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Quantifying Climate and Landscape Position Controls on Soil Development in Semiarid Ecosystems

Rebecca A. Lybrand*
Craig Rasmussen
Dep. of Soil, Water and Environmental Science
Univ. of Arizona
429 Shantz Building, #38
PO Box 210028
1177 E. Fourth
Tucson, AZ 85721-0038

Soils require study across semiarid ecosystems to better understand soil organic C storage and landscape evolution in water-limited environments. The objective of this research was to quantify soil morphologic development in contrasting climate–vegetation zones and landscape positions along a semiarid environmental gradient. Five ecosystems were examined across the Santa Catalina Mountains, Arizona, that exhibit variation in precipitation (45–95 cm yr^{-1}), temperature (18–9°C), and vegetation (desert scrub to mixed conifer). Granitic soil, saprock, and parent rock were sampled from divergent summit and convergent footslope positions within each ecosystem. Laser particle size analysis was combined with elemental analysis to determine particle size distribution and total C for all soils. Harden's profile development index was applied to explore changes in soil development with climate and landscape position. Soil organic C increased significantly from 0.37 to 1.1 kg m^{-3} in the transition from desert scrub to mixed conifer convergent soils. Silt concentrations also increased significantly between the two convergent field sites, with values increasing from 4.6 to 23 kg m^{-3}. Profile development indices more than doubled from the desert scrub to mixed conifer sites. At the hillslope scale, indices were similar between desert scrub divergent and convergent landscape positions. However, profile development indices in mixed conifer convergent positions were twofold higher than those of divergent sites, suggesting a stronger topographic control on soil development in these forests. The results demonstrate links between water availability and soil organic C accumulation, both regionally across climate–vegetation zones and locally at the hillslope scale of study.

Abbreviations: MAP, mean annual precipitation; PDI, profile development index; PET, potential evapotranspiration; SCM, Santa Catalina Mountains; SOC, soil organic carbon.

In the hot, dry ecosystems of the southwestern United States, water availability and topography are central to understanding soil and landscape evolution. Water availability is the dominant driver of soil formation in water-limited climates where precipitation regulates soil production and erosion, vegetation distribution and primary production, soil organic C (SOC) storage, and the degree of primary mineral alteration to secondary products. Topography and landscape position are particularly important in water-limited systems through their control on the redistribution of limited water resources that can lead to significant variation in hillslope-scale soil development and physiochemical properties (Muhs, 1982). It is necessary to understand the coupling of soil, climate, and landscape position in the Desert Southwest where predicted changes in temperature extremes and precipitation variability may drive significant shifts in water availability and biological production (Seager et al., 2007; Intergovernmental Panel on Climate Change,

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*Corresponding author (rlybrand@email.arizona.edu).
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2013). In this study, we assessed soil development across an array of semiarid ecosystems and examined climate–landscape position controls on soil properties.

Elevation gradients compress large precipitation and temperature fluctuations across short distances and can encompass a wide range of ecosystems (Dahlgren et al., 1997), making these systems ideal for examining the effects of climate on soils, C, and vegetation (Koch et al., 1995). In general, elevation gradients in the western United States that extend across >1500 m of elevation gain exhibit a substantial increase in water availability with elevation. The increase in water availability results from greater precipitation, decreased temperature, and decreased evapotranspirative demands at higher elevations. In many cases, such gradients span the transition from water-limited to energy-limited ecosystems. Water and energy limitations have been defined by the ratio of mean annual precipitation (MAP) to potential evapotranspiration (PET), or a MAP/PET ratio <1 in water-limited sites and MAP/PET >1 in energy-limited sites (Budyko, 1974). This transition can manifest as significant variations in primary production and soil development, with strong climate-related gradients in SOC stocks (Landi et al., 2003; Dai and Huang, 2006; Homann et al., 2007; Meier and Leuschner, 2010) and degree of soil development (Whittaker et al., 1968; Dahlgren et al., 1997; Bockheim et al., 2000; Egli et al., 2003; Rasmussen et al., 2007, 2010; Graham and O'Geen, 2010).

Previous work across arid and semiarid climate gradients has identified several distinct trends among climate, landscape position, vegetation, and soil development. The importance of moisture availability and primary productivity for SOC storage was demonstrated along an arid to humid West African precipitation gradient where SOC stocks increased from 20 to >120 Mg C ha^{-1} when precipitation increased from 400 to >1200 mm yr^{-1} (Saiz et al., 2012). The researchers identified sand content and available water content as the strongest combined predictors of SOC, explaining 85% of the SOC variability across sites. Soil CO_2 levels increased along an arid to subhumid eastern Mojave Desert climate gradient in relation to increased moisture availability and primary productivity with greater elevation (Amundson et al., 1989a). Elevated soil CO_2 concentrations can increase carbonic acid weathering and transformation of primary minerals, with a strong seasonal variation in soil CO_2 related to limited moisture availability in summer months (Amundson et al., 1989b).

Landscape position regulates the local redistribution of water, clays, ions, and minerals (Jenny, 1941; Tardy et al., 1973; Schimel et al., 1985; Pennock and Jong, 1990; Weitkamp et al., 1996; Applegarth and Dahms, 2001). Divergent, erosional landscape positions shed soil, C, and water constituents to adjacent water-receiving or convergent portions of the landscape (Nicolau et al., 1996; Birkeland, 1999; Ritchie et al., 2007). Soils that accumulate in depositional convergent positions contain distinct patterns of soil mineral assemblage (Berry, 1987; Hattar et al., 2010; Khomo et al., 2011; Owliaie, 2014), vegetation composition and biomass (Gessler et al., 1995), and C sequestration (Rosenbloom et al., 2006; Hancock et al., 2010). Knowledge of this local-scale variation, in addition to climate-controlled water availability, is critical for estimating ecosystem-level C storage (Webster et al., 2011) and for assessing the coupling among soil, landscape position, and vegetation (Yoo et al., 2006; Ziadat et al., 2010). In this study, we used soil morphologic, physical, and chemical data and profile development indices to quantify soil variation with landscape position across a gradient of water availability.

The profile development index (PDI; Harden, 1982) is an empirical tool developed to quantify soil development based on soil morphologic properties. The Harden PDI was adapted from Bilzi and Ciolkosz (1977) and assigns point scores to soil horizons based on properties that differ from those of the parent material. The PDI has been demonstrated to effectively capture soil development variations with climate, relief, and time (Swanson and Paul, 1985; Birkeland and Burke, 1988; Birkeland and Gerson, 1991; Miller and Birkeland, 1992; Birkeland, 1994; Vidic and Lobnik, 1997; Applegarth and Dahms, 2001; Munroe and Bockheim, 2001; Badía et al., 2009; Sauer, 2010; Calero et al., 2013). Significant correlations between PDI and time are well established in the literature across a range of climatically distinct study sites. For example, PDI increased systematically with age across semiarid Mediterranean sites in Spain where carbonate accumulation was the dominant mechanism driving increases in the PDI (Badía et al., 2009). Similarly, PDI values increased significantly with age along a 1.6 million yr old xeric–thermic chronosequence in the Sacramento Valley, California, where clay accumulation and reddening were the dominant changes driving PDI increases (Busacca, 1987). Climate was identified as the primary factor driving PDI variation among terrace deposits in the temperate–humid climate of the Ljubljana basin, Slovenia (Vidic and Lobnik, 1997), and topography was a controlling factor in PDI variation in comparing soils from bar and swale sites (Harrison et al., 1990).

A number of studies have specifically focused on comparing PDI values among different topographic positions. Generally, PDI values indicate that soil development is greater in convergent footslope positions than adjacent divergent summit positions. For example, PDIs were greatest in the footslope positions of two granitic catenas formed on moraines in southern Idaho that varied in age from ~20,000 to 140,000 yr (Swanson and Paul, 1985; Berry, 1987; Applegarth and Dahms, 2001). Interestingly, PDIs for the corresponding summit positions were comparable and did not increase with time, suggesting that in this system, topographic controls on soil development are more important than landscape age. Research across catenas spanning a precipitation gradient in Peru indicated that PDI values for soils in drier, footslope positions were two times lower than for footslopes in wetter climates compared with the respective summit positions, where only minor differences in PDIs were documented (Miller and Birkeland, 1992).

The objective of this study was to examine how both water availability and landscape position control soil development across a semiarid environmental gradient. Profile development indices were combined with soil taxonomic classification, soil texture, and SOC to characterize profile development.

METHODS

Experimental Design

The experimental design for this study included sampling soils from two landscape positions, a convergent footslope and a divergent summit, in each of five separate ecosystems that span the range of climate and vegetation variation encompassed by the Santa Catalina Mountains (SCM) environmental gradient in southeastern Arizona (Fig. 1). Mean annual temperature decreases from 18 to 9°C and MAP increases from 450 mm yr^{-1} at low elevations of 1092 m asl to 950 mm yr^{-1} at high elevations of 2408 m asl (Table 1; PRISM Climate Group, 2008). Moisture availability was defined as the MAP/PET ratio, and the sites were grouped as water limited (MAP/PET < 1) or energy limited (MAP/PET > 1). The MAP/PET ratios increased from 0.53 at the desert scrub sites to 1.47 in the mixed conifer sites, with PET based on the Thornthwaite–Mather approximation (Thornthwaite and Mather, 1957).

Vegetative communities change concurrent with climate variation across the gradient, ranging from desert scrub to mixed conifer, and are well characterized in terms of aspect, climate, and net primary productivity (Whittaker and Niering, 1965; Whittaker et al., 1968). Aboveground biomass and net aboveground primary productivity range from 0.26 to 79 kg m^{-2} and 0.092 to 1.05 kg m^{-2} yr^{-1}, respectively (Whittaker and Niering, 1975). The sampled climate–vegetation zones include desert scrub (1092 m asl, Fig. 2a), desert grassland–oak woodland (1436 m asl, Fig. 2b), low ponderosa pine (2111 m asl, Fig. 2c), mid ponderosa pine (2230 m asl, Fig. 2d), and mixed conifer (2408 m asl, Fig. 2e). The desert scrub site contained saguaro [*Carnegiea gigantea* (Engelm.) Britton & Rose], ocotillo (*Fouquieria splendens* Engelm.), *Acacia* spp., Arizona barrel cactus [*Ferocactus wislizeni* (Engelm.) Britton & Rose], agave (*Agave schottii* Engelm., *A. palmeri* Engelm.), and buckhorn cholla (*Opuntia acanthocarpa* Engelm. & J.M. Bigelow). The desert grassland–oak woodland site was a mixed community of oak (*Quercus* spp., including *Q. arizonica* Sarg.), with an open understory characterized by manzanita (*Arctostaphylos* spp.) and beargrass (*Nolina microcarpa* S. Watson). The low ponderosa pine ecosystem was located at the ecotone between the mixed oak–pine woodland ecosystem and the higher elevation mixed conifer ecosystem, which captured the transition from

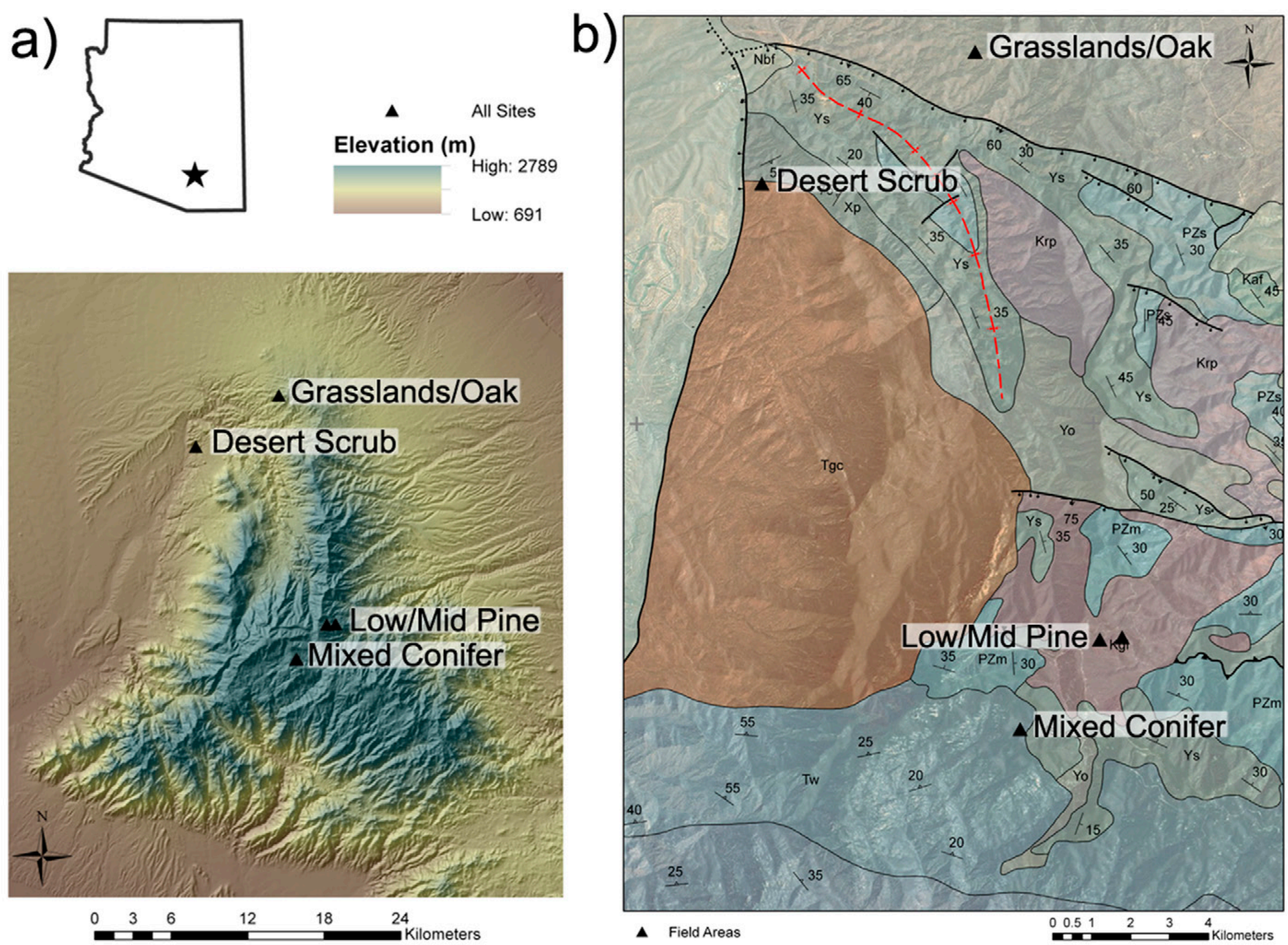

Fig. 1. (a) Locations of the field sites encompassed by the Santa Catalina Mountain environmental gradient in southern Arizona and (b) a geological map denoting differences in granitic terrain across the SCM.

Table 1. General properties for the Santa Catalina Mountain field sites including landscape position, elevation, mean annual precipitation (MAP), mean annual temperature (MAT), mean annual precipitation/potential evapotranspiration ratio (MAP/PET), and soil taxonomic classification.

Site	Landscape position	Elevation	MAP	MAT	MAP/PET	Taxonomic classification†
		m	cm yr^{-1}	°C		
Desert scrub	divergent	1092	45	18	0.53	sandy-skeletal, mixed, superactive, thermic, shallow Typic Torriorthent
	convergent					sandy-skeletal, mixed, superactive, thermic, shallow Typic Torriorthent
Grasslands	divergent	1436	56	17	0.69	loamy-skeletal, mixed, superactive, thermic, shallow Aridic Haplustoll
	convergent					loamy-skeletal, mixed, superactive, thermic, shallow Aridic Haplustoll
Low pine	divergent	2111	87	12	1.14	loamy, mixed, superactive, mesic, shallow Typic Ustorthent
	convergent					loamy, mixed, superactive, mesic, shallow Typic Ustorthent
Mid pine	divergent	2230	91	10	1.26	loamy-skeletal, mixed, superactive, mesic Lithic Ustorthent/Lithic Haplustoll
	convergent					loamy-skeletal, mixed, superactive, mesic Typic Ustorthent/Typic Haplustoll
Mixed conifer	divergent	2408	95	9	1.47	loamy-skeletal, mixed, superactive, mesic Typic Ustorthent
	convergent					loamy-skeletal, mixed, superactive, mesic Typic Haplustoll

† Classified according to Soil Survey Staff (2010).

water-limited to energy-limited ecosystems. The mid ponderosa pine site was dominated by ponderosa pine (*Pinus ponderosa* P. Lawson & C. Lawson), with sparse Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco], and the mixed conifer site was characterized by Douglas-fir, ponderosa pine, and white fir [*Abies concolor* (Gordon & Glend.) Lindl. ex Hildebr.].

Soil moisture regimes varied from aridic in the desert scrub sites, to aridic bordering on ustic in the grasslands–oak woodlands sites, to ustic in the pine and mixed conifer sites. The soil temperature regimes were classified as thermic in the desert scrub and grasslands–oak woodland sites and transitioned to mesic starting in the low ponderosa pine sites.

Landscape positions were selected to represent catena end members of the local topography that included soils from two water-shedding summits, referred to as *divergent positions*, and two adjacent water-gathering footslope sites, referred to as *convergent positions* (Birkeland, 1999). The soils were collected from north-facing transects that ran perpendicular to the slope to minimize colluvial layer differences among sites (Fig. 3). Four pedons, two convergent and two divergent, were sampled in each of the field areas with the exception of the grasslands–oak woodlands site, where only one suitable convergent soil pedon was studied.

The SCM geology spans Precambrian to Tertiary aged intrusive parent rock as characterized based on a 1:125,000 spatial database (Dickinson, 1991, 2002). All sampled soils formed on granitic materials that have a relatively narrow range in mineral composition and grain size. Desert scrub soils were sampled on the Catalina granitic pluton (Oligocene–Miocene), the grasslands–oak woodlands on the Oracle Ruin granite suite (Middle Proterozoic), the low and mid ponderosa pine sites on Leatherwood quartz diorite (Upper Cretaceous–Paleocene), and the mixed conifer on the Wilderness granite suite (two-mica granite; Eocene) (Fig. 1b).

Soil and Saprock Collection and Characterization

Soil and saprock materials were sampled by genetic horizon and morphology described following standard methods (Schoeneberger et al., 2002), with data collected for structure, consistence, horizonation, rock fragment percentage, roots, and

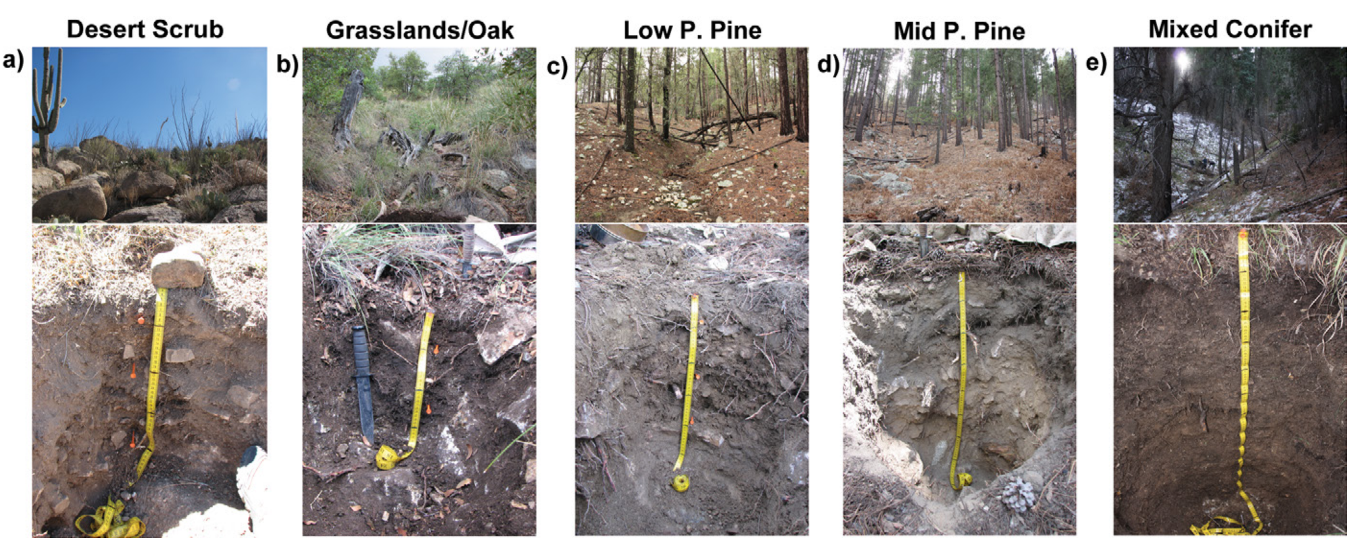

Fig. 2. Landscape and convergent pedon photographs for the (a) desert scrub, (b) desert grasslands–oak woodlands, (c) low ponderosa pine, (d) mid ponderosa pine, and (e) mixed conifer sites in the Santa Catalina Mountains, Arizona.

Munsell color. Saprock, defined as material that is similar to parent rock structure, breakable with bare hands, and composed of primary minerals not extensively transformed by chemical alteration (Graham et al., 2010), was collected at the depth of refusal for parent material characterization. Base saturation percentage was estimated based on its correlation with pH (Whittaker et al., 1968) to distinguish between umbric and mollic epipedons in the conifer ecosystems for soil taxonomic purposes. All pedons were classified using Soil Survey Staff (2010).

Collected soils and saprock were air dried, sieved to isolate the fine-earth fraction (<2 mm), and prepared for physical, mineralogical, and organic C laboratory analyses (Soil Survey Staff, 2004). Samples were pretreated to remove organic matter using NaOCl adjusted to pH 9.5 with H_2SO_4 (Soil Survey Staff, 2009) before laser particle size analysis and secondary mineral characterization (Soil Survey Staff, 2009). Particle size distribution was determined on pretreated, sieved samples using a LS 13 320 laser diffraction particle size analyzer (Beckman Coulter) following dispersion with 5% sodium hexametaphosphate and mixing for 48 h on a rotary shaker.

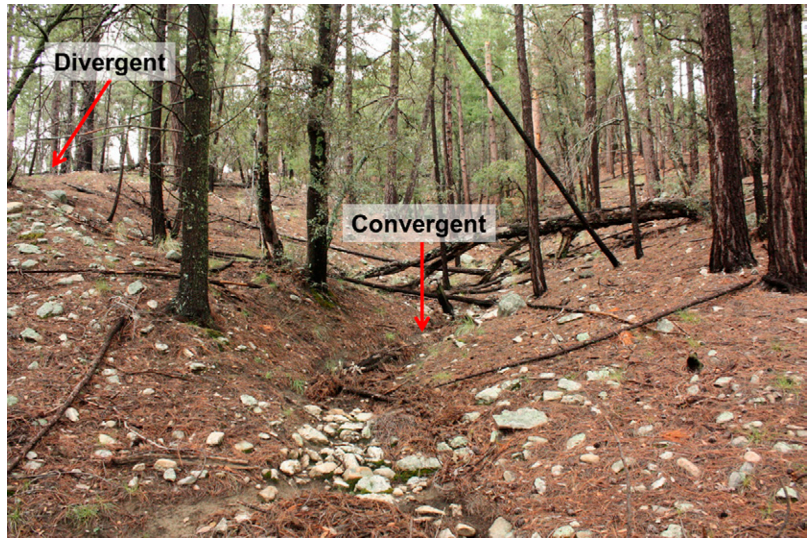

Fig. 3. Examples of divergent and convergent landscape positions at the low ponderosa pine site in the Santa Catalina Mountains, Arizona.

Total C and N measurements were made on all samples at the University of Arizona's Environmental Isotope Laboratory. Each sample was prepared by ball-milling ~3.5 g of material in a stainless steel canister with three tungsten carbide ball bearings for 10 min. The ground samples were analyzed on a Finnigan Delta Plus XL (Thermo Fisher Scientific) coupled to an elemental analyzer (Costech Analytical Technologies). Samples did not exhibit any evidence of carbonates, so total C and N were assumed to equal organic C and N. Organic C and N weight percentages are reported on an oven-dry basis.

Soil bulk density, ρ_s, was estimated following Rawls (1983):

$$\rho_s = \frac{100}{\mathrm{OM}/0.224 + (100 - \mathrm{OM})/\rho_{\mathrm{Rawls}}} \qquad [1]$$

where OM is the organic matter content (% w/w), 0.224 is the average organic matter bulk density reported by Rawls (1983), and ρ_{Rawls} is the mineral density estimated using sand and clay concentrations (%).

Soil C stocks (kg m^{-2}) in the ith horizon (C_i) were calculated as

$$C_i = \left[\frac{\rho_s z_i (1 - V_r) C}{100}\right] 10 \qquad [2]$$

where ρ_s is the soil bulk density, z_i is the thickness of the ith horizon, V_r is volumetric rock fragments, and C is C concentration (%, w/w) as determined by the laboratory analyses described above. The C_i values were determined for each horizon and then summed to report C per pedon. Bulk density was estimated following Eq. [1]. The value of V_r was based on the >2-mm fraction sieved from field samples and converted from a weight percentage to a volume percentage following Torri et al. (1994).

The volumetric concentration of soil C (kg m^{-3}) was calculated as

$$C_i\left(\mathrm{kg\ m}^{-3}\right) = \frac{C_i\left(\mathrm{kg\ m}^{-2}\right)}{z_i} \qquad [3]$$

where C_i (kg m^{-2}) is the total horizon C determined in Eq. [2] and z_i is the total horizon thickness. The C_i (kg m^{-3}) values are reported on a horizon and pedon basis.

The soil texture components (sand, silt, and clay) and SOC are reported on an oven-dry weight basis, on a mass per area basis (Eq. [2]), and on a concentration basis (Eq. [3]) to explore patterns across field sites, with pedon depth, and for statistical testing. The data sets are presented in three forms to effectively compare the findings of the current work with other studies where results are often given in contrasting units of measurement.

Profile Development Index Calculation

Profile development index values were calculated for all soil profiles. The index was based on assigning points for increases in soil property development compared with the parent material at a given site (Harden, 1982; Harden and Taylor, 1983). For example, structure is quantified by allocating points for changes in structural grade and aggregate type when compared with the parent material (Harden, 1982). Site-specific saprock was used as the parent material for each field area to account for differences in parent rock composition. Once points were assigned for each of the seven field properties, the resulting values were input into the corresponding PDI equations, quantified for each genetic horizon, and normalized according to steps outlined by Harden and Taylor (1983). Dry and moist Munsell color data were used to calculate rubification, color paling, melanization, and color lightening. Soil structure, dry consistence, and texture were also integrated into the index.

Profile development indices were also calculated from soil field descriptions for an additional 24 summit and backslope pedons in the Santa Catalina and Rincon mountain ranges to expand the sample set for comparison with other soil development studies across the southwestern United States. Twelve of the soil field descriptions originated from an environmental gradient study in the Rincon Mountains, which are adjacent to the SCM, with sites spanning desert scrub, oak woodland, and pine (Rasmussen, 2008) and another four from a granitic soils study in the SCM pine forest (Heckman and Rasmussen, 2011). Nine additional SCM sites ranging from desert scrub to mixed conifer described as part of graduate and undergraduate class field trips were also included (Rasmussen, unpublished data, 2008–2013). The PDIs calculated for each representative field area were averaged and are presented as a site average.

Statistical Analyses

One-way ANOVAs and post-hoc Student's *t*-tests were used to evaluate differences among soil properties, with ecosystem, landscape position, and moisture availability as the main effects. We could not directly test for ecosystem × landscape position interactions due to the limited number of pedons sampled at each field site. The tests were performed using JMP software (Version 11.0, SAS Institute) on natural-log-transformed soil properties including percentages [g (100 g)$^{-1}$], mass per area (kg m^{-2}), and concentrations (kg m^{-3}), and on natural-log-transformed PDI values. The results of the statistical tests are available as a supplement (Supplementary Table A1).

RESULTS AND DISCUSSION

General Soil Properties

Soil Taxonomic Classification

The soil taxonomic classification varied with ecosystem type and landscape position. The observed soil profiles were generally <50 cm to the saprock contact, contained >35% (v/v) rock fragments, and exhibited no subsurface diagnostic horizon development (Table 1). Soils were predominantly classified as Entisols or Mollisols, with classifications of Typic Torriorthents in the desert scrub convergent and divergent sites, Aridic Haplustolls in the grasslands–oak woodlands convergent and divergent sites, and Typic Ustorthents in the low ponderosa pine convergent and divergent sites (Table 1). Little taxonomic variation was observed across the drier, low-elevation sites. The exception was the desert grasslands–oak woodlands soils, which were classified as Mollisols, a result of increased belowground C accumulation in the grass-dominated ecosystem. The taxonomic classification for the mid ponderosa pine and mixed conifer soils differed by landscape position, where the divergent sites were classified as Entisols and the convergent sites as Mollisols. For example, the mixed conifer divergent soils were both Typic Ustorthents while the convergent soils were Typic Haplustolls. The conifer locations classified as Entisols typically exhibited ochric epipedons and were too shallow and/or too high in soil color value to be classified as mollic epipedons. In contrast, the darker, deeper, C-rich soils in the convergent landscapes classified as Mollisols, indicating an accumulation of both C and exchangeable cations in the convergent positions. Distinct taxonomic differences by landscape position occurred in the systems where the MAP/PET ratio was >1, suggesting greater topographic effects on taxonomy in wetter climates.

Soil Carbon Profiles

Soil organic C percentages by weight increased across the gradient, with a marked transition from the water-limited to energy-limited systems (Table 2). The mixed conifer soils contained significantly more SOC on a weight percentage basis than the desert scrub ($p < 0.0005$), low ponderosa pine ($p < 0.005$), and mid ponderosa pine soils ($p < 0.02$) (Table 2 and Supplementary Table A1). These data demonstrate an increased accumulation of SOC in the mineral matrix across ecosystems with greater moisture availability and higher rates of primary production, a trend widely recognized in other mountainous environments

Table 2. Depth-weighted pedon averages for C, sand, silt, and clay contents for all field sites in the Santa Catalina Mountains, Arizona, including within-profile and between-profile clay contrast indices (CCIs).

Site	Landscape position	Pedon C	Pedon sand	Pedon silt	Pedon clay	Pedon C	Pedon sand	Pedon silt	Pedon clay	CCI Within profile	CCI Between profiles
		% (w/w)				kg m^{-2}					
Desert scrub	divergent	0.47 ± 0.16†	82 ± 4.3	12 ± 3.0	6.7 ± 1.3	1.2 ± 0.10	218 ± 96	30 ± 4.7	17 ± 3.2	0.12 ± 0.27	0.26 ± 0.02
	convergent	0.79 ± 0.44	79 ± 5.4	12 ± 3.2	9.1 ± 2.1	3.7 ± 2.3	352 ± 7.9	54 ± 19	40 ± 13	0.59 ± 0.13	
Grasslands	divergent	1.1 ± 0.19	58 ± 2.5	26 ± 2.6	16 ± 0.12	3.4 ± 1.9	143 ± 45	66 ± 15	37 ± 10	0.42 ± 0.07	0.08 ± 0.02
	convergent	2.2 ± 0.0	57 ± 0.0	26 ± 0.0	17 ± 0.0	6.2 ± 0.0	160 ± 0.0	72 ± 0.0	43.5 ± 0.0	0.33 ± 0.0	
Low pine	divergent	0.62 ± 0.15	69 ± 3.9	23 ± 0.11	7.3 ± 4.0	2.8 ± 0.09	326 ± 111	109 ± 32	32 ± 8.7	0.23 ± 0.18	0.0 ± 0.00
	convergent	1.0 ± 0.52	79 ± 1.2	17 ± 1.0	3.9 ± 0.14	6.6 ± 4.4	500 ± 76	126 ± 0.25	27 ± 1.1	0.47 ± 0.04	
Mid pine	divergent	1.1 ± 0.27	62 ± 8.1	28 ± 4.6	9.4 ± 3.5	4.8 ± 2.1	256 ± 82	113 ± 3.8	36 ± 6.2	0.21 ± 0.12	0.0 ± 0.00
	convergent	0.97 ± 0.27	68 ± 6.0	25 ± 5.9	6.4 ± 0.15	6.8 ± 1.4	443 ± 94	152 ± 5.2	39 ± 7.0	0.33 ± 0.12	
Mixed conifer	divergent	2.4 ± 0.25	62 ± 3.2	29 ± 2.8	8.5 ± 0.53	8.7 ± 0.02	218 ± 12	105 ± 20	30 ± 4.5	0.06 ± 0.09	0.35 ± 0.01
	convergent	1.8 ± 0.50	48 ± 7.4	39 ± 6.7	13 ± 0.63	17 ± 0.07	487 ± 169	381 ± 15	129 ± 19	0.15 ± 0.23	

† Average ± 1 SD.

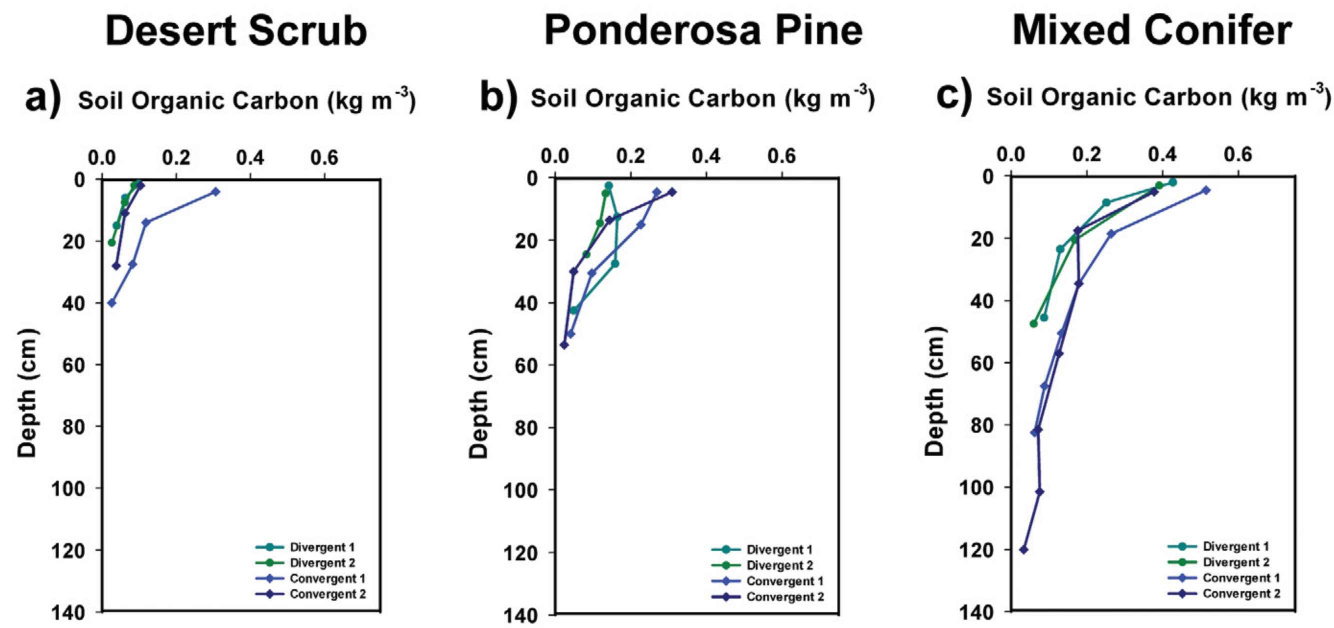

Fig. 4. Soil depth plots for soil organic C distribution for divergent and convergent landscape positions within the (a) desert scrub, (b) ponderosa pine, and (c) mixed conifer field sites in the Santa Catalina Mountains, Arizona.

(Whittaker et al., 1968; Galioto, 1985; Jobbágy and Jackson, 2000; Homann et al., 2007; Meier and Leuschner, 2010).

Similarly, SOC concentrations increased with elevation (Fig. 4). The desert scrub, grass–oak woodland, and ponderosa pine locations all exhibited greater concentrations of C in convergent surface horizons, suggesting a lateral transport and accumulation of organic materials from adjacent landscape positions. In contrast, the mixed conifer locations did not vary substantially in surface C concentrations, with a divergent site average of 0.41 ± 0.03 kg m^{-3} relative to a convergent site average of 0.45 ± 0.10 kg m^{-3} (Fig. 4c). Organic C concentrations generally decreased with depth across all ecosystems and landscape positions; however, convergent locations tended to show higher C concentrations with depth relative to divergent locations. The desert scrub divergent soils exhibited the most uniform C concentrations with depth, where surface values averaged 0.09 ± 0.01 kg m^{-3} compared with an average concentration of 0.03 ± 0.01 kg m^{-3} in saprock horizons. The lack of variation with depth is a function of the overall low primary productivity in desert scrub locations (Whittaker and Niering, 1975) (Fig. 4a).

The SOC stocks (kg m^{-2}) increased significantly with elevation (Table 3). Soil organic C stocks increased nearly eightfold in the divergent positions, from 1.2 ± 0.10 kg C m^{-2} in the desert scrub soils to 8.7 ± 0.02 kg C m^{-2} in the mixed conifer divergent soils. In comparison, the SOC stocks in the convergent landscapes increased more than fourfold, from 3.7 ± 2.3 kg m^{-2} in the desert scrub soils to 16.7 ± 0.07 kg m^{-2} in the mixed conifer soils. Convergent locations generally exhibited SOC stocks twice that of adjacent divergent landscape positions, supporting the concept of SOC accumulation in the foot- and toeslope positions (Schimel et al., 1985; Miller and Birkeland, 1992; Hancock et al., 2010), although the relative increase from desert scrub to

Table 3. One-way ANOVA results for log-transformed field properties across the Santa Catalina Mountains, Arizona, where climate was used as the main effect. Desert scrub, low pine, mid pine, and mixed conifer field sites were tested as climate groupings; *n* = 4 pedons analyzed within each climate grouping. The desert grassland sites were not included in the statistical evaluation due to variation in parent material composition when compared with other sites.

Climate grouping	Mean
Log(profile development index)	
Desert scrub	1.5 ± 0.65 B†
Low pine	1.9 ± 0.13 AB
Mid pine	2.1 ± 0.45 AB
Mixed conifer	2.4 ± 0.47 A
Log(C content), kg m^{-3}	
Desert scrub	−1.4 ± 0.52 C
Low pine	−1.0 ± 0.43 BC
Mid pine	−0.68 ± 0.32 AB
Mixed conifer	−0.09 ± 0.30 A
Log(sand content), kg m^{-3}	
Desert scrub	3.3 ± 0.13 AB
Low pine	3.5 ± 0.23 A
Mid pine	3.3 ± 0.25 AB
Mixed conifer	3.0 ± 0.49 B
Log(silt content), kg m^{-3}	
Desert scrub	1.5 ± 0.21 B
Low pine	2.3 ± 0.12 A
Mid pine	2.4 ± 0.17 A
Mixed conifer	2.5 ± 0.74 A
Log(clay content), kg m^{-3}	
Desert scrub	0.93 ± 0.29 A
Low pine	0.87 ± 0.34 A
Mid pine	1.1 ± 0.20 A
Mixed conifer	1.4 ± 0.78 A

† Mean ± 1 SD. Means followed by the same letter within a field property are not significantly different ($p < 0.05$).

mixed conifer systems was half that of the divergent positions. The mixed conifer C stocks were similar to mixed conifer C stocks of 10 to 15 kg C m^{-2} observed in the Sierra Nevada of California (Dahlgren et al., 1997) and stocks of 5 to 7 kg C m^{-2} in mixed pine and spruce–fir forests in the Rocky Mountains (Kueppers and Harte, 2005). The data indicate that SOC varies significantly by ecosystem type and landscape position, suggesting that both must be accounted for when quantifying SOC stocks in the topographically complex regions of the Desert Southwest (Hanawalt and Whittaker, 1976).

Particle Size Profiles

Sand-sized particles dominated the fine-earth fractions across all sites, with a general decrease in sand content with increasing elevation (Table 2). The desert scrub soils contained significantly greater sand contents than the mid ponderosa pine ($p < 0.001$) and mixed conifer soils ($p < 0.03$), and sand contents in the mixed conifer soils were significantly lower than in the low ponderosa pine sites ($p < 0.003$, Supplementary Table A1). The desert scrub silt contents were significantly lower than the low ponderosa pine ($p < 0.002$), mid ponderosa pine ($p < 0.001$), and mixed conifer soils ($p < 0.0001$, Table 3). Clay contents tended to increase from the desert scrub to mixed conifer field sites (Table 2), but the differences were not significant (Table 3). The high sand contents observed across all field sites reflects a strong parent material control on soil texture, particularly in the water-limited, low-elevation systems. However, a general fining of the particle size distribution with increasing elevation was observed that may be related to greater water availability and primary production facilitating greater physical and chemical weathering. Sand, silt, and clay concentrations were uniform with depth and exhibited minimal variation across all observed pedons (Fig. 5), with the greatest differences observed between landscape positions in the mid ponderosa pine and mixed conifer field sites (Fig. 5b, 5f, and 5i).

Changes in particle size distribution across landscape positions were generally minimal and varied by <15% in most cases (Tables 2 and 4). These data contrast with a toposequence study of granitic soils in southern California with xeric and thermic soil moisture and temperature regimes. In that study, the researchers found that summit and shoulder landscape positions contained maximum sand and clay contents of 83 and 12%, relative to 68 and 39% in footslope positions (Nettleton et al., 1968; Graham and O'Geen, 2010). The contrast in particle size distribution with landscape position between the SCM sites and the southern California soils may reflect differences in climate patterns, where mineral weathering is enhanced in the xeric soil systems. The largest accumulation of clay was observed in the mixed conifer convergent soils (Fig. 5i; Table 2) with a clay content of 129 kg m^{-2} compared with 30 kg m^{-2} in the divergent soils. These results contrast with those of Dahlgren et al. (1997), who found a maximum clay accumulation of 536 kg m^{-2} in a similar mixed conifer ecosystem where precipitation, temperature, vegetation, and parent material were comparable to the SCM mixed conifer site.

The mechanisms driving the large variation in clay accumulation between the Sierra Nevada and the SCM soils could not be identified in this study. However, we hypothesize that the differences between the Sierra Nevada and SCM field areas may result from contrasting precipitation patterns, timing of evaporative demands, and/or differences in soil age. The Sierra Nevada locations occur in a winter rainfall regime, where precipitation arrives in large, low-intensity events. Evapotranspiration demands decrease in the winter months when temperatures are cooler and plant transpiration is low, supporting maximum water flux, deep percolation, and the potential for a greater degree of mineral weathering.

In comparison, the SCM sites are characterized by a bimodal precipitation regime, with ~50% of the annual rainfall delivered as short, intense summer rainfall events when evapotranspirative demand is high (Sala et al., 1992). Warmer summer temperatures drive increased evaporative rates, leading to substantial precipitation losses to evapotranspiration and limited fluxes of water through the soil profile (Cavanaugh et al., 2011; Sponseller et al., 2012). We speculate that the bimodal precipitation pattern in the SCM, specifically the high evaporative demands during summer rain events, leads to drier soil conditions and subsequently less mineral weathering compared with the Sierra Nevada soils. Furthermore, the mean residence times estimated for the SCM soils (~5000–12,000 yr; Rasmussen, 2008) may be shorter than those for the Sierra Nevada soils, which would also contribute to differences in clay production and other mineral weathering processes.

The interception of precipitation by vegetation canopies may also contribute to differences in soil moisture inputs across contrasting vegetation types and climates. However, studies of hydrologic loss in semiarid and arid ecosystems have documented canopy interception ranging from 8.6 to 20% (Pressland, 1973; Whitford et al., 1997; Coble and Hart, 2013), which is comparable to interception of 9.7 to 20% in temperate deciduous forests (Carlyle-Moses, 2004). Differences in canopy interception among plant types have been attributed to both contrasting leaf morphology and canopy architecture (Martinez-Meza and Whitford, 1996; Coble and Hart, 2013).

Clay Contrast Indices

The clay contrast index (CCI) was used to characterize clay redistribution within profiles and between landscape positions following Young (1976) and Khomo et al. (2011). The within-profile CCI was calculated as a ratio between the clay content (% w/w) in the uppermost mineral horizon and the maximum clay content observed in the subsurface. The between-profile CCI was determined by dividing the depth-weighted average clay content from the divergent locations by the maximum depth-weighted clay content in the convergent locations (Khomo et al., 2011). The between-profile CCIs ranged from 0.26 ± 0.02 in the desert scrub site to 0.35 ± 0.01 in the mixed conifer site (Table 2). These values fall within the CCI < 0.5 grouping described by Khomo et al. (2011) for dry

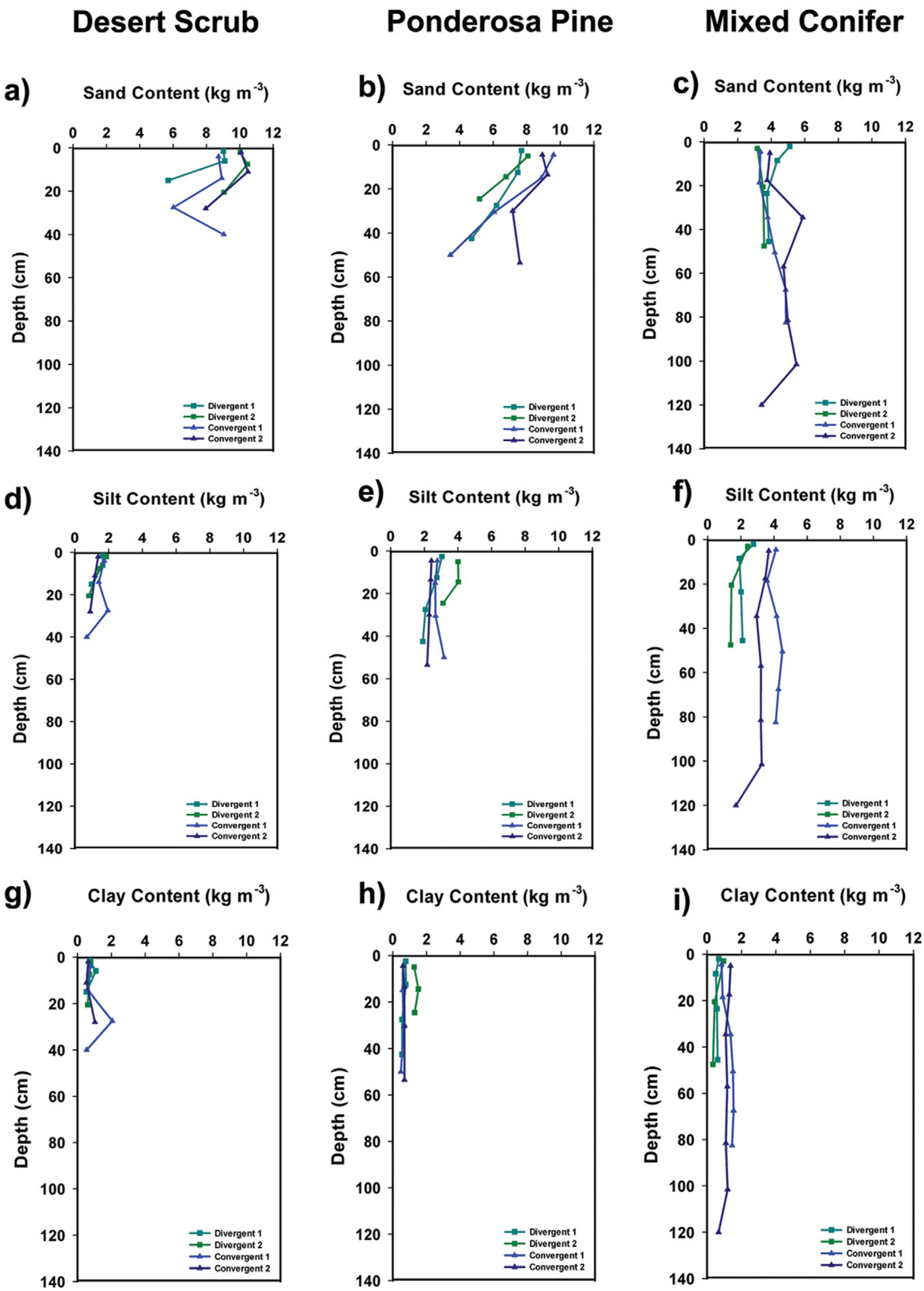

Fig. 5. Soil depth plots documenting particle size distribution in the Santa Catalina Mountain soils including sand content of (a) desert scrub, (b) ponderosa pine, and (c) mixed conifer sites, silt contents of (d) desert scrub, (e) ponderosa pine, and (f) mixed conifer sites, and clay contents of (g) desert scrub, (h) ponderosa pine, and (i) mixed conifer sites.

Table 4. One-way ANOVA results where landscape position was tested as the main effect for log-transformed field properties across the Santa Catalina Mountains, Arizona; *n* = 8 pedons examined within each landscape position.

Landscape position	Mean
Log(profile development index)	
convergent	2.3 ± 0.42 A†
divergent	1.6 ± 0.49 B
Log(C content), kg m^{-3}	
convergent	−0.56 ± 0.59 A
divergent	−1.0 ± 0.57 A
Log(sand content), kg m^{-3}	
convergent	3.5 ± 0.17 A
divergent	3.1 ± 0.36 B
Log(silt content), kg m^{-3}	
convergent	2.3 ± 0.65 A
divergent	2.0 ± 0.41 A
Log(clay content), kg m^{-3}	
convergent	1.2 ± 0.55 A
divergent	0.92 ± 0.31 A

† Mean ± 1 SD. Means followed by the same letter within a field property are not significantly different ($p < 0.05$).

sites exhibiting low clay contents and a relatively uniform clay distribution across landscape positions.

The within-profile CCI values were relatively low for the conifer soils, with average values of 0.21 ± 0.012 for the divergent sites and 0.33 ± 0.12 for the soils in convergent landscape positions, indicating a relatively uniform clay distribution with depth. The mixed conifer soils exhibited the lowest degree of within-profile clay redistribution, where soils in divergent and convergent landscapes averaged 0.06 ± 0.09 and 0.15 ± 0.23, respectively. In contrast, the desert scrub pedons exhibited greater CCI values, with an average within-profile CCI of 0.59 ± 0.01 in the convergent sites and 0.12 ± 0.20 in adjacent divergent sites, indicating greater subsurface redistribution of clays in convergent desert scrub profiles relative to any other location sampled across the gradient. Greater within-profile CCIs in the desert scrub convergent position may be a function of greater water availability and mineral weathering or the preferential transport, accumulation, and translocation of fines in the convergent positions. Greater within-profile CCI values in these profiles may also reflect the preferential accumulation of dust. Dust inputs can contribute significantly to the fine-earth fraction in the southwestern United States (Reynolds et al., 2006; Reheis, 2006; Hirmas and Graham, 2011), with dust inputs occurring as wet and dry deposition (Osada et al., 2014) and during intense rainfall events (Burt, 1991; Sala et al., 1996; Hopkins, 2010) that can rapidly transport dust into the subsurface.

Profile Development Index Normalized Field Properties

Normalized melanization and structure generally increased with elevation, whereas the other properties, including rubification, texture, color lightening, color paling, and consistence exhibited little to no change (Table 5). Structure and melanization were most strongly expressed in the high-elevation conifer sites. Melanization generally decreased with depth, reflecting greater organic matter content in surface horizons. Melanization and structure were one- to twofold higher than rubification in all SCM soil pedons (Table 5). Rubification, texture, consistence, and clay film expression generally correspond most significantly with soil age in studies of soils formed from coarse, granitic parent rock (Harden and Taylor, 1983). The mean residence time of soils in the SCM ranges from 5000 to 12,000 yr (Rasmussen, 2008), indicating soils of Holocene age. The lack of any strong pattern in rubification and other properties associated with soil age is thus probably a function of the relatively young and uniform ages of soils in the SCM. In comparison, structure, melanization, and other properties are generally associated more strongly with other factors such as climate and water availability (Harden and Taylor, 1983), similar to the patterns observed here.

Profile Development Index

Profile development index values increased more than twofold across the SCM, with the highest PDIs observed at the mixed conifer convergent sites (Fig. 6; Table 5). The desert scrub PDIs were significantly less than those calculated for the mixed conifer soils ($p < 0.02$, Table 3 and Supplementary Table A1). The PDIs calculated for divergent positions were also significantly lower than than those determined for congruent positions ($p < 0.02$, Table 4). Divergent PDI values increased from 2.6 to 7.4 across the SCM gradient, whereas convergent PDI values increased from 7.6 to 17. The PDI values for the additional SCM and Rincon Mountains summit and backslope pedons increased from 1.1 to 10 with increasing elevation and water availability following a logarithmic function ($r^2 = 0.58$, $p < 0.008$; Fig. 6). The sampled SCM divergent profiles fall well within the 95% confidence limits of this function, suggesting a consistent trend of increasing PDI with increasing water availability. Interestingly, four of the five convergent sites plot outside of and above the 95% confidence interval calculated for the PDI–climate function, indicating significantly greater PDI values than expected for a given MAP/PET ratio. These data strongly suggest that focused water accumulation in conver-

Table 5. Pedon averages for profile development index (PDI), melanization, structure, and rubification in the soils from the Santa Catalina Mountains.

Site	Landscape position	PDI	Melanization	Structure	Rubification
Desert scrub	divergent	2.6 ± 0.50†	0.26 ± 0.10	0.15 ± 0.18	0.08 ± 0.0
	convergent	7.6 ± 0.97	0.33 ± 0.0	0.39 ± 0.0	0.10 ± 0.01
Grasslands	divergent	5.8 ± 2.8	0.43 ± 0.10	0.75 ± 0.35	0.0 ± 0.0
	convergent	6.1 ± 0.0	0.71 ± 0.0	0.50 ± 0.0	0.0 ± 0.0
Low pine	divergent	6.2 ± 1.0	0.21 ± 0.03	0.46 ± 0.06	0.15 ± 0.04
	convergent	6.7 ± 0.92	0.35 ± 0.02	0.55 ± 0.23	0.02 ± 0.02
Mid pine	divergent	6.6 ± 2.8	0.55 ± 0.30	0.44 ± 0.0	0.04 ± 0.05
	convergent	11 ± 4.5	0.43 ± 0.20	0.49 ± 0.16	0.02 ± 0.03
Mixed conifer	divergent	7.4 ± 0.02	0.29 ± 0.06	0.44 ± 0.08	0.0 ± 0.0
	convergent	17 ± 1.1	0.20 ± 0.02	0.58 ± 0.02	0.04 ± 0.0

† Average ± 1 SD.

gent areas significantly increases soil development relative to that expected for a given climate regime, highlighting topography as an important control on PDI variability in these environments. For example, the desert scrub convergent PDI value of 7.6 is identical to that of the divergent mixed conifer PDI of 7.4, suggesting a localized MAP/PET ratio equivalent to ~1.5, rather than the MAP/PET ratio of ~0.6 calculated for the desert scrub location.

Profile development indices from this study were similar to other arid and semiarid Holocene aged sites in the southwestern United States (Harden, 1982; Harden and Taylor, 1983; Harden et al., 1991). For example, maximum PDIs ranged from 7.9 to 51 in Las Cruces, NM, from 2.3 to 19.7 at Silver Lake Playa, CA, and from 6 to 34 in soils at Kyle Canyon and Fortymile Wash in Nevada. The conifer PDIs in the current study also overlapped with the lower PDI end members of the xeric Ventura and Merced soils in California (Harden et al., 1991). Overall, the SCM soils exhibit PDIs similar to other water-limited ecosystems in the southwestern United States.

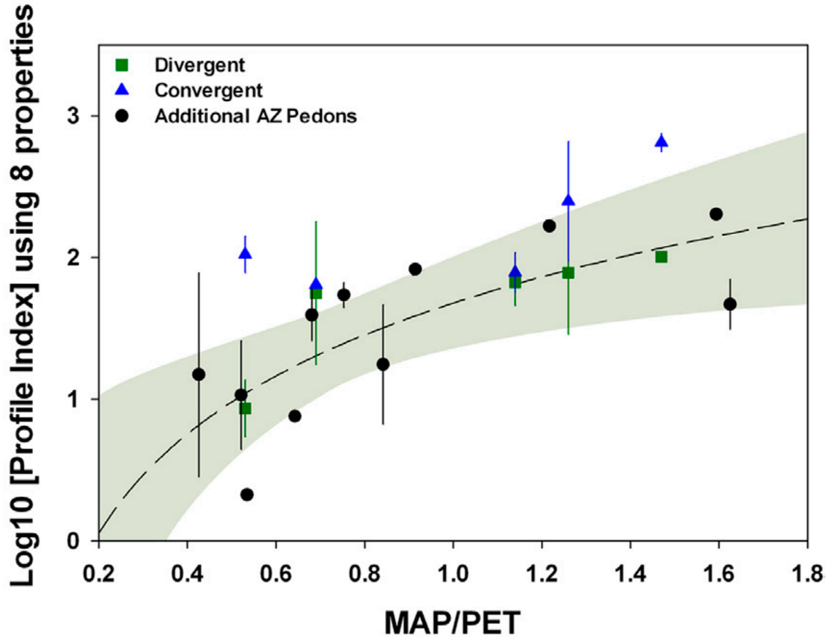

Fig. 6. Profile development indices (PDIs) for the Santa Catalina Mountain soils (distinguished by landscape position and mean annual precipitation/potential evapotranspiration ratios [MAP/PET]) and PDIs calculated for additional southern Arizona pedons.

The increase in PDI values with elevation were a function of the increase in normalized melanization and structure values across the SCM gradient. These changes were largely related to an increase in SOC content with elevation that corresponded to greater primary productivity and water availability. Indeed, PDI values were highly correlated to soil C stocks for both convergent ($r^2 = 0.66$, $p < 0.01$) and divergent ($r^2 = 0.74$, $p < 0.01$) profiles. These data indicate that SOC accumulation is the dominant control on PDI variation across the SCM locations and can be related directly to variation in water availability. Therefore, water availability appears to produce the greatest variation across semiarid ecosystems in the SCM sites, in agreement with previous work in water-limited ecosystems that linked PDI variation to both water and C availability (Harden et al., 1991; Vidic and Lobnik, 1997; Badía et al., 2009). Furthermore, the SCM sites exhibited PDI variation by landscape position, where convergent PDI values were more than twofold higher relative to divergent sites across the SCM gradient. These results are similar to others who found PDI values to be greatest in footslope landscape positions (Swanson and Paul, 1985; Berry, 1987; Applegarth and Dahms, 2001). The SCM sites also corresponded to a study where PDIs in footslope positions increased with moisture availability across a Peruvian alpine gradient compared with summit positions that exhibited little to no PDI increase in wetter climates (Miller and Birkeland, 1992).

SUMMARY

The results of this research demonstrate that climate and landscape position exert significant control on soil development in semiarid ecosystems. The key findings include:

- Profile development indices and SOC storage were greatest in the mixed conifer soils, where moisture availability facilitates increased primary productivity and organic C accumulation.

- Water-gathering convergent locations concentrate SOC and fine-grained soil materials relative to upslope divergent sites.

- The PDIs for convergent landscape positions were twofold greater than those for adjacent divergent landscape positions, reflecting the topographic concentration of limited water resources into downslope portions of the landscape.

- The PDI was effective for quantifying variation in Holocene-aged soils across contrasting climates and landscape positions, both of which must be considered when examining soil morphology and soil C storage in semiarid ecosystems.

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