Landscape Determinants of Exchangeable Calcium and Magnesium in Ozark Highland Forest Soils

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Exchangeable base cations, particularly Ca and Mg, largely govern soil acidity and, consequently, plant species composition in temperate forests. Although studies have identified soil and terrain characteristics affecting exchangeable Ca and Mg, few studies have identified the relative importance of factors affecting Ca and Mg distribution across landscapes. Objectives of this study were to: (i) identify the relative importance of geomorphic and soil properties for exchangeable Ca and Mg concentrations and quantities, and (ii) examine relationships between these properties and tree species abundance. A classification and regression tree (CART) analysis was applied to 74 pedons sampled across a 3800-ha forested research area in the Ozark Highlands in southeastern Missouri. This analysis identified depth to bedrock and the bedrock lithology as important factors associated with exchangeable Ca and Mg concentrations, which ranged from 0.30 to 2.88 and 0.24 to 1.35 g kg^{-1}, respectively. The CART analysis also indicated that the underlying bedrock was associated with exchangeable base cation quantity, and values ranged from 4263 to 20,144 kg ha^{-1} for Ca and 1650 to 9977 kg ha^{-1} for Mg. Analysis of variance indicated that the most common oak (*Quercus* L.) and hickory (*Carya* Nutt.) species were significantly more abundant on soils with lower Ca concentrations. The analysis framework applied in this study provides a basis for distinguishing among soils and ecological land types by pools of exchangeable Ca and Mg, thereby aiding in the identification of locales where base cation depletion may be of concern.

Abbreviations: CART, classification and regression tree; CEC, cation exchange capacity; MOFEP, Missouri Ozark Forest Ecosystem Project.

The exchangeable Ca and Mg pools are two of the more important in forest soils. The large quantities of Ca and Mg retained on the cation exchange sites resupply the soil solution when these nutrients are removed by uptake or leaching (Richter et al., 1994), consequently playing an important role in the cycling and retention of these and other nutrients. The exchangeable concentrations of base cations largely govern soil acidity, and Ca and Mg are the two most abundant base cations in the forest soils of eastern North America. Soil acidity is an important factor affecting the distribution of both tree and ground flora species composition in temperate forests (Ware et al., 1992; Pallardy, 1995; Finzi et al., 1998). Low concentrations of exchangeable Ca in the soil have been linked with Al mobilization and toxicity in red spruce (*Picea rubens* Sarg.) (Lawrence et al., 1997), and low B-horizon concentrations of exchangeable Ca and Mg are associated with the decline of sugar maple (*Acer saccharum* Marshall) on the Alleghany Plateau (Bailey et al., 2004). Soils having low exchangeable concentrations of Ca and containing few Ca-bearing minerals are most vulnerable to depletion by timber harvesting, plant uptake, and leaching (Huntington et al., 2000).

The exchangeable Ca and Mg pools are affected by several factors, including those related to the origin and nature of soil parent materials, slope position, and water movement within the soil (Trettin et al., 1999; Huntington et al., 2000; Johnson et al., 2000; Bailey et al., 2004). Parent materials strongly influence Ca and Mg concentrations via mineral weathering and soil formation processes, which

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subsequently affect the cation exchange capacity (CEC) and base saturation of exchange sites (Huntington et al., 2000; Bailey et al., 2004). Slope position affects the flow of water across the landscape, redistributing Ca and Mg carried in the soil solution over long time periods (Johnson et al., 2000; Bailey et al., 2004). Within a soil profile, features that affect the vertical or horizontal movement of water also affect the movement and leaching of base cations.

Despite acknowledging the importance of soil and geomorphic factors, few studies have afforded a systematic examination of the relative influence of these factors on exchangeable Ca and Mg concentrations or quantities across forested landscapes. This systematic examination is needed for identifying important factors predicting where in the soil-landscape Ca and Mg supplies are low or high. Predicting where small and large pools of exchangeable Ca and Mg pools are located is also useful for explaining the distribution of tree species and other native plants in forested ecosystems and for identifying soils potentially vulnerable to base cation depletion by timber harvesting and leaching.

Initiation of the Missouri Ozark Forest Ecosystem Project (MOFEP) has provided a unique opportunity to systematically examine the geomorphic and soil factors affecting exchangeable levels of Ca and Mg. As part of this long-term, landscape-scale study examining forest management system effects on Ozark flora and fauna, a detailed soil-landscape characterization and mapping project was conducted to provide baseline information for other studies (Meinert et al., 1997; Kabrick et al., 2000). This soil-landscape investigation included sampling pedons on different types of bedrock (referred to subsequently as *geologic formations*) and topographic positions, and soils developed in a number of different parent materials including alluvium, pedisediment, and a combination of pedisediment over residuum derived from both sandstones and dolomites. Initial data examination showed that exchangeable Ca and Mg concentrations in soil horizons ranged from trace amounts to >6 g kg^{-1} among pedons. Evidence from this work suggested that some variation in Ca and Mg concentrations is attributable to the origin and nature of the parent material derived from the different bedrock lithologies underlying the soils (Meinert et al., 1997). It was postulated that other factors related to the movement and redistribution of soil water also influence Ca and Mg availability across the landscape.

Our first objective was to identify the relative contribution and importance of geomorphic and soil properties on exchangeable Ca and Mg concentrations and quantities. Properties of interest included the origin and type of parent material, soil depth and underlying bedrock formation, soil drainage, and the presence or absence of a fragipan. These properties were selected because they are used for identifying and mapping soils (Meinert et al., 1997) and allocating stands into ecological land types in this region (Nigh et al., 2000) and elsewhere in temperate ecosystems (Keys et al., 1995). Because the concentrations and quantities of exchangeable Ca and Mg play a prominent role in governing soil acidity and consequently influencing plant community composition, our second objective was to examine the relationships between the abundance of specific tree species and factors related to the exchangeable Ca and Mg levels. An additional goal of this study was to identify soil map units and ecological land types that may be at risk of Ca and Mg depletion caused by harvesting.

MATERIALS AND METHODS

Study Sites

The MOFEP was established in 1989 by the Missouri Department of Conservation to quantify forest management effects on upland oak systems (Brookshire and Shifley, 1997; Shifley and Brookshire, 2000; Shifley and Kabrick, 2002). This project is a long-term study intended to last one to three full rotations (i.e., 100–300 yr) on operational forest compartments. The study consists of nine compartments or "sites" ranging in size from 314 to 516 ha located in Carter, Reynolds, and Shannon counties, Missouri (Fig. 1).

The study sites occur within the Current River Oak Forest Breaks and the Current River Oak–Pine Woodland Hills land type associations of the Ozark Highlands ecological section (Nigh and Schroeder, 2002). The Current River Oak Forest Breaks has narrow ridges and steep sideslopes with relief of 90 to140 m, and three sedimentary bedrock formations are exposed: Roubidoux, Gasconade (both Ordivician age), and Eminence (Cambrian age) (Thompson, 1995). The Current River Oak–Pine Hills has broad ridges with relief <90 m and only the Roubidoux and Gasconade bedrock formations are exposed. Precambrian rhyolites are exposed in some locations of the Ozark Highlands but they are of minor importance in the study area.

The lithologies of each bedrock unit differ considerably (Meinert et al., 1997). The Roubidoux formation in this region comprises interbedded sandstone, sandy dolomite, and silicified stromatolite algal and chert beds. The upper portion of the Gasconade formation comprises thick beds of coarsely crystalline dolomites interbedded with chert and layers of silicified stromatolites. The lower half of the Gasconade formation comprises finely crystalline dolomite with few chert nodules and a bed of sandstone and quartzose 1 to 3 m thick at the base. Because of the finely crystalline nature and the lack of chert in the lower portion of the Gasconade formation, it was originally mapped as a different formation or a different member named the Van Buren (Thompson, 1995). The Eminence formation comprises thick beds of coarsely crystalline dolomite occasionally interbedded with chert beds ranging from 1 to 2 m thick.

When the MOFEP was initiated, forests and woodlands of the region were second growth and fully stocked (sensu Gingrich, 1967) and 68% of the canopy dominant and codominant trees were 45 to 65 yr old (Brookshire et al., 1997). Oaks were the dominant trees and four oak species, white oak (*Quercus alba* L.), black oak (*Q. velutina* Lam.), scarlet oak (*Q. coccinea* Münchh.), and post oak (*Q. stellata* Wangenh.) comprised 71% of the basal area (Kabrick et al., 2004b). Other oaks found at MOFEP included chinkapin oak (*Q. muehlenbergii* Engelm.), blackjack oak (*Q. marilandica* Münch.), Shumard oak (*Q. shumardii* Buckl.), and northern red oak (*Q. rubra* L.), but in combination they comprised only 1% of the basal area. Shortleaf pine (*Pinus echinata* Mill.) (8%), pignut hickory [*Carya glabra* (Mill.) Sweet] (4%), black hickory (*Carya texana* Buckl.) (4%), mockernut hickory [*Carya tomentosa* (Lam.) Nutt.] (4%), flowering dogwood (*Cornus florida* L.)

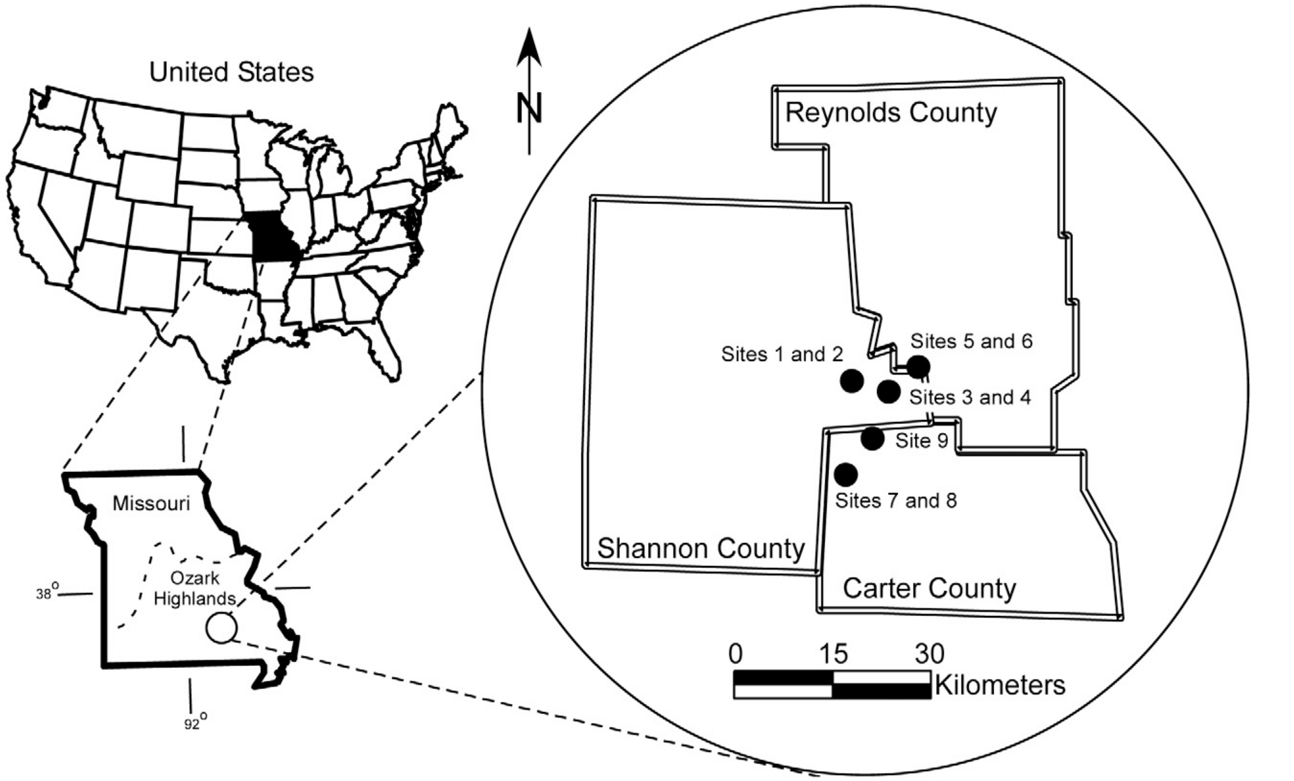

Fig. 1. Approximate location of the nine Missouri Ozark Forest Ecosystem Project study sites in Carter, Reynolds, and Shannon counties, Missouri. Pedons were sampled on sites 2 to 5 and 7.

(3%), blackgum (*Nyssa sylvatica* Marsh.) (2%), and maples including red maple (*Acer rubrum* L.) and sugar maple (together, 1%) also were in the study area.

Pedon Sampling

Seventy-four pedons were described, sampled, and analyzed on five of the nine MOFEP sites (Sites 2–5 and 7). They were located in the most prominent soils of land units comprising a combination of the bedrock formations, slope positions, and soil properties (Table 1) that were used to map and classify soils at the MOFEP. The mapping procedure was described in detail by Meinert et al. (1997) and Kabrick et al. (2000). Bedrock formations associated with the sampled pedons included the Roubidoux, Gasconade, and Eminence. The Gasconade formation was treated as two strata of approximately equal thickness because the upper half of the formation generally yielded Alfisols and Ultisols that comprised gravelly pedisediment and the lower half yielded primarily Alfisols that comprised gravelly pedisediment overlying clayey residuum. Slope positions included the designations of summit, shoulder, backslope, footslope, and floodplain (Table 1).

The sampled pedons were approximately proportional to the frequency at which the geologic formation and slope position combinations occurred in the landscape. For example, floodplains were most extensive on the Roubidoux and Eminence formations, and backslopes were common on all formations. Other physiographic features that were mapped included alluvial fans, terraces, and sinkholes but they were not included in the pedon sampling because they comprised <3% of the land area.

Soil excavations were made in locations where the backhoe could be driven without adversely affecting the site conditions (forest floor and vegetation) and other ongoing experiments or where steep slopes and other site conditions prohibited backhoe operation.

Pedons were excavated to a depth of about 1.5 m with a backhoe unless prohibited by the underlying bedrock or other impenetrable material. In each excavation, the soils were described and approximately 500 mL of soil from each horizon was removed for analysis at the University of Missouri Soil Characterization Laboratory. Analyses included particle size distribution, extractable acidity, extractable Al, exchangeable bases (Ca, K, Mg, and Na), CEC, base saturation, organic C, and pH. All methods followed standards established by the National Cooperative Soil Survey for routine analysis of soil survey samples (Soil Survey Laboratory Staff, 2004). In brief, particle size distribution was performed using pipette analysis, exchangeable cations were displaced via compulsive exchange in 1 mol L^{-1} NH_4OAc at pH 7, extractable acidity was measured in 0.5 mol L^{-1} $BaCl_2$/0.2 mol L^{-1} triethanolamine (TEA) at pH 8.2 and back-titrated with 0.13 mol L^{-1} HCl, the effective CEC was calculated from the sum of the cations exchanged in NH_4OAc at pH 7, organic C content was measured using a Leco C analyzer (Leco Corp., St. Joseph, MI), and pH was measured in water (1:1 solid/solution ratio) and 0.01 mol L^{-1} $CaCl_2$ (1:2 solid/solution ratio). All pedon information is accessible through the Missouri Cooperative Soil Survey (http://www.soilsurvey.org; verified 15 Oct. 2010) and data can be accessed using pedon identifications provided in Table 1.

Calculation of Exchangeable Calcium and Magnesium Concentrations and Quantities

Exchangeable Ca and Mg were expressed in four ways: (i) on a concentration basis by each soil horizon (either $cmol_c$ kg^{-1} or g kg^{-1}) based directly on the laboratory data; (ii) on a mass-weighted

Table 1. Site characteristics associated with each pedon.

Pedon†	Bedrock formation	Slope position‡	Parent material	Drainage§	Depth¶	Particle-size class	Mineralogy	Classification
M9560101	upper Gasconade	footslope	pedisediment	MWD	very deep	fine-loamy	siliceous	Fragic Hapludult
M9560102	upper Gasconade	summit	pedisediment	WD	very deep	fine-loamy	siliceous	Typic Hapludalf
M9560103	upper Gasconade	summit	pedisediment	MWD	very deep	fine-loamy	siliceous	Oxyaquic Fragiudalf
M9560104	upper Gasconade	summit	pedisediment/residuum#	MWD	very deep	fine-loamy	siliceous	Typic Fragiudalf
M9560105	Roubidoux	summit	pedisediment	MWD	very deep	fine-loamy	siliceous	Typic Fragiudult
M9560106	Roubidoux	summit	pedisediment	MWD	very deep	fine-loamy	siliceous	Typic Fragiudult
M9560107	Roubidoux	summit	pedisediment	MWD	very deep	fine-loamy	siliceous	Typic Fragiudult
M9560108	Roubidoux	summit	pedisediment	MWD	very deep	fine-loamy/clayey	siliceous	Typic Paleudult
M9560109	Roubidoux	backslope	pedisediment	ED	very deep	loamy-skeletal	siliceous	Typic Paleudult
M9560110	Roubidoux	backslope	pedisediment	WD	very deep	loamy-skeletal	siliceous	Typic Paleudult
M9560111	Roubidoux	backslope	pedisediment	WD	deep	loamy-skeletal	siliceous	Typic Paleudult
M9560114	Roubidoux	floodplain	alluvium	ED	very deep	loamy-skeletal	siliceous	Humic Dystrudept
M9560115	Roubidoux	floodplain	alluvium	ED	very deep	loamy-skeletal	siliceous	Typic Dystrudept
M9560116	Roubidoux	floodplain	alluvium	ED	very deep	loamy-skeletal	siliceous	Humic Hapludult
M9560117	Roubidoux	floodplain	alluvium	ED	very deep	loamy-skeletal	siliceous	Cumulic Hapludoll
M9561322	lower Gasconade	shoulder	pedisediment/residuum	WD	very deep	loamy-skeletal/clayey	mixed	Typic Paleudalf
M9561323	lower Gasconade	shoulder	pedisediment	MWD	very deep	loamy-skeletal/clayey	siliceous	Typic Paleudalf
M9561324	lower Gasconade	summit	pedisediment/residuum	MWD	deep	loamy-skeletal/clayey	mixed	Typic Hapludalf
M9561325	lower Gasconade	summit	pedisediment	MWD	very deep	loamy-skeletal/clayey	mixed	Typic Paleudalf
M9561326	lower Gasconade	shoulder	pedisediment	WD	very deep	loamy-skeletal	siliceous	Typic Paleudult
M9561327	lower Gasconade	summit	pedisediment/residuum	MWD	very deep	fine-loamy	siliceous	Oxyaquic Fragiudalf
M9561328	lower Gasconade	summit	pedisediment/residuum	MWD	very deep	fine-silty	siliceous	Oxyaquic Fragiudalf
M9561329	lower Gasconade	shoulder	pedisediment/residuum	WD	mod. deep	fine	mixed	Typic Hapludalf
M9561330	lower Gasconade	shoulder	pedisediment	MWD	deep	fine-loamy/clayey	mixed	Typic Hapludalf
M9561331	lower Gasconade	summit	pedisediment	WD	very deep	fine-loamy/clayey	siliceous	Oxyaquic Paleudalf
M9561332	lower Gasconade	summit	pedisediment	MWD	very deep	fine-loamy	siliceous	Fragiaquic Paleudult
M9561333	lower Gasconade	summit	pedisediment	WD	very deep	clayey-skeletal	mixed	Typic Paleudult
M9561334	lower Gasconade	shoulder	pedisediment/residuum	WD	very deep	loamy-skeletal/clayey	mixed	Typic Paleudalf
M9561335	lower Gasconade	summit	pedisediment/residuum	WD	very deep	loamy-skeletal	siliceous	Typic Paleudalf
M9561336	lower Gasconade	summit	pedisediment	MWD	very deep	fine-silty	siliceous	Typic Fragiudult
M9561337	lower Gasconade	summit	pedisediment	MWD	very deep	fine-silty	siliceous	Typic Fragiudult
M9561338	Eminence	backslope	pedisediment	WD	very deep	loamy-skeletal	mixed	Typic Paleudult
M9561339	Eminence	backslope	pedisediment	WD	very deep	loamy-skeletal	mixed	Typic Paleudalf
M9561340	Eminence	backslope	pedisediment	WD	very deep	fine-loamy	siliceous	Typic Paleudalf
M9561341	Eminence	backslope	pedisediment/residuum	WD	very deep	loamy-skeletal	siliceous	Mollic Paleudalf
M9561342	Eminence	backslope	pedisediment/residuum	WD	very deep	loamy-skeletal/clayey	mixed	Typic Paleudalf
M9561343	Eminence	backslope	pedisediment/residuum	WD	very deep	loamy-skeletal/clayey	mixed	Mollic Paleudalf
M9561344	Eminence	backslope	pedisediment	WD	very deep	loamy-skeletal	siliceous	Typic Paleudalf
M9561345	Eminence	backslope	pedisediment/residuum	WD	very deep	loamy-skeletal/clayey	siliceous	Mollic Paleudalf
M9561346	Eminence	backslope	pedisediment	WD	very deep	loamy-skeletal/clayey	mixed	Typic Hapludalf
M9561347	Eminence	backslope	pedisediment/residuum	WD	very deep	loamy-skeletal/clayey	siliceous	Typic Hapludalf

Table 1 continued on next page.

Table 1 (continued).

Pedon†	Bedrock formation	Slope position‡	Parent material	Drainage§	Depth¶	Particle-size class	Mineralogy	Classification
M9561348	Eminence	backslope	pedisediment/residuum	WD	mod. deep	clayey-skeletal	mixed	Mollic Hapludalf
M9561349	Eminence	backslope	pedisediment/residuum	WD	mod. deep	loamy-skeletal/clayey	mixed	Typic Hapludalf
M9561350	Eminence	floodplain	alluvium	ED	very deep	loamy-skeletal	siliceous	Dystric Eutrudept
M9561351	Eminence	floodplain	pedisediment	ED	very deep	loamy-skeletal	mixed	Cumulic Hapludoll
M9561352	Eminence	floodplain	alluvium	ED	very deep	loamy-skeletal	siliceous	Ultic Hapludalf
M9561353	upper Gasconade	shoulder	pedisediment	MWD	very deep	loamy-skeletal/clayey	siliceous	Fragic Paleudult
M9561354	upper Gasconade	shoulder	pedisediment	WD	very deep	fine	mixed	Typic Paleudult
M9561355	upper Gasconade	shoulder	pedisediment	WD	very deep	loamy-skeletal/clayey	siliceous	Typic Paleudult
M9561356	upper Gasconade	shoulder	pedisediment	MWD	very deep	loamy-skeletal/clayey	mixed	Typic Paleudalf
M9561357	upper Gasconade	shoulder	pedisediment	WD	very deep	loamy-skeletal/clayey	kaolinitic	Typic Paleudult
M9561358	upper Gasconade	shoulder	pedisediment	MWD	very deep	fine-loamy	siliceous	Humic Fragiudult
M9561359	upper Gasconade	shoulder	pedisediment	MWD	very deep	loamy-skeletal	siliceous	Humic Fragiudult
M9561360	upper Gasconade	shoulder	pedisediment	MWD	very deep	loamy-skeletal	mixed	Typic Paleudalf
M9561361	upper Gasconade	shoulder	pedisediment	WD	very deep	loamy-skeletal/clayey	siliceous	Typic Paleudult
M9561362	lower Gasconade	shoulder	pedisediment/residuum	WD	very deep	loamy-skeletal/clayey	siliceous	Typic Paleudalf
M9561363	lower Gasconade	shoulder	pedisediment/residuum	WD	very deep	loamy-skeletal	siliceous	Typic Paleudalf
M9561364	lower Gasconade	shoulder	pedisediment	WD	very deep	loamy-skeletal	siliceous	Typic Paleudalf
M9561365	Roubidoux	shoulder	pedisediment	MWD	very deep	loamy-skeletal	siliceous	Typic Fragiudult
M9561366	Roubidoux	summit	pedisediment	MWD	very deep	loamy-skeletal	siliceous	Typic Fragiudult
M9561367	Roubidoux	summit	pedisediment/residuum	WD	very deep	loamy-skeletal	siliceous	Typic Paleudult
M9561368	Roubidoux	shoulder	pedisediment/residuum	WD	mod. deep	loamy-skeletal	siliceous	Typic Fragiudult
M9561369	lower Gasconade	backslope	pedisediment	WD	mod. deep	very-fine	mixed	Typic Hapludalf
M9561370	lower Gasconade	backslope	pedisediment/residuum	WD	shallow	very-fine	smectitic	Lithic Hapludalf
M9561371	lower Gasconade	backslope	pedisediment	WD	mod. deep	loamy-skeletal/clayey	mixed	Typic Hapludalf
M9561372	lower Gasconade	backslope	pedisediment	WD	mod. deep	very-fine	mixed	Typic Hapludalf
M9561383	upper Gasconade	backslope	pedisediment	WD	very deep	loamy-skeletal	siliceous	Typic Paleudalf
M9561384	upper Gasconade	backslope	pedisediment	WD	very deep	loamy-skeletal	siliceous	Typic Paleudult
M9561385	upper Gasconade	backslope	pedisediment/residuum	WD	very deep	loamy-skeletal	siliceous	Fragic Paleudult
M9561386	upper Gasconade	backslope	pedisediment/residuum	WD	very deep	loamy-skeletal	siliceous	Typic Paleudult
M9561387	lower Gasconade	backslope	pedisediment	WD	very deep	loamy-skeletal/clayey	siliceous	Typic Paleudalf
M9561388	lower Gasconade	backslope	pedisediment	WD	very deep	loamy-skeletal/clayey	mixed	Typic Paleudalf
M9561389	lower Gasconade	backslope	pedisediment/residuum	WD	deep	loamy-skeletal/clayey	mixed	Typic Hapludalf
M9561390	lower Gasconade	backslope	pedisediment	WD	very deep	loamy-skeletal	siliceous	Typic Paleudalf

† Pedon identification in the Missouri Cooperative Soil Survey database (http://www.soilsurvey.org).

‡ Slope positions included summits (broad ridges ³60 m wide with slopes <8%), shoulders (convex, slopes 8–20%), backslopes (slopes >20% including sideslopes, nose slopes, and head slopes), footslopes (concave, slopes <20%), and floodplains (slopes <4%).

§ Drainage classes are excessively drained (ED), well drained (WD), and moderately well drained (MWD).

¶ Soil depth classes are shallow (<50cm), moderately deep (mod. deep, 51–100 cm), deep (101–150 cm), and very deep (>150 cm).

Pedisediment overlying residuum.

concentration basis for the epipedon and upper and lower portions of the diagnostic subsurface horizons (sensu Soil Survey Staff, 1999); (iii) on a mass-weighted concentration basis for the entire pedon; and (iv) on a total quantity basis for the entire pedon. For the mass-weighted basis, we multiplied the element concentration in the fine-earth fraction (<2 mm) in each soil horizon by its mass fraction (horizon thickness of unit area × bulk density × fine-earth fraction/total mass of the epipedon, diagnostic horizon, or profile). The total quantity of Ca and Mg (kg ha^{-1}) in each pedon was determined by calculating the total mass of Ca and Mg in the fine-earth fraction of 1 ha (horizon thickness of unit area × bulk density × fine-earth fraction × conversion factor for 1 ha). Bulk density data for these calculations were estimated using Soil Survey Staff (2009) based on work by Rawls (1983) and are included in the Missouri Soil Survey pedon database. Example calculations for Ca are shown in Table 2.

Woody Vegetation Sampling

Woody vegetation was inventoried periodically in 648 permanent, 0.2-ha plots distributed almost equally among the nine MOFEP sites. Since 1992, these plots have been reinventoried on a cycle of ~3 yr to document woody vegetation conditions. Characteristics recorded for each tree included species, diameter at breast height (dbh) or size class for trees <4 cm dbh, status (e.g., live, dead, den, cut, blow-down), and crown class (e.g., dominant, codominant, intermediate, suppressed). Trees 1 m tall to 4 cm dbh were inventoried in four 0.004-ha subplots, and trees between 4 and 11 cm dbh were inventoried in four 0.02-ha subplots nested within the 0.2-ha vegetation plots. To examine the relationship between tree species abundance and the concentration or quantity of exchangeable Ca and Mg, preharvest inventory data collected during the winter of 1994 to 1995 were used. For all tree species >1 m tall, basal area (per-hectare basis) was calculated for each of the five most common species—white oak, black oak, scarlet oak, post oak, and shortleaf pine– and by species group including the categories of other oaks, hickory, maple, dogwood, and other species. During the soil-landscape investigation, bedrock formation, landform and slope position, and aspect were recorded for each vegetation plot. Near the center of each plot, a soil pit was excavated by hand to describe the soil and determine distinguishing morphological features including diagnostic and genetic soil horizons, parent material type(s), depth to bedrock, presence of a fragipan, and soil drainage class (for details, see Kabrick et al., 2000). These data allowed us to select a subset of 297 permanent vegetation plots that were each uniform in slope position and soil properties.

Analysis

Conducting meaningful parametric tests of soil and topographic factors was not possible because (i) not all combinations of soil and topographic factors occurred in the landscape and (ii) many of these factors are not completely independent of one another. In fact, this lack of independence is a common problem plaguing many pedological and ecological investigations. Consequently, we used CART analysis to examine the role of the soil and geomorphic factors in the concentrations and quantities of exchangeable Ca and Mg. Classification and regression tree analysis (Breiman et al., 1984) is a nonparametric, binary, recursive partitioning technique that has been applied to examine factors associated with ecological phenomena such as species abundance (De'ath 2002), tree mortality (Fan et al., 2006; Kabrick et al., 2004a), wood quality (LeMay et al., 1994), and insect infestations in forests (Negron, 1998). It has also been applied to soil and physiographic data to identify factors associated with the storage of soil C and N in forested landscapes (Kulmatiski et al., 2004; Johnson et al., 2009; Bedison and Johnson, 2009). The great benefit of CART is that this analysis procedure can be used to examine complex data that include imbalances, interactions, and nonlinear relationships found in many ecological, pedological, and forestry data sets (De'ath, 2002; Kulmatiski et al., 2004).

Generally, CART modeling includes two parts: a top-down recursive partitioning process and a bottom-up pruning process (i.e., cross-validation procedure). For this study, exchangeable Ca and Mg concentrations (g kg^{-1}) and quantities (kg ha^{-1}) for each pedon were examined and treated as continuous response variables. Explanatory variables investigated included: (i) type of parent material (alluvium, pedisediment, residuum, or pedisediment overlying residuum); (ii) un-

Table 2. Example calculation of mass-weighted exchangeable Ca concentration and quantity for Pedon M9561326.

Horizon	Depth	Fine-earth fraction	Bulk density†	Horizon mass‡	Horizon mass fraction§	Ca conc.¶	Mass-weighted conc.#	Exchangeable Ca quantity††
	cm		g cm^{-3}	g		—— cmol$_c$ kg^{-1} ——		kg ha^{-1}
A	0–10	0.65	1.4	9.1	0.08	0.7	0.1	127
E	10–23	0.65	1.5	12.7	0.12	0.2	0.02	51
Bt1	23–41	0.60	1.5	16.2	0.15	0.5	0.1	162
Bt2	41–64	0.48	1.6	17.7	0.16	1.4	0.2	495
2Bt3	64–99	0.53	1.3	24.1	0.22	1.9	0.4	916
2Bt4	99–145	0.40	1.3	23.9	0.22	0.9	0.2	431
2Bt5	145–150	0.85	1.4	6.0	0.05	0.5	0.03	60
Total				109.6			1.0	2241

† Obtained from the Missouri Cooperative Soil Survey.
‡ Horizon mass = depth × bulk density × fine-earth fraction.
§ Horizon mass fraction = horizon mass/total mass (sum of all horizons).
¶ Exchangeable Ca concentration obtained from soil characterization laboratory report and this value can be converted to grams Ca per kilogram soil by multiplying by 0.2.
# Mass-weighted concentration = horizon mass fraction × Ca concentration.
†† Exchangeable Ca quantity = Ca concentration × depth × bulk density × fine-earth fraction × 20 (to convert to kg ha^{-1} basis).

derlying bedrock formation (Roubidoux, upper or lower Gasconade, or Eminence); (iii) depth to bedrock (shallow, <50 cm; moderately deep, 51–100 cm; deep, 101–150 cm; or very deep, >150 cm); (iv) soil drainage class (excessively drained, well drained, or moderately well drained); (v) the presence or absence of a fragipan; and (vi) slope position (as defined in Table 1).

During the first iteration of the partitioning process, an algorithm was used to split the data into two mutually exclusive groups or "nodes" (high and low exchangeable Ca or Mg concentration or quantity) using explanatory variables such that the variation of the two groups or nodes created by splitting the data was minimized. For continuous data such as Ca and Mg concentrations and quantities, splitting was done to maximize the deviance criteria $SS_T - (SS_L + SS_R)$, where SS_T is the the sum of squares for the data and SS_R and SS_L are the sums of squares for the right and left nodes created by splitting the data (Breiman et al., 1984). During successive iterations of the partitioning process, each of the two groups or nodes created during a previous iteration was further partitioned into two subsets using the explanatory variables, further reducing the overall variation in the data set. We continued this process until further splitting failed to reduce the residual variation of the data below 1%, thus leaving the final or "terminal" nodes unsplit. Terminal nodes are represented graphically in a "tree" where each branch is labeled with the variables associated with the splitting.

The second stage or part of the CART process was the bottom-up pruning of the trees to identify optimal branching. We pruned the trees using a 10-fold cross-validation that allowed us to identify a tree with the number of branches and having the smallest overall error. During this procedure, the data were partitioned into 10 equal groups, each having a similar distribution. The largest possible trees were created using 0.9 of the data and the error was calculated between this tree and another comprising the remaining 0.1 of the data. This process was continued until each group of 0.1 of the data served once for the error comparison. The optimum tree had the lowest overall error rate or was the smallest tree, where larger trees failed to substantially reduce the overall error. Further discussion of the cross-validation procedure used can be found in Efron (1983).

Once the optimum tree was identified, we used a bootstrap procedure ($n = 200$) to estimate 95% confidence intervals for the mean exchangeable Ca or Mg concentrations or quantities of the terminal nodes of the pruned trees. The CART modeling and bootstrapping were conducted using R version 2.8.1 (rpart version 3.1–42 and bootstrap version 1.0–21, The R Foundation for Statistical Computing, Vienna, Austria).

Linear regression was used to examine the relationships between CEC (independent variable) and exchangeable Ca or Mg concentrations (dependent variable). Analyses were performed using mass-weighted estimates in the epipedon and the upper and lower diagnostic subsurface horizons (sensu Soil Survey Staff, 1999) by parent material type (i.e., alluvium, pedisediment, or pedisediment over residuum). To determine if factors associated with exchangeable Ca and Mg concentrations or quantities were related to tree species composition, an ANOVA was conducted using the basal area of each tree species as the response variable and factors (i.e., terminal nodes) identified in the CART analyses for exchangeable Ca and Mg concentration and quantity as effects in a model. The most abundant tree species investigated were black oak, scarlet oak, white oak, and post oak. Less abundant species were grouped as follows: other oaks (comprising primarily chinkapin oak and minor basal areas of northern red oak, Shumard oak, and blackjack oak); hickory (primarily pignut hickory, black hickory, and mockernut hickory); maple (red maple and sugar maple); and dogwood (primarily flowering dogwood). Analyses were conducted separately by species or species group. Because all nine MOFEP sites were used for this analysis, interaction of the effect with site was used as the error term. To normalize the data, species basal area data were transformed before analyses by taking the square root. For significant effects, Fisher's LSD was used to compare individual means. Regression analyses and ANOVA were conducted using the general linear models procedure (PROC GLM) in SAS statistical software (SAS version 9.1, SAS Institute, Cary, NC).

RESULTS

In the most common soil horizons in the 74 pedons, the average exchangeable Ca concentrations ranged from 0.1 to 1.2 g kg^{-1} and the average exchangeable Mg concentrations ranged from 0.1 to 0.7 g kg^{-1} (Table 3). Exchangeable Ca concentrations were one- to twofold greater than Mg, and exchangeable concentrations of these two base cations were one- to >10-fold greater than exchangeable K concentrations in each horizon. There was considerable variation in the Ca and the Mg concentrations in each horizon, however, and values ranged from about 0 to 6 g kg^{-1} for Ca and 0 to 3 g kg^{-1} for Mg. Despite the low concentrations of these cations when examined individually, the average base saturation (determined by summation) was never zero in any single horizon and base saturation was ≥14% in the most common soil horizons. The absence of zero values can be attributed to one or more other base cations being present when Ca or Mg was undetected. The wide range of exchangeable Ca and Mg concentrations prompted us to examine the geomorphic and soil characteristics potentially explaining this variation, providing insight into where soils in the landscape are more likely to have greater or lower exchangeable supplies of these base cations.

Table 3. Exchangeable base cation concentrations and base saturation (by summation) for selected horizons from 74 pedons sampled at the Missouri Ozark Forest Ecosystem Project.

Horizon	n†	Ca	Mg	K	Base saturation
		g kg^{-1}			%
A	72	0.8 ± 1.0 (0–6.4)‡	0.2 ± 0.2 (0–1.9)	0.1 ± 0.1 (0–0.2)	28 ± 19 (3–71)
E	18	0.1 ± 0.1 (0–0.3)	0.1 ± 0.1 (0–0.1)	0.1 ± 0.1 (0–0.1)	14 ± 9 (6–39)
Bt1	68	0.4 ± 0.8 (0–4.8)	0.2 ± 0.4 (0–2.1)	0.1 ± 0.1 (0–0.3)	28 ± 16 (2–78)
Bt2	62	0.4 ± 0.7 (0–5.5)	0.2 ± 0.3 (0–2.1)	0.1 ± 0.1 (0–0.2)	32 ± 16 (2–78)
2Btx1	12	0.2 ± 0.1 (0–0.4)	0.1 ± 0.1 (0–0.2)	0.1 ± 0.1 (0–0.1)	20 ± 8 (3–71)
2Bt3	23	1.2 ± 1.3 (0.04–4.5)	0.7 ± 0.8 (0.1–2.6)	0.1 ± 0.1 (0–0.3)	47 ± 20 (12–81)
2Bt4	27	0.9 ± 1.1 (0.04–5.0)	0.6 ± 0.8 (0–3.2)	0.1 ± 0.1 (0–0.3)	39 ± 21 (10–88)
2Bt5	27	1.0 ± 1.3 (0–6.1)	0.6 ± 0.8 (0–3.3)	0.1 ± 0.1 (0–0.3)	37 ± 21 (8–78)

† Number of samples for each horizon that were used in the statistical analyses.
‡ Values are means ± 1 standard deviation with range in parentheses.

Relationships between Exchangeable Calcium and Magnesium and Predictor Variables from the Classification and Regression Tree Analysis

The CART procedure indicated that the depth to the underlying bedrock and the bedrock lithology were the two most important factors explaining the variation in exchangeable Ca and Mg concentrations. Together these variables explained 61 and 41% of the total variation in the exchangeable Ca and Mg concentrations, respectively (Fig. 2). Depth to bedrock was the single most important explanatory variable and alone it accounted for most of the variation: soils <1 m deep had approximately 4.8 times greater exchangeable Ca concentrations and 3.8 times greater exchangeable Mg concentrations than soils >1 m deep.

For soils >1 m deep, partitioning by the underlying bedrock formation accounted for an additional 7% of the variation in exchangeable Ca concentrations. The soils >1 m deep overlying the Roubidoux or upper Gasconade formations had lower Ca concentrations (0.30 g kg^{-1} Ca) than the deep or very deep soils overlying the Eminence and lower Gasconade formations (0.84 g kg^{-1}). Magnesium concentrations followed a similar trend except that the grouping of bedrock formations was slightly different. For Mg, soils >1 m deep overlying the Roubidoux, the upper Gasconade, or the Eminence formation had an average concentration of about 0.24 g kg^{-1}, while those overlying the lower Gasconade formation had Mg concentrations 2.5-fold greater.

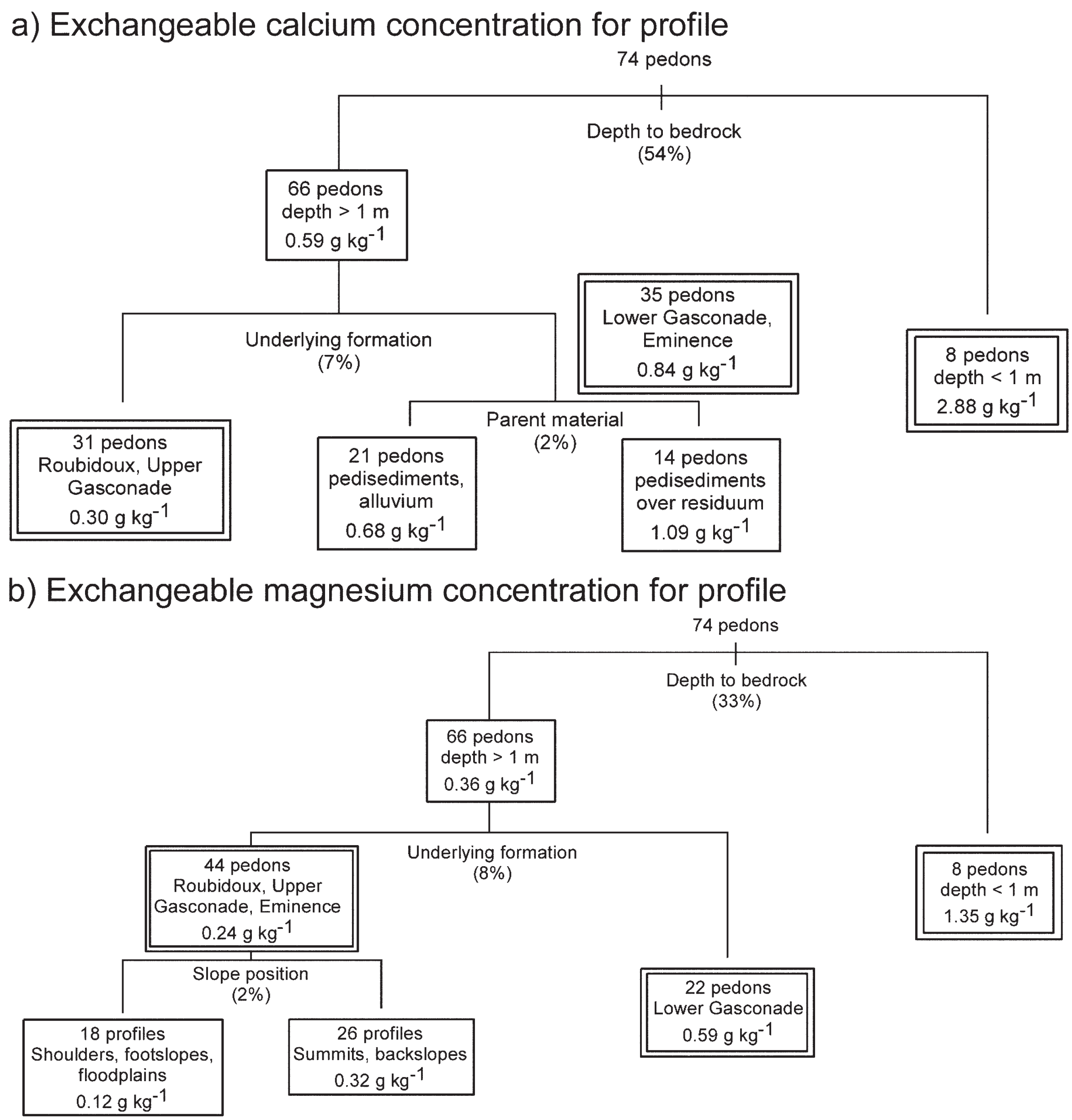

Fig. 2. Regression trees for exchangeable (a) Ca and (b) Mg concentrations developed from the classification and regression tree analysis. Concentrations were estimated on a mass basis by horizon and averaged for the profile. Each branch of the regression tree is labeled with the explanatory variable associated with the partitioning of the response variable. Boxes represent the nodes determined by the splitting criterion and include the number of profiles, the explanatory variable associated with the splitting criterion, and the mean exchangeable Ca or Mg concentration. Double-lined boxes represent terminal nodes of the optimal trees derived from the cross-validation procedure.

During the initial recursive partitioning step of the analysis, other factors were identified as significantly related to exchangeable Ca and Mg concentrations. For soils >1 m deep and overlying the Eminence and lower Gasconade formations, those that formed in gravelly alluvium and gravelly pedisediment had lower Ca concentrations than soils that contained clayey residuum. For Mg, soils overlying the Roubidoux, upper Gasconade, and Eminence formations had higher exchangeable concentrations on summits and backslope positions. These factors, however, each accounted for only 2% of the total error and the cross-validation procedure suggested that these factors should be omitted from the optimum regression trees shown in Fig. 2. Our analysis also indicated that exchangeable Ca and Mg concentrations were not related to soil drainage class or the presence or absence of a fragipan.

Although exchangeable base cation concentrations provide a good indication of cation supply, the quantity of cation supply is also affected by the total soil volume. Soils that have low cation concentrations may have moderate or high total quantities of base cations if they are deep. Consequently, we examined the total exchangeable quantity of Ca or Mg (in kg ha^{-1}) with the CART procedure using the same explanatory variables (Fig. 3). The CART analysis indicated that

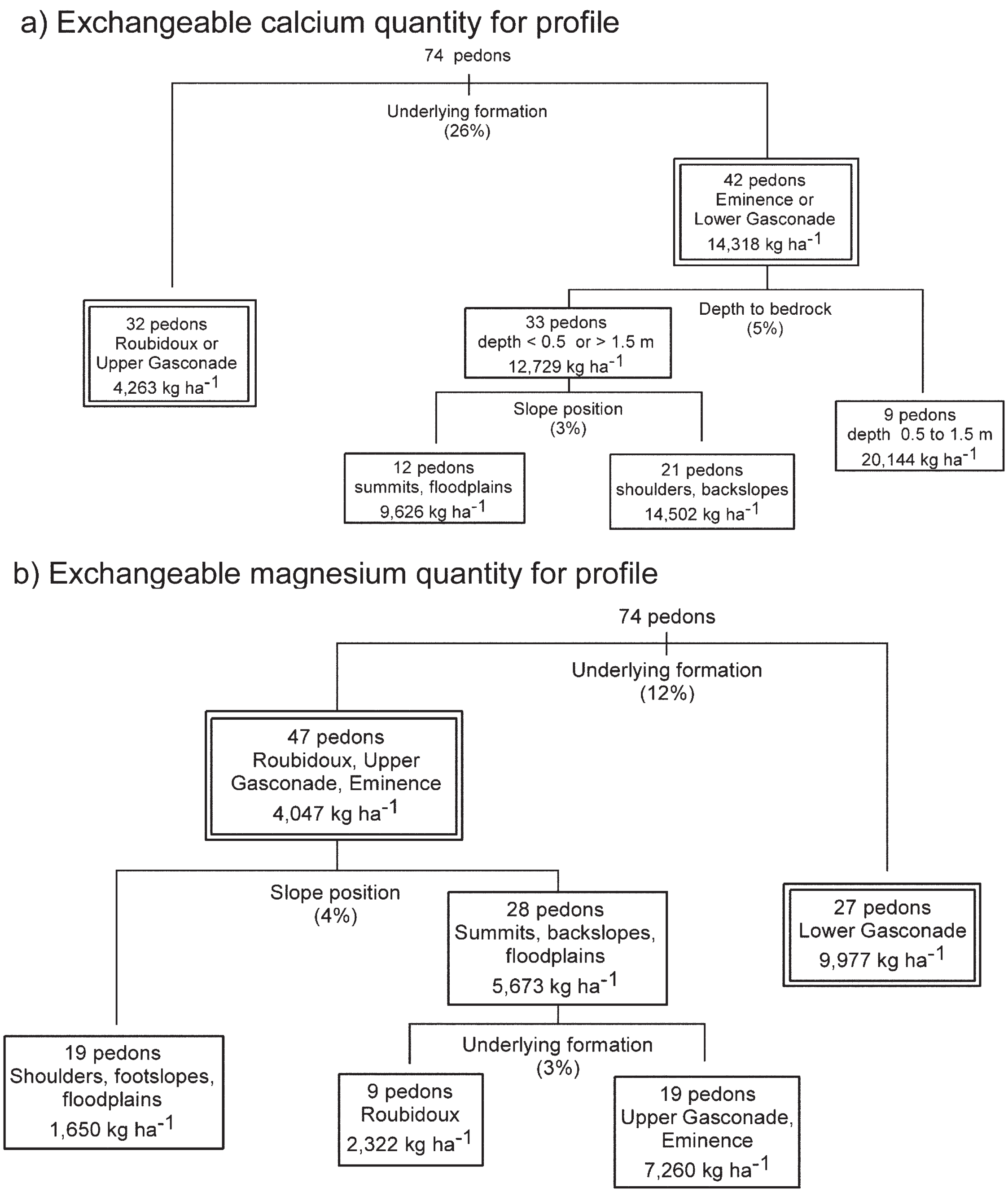

Fig. 3. Regression trees for exchangeable (a) Ca and (b) Mg quantities developed from the classification and regression tree analysis. Quantities were estimated for the entire profile. Each branch of the regression tree is labeled with the explanatory variable associated with the partitioning of the response variable. Boxes represent the nodes determined by the splitting criterion and include the number of profiles, the explanatory variable associated with the splitting criterion, and the mean exchangeable Ca or Mg quantity. Double-lined boxes represent terminal nodes of the optimal trees derived from the cross-validation procedure.

bedrock formation underlying the soil was the most important factor, accounting for 26 and 12% of the variation in the exchangeable Ca and Mg quantities, respectively. Similar to the concentrations analysis, higher exchangeable Ca quantities occurred in soils overlying the Eminence and lower Gasconade formations and higher quantities of exchangeable Mg occurred in soils overlying the lower portion of the Gasconade formation. Depth to the underlying bedrock and slope position were also identified as important factors related to exchangeable Ca quantities but each accounted for <5% of the variation in exchangeable Ca. For the quantity of exchangeable Mg, slope position and an additional split by bedrock formation were also identified as important factors, but each accounted for only <4% of the variation. The cross-validation step of the CART procedure indicated that optimum regression trees included only a single split of bedrock formation underlying the soil. For all CART analyses, the means and 95% confidence intervals for the terminal nodes of cross-validated regression trees for both exchangeable Ca and Mg concentrations and quantities are included in Table 4.

Relationships between Exchangeable Calcium and Magnesium by Parent Material and Cation Exchange Capacity

Although the CART analysis suggested that soil parent material was a minor explanatory variable in the analysis of exchangeable Ca and Mg concentration or quantity, there are important differences in element vertical distributions among pedons of different parent material type. We initially postulated that clayey residuum in the subsoil underlying gravelly pedisediment would probably retain a greater concentration of exchangeable cations than soils formed exclusively in gravelly alluvium or gravelly pedisediment. When the data were partitioned by surface and subsurface diagnostic horizons, the exchangeable Ca concentration was found to be nominally greater in epipedons of alluvial soils relative to epipedons of soils formed in other parent materials (Fig. 4a). In contrast, exchangeable Mg concentrations in epipedons were similar in magnitude regardless of parent material type (Fig. 4b). Exchangeable Ca or Mg concentrations were considerably greater in the subsoil diagnostic horizons formed in pedisediment overlying clayey residuum compared with the other parent material types.

Exchangeable Ca and Mg concentrations were highly correlated to CEC irrespective of parent material type (Fig. 5), indicating its importance for retaining Ca and Mg in these soils. Linear regression analysis suggested that the relationship between exchangeable Ca concentration and CEC differed slightly by parent material type. For soils formed in pedisediment or pedisediment overlying residuum, the relationships between exchangeable Ca concentration and CEC were very similar to each other. We observed, however, that alluvium generally had a greater Ca concentration for a given level of CEC. This was not observed for Mg in alluvial soils and the relationship between Mg concentration and CEC was about the same regardless of parent material type.

Relationship between Forest Vegetation and Factors Related to Exchangeable Calcium and Magnesium

We examined the MOFEP woody vegetation inventory data to determine if the same factors associated with exchangeable Ca or Mg concentrations or quantities were related to tree species composition (Tables 5 and 6). Black oak, scarlet oak, white oak, and hickories were significantly ($P < 0.03$) more abundant with factors associated with low exchangeable Ca and Mg concentrations. The categories of "other oaks" and "other species" were significantly ($P < 0.05$) more abundant on soils having greater exchangeable Ca concentrations. Although not significant, we observed that maples were nominally more abundant on soils having high Ca concentrations. Similar trends occurred when partitioned by the factors related to exchangeable Ca or Mg quantity, but abundance differences were not as large or as significant, particularly for Mg. Black oaks were significantly ($P < 0.01$) more abundant on soils having lower Ca quantities. Dogwoods, "other oaks," and "other species" were significantly ($P < 0.04$) more abundant on soils having greater Ca quantities. Only "other oaks" were significantly ($P = 0.02$) more abundant on soils having higher Mg quantities.

Table 4. Exchangeable Ca and Mg means and 95% confidence intervals (CI) for terminal nodes identified after applying a 200-fold cross-validation to the optimal regression trees obtained from the classification and regression tree analysis.

Terminal node	Mean	95% CI
Exchangeable Ca concentration, g kg^{-1}		
Deep or very deep (>1-m) soils formed in materials from the Roubidoux or upper Gasconade formations	0.30	0.21–0.41
Deep or very deep (>1-m) soils formed in materials from the Eminence or lower Gasconade formations	0.84	0.65–1.04
Shallow to moderately deep soils (<1 m) regardless of the source of the parent materials	2.88	1.87–3.78
Exchangeable Mg concentration, g kg^{-1}		
Deep or very deep (>1-m) soils formed in materials from the Roubidoux, upper Gasconade, or Eminence formations	0.24	0.17–0.32
Deep or very deep (>1-m) soils formed in materials from the lower Gasconade formation	0.59	0.38–0.84
Shallow to moderately deep (<1-m) soils regardless of the source of the parent materials	1.35	0.95–1.64
Exchangeable Ca quantity, kg ha^{-1}		
Soils formed in material from the Roubidoux or upper Gasconade formations	4,263	2,829–6,196
Soils formed in material from the Eminence or lower Gasconade formations	14,318	10,900–17,348
Exchangeable Mg quantity, kg ha^{-1}		
Soils formed in material from the Roubidoux, upper Gasconade, or Eminence formations	4,047	2,691–6,095
Soils formed in material from the lower Gasconade formation	9,977	6,827–13,931

DISCUSSION

Factors Affecting Exchangeable Calcium and Magnesium Concentrations and Quantities Identified in the Classification and Regression Tree Analyses

The CART analysis average exchangeable Ca and Mg concentrations were primarily related to the depth to the underlying bedrock. Soils <1 m deep had higher Ca and Mg concentrations than those that were deeper than 1 m. In this region of the Ozark Highlands, the lithology of the underlying bedrock is primarily dolomite (Keys et al., 1995), which undoubtedly serves as the primary source of the Ca and Mg found in the soils. In shallow soils, all parts of the soil profile appear to benefit from the release of Ca and Mg during the weathering of the underlying dolomite, thus raising the overall Ca and Mg concentration throughout the soil profile. Depth to bedrock also appeared to affect many soil properties that influence Ca and Mg retention. For example, deeper soils tended to have less clay, a greater volume of cherty coarse fragments, and a lower CEC than shallower soils (Fig. 6).

The cycling of Ca and Mg by trees probably plays an important role in retaining these cations as well (Johnson and Todd, 1998; Trettin et al., 1999). Our soil descriptions indicated the presence of fine roots throughout most horizons, but the majority of roots were found in the upper 1 m of soil. Therefore, in shallow and moderately deep soils (i.e., <1 m), tree roots are sufficiently close to the underlying dolomite to exploit the reserves of Ca and Mg released during weathering. For very deep soils (i.e., >1.5 m deep), however, Ca and Mg reserves may be too deep for most roots to reach except where deep rooting from the largest and oldest trees occurs (Johnson and Todd, 1998; Trettin et al., 1999). There probably are few other sources of Ca and Mg in these soils because they do not contain dolomite coarse fragments and most of the soils have a siliceous mineralogy (Table 1).

Of the soils that were >1 m deep, the bedrock formation underlying the soil was also related to exchangeable Ca and Mg concentrations (Fig. 2). Soils formed in parent materials derived from the underlying Eminence and lower Gasconade formations had greater concentrations of Ca than the soils formed from parent materials derived from the underlying Roubidoux and upper Gasconade formations. In the study region, the Roubidoux formation comprises interbedded layers of sandstone and cherty dolomite and the loamy sediments derived from the sandstone contain substantial amounts of quartz, which does not supply Ca when weathered or does not contribute to the CEC (Bailey, 2000). Similarly, the upper Gasconade formation contains a number of chert beds and the parent materials derived from it largely comprise multiple layers of cherty and highly weathered pedisediment (Meinert et al., 1997). Much like quartz, chert does not supply base cations when it is weathered (Keller, 1961). Thirteen of the 16 pedons sampled in the parent materials derived from the upper Gasconade formation contained only layers of pedisediment (Table 1) and generally had less exchangeable Ca and Mg concentrations in the lower profile than did those that also included residuum (Fig. 4). In contrast, parent materials derived from dolomites of the lower Gasconade and Eminence formations appeared to be less weathered. Twelve of the 27 pedons in parent materials derived from the lower Gasconade formation and eight of the 15 pedons in parent materials derived from the Eminence formation were each classified as having a mixed mineralogy rather than a siliceous mineralogy (Table 1). These soils also contained clayey residuum or clayey pedisediment in the lower part of their profiles, which had greater concentrations of exchangeable Ca and Mg (Fig. 4).

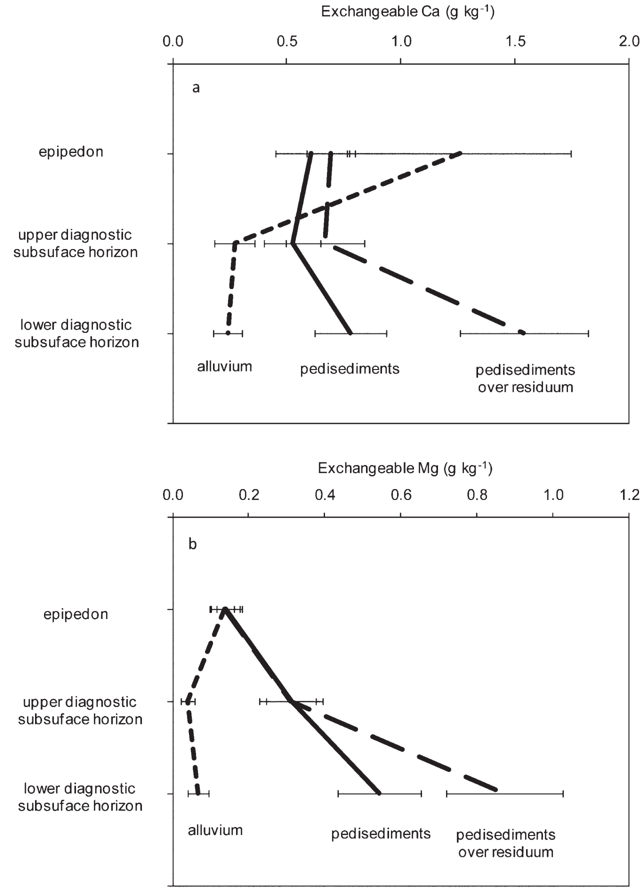

Fig. 4. Exchangeable (a) Ca and (b) Mg concentrations in the diagnostic surface and subsurface horizons by parent material type. Error bars indicate ± one standard error.

The finding that factors associated with Ca concentrations or quantities were also associated with Mg was anticipated. It was surprising, however, to find greater Mg concentrations and quantities in soils overlying the lower Gasconade formation. This result suggests that the Mg content of the dolomite comprising the lower Gasconade formation is greater than that of the dolomite of other formations in the study area. Presently, we are unaware of any published information on the chemical composition of the bedrock or geospatial chemical composition data for this region. Additional studies required to test this hypothesis are beyond the scope of this work, but such studies are warranted to more fully elucidate the cause of elevated Mg concentrations in soils overlying the lower Gasconade formation.

The CART analysis also showed that factors closely related to exchangeable Ca and Mg concentrations were also related to exchangeable Ca and Mg quantity; however, the total quantity

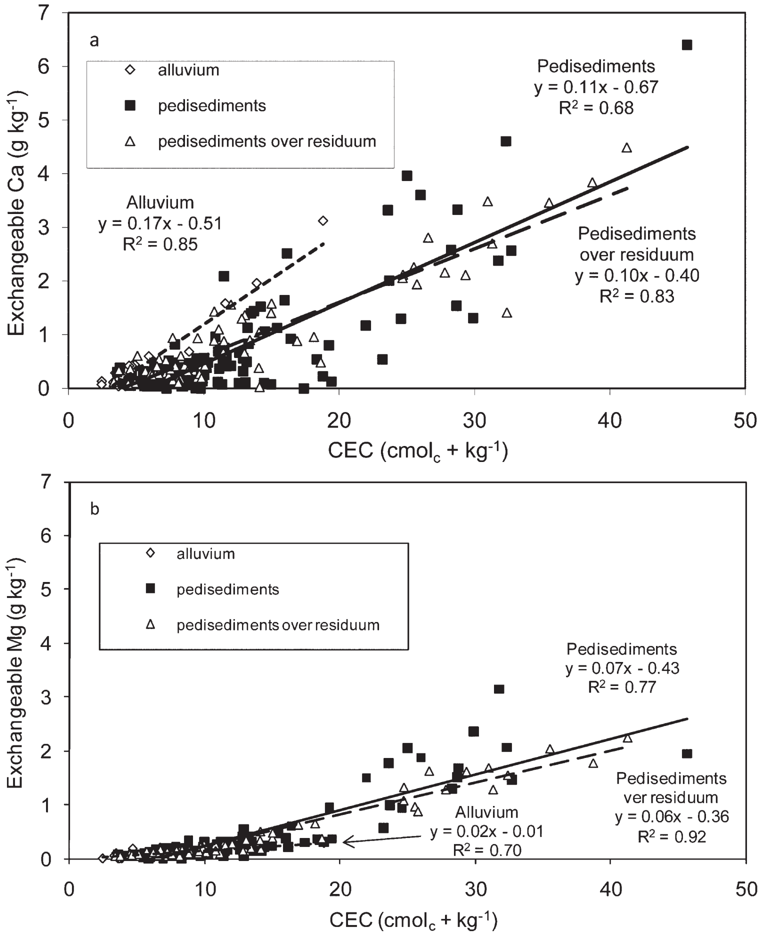

Fig. 5. Relationship between exchangeable (a) Ca and (b) Mg concentrations and soil cation exchange capacity (CEC) in the diagnostic surface and subsurface horizons by parent material type.

of exchangeable Ca and Mg appears to be much more variable and difficult to predict. The analysis could only account for 26% of the variation in Ca quantity and 12% of the variation in Mg quantity, considerably less than the 61% and 41% observed for Ca and Mg concentrations, respectively. It is likely that other factors are more closely correlated with exchangeable Ca or Mg quantity than the set of soil and geomorphic explanatory variables analyzed. We were interested in the selected variables because they are commonly identified as important factors affecting exchangeable Ca and Mg and are used for mapping soils and allocating stands into ecological land types in this region. Our findings suggest that the factors that we investigated are more useful for predicting exchangeable concentrations of Ca and Mg than exchangeable quantities.

It is also interesting to note that the CART analysis suggested that landform and slope position had a less prominent role in determining the exchangeable Ca and Mg in these landscapes. Collectively, these factors largely govern the redistribution of water in the landscape and consequently are reported to be important for redistributing cations (Trettin et al., 1999). The CART analysis suggested that slope position played a much lesser role in these ecosystems than factors more closely related to depth to bedrock and the nature of the underlying bedrock formation in our study area. Johnson et al. (2000) also found that terrain features derived from geographic information system models were poorly correlated with base cation concentrations and other chemical properties in forest soils of the Catskill Mountains in New York. We included variables related to drainage and the presence of a fragipan (which both act to inhibit downward movement of nutrients) in our analyses; however, the CART analysis indicated that these factors were not important in our study area.

Relationships between Exchangeable Calcium and Magnesium by Parent Material

Even though soil parent material type (e.g., alluvium, pedisediment, or pedisediment over residuum) identified in the CART analysis was pruned from regression trees during the cross-

Table 5. Average basal area of tree species by terminal nodes from the classification and regression tree analysis for exchangeable soil Ca concentration and quantity.

Terminal node	Ca level	Average basal area									
		Black oak	Scarlet oak	White oak	Post oak	Other oaks	Hickory	Maple	Pine	Dogwood	Other species
		m² ha⁻¹									
By factors related to Ca concentration within pedons											
Deep or very deep (>1-m) soils formed in materials from the Roubidoux or upper Gasconade formations	low	7.3 a†	4.6 a	4.0 ab	1.7 a	0.8 a	2.6 a	0.2 a	2.4 a	0.6 a	0.7 a
Deep or very deep (>1-m) soils formed in materials from the Eminence or lower Gasconade formations	⇓	4.1 b	4.8 a	5.3 a	2.2 a	0.7 a	2.8 a	0.2 a	2.3 a	0.9 b	1.2 b
Shallow to moderately deep soils (<1-m) regardless of the source of the parent materials	high	2.1 c	2.8 b	3.9 b	2.1 a	2.1 b	1.6 b	0.4 a	2.7 a	0.7 ab	2.3 b
By factors related to Ca quantity within pedons											
Soils formed in material from the Roubidoux or upper Gasconade formations	low	7.3 a	4.6 a	4.1 a	1.8 a	0.8 a	2.6 a	0.2 a	2.4 a	0.6 a	0.7 a
Soils formed in material from the Eminence or lower Gasconade formations	high	3.7 b	4.3 a	5.0 a	2.2 a	1.4 b	2.6 a	0.2 a	2.4 a	0.8 b	1.4 b

† Within columns, means followed by different letters are significantly different ($\alpha = 0.5$)

validation, parent material had an important effect on the vertical distribution of Ca and Mg within pedons (Fig. 4). The alluvial soil epipedons had greater concentrations of exchangeable Ca than alluvial subsoils and greater concentrations than epipedons of soils from other parent material types. This finding suggests considerable enrichment with Ca in alluvial soils, presumably by surface and subsurface flow from the adjacent uplands and by the deposition of relatively unweathered sediments during flooding. The vertical distribution of Mg was very different from that of Ca. Relatively low Mg concentrations were observed in epipedons compared with the subsoil diagnostic horizons, suggesting greater leaching of Mg than Ca or differences in nutrient cycling. In temperate forest ecosystems, Ca availability is largely driven by uptake and cycling (Knoepp and Swank, 1994; Richter et al., 1994; Trettin et al., 1999; Johnson et al., 2008) which may explain the greater concentrations of Ca higher in the profile. The uptake and cycling of Mg has been shown to be considerably less compared with Ca in temperate forests, and consequently Mg is more vulnerable to leaching losses (Johnson et al., 2008). This mechanism may explain the relatively low Mg concentrations in epipedons and the greater exchangeable Mg concentrations lower in the profile compared with Ca. The greater clay content (and consequently greater CEC) that occurs lower in the profile of the soils formed in pedisediment or pedisediment overlying residuum appears to play an important role in retaining cations, particularly Mg, perhaps by reducing leaching losses.

Regional Comparisons of Exchangeable Calcium and Magnesium

The average concentrations of Ca and Mg at our study sites are similar in magnitude to those reported for mineral soil horizons of forested Alfisols and Ultisols formed in unglaciated parent materials elsewhere in eastern North America (Table 7), including the Southern Appalachian Piedmont Section in northern Georgia (Huntington et al., 2000), and the Allegheny Plateau of northwestern Pennsylvania and southern New York (Bailey et al., 2004). Average concentrations of Ca and Mg at our study area are about an order of magnitude greater than those reported for soils having similar parent materials in the Ridge and Valley Section in eastern Tennessee (Johnson et al., 2008).

Of greater interest than average concentrations is the variation in exchangeable Ca and Mg across the landscape and the soil and geomorphic factors associated with this variation. For soils of the Ridge and Valley Section of eastern Tennessee, Trettin et al. (1999) reported that total exchangeable pools and nutrient fluxes were greater in lower slope positions and depressional settings where nutrients carried in the soil water accumulate. They found few differences that could be attributed to the type of parent material, largely because the soils were highly weathered and consequently similar to one another. These findings suggest that slope position probably plays a more important role than parent material in the Ridge and Valley Section than in the Ozark Highlands despite many similarities in parent material types, bedrock lithologies, and soil properties in our respective study areas. Johnson et al. (2000) also reported that terrain characteristics such as slope, aspect, and flow accumulation accounted for very little variation (5–24%) in exchangeable cations for the Catskill Mountains in New York compared with other soil properties such as CEC and pH. Soil parent materials and the depth to regolith appear to play a more prominent role in exchangeable Ca and Mg pools in the Allegheny Plateau (Bailey et al., 2004), where soils developed in the relatively unweathered glacial till containing Ca- and Mg-bearing minerals supply exchangeable Ca and Mg fairly evenly across all slope positions. Slope position appears to play a more important role in the unglaciated soils of the Allegheny Plateau, however, where the groundwater percolating through the underlying bedrock is enriched with Ca and Mg and is directed laterally to the soils in lower slope positions (Bailey et al., 2004).

Comparison of Ca and Mg quantities at the MOFEP (Fig. 2 and 3) with other reported values revealed that the range in

Table 6. Average basal area of tree species by terminal nodes from the classification and regression tree analysis for exchangeable soil Mg concentration and quantity.

Terminal node	Mg level	Average basal area									
		Black oak	Scarlet oak	White oak	Post oak	Other oaks	Hickory	Maple	Pine	Dogwood	Other species
		m^2 ha^{-1}									
By factors related to Mg concentration within pedons											
Deep or very deep (>1-m) soils formed in materials from the Roubidoux, upper Gasconade, or Eminence formations	low	6.7 a†	4.7 a	4.2 ab	1.8 a	0.8 a	2.6 a	0.2 a	2.4 a	0.6 a	0.8 a
Deep or very deep (>1-m) soils formed in materials from the lower Gasconade formation	⇓	4.7 b	4.6 a	5.3 a	2.3 a	0.5 a	2.9 a	0.1 a	2.2 a	0.9 a	0.9 b
Shallow to moderately deep soils (<1-m) regardless of the source of the parent materials	high	2.1 c	2.8 b	3.9 b	2.1 a	2.1 b	1.6 b	0.4 a	2.7 a	0.7 a	2.3 b
By factors related to Mg quantity within pedons											
Soils formed in material from the Roubidoux, upper Gasconade, or Eminence formations	low	6.3 a	4.5 a	4.2 a	1.7 a	1.2 a	2.5 a	0.2 a	2.5 a	0.6 a	1.0 a
Soils formed in material from the lower Gasconade formation	high	4.8 a	4.4 a	5.2 a	2.4 a	0.5 b	2.8 a	0.1 a	2.2 a	0.8 a	1.0 a

† Within columns, means followed by different letters are significantly different (α = 0.5).

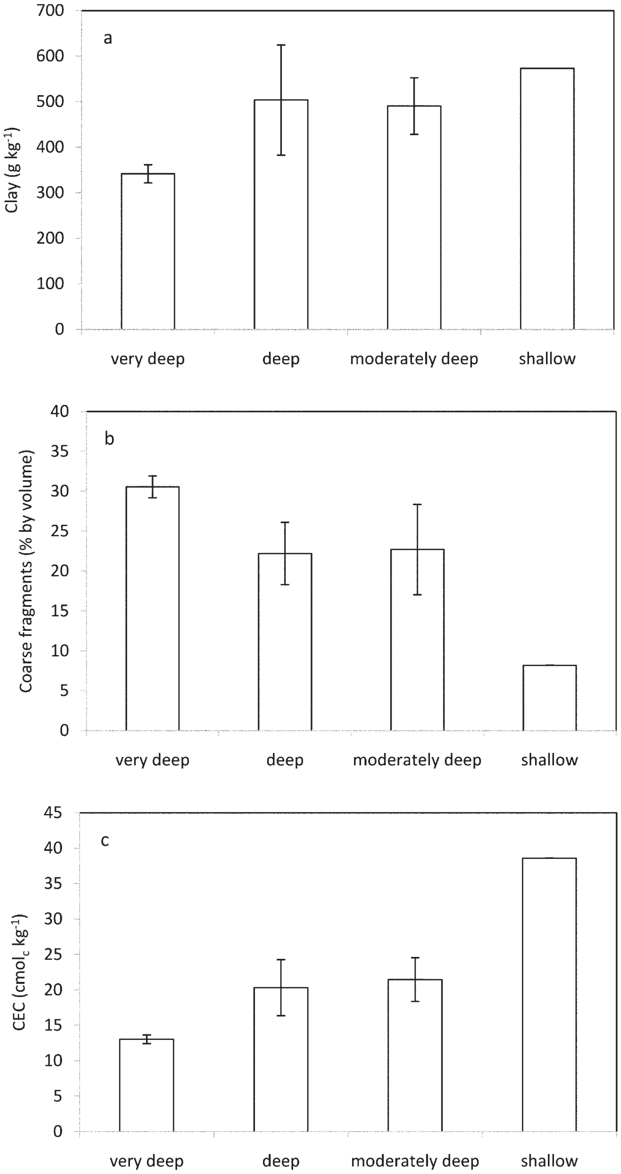

Fig. 6. Influence of soil depth on (a) clay content, (b) volumetric coarse fragment content, and (c) cation exchange capacity (CEC). Values are mean values for the entire profile weighted by mass on a horizon basis. Error bars indicate ± one standard error.

exchangeable Ca quantities is greater in our study area than elsewhere in eastern North America. Huntington et al. (2000) compiled exchangeable soil Ca quantity data from 15 sites in southeastern U.S. forest ecosystems and reported values ranging from <100 to ~7000 kg ha^{-1} Ca. Bailey et al. (2004) reported exchangeable Ca ranges from 360 to 4700 kg ha^{-1} and exchangeable Mg ranges from 110 to 1600 kg ha^{-1} within 19 sites across the Allegheny Plateau. In our study region, exchangeable Ca and Mg quantities among soils identified in the terminal nodes from the CART analysis ranged from 4263 to 14,318 kg ha^{-1} for Ca and 4047 to 9977 kg ha^{-1} for Mg. In fact, 13 of the 74 pedons had <2000 kg ha^{-1} of Ca and 13 pedons had >20,000 kg ha^{-1}. These ranges are greater than the total soil pools of Ca compiled by Federer et al. (1989) for a number of forest ecosystems in eastern North America (3300–10,300 kg ha^{-1}). It is difficult to know whether the wide range in values observed at the MOFEP is unique to the Ozark Highlands ecosystems or if they also occur in other study regions of comparable size, but our findings highlight the wide range in base cation availabilities that can occur within hillslopes representing only a few thousand hectares.

Forest Vegetation and Factors Related to Exchangeable Calcium and Magnesium

Although forest growth is most commonly limited by N (Federer et al., 1989; Johnson and Todd, 1998) or nutrients other than Ca and Mg, base cation saturation largely controls the degree of acidity in soils, thereby affecting the distribution of plants that are soil pH indicators (Pallardy, 1995). In the southeast Missouri Ozarks, Grabner (2002) found that some ground flora are indicators of acid soils (e.g., *Vaccinium* L. or blueberries) or indictors of high-pH soil (e.g., *Smilax* L. or green briers). In this study, relationships between soil and geomorphic factors related to exchangeable Ca and Mg concentration or quantity and the abundance of tree species present at the MOFEP were observed (Tables 5 and 6). Black and scarlet oak were each more abundant on soils with low exchangeable Ca and Mg concentration or quantity. These species are reportedly tolerant of sites having low nutrient and water supplies, and they often occur as the

Table 7. Exchangeable Ca and Mg concentrations in mineral soils of physiographic regions of the eastern United States.

Region†	Physiography	Component or horizon	Ca	Mg	Source
			— cmol$_c$ kg^{-1} —		
Allegheny Plateau (PA, NY)	middle backslopes in glacial materials	upper B	2.8 (0.7)‡	0.6 (0.3)	Bailey et al., 2004
Allegheny Plateau (PA, NY)	middle backslopes in nonglacial materials	upper B	2.2 (1.2)	0.4 (0.2)	Bailey et al., 2004
Piedmont (GA)	colluvium, residuum, or alluvium	A	3.2 (0.8)§	0.7 (0.1)§	Huntington et al., 2000
Piedmont (GA)	colluvium, residuum, or alluvium	Bt	0.5 (0.1)§	0.6 (0.1)	Huntington et al., 2000
Catskill Mountains (NY)	mineral soil	profile	0.2 (0.1)	0.1 (0.1)	Johnson et al. 2000
Ridge and Valley (TN)	colluvium and residuum	A	0.3 (0.3)	0.1 (0.1)	Johnson et al. 1998
Ridge and Valley (TN)	colluvium and residuum	Bt	0.2 (0.2)	0.2 (0.2)	Johnson et al. 1998
Ozark Highlands (MO)	colluvium, residuum, or alluvium	A	4.1 (5.1)	1.3 (2.1)	This study
Ozark Highlands (MO)	colluvium, residuum, or alluvium	Bt	2.1 (4.2)	1.5 (3.1)	This study
Ozark Highlands (MO)	colluvium, residuum, or alluvium	Bt2	2.0 (3.6)	1.7 (2.8)	This study

† States include Pennsylvania (PA), New York (NY), Georgia (GA), Tennessee (TN), and Missouri (MO).

‡ Values for Ca and Mg are means with standard deviations in parentheses unless otherwise noted.

§ Standard error in parentheses.

dominant species under these site conditions (Johnson, 1990b; Sander, 1990a). An abundance of "other oaks," largely comprising chinkapin oak as well as bur oak and Shumard oak, was observed on shallow soils overlying dolomite that are high in exchangeable Ca and Mg concentration and quantity. These three oak species are among the few oaks reportedly having a strong association with sites where soil pH is high or limestone outcrops are prevalent (Edwards, 1990; Johnson, 1990a; Sander, 1990b).

Given the wide distribution and ecological amplitude of the tree species present at the study sites, it is not too surprising that the associations between exchangeable base cation supply and the abundance of tree species were not particularly strong. For oaks in southern Ohio, Scherzer et al. (2003) reported foliar Ca

Table 8. Soil map units, series names, and ecological land types associated with the terminal nodes identified by the classification and regression tree analysis on exchangeable Ca concentration.

Terminal node	Soil map unit	Associated series	Ecological land type
By factors related to exchangeable Ca concentration within pedons			
Deep or very deep (>1-m) soils formed in materials from the Roubidoux or upper Gasconade formations	31	Midco	dry-mesic upland drainageway forest
	61C	Tonti	loess fragipan upland woodland
	63C	Scholton	chert fragipan upland woodland
	63D	Bendavis	ultic chert various depth upland woodland
	63F	Bender	sandstone various depth upland woodland
	72C	Tonti	loess fragipan upland woodland
	72D	Clarksville	ultic chert upland woodland
	80C	Clarksville	ultic chert upland woodland
	80D	Poynor	ultic chert upland woodland
	80F	Clarksville	ultic chert upland woodland
Deep or very deep (>1-m) soils formed in materials from the Eminence or lower Gasconade formations	27	Hercules	dry-mesic upland drainageway forest
	73C or D	Clarksville	ultic chert upland woodland
	75D	Alred	alfic chert upland woodland
	75F	Alred	alfic chert upland forest/woodland
	82D	Rueter	alfic chert upland woodland
	82F	Alred	alfic chert upland forest/woodland
	89C	Mano	alfic chert upland woodland
	89D	Ocie	chert/dolomite upland woodland
Shallow to moderately deep soils (<1-m) regardless of the source of the parent materials	74D	Arkana	chert/dolomite upland woodland
	74F	Arkana	chert/dolomite upland woodland
	81D	Bardley	chert/dolomite upland woodland
	81F	Bardley	chert/dolomite upland woodland
By factors related to exchangeable Ca quantity within pedons			
Soils formed in material from the Roubidoux or upper Gasconade formations	31	Midco	dry-mesic upland drainageway forest
	61C	Tonti	loess fragipan upland woodland
	63C	Scholton	chert fragipan upland woodland
	63D	Bendavis	ultic chert various depth upland woodland
	63F	Bender	sandstone various depth upland woodland
	72C	Tonti	loess fragipan upland woodland
	72D	Clarksville	chert upland woodland
	80C	Clarksville	ultic chert upland woodland
	80D	Poynor	ultic chert upland woodland
	80F	Clarksville	ultic chert upland woodland
Soils formed in material from the Eminence or lower Gasconade formations	27	Hercules	dry-mesic upland drainageway forest
	73C or D	Clarksville	ultic chert upland woodland
	74D	Arkana	chert/dolomite upland woodland
	74F	Arkana	chert/dolomite upland woodland
	75D	Alred	alfic chert upland woodland
	75F	Alred	alfic chert upland forest/woodland
	81D	Bardley	chert/dolomite upland woodland
	81F	Bardley	chert/dolomite upland woodland
	82D	Alred	alfic chert upland woodland
	82F	Alred	alfic chert upland forest/woodland
	89C	Mano	alfic chert upland woodland
	89D	Ocie	chert/dolomite upland woodland

or Mg concentration to be poorly correlated with the concentrations of these elements in soil A horizons. Other tree species are known to be more sensitive to nutrient supply than are oaks. For example, there is generally a greater correlation between soil base cation availability and foliar concentrations for sugar maple (Bailey et al., 2004; Hallett et al., 2006) and the health of sugar maple appears to be closely related to the base cation concentrations in the soil (Long et al., 1997). Liming soils has been shown to ameliorate decline in sugar maple stands that probably originates from inadequate supplies of Ca and Mg (Long et al., 1997). Accordingly, we found that maples were nominally more abundant on soils having higher Ca and Mg concentrations. We also recognize that for many of the other tree species in this region, factors controlling soil water availability such as slope position, aspect, and soil depth also influence species distribution (Pallardy, 1995; Kabrick et al., 2004b). The availability of soil water may be an equal or more important determinant of tree species abundance than base cation supply.

Application to the Soil Landscape

The soil and geomorphic properties examined in this study are used to map soils in this region and, when applied in conjunction with vegetation information, the properties are also used to allocate stands into ecological land types and phases. Linkage of these data to appropriate spatial databases will provide forest managers and soil scientists working in this region with a tool that can be used to estimate where in the landscape exchangeable Ca and Mg concentrations or quantities are likely to be high or low. This tool will aid in identifying soils potentially at risk for cation depletion by timber harvesting and effectively focus forest soil nutrient studies on mapping units where cation deficiencies may occur. By way of example, we grouped the soil map units and their associated series and ecological land types using the criteria identified in the terminal nodes for exchangeable Ca concentrations and quantities (Table 8). This analysis framework offers an additional means for grouping soils and ecological land types by their ability to supply Ca and Mg that complements the information afforded by traditional soil surveys or ecological classification systems. Similarly, others can use the approach developed here to identify soils that are potentially vulnerable to nutrient depletion in different regions and landscapes.

CONCLUSIONS

Concentrations of exchangeable Ca and Mg vary widely in soils of the Ozark Highlands, and the range in total Ca quantity in soils of the study area exceeded those reported across forested portions of eastern North America. Our CART analysis indicated that of the soil and geomorphic properties used to map soils and ecological land types in this region, depth to the underlying bedrock and bedrock lithology, were the two most important factors related to Ca and Mg concentrations. In combination, these two properties explained about 61 and 41% of the variation in exchangeable Ca and Mg, respectively. The underlying bedrock formation was the most important factor related to total exchangeable Ca and Mg quantity, but this variable only accounted for 26 and 12% of the variation, respectively. Other factors examined, such as parent material type and slope position, were also related to exchangeable Ca and Mg concentrations and quantities, but the analysis indicated that they were of minor importance. The common species of oak and hickory were significantly more abundant on soils having lower exchangeable Ca concentrations. Many of the other, less common tree species were significantly more abundant on soils having greater exchangeable Ca concentrations. Similar relationships were found for the factors associated with the total quantity of Ca in the soil (e.g., the underlying bedrock formation), although the relationships were not as strong. The analysis framework applied in this study provides a basis for distinguishing among soil map units and ecological land types by their pools of exchangeable Ca and Mg for further study of nutrient dynamics.

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