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Characterizing Rugged Terrain in the United States

Elizabeth A. Dobis, John Cromartie, Ryan Williams, and Kyle Reed

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Abstract

Mountains and other topographic features with variable elevation provide benefits to residents and visitors but may also impose barriers to travel and restrict development. The authors developed two national representations of relative topographic variability for census tracts: the Area Ruggedness Scale characterizes overall ruggedness and the Road Ruggedness Scale characterizes ruggedness along roads. To understand variation of characteristics by terrain ruggedness, the authors analyzed population, population density, and income across road ruggedness categories, rurality, and regions in the United States. The authors found that as land becomes more rugged, population density decreases, more people live in rural locations, and more rural residents live in low-income census tracts. Ruggedness is distinct from rurality, but in locations that are both highly rugged and rural, unique challenges may arise.

Keywords: topography, ruggedness, population, population density, rural-urban continuum, Area Ruggedness Scale, Road Ruggedness Scale, Terrain Ruggedness Index (TRI), Area TRI, Road TRI

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Contents

USDA Economic Research Service
U.S. DEPARTMENT OF AGRICULTURE

A report summary from the Economic Research Service *August 2023*

Characterizing Rugged Terrain in the United States

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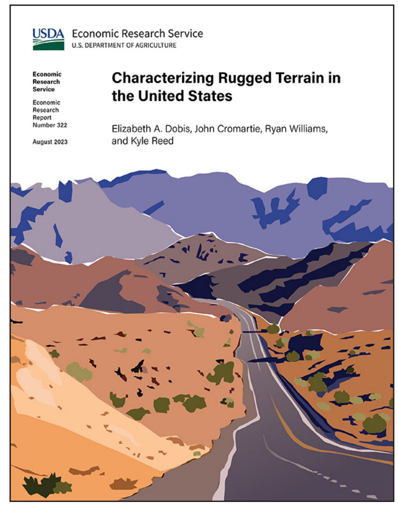


What is the Issue?

Rugged terrain affects communities and their residents in complex and often contradictory ways. Whether made up of mountains, canyons, or other landscape features with variable elevation, research has shown that rugged terrain bestows benefits on long-term residents and may spur economic growth through tourism and migration. Rugged terrain may also be a barrier to settlement and travel, limiting the amount of land available for development and making it more time-consuming for residents living in or traveling through rugged terrain to access needed goods and services. However, the role of rugged terrain as a barrier remains understudied, in part because of the lack of a geographically detailed measure of ruggedness.

In this report, we introduced two nationwide classifications of census tracts: the Area Ruggedness Scale (ARS) and the Road Ruggedness Scale (RRS). To our knowledge, these are the first detailed ruggedness measures with full nationwide coverage for the United States and the first to provide a roads-only version to help study the impact of rugged terrain on travel by car. These scales have the potential to contribute to research on the linkages between the geography and well-being of individuals, especially those living in rural areas.

What Did the Study Find?

In this report, we analyzed how population, population density, and income vary by ruggedness and rurality both nationally and across regions. To do this, we developed two census tract-level ruggedness scales:

- The Area Ruggedness Scale (ARS) has six categories based on the changes in elevation for all terrain and classifies census tracts as: (1) level; (2) nearly level; (3) slightly rugged; (4) moderately rugged; (5) highly rugged; and (6) extremely rugged.
- The Road Ruggedness Scale (RRS) has five categories based on the changes in elevation beneath roads and classifies census tracts as: (1) level; (2) nearly level; (3) slightly rugged; (4) moderately rugged; and (5) highly rugged.

Analyzing by RRS categories, we found that nationally:

- In 2010, 11.6 percent of U.S. residents (35.7 million people) lived in slightly to highly rugged census tracts, and 1.4 percent (4.5 million people) lived in highly rugged census tracts.
- Population density was highest, on average, for nearly level census tracts (5,514 people per square mile) and lowest for highly rugged census tracts (3,390 people per square mile).
- As ruggedness increased, the share of the population living in rural areas increased from 16.1 percent for level census tracts to 29.7 percent for highly rugged areas. However, ruggedness is distinct from rurality as most people live in urbanized census tracts, even in the top ruggedness categories.
- Nearly 60 percent of residents in highly rugged, rural locations lived in low-income census tracts compared with about 42 to 48 percent of rural residents in less rugged census tracts.

Introducing regional variation to the ruggedness analysis, we found:

- The region with the largest share of its population living in highly rugged census tracts in 2010 was Hawaii (10.2 percent), followed by the Appalachian Mountains (6.1 percent). The Pacific Coast was the most rugged region for road travel, with 37.0 percent of its land classified as highly rugged.
- Among States, Washington had the largest share of highly rugged land (29.9 percent), but West Virginia had the largest share of people living in highly rugged census tracts (15.0 percent).
- The rural share of residents in highly rugged census tracts was much higher in the Intermountain West and the Appalachian Mountains (57.7 and 45.7 percent, respectively) and much lower in the Pacific Coast (18.6 percent). Thus, not only is the correlation between ruggedness and rurality low overall but regionally variable as well.

How Was the Study Conducted?

We used the Terrain Ruggedness Index (TRI) method of measuring topographic variability to develop two nationwide grid-cell datasets from the high-resolution, 0.15 square mile Global Multi-resolution Terrain Elevation Data 2010, which was developed by the U.S. Department of the Interior's U.S. Geological Survey and the U.S. Department of Defense's National Geospatial-Intelligence Agency. Two TRIs were developed—one using all grid cells nationwide (the Area TRI) and one using just the subset of grid cells that contain roads (the Road TRI). The TRI results were then aggregated to census tracts to create the ARS and RRS ruggedness scales.

Analysis of rurality, population, and population density across census tracts was conducted using data available from the USDA, Economic Research Service's (ERS) 2010 Rural-Urban Commuting Areas (RUCA) data file. Census tracts and population counts from the 2010 decennial census were chosen over the more recent 2020 data to match the current RUCA code classification. A list of low-income census tracts was obtained from USDA, ERS's 2010 Food Access Research Atlas (FARA) for the income analysis. The criteria used to identify low-income census tracts is from the U.S. Department of the Treasury's New Markets Tax Credit program.

Characterizing Rugged Terrain in the United States

Introduction

Rugged terrain, defined here as any location with significant variation in elevation, can be found in diverse forms in hilly and mountainous regions throughout the United States. Rugged terrain is a critical landscape component that helps shape the size, geographic distribution, and economic vitality of communities in complex and often contradictory ways. On the one hand, long-term residents and newcomers alike find myriad benefits provided by rugged terrain, including appealing natural beauty, sparse population and remoteness, small-town ambiance, less air and noise pollution, lower cost of living, and opportunities for outdoor recreation (Beyers & Nelson, 2000; Cromartie et al., 2015; McGranahan, 2008). Locations with rugged terrain are also attractive tourist and migration destinations; thus, they play a role in spurring economic growth (Moss, 2006; Rudzitis, 1999). Mountainous counties in the southern Appalachian Mountains, the Rocky Mountains, and elsewhere have been among the fastest-growing nonmetropolitan counties in the United States for decades (Cromartie & Wardwell, 1999; Fuguitt & Beale, 1978; Johnson & Lichter, 2019).

On the other hand, rugged terrain can be a barrier to settlement and travel, making it difficult for some residents living in or driving through rugged terrain to access needed goods and services. Topographic variation makes it more difficult to navigate land and waterways while also limiting the space available for residential and commercial expansion. It also likely takes more time for residents living in areas of rugged terrain to travel to hospitals, schools, social services, grocery stores, and other critical destinations compared with those living in less rugged locations. And rural residents of rugged areas may need to traverse rugged terrain more frequently to access more specialized goods and services that may not be available nearby. This aspect of rugged terrain's role as a hindrance to accessibility and economic development has not been as well documented, in part because of the lack of any geographically detailed measures of ruggedness.

To understand the unique role of rugged terrain as both a benefit and hindrance, we developed two versions of a Terrain Ruggedness Index (TRI). These TRIs are nationwide, statistically derived measures that capture variation in elevation using grid cells that average 0.15 square miles in size. The TRIs capture elevation variation by summing the difference in elevation between each grid cell and its neighboring grid cells. These measures provide a continuum of topographic variation at a very localized scale, ranging from flat to extremely rugged.

We calculated the first TRI, the Area TRI, using all grid cells nationwide. The second TRI, the Road TRI, was created using just the subset of grid cells that contain roads. To aid research and program applications, we aggregated the TRI results up to census tracts. Using the mean TRI values across census tracts, we created two ruggedness scales: the six-level Area Ruggedness Scale (ARS) and the five-level Road Ruggedness Scale (RRS). To our knowledge, these are the first ruggedness measures with full nationwide coverage for the United States and the first to provide a roads-only version to help study the impact of rugged terrain on travel by car.

The rugged terrain measures and classifications presented here have the potential to contribute to research on the linkages between geography and the health and well-being of individuals, especially those living in rural areas. This research may also aid ongoing assessments of urban-rural classifications, especially in cases like the U.S. Department of Agriculture, Economic Research Service's (ERS) Frontier and Remote Area (FAR) codes, which incorporate travel time by car as a measure of accessibility. It is important to determine whether different measures of travel time adequately capture the unique barriers to accessibility found in rugged areas. Federal and State programs that use such urban-rural definitions to target funding for rural development may benefit from the ARS and RRS. Finally, the uses of this new measure will likely extend to research and program applications focused on the benefits of rugged terrain, that is, in gaining a better understanding of the role of scenic amenities as a driver of population and job growth. However, this extension is beyond the scope of this report.

These new rugged terrain measures are likely to be beneficial to researchers and policymakers focused on rural areas. However, rugged terrain is distinct from rurality and is not meant to be a component of any rural definition. Our findings here show that 85 percent of rural residents live outside census tracts characterized as rugged, broadly defined.[1] Similarly, a significant portion of rugged terrain, broadly defined, is found in urban areas.

Previous USDA, ERS Measures of Topographic Variation

Natural amenities have long been understood as critical place characteristics that draw new residents and jobs to specific advantaged rural areas (McGranahan et al., 2011). Natural amenities are attractive aspects of the physical environment, as opposed to the built environment. Mountainous terrain is one such aspect. The attractiveness of mountain regions as tourist and recreation destinations goes back to the colonial era in this country, in places such as Warm Springs, Virginia,[2] but really took off with advances in automobile travel and the increase in prosperity after World War II. Beginning in the 1950s, geographers and other researchers began documenting how preferences for living in pleasant climates and scenic settings were shaping new migration patterns (Ullman, 1954; Beale, 1975; McGranahan, 2008).

Since 1993, USDA, ERS has included measures of mountainous terrain in different versions of a county-level natural amenities scale, along with measures of climate and access to bodies of water. The initial scale, used internally to analyze rural population change, measured topography as the elevation at a county's centroid combined with a measure of varied topography (McGranahan, 1993). Results for elevation contradicted expectations, showing a negative correlation between county elevation and population growth. Further analysis led to the conclusion that topographic variability, rather than elevation, better captured the appeal of mountainous regions, drawing visitors and new residents to these areas.

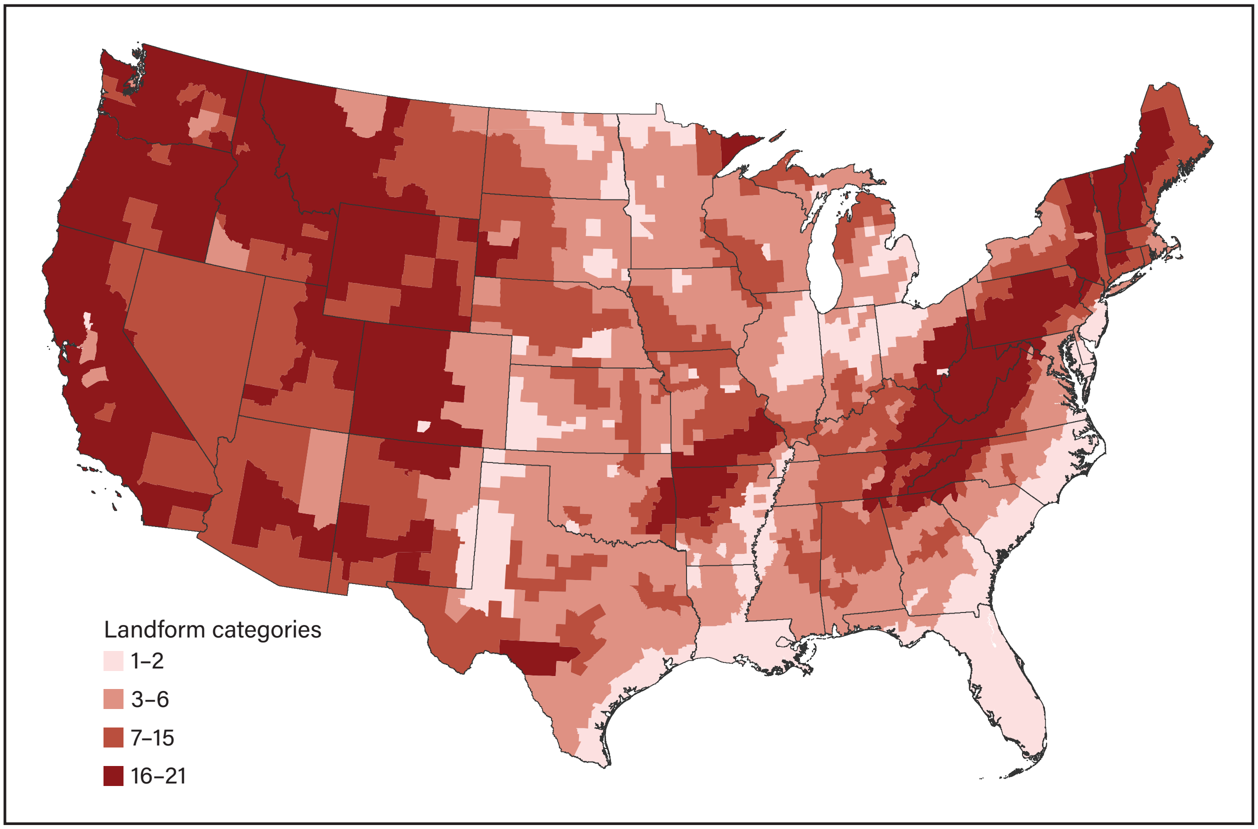
The next version of the natural amenities scale, published in 1999 and since adopted widely in demographic and economic research, combined qualities of climate, access to bodies of water, and a measure called topographic variation (McGranahan, 1999). Although delineated at a different scale (counties as opposed to grid cells), the underlying concept is similar to the concept of rugged terrain presented here, with the idea that "…the more variable the topography, the more appealing the setting" (McGranahan, 1999). To create

[1] Throughout this report, "broadly defined" ruggedness refers to any RRS or ARS category labelled as "rugged." This includes census tracts in categories 3–5 (slightly to highly rugged) for the RRS and census tracts in categories 3–6 (slightly to extremely rugged) for the ARS.

[2] European settlement in the Warm Springs, Virginia area began in the mid-1700's after colonists discovered the natural springs. News of their curative properties spread, and visitors began to arrive in large numbers to "take the waters." To encourage more visitors, the Virginia legislature funded a turnpike over the mountains to the springs in 1772 (Preservation Bath, n.d.). Other rural population centers developed around similar resorts throughout the 19th century, such as Hot Springs, Arkansas, and Glenwood Springs, Colorado.

the measure, McGranahan (1999) drew on topographic data from a U.S. Department of the Interior, U.S. Geological Survey (USGS) map depicting landforms (e.g., plains, hills, and mountains) and an indicator of variability within each landform. He then used a county map overlay to select the dominant land formation in each county. The resulting index of topographic variation closely followed expected regionalization patterns. The Southern Coastal Plains, Midwest, and Great Plains contain lower values—less topographic variation—while the Appalachians Mountains, the Rocky Mountains, and along the Pacific Coast have the highest values (figure 1).

Figure 1
County-level topographic variation



Note: Categories depict landforms (e.g., plains, hills, and mountains) and an indicator of variability within each landform. Map intervals are standard deviation (SD) units from the mean, with the darkest color more than 1 SD above the mean and the lightest more than 1 SD units below. Data for Alaska and Hawaii are not available.

Source: USDA, Economic Research Service using McGranahan, D.A. (1999). *Natural amenities drive rural population change*. U.S. Department of Agriculture, Economic Research Service. AER-718.

This measure of topographic variation is one component of the county-based USDA, ERS Natural Amenities Scale. The index is the most widely used measure of its kind, applied across research disciplines to understand the impact of scenic amenities on an array of county-level population, social, and economic trends (e.g., Brooks & Mueller, 2020; Cromartie & Nelson, 2009; Pitts et al., 2013; Rickman & Wang, 2020).

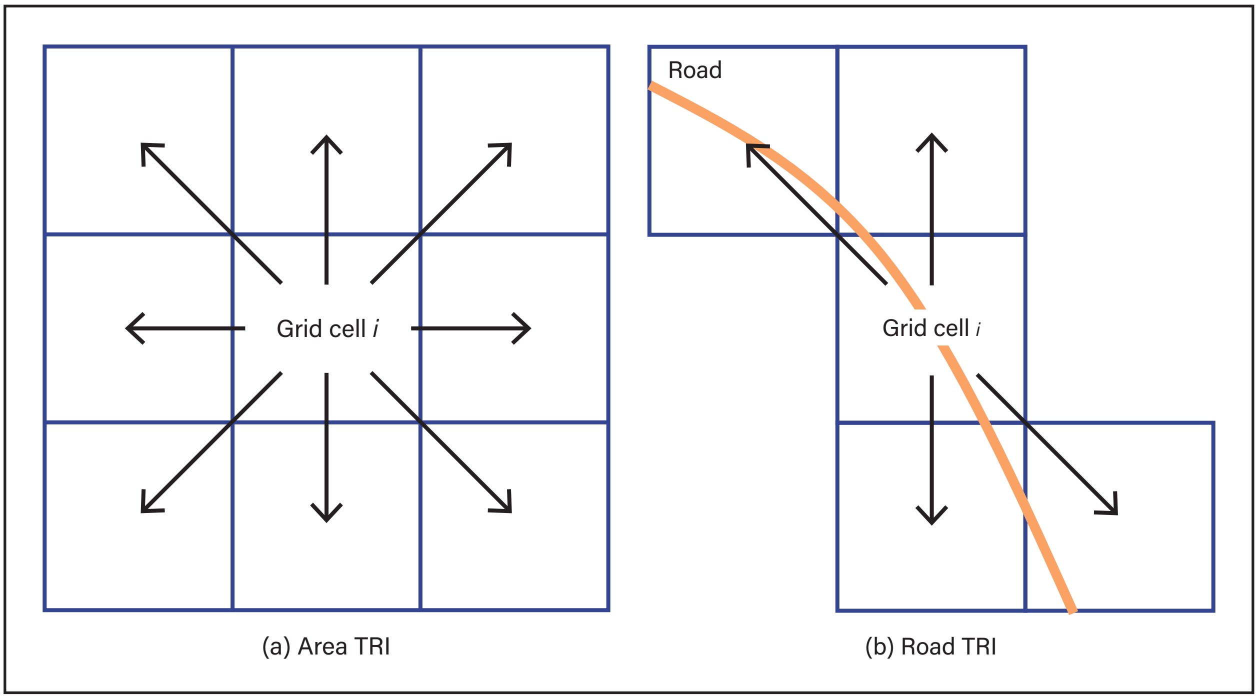
However, understanding the role of rugged terrain as a hindrance to settlement and travel requires a different measure. First, the new indicator needs to be based on a more geographically detailed analysis of local-scale differences in elevation and able to depict rugged terrain in specific locales and along specific road networks. Second, the new indicator needs to be flexible, allowing for the aggregation of grid-cell results to larger geographic units (e.g., census tracts) that are used in definitions of rurality (e.g., the Rural-Urban

Commuting Area codes). Third, the new indicator needs to be statistically consistent using a methodology that ensures local variation in elevation is measured consistently in all locations. The data and procedures presented in the next section meet these requirements. Together, the data and methods provide a robust indicator of the characteristics of landscape that present an impediment to settlement and travel and, therefore, accessibility to services for people residing in mountainous areas.

Data and Methods

The ruggedness measures introduced in this report are based on the Terrain Ruggedness Index (TRI) developed by Riley et al. (1999) to study the effects of rugged terrain on wildlife density. The TRI is calculated using data from a digital elevation model (DEM), a detailed representation of the Earth's terrain at the scale of small, regularly spaced grid cells. A TRI value is computed for each grid cell of a DEM by calculating "the sum change in elevation between (the given) grid cell and its eight neighbor cells," as illustrated in figure 2a (Riley et al., 1999). Lower values indicate less change in elevation within the 3- by 3-grid-cell neighborhood, and higher values indicate areas with higher elevation differences. Riley et al. (1999) classified their continuous TRI values into seven levels, applying descriptive terms to each level. The five highest levels were described using the term "rugged" and ranged from slightly to extremely rugged.

Figure 2
Computation window for Terrain Ruggedness Index values



Note: This figure illustrates the computation window used when calculating the Terrain Ruggedness Index (TRI) value for a grid cell. For the Area TRI, the computation includes the grid cell of interest, *i*, and its eight adjacent, neighboring grid cells. For the Road TRI, the computation includes the grid cell of interest, *i*, and the adjacent, neighboring grid cells in which a road is present.

Source: USDA, Economic Research Service.

The TRI has been adopted widely across a number of disciplines to study a diverse range of topics, including wildlife habitat analysis (Nayeri et al., 2022), ecosystem sensitivity (Pastick et al., 2019), urban flood control (Lei et al., 2021), economic development (Nunn & Puga, 2012), and landscape aesthetics (Vukomanovic & Orr, 2014). All of this work has focused on limited geographical regions, whereas the two TRI measures we developed provide full nationwide coverage for the United States. One of our TRI measures, the Area TRI, includes all grid cells; and the other, the Road TRI, measures terrain ruggedness along roads specifically.

The elevation data underlying our two TRIs came from the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010), a DEM developed by the USGS in collaboration with the U.S. Department of Defense's National Geospatial-Intelligence Agency (NGA).[3] GMTED2010 elevation data points are available for three grid-cell sizes (30-, 15-, and 7.5-arc-seconds). We chose the 7.5 arc-second grid cells to maximize the spatial resolution of the data. The 7.5 arc-second grid cells have an average size of 0.15 square miles in the contiguous United States.[4] We used the median elevation and the "Spatial Eco" package in the statistical software program R to calculate grid-cell TRIs for the United States.

For the Area TRI, ruggedness values were calculated for all 263 million grid cells covering the United States. The Area TRI has a minimum value of zero, indicating no change in elevation between that grid cell and its eight neighboring grid cells. The maximum Area TRI grid-cell value of 1,836 meters (located near Juneau, Alaska) represents the largest difference in elevation between that grid cell and its neighbors. For the Roads TRI, ruggedness was measured using elevation data from only the 47 million grid cells containing roads. Whereas the Area TRI value for a given grid cell was derived from a comparison with all eight neighbors (except on the edges of the grid), Road TRI values did not include values from a neighboring grid if that neighbor did not contain a road (figure 2b). We used all streets included in the ArcGIS StreetMap Premium 2021 data in our calculations, including highways, arterial, collector, local, and semiprivate roads. The maximum Road TRI grid-cell value of 563 meters is located east of Saint George in southwestern Utah.

Although the grid-cell TRI values are helpful for research requiring detailed spatial information, many research and policy applications need values aggregated to larger geographic units, such as census tracts. Census tracts are the smallest geographic unit for which socioeconomic data are generally produced. They provide a more accurate description of the variable topography within an area than would larger geographic units, such as counties. Census tracts are also the smallest geographic unit for which USDA, ERS has a measure of rurality (the Rural-Urban Commuting Area codes).

We produced aggregate TRI measures for 2010 census tracts from both the Area and Road TRIs by calculating the mean value of all grid cells located in each census tract. The mean Area TRI census tract values range from 0 to 243 meters, while the mean Road TRI census tract values range from 0 to 135 meters. The Road TRI data has a lower maximum value because roads are constructed along paths of least resistance. The only census tract with a minimum value of zero for its mean Area TRI is in New York City. However, several census tracts in California and New York have a mean Road TRI value of zero. The maximum census tract Area TRI value is in the Rocky Mountains near Provo, Utah, while the census tract Road TRI reaches its maximum value near San Bernadino, California, in the Pacific Mountain System.

The census tract Area and Road TRI values are useful as continuous measures of variable topography. The detailed information they provide may be the preferred measure for certain types of research, such as regression analysis. However, classifying the census tract TRI values into a limited number of categories allows for easier statistical comparisons and mapping and, thus, a more comprehensible understanding of the degree of

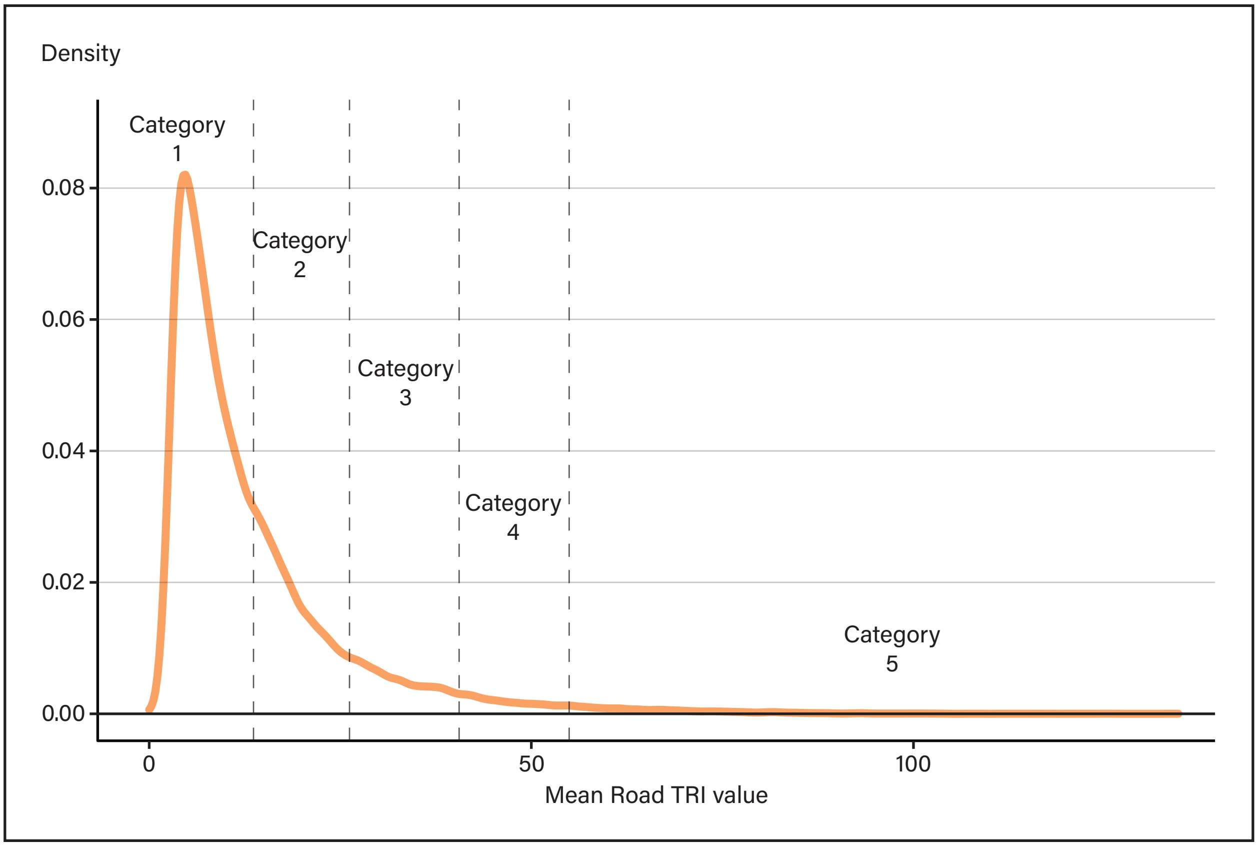
[3] Danielson and Gesch (2011) provide technical documentation of how the GMTED 2010 data were created.

[4] An arc-second is a measure of distance on the surface of a sphere and equals approximately 30 meters or 100 feet at the Earth's equator. Thus a 7.5 arc-second grid cell is about 231 by 231 meters, 760 by 760 feet, or ¼ square mile at the equator. The length of an arc-second remains constant north-south but decreases east-west as lines of longitude converge towards the poles. This means that in the United States, grid cells decrease in size as you move farther north.

ruggedness as it varies across locations. It is important to choose a classification method that helps identify trends and patterns more easily, as different classification methods emphasize different aspects of the underlying data (Foster, 2019).

A good classification method should reflect the underlying data rather than distort it (Jiang, 2013). The Area and Road TRI values have similar distributions across census tracts (figure 3; appendix A, figure A1). There are many census tracts concentrated across a very small range of low TRI values (the "head" of the distribution on the left side of the graph) and far fewer census tracts across a large range of high TRI values (the long "tail" to the right). More categories are needed across the higher range of values in the tail to distinguish among different levels of ruggedness. We employed the head/tail breaks classification method introduced by Jiang (2013) for use with this specific type of distribution.[5]

Figure 3
Distribution of census tract Road Terrain Ruggedness Index values



Note: The Road Terrain Ruggedness Index (Road TRI) of grid cells was calculated using the method outlined in Riley et al. (1999) and only grid cells with a road passing through them as an input. The figure graphs the average Road TRI value of grid cells along roads in 2010 census tracts. Head/tail breaks values were calculated using the "ClassInt" package in R with a threshold of 0.39 (Bivand et al., 2020).

Source: USDA, Economic Research Service calculations using U.S. Department of the Interior, U.S. Geological Survey and U.S. Department of Defense, National Geospatial-Intelligence Agency, 7.5 arc-second resolution, Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010); ESRI, ArcGIS StreetMap Premium 2021 Q3 data; and U.S. Department of Commerce, Bureau of the Census, 2010 Census of Population and Housing, TIGER (Topographically Integrated Geographic Encoding and Referencing)/Line boundary files; and Bivand et al. (2020).

[5] The heavy-tailed distribution is a common pattern found in a variety of geographical and social phenomenon, with far more low values than high ones (Jiang and Sui, 2014). Like the ruggedness scale described here, interest invariably lies in differentiating among higher values in the tail of the distribution. Other examples include population distributions (far more small cities or counties than large ones), roads or waterways (far more short roads or rivers than long ones), and dwellings (far more smaller housing units than large ones).

The head/tail breaks method uses an iterative process that first partitions data into two groups based on the mean, creating one group with a large number of low values below the mean and a second group of high values found in the tail, or above the mean.[6] The method then partitions the tail into two groups around the mean value of this second group. It continues partitioning the remaining tail in this manner until the remaining set of values is no longer considered a heavy-tailed distribution (i.e., until the mean is more centrally located among the data values). Because partitioning depends on the underlying distribution of data values, the number of categories and range of values in each category are different for each dataset that is calculated using head/tail breaks. The resulting scales place more emphasis on differentiating among high values. The head/tail breaks method was ideal for categorizing the census tract Area and Road TRI values into ruggedness scales, as it allowed us to model and analyze differing levels of ruggedness.

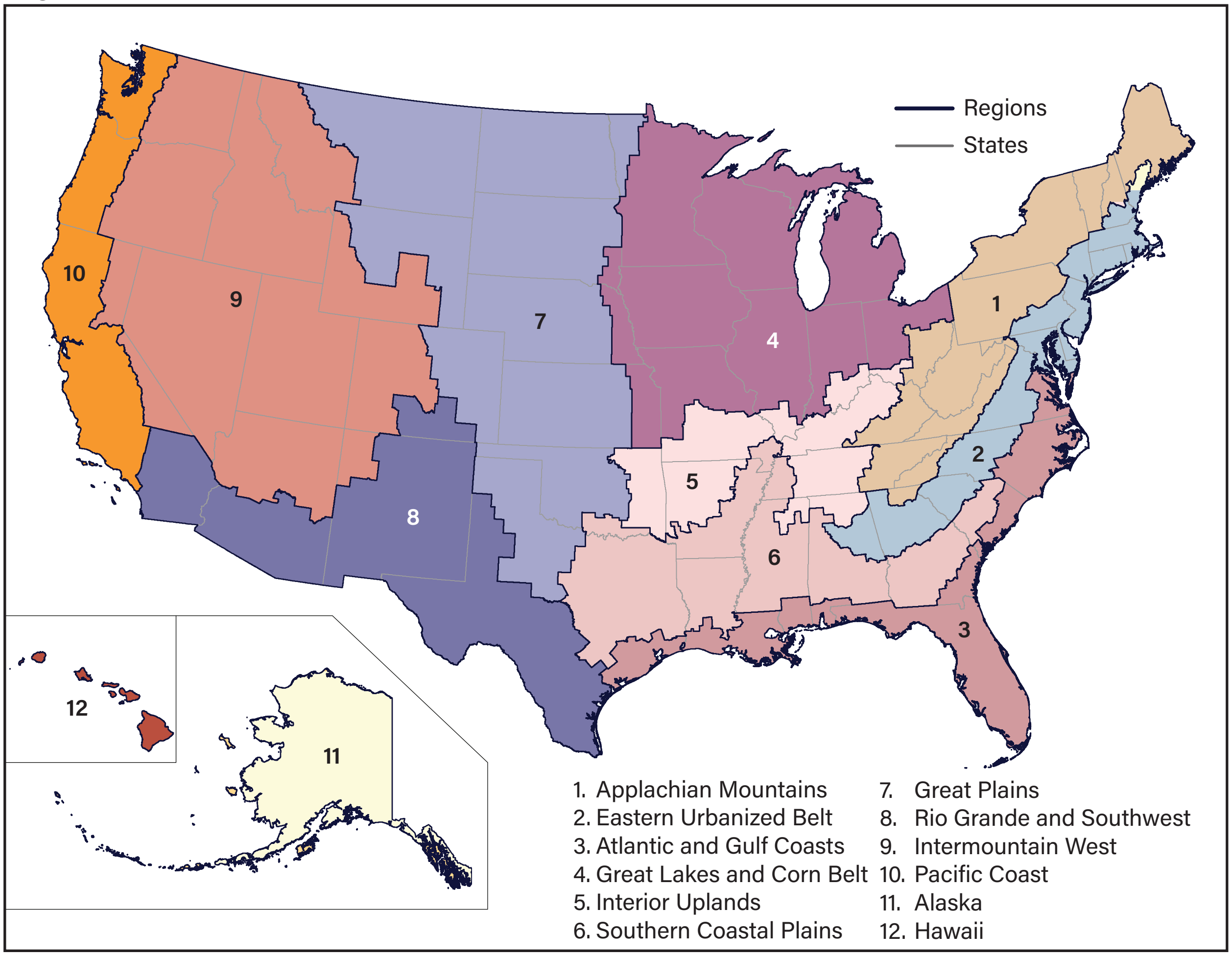
The Area Ruggedness Scale (ARS) is the categorization of the census tract Area TRI using the head/tails method, while the Road Ruggedness Scale (RRS) is the categorization of the census tract Road TRI. See appendix A for more details on the data and methods used to create the TRI values, ARS, and RRS. In this report, we used the RRS for our analysis of population, population density, and income differences across levels of ruggedness by regions and rurality in the United States.

Geographic Divisions for Analysis

We used a regional definition adapted from Fuguitt and Beale (1978) to divide U.S. counties into 12 distinct regions (figure 4). We then used these regions to analyze differences in relative ruggedness and settlement patterns across the Nation. They include: (1) the Appalachian Mountains; (2) the Eastern Urbanized Belt; (3) the Atlantic and Gulf Coasts; (4) the Great Lakes and Corn Belt; (5) the Interior Uplands, including the Ozark and Ouachita Mountains; (6) the Southern Coastal Plains; (7) the Great Plains; (8) the Rio Grande and Southwest; (9) the Intermountain West, from the Rocky Mountains to the Sierra Nevada and Cascade Ranges; (10) the Pacific Coast; (11) Alaska; and (12) Hawaii. Alaska and Hawaii are the only two States that are also regions because they are quite distant from the contiguous United States and topologically distinct from each other. The counties of most other States are split among two or more regions based on their topography. See appendix B for more information on the creation of these regions.

[6] Jiang (2013) used a rank-size distribution to introduce the head/tail breaks method, plotting the value on the y-axis and the rank of the frequency on the x-axis. That is the opposite of how the distribution of Road TRI values is presented in figure 3. We adapted Jiang's terminology to fit the way the data are illustrated in figure 3, so how we used "head" and "tail" differs from how Jiang does.

Figure 4
Regions of the United States

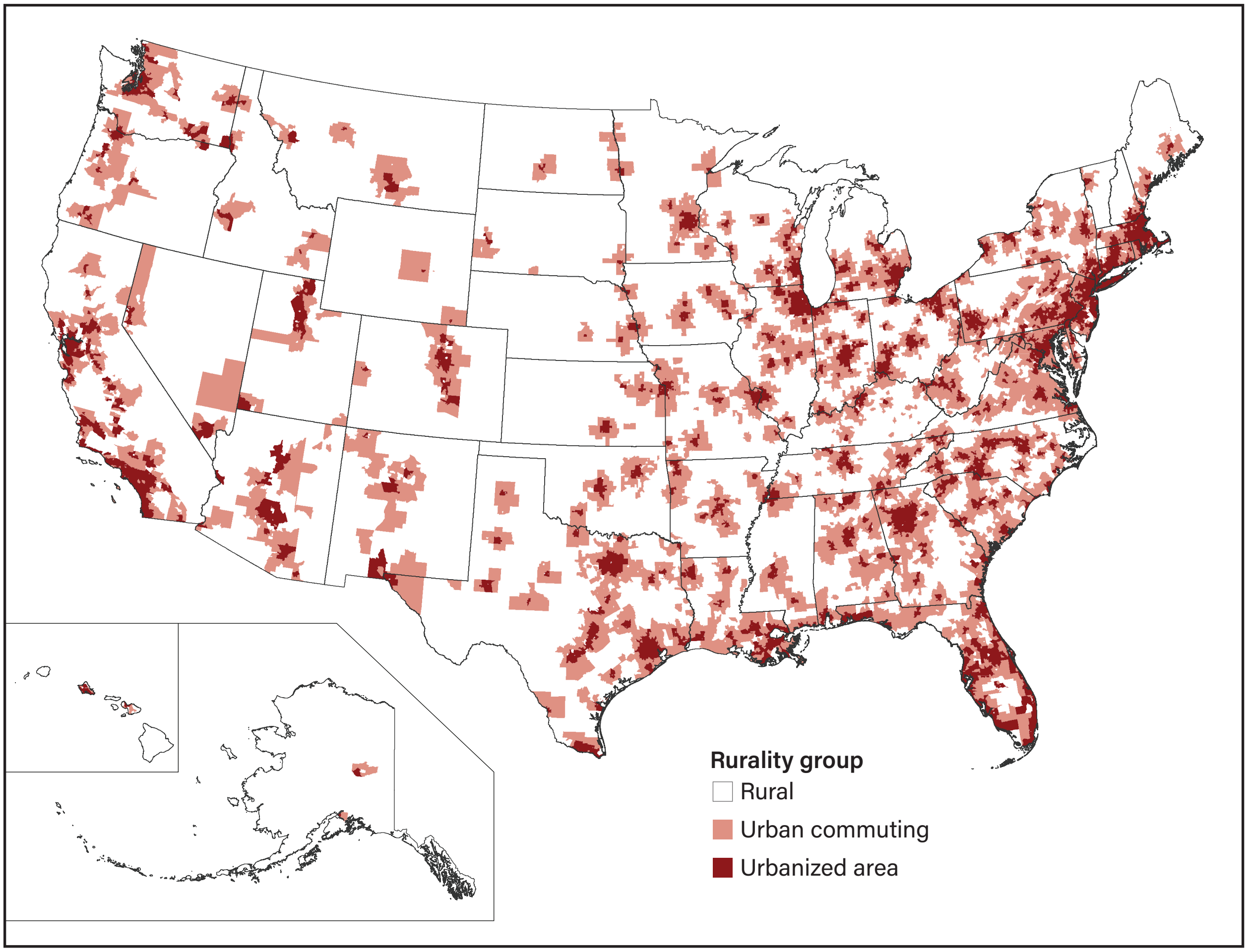


Note: County-level regional definitions were adapted from Fuguitt and Beale (1978). See appendix B for more information.

Source: USDA, Economic Research Service adapting data from Fuguitt, G.V., & Beale, C.L. (1978). Population trends of nonmetropolitan cities and villages in subregions of the United States. *Demography*, *15*(4).

To explore the relationship between ruggedness and rurality, we categorized census tracts using USDA, ERS's Rural-Urban Commuting Area (RUCA) codes. RUCA codes are a census-tract-level classification that mirrors criteria used by the U.S. Office of Management and Budget to define metropolitan and micropolitan areas. In this report, we combined the 10 primary RUCA codes into 3 groups. Census tracts that are part of an urbanized area, defined by the Census Bureau as an urban core of at least 50,000 residents, comprise the urbanized area group (RUCA 1). These census tracts are analogous to central counties of metropolitan areas. Census tracts that are not part of an urbanized area but are economically tied to an urbanized area census tract through commuting, comprise the urban commuting group (RUCAs 2 and 3). These census tracts are analogous to outlying counties of metropolitan areas and may not be urban in character. Finally, census tracts that are not part of either the urbanized area group or urban commuting group comprise the rural group (RUCAs 4–10). These census tracts contain micropolitan areas and smaller communities, as well as sparsely populated land. They are analogous to nonmetropolitan counties. Census tracts are mapped by their rurality group in figure 5.

Figure 5
Census tract rurality groups based on Rural-Urban Commuting Area codes



Note: Census tracts are classified into rurality groups based on their 2010 Rural-Urban Commuting Area (RUCA) codes. The groups are: urbanized area (RUCA 1), urban commuting (RUCA 2 and 3), and rural (RUCA 4–10).

Source: USDA, Economic Research Service 2010 Rural-Urban Commuting Area codes.

Demographic and Socioeconomic Analysis

Communities are not uniform. They vary by population size and density, land area, physical environment (e.g., minerals, water, ruggedness), variety and specialization of goods and services available, and characteristics of the residents (e.g., education and income levels, race and ethnicity, and culture). Residents of smaller rural communities may need to travel longer distances to access hospitals, schools, social services, grocery stores, and other critical destinations. Ultimately, this circumstance can affect the well-being of rural residents, and when residents also need to travel through rugged terrain to access resources, any negative effects on well-being may be compounded.[7]

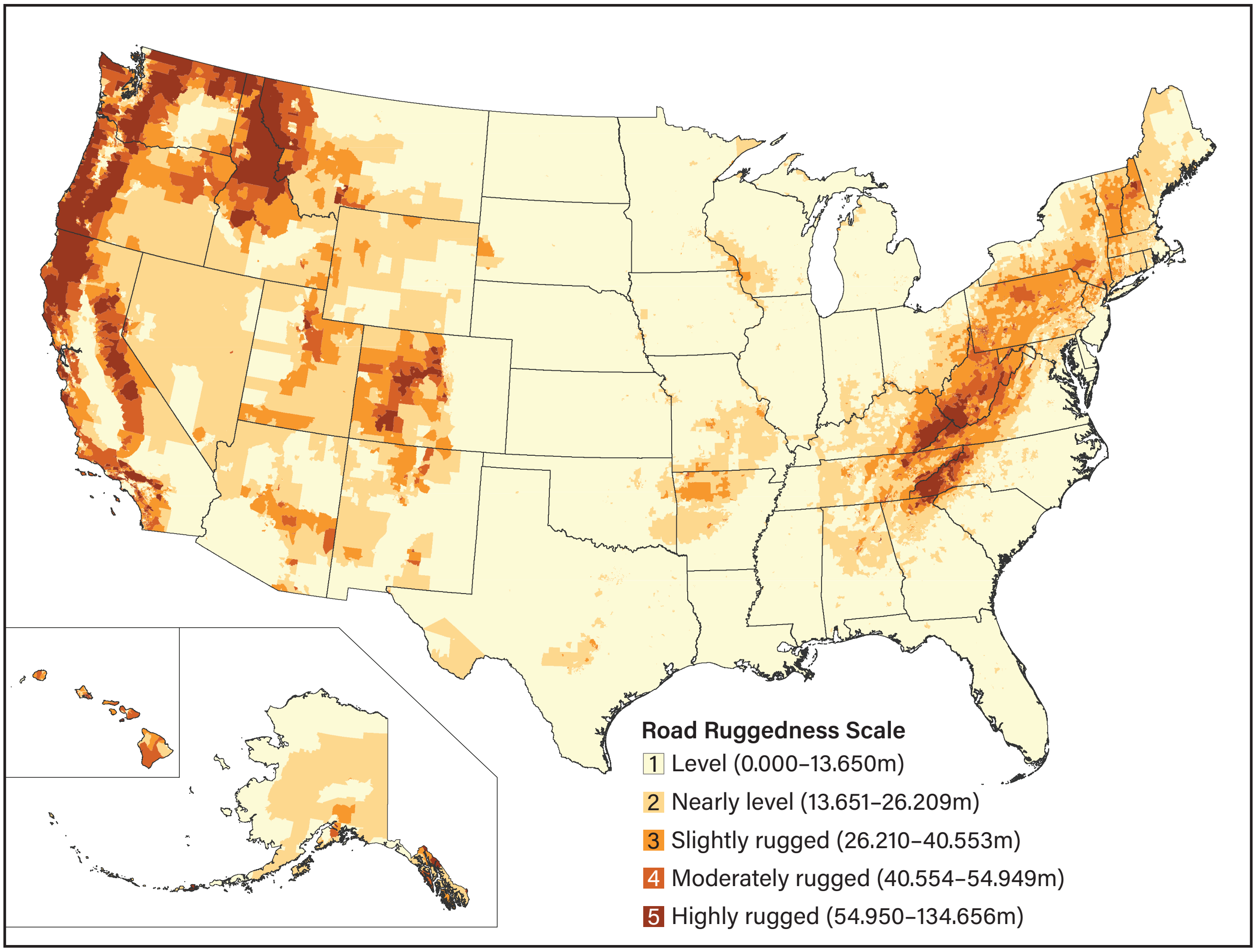
[7] Well-being is a complex, multifaceted concept that can be measured in a variety of different ways, such as income or happiness, as well as at a variety of levels, including individuals or communities. A comprehensive analysis of well-being is beyond the scope of this report. Here, we analyzed the population living in low-income census tracts across rurality, ruggedness, and regions as an initial demonstration of the work that can be done relating ruggedness with well-being.

To understand variation in community characteristics by terrain ruggedness, we analyzed population, population density, and income. We obtained 2010 decennial census population counts and population density from the RUCA code data. Census tracts and population counts from the 2010 decennial census were chosen over more recent 2020 data to match the current RUCA code classification. We also obtained a list of low-income census tracts from USDA, ERS's 2010 Food Access Research Atlas (FARA) to use as a broad measure of economic well-being. The criteria used to identify low-income census tracts is from the U.S. Department of the Treasury's New Markets Tax Credit (NMTC) Program and include poverty rates and comparisons of census tract median family income to State and metropolitan values.

The Road Ruggedness Scale

The Road Ruggedness Scale (RRS) is a classification of topographic variation, or "ruggedness," along roads within census tracts. This measure classifies census tracts into ordinal categories based on their Road TRI, where the census tracts with the lowest average TRI values have the least topographic variation, and the census tracts with the highest average TRI values have the most topographic variation. The RRS has five categories ranging from 1–level to 5–highly rugged. The RRS categories indicate the level of topographic variation under a census tract's roads when compared with census tracts in other categories. The categories are mapped in figure 6, and the range of Road TRI values included in each category, as well as a description of each category, are available in the legend.

Figure 6
Map of the Road Ruggedness Scale



m = Meters.

Note: The Road Ruggedness Scale (RRS) is an ordinal scale of topographic variation along roads in the United States. The RRS is calculated using the average Road Terrain Ruggedness Index (Road TRI) of grid cells within 2010 census tracts.

Source: USDA, Economic Research Service calculations using U.S. Department of the Interior, U.S. Geological Survey and U.S. Department of Defense, National Geospatial-Intelligence Agency, 7.5 arc-second resolution, Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010); ESRI, ArcGIS StreetMap Premium 2021 Q3 data; and U.S. Department of Commerce, Bureau of the Census, 2010 Census of Population and Housing, TIGER (Topographically Integrated Geographic Encoding and Referencing)/Line boundary files.

Each of the 72,765 land-based census tracts from the 2010 decennial census was classified into one of these categories based on its average Road TRI. Summary statistics for the census tracts in each RRS category are available in table 1. The majority of census tracts have very little topographic variation, with 65.6 percent of census tracts classified as category 1–level in the RRS. The next largest category is 2–nearly level, with 22.4 percent of census tracts. This results in 12.0 percent of census tracts being classified as slightly to highly rugged (categories 3–5) and only 4.4 percent being classified as moderately or highly rugged (categories 4 and 5). The top category has the largest range of Road TRI values, with a difference of nearly 80 meters between the largest and smallest values, while the other four categories have a range of about 13 to 14 meters.

Table 1
Census tract Road Terrain Ruggedness Index summary statistics by Road Ruggedness Scale

RRS category	N	Mean (m)	SD (m)	Median (m)	Min. (m)	Max. (m)
1–Level	47,740	7.068	3.055	6.598	0.000	13.650
2–Nearly level	16,297	18.528	3.461	17.889	13.651	26.209
3–Slightly rugged	5,518	32.178	4.082	31.576	26.217	40.546
4–Moderately rugged	1,956	46.569	4.137	46.000	40.578	54.940
5–Highly rugged	1,254	68.022	12.189	64.642	54.950	134.656
U.S. total	72,765	13.651	12.368	9.573	0.000	134.656

N = Number of census tracts. m = Meters. SD = Standard deviation. Min. = Minimum. Max. = Maximum.

Note: The Road Ruggedness Scale (RRS) is an ordinal scale of topographic variation along roads in the United States, ranging from category 1–level to category 5–highly rugged.

Source: USDA, Economic Research Service calculations using U.S. Department of the Interior, U.S. Geological Survey and U.S. Department of Defense, National Geospatial-Intelligence Agency, 7.5 arc-second resolution, Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010); ESRI, ArcGIS StreetMap Premium 2021 Q3 data; and U.S. Department of Commerce, Bureau of the Census, 2010 Census of Population and Housing, TIGER (Topographically Integrated Geographic Encoding and Referencing)/Line boundary files.

In figure 6, the light-yellow color represents category 1, which has the most level land, whereas dark brown represents category 5, the highest level of ruggedness. The geographic patterns illustrated by the RRS categories are similar to those of a topographic relief map. In the Eastern United States, the Appalachian Mountains are clearly visible, stretching from western Maine down to northeastern Alabama. There are clusters of census tracts with roads on very rugged land in the Appalachian Mountains, particularly along the Tennessee-North Carolina border and along the Kentucky-Virginia border into southwestern West Virginia.

In the Western United States, parts of the Rocky Mountains are clearly visible. In particular, there are clusters of census tracts with roads on very rugged land in western Montana and the Idaho panhandle, east of the Great Salt Lake in Utah, and in west-central Colorado roughly coinciding with the Colorado Mineral Belt. The Pacific Mountain System is also clearly visible along the Pacific Coast in Washington, Oregon, northern California, and southeast Alaska. The Sierra Nevada mountains in eastern California and many of the Hawaiian Islands also have roads on rugged land.

In contrast, the roads of the coasts of the Atlantic Ocean and Gulf of Mexico, as well as the Great Plains and the Corn Belt, are on relatively level land. However, prominent exceptions to this statement are the Ozark and Ouachita Mountains in Arkansas, southern Missouri, and eastern Oklahoma; the Black Hills in western South Dakota; and the Driftless Area in western Wisconsin along the borders with Minnesota, Iowa, and Illinois. A similar discussion of the Area Ruggedness Scale (ARS) is available in appendix C.

Exploring the Road Ruggedness Scale

We explored the variation of community characteristics by terrain ruggedness to provide insight into the interaction of residents with their environment. To better understand these interactions, we analyzed how population, population density, and income vary by the RRS and rurality both nationally and across regions. In addition, because regions do not have official political boundaries, we also explored the population and land distribution by RRS for States.

Population Distribution and Ruggedness

Two-thirds of the U.S. population, more than 200 million people, lived in level (category 1) census tracts in 2010 (table 2). This number includes most of the population in the Nation's largest cities, such as New York City, Los Angeles, Chicago, Houston, and Philadelphia. About 22 percent of residents (or more than 70 million people) lived in census tracts that are category 2, slightly level. Only about 12 percent of residents lived in the top three categories, which range from slightly rugged to highly rugged. The number of residents decreased as the categories became more rugged, with less than 4.5 million people (1.4 percent) living in the highest RRS category.

Table 2
Census tract population and population density by Road Ruggedness Scale, 2010

RRS category	Population			Population density		Mean land area (square miles)
	Count	Mean	Median	Mean	Median	
1–Level	202,420,576	4,240	3,983	5,275	2,413	42.9
2–Nearly level	70,587,330	4,331	4,134	5,514	2,136	59.3
3–Slightly rugged	23,465,960	4,253	4,064	4,712	1,151	49.3
4–Moderately rugged	7,815,559	3,996	3,812	4,443	1,209	63.7
5–Highly rugged	4,456,113	3,554	3,369	3,390	695	94.5
U.S. total	308,745,538	4,243	4,005	5,231	2,183	48.5

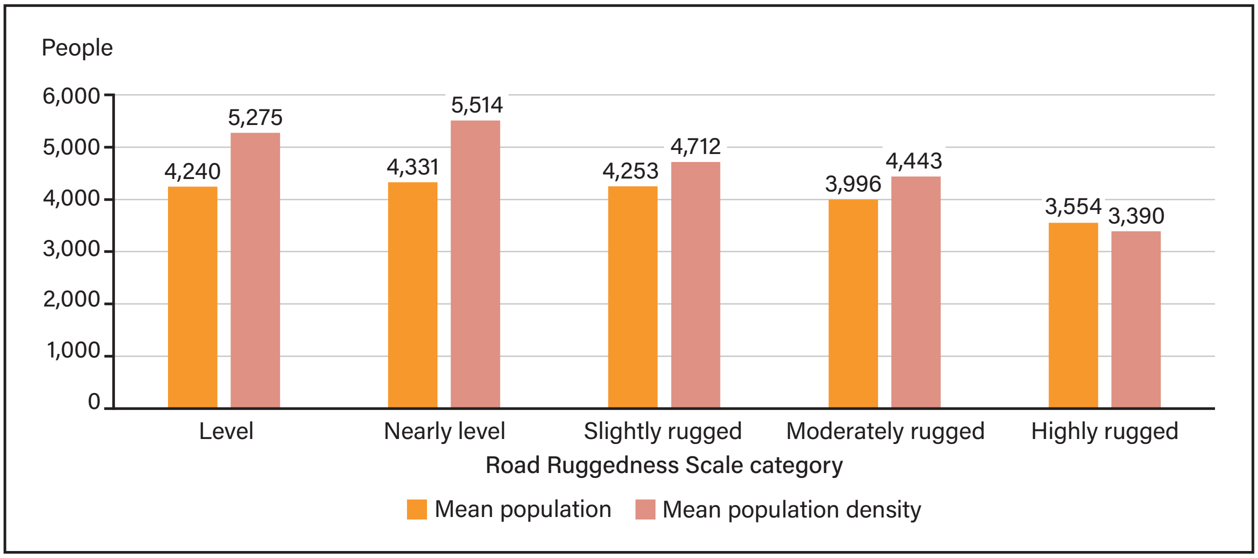
Note: The Road Ruggedness Scale (RRS) is an ordinal scale of topographic variation along roads in the United States, ranging from category 1–level to category 5–highly rugged. Population density is given in people per square mile.

Source: USDA, Economic Research Service calculations using U.S. Department of the Interior, U.S. Geological Survey and U.S. Department of Defense, National Geospatial-Intelligence Agency, 7.5 arc-second resolution, Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010); ESRI, ArcGIS StreetMap Premium 2021 Q3 data; and U.S. Department of Commerce, Bureau of the Census, 2010 Census of Population and Housing, Summary File 1 and TIGER (Topographically Integrated Geographic Encoding and Referencing)/Line boundary files.

As expected, the mean population of census tracts within each category decreased only slightly as the terrain became more rugged, only ranging from 4,240 to 3,554 residents between categories 1 and 5 (figure 7; table 2).[8] The reason that there was only a small amount of variation in the mean population is that census tracts were designed to maintain, as close as possible, a consistent population size of around 4,000 people. However, census tracts were larger and population densities were lower in areas where the population was more spread out, including in rugged terrain. The average land area was 94.5 square miles for highly rugged census tracts compared with 42.9 square miles for level census tracts (table 2). Average population density was lowest in highly rugged census tracts (category 5) at 3,390 people per square mile and highest for nearly level census tracts (category 2) at 5,514 people per square mile (figure 7; table 2).

[8] We tested the values in table 2 and figure 7 for statistical significance. We found that the means were jointly statistically significantly different from each other and that all specific comparisons were also statistically different.

Figure 7
Mean population and population density by Road Ruggedness Scale, 2010



Note: The Road Ruggedness Scale (RRS) is an ordinal scale of topographic variation along roads in the United States, ranging from category 1–level to category 5–highly rugged. Population density is given in people per square mile.

Source: USDA, Economic Research Service calculations using U.S. Department of the Interior, U.S. Geological Survey and U.S. Department of Defense, National Geospatial-Intelligence Agency, 7.5 arc-second resolution, Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010); ESRI, ArcGIS StreetMap Premium 2021 Q3 data; and U.S. Department of Commerce, Bureau of the Census, 2010 Census of Population and Housing, Summary File 1 and TIGER (Topographically Integrated Geographic Encoding and Referencing)/Line boundary files.

Regional Variation in Population and Ruggedness

The Intermountain West was the largest of the 12 regions we used to analyze variation in ruggedness and population, comprising more than 620,000 square miles and 17.6 percent of the Nation's land area (table 3). The Eastern Urbanized Belt had the largest population in 2010, with nearly 69 million residents (22.3 percent of the Nation's population) and the highest average population density (11,055 people per square mile). Alaska and Hawaii had the smallest populations, with about 700,000 and 1.4 million residents in 2010, respectively, while the Interior Uplands had the lowest average population density at 1,463 people per square mile.

Table 3
Census tracts, population, and land area by U.S. region, 2010

Regions	Census tracts	Total population	Mean population density (per square mile)	Total land area (square miles)	Mean census tract area (square miles)
1. Appalachian Mountains	5,773	22,252,021	1,827	209,939.0	36.4
2. Eastern Urbanized Belt	15,903	68,716,623	11,055	128,595.2	8.1
3. Atlantic and Gulf Coasts	8,326	37,296,998	3,233	145,922.2	17.5
4. Great Lakes and Corn Belt	14,770	58,112,446	3,502	405,748.3	27.5
5. Interior Uplands	3,465	14,576,292	1,463	145,625.3	42.0
6. Southern Coastal Plains	5,257	22,977,041	1,868	242,268.4	46.1
7. Great Plains	3,073	11,324,301	2,152	570,701.4	185.7
8. Rio Grande and Southwest	4,728	21,657,979	3,825	338,601.4	71.6
9. Intermountain West	2,712	11,977,556	2,694	621,036.2	229.0
10. Pacific Coast	8,264	37,783,749	7,924	146,427.5	17.7
11. Alaska	167	710,231	1,518	570,641.1	3,417.0
12. Hawaii	327	1,360,301	9,051	6,423.4	19.6
United States	72,765	308,745,538	5,231	3,531,929.0	48.5

Note: County-level regional definitions were adapted from Fuguitt and Beale (1978).

Source: USDA, Economic Research Service calculations using U.S. Department of the Interior, U.S. Geological Survey and U.S. Department of Defense, National Geospatial-Intelligence Agency, 7.5 arc-second resolution, Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010); ESRI, ArcGIS StreetMap Premium 2021 Q3 data; U.S. Department of Commerce, Bureau of the Census, 2010 Census of Population and Housing, Summary File 1 and TIGER (Topographically Integrated Geographic Encoding and Referencing)/Line boundary files; and Fuguitt, G.V., & Beale, C.L. (1978). Population trends of nonmetropolitan cities and villages in subregions of the United States. *Demography*, *15*(4).

Comparing the regional distributions of land across RRS categories captured large differences in the relative ruggedness of roads (table 4). Two regions did not have any census tracts classified into the highest levels of topographic variability: the Atlantic and Gulf Coasts and the Southern Coastal Plains. These were also the flattest regions in the United States. The Atlantic and Gulf Coasts had 99.5 percent of its land classified as level based on the terrain under its roads, and the Southern Coastal Plains had 95.9 percent level and 4.0 percent nearly level land. The Great Lakes and Corn Belt was close behind with land that was 93.2 percent level and 6.3 percent nearly level.

Table 4
Share of land area by Road Ruggedness Scale in U.S. regions

Regions	Road Ruggedness Scale category				
	1	2	3	4	5
1. Appalachian Mountains	14.8	31.2	35.5	11.9	6.7
2. Eastern Urbanized Belt	46.6	41.3	10.6	1.3	0.1
3. Atlantic and Gulf Coasts	99.5	0.5	0.0	-	-
4. Great Lakes and Corn Belt	93.2	6.3	0.5	0.0	0.0
5. Interior Uplands	44.9	49.0	6.0	0.1	0.0
6. Southern Coastal Plains	95.9	4.0	0.1	0.0	-
7. Great Plains	88.2	10.3	1.2	0.2	0.1
8. Rio Grande and Southwest	71.6	21.1	5.3	1.7	0.3
9. Intermountain West	17.5	49.4	17.7	8.2	7.1
10. Pacific Coast	17.2	10.3	13.2	22.2	37.0
11. Alaska	45.4	50.2	3.0	0.8	0.7
12. Hawaii	3.7	23.8	25.5	45.0	2.0
United States	58.1	27.4	7.7	3.5	3.4

- = No census tracts in this group.

Note: The Road Ruggedness Scale (RRS) is an ordinal scale of topographic variation along roads in the United States, ranging from category 1–level to category 5–highly rugged. County-level regional definitions were adapted from Fuguitt and Beale (1978).

Source: USDA, Economic Research Service calculations using U.S. Department of the Interior, U.S. Geological Survey and U.S. Department of Defense, National Geospatial-Intelligence Agency, 7.5 arc-second resolution, Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010); ESRI, ArcGIS StreetMap Premium 2021 Q3 data; U.S. Department of Commerce, Bureau of the Census, 2010 Census of Population and Housing, TIGER (Topographically Integrated Geographic Encoding and Referencing)/Line boundary files; and Fuguitt, G.V., & Beale, C.L. (1978). Population trends of nonmetropolitan cities and villages in subregions of the United States. *Demography*, *15*(4).

In contrast, the most rugged region for road travel in the United States was the Pacific Coast, with 37.0 percent of its land classified as highly rugged, followed by the Intermountain West and Appalachian Mountains, with 7.1 percent and 6.7 percent of their land classified as highly rugged, respectively. Broadening the definition of ruggedness to consider census tracts that were classified as slightly to highly rugged, we found that the Pacific Coast and Hawaii were the most rugged regions (both 72.5 percent), followed by the Appalachian Mountains (54.0 percent) and the Intermountain West (33.1 percent).

The ruggedness of a region's land only tells part of the story. It's also important to understand how many people are living in rugged terrain and may experience more difficult travel to access goods and services (table 5). As with land area, the Atlantic and Gulf Coasts region had the greatest share of its residents living in level census tracts in 2010 (96.7 percent), followed by the Southern Coastal Plains (87.8 percent) and Great Lakes and Corn Belt (84.8 percent). The region with the largest share of its population living in highly rugged census tracts was Hawaii (10.2 percent), followed by the Appalachian Mountains (6.1 percent). Once again broadening the definition of rugged to include slightly to highly rugged terrain, the Appalachian Mountains became the region with the highest share of residents living in these categories (48.9 percent), followed by Hawaii (43.3 percent). The Pacific Coast was third with 25.2 percent, and the Intermountain West followed closely in fourth with 21.5 percent. These values were much larger than the 11.6 percent of the national population living in slightly to highly rugged census tracts.

Table 5

Share of population and mean population density by Road Ruggedness Scale in U.S. regions, 2010

Regions	Road Ruggedness Scale category				
	1	2	3	4	5
	Population share (percent)				
1. Appalachian Mountains	21.8	29.3	32.1	10.7	6.1
2. Eastern Urbanized Belt	45.4	44.8	8.2	1.3	0.3
3. Atlantic and Gulf Coasts	96.7	3.2	0.1	-	-
4. Great Lakes and Corn Belt	84.8	13.8	1.2	0.1	0.0
5. Interior Uplands	54.8	38.1	5.9	0.9	0.3
6. Southern Coastal Plains	87.8	11.6	0.6	0.1	-
7. Great Plains	78.5	17.3	2.9	0.6	0.7
8. Rio Grande and Southwest	69.0	18.2	9.2	2.9	0.8
9. Intermountain West	52.8	25.7	12.0	5.8	3.7
10. Pacific Coast	58.0	16.8	12.7	7.2	5.3
11. Alaska	62.0	19.4	10.9	2.5	5.3
12. Hawaii	25.0	31.7	20.3	12.8	10.2
United States	65.6	22.9	7.6	2.5	1.4
	Mean population density (per square mile)				
1. Appalachian Mountains	3,089.2	1,640.7	1,206.2	1,754.5	1,578.8
2. Eastern Urbanized Belt	13,398.8	8,450.8	10,108.5	15,352.1	22,887.1
3. Atlantic and Gulf Coasts	3,181.2	3,637.7	*	-	-
4. Great Lakes and Corn Belt	3,559.8	3,117.6	3,730.1	4,362.9	*
5. Interior Uplands	1,579.1	1,194.8	1,512.9	3,634.0	*
6. Southern Coastal Plains	1,778.9	2,505.1	1,949.5	*	-
7. Great Plains	1,924.4	3,466.2	2,445.5	*	524.9
8. Rio Grande and Southwest	3,873.6	4,002.2	3,720.8	2,467.7	1,890.6
9. Intermountain West	3,934.3	2,017.8	1,127.9	699.0	402.6
10. Pacific Coast	9,036.2	8,017.5	6,321.0	5,435.9	3,767.4
11. Alaska	2,244.7	872.0	203.3	*	*
12. Hawaii	13,693.3	10,529.4	7,141.7	3,282.9	4,031.6
United States	5,274.6	5,513.9	4,712.1	4,442.6	3,389.7

- = No census tracts in this group.

Note: The Road Ruggedness Scale (RRS) is an ordinal scale of topographic variation along roads in the United States, ranging from category 1–level to category 5–highly rugged. County-level regional definitions were adapted from Fuguitt and Beale (1978). Regional RRS categories with fewer than 20 census tracts have been omitted and are indicated by an '*'.

Source: USDA, Economic Research Service calculations using U.S. Department of the Interior, U.S. Geological Survey and U.S. Department of Defense, National Geospatial-Intelligence Agency, 7.5 arc-second resolution, Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010); ESRI, ArcGIS StreetMap Premium 2021 Q3 data; U.S. Department of Commerce, Bureau of the Census, 2010 Census of Population and Housing, Summary File 1 and TIGER (Topographically Integrated Geographic Encoding and Referencing)/Line boundary files; and Fuguitt, G.V., & Beale, C.L. (1978). Population trends of nonmetropolitan cities and villages in subregions of the United States. *Demography*, *15*(4).

The Pacific Coast had a significantly higher share of land classified as rugged compared with the Appalachian Mountains but a significantly lower share of its population living there. This highlights important differences in regional settlement patterns in relation to rugged terrain. The population in the West is more concentrated in river valleys, basins, plains, and other relatively flat terrain, with large areas remaining unpopulated or sparsely populated. These sparsely populated areas include much of the West's rugged terrain. Settlement in the Appalachian Mountains has been more widely distributed across all levels of ruggedness, as measured by land under roads. Therefore, challenges associated with travel by car in rugged terrain may be more widely felt across the Appalachian Mountains than the Pacific Coast.

Focusing on population density allows us to see if the impact of ruggedness on settlement patterns that was apparent at the national level continues at the regional level. Table 5 illustrates that this is indeed the case as mean population density generally decreased as the level of census tract ruggedness increased.[9] However, a few regions displayed the opposite characteristic, with population density increasing as ruggedness increased, sometimes drastically. These regions included the Eastern Urbanized Belt, the Atlantic and Gulf Coasts, the Great Lakes and Corn Belt, and the Interior Uplands. The largest regional change in population density across ruggedness categories occurred in the Eastern Urbanized Belt, where the population density increased by more than 7,500 people per square mile between moderately to highly rugged census tracts. This increase reflected census tracts with very high population densities in Manhattan near the George Washington Bridge.

The relative density of regions also persisted across all levels of ruggedness. For example, the Eastern Urbanized Belt and Pacific Coast have the greatest overall mean population densities, and this trend continued through all ruggedness levels. As for the three most prominent and well-known rugged regions, the Pacific Coast has the highest population density, then the Appalachian Mountains, and finally the Intermountain West. The Southern Coastal Plains region is unique because mean population density is more consistent across ruggedness levels.

Topographic Variation and Population in States

While we have explored the topography and settlement of several well-known, physiographic and demographically distinct regions of the United States, these regions do not have official political boundaries. The effects of national and State policies may differ based on challenges to accessing necessary goods and services, whether those challenges are related to the total distance traveled or the ruggedness of the roads traversed. Therefore, we explored the topographic variability of States and the different settlement patterns they had across that variability.

The flattest State to travel in the United States was Louisiana, followed closely by North Dakota—with nearly all of their land area classified as level based on the terrain beneath their roads (table 6). Florida (99.5 percent), Nebraska (95.5 percent), and Kansas (99.4 percent) rounded out the top five flattest States. Broadening the definition of flat terrain to include census tracts with land that is considered either level or nearly level changed the flattest State ranking only slightly. Mississippi took the fourth spot, while Nebraska was bumped down to sixth.

[9] The mean population densities included in table 5 were restricted to only region and RRS category combinations with at least 20 census tracts.

Table 6
Top 10 States by share of land or population by topographic variability, 2010

Rank	Flattest States to travel		Most rugged States to travel		
	Level (RRS 1)	Level and nearly level (RRS 1 and 2)	Slightly to highly rugged (RRS 3–5)	Moderately to highly rugged (RRS 4 and 5)	Highly rugged (RRS 5)
Share of land by RRS					
1	Louisiana	Louisiana	West Virginia	West Virginia	Washington
2	North Dakota	North Dakota	Hawaii	Washington	Idaho
3	Florida	Florida	Washington	Hawaii	Oregon
4	Nebraska	Mississippi	Vermont	California	California
5	Kansas	Kansas	Pennsylvania	Oregon	West Virginia
6	Mississippi	Nebraska	New Hampshire	Idaho	Kentucky
7	Illinois	Illinois	Oregon	Colorado	North Carolina
8	Michigan	Delaware	Idaho	Montana	Montana
9	Iowa	Michigan	California	Kentucky	Colorado
10	South Dakota	Indiana	Colorado	North Carolina	New Hampshire
Share of population by RRS					
1	Louisiana	Louisiana	West Virginia	West Virginia	West Virginia
2	Florida	Mississippi	Vermont	Hawaii	Hawaii
3	Illinois	Florida	Hawaii	Oregon	Oregon
4	Mississippi	Indiana	Pennsylvania	Montana	Montana
5	Michigan	Illinois	Washington	Washington	Kentucky
6	Indiana	Oklahoma	Oregon	California	Alaska
7	North Dakota	Michigan	Montana	Pennsylvania	Idaho
8	Oklahoma	North Dakota	Tennessee	Idaho	California
9	Texas	Texas	California	Utah	Washington
10	Wisconsin	Wisconsin	Connecticut	Kentucky	Utah

Note: The Road Ruggedness Scale (RRS) is an ordinal scale of topographic variation along roads in the United States, ranging from category 1–level to category 5–highly rugged. RRS category combinations indicate different possible ruggedness combinations.

Source: USDA, Economic Research Service calculations using U.S. Department of the Interior, U.S. Geological Survey and U.S. Department of Defense, National Geospatial-Intelligence Agency, 7.5 arc-second resolution, Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010); ESRI, ArcGIS StreetMap Premium 2021 Q3 data; and U.S. Department of Commerce, Bureau of the Census, 2010 Census of Population and Housing, Summary File 1 and TIGER (Topographically Integrated Geographic Encoding and Referencing)/Line boundary files.

The most rugged State to travel was Washington (29.9 percent highly rugged land), followed by Idaho (23.4 percent), Oregon (20.3 percent), California (16.8 percent), and West Virginia (15.2 percent). Broadening the definition of rugged terrain to include census tracts that are slightly to highly rugged, the top five States by share of rugged land were: West Virginia (94.6 percent), Hawaii (72.5 percent), Washington (66.0 percent), Vermont (65.2 percent), and Pennsylvania (63.4 percent). Choosing different definitions of rugged or flat terrain impacted the State rankings, emphasizing the importance of choosing a classification of rugged that is appropriate to the use.

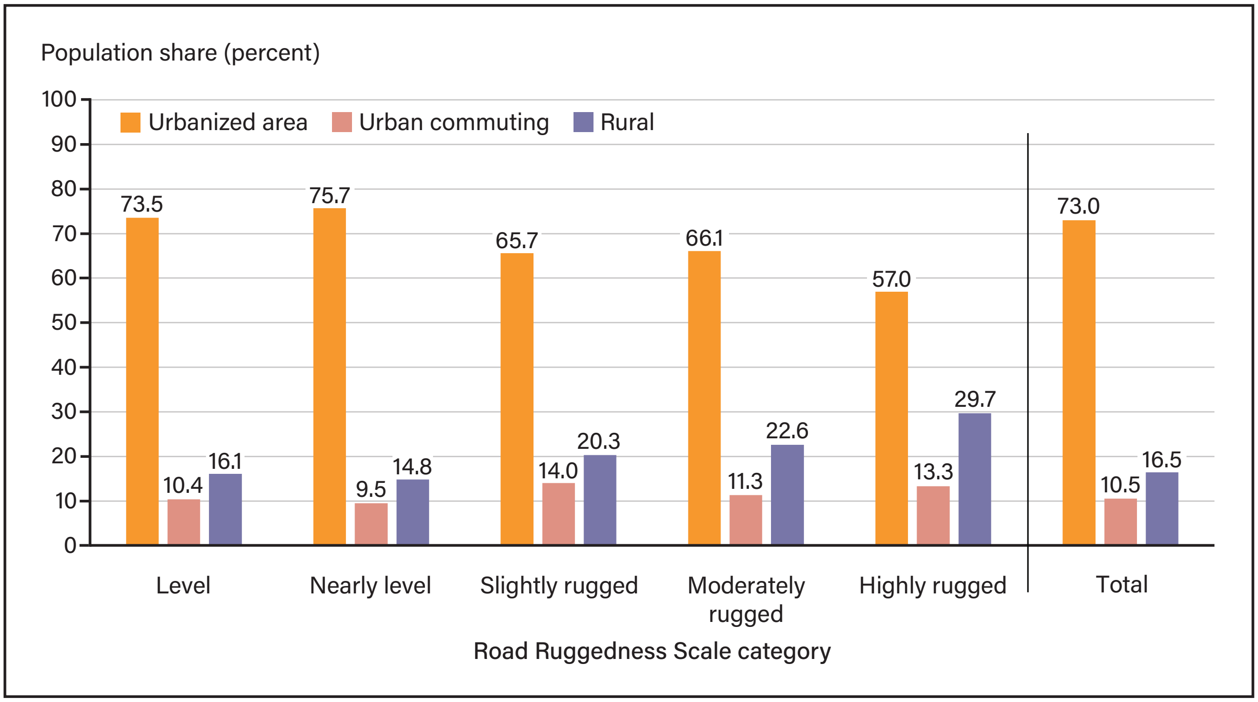
The State with the greatest share of its residents living in census tracts that are considered level was Louisiana (99.6 percent), followed by Florida (97.8 percent), Illinois (96.2 percent), Mississippi (95.7 percent), and Michigan (94.5 percent). Again, broadening the definition of flat to include both level and slightly level census tracts, Louisiana maintained its top position, while Florida dropped to become the State with the third largest share of its population living in flat census tracts. Mississippi became the State with the second largest share of its population living in flat census tracts, while Illinois and Indiana rounded out the top five.

The State with the largest share of its population living in highly rugged census tracts was West Virginia (15.0 percent), followed by Hawaii (10.2 percent), Oregon (7.9 percent), Montana (7.3 percent), and Kentucky (5.5 percent). Considering rugged census tracts to be slightly to highly rugged, West Virginia remained the State with the largest share of its population living in rugged census tracts by a wide margin (80.7 percent). The remaining top five included Vermont (51.6 percent), Hawaii (43.3 percent), Pennsylvania (39.9 percent), and Washington (38.0 percent).

Rurality and the Road Ruggedness Scale

In this section, we explored the relationship between ruggedness and rurality, particularly in the context of using road networks. As discussed in the Data and Methods section, we classified census tracts into one of three rurality groups by RUCA code: urbanized area, urban commuting, and rural. Most U.S. residents lived in urbanized area census tracts in 2010 (73.0 percent; figure 8). Urban commuting census tracts included 10.5 percent of the population, while the remaining 16.5 percent resided in rural census tracts.

Figure 8
Population shares across rurality groups by Road Ruggedness Scale, 2010



Note: Census tracts are divided into rurality groups based on Rural-Urban Commuting Area (RUCA) codes: urbanized area (RUCA 1), urban commuting (RUCA 2 and 3), and rural (RUCA 4–10). The Road Ruggedness Scale (RRS) is an ordinal scale of topographic variation along roads in the United States, ranging from category 1–level to category 5–highly rugged.

Source: USDA, Economic Research Service calculations using U.S. Department of the Interior, U.S. Geological Survey and U.S. Department of Defense, National Geospatial-Intelligence Agency, 7.5 arc-second resolution, Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010); ESRI, ArcGIS StreetMap Premium 2021 Q3 data; U.S. Department of Commerce, Bureau of the Census, 2010 Census of Population and Housing, Summary File 1 and TIGER (Topographically Integrated Geographic Encoding and Referencing)/Line boundary files; and USDA, Economic Research Service, 2010 Rural-Urban Commuting Area Codes.

However, the share of the population living in rural areas increased with ruggedness, from 14.8 percent in nearly level census tracts to 29.7 percent in highly rugged census tracts in 2010 (figure 8). The increase in the share of rural residents was particularly notable between moderately and highly rugged census tracts, jumping from 22.6 to 29.7 percent. The exception to this trend was a slight decrease in the rural share of residents between level to nearly level census tracts. Similarly, the percentage of residents living in urbanized area census tracts declined from 75.7 percent in nearly level census tracts to 57.0 percent in highly rugged ones. The share of the population living in urban commuting census tracts did not vary consistently with ruggedness, and there was always a smaller share of residents in urban commuting census tracts than in rural census tracts. This gap generally increased with ruggedness, so that in highly rugged census tracts, the urban commuting population was less than half that of the rural population.

The effect of ruggedness on rurality varies regionally (table 7). The Pacific Coast had the largest share of its overall population living in urbanized area census tracts (86.5 percent), and the Appalachian Mountains and Alaska had the smallest shares (46.2 and 45.6 percent, respectively). The population living in urban commuting census tracts was the largest in the Appalachian Mountains (19.0 percent), while the population living in rural census tracts was the largest in the Interior Uplands (36.5 percent) and the Appalachian Mountains (34.8 percent).

Table 7
Share of population across rurality groups in U.S. regions by Road Ruggedness Scale, 2010

Rurality group	Road Ruggedness Scale category					Total
	1	2	3	4	5	
Region 1: Appalachian Mountains						
Urbanized area	63.5	38.9	40.6	52.4	37.9	46.2
Urban commuting	14.5	18.7	23.6	16.9	16.4	19.0
Rural	22.0	42.4	35.8	30.7	45.7	34.8
Region 2: Eastern Urbanized Belt						
Urbanized area	85.9	85.6	84.1	88.5	97.5	85.7
Urban commuting	8.6	8.8	9.8	4.4	2.5	8.7
Rural	5.5	5.6	6.2	7.1	0.0	5.6
Region 3: Atlantic and Gulf Coasts						
Urbanized area	81.0	95.8	100.0	-	-	81.5
Urban commuting	10.5	1.2	-	-	-	10.2
Rural	8.5	3.0	-	-	-	8.3
Region 4: Great Lakes and Corn Belt						
Urbanized area	66.3	81.2	78.5	76.2	38.3	68.5
Urban commuting	12.7	6.2	6.4	-	-	11.7
Rural	21.0	12.6	15.1	23.8	61.7	19.8
Region 5: Interior Uplands						
Urbanized area	49.5	43.8	55.7	90.1	100.0	48.2
Urban commuting	14.6	17.4	11.9	1.5	-	15.3
Rural	35.9	38.8	32.4	8.4	-	36.5
Region 6: Southern Coastal Plains						
Urbanized area	55.1	77.5	80.7	100.0	-	57.9
Urban commuting	16.2	7.8	16.1	-	-	15.3
Rural	28.7	14.6	3.2	-	-	26.9
Region 7: Great Plains						
Urbanized area	51.5	82.3	85.0	73.4	27.6	57.8
Urban commuting	8.7	3.6	5.3	21.7	65.0	8.1
Rural	39.8	14.2	9.7	5.0	7.4	34.1

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Rurality group	Road Ruggedness Scale category					Total
	1	2	3	4	5	
Region 8: Rio Grande and Southwest						
Urbanized area	81.8	83.5	86.3	88.2	68.8	82.6
Urban commuting	8.0	7.1	6.1	3.5	12.1	7.5
Rural	10.3	9.4	7.7	8.3	19.1	9.9
Region 9: Intermountain West						
Urbanized area	74.1	56.1	40.9	29.1	28.5	61.2
Urban commuting	4.6	7.0	11.2	13.1	13.8	6.8
Rural	21.3	37.0	47.9	57.8	57.7	32.0
Region 10: Pacific Coast						
Urbanized area	91.0	86.2	79.5	74.8	70.9	86.5
Urban commuting	3.9	8.0	10.6	9.9	10.5	6.2
Rural	5.1	5.8	10.0	15.3	18.6	7.3
Region 11: Alaska						
Urbanized area	60.6	29.4	14.8	29.1	-	45.6
Urban commuting	0.3	11.5	33.4	33.1	37.0	8.9
Rural	39.1	59.1	51.7	37.8	63.0	45.6
Region 12: Hawaii						
Urbanized area	79.1	57.6	54.7	44.2	85.5	63.5
Urban commuting	7.8	8.9	19.2	18.8	6.2	11.7
Rural	13.1	33.4	26.1	37.0	8.4	24.8

- = No census tracts in this group.

Note: Census tracts are divided into rurality groups based on Rural-Urban Commuting Area (RUCA) codes: urbanized area (RUCA 1), urban commuting (RUCA 2 and 3), and rural (RUCA 4–10). The Road Ruggedness Scale is an ordinal scale of topographic variation along roads in the United States, ranging from category 1–level to category 5–highly rugged. County-level regional definitions were adapted from Fuguitt and Beale (1978).

Source: USDA, Economic Research Service calculations using U.S. Department of the Interior, U.S. Geological Survey and U.S. Department of Defense, National Geospatial-Intelligence Agency, 7.5 arc-second resolution, Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010); ESRI, ArcGIS StreetMap Premium 2021 Q3 data; U.S. Department of Commerce, Bureau of the Census, 2010 Census of Population and Housing, Summary File 1 and TIGER (Topographically Integrated Geographic Encoding and Referencing)/Line boundary files; USDA, Economic Research Service, 2010 Rural-Urban Commuting Area Codes; and Fuguitt, G.V., & Beale, C.L. (1978). Population trends of nonmetropolitan cities and villages in subregions of the United States. *Demography*, *15*(4).

The rural population share in highly rugged areas was much higher in the Intermountain West and Appalachian Mountains (57.1 and 45.7 percent, respectively) and much lower in the Pacific Coast (18.6 percent), compared with the national share of 29.7 percent (table 7; figure 8). We also found an increasingly rural population as the relative ruggedness of roads increased in the Intermountain West and Pacific Coast regions. For instance, only 5.1 percent of residents in level census tracts were rural in the Pacific Coast region, compared with 18.6 percent of residents in highly rugged census tracts. This pattern is reflective of national trends but did not hold in other regions. In fact, the pattern reversed in some relatively flat regions. In the Great Plains, 39.8 percent of the population living in level census tracts was rural, compared with less than 10 percent in each of the three most rugged categories. In the Appalachian Mountains, highly rugged (category 5) census tracts had the highest share of rural residents, but it was nearly matched by the share of rural residents in nearly level census tracts.

It is clear that as ruggedness increased, the population living in mountainous locations became more rural. However, it is important to emphasize that ruggedness does not equate to rurality. Many people lived in urbanized census tracts even in the top ruggedness categories. The greatest share of highly rugged residents lived in urbanized area census tracts in regions such as the Interior Uplands, Eastern Urbanized Belt, and Pacific Coast. In other regions, such as the Great Plains, a greater share of people living in level census tracts were rural than in rugged census tracts. Not only was the overlap between ruggedness and rurality low overall, but it was regionally variable as well.

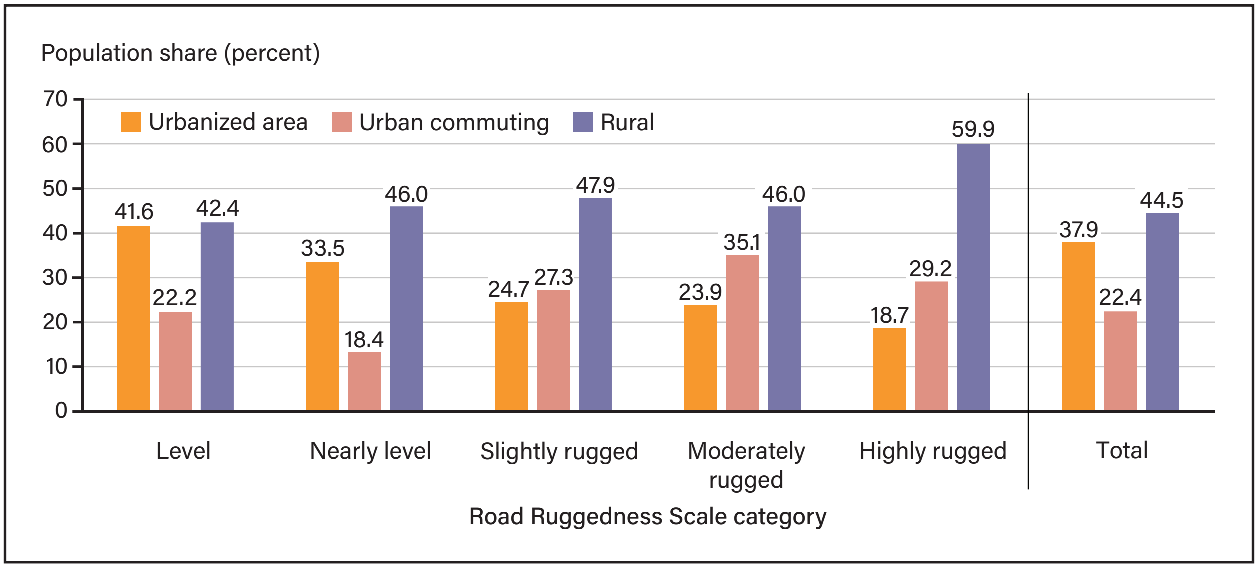
Though ruggedness and rurality are distinct, when they occur simultaneously, unique challenges may arise. For example, residents of urban commuting and rural census tracts likely need to travel longer distances than residents of urbanized area census tracts to access certain goods and services. These longer distances, combined with transportation challenges often associated with rugged terrain, may result in these residents experiencing more difficulty accessing needed goods and services. The Intermountain West region had the greatest share of its highly rugged population living in urban commuting and rural census tracts (71.5 percent). However, the population share in highly rugged urban commuting and rural census tracts was quite high in the Appalachian Mountains as well (62.1 percent). This difference in the rurality of rugged populations among regions illustrates how rurality and ruggedness may have differing impacts on residents throughout the United States.

As a broad measure of the economic well-being of individuals by rurality and ruggedness, we analyzed the share of the population living in low-income census tracts in 2010 (figure 9).[10] Two patterns emerged. First, as road ruggedness increased from level to highly rugged, the share of the population living in low-income census tracts increased for rural locations and decreased for urbanized area locations. Nearly 60 percent of residents in highly rugged, rural locations lived in low-income census tracts, compared with about 42 to 48 percent of rural residents in less rugged census tracts. Conversely, less than 20 percent of residents in highly rugged, urbanized area locations lived in low-income census tracts, compared with nearly 42 percent of urbanized area residents in level census tracts. In urban commuting locations, the share of the population living in low-income census tracts generally increased with ruggedness, but the trend was more variable.

[10] Our discussion focuses on census tract rurality as it is defined by the RUCA codes, whereas the Food Access Research Atlas (FARA) defines urban and rural differently. To remove noise from the data due to these different definitions, for urbanized areas we only considered urban FARA census tracts, and for urban commuting and rural locations, we only considered rural FARA census tracts.

Figure 9

Share of the population living in low-income census tracts by Road Ruggedness Scale and rurality group, 2010



Note: Census tracts are divided into rurality groups based on Rural-Urban Commuting Area (RUCA) codes: urbanized area (RUCA 1), urban commuting (RUCA 2 and 3), and rural (RUCA 4–10). The Road Ruggedness Scale is an ordinal scale of topographic variation along roads in the United States, ranging from category 1–level to category 5–highly rugged. Low-income census tracts are defined using the criteria from the U.S. Department of Treasury's New Markets Tax Credit program. See the USDA, Economic Research Service's 2010 Food Access Research Atlas (FARA) documentation for more details. Only census tracts considered "urban" by FARA are included when calculating urbanized area population shares, while only rural census tracts in FARA are used for urban commuting and rural population shares.

Source: USDA, Economic Research Service calculations using U.S. Department of the Interior, U.S. Geological Survey and U.S. Department of Defense, National Geospatial-Intelligence Agency, 7.5 arc-second resolution, Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010); ESRI, ArcGIS StreetMap Premium 2021 Q3 data; U.S. Department of Commerce, Bureau of the Census, 2010 Census of Population and Housing, Summary File 1 and TIGER (Topographically Integrated Geographic Encoding and Referencing)/Line boundary files; USDA, Economic Research Service, 2010 Rural-Urban Commuting Area Codes; and USDA, Economic Research Service, 2010 Food Access Research Atlas data.

Second, at every ruggedness level, a greater share of the population living in rural census tracts was also living in a low-income census tract than for urbanized area census tracts. And in each of the top three ruggedness categories (slightly to highly rugged), the percentage of rural residents living in low-income census tracts was twice as high as for urbanized area residents. The share of slightly to highly rugged urban commuting residents living in low-income census tracts was also greater than those in urbanized areas.

Taking a closer look by region, we found that the national trend of greater shares of rural residents living in low-income census tracts as road ruggedness increased was driven entirely by the Appalachian Mountains (table 8). In that region, 44.5 percent of rural residents lived in low-income census tracts that were level, and that share increased consistently as road ruggedness increased to 75.0 percent in highly rugged census tracts. For all other regions, no such relationship between ruggedness and income existed. In the Eastern Urbanized Belt region, the relationship was reversed, with the highest shares of rural residents living in low-income census tracts also living in level areas and the lowest shares in highly rugged areas (51.6 percent versus 25.6 percent). This is just one indicator of individual economic well-being, but it suggests that some of the challenges associated with rugged terrain may be more acute in the Appalachian Mountains region than elsewhere.

Table 8

Share of the rural population living in low-income census tracts by Road Ruggedness Scale and U.S. region, 2010

Regions	Road Ruggedness Scale category				
	1	2	3	4	5
1. Appalachian Mountains	44.5	50.9	57.4	63.5	75.0
2. Eastern Urbanized Belt	51.6	41.4	31.9	25.6	*
3. Atlantic and Gulf Coasts	55.7	0.0	-	-	-
4. Great Lakes and Corn Belt	30.4	28.9	25.4	*	-
5. Interior Uplands	39.5	51.4	45.3	*	-
6. Southern Coastal Plains	56.6	53.6	-	-	-
7. Great Plains	29.7	24.1	38.1	-	*
8. Rio Grande and Southwest	54.4	44.4	58.2	18.5	31.5
9. Intermountain West	43.1	40.0	32.3	30.9	36.5
10. Pacific Coast	61.7	55.3	32.8	38.0	53.0
11. Alaska	38.6	42.6	30.1	0.0	30.6
12. Hawaii	0.0	48.3	17.2	28.2	0.0
United States	42.4	46.0	47.9	46.0	59.9

- = No census tracts in this group.

Note: Rural census tracts are defined by Rural-Urban Commuting Area (RUCA) codes 4–10, and only census tracts considered "rural" by the Food Access Research Atlas (FARA) are included when calculating rural population shares. The Road Ruggedness Scale (RRS) is an ordinal scale of topographic variation along roads in the United States, ranging from category 1–level to category 5–highly rugged. County-level regional definitions were adapted from Fuguitt and Beale (1978). Regional RRS categories with only one census tract have been omitted and are indicated by an '*'. Low-income census tracts are defined using the criteria from the U.S. Department of Treasury's New Markets Tax Credit program. See the 2010 FARA documentation for more details.

Source: USDA, Economic Research Service calculations using U.S. Department of the Interior, U.S. Geological Survey and U.S. Department of Defense, National Geospatial-Intelligence Agency, 7.5 arc-second resolution, Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010); ESRI, ArcGIS StreetMap Premium 2021 Q3 data; U.S. Department of Commerce, Bureau of the Census, 2010 Census of Population and Housing, Summary File 1 and TIGER (Topographically Integrated Geographic Encoding and Referencing)/Line boundary files; USDA, Economic Research Service, 2010 Rural-Urban Commuting Area Codes; USDA, Economic Research Service, 2010 Food Access Research Atlas data; and Fuguitt, G.V., & Beale, C.L. (1978). Population trends of nonmetropolitan cities and villages in subregions of the United States. *Demography, 15*(4).

Possibilities for Defining Rugged Terrain

Topographic variation exists on a continuum with no clear line dividing rugged from non-rugged terrain. For research or program applications where such a dichotomy is needed, the choice of which categories to include as rugged should be made based on the goals of the project. Findings reported here for the Road Ruggedness Scale may provide some initial guidance in the form of differences in population characteristics between categories. Such shifts could be related to the difficulty of building and maintaining property, the services available nearby, or adverse road conditions. For instance, the largest decrease in the average census tract population density occurred between the moderately and highly rugged road categories (categories 4 and 5), with a loss of 1,053 people per square mile (table 2). Another large decrease in population density occurred between the nearly level and slightly rugged categories (categories 2 and 3), a drop of 802 people per square mile.

Several indicators reported here showed relatively large changes between moderately and highly rugged census tracts (categories 4 and 5). These changes were true for both the percentage of the population that is rural and the percentage of the rural population living in low-income census tracts. However, highly rugged census tracts included just 1.4 percent of the overall U.S. population, around 4.5 million people (table 2). Some applications may benefit from a broader, more inclusive definition of rugged terrain, such as slightly to highly rugged census tracts (categories 3–5), which included 11.6 percent of the U.S. population or around 35.7 million people.

The analysis here has focused exclusively on the RRS. By limiting the measurement of topographic variation to grid cells with roads, we believe the RRS does a more thorough job of capturing travel limitations associated with rugged terrain. Thus, the RRS is likely to be the preferred choice for research aimed at better understanding economic challenges associated with rugged terrain. Alternatively, the ARS provides a measure of overall topographic variation for a census tract. Although we have not provided a descriptive analysis for the ARS in this report, we believe the ARS may be better suited to capturing the scenic attractiveness of rugged terrain cherished by long-term residents, tourists, and newcomers alike. The RRS cannot capture the full range of topographic variation in areas where roads do not traverse the most rugged terrain. The ARS's capability to capture scenic attractiveness in such locations may be especially important for regions like the Intermountain West and Alaska.

The range of TRI values extends much higher in the ARS, up to 242.8 meters compared with 134.7 meters for the RRS. As a result, the head/tail breaks method of classifying Area TRI values yields six categories, instead of five, with the additional category described as extremely rugged. Comparing the distribution of land area across ARS and RRS ruggedness levels shows that, in both measures, the most rugged category includes 3.4 percent of the Nation's land area (table 9). The four categories described as slightly to extremely rugged in the ARS include a much larger share of the Nation's land (37.8 percent) than the three RRS categories described as slightly to highly rugged (14.6 percent).

Table 9
Share of land area for differing ruggedness definitions by U.S. region

Regions	Area Ruggedness Scale (ARS)		Road Ruggedness Scale (RRS)	
	Slightly to extremely rugged (ARS 3–6)	Extremely rugged (ARS 6)	Slightly to highly rugged (RRS 3–5)	Highly rugged (RRS 5)
1. Appalachian Mountains	66.2	3.2	54.0	6.7
2. Eastern Urbanized Belt	15.8	0.1	12.0	0.1
3. Atlantic and Gulf Coasts	-	-	0.0	-
4. Great Lakes and Corn Belt	1.6	-	0.5	0.0
5. Interior Uplands	18.3	-	6.2	0.0
6. Southern Coastal Plains	0.0	-	0.1	-
7. Great Plains	7.4	0.2	1.5	0.1
8. Rio Grande and Southwest	28.4	0.3	7.3	0.3
9. Intermountain West	75.3	9.5	33.1	7.1
10. Pacific Coast	76.9	25.0	72.5	37.0
11. Alaska	73.4	2.8	4.5	0.7
12. Hawaii	79.9	9.3	72.5	2.0
United States	37.8	3.4	14.6	3.4

- = No census tracts in this group.

Note: The Road Ruggedness Scale (RRS) is an ordinal scale of topographic variation along roads in the United States, ranging from category 1–level to category 5–highly rugged. The Area Ruggedness Scale (ARS) is an ordinal scale of topographic variation among U.S. census tracts, ranging from category 1–level to category 6–extremely rugged. County-level regional definitions were adapted from Fuguitt and Beale (1978). ARS and RRS category combinations indicate different possible ruggedness combinations.

Source: USDA, Economic Research Service calculations using U.S. Department of the Interior, U.S. Geological Survey and U.S. Department of Defense, National Geospatial-Intelligence Agency, 7.5 arc-second resolution, Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010); ESRI, ArcGIS StreetMap Premium 2021 Q3 data; U.S. Department of Commerce, Bureau of the Census, 2010 Census of Population and Housing, Summary File 1 and TIGER (Topographically Integrated Geographic Encoding and Referencing)/Line boundary files; and Fuguitt, G.V., & Beale, C.L. (1978). Population trends of nonmetropolitan cities and villages in subregions of the United States. *Demography*, *15*(4).

The difference between the ARS and RRS can be seen best when comparing the Appalachian Mountains and the Intermountain West regions. In the ARS, for ruggedness broadly defined as slightly rugged to extremely rugged census tracts, the Intermountain West showed a higher share of rugged land (75.3 percent) compared with the Appalachian Mountains (66.2 percent). But in the more densely settled Appalachian Mountains, the share of land in the slightly to highly rugged RRS categories was much higher (54.0 percent) than in the Intermountain West (33.1 percent). These and other regional differences may be helpful to consider when choosing a specific measure of rugged terrain for a given research or policy application.

Conclusion

Rugged terrain affects communities and their residents in complex and often contradictory ways. While rugged terrain may have positive economic impacts through tourism and migration, it may also hinder the expansion of settlements and the accessibility of specialized goods and services. This negative impact may particularly affect rural areas where residents may need to travel to more urban locations for specialized goods and services.

To better understand the role of rugged terrain as both a benefit and a hindrance, we developed two national representations of variable topography for census tracts. These representations, the Area Ruggedness Scale (ARS) and Road Ruggedness Scale (RRS), characterize the relative topographic variation among U.S. census tracts in 2010. The ARS has six categories to describe the land area, varying from category 1–level to category 6–extremely rugged, whereas the RRS has five categories describing the ruggedness of land beneath roads, varying from category 1–level to category 5–highly rugged. These categories represent relative increases in the ruggedness of land and allow for flexibility in defining locations that are considered to have rugged or difficult terrain and those that are not.

To understand the variation of community characteristics by terrain ruggedness, we analyzed population, population density, and income across RRS categories, rurality, and regions within the United States. In 2010, two-thirds of U.S. residents lived in level census tracts, about 22 percent lived in nearly level census tracts, and only around 12 percent lived in census tracts with the highest levels of topographic variation (slightly to highly rugged). Population density also decreased with increased ruggedness. Across rurality groups, 73 percent of U.S. residents lived in urbanized area census tracts in 2010, followed by 16.5 percent in rural census tracts and 10.5 percent in urban commuting census tracts. Again, as ruggedness increased, the rurality of the population also increased. Finally, as ruggedness increased, the share of the population living in low-income census tracts increased for rural locations and decreased for urbanized area locations.

Together these facts illustrate an important point. While fewer people lived in increasingly rugged locations, an increasingly larger share of these people resided in urban commuting or rural census tracts. Residents of urban commuting and rural census tracts likely need to travel more frequently or longer distances than those living in urbanized area census tracts to access more specialized goods and services. This situation, combined with transportation challenges sometimes associated with rugged terrain, may result in rural and urban commuting residents that live in or travel through rugged terrain experiencing more difficulty accessing the goods and services they need. Therefore, the challenges associated with maintaining the well-being of residents living in difficult or rugged terrain—such as accessing hospitals, schools, social services, and grocery stores—are disproportionately a rural challenge.

It is important to reiterate that despite its particular relevance to rural studies and policymaking, rugged terrain does not equate to rurality and is not meant to be a component of any rural definition. Our findings here show that 85 percent of rural residents in the United States live outside census tracts characterized as rugged, broadly defined. Similarly, a significant portion of rugged terrain, broadly defined, is found in urban areas. The relationship between rurality and ruggedness also varies regionally across the United States.

Because the United States is a geologically and demographically diverse nation, certain regions of the country may be more affected by the challenges of rugged terrain than others. For instance, the Atlantic and Gulf Coasts region had the largest level land area, as well as the largest proportion of its population living in level census tracts. Conversely, Hawaii and the Pacific Coast had the greatest share of land area in slightly to highly rugged census tracts, whereas Hawaii and the Appalachian Mountains had the largest share of their populations living in such census tracts. However, when considering varying degrees of rurality, the Pacific Coast had the greatest share of urban residents, while the Appalachian Mountains had the smallest share of urban residents (besides Alaska). The Interior Uplands region, which includes the Ozark and Ouachita Mountains, had the largest share of rural residents (besides Alaska), whereas the Appalachian Mountains had the largest share of urban commuting residents. These findings suggest that more of the residents living in the Appalachian Mountains and Interior Uplands regions may face increased challenges to maintaining their well-being due to rugged terrain when compared with residents living in flatter, more urban regions, such as the Atlantic and Gulf Coasts region.

As a census-tract-level measure, the ARS provides a more geographically detailed measure of topographic variation than is currently available. We are also the first to develop a Terrain Ruggedness Index (TRI), the ruggedness measure underlying our ruggedness scales, to study the impact of rugged terrain on travel by car. By focusing on topographic variation along roads, the RRS more accurately depicts the experience of traveling across varying types of terrain to access resources. To our knowledge, these are the first ruggedness measures with full nationwide coverage for the United States. Future work may use the RRS, ARS, or their corresponding TRI values to analyze impediments to transportation and settlement in mountainous areas, assess whether current urban-rural classifications based on commuting and travel time adequately capture those impediments, or extend the research on how the scenic amenities in mountainous areas drive rural population and job growth.

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Appendix A: Technical Explanation of the Data Creation

To understand the unique role of rugged terrain as both a benefit and hindrance to individuals and communities, we need a more geographically detailed and flexible measure of topographic variation than is currently available. In this appendix, we described the process of creating two ruggedness scales, one reflecting ruggedness across the entire area of a census tract (the Area Ruggedness Scale, or ARS) and one limited to grid cells containing roads (the Road Ruggedness Scale, or RRS). For both of these scales, the process began by identifying a grid-cell level elevation dataset, which was then converted to a grid-cell measure of ruggedness. Next, the grid-cell values were aggregated to census tracts, a larger geographic unit that allows for statistical analysis of socioeconomic variables related to neighborhoods and communities. Finally, a classification method was chosen that grouped the continuous values into a discrete number of categories from low (completely level) to high (highly or extremely rugged) and that accurately represented the distribution of the aggregated data across census tracts.

Data Inputs

The input digital elevation model (DEM) we used to create the two ruggedness scales needed to satisfy three criteria. First, the data needed to have national coverage. Second, the data needed to be an appropriate spatial resolution, small enough to capture local changes in topographic variation but large enough to avoid burdensome computational time. Third, we restricted our search to publicly available data released by Federal agencies. We chose the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) from the U.S. Department of the Interior, U.S. Geological Survey and the U.S. Department of Defense, National Geospatial-Intelligence Agency. Upon its release, GMTED2010 became the "dataset of choice for global and continental scale applications" because it improved the consistency and vertical accuracy of measured elevations when compared with the previous standard (i.e., the Global 30 Arc-Second Elevation (GTOPO30) data) (Danielson & Gesch, 2011).

GMTED2010 was created from 11 data sources of varying spatial resolutions, which were aggregated to produce data at 7.5-, 15-, and 30-arc-second spatial resolutions. Seven different elevation measures are available from the GMTED2010, including mean, median, minimum, maximum, and standard deviation. We used the median elevation as our input elevation to calculate the grid-cell-level Terrain Ruggedness Index (TRI) values because it represents the typical elevation within the grid cell without being unduly influenced by outliers. The grid-cell TRI data were calculated for every 7.5 arc-second GMTED2010 grid cell in the United States using the "SpatialEco" package, version 1.3-7, in R (Evans & Murphy, 2021). At the 7.5 arc-second spatial resolution, the GMTED2010 data are available between 56°S latitude and 84°N latitude, which includes Alaska. Other higher-resolution DEMs that we considered (such as the Shuttle Radar Topography Mission (SRTM)) exclude most of Alaska, making them inappropriate for our analysis, as they do not have national coverage.

We aggregated the grid-cell level ruggedness data to census tracts using the 2010 Topographically Integrated Geographic Encoding and Referencing (TIGER)/Line shapefiles from the U.S. Department of Commerce, Bureau of the Census (Census Bureau). Although the 2020 census tract boundary files were available at the time of data creation, we chose to use the 2010 census tracts for the analysis reported here as they correspond to the current version of the USDA, Economic Research Service's (ERS) Rural-Urban Commuting Area (RUCA) codes. The RUCA codes provide an urban-rural continuum for census tracts that was needed for this report's analysis. However, a version of both ruggedness scales based on 2020 census tracts will be available as part of the USDA, ERS Area and Road Ruggedness Scales data product.

We also needed a digital road network input to the RRS. We chose ESRI's ArcGIS StreetMap Premium data as it has national coverage and uses up-to-date data from commercial, community, and government sources. The data are updated quarterly to ensure they are as current as possible. We used all the roads available in the 2021 Q3 North American data as our road data input for the RRS, which includes highways, arterial, collector, local, and semiprivate roads. We considered other sources, such as NAVTEQ Streets, but those sources did not include Alaska and Hawaii.

Ruggedness Measure and Method

To measure ruggedness, we chose to use the method developed by Riley et al. (1999) to measure topographic heterogeneity, the Terrain Ruggedness Index (TRI). We created two TRIs, one based on all grid cells (the Area TRI) and the other restricted to grid cells with roads (the Road TRI). To calculate the Area TRI of a given grid cell, the sum of the difference in elevation between that grid cell and its eight adjacent grid cells is calculated using the formula:

$$TRI_{00} = \Upsilon\left[\sum(x_{ij} - x_{00})^2\right]^{1/2},$$

where x_{ij} is the elevation of each neighbor grid cell (i,j) and x_{00} is the elevation of grid cell (0,0), the grid cell for which we are calculating the TRI. The neighboring grid cells are identified by their relation to grid cell (0,0), where i = {-1,0,1} indicates the neighboring cell's horizontal location and j = {-1,0,1} indicates its vertical location.

Area TRI values were calculated for all 262,587,389 grid cells in the United States. Lower Area TRI values indicate less change in elevation within the 3- by 3-grid-cell neighborhood whereas higher values indicate areas with more elevation change. The same procedure was used to calculate the Road TRI, except that only the 46,643,440 grid cells containing roads were included in the summation of elevation differences. Whereas the Area TRI measure always includes input from all eight grid-cell neighbors, except along the U.S. border, Road TRI measures may not. Grid cells in urban areas with dense road networks would likely include all eight neighbors in their Road TRI calculation, while rural grid cells would typically include fewer. For example, along a straight-line road running east-west or north-south with no intersecting roads, only two neighbors of a given grid cell along the road would be included in the calculation.

Both the Area and Road TRI values were then aggregated to 72,765 census tracts using the "Zonal Statistics as a Table" tool in ArcGIS Pro 2.9. This function produced a count of the grid cells that had centroids fall within the boundary of each census tract as well as the mean, standard deviation, and median TRI of the aggregated grid cells. The 2010 census tract TIGER/Line shapefiles do not follow the exact coastline and, therefore, include some water areas in the census tract area. Water was coded as zero for the DEM, and these values pulled down the mean and median Area TRI values slightly in census tracts that contain water. However, large areas of coastal waters (bays, the Great Lakes, etc.) were not included when calculating the Area TRI. Water is only a factor in the Road TRI where there are bridges over large rivers or other bodies of water.

The Area and Road Ruggedness Scales: Classification Method

Classifying the tract TRI values into a limited number of categories to create our two ruggedness scales enhances statistical comparisons and mapping, making it easier to visualize how ruggedness varies across U.S. census tracts. We chose the mean of the grid cell Area and Road TRI values within each census tract as the best measure of ruggedness within a census tract. The mean accounts for the distribution of the grid-cell TRI values within each census tract, including very rugged (high) and very flat (low) TRI values, even if they do not represent the majority of the grid-cell TRI values within the census tract. This allows us to account for steep mountains, deep gorges, or flat plains within the census tract that may not be accounted for by the median.

Different classification methods emphasize different aspects of the underlying data, and a good classification should reflect the distribution of the underlying data rather than distort it (Foster, 2019; Jiang, 2013). For example, the equal interval method, which breaks the data into equally sized categories, works best for classifying data that is uniformly distributed across the range of values. Conversely, the natural breaks method, which minimizes the differences within categories and maximizes the differences between categories, works best for classifying clustered data (Foster, 2019). See table A1 for a description of the best classification methods for different data distributions.

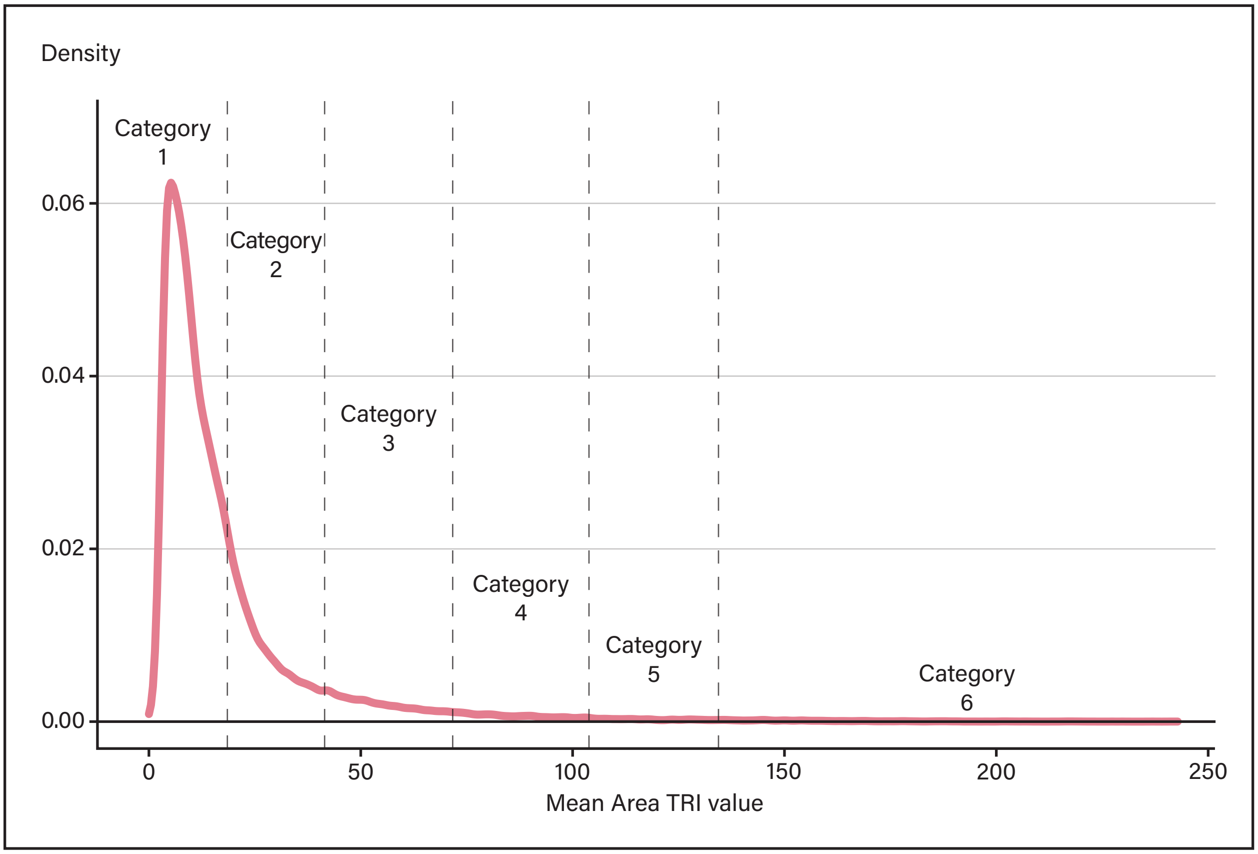
Table A1
Recommended classification methods by data distribution

Classification method	Data distribution
Equal interval	Uniformly distributed data
Quantiles	Evenly distributed data and ordinal data
Natural breaks	Clustered data
Mean-standard deviation	Normally distributed data
Maximum breaks	Piecewise and clustered data
Jenks-Caspall/Fisher-Jenks	Clustered and skewed data
Head/tail breaks	Heavily skewed data
Unique	No particular distribution, used if key numbers are important

Source: USDA, Economic Research Service adapted from Foster, M. (2019). Statistical mapping (enumeration, normalization, classification). In J. P. Wilson (Ed.), *The geographic information science & technology body of knowledge.* American Association of Geographers.

To determine the distributional characteristics of the Area and Road TRI census tract data, we ran several tests using the "fitdistrplus" package, version 1.1-8, in R (Delignette-Muller et al., 2022). The Cullen and Frey skewness-kurtosis plot indicated that the data were neither normally nor uniformly distributed; rather, the data were most similar to the beta or gamma distributions. The data were also highly skewed with a long right tail (skewness = 2.42 for the Road TRI and 3.35 for the Area TRI). A visual inspection of the Area and Road TRI density plots (figure A1; figure 3) indicated there was no clustering in the data. Therefore, we determined that the head/tail breaks classification method was the best choice for the TRI census tract data distributions.

Figure A1
Distribution of census tract Area Terrain Ruggedness Index values



Note: The Area Terrain Ruggedness Index (Area TRI) of grid cells within 2010 census tracts was calculated using the method outlined in Riley et al. (1999). The figure graphs the average TRI value of grid cells in census tracts. Head/tail break values were calculated using the "ClassInt" package in R with the default threshold of 0.4 (Bivand et al., 2020).

Source: USDA, Economic Research Service calculations using U.S. Department of the Interior, U.S. Geological Survey and U.S. Department of Defense, National Geospatial-Intelligence Agency, 7.5 arc-second resolution, Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010); ESRI, ArcGIS StreetMap Premium 2021 Q3 data; and U.S. Department of Commerce, Bureau of the Census, 2010 Census of Population and Housing, TIGER (Topographically Integrated Geographic Encoding and Referencing)/Line boundary files; and Bivand et al. (2020).

The head/tail breaks method was first introduced by Jiang (2013) to emphasize low-frequency values in a heavy-tailed distribution. According to Jiang, low-frequency events tend to have a high impact and contain much more information than high-frequency events. This observation is true of topographic variation as well. There are many more census tracts that are relatively flat on average (high frequency) than those that are more rugged (low frequency), but the rugged census tracts cover a much larger range of values. Therefore, even though there were relatively few rugged census tracts in the tail of the distribution, the head/tail breaks method divided them into more classification units in order to capture their disproportionate impact.[11]

[11] Jiang (2013) introduced the head/tail breaks method using the rank-size distribution, which plots the value of interest on the y-axis and the rank of the value's frequency on the x-axis. This plotting method is opposite of how most density plots are presented, including the TRI distributions in figure A1 and figure 3. Here, we presented the head/tail breaks method using descriptions related to the standard density plot, where the frequency is on the y-axis and the value is on the x-axis, rather than the rank-size distribution. The resulting break points are the same, but the terminology differs slightly from what Jiang used.

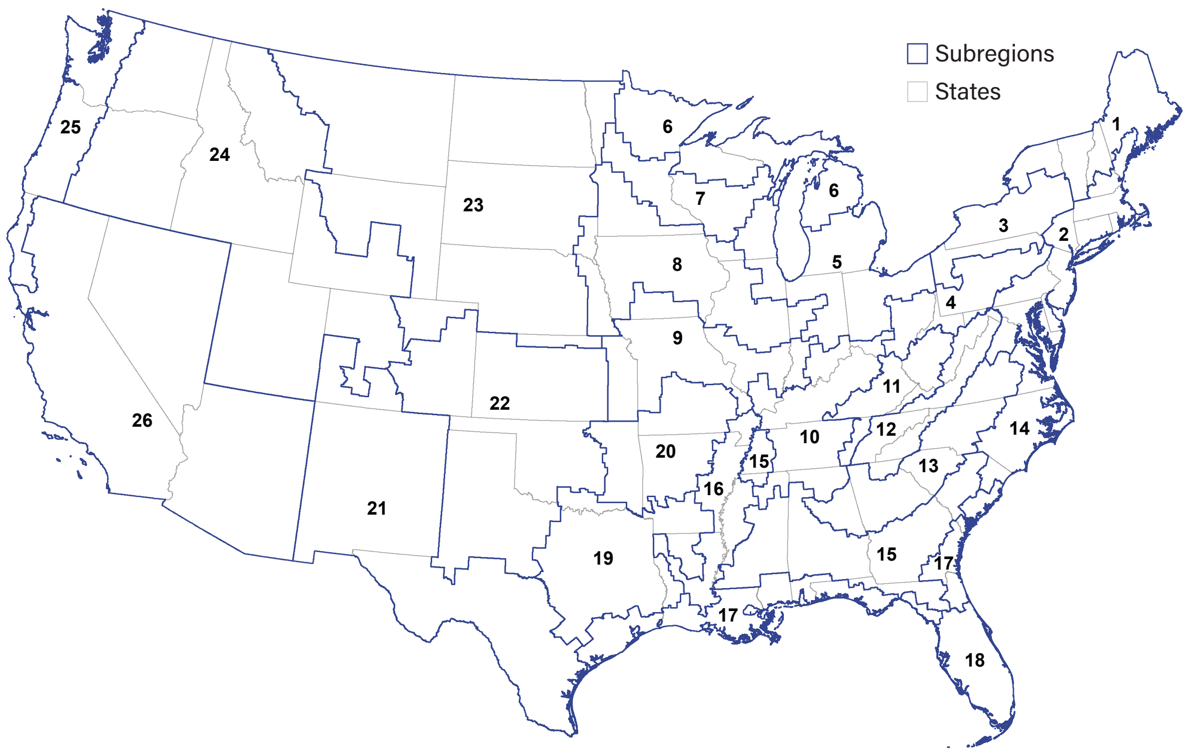
The head/tail breaks method uses an iterative process of partitioning data around the mean until the data are no longer considered heavy-tailed. The first partition occurred around the mean of the entire dataset, creating one group from the head of the distribution below the mean and another from the tail of the distribution above the mean. Once this partition occurred, values in the high-frequency head of the distribution became the first category of the classification, which contained roughly 70 percent of census tracts in both the ARS and RRS and was described as "level." The second partition occurred around the mean of the remaining observations in the tail, splitting them into a new head below the mean and tail above the mean, with the new head becoming the second ("nearly level") category and including roughly 66 percent of the remaining observations. This iterative process continued until the head included about 60 percent or fewer of the remaining observations, indicating that the distribution was no longer heavy-tailed. We used the "ClassInt" package, version 0.4-3, in R to calculate the break points between categories (Bivand et al., 2020).

Because the head/tail breaks method uses the underlying data distribution to partition the data, the number of categories and range of values in each category are different for the ARS and RRS. With a much larger range of values at the high end of the distribution, the ARS has six categories (see figure C1 in Appendix C) compared with five for the RRS (figure 6).

Appendix B: Regions of the United States

We captured regional differences in the extent and severity of rugged terrain in the United States using a 12-level, county classification system designed to group areas with reasonably similar climatic, physiographic, economic, and cultural characteristics (figure 4). These regions are mostly aggregations from a 26-level delineation (figure B1) used to study rural population trends (Fuguitt & Beale, 1978). These regions, in turn, were combinations of more than 500 State Economic Areas (Bogue & Beale, 1961). Although the regions were originally drawn to analyze and compare regional demographic trends, they were also helpful in this context to show how ruggedness may have differing impacts on travel time and access to services in different regions of the United States.

Figure B1
Subregions for the analysis of U.S. nonmetropolitan population change



1. Northern New England–St. Lawrence
2. Northeastern Metropolitan Belt
3. Mohawk Valley and New York–Pennsylvania Border
4. Northern Appalachian Coal Fields
5. Lower Great Lakes Industrial
6. Upper Great Lakes
7. Dairy Belt
8. Central Corn Belt
9. Southern Corn Belt
10. Southern Interior Uplands
11. Southern Appalachian Coal Fields
12. Blue Ridge, Great Smokies, and Great Valley
13. Southern Piedmont
14. Coastal Plain Tobacco and Peanut Belt
15. Old Coastal Plain Cotton Belt
16. Mississippi Delta
17. Gulf of Mexico and South Atlantic Coast
18. Florida Peninsula
19. East Texas and Adjoining Coastal Plain
20. Ozark–Ouachita Uplands
21. Rio Grande
22. Southern Great Plains
23. Northern Great Plains
24. Rocky Mountains, Mormon Valleys, and Columbia Basin
25. North Pacific Coast (including Alaska)
26. The Southwest (including Hawaii)

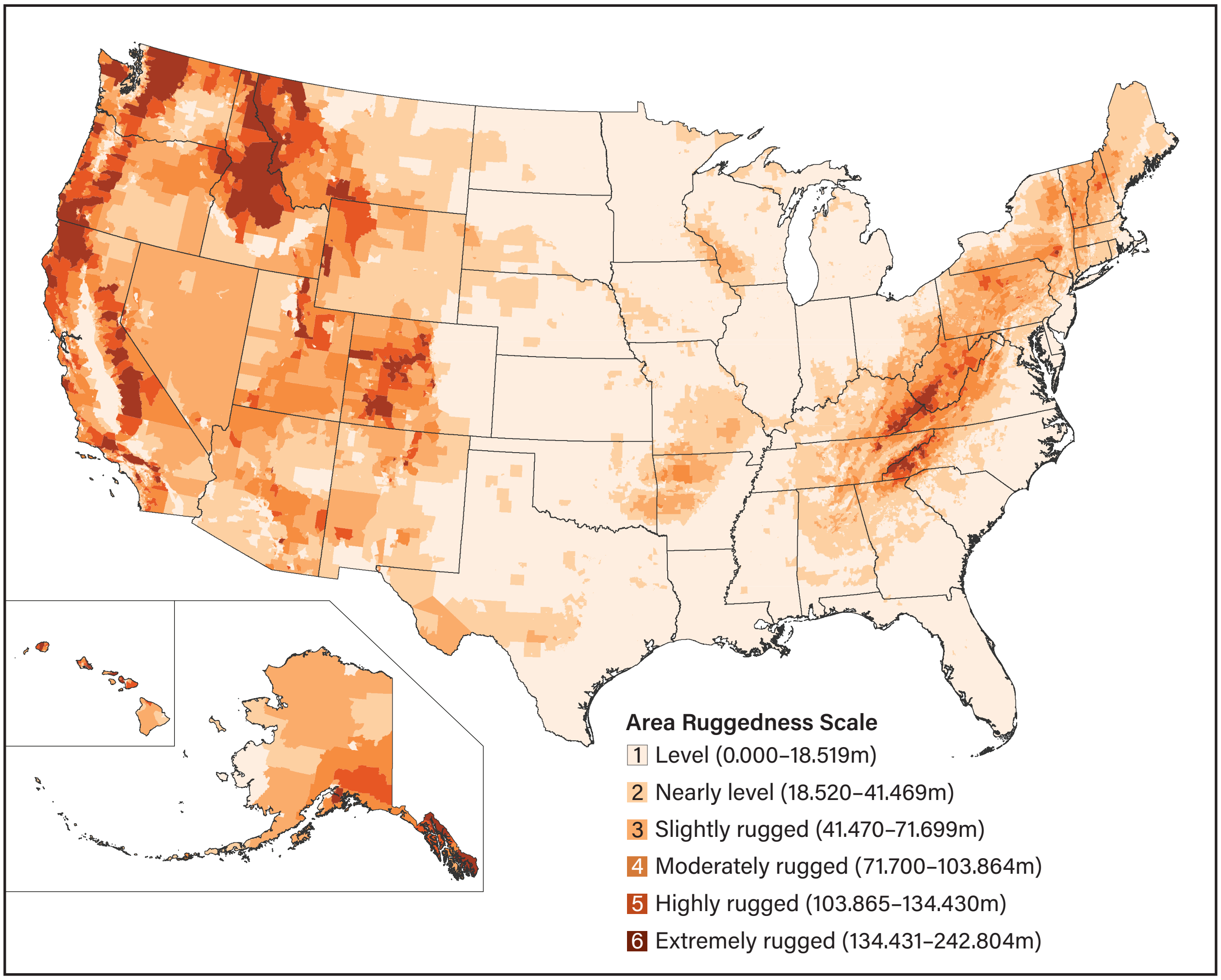
Source: USDA, Economic Research Service using Fuguitt, G.V., & Beale, C.L. (1978). Population trends of nonmetropolitan cities and villages in subregions of the United States. *Demography, 15*(4).

In addition to aggregation, modifications were made to the 26 regions to: (1) shift the boundary between the Rio Grande, Southwest, and Rocky Mountains-Mormon Valleys-Columbia Basin regions to better demarcate differing physiographic regions; (2) extend the Pacific Coast region further into California; (3) combine the Ozark-Ouachita Mountains and other Interior Highlands regions into one undivided region; (4) add counties in Florida to the Atlantic and Gulf Coasts region to make it a contiguous region; and (5) treat Alaska and Hawaii as separate regions. Otherwise, boundaries follow combinations of the initial set of 26 uniform regions. See Fuguitt and Beale (1978) for a detailed discussion.

Appendix C: The Area Ruggedness Scale

The Area Ruggedness Scale (ARS) is a classification of topographic variation within census tracts. This measure classifies census tracts into ordinal categories based on their Area TRI, where the census tracts with the lowest average TRI values have the least topographic variation, and the census tracts with the highest average TRI values have the most topographic variation. The ARS has six categories, ranging from 1–level to 6–extremely rugged. The ARS categories indicate the level of topographic variation within a census tract when compared to the census tracts in other categories. The categories are mapped in figure C1, and the range of Area TRI values included in each category, as well as a description of each category, are available in the legend.

Figure C1
Map of the Area Ruggedness Scale



m = Meters.

Note: The Area Ruggedness Scale (ARS) is an ordinal scale of topographic variation among U.S. census tracts. The ARS is calculated using the average Area Terrain Ruggedness Index of grid cells within 2010 census tracts.

Source: USDA, Economic Research Service calculations using U.S. Department of the Interior, U.S. Geological Survey and U.S. Department of Defense, National Geospatial-Intelligence Agency, 7.5 arc-second resolution, Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010); ESRI, ArcGIS StreetMap Premium 2021 Q3 data; and U.S. Department of Commerce, Bureau of the Census, 2010 Census of Population and Housing, TIGER (Topographically Integrated Geographic Encoding and Referencing)/Line boundary files.

Each of the land-based census tracts from the 2010 decennial census was classified into one of these categories based on its average Area TRI. Summary statistics for the census tracts in each ARS category are available in table C1. The majority of census tracts have very little topographic variation, with 71.0 percent of census tracts being classified as category 1–level in the ARS. However, this category has the smallest range of average Area TRI values (18.5 meters). The next largest category is 2–nearly level, with 19.4 percent of census tracts. This results in 9.6 percent of census tracts being classified as at least slightly rugged (categories 3–6) and only 0.5 percent being classified as extremely rugged (category 6). The top category has the largest range of average Area TRI values, with a difference of about 108 meters between the largest and smallest values.

Table C1

Census tract Area Terrain Ruggedness Index summary statistics by Area Ruggedness Scale

ARS category	**N**	**Mean** (m)	**SD** (m)	**Median** (m)	**Min.** (m)	**Max.** (m)
1–Level	51,639	9.131	4.341	8.454	0.000	18.519
2–Nearly level	14,125	26.485	6.280	24.823	18.520	41.466
3–Slightly rugged	4,478	53.577	8.517	52.141	41.475	71.699
4–Moderately rugged	1,572	85.373	9.249	84.074	71.706	103.786
5–Highly rugged	559	117.549	8.871	116.570	103.917	134.419
6–Extremely rugged	392	158.504	21.458	152.621	134.635	242.804
U.S. total	72,765	18.520	21.410	11.580	0.000	242.804

N = Number of census tracts. m = Meters. SD = Standard deviation. Min. = Minimum. Max. = Maximum.

Note: The Area Ruggedness Scale (ARS) is an ordinal scale of topographic variation within census tracts in the United States, ranging from category 1–level to category 6–extremely rugged.

Source: USDA, Economic Research Service calculations using U.S. Department of the Interior, U.S. Geological Survey and U.S. Department of Defense, National Geospatial-Intelligence Agency, 7.5 arc-second resolution, Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010); ESRI, ArcGIS StreetMap Premium 2021 Q3 data; and U.S. Department of Commerce, Bureau of the Census, 2010 Census of Population and Housing, TIGER (Topographically Integrated Geographic Encoding and Referencing)/Line boundary files.

The Area TRI summary statistics for census tracts by ARS category exhibit patterns similar to those reported for the RRS. However, when comparing the range of average census tract TRI values included in each ARS and RRS category, it is clear that—although the categories have similar names describing the relative relationship between census tracts in the ruggedness scales—they are very different scales. The average Road TRI values within census tracts are comparatively lower, so if a census tract had the same average Area and Road TRI values, it would be classified into different categories of the ARS and RRS. For example, a census tract with an average Area and Road TRI value of 70 meters would be considered a highly rugged RRS census tract but a slightly rugged ARS census tract. Interestingly, the maximum average Road TRI value used to construct the RRS (134.7 meters) is only slightly larger than the minimum average Area TRI value included in the extremely rugged category of the ARS. Therefore, nearly all census tracts whose land area is classified as extremely rugged by the ARS have a higher average degree of ruggedness than the most rugged road system of any census tract.

In figure C1, the light orange color represents category 1, which has the most level land, while dark orange represents the highest level of ruggedness (category 6). Again, the geographic patterns illustrated by the ARS categories are similar to those of a topographic relief map and are very similar to those displayed by the RRS. The Appalachian Mountains, the Rocky Mountains, the Pacific Mountain System, and the Sierra Nevada were clearly visible in the ARS. The Southern Coastal areas, Great Plains, and Corn Belt are still relatively level. However, slightly more rugged terrain in these areas can now be identified, such as the Badlands in North and South Dakota and the Sandhills in Nebraska.