in aquic and non-aquic soil moisture categories in temperate forests such as the PCTR. We have established a range of depths to the water table within soil types associated with specific landscape positions. The change from upland to wetland landscape positions is related to an annual average water table position of approximately 27 cm below the soil surface. It is important to recognize that there is some uncertainty in this value as an absolute threshold for changes in plant community or soil biogeochemical properties. However, the water table position in the catenas is a key to understanding fine-scale plant community distribution and change. Many soil hydrosequences have used a single catena to test relationships between soil saturation and hydromorphic conditions. The multiple catenas observed during several years bolsters our ability to link landscape position with depth to water table across a broader area. The consistency of the relationships across different areas represented by the various sites provides a valuable foundation for building a land-type phase model for ecosystems in the PCTR.

The seasonal water table drawdown is another key distinction in soil saturation patterns of PCTR ecosystems. This seasonal "drought" condition indicates a distinct relationship between the evapotranspirative influences of vegetation, even in the humid, maritime climate of the PCTR. Near-surface, unsaturated soil horizons are important sources of nutrients to sustain aboveground tree productivity in coniferous forests (Cole, 1995). Once the surface threshold is crossed by the incursion of groundwater, nutrient cycling is curtailed along with aboveground biomass. The distinct lowering of the water table in June and July during each year illustrated in our data is evident across all landscape positions, which is a key functional attribute of the soil ecosystem in the PCTR.

CONCLUSIONS

The development of redoximorphic features in Spodosols was related to patterns of soil saturation and reduction in mountainous terrain in Southeast Alaska. The presence of clear color changes was associated with soil saturation and reduction. Our interpretations are based on distinctions in soil morphology combined with well-constrained estimates of soil saturation and redox potential by multiyear continuous measurements of water table position and association with landscape position. The multiple locations in this study allow a broader scope of inference and application across soils of similar morphology and landscape position. The patterns of hydromorphic soil properties and redox potential linked to depth to water table can be applied with confidence in temperate forested areas with Spodosols similar to the PCTR.

ACKNOWLEDGMENTS

We would like to acknowledge the NRCS, National Wet Soil Monitoring Program, the USDA Hatch project (NIFA), and the Alaska State Soil Classification project for funding assistance with this project. We would also like to acknowledge the statistical advice of Pat Cunningham and Frances Biles and thank the two reviewers and associate editor for the critical and helpful review of this manuscript. We would also like to acknowledge the contributions of the late Dr. Warren Lynn to the successful implementation of this project.

REFERENCES

Alaback, P.B. 1996. Biodiversity patterns in relation to climate: The coastal temperate rainforests of North America. Ecol. Stud. 116:105–133. doi:10.1007/978-1-4612-3970-3_7

Alexander, E.B. 1990. Influences of inorganic substrata on chemical properties of Lithic Cryofolists in Southeast Alaska. Soil Surv. Horiz. 31:92–99.

Alexander, E.B., and R. Burt. 1996. Soil development on moraines of Mendenhall Glacier, Southeast Alaska: 1. The moraines and soil morphology. Geoderma 72:1–17. doi:10.1016/0016-7061(96)00021-3

Amundson, R., and H. Jenny. 1997. On a state factor model of ecosystems. BioScience 47:536–543. doi:10.2307/1313122

Austin, W.W., and J.H. Huddleston. 1999. Viability of permanently installed platinum redox electrodes. Soil Sci. Soc. Am. J. 63:1757–1762. doi:10.2136/sssaj1999.6361757x

Bormann, B.T., H. Spaltenstein, M.H. McClellan, F.C. Ugolini, J.K. Cromack, and S.M. Nay. 1995. Rapid soil development after windthrow disturbance in pristine forests. J. Ecol. 83:747–756. doi:10.2307/2261411

Bowers, F. 1987. Effects of windthrow on soil properties and spatial variability in Southeast Alaska. Tech. Rep. R10-TP-103. US For. Serv., Alaska Region, Juneau.

Burt, R., and E.B. Alexander. 1996. Soil development on moraines of Mendenhall Glacier: 2. Chemical transformations and soil micromorphology. Geoderma 72:19–36. doi:10.1016/0016-7061(96)00022-5

Caouette, J.P., and E.J. DeGayner. 2005. Predictive mapping for tree sizes and densities in Southeast Alaska. Landsc. Urban Plan. 72:49–63. doi:10.1016/j.landurbplan.2004.09.012

Chandler, R.F. 1943. The time required for podzol formation as evidenced by the Mendenhall glacial deposits near Juneau, Alaska. Soil Sci. Soc. Am. Proc. 7:454–459. doi:10.2136/sssaj1943.036159950007000C0077x

Cole, D.W. 1995. Soil nutrient supply in natural and managed forests. Plant Soil 168–169:43–53. doi:10.1007/BF00029312

Creed, I., S. Sanford, F. Beall, L. Molot, and P. Dillon. 2003. Cryptic wetlands: Integrating hidden wetlands in regression models of the export of dissolved organic carbon from forested landscapes. Hydrol. Processes 17:3629–3648. doi:10.1002/hyp.1357

Crocker, R.L., and B.A. Dickson. 1957. Soil development on the recessional moraines of the Herbert and Mendenhall glaciers, south-eastern Alaska. J. Ecol. 45:169–185. doi:10.2307/2257083

Crocker, R.L., and J. Major. 1955. Soil development in relation to vegetation and surface age at Glacier Bay, Alaska. J. Ecol. 43:427–448. doi:10.2307/2257005

D'Amore, D.V., J.B. Fellman R.T. Edwards, E. Hood, and C.L. Ping. 2012. Hydropedology of the North American coastal temperate rainforest. In: H. Lin, editor, Hydropedology: Synergistic integration of hydrology and pedology. Academic Press, Waltham, MA. p. 351–380.

DeMeo, T.E., and W.D. Loggy. 1989. Development of wetlands mapping procedures for forest planning in Southeast Alaska. In: E.B. Alexander, editor, Proceedings of Watershed '89: A conference on the stewardship of soil, air and water resources, Juneau, Alaska. 21–23 Mar. 1989. Rep. R10-MB-77. US For. Serv., Alaska Region, Juneau. p. 57–72.

Dudley, K., and E.A. Rochette. 2005. Indicators of saturation in albic horizons of New Hampshire and Maine. Soil Surv. Horiz. 46:59–67.

Evans, C.V., and D.L. Mokma. 1996. Sandy wet Spodosols: Water tables, chemistry, and pedon partitioning. Soil Sci. Soc. Am. J. 60:1495–1501. doi:10.2136/sssaj1996.03615995006000050030x

Faulkner, S.P., W.H. Patrick, and R.P. Gambrell. 1989. Field techniques for measuring wetland soil parameters. Soil Sci. Soc. Am. J. 53:883–890. doi:10.2136/sssaj1989.03615995005300030042x

Farr, W.A., and J.S. Hard. 1987. Multivariate analysis of climate along the southern coast of Alaska: Some forestry implications. Res. Pap.PNW-RP-372.US For. Serv., Pac. Northw. Res. Stn., Juneau, Alaska.

Harris, W.G., and K.A. Hollien. 2000. Changes across artificial E–Bh boundaries formed under simulated fluctuating water tables. Soil Sci. Soc. Am. J. 64:967–973. doi:10.2136/sssaj2000.643967x

Hartshorn, A.S., R.J. Southard, and C.S. Bledsoe. 2003. Structure and function of peatland–forest ecotones in southeastern Alaska. Soil Sci. Soc. Am. J. 67:1572–1581. doi:10.2136/sssaj2003.1572

Heilman, P.E., and C.R. Gass. 1974. Parent materials and chemical properties of mineral soils in Southeast Alaska. Soil Sci. 117:21–27. doi:10.1097/00010694-197401000-00003

Helmers, A.E. 1974. The forest ecosystem of southeast Alaska. In: The forest ecosystem of Southeast Alaska: I. The setting. Gen. Tech. Rep. PNW-12. US For. Serv., Pac. Northw. For. Range Exp. Stn., Portland, OR. p. 7–10.

Hennon, P.E., E.M. Hansen, and C.G. Shaw III. 1990. Dynamics of decline and mortality of *Chamaecyparis nootkatensis* in Southeast Alaska. Can. J. Bot. 68:651–662. doi:10.1139/b90-085

Humphrey, C.P., Jr., and M.A. O'Driscoll. 2011. Evaluation of soil colors as indicators of the seasonal high water table in coastal North Carolina. Int. J. Soil Sci. 6:103–113. doi:10.3923/ijss.2011.103.113

Julin, K.R., and D.V. D'Amore. 2003. Tree growth on forested wetlands of southeastern Alaska following clear cutting. West. J. Appl. For. 18:30–34.

Kahklen, K., and J. Moll. 1999. Measuring effects of roads on groundwater: Five case studies. SDTDC 9977-1801. US For. Serv. Technol. Dev. Progr., San Dimas, CA.

Klinger, L.F. 1996. Coupling of soils and vegetation in peatland succession. Arct. Alp. Res. 28:380–387. doi:10.2307/1552117

Krosse, P.C. 1993. Preliminary soil resource inventory report, Stikine area, Tongass National Forest. US For. Serv., Juneau, AK.

Lin, H., J. Bouma, Y. Pachepsky, A. Western, J. Thompson, R. van Genuchten, et al. 2006. Hydropedology: Synergistic integration of pedology and hydrology. Water Resour. Res. 42:W05301. doi:10.1029/2005WR004085

Lynn, W.C., S.W. Sprecher, and J.S. Wakeley. 1996. Background of the wet soils monitoring project. In: J.S. Wakeley et al., editors, Preliminary investigations of hydric soil hydrology and morphology in the United States. Wetlands Res. Prog. Tech. Rep. WRP-DE-13. U.S. Army Corps of Engineers, Waterways Exp. Stn., Vicksburg, MS.

Mann, D.H., and T.D. Hamilton. 1995. Late Pleistocene and Holocene paleoenvironments of the North Pacific Coast. Quat. Sci. Rev. 14:449–471. doi:10.1016/0277-3791(95)00016-I

Mantua, N.J., and S.R. Hare. 2002. The Pacific decadal oscillation. J. Oceanogr. 58:35–44. doi:10.1023/A:1015820616384

McBratney, A.B., I.O.A. Odeh, T.F.A. Bishop, M.S. Dunbar, and T.M. Shatar. 2000. An overview of pedometric techniques for use in soil survey. Geoderma 66:15–42.

McKeague, J.A. 1965. Properties and genesis of three members of the uplands catena. Can. J. Soil Sci. 45:63–77. doi:10.4141/cjss65-009

Mokma, D.L. 1983. New chemical criteria for defining the spodic horizon. Soil Sci. Soc. Am. J. 47:972–976. doi:10.2136/sssaj1983.03615995004700050026x

Mokma, D.L., and S.W. Sprecher. 1994a. Water table depths and color patterns in Spodosols of two hydrosequences in northern Michigan, USA. Catena 22:275–286. doi:10.1016/0341-8162(94)90038-8

Mokma, D.L., and S.W. Sprecher. 1994b. Water table depths and color patterns in soils developed from red parent materials in Michigan, USA. Catena 22:287–298. doi:10.1016/0341-8162(94)90039-6

Moore, I.D., P.E. Gessler, G.A. Nielsen, and G.A. Peterson. 1993. Soil attribute prediction using terrain analysis. Soil Sci. Soc. Am. J. 57:443–452. doi:10.2136/sssaj1993.03615995005700020026x

Neiland, B.J. 1971. The forest–bog complex in Southeast Alaska. Vegetatio 22:1–63. doi:10.1007/BF01955719

Nowacki, G., P. Krosse, G. Fisher, D. Brew, T. Brock, M. Shephard, et al. 2001. Ecological subsections of Southeast Alaska and neighboring areas of Canada. Tech. Publ. R10-TP-75. US For. Serv., Alaska Region, Anchorage.

NRCS. 2010. Field indicators of hydric soils in the United States: A guide for identifying and delineating hydric soils. Version7.0. NRCS, Washington, DC.

Owens, P.R., L.P. Wilding, L.M. Lee, and B.E. Herbert. 2005. Evaluation of platinum electrodes and three electrode potential standards to determine electrode quality. Soil Sci. Soc. Am. J. 69:1541–1550. doi:10.2136/sssaj2003.0205

Patric, J.H., and P.E. Black. 1968. Potential evapotranspiration and climate in Alaska by Thornthwaite's classification. Res. Pap. PNW-71. US For. Serv., Pac. Northw. For. Range Exp. Stn., Juneau, AK.

Patrick, W.H., R.P. Gambrell, and S.P. Faulkner. 1996. Redox measurements of soils. In: D.L. Sparks, editor, Methods of soil analysis. Part 3. Chemical methods. SSSA Book Ser. 5. SSSA and ASA, Madison, WI. p. 1255–1273. doi:10.2136/sssabookser5.3.c42

Pickering, E.W., and P.L.M. Veneman. 1984. Moisture regimes and morphological characteristics in a hydrosequence in central Massachusetts. Soil Sci. Soc. Am. J. 48:113–118. doi:10.2136/sssaj1984.03615995004800010021x

Rabenhorst, M.C., W.D. Hively, and B.R. James. 2009. Measurements of soil redox potential. Soil Sci. Soc. Am. J. 73:668–674. doi:10.2136/sssaj2007.0443

Reiger, S. 1983. Genesis and classification of cold soils. Academic Press, New York.

Reuter, R.J., and J.C. Bell. 2001. Soils and hydrology of a wet-sandy catena in east-central Minnesota. Soil Sci. Soc. Am. J. 65:1559–1569. doi:10.2136/sssaj2001.6551559x

Schoeneberger, P.J., D.A. Wysocki, E.C. Benham, and W.D. Broderson. 2002. Field book for describing and sampling soils, Version 2.0. Natl. Soil Surv. Ctr., Lincoln, NE

Schwertmann, U., and R.M. Taylor. 1989. Iron oxides. In: J.B. Dixon, and S.B. Weed, editors, Minerals in soil environments. 2nd ed. SSSA Book Ser. 1. SSSA, Madison, WI.

Soil Survey Division Staff. 1993. Soil survey manual. Agric. Handbk. 18. U.S. Gov. Print. Office, Washington, DC.

Soil Survey Laboratory Staff. 1996. Soil survey laboratory methods manual. Soil Surv. Invest. Rep. 42. Version 3.0. Natl. Soil Surv. Ctr., Lincoln, NE.

Soil Survey Staff. 1999. Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys. Agric. Handbk. 436. U.S. Gov. Printing Office, Washington, DC.

Sprecher, S.W. 2008. Installing monitoring wells in soils. Version 1.0. Natl. Soil Surv. Ctr., Lincoln, NE.

Thompson, J.A., and J.C. Bell. 1998. Hydric conditions and hydromorphic properties within a Mollisol catena in southeastern Minnesota. Soil Sci. Soc. Am. J. 62:1116–1125. doi:10.2136/sssaj1998.03615995006200040037x

Ugolini, F.C., and D.H. Mann. 1979. Biopedological origin of peatlands in Southeast Alaska. Nature 281:366–368.

US Forest Service. 1996. Landforms of the Alaska Region classification guide. US For. Serv., Alaska Region, Juneau.

van Bochove, E., S.B. Beauchemin, and G. Theriault. 2002. Continuous multiple measurement of soil redox potential using platinum electrodes. Soil Sci. Soc. Am. J. 66:1813–1820. doi:10.2136/sssaj2002.1813

Veneman, P.L.M., and S.M. Bodine. 1982. Chemical and morphological soil characteristics in a New England drainage-toposequence. Soil Sci. Soc. Am. J. 46:359–363. doi:10.2136/sssaj1982.03615995004600020029x

Vepraskas, M.J., and S.P. Faulkner. 2001. Redox chemistry of hydric soils. In: J.L. Richardson, and M.J. Vepraskas, editors, Wetland soils: Genesis, hydrology, landscapes, and classification. Lewis Publ., Boca Raton, FL. p. 85–105.

Vepraskas, M.J., and S.W. Sprecher. 1997. Overview of aquic conditions and hydric soils. In: M.J. Vepraskas and S.W. Sprecher, editors, Aquic conditions and hydric soils: The problem soils. SSSA Spec. Publ. 50. SSSA, Madison, WI. p. 1–22. doi:10.2136/sssaspecpub50.c1

Vepraskas, M.J., and L.P. Wilding. 1983. Aquic moisture regimes in soils with and without low chroma colors. Soil Sci. Soc. Am. J. 47:280–285. doi:10.2136/sssaj1983.03615995004700020022x

Wahrhaftig, C. 1965. Physiographic divisions of Alaska. USGS Prof. Pap. 482. US Gov. Print. Office, Washington, DC.

Zobeck, T.M., and A.J. Ritchie. 1984. Analysis of long-term water table depth records from a hydrosequence of soils in central Ohio. Soil Sci. Soc. Am. J. 48:119–125. doi:10.2136/sssaj1984.03615995004800010022x