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DISTRIBUTION OF GEOMORPHIC LANDFORMS AND SOILS ALONG THE EL CAMINO REAL DE TIERRA ADENTRO IN THE SOCORRO AREA: IMPLICATIONS FOR TRAFFICABILITY AND TRAIL ROUTING

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Abstract—Establishment of trail systems was critical for early Euro-American discovery and expansion in North America. Despite the historical significance of these trail systems, few studies have documented the relationships between the physical landscape and the trails themselves. In particular, the spatial heterogeneity of terrain conditions and their control on trail establishment and preservation has seldom been evaluated in a quantitative manner. This study explores these themes along a segment of the El Camino Real de Tierra Adentro (ECR), one of the longest and most historic trails in the Americas. Specifically, we catalogue and assess major terrain features in the Socorro area of central New Mexico to evaluate their influence on trail routing decisions. This approach incorporates a cost-weighted trafficability analysis based on interpretations of the terrain qualities that most significantly affect mobility of large caravans common to the ECR. Our results demonstrate systematic linkages between terrain characteristics and trail routing locations. We hypothesize that this approach may have a range of future applications in evaluation of trail systems in other geographic locations, including assessment of human behavioral components of trail development or identification of trail segments and archaeological sites not previously known.

INTRODUCTION

El Camino Real de Tierra Adentro (ECR), "The Royal Road of the Interior Land," was a particularly important early Euro-American trade route that led through ~2500 km of rugged desert terrain from Mexico City, Mexico, to Santa Fe, New Mexico, USA. During the 17th and 18th centuries, Spaniards used the ECR as a means to provide supplies to numerous New Mexican missions. Thousands of livestock, hundreds of mules, and numerous goods were transported along the route via caravans of wagons that required wide and robust paths (Scholes, 1930). Unlike other trades routes of this period, ECR proved particularly formidable due to the harsh arid climate of the Chihuahuan Desert and logistically challenging terrain (Palmer et al., 1999). Conditions were especially arduous along the ~150 km stretch of trail passing through the Jornada del Muerto Basin near Las Cruces in southern New Mexico (Fig. 1). In addition to lacking access to fresh water or resting points on this section of trail (Kludt et al., 2015), travelers were forced to cross deep arroyos, traverse uneven and loose or unconsolidated terrain, and occasionally make wide swings through canyons and mountainous settings away from the Rio Grande Valley. Along the way, a variety of geomorphic features would have been encountered, many with mobility conditions that likely served as an impediment to wheeled traffic, slowed travel dramatically, or deterred it altogether.

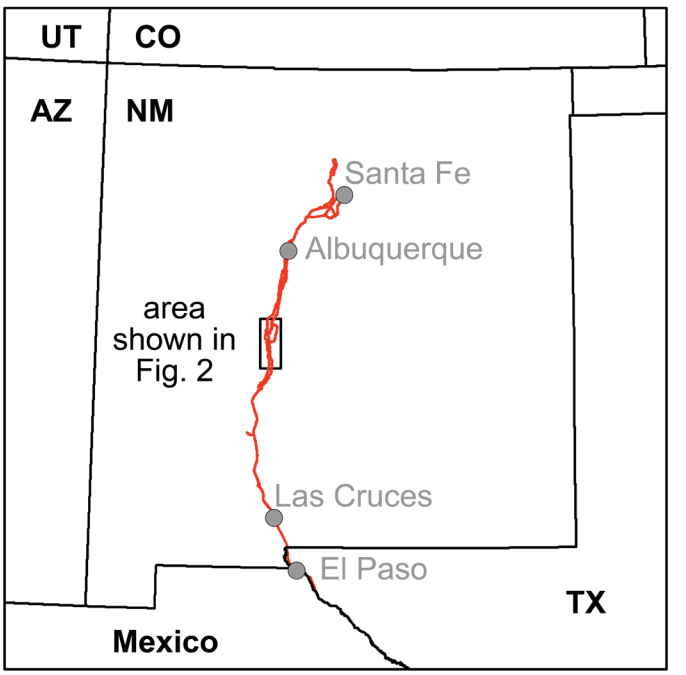


FIGURE 1. Location of the El Camino Real (ECR) trail route in New Mexico (red line). The trail enters the southern New Mexico border from El Paso, TX, and heads north through Las Cruces, Socorro, and Albuquerque, finally ending in the Santa Fe area of northern New Mexico. The black box indicates the location of the study area shown in Figure 2.

The literature utilizing detailed terrain analyses to evaluate and interpret the routes taken by historic trail systems like the ECR is sparse, but some examples do exist. A 2012 study examined soil properties along portions of the Mormon Pioneer Historic Trail (MPHT) in Iowa to evaluate the influence of past trail use on soil compaction (Brevik and Fenton, 2012). Historical aerial photographs were analyzed along portions of the MPHT in Wyoming to assess the effects of modern recreation on trail preservation (McDougal et al., 2008). A GIS database of major geologic, hydrologic, and soil characteristics was developed for the El Camino Real de Los Tejas to identify and

characterize the archaeological expression of various trail segments (Williams, 2007). Although these studies provided vital information for locating and/or ensuring proper management of historic trail systems, they focused little on exploring the influence of terrain conditions on human travel behavior and mobility patterns.

Many early trans-American trail systems had pre-colonial origins, but the utilization of these trails for settling new regions or transporting goods necessitated the use of large wagons that required much different conditions than simple foot traffic. In particular, the ECR supported caravans with upwards of 32 wagons carrying three years' supply for each mission (Scholes, 1930). Successful navigation of the ECR and the overall trafficability of the transit corridor (i.e., Rio Grande Valley) was therefore critical for these early missions.

The goal of this study is to report on the relationships between terrain conditions and trail routing locations along a segment of the ECR near Socorro, New Mexico. To accomplish this, we perform a GIS-based cost-weighted analysis of terrain trafficability potential, focusing on the land-surface features that most likely influenced routing decisions, namely terrain roughness, soil-landform properties, and land cover characteristics. Soil-landform units—landscape features characterized by unique associations of landform patterns and soil-forming factors—are the focus of this study because they provide linkages between geomorphic process and surface characteristics that help to characterize the range of physical properties of a map unit. The trafficability potential is then used to examine the relationships between known or inferred trail locations and terrain conditions. Our principal aim is to construct a predictive model for detecting and mapping mobility corridors, with the intention of determining characteristic relationships between trail locations and terrain properties, by applying and evaluating this model in the Socorro area. As such, this analysis provides a reference framework for future studies intending to locate, preserve, and manage historic trail segments for management and protection.

METHODS

Processing and Interpretation of Topographic Datasets

We utilize a 10 m resolution digital elevation model (DEM) of the study area (obtained from the USGS 3D Elevation Program) as the primary data product for topographic analysis (Fig. 2A). We compute the Terrain Ruggedness Index (TRI; Riley et al., 1999) from the DEM data to provide a quantitative metric of terrain roughness. The TRI enables classification of terrain heterogeneity that occurs as a result of geomorphic processes and is used here to determine relationships between the historic trail route and terrain morphological characteristics in the study area. TRI is computed over a raster grid by determining the total elevation difference between a central grid cell and the neighboring eight adjacent cells, where

$$TRI = \sqrt{\sum_{i=-1,j=-1,}^{i=1,j=1} (z_{i,j} - z_{0,0})^2},$$

and $z_{0,0}$ is the elevation of the central grid cell in the moving window and i and j represent the locations of neighboring cells. TRI values were computed using the GDALDEM TRI function (GDAL/OGR Contributors, 2020) and have elevation units in meters (m). We follow the classification scheme of Riley et al. (1999) to group TRI values into ordinal categories of terrain ruggedness that are ranked from low to high index values as follows: level (0–80 m), nearly level (81–116 m), slightly rugged (117–161 m), intermediately rugged (162–239 m), moderately rugged (240–497 m), highly rugged (498–958 m), and extremely rugged (>959 m). This classification scheme is appropriate for both wheeled and foot traffic over long distances and therefore enables quantitative characterization of terrain roughness along each segment of the historic trail.

Landform Maps and Unit Assignments

Landforms are topographic features of Earth's surface that are intimately tied to the geomorphic processes that formed them. Landforms exhibit physical, spatial, and temporal characteristics, such as scale, shape, compositional make-up, relief, and age, among others, that distinguish them from each other. For example, depositional eolian landforms (i.e., sand dunes) common to coastal settings and arid or semi-arid environments generally consist of loose well-sorted sand deposits that commonly exist as repeated dune forms in the landscape and exhibit variable surface morphologies. In contrast, alluvial fans common to arid and semi-arid regions consist of variably sorted alluvial and colluvial deposits that typically form conspicuous cone-shaped features at the bases of mountains. The distribution and characteristics of landforms in an area can therefore be inferred from terrain characteristics and basic knowledge of the geology as well as the geomorphic context and process. Considering this relationship between geology and landforms, surficial geologic maps were used in this study to obtain relevant terrain information within the study area.

Available geologic quadrangle maps (scale of 1:24,000) of the study area were first digitized within a 3 km zone (or buffer) of the approximate designated route of the ECR to delineate major landform unit boundaries. We note that the trail route is based on previous smaller-scale mapping (nominally 1:100,000) by the National Park Service from planning maps and USGS topographic maps and does not always coincide with the trace of the historic trail. However, this level of resolution is accurate to a degree that permits investigation of its location with respect to general terrain characteristics. Map units were then grouped into distinct categories that reflect their primary geologic and geomorphic characteristics, similar to the approach taken by Kludt et al. (2015). We adopted a hierarchical landform classification scheme, similar to the geoform classification system of Zinck (2016), to subdivide the study area into discrete landscape settings that could be further differentiated into landform classes and landform types. Each hierarchical level provides additional layers of geologic and geomorphic information, including depositional age and lithology, for distinction of individual landform units.

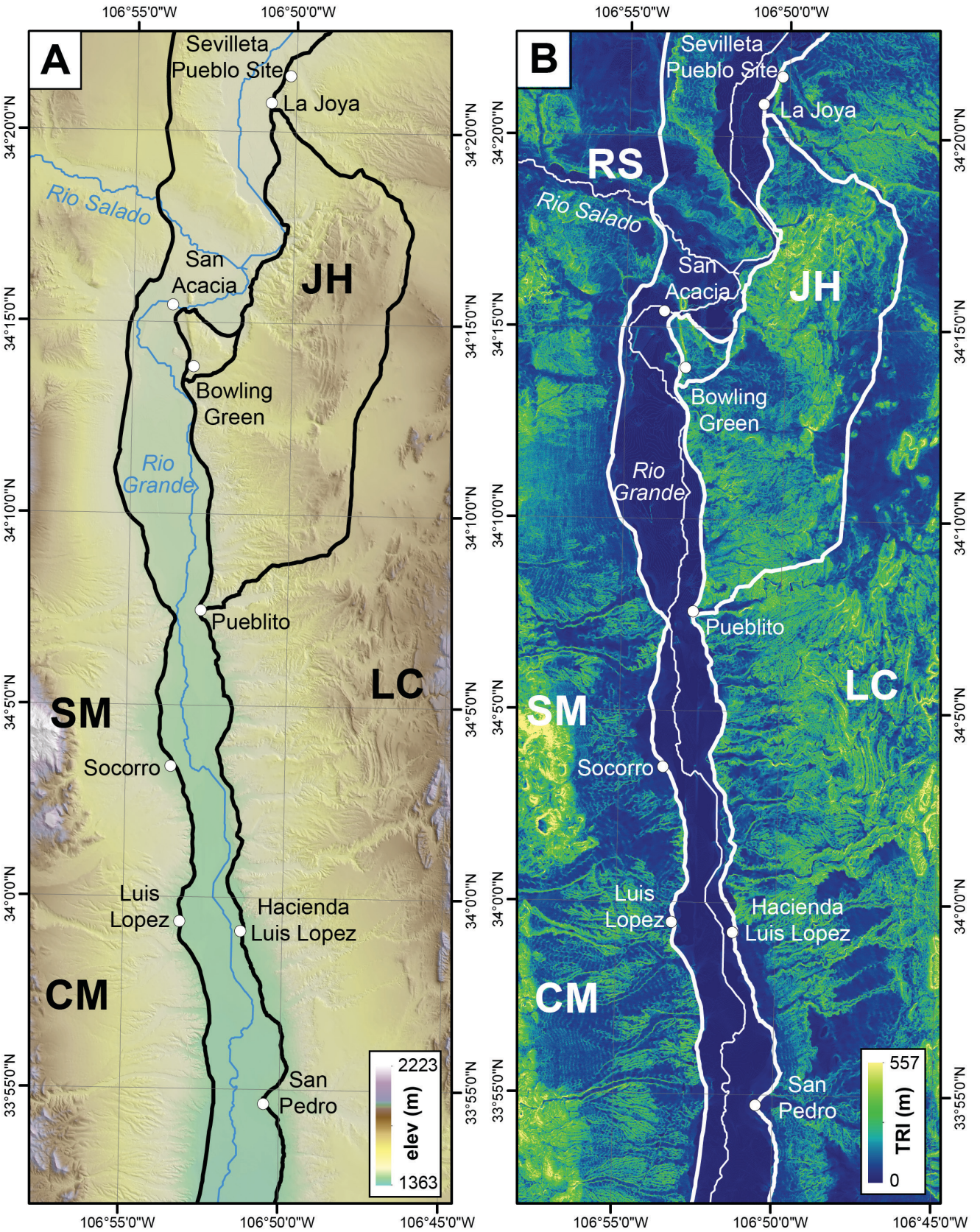


FIGURE 2. Shaded relief map (A) and map of terrain ruggedness index (TRI) values (B) of the study area showing the locations of the ECR (solid black lines (left) and white lines (right)), historic settlements (white points), and relevant physiographic features. Abbreviations for physiographic features are as follows: Joyita Hills (JH), Socorro Mountain (SM), Las Cañas (LC), and Chupadera Mountains (CM). Details pertaining to the calculation of TRI values in panel B are provided in the text. TRI values are categorized according to (Riley et al., 1999) as follows: level (0–80 m), nearly level (81–116 m), slightly rugged (117–161 m), intermediately rugged (162–239 m), moderately rugged (240–497 m), highly rugged (498–958 m), and extremely rugged (>959 m).

Soil and Land Cover Datasets

While geomorphic datasets provide information regarding the spatial distribution of terrain elements, their trafficability is highly dependent on soil characteristics (e.g., drainage conditions, shrink-swell properties of clay minerals, degree of cementation by soluble salts). Digital Natural Resources Conservation Service (NRCS) soil survey data for Socorro County (downloaded from the Gridded National Soil Survey Geographic Database, gNATSGO) therefore provides general soil properties and their relationships to mapped landform units. We used information from this dataset to infer relative terrain properties within the buffered regions around the historic trail. In particular, the soils data helped to constrain general soil-landform relationships and provided an additional level of detail by identifying surface and subsurface properties useful for trafficability interpretations. We focused on the spatially dominant soil types occurring within each landform unit for characterization and evaluated taxonomic information at the great group level to determine the primary surface and subsurface properties for all major soil types. Unlike the higher-level taxonomic categories, the great groups consider the arrangement of all important horizons and the most significant properties of the whole soil (Soil Survey Staff, 1999); thus, they allow greater confidence in the spatial prediction of soil conditions that may influence trafficability.

We also considered other relevant soil information, e.g., typical profile morphologies and expression of diagnostic features, as reported in the local soil survey (Johnson, 1988). Additionally, we utilized soil textures as a primary dataset to inform our trafficability analysis. Finally, we incorporated land cover classifications within the study area using a 30 m resolution land cover dataset from the National Land Cover Database (Dewitz and U.S. Geological Survey, 2021) to incorporate dominant land cover features (e.g., bare rock, water, woodland) for trafficability considerations.

SUMMARY OF TERRAIN AND SOIL-LANDFORM CHARACTERISTICS

The distribution of landform types, their sedimentology, and associated soils developed at the surface reflect the dominant geomorphic processes and geomorphic history in this region and contain important information used to infer, and ultimately predict, terrain trafficability along the ECR. We present our terrain analysis in terms of a hierarchical classification scheme and document the terrain characteristics, landform distributions, and dominant soil properties of each landform unit in this section. At the largest scale, the landscape is broken into upland hills, piedmont, and valley geomorphic settings (Table 1). Each of these landscape settings is subdivided into landform classes that indicate the principal geomorphic process associated with each landform unit. The landform classes are further separated into distinct landform subunits (i.e., landform type in Table 1) that represent the range of expected facies and lithologies in terms of their relationships to the geomorphic process being captured while also accounting for the deposit and landform ages. Additionally, we summarize the principal soil types associated with each landform type and report on their dominant characteristics.

Upland Settings

Upland areas in the region occur along the flanks of the Rio Grande rift where large-scale tectonic activity has resulted in uplifted mountain blocks. Locally, the uplands represent an erosional geomorphic regime where exposed bedrock has been exhumed by a series of deformation events over geologic time. The Joyita Hills (Fig. 2) preserve uplifted and tilted Proterozoic to Mesozoic strata that have been extensively faulted and deformed (Beck and Chapin, 1994). Upland settings in the study area form a series of hills and valleys with up to 100 m of relief and, although geographically limited, exhibit unique terrain characteristics (e.g., variable terrain roughness and bare rock surfaces on steep slopes) that influence mobility.

Upland hills

This landform class covers a minor proportion (~9%) of the study area and is located primarily in the Joyita Hills region (Figs. 2A, 3). The terrain is level to moderately rugged (mean TRI values of 66–132 m; Table 1) and contains a relatively low percentage of level or nearly level surfaces that could enable wheeled traffic. Hillslopes are underlain by variable bedrock lithologies that form the basis for landform unit distinction according to their geologic age and lithology. Detailed lithologic information is summarized by de Moor et al. (2005). Primary units recognized here include Tertiary volcanic (Rtv) and sedimentary (Rts), Mesozoic (Rms), Paleozoic (Rps), and pre-Cambrian (Rpcs) sedimentary bedrock units, following the landform designation for rock units used by Kludt et al. (2015) based on depositional ages and sedimentary units.

Soil occurrence in upland settings is highly discontinuous and limited to stable landscape positions on colluvial and alluvial deposits that have accumulated at the base of rock outcrops and in local valleys. Slopes on these surfaces generally range between 15–50%, and the sediment cover tends to be of variable thickness, such that many soils (where present) have a lithic contact (i.e., bedrock within 50 cm of the soil surface). Parent materials are typically clast-supported (very gravelly to very stony), regardless of location, lithology, or age. Haplocalcids are the dominant soil type and occur on all units (Table 1). These soils tend to have loamy to coarse-loamy textures and moderately developed (A-Bk-C or A-Bk-R) profiles with an appreciable (>15%) accumulation of calcium carbonate ($CaCO_3$) in the subsoil (i.e., calcic horizon). The calcic (Bk) horizon may exhibit a range in morphological expression but is seldom cemented, even in the best developed soils. Torriorthents are dominant soils found on the Mesozoic and Paleozoic units (Table 1). These soils tend to have fine-silty to clayey textures and shallow, very weakly developed (A-C or A-C-R) profiles with only slight accumulation of organic matter (OM) in the soil surface.

TABLE 1. Hierarchical landform classification and associated soil types. Landform boundaries are from surficial geologic maps of the study area, and landform designations are based on generalized surficial geologic map units. Areal percentages of landform types are shown in terms of the entire study area outlined in Figure 3. Soil great groups represent dominant soil types recognized from the Socorro County soil survey. Areas of the representative soil series associated with dominant soil types are shown in terms of their total areas and relative percentages within the associated landform type.

Landscape Setting	Landform Class	Landform Type	Unit	Area of Landform Type	TRI of Landform Type		Dominant Soil Great Group(s)	Representative Soil Series	Area of Representative Soil Series within Landform Type	
	(% area)			(%)	mean (m)	st. dev (m)			(km^2)	(%)
Upland	Hills (9%)	Tertiary volcanic bedrock	Rtv	4	105	39	Haplocalcids	Laborcita	27.08	93
		Tertiary sedimentary bedrock	Rts	2	93	40	Haplocalcids	Laborcita	10.81	89
		Mesozoic bedrock	Rms	<1	66	31	Torriorthents	Elbutte	0.51	42
							Haplocalcids	Turney	0.35	29
		Paleozoic bedrock	Rps	2	132	43	Torriorthents	-	7.71	62
							Haplocalcids	Laborcita	4.13	33
		Pre-Cambrian bedrock	Rpcs	<1	124	35	Haplocalcids	Laborcita	4.18	96
Piedmont	Alluvial (64%)	Active/historic channels	Qay	30	50	27	Haplocalcids	Nickel	76.07	38
							Torriorthents	Arizo	34.48	17
							Haplargids	Berino	27.85	14
		Intermediate-aged fan deposits/surfaces	Qai	10	53	29	Haplocalcids	Nickel	35.81	49
							Torripsamments	Bluepoint	7.15	10
							Haplocambids	Adelino	6.81	9
		Old dissected fan deposits/surfaces	Qao	5	69	34	Haplocalcids	Nickel	28.3	82
							Haplocambids	-	3.02	9
		Hillslopes underlain by Plio-Pleistocene basin fill	QTsf	17	96	36	Haplocalcids	Nickel	72.19	60
							Haplocambids	-	33.46	28
		Hillslopes underlain by Mio-Pliocene basin fill	Tsf	2	78	35	Torripsamments	Bluepoint	9.47	59
							Haplocalcids	Nickel	3.06	19
	Eolian (7%)	Dunes and active/stabilized sand sheets	Qe	7	55	28	Halocalcids	Whitlock	21.36	42
							Torripsamments	Bluepoint	17.7	35
Valley	Borders (2%)	Intermediate-aged river alluvium	Qri	1	83	40	Haplocalcids	Nickel	3.57	43
							Torripsamments	Bluepoint	2.05	25
		Old dissected river alluvium	Qro	<1	82	34	Haplocalcids	Nickel	0.84	78
	Bottoms (19%)	Active channel and floodplains	Qry	19	15	18	Torrifluvents	Saneli/Anthony	88.69	65
							Torrerts	Armijo	12.21	9
							Torripsamments	Bluepoint	8.32	6

Piedmont Settings

The piedmont is a zone of sediment transport between the mountain front areas at the basin margins and the Rio Grande Valley and is dominated by alluvial landforms. Piedmont areas are characterized by broad, level to nearly-level terrain (mean TRI values of 50–96 m; Table 1) and geomorphic surfaces that slope gently toward the valley. East-west oriented arroyos and channels tributary to the Rio Grande traverse piedmont slopes, and many have relatively small contributing areas and are incised to various depths into alluvial deposits. The sand-rich ephemeral washes in the piedmont and in the valley border settings (described below) provide source material for eolian deposits that commonly cap and preserve intact alluvial surfaces (i.e., fans) within the piedmont setting. The piedmont, which consists of highly variable terrain and surface deposits, is therefore important for mobility considerations in the study area.

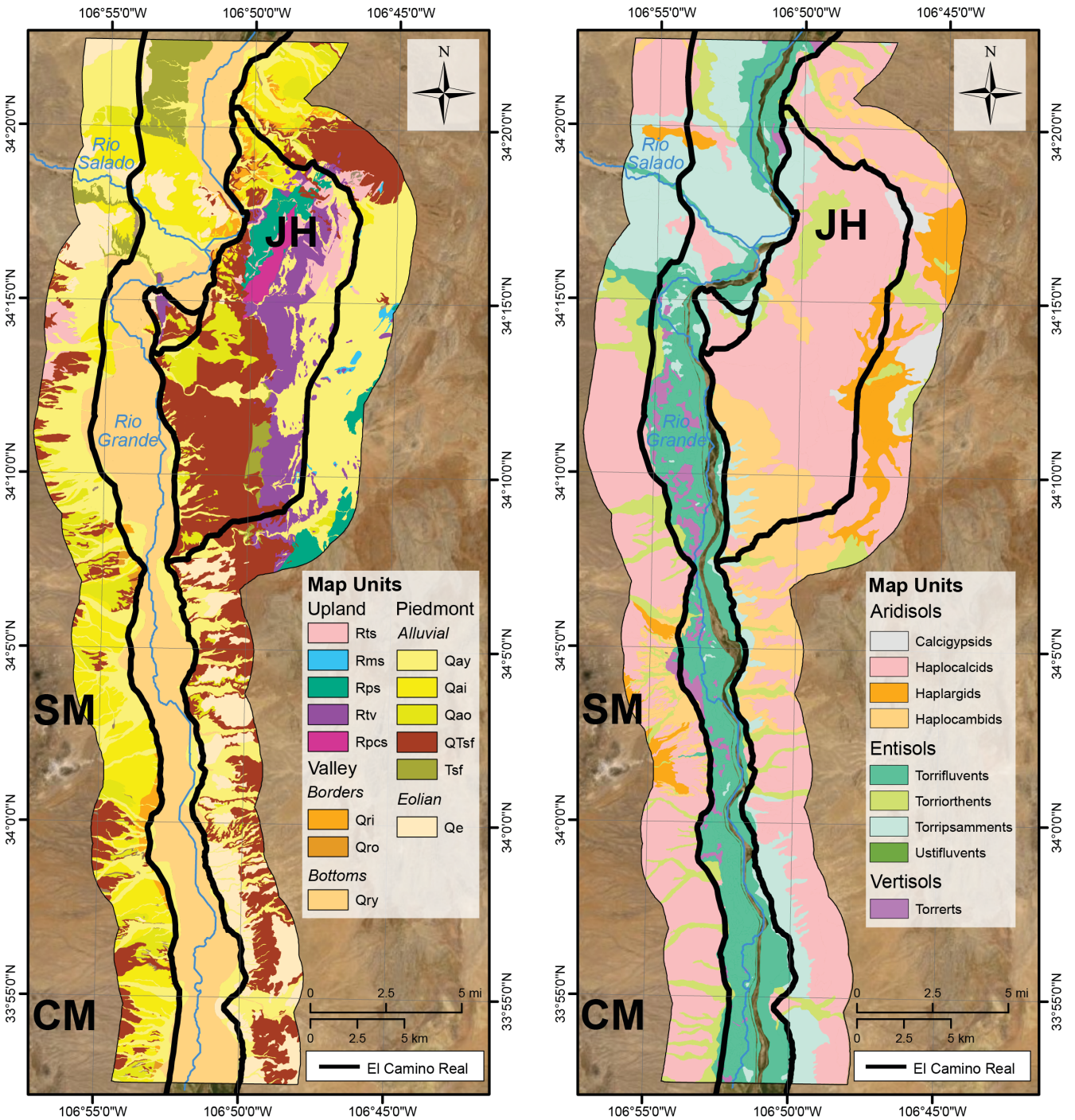


FIGURE 3. Results showing distributions of geomorphic landforms (A) and dominant soil types (B) within the study area. The dominant landforms in the region are piedmont alluvial units and river valley floodplains. The ECR generally follows these landform boundaries for most of the distance along the trail in this region. Haplocalcids and Torrifluvents are the dominant soil great groups on these landforms.

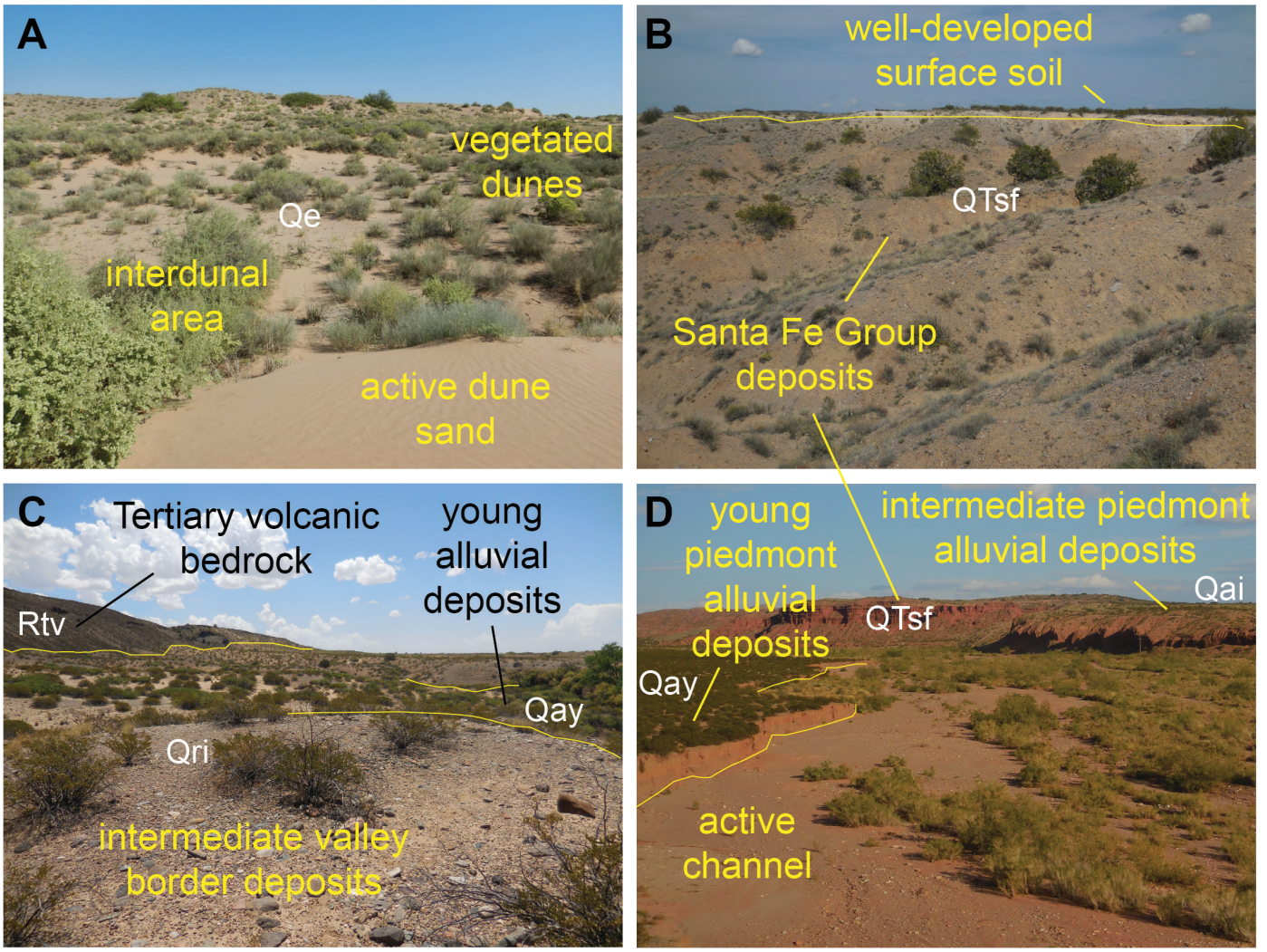


FIGURE 4. Example photographs of representative landform units identified along the ECR in the study area. (A) piedmont eolian (Qe), (B) piedmont alluvial (QTsf), (C) a combination of upland bedrock (Rtv), valley border alluvial (Qri), and piedmont alluvial (Qay) units, and (D) piedmont alluvial (QTsf, Qai, Qay) units.

Alluvial landform units

Alluvial landform units are dominant in the piedmont setting and in the study area in general (~64% of the study area). The alluvial landform class is subdivided into distinct units based on surface morphology and relative age of the associated deposits. These landforms consist of active/historic channels and intermediate-aged to old fan deposits and associated geomorphic surfaces that exhibit level to nearly level terrain, except in transitional areas between landform types where short steep slopes are common. The active channels and alluvial fan deposits are characterized by relatively poorly sorted, sub-angular, and clast-supported gravelly sand with dominant volcaniclastic lithologies (e.g., Chamberlin, 1999). The relative degree of soil development observed on fluvial terrace treads is a strong indicator of relative surface age (e.g., Birkeland et al., 1991; Machette, 1985). The relative abundance of pedogenic $CaCO_3$ in subsoil (Bk) horizons and the relative geomorphic positions of the geomorphic surfaces with respect to local baselevel enable separation of the alluvial landform units into older (Qao), intermediate (Qai), and young (Qay) subunits (Sion et al., 2022; Sion et al., 2020). Soils predominantly classify as Haplocalcids, with minor components consisting of Haplargids, Haplocambids, and Torripsamments (Table 1, Fig. 3B), reflecting the high degree of variability in soil-forming conditions and developmental stages.

Significantly older (>818 ka; Sion et al., 2020) alluvial deposits form the basis for a separate and distinct set of alluvial landform units, expressed as erosional features in the piedmont setting, where incision has dissected these deposits. These landforms are underlain by unconsolidated to well-consolidated Santa Fe Group deposits associated with the basin-filling phase of the Rio Grande rift (Chapin and Cather, 1994). Landform units are subdivided into two subunits to distinguish the older and more cemented Popotosa Formation deposits (Tsf; Denny, 1940) from the younger and less cemented Sierra Ladrones Formation deposits (QTsf; Machette, 1978). Dominant landforms include variably dissected hillslopes with little to no soil development (i.e., Torripsamments and Haplocambids), except where the upper depositional surface QTsf subunit (Table 1) has been preserved. This prominent geomorphic surface is locally termed the Las Cañas geomorphic surface.

In places, the Las Cañas surface is buried and preserved by eolian deposits, but relict and relatively intact surfaces exhibit very strong soil development, as indicated by the presence of a thick, well-developed calcic horizon (e.g., Fig. 4B). Soils here classify as Haplocalcids that contain petrocalcic horizons with Stage IV carbonate morphologies (Machette, 1985) and have concrete-like engineering properties (Netterberg, 1982). Relict Las Cañas surfaces are generally found in relatively high geomorphic positions compared to the channel and fan-surface landform units described previously. Surface exposure of the QTsf landform units is dominant (17%) in the study area in comparison with the Tsf (2%) units that generally occur at the surface only in isolated areas in the northern and eastern portions of the study area (Fig. 3A).

Eolian units

The eolian landform class consists of a single landform unit (Qe), although several different types of eolian landforms are common in the study area, including barchan and transverse dune forms and sand sheets (Machette, 1978). Overall, eolian units cover a minor (~7%) proportion of the study area and are associated with level to nearly level terrain (mean TRI values of 55 m; Table 1). Barchan and transverse dune forms are common north and south of the Rio Salado (Fig. 3A). Most dunes in this area are presently stabilized by mesquite vegetation, although dune activity is spatially variable. Dunes are ~1–5 m high, have interdunal spacings on the order of 10s to 100s of meters, and consist of loose, well-sorted, very fine to fine and medium sand (Fig. 4A). Dune morphology indicates a prevailing southwesterly wind direction, suggesting the Rio Salado Valley as the major sand source. Sand sheets are also common to areas on the eastern margin of the Rio Grande Valley (Fig. 3A). These are generally thinner than dunes in the Rio Salado watershed (1–2 m) and have subdued topography. Sand sheets commonly cap gently sloping alluvial surfaces that have been incised by active arroyos.

Soils on dunes and sand sheets classify as Torripsamments or Haplocalcids (Table 1). The Torripsamments are more prominent in geomorphic positions adjacent to active washes (Fig. 3B). These soils tend to have very weakly developed (A-C) profiles with only a slight accumulation of OM in the soil surface, indicative of the youth and geomorphic instability of the landscape in these areas. Soils on stabilized sand sheets occurring on older, relatively isolated, alluvial surfaces tend to have better developed (A-Bk-C) profiles with an appreciable (>15%) accumulation of $CaCO_3$ in the subsoil and thus classify primarily as Haplocalcids (Table 1).

Valley Settings

The river valley has been an area of sediment deposition and transport both in modern times and throughout the Quaternary. Geomorphic surfaces in valley settings are generally broad, continuous, and level to nearly level (mean TRI values of 15–83 m; Table 1) and therefore are critical landscape positions for trafficability studies. The primary landform classes in river valley settings consist of valley border and valley bottom landform types. These are generally analogous to the piedmont alluvial landform units except that their sedimentology and proximity to the piedmont and to the dynamic Rio Grande River result in obscured (i.e., buried) or dissected conditions. Additionally, river valley deposits are generally thicker, better sorted, sandier, and more quartz-rich than those found in piedmont regions. These distinct characteristics have produced very different terrain properties that influence geomechanical properties of associated soils at the surface.

Valley borders

Axial valley landform units (i.e., river terraces) consist of isolated geomorphic surfaces that exhibit level to nearly level terrain conditions and are generally underlain by weakly consolidated, well-sorted, rounded to subrounded sand and gravelly sand. Gravel lenses within the axial valley deposits are composed of variable lithologies that commonly contain quartzites and other exotic lithologies that are either not local to or are found in higher proportions than those found in tributary watersheds. The axial valley units are ~3 to >30 m thick and exceed that of their tributary counterparts (1 to 5 m thick). These landforms tend to be highly discontinuous owing to their poor preservation along active valley margins where tributary channels have dissected and or buried older river deposits.

Where valley border landforms are preserved, the dominant soils are remarkably similar to those in the piedmont setting. These soils classify either as Haplocalcids on stable surfaces of geormorphically higher surfaces (Qro and Qri), or as Torripsamments either on unstable side slopes and eroded surfaces (QTsf, Tsf) or on young fluvial deposits (Qry). Dominant soil series are similar to those found in piedmont environments, but commonly exhibit different parent material lithologies (Sion et al., 2020).

Valley bottoms

The valley bottoms are restricted to the historic and active Rio Grande River floodplain. This setting is characterized by level terrain that is broad and continuous for 10s of kms (Fig. 2A). The valley width is variable and becomes constricted in places, especially south of La Joya and near San Acacia where the Rio Grande flows through a narrow floodplain, likely related to shallow basin depths associated with a structural transition from the Albuquerque Basin to the north into the Socorro Basin (Grauch and Connell, 2013). Much of the land in the valley bottom is now used for agricultural activities.

Soils on stable channel and floodplain positions within the valley are taxonomically diverse and exhibit high spatial variability, especially west of the Rio Grande (Fig. 3B). This distribution is largely reflected in the spatial textural heterogeneity of parent materials. Generally, where the deposits are sandy, clayey, or both (due to stratification), soils classify primarily as Torripsamments or Torrifluvents, Torrerts, or Torrifluvents, respectively. Because deposits are very young (decades to a few centuries), these soils tend to be very weakly developed

with only a slight accumulation OM in the soil surface; however, due to plowing for cultivation, most tend to have modified (Ap-C) profiles with overthickened A horizons. Despite general developmental similarities, the Torrerts and stratified Torrifluvents differ markedly from the Torripsamments and sandy Torrifluvents in their the geomechanical properties. This is because the clayey parent materials of Torrerts and Torrifluvents typically contain high concentrations of montmorillinitic (expansive) clay minerals, such that many soils have vertic features (i.e., shrink-swell cracks). These features can occur to depths of 25 cm in the stratified Torrifluvents but usually extend much deeper in the Torrerts.

TRAFFICABILITY ANALYSIS AND INTERPRETATIONS

Our landscape characterization and analysis summarized in the previous section demonstrates first-order relationships between terrain characteristics and the properties and distribution of both soil and landform units. These relationships provide a unified perspective of the terrain and have important implications for early historic trail trafficability. As such, the development of a trafficability map enables a holistic view of the landscape from a geomechanical perspective and allows for a trafficability analysis along this segment of the ECR. We document the construction of a cost-weighted trafficability map in this section that leverages available digital data products and demonstrate its potential applications for understanding the challenges imposed by the terrain. Additionally, this analysis documents a tool that has potentially significant advantages toward the analysis or interpretation of historic trail systems at a variety of spatial and temporal scales.

Trafficability Mapping

We perform a terrain-cost analysis that is used to construct a trafficability map of the study area. The cost analysis consists of interpreting available terrain datasets in terms of relative geomechanical conditions, weighting the datasets in terms of relative importance to trafficability, and combining the datasets together into a single comprehensive raster friction surface that reflects the relative "costs" associated with terrain conditions. In this context, the total cost represents the combined terrain effects that promote or inhibit trafficability. Each raster dataset is ranked according to relative degree of mobility based on quantitative and qualitative metrics summarized in Table 2. The raster surfaces are then weighted according to our assumptions of the relative importance of each for mobility interpretations. For this application, we place greater emphasis on surface texture and terrain roughness (numerical weights of 0.3) compared with landform designation and land cover class (numerical weights of 0.2), such that the weights sum to unity. The final "cost surface" is obtained by weighting each ranked property raster and summing those weighted rasters to obtain a 30 m resolution cost surface map (Fig. 5).

Each dataset was ranked on a scale from 0–100, with high values being associated with high-cost terrain elements (i.e., poor trafficability) and low values representing low-cost terrain. In general, we assigned low costs to landforms exhibiting relatively continuous, level terrain with loamy textures and relatively stable landforms (e.g., Haplocalcids on intermediate-aged fan surfaces) and high costs to areas of relatively rugged terrain and/or a combination of either fine- or coarse-textured soils (e.g., clay-rich or well-sorted loose sand), soils with vertic (e.g., Torrerts) properties, or geomorphically active environments (e.g., floodplains, dunes). Justifications for each ranking are provided in Table 2. Classification of the final cost surface into four trafficability classes was accomplished using a standard deviation method that differentiates classes based on variations from the mean value in intervals of one standard deviation. This approach was used to visually maximize differences in the classes that were identified.

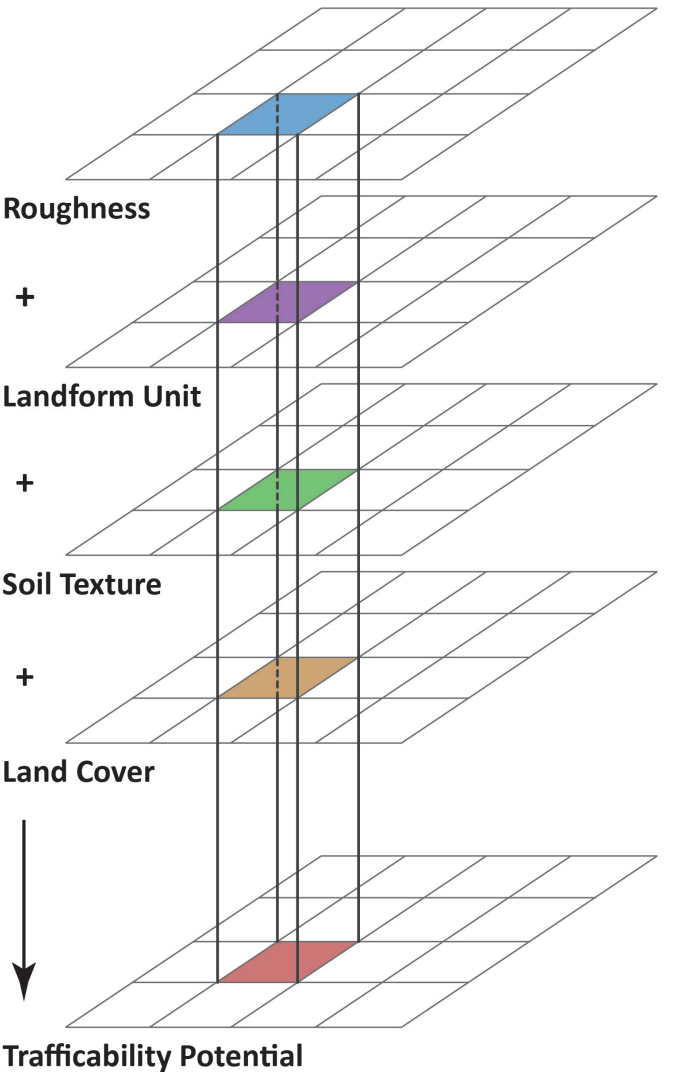


FIGURE 5. Conceptual diagram illustrating the method used for constructing a cost surface raster of trafficability potential. Individual property rasters are first weighted according to their relative importance, in this case for trafficability potential. The weighted rasters are then summed cell-by-cell such that the associated grid cell in the trafficability raster is the linear combination of property weights and ranked values.

Analysis and Interpretation of Trafficability Along the El Camino Real

The resulting trafficability map of the study area is shown in Figure 6, along with the trail route. We highlight several features of this map that show strong correlations between the combined terrain properties and the location of the ECR. Two principal routes of the ECR are present in the study area and systematically follow low-cost terrain. These two segments are primarily associated with the margins of the floodplain units

TABLE 2. Breakdown of cost surface rankings by data type for trafficability analysis. Costs are assigned based on expected effects to wheeled traffic and caravans. Classes within each data type are linearly scaled from 0–100.

Data Type	Classification	Assigned Cost	Justification
Land Cover	Desert & Semi-desert	0	Open, broad landscape; limited vegetal obstructions
	Developed & other human use	0	Most developments are co-located with the desert/semi-desert class
	Shrub & herb veg.	20	Minor component, limited to small discontinuous areas
	Open rock veg.	40	Bare rock associated with denied terrain
	Forest woodland	60	Dense tree stands prohibit wheeled traffic
	Agricultural & developed veg.	80	Located in flood-prone areas
	Open water	100	Located in flood-prone areas
Terrain Ruggedness*	Level (0-80)	0	Easily accessible for wheeled and foot traffic
	Nearly Level (81-116)	20	Moderately accessible for wheeled traffic; easily accessible for foot traffic
	Slightly Rugged (117-161)	40	Difficult accessibility for wheeled traffic; moderate accessibility for foot traffic
	Int. Rugged (162-239)	60	Denied terrain for common wheeled vehicles; difficult for foot traffic
	Mod. Rugged (240-497)	80	Denied terrain for most wheeled traffic
	Highly Rugged (498-958)	100	Denied terrain for all wheeled and most foot traffic
	Ext. Rugged (958-4367)	100	Denied terrain for all wheeled and foot traffic
Soil Texture	Matrix supported	0	High shear strength wet or dry, well-drained
	Loamy textures	25	High trafficability when dry, moderate when moist, dry for majority of year
	Sand-rich textures	50	Associated with cohesionless material, low trafficability when dry
	Bedrock	75	Bare rock associated with denied terrain
	Clay-rich textures	100	Low shear strength when wet, poor drainage conditions
Landform Unit	Floodplains and active river channel	0	Broad, level, continuous surface
	Intermediate-aged river alluvium	15	Broad, level surfaces, discontinuous or poorly preserved
	Intermediate-aged fan deposits/surfaces	15	Broad, level surfaces, interrupted by channels and gullies perpendicular to trail
	Active/historic channels	30	Channels are narrow, perpendicular to trail, and commonly have steep banks
	Hillslopes underlain by Mio-Pliocene basin fill	45	Moderately to heavily dissected, discontinuous irregular surfaces
	Hillslopes underlain by Plio-Pleistocene basin fill	45	Moderately to heavily dissected, discontinuous irregular surfaces
	Old dissected fan deposits/surfaces	60	Discontinuous, isolated surfaces
	Old dissected river alluvium	60	Discontinuous, isolated surfaces
	Mesozoic bedrock	85	Rough, irregular terrain
	Paleozoic bedrock	85	Rough, irregular terrain
	Pre-Cambrian bedrock	85	Rough, irregular terrain
	Tertiary sedimentary bedrock	85	Rough, irregular terrain
	Dunes and active/stabilized sand sheets	100	Loose, cohesionless material, irregular terrain

*TRI classes are from Riley (1999). Maximum TRI values from these classes exceed the maximum values identified in this study area but are shown for completeness.

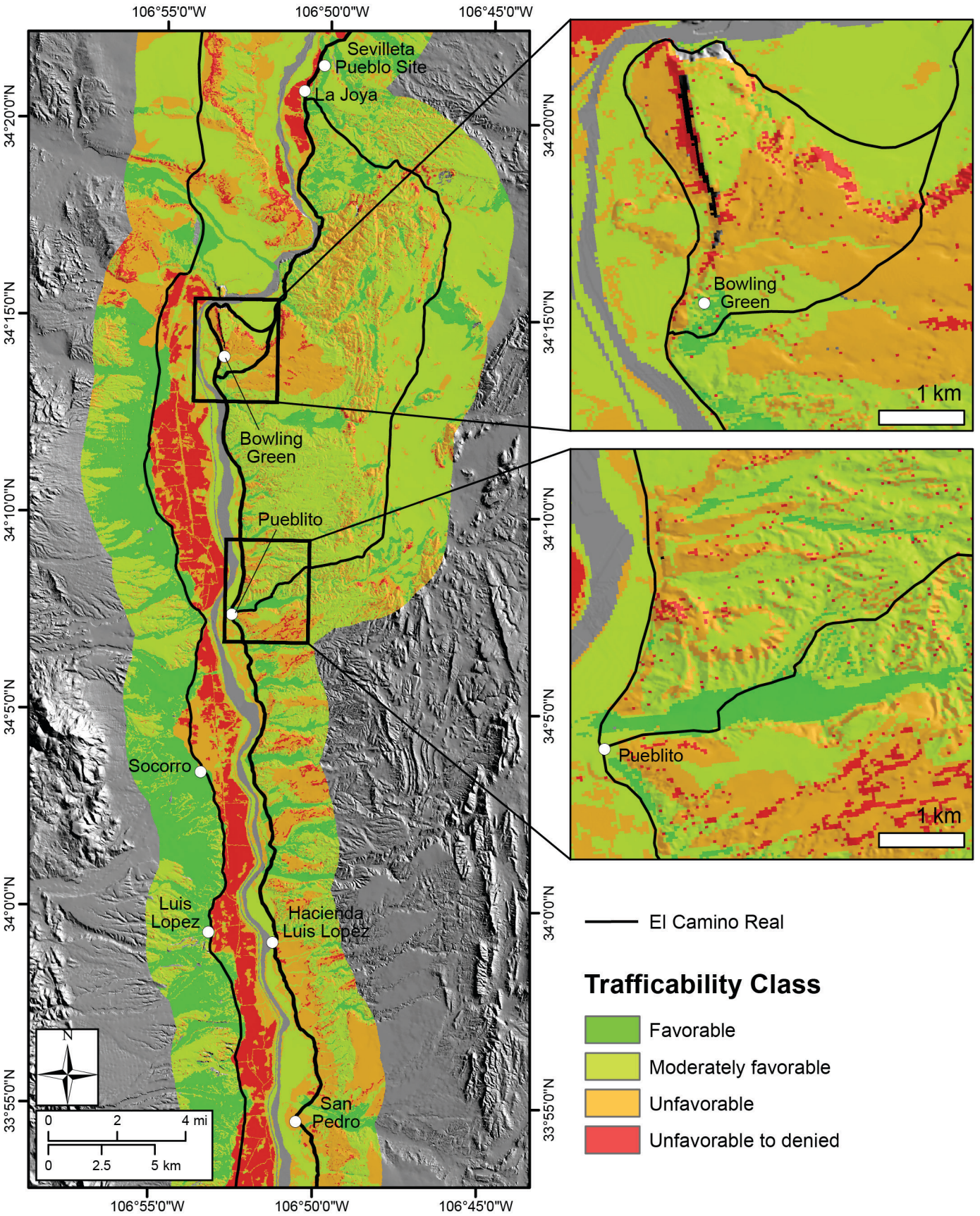


FIGURE 6. Trafficability map showing the computed terrain-cost raster surface. Trafficability classes are relative but show strong correlations between favorable areas (i.e., low-cost terrain) and the location of the ECR. The expanded views near Bowling Green and Pueblito highlight trail excursions where favorable to moderately favorable terrain was sought to avoid flood risks in valley bottom or valley border geomorphic positions.

and very clearly avoid areas identified as moderate- or high-cost regions (i.e., unfavorable and unfavorable to denied). Two trail segments also diverge from the primary routes at historic sites in the study area. These locations have strong terrain associations that are interpreted below.

The principal western route appears to follow topographic contours that mark the transition between the piedmont alluvial fan toes and the Rio Grande floodplain. Although the piedmont areas are identified as low-cost zones, these areas are heavily dissected in places and increase the risk of encountering higher-cost terrain where intermittent streams cause locally high-relief at the boundaries of the adjacent geomorphic surfaces. Thus, the TRI associated with these areas is quite variable compared to the level floodplain environments and would have required considerable effort to traverse with wheeled traffic, despite the presence of desirable soil conditions. Conversely, the terrain cost along much of the western Rio Grande floodplain is relatively high and has historically been used as agricultural land. While these are productive areas for crops, the sedimentology of the floodplain deposits is quite variable and tends to contain abundant clay-sized and montmorillinitic clay minerals that together promote vertic soil properties. When wet, these soils may be impassible, even for the most capable modern off-road vehicles. These relationships indicate that early travelers carefully selected their route along the western valley margin to reduce the overall distance traveled along dissected terrain, but also in an attempt to avoid sinkage and slippage associated with moist soil conditions.

The eastern route, much like the western route, tends to be situated valleyward of the piedmont zones, again reflecting the limitations imposed by terrain roughness. Additionally, the trail attempts to avoid proximal river locations. The primary reason for this is the obvious risk associated with traveling the trail during high stream discharge conditions. Historic floods on the Rio Grande in the late 19th and early 20th century completely erased several historic settlements along the trail, including San Marcial (1866 and 1929; not shown on map), Bowling Green (1886), and San Acacia (1929; Fig. 6; Julyan, 1996; Phillips et al., 2015). Although the climate and river discharge patterns were likely well-recognized by the Spaniards and early settlers who frequented the trail and settled the area, the combined risk from flood and/or elevated soil moisture conditions during wet periods, and relatively coarse texture that reduced soil cohesion during dry periods, would have severely limited trafficability along the valley margins. Additionally, the trail appears to coincide with a narrow low-cost zone that is also constrained by the limit of forest woodland in the valley, commonly referred to as the *bosque* (Fig. 7A). Despite favorable terrain conditions, the dense woodland vegetation (now also occupied by invasive *Tamarix*) would have meant impassable conditions for large supply trains and caravans.

In addition to the two trail segments discussed above, the trail takes detours to the east at two locations near the Bowling Green and Pueblito historic sites (Fig. 6). The excursion at Bowling Green is clearly marked by cairns that stand today on a vista point overlooking the Rio Grande Valley (Fig. 7B). Despite encountering more rugged terrain conditions at these locations, deviations from the main trail may have been less risky than the valley bottom routes. For example, the excursion at Pueblito deviated along an 8 km stretch through dissected Plio-Pleistocene basin-fill deposits before heading north again in an upland valley. We hypothesize one of several possible terrain influences that may have played a role in determining the location of this segment based on our terrain analysis. First, the upland valley area consists of soils classified as Haplocambids that contain relatively higher organic matter contents than the surrounding desert regions. These soils support healthier grasses that may have been sought for grazing, so would be a potential candidate destination for caravans traveling northward after stocking up on rest and supplies in Socorro. Second, the route swings wide of the valley bottom, eliminating the flood risk from high discharge and soil moisture conditions near the river channel. The path is similar in length to the primary path in the valley, prior to converging at La Joya, but without the risk of navigating the narrow floodplains in the San Acacia area. Whichever the case, and despite the initially rugged

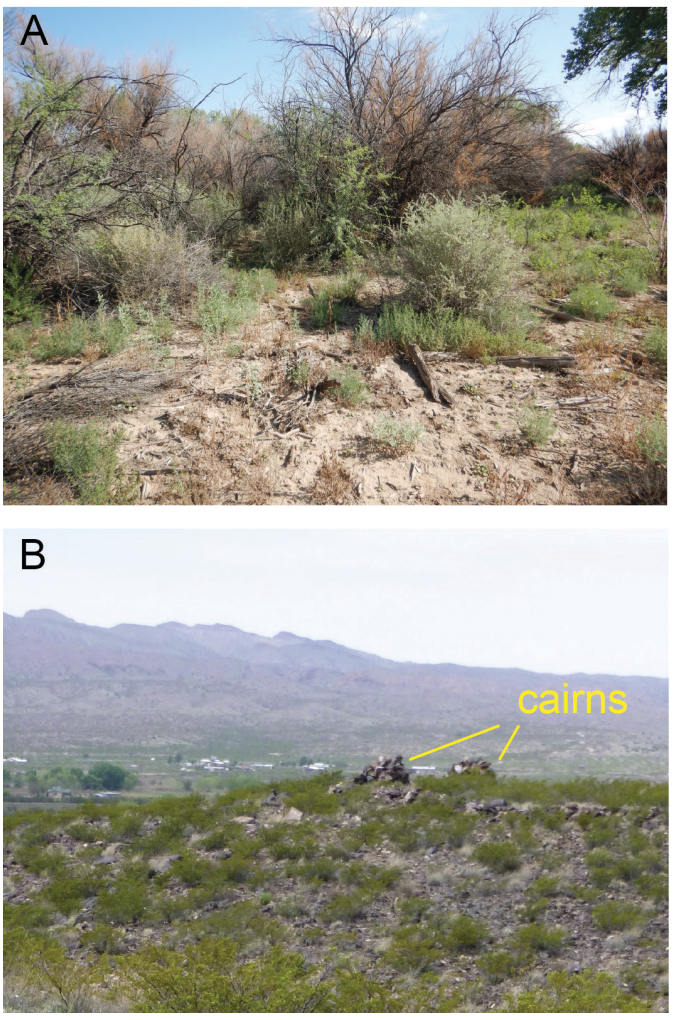


FIGURE 7. Field photographs taken in the vicinity of the ECR near the Bowling Green site. (A) The bosque in this area consists of dense woody vegetation, loose and unconsolidated coarse sediments, large flotsam piles, and other major impediments to wheeled traffic. (B) The cairns are located in an upland position adjacent to the bosque and were used to identify a branching of the trail at Bowling Green, presumably to avoid flood risks in the valley bottom.

approach to this route, the cost analysis indicates that this route would have been a good alternative to the valley-bottom section between Pueblito and La Joya during wet periods.

SUMMARY AND CONCLUSIONS

The results from this study demonstrate the utility of modern digital datasets and geospatial approaches toward gaining a holistic view of terrain characteristics that can be applied in numerous settings. Our terrain analysis of the ECR in Socorro indicates that there is a strong correlation among terrain characteristics, trafficability, and early Euro-American trade routes in the semi-arid desert environment of New Mexico. Although this study represents a localized analysis of trail trafficability, we hypothesize that our analysis may be expanded to a variety of spatial and temporal scales, and to other trail systems globally, to enable further study of the feedback between humans and the landscape that was not explored in this study.

The relationships between primary soil characteristics and terrain conditions are of significant interest for numerous off-road vehicle studies but have largely been overlooked for applications to the social sciences. For example, recent trafficability studies leverage the use of sophisticated numerical modeling and statistical analyses to evaluate soil trafficability conditions for evaluation of soil function (Devine et al., 2022), temporal and seasonal restrictions for off-road maneuver activities (Pundir and Garg, 2022), monitoring forest conditions for rutting and compaction (Niemi et al., 2017), and many others. There have been comparatively few geospatially focused studies applied to evaluate the significance of terrain effects on human or animal behavior. The database study conducted by Williams (2007) parallels the approaches taken in this study, and we have built on that analysis with the incorporation of more detailed soil information. Future trafficability studies like ours should incorporate combined geologic, geomorphic, and geotechnical datasets to enhance the study of historic trade routes. After all, many historic routes have been developed and are still in use today. The approach identified in this study therefore represents a viable and promising direction toward advancing the field of geoarcheology and similar sciences where the terrain constitutes a critical component.

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