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EVALUATION OF THE COLORBREWER COLOR SCHEMES FOR ACCOMMODATION OF MAP READERS WITH IMPAIRED COLOR VISION

A Thesis in

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by

Steven D. Gardner

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The thesis of Steven D. Gardner was reviewed and approved* by the following:

Cynthia A. Brewer
Associate Professor of Geography
Thesis Advisor

Lorraine Dowler
Associate Professor of Geography

Roger M. Downs
Professor of Geography
Head of the Department of Geography

*Signatures are on file in the Graduate School

ABSTRACT

Color-vision impairment, or "colorblindness," affects over four percent of the population. Depending on the type and extent of abnormality, colors that look different to people with normal color vision may look the same to the color-vision impaired. This can lead to problems understanding maps in which color schemes are used to represent data. Thus, map design benefits from knowledge of which color schemes inhibit map reading ability for this group. In this thesis I will describe the methods and results of an experiment testing the color schemes of an online Flash-based tool called ColorBrewer (http://www.colorbrewer.org). This tool aids thematic map design by providing users with color scheme options and specifications based on data type and number of classes. In this study, each color scheme was tested for accommodation of red-green color-vision impairment through a concurrent mixed-method experiment collecting both quantitative and qualitative data. Choropleth maps were presented on an LCD computer screen to both an experimental group of the color-vision impaired and a control group of normal color vision individuals. Multiple-choice map reading questions were asked, followed by a semi-structured interview on perception of the scheme. These answers allow for an evaluation of the effectiveness of each scheme. Quantitative results show that subjects could generally answer the multiple-choice questions correctly, but interview responses reveal the level of difficulty that they had with certain schemes. The sequential schemes all accommodate the color-vision impaired due to their change in lightness. Diverging schemes also accommodate when using a hue pair that is differentiable. The diverging schemes that do not accommodate use reds/oranges and greens on opposite ends of the scheme which lead to confusion. Variations of the qualitative schemes, which use many different hues, were found to be either possibly confusing or definitely confusing to the color-vision impaired based on subjects' responses. Blue/purple and green/orange pairs commonly caused difficulty in differentiation. Also, the lighter, pastel colors were found to be much more confusing to the color-vision impaired than darker colors. These findings will help refine the ColorBrewer tool while improving graphic communication by enhancing knowledge of accommodating color schemes.

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Chapter 1

Introduction

Color-vision impairment, more commonly known as colorblindness, affects nearly eight percent of the male population and less than one percent of the female population (Sharpe et al., 1999). This impairment alters the way in which colors are perceived; it is due to abnormalities in the color-sensitive photoreceptors in the retina known as cones. Depending on the type and extent of cone abnormality, colors that are differentiable to those with normal color vision may appear similar or the same to the color-vision impaired. This can lead to problems understanding maps which use a color scheme containing colors similar in perception, such as a choropleth map showing various shades of red and green. A poor color scheme will limit a map's ability to communicate. When you consider that most maps are produced to be read by a large number of people and that in a group as small as 25 at least one individual will likely have abnormal color vision, it becomes apparent that this problem needs to be addressed during map design.

Color choice on maps is an important, and often overlooked, aspect of map design. Use of color on maps can be traced back to Ancient Egyptian maps produced around 1250 BC (Ehrensvard, 1987), and color has always been an integral part of the field of cartography. Two of Bertin's (1983) primary visual variables, or ways of graphically symbolizing difference between entities, involve color. Both hue (what we commonly know as color, e.g., yellow or blue) and value (the lightness or darkness of a

color) were described by Bertin as possibilities for distinguishing the different data values to be represented on a map. This use of color as way to symbolize data gives the map reader a quick, clear visual impression and is intuitively appropriate for giving a pictorial description of Earth's surface (Ehrensvard, 1987). This communication of spatial information is the essence of cartography. Thus, to communicate effectively with those individuals with color-vision impairment, an understanding of this condition is needed when designing a map.

ColorBrewer

For the average map designer, who most likely is not going to have a thorough understanding of color space, choosing an appropriate color scheme for a map can be a difficult task, let alone trying to find one that accommodates the color-vision impaired. This is why Mark Harrower and Cynthia Brewer (2003) have developed an online tool called ColorBrewer (http://www.colorbrewer.org) to help thematic map designers choose color schemes that are appropriate to their needs. A screen shot of the ColorBrewer interface can be seen in Figure 1.

This tool, developed in Flash, allows users to enter the number of classes of data to be mapped and the nature of the data (sequential, diverging, or qualitative) and presents the user with a series of appropriate color schemes from which to choose. The tool, designed with federal agencies in mind, was funded through the NSF's Digital Government Program. These agencies collect spatial data and communicate these data in

cartographic form, yet typically they do not have the time to create color schemes for each map. This is where ColorBrewer can help (Harrower and Brewer, 2003).

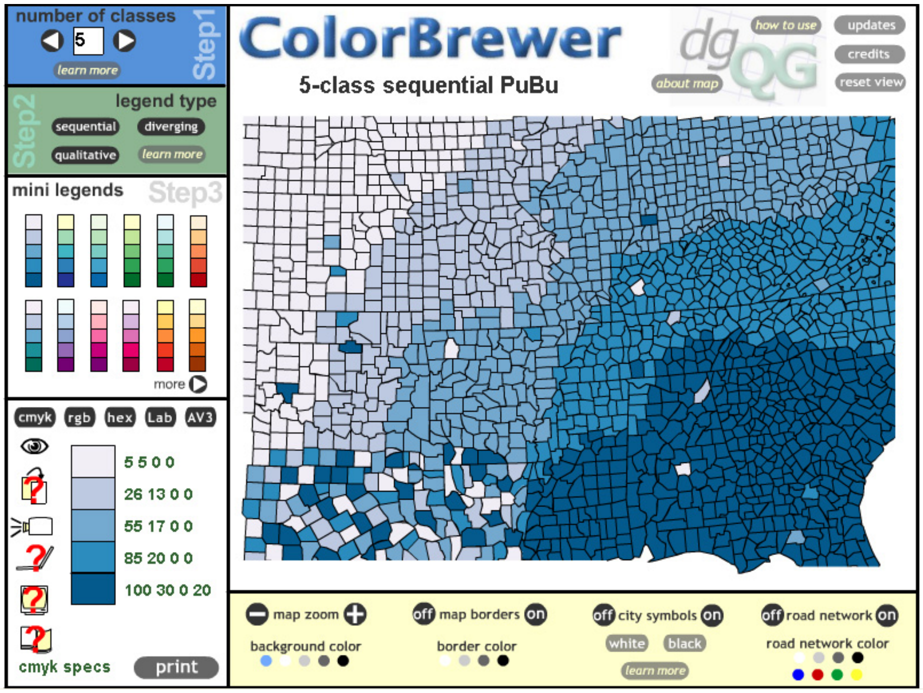

Figure 1: Screenshot of ColorBrewer (http://www.colorbrewer.org)

Thirty-five color schemes are divided into three groups: sequential (18 schemes), diverging (9), and qualitative (8). Each group has its own number of possible classes for the color schemes, based on the nature of the group. All start with three classes and increase, with the diverging group having the most with 12. Examples of the thirty-five color schemes shown in five classes can be seen in Figure 2.

The possible color schemes are shown in legend format, and when one is selected it is displayed on a diagnostic choropleth map of U.S. counties giving the user an example of what a map using that scheme will look like. The diagnostic map displays counties so that colors can be seen in a variety of patterns, allowing simultaneous contrast

effects to be determined. A more in-depth discussion of the color schemes can be seen in Brewer et al. (2003).

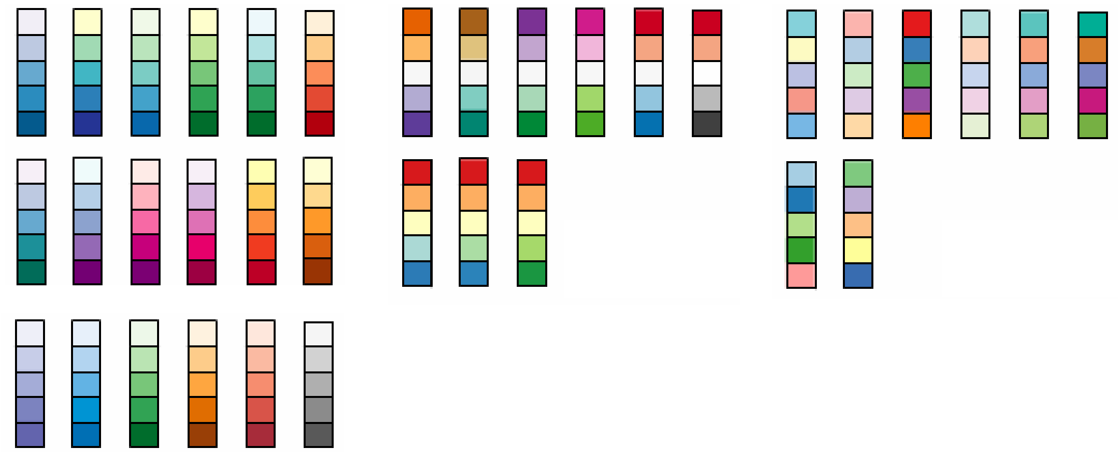

Figure 2: Sequential (left), diverging (center), and qualitative (right) ColorBrewer color schemes in the five class format. Source: http://www.colorbrewer.org

ColorBrewer gives numerical specifications of a selected color scheme in five color formats typically used for graphics and printing: CMYK, RGB, Hexadecimal, CIE Lab, and ArcView 3.x HSV. The tool also provides information on each scheme through the display of usability icons (see Figure 3). These icons indicate suitability of the chosen scheme for photocopying, color printing, use on a CRT, use on an LCD projector, use on an LCD laptop, and accommodation of red-green color-vision impairment. Lack of suitability is indicated by an **X** on top of the icon, while a **?** over an icon indicates uncertainty (see Figure 3). The top icon on the left of Figure **3**, shaped like an eye, is the accommodation icon. The evaluation for this icon was determined from Brewer's theoretical understanding of color space, experience she gained in research with Judy Olson (Olson and Brewer, 1997), and through evaluation of each scheme by a single individual with red-green color-vision impairment.

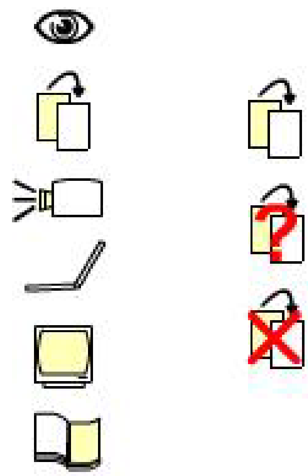

Figure 3: ColorBrewer usability icons (left) and examples of suitability ratings for one icon (right). The eye icon (top left) indicates suitability for color-vision impaired readers.

A majority of the diverging schemes were chosen to potentially accommodate color-vision impaired readers. Sequential schemes use changes in lightness to accommodate all users. Qualitative schemes, on the other hand, use primarily change in hue and are potentially confusing for the color-vision impaired reader. Thorough testing of these color schemes with a group of red-green color-vision impaired individuals is necessary to ensure the reliability of the accommodation icon in ColorBrewer, and to increase knowledge of map reading by and perceptions of this portion of the population.

To address this, I have conducted experimental testing of each individual color scheme with the color-vision impaired, with the purpose of better understanding the map reading and perception abilities of individuals with red-green color-vision impairment when using the various ColorBrewer color schemes. Through advertising and offer of compensation, I gathered a group of twenty volunteers with impaired color-vision and a group of twenty volunteers with normal color vision to take part in my experiment. Ten individuals from each group tested seventeen of the ColorBrewer color schemes. During

these experimental sessions, I gathered both quantitative and qualitative data. Multiple-choice map reading questions, on both overall map patterns and individual unit values, were used to measure the relationship between map color scheme and the map reading ability of individuals with color-vision impairment as compared to individuals with normal color vision. At the same time, the usefulness of the various color schemes was explored using a semi-structured interviewing technique in which participants were asked questions after they had experience with each color scheme.

The following are questions I address in this research:

- *For each individual ColorBrewer color scheme, can color-vision impaired users read and understand maps using the selected scheme as accurately and efficiently as normal vision users?*
- *What color schemes pose the most problems for the color-vision impaired*
- *Among the color-vision impaired, is there a difference in their ability to perceive the various colors of the ColorBrewer tool?*
- *Which color schemes are best at accommodating the color-vision impaired?*
- *Is there a difference in perception between viewing the color schemes on screen versus on paper?*
- *How does a change in the number of classes used in each scheme affect a map's readability?*

The results gained through triangulation of both quantitative and qualitative data can be used to refine the ColorBrewer tool, and will improve map communication by enabling maps to be produced that use color schemes that accommodate the color-vision impaired. The findings will validate or correct the information displayed in the accommodation usability icon for each of the ColorBrewer color schemes tested, telling

the user whether the chosen scheme will be appropriate for those with impaired color vision. The study will also improve understanding of the map reading ability of the color-vision impaired compared to the ability of normal color vision individuals.

The accommodation of this group of individuals is not only an effort cartographers should make in good conscience, but also is a standard that must be upheld by all federal agencies. Section 508 of the 1998 Amendment to the Workforce Rehabilitation Act requires that all electronic and information technology used by federal agencies must be accessible to people with disabilities, including both employees and the general public (U.S. Department of Justice, 2004). Even though it is not a severe disability, color-vision impairment must be accommodated under these Federal 508 Standards. Thus, an improved ColorBrewer tool can play a more important role to federal agencies.

Enhanced knowledge of appropriate color schemes for the color-vision impaired will benefit the cartographic community, while also increasing the limited amount of literature that has previously been written on this topic. The results of this study, along with a more reliable ColorBrewer tool, will also be important to non-cartographic communities, such as graphic design and web development, in which it is essential to communicate effectively with color to large populations.

Chapter 2

Review of Literature

In this section I discuss the existing literature on the topics of color and its use in graphic communication. First I will give an overview of color vision, followed by impaired color vision. I will then discuss the use of color in cartography, and lastly how color plays an important role in accessible graphic and web design.

Color-vision

The history of color-vision research is long and elaborate. Sir Isaac Newton was the first to propose the *received view* (Thompson, 1995), which states that things in and of themselves do not have color, but have color by virtue of how they appear to us. Since we perceive different wavelengths of light as different colors, an object reflecting a certain range of wavelengths of light more than others leads us to perceive this reflection as the object's color. The portion of the electromagnetic spectrum visible to humans includes light with wavelengths ranging from just under 400 nanometers to slightly above 700 nanometers (nm). This light is essentially "photons vibrating at energies that allow them to interact with" our retina (Purves and Lotto, 2003, 17). Lights at the end of the visible spectrum with the longest wavelengths, corresponding to a perception of red, have lower frequencies, and thus the least amount of energy. Lights with the shortest

wavelengths have higher frequencies and more energy, and correspond to a perception of violet (see Figure 4).

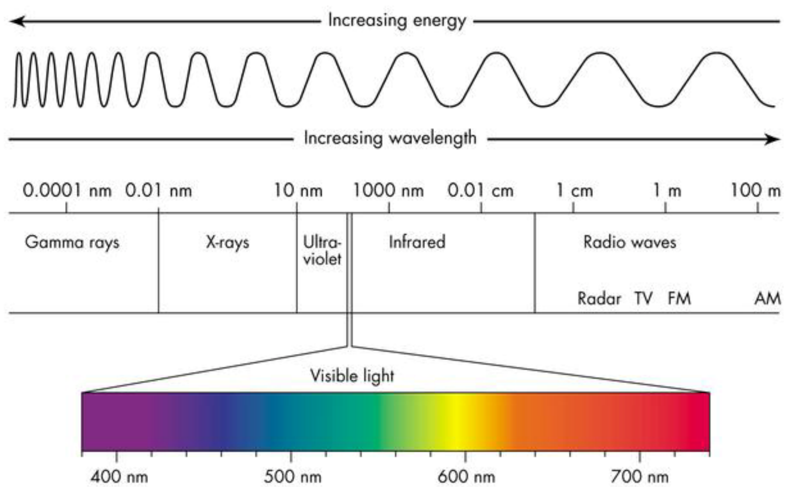

Figure 4: Electromagnetic Spectrum. Source: MacGraw-Hill, http://www.mhhe.com/physsci/astronomy/arny/instructor/graphics/ch03/0305.html

Thompson (1995) and Travis (1991) both discuss the trichromacy of human vision. The basis of trichromacy is that there are three types of photoreceptor cells in the retina that are sensitive to different wavelengths of light. These cells, called cones, are sensitive to either short (S, corresponding to the blue portion of the visual spectrum), medium (M, green), or long (L, red) wavelengths, and our visual system responds to the differences in activity of the three types of cones. The ratio of L and M cones to S cones is 100:1. Each cone contains one of three different types of photopigments, and Merbs and Nathans (1992) have found that these three photopigments exhibit maximum absorption of light at wavelengths of 426, 530, and 557 nanometers.

Mollon et al. (2003) describes a possible explanation for trichromacy derived from primate evolution. He states that development of a third photopigment in the retina,

in addition to the photopigments most sensitive to red and blue, gave primates a distinct advantage in finding fruit amongst foliage (i.e., red against green). All mammals with sight can distinguish luminance differences, or differences in brightness, but a visual system that can identify objects based both on luminance and spectral differences is much more effective for distinguishing objects in the environment.

De Valois and De Valois (1997) discuss how each cone type is excited by all wavelengths of light, but the three different photopigments are more sensitive to certain portions of the spectrum. These cones, though, are just the first part of the color perception process. Spectrally opponent cells extract information from differing intensities of response by the three types of cone photopigments. These cells integrate the responses of cones in a receptive field by determining which cone type absorbs more light than another. This color information is then sent to the brain by the optic nerve and processed in an area of the cortex appropriately termed the visual cortex. Limited investigation has been done on how the visual cortex processes this information. De Valois and De Valois (1997) describe how information may go into color-specific channels in the visual cortex that separate the information by hue and luminance, or that it may go into channels carrying multiple colors that generalize information across hue but extract luminance differences.

Color-vision Impairment

For those with impaired color vision, cone photopigments in the retina are either lacking or abnormal. These individuals “are incapable of making some of the

comparisons of cone activity needed to generate the full range of color sensation" (Purves and Lotto, 2003, 104). They are at a disadvantage in distinguishing objects based on their spectral qualities because they do not have the full use of three photopigments. Thus, their neurological responses to different wavelengths of light may be similar, while the responses for someone with all three cone photopigments would be perception of different hues.

Sharpe et al. (1999) and Rushton (1975) explain how this is commonly a sex-linked recessive genetic characteristic. The genes determining cone structure are held in the X chromosome. Thus, women, with two X chromosomes, have two chances of receiving the proper genes, while men have only one chance with one X chromosome. This explains the great disparity in proportions of men and women with color-vision deficiency.

Sharpe et al. (1999) give an in-depth discussion of the different types of color-vision impairment. The three types are anomalous trichromacy, dichromacy, and monochromacy. While normal color vision uses three primary cone photopigments to match colors, anomalous trichromats are individuals who have all three cone primaries but have weakness in sensitivity in one of them, leading to abnormal color perception. The types of anomalous trichromat are protanomalous (with long wavelength cone weakness), deuteranomalous (medium wavelength weakness), and tritanomalous (short wavelength weakness). Dichromats are individuals who have only two primary cone photopigments with which to match colors. The three types of dichromat are protanopes, deuteranopes, and tritanopes. Protanopes lack the long wavelength (red) cones, deuteranopes lack medium wavelength (green) cones, and tritanopes lack short

wavelength (blue) cones. Monochromats are extremely rare individuals who have only one type of cone, leading to truly colorblind (black and white) vision. The previous types, though, make up virtually all of the cases of impairment. They are not colorblind, but rather simply do not see the full range of colors that are seen in normal color vision. Thus, I am using the term proposed in Olson and Brewer (1997) of "color-vision impaired" to describe this group.

In a more philosophical view on color-vision impairment, Broackes (1997) describes his own red-green color deficiency. He describes how he confuses these two colors in certain situations yet after being told of his mistake he can often "come to see the object as having its true color" (216). To him the object will look different even though the visual circumstances may be the same. For this reason, the author describes how color deficients may just be individuals who are not as good at viewing how an object reflects specific wavelengths, or "changes the light," from just one viewing. He believes this ambiguity can be cleared up by more viewings.

The CIE 1931 color system, which is well described in Wyszecki and Stiles (1982), shows how combinations of three primaries can describe perceptions of all of the millions of different hues that we see. The French Commission Internationale de l'Eclairage (CIE) recommended this as the first color system. This system, represented by a horseshoe shaped diagram (see Figure 5), shows the relative amounts of each primary needed to specify all colors. Values of lowercase x, y, and z, correspond to the percentage of each primary. As described in MacAdam (1997), these values always add up to one, and can be mapped on the two-dimensional diagram using only two values (in this case x and y), one for each axis. The third is simply one minus x minus y.

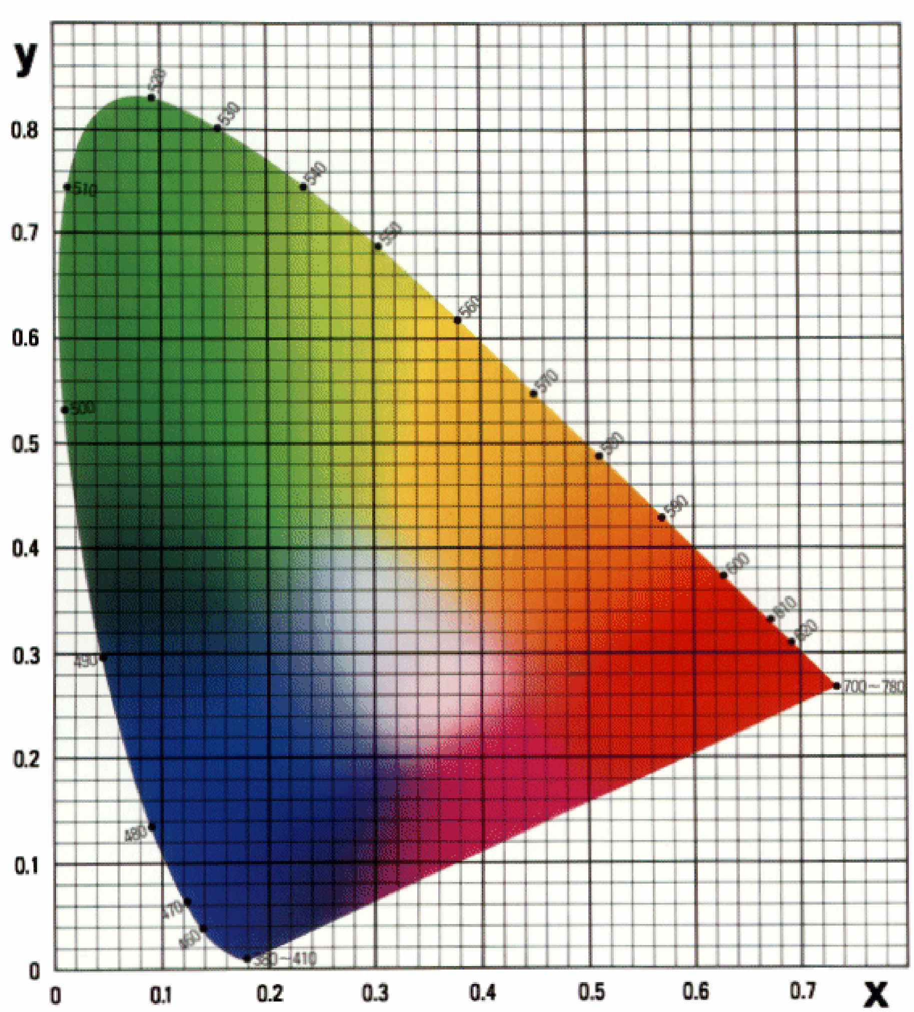

Figure 5: CIE 1931 xy color system chromaticity diagram; wavelengths in nanometers. Source: http://groups.csail.mit.edu/graphics/classes/6.837/F01/Lecture02/CIE1931.gif

As can be seen in Figure 5, an x value near 0.5 and a y value near 0.5 corresponds to a yellowish-orange hue. The solid curve on the outside represents the entire spectrum of hues at full saturation. A central point represents neutral (gray or white), where each value is near one-third. Luminance is often represented as a capital Y, creating a third dimension. Chromaticity xy coordinates for the three primaries are x=1, y=0; x=0, y=1; and x=0, y=0. This system can be misleading, though, because the values do not directly correspond to the underlying cone responses (Luo, 1999).

On this chromaticity diagram, confusion lines can be drawn that indicate colors that are confusing to the color-vision impaired. Lines are drawn from certain points on the diagram (co-punctal points), depending on the type of impairment, and colors that fall along the same line will pose problems. Abnormalities with the red cones (protan-), and abnormalities with the green cones (deuteran-) produce very similar confusion lines as can be seen in Figure 6.

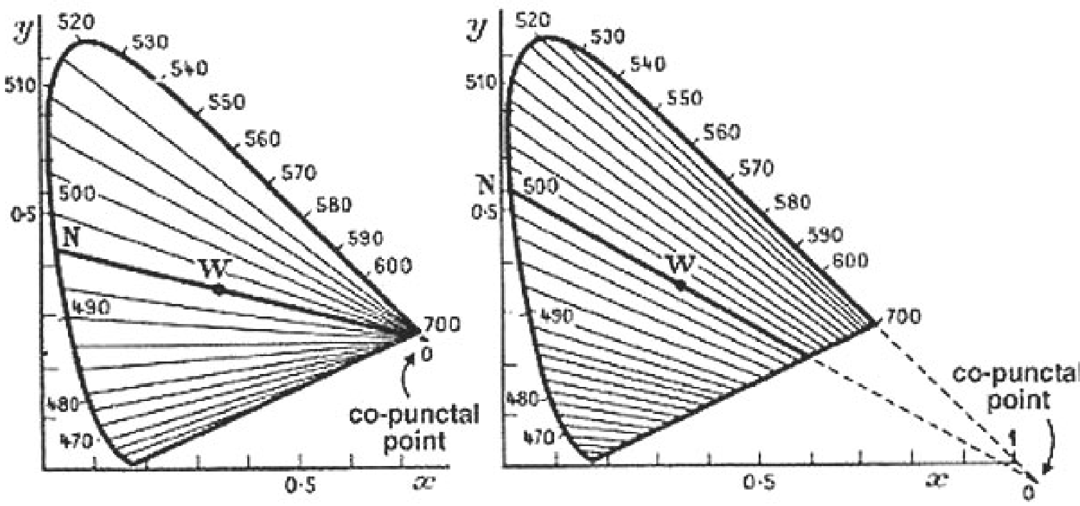

Figure 6: Confusion lines for protanopes (left) and deuteranopes (right), on the 1931 CIE color system chromaticity diagram. Source: Legrand (1968, 348).

As evidenced by the diagram, these two types of impairment are comparable in color perception abilities. The lines running across the top of the diagram, from the green to yellow to orange to red hues, are virtually the same for both protanopes and deuteranopes. Thus, they are collected into a general category referred to as red-green colorblindness. The lines across the bottom are not as similar but still run through the blue and purple hues for both. Blue cone (tritan-) impairment leads to a very different perception of colors than red and green abnormalities. Its genetic frequency has been

estimated as low as 1:65,000 (Kalmus, 1965), yet it is more commonly an acquired deficiency. ColorBrewer color schemes are identified as accommodating those with red-green impairment, so I will consider them together in this proposed study.

A good online resource for color-vision impairment is Vischeck (http://www.vischeck.com). Vischeck allows you to upload your own graphic and choose a type of color-vision impairment. It returns a simulation of how someone with that type of impairment would perceive the graphic. This simulation takes into account all phases of human vision, from physical display properties to retinal transformation and cortical processing. The Vischeck simulation, developed by Dr. Robert Dougherty and Dr. Alex Wade, incorporates S-CIELAB (created at Stanford University from spatial-color measurements gathered in Poirson and Wandell (1993)) and a dichromat simulation algorithm presented in Brettel et al. (1997). After seeing their graphic simulation, the site then gives users the opportunity to utilize an algorithm which will correct their graphic for color-vision impairment. The site also provides users with helpful information about color-vision impairment and examples of simulated graphics.

Color in Cartography

Literature on color use in cartography has increased greatly as technological advancements have allowed for the automated production of maps and improved printing abilities for large ranges of colors. The literature includes color usage discussion in cartography textbooks (Dent, 1999; Robinson et al., 1995), importance of color scheme selection in choropleth map design and communication (Mersey, 1990), evaluation of

color choice for bivariate mapping (Wainer and Francolini, 1980; Olson, 1981; Trumbo, 1981), color printing of maps (Kimerling, 1980), surround-induced change on color maps (Brewer, 1991; 1992; 1997b), color use for maps on computer (Olson, 1987; Meyer and Greenberg, 1988), color use in visualization (Brewer, 1994a; Maxwell, 2000), and color selection in a GIS environment (Olson, 2001).

Olson and Brewer (1997) provide the primary work in the area of map color selection to accommodate the color-vision impaired. They found that color schemes can be chosen for maps that allow those without a full range of color-vision ability to read the map accurately. Their experiment tested seven pairs of maps, with each pair consisting of the same base map with two different color schemes. One was a scheme that was chosen to potentially be confusing to those with red-green color-vision impairment based on color-vision theory, and the other scheme was chosen to potentially accommodate this group. The colors used were also selected in an attempt to be representative of the types of color schemes commonly used in thematic mapping.

In Olson and Brewer's (1997) study, all pairs of maps were tested with a sample of people with red-green color-vision impairment and a sample with normal color vision. Map reading questions were asked of the subjects and response times were collected. For the potentially accommodating color schemes, the group with red-green color-vision impairment responded as accurately as the control group and found them significantly easier to read than the potentially confusing schemes. The impaired tended to take longer than the control group on both versions of the seven maps, perhaps due to lack of trust in past color perceptions. Thus the authors concluded that color schemes can be chosen,

based on the theory of confusion lines in the CIE 1931 diagram, to accommodate this group and that this effort is necessary for a map to communicate effectively.

An evaluation of color schemes for use on choropleth maps representing health statistics was produced in Brewer et al. (1997) that applied the theory from Olson and Brewer (1997). Though they did not test subjects with color-vision impairment, sequential and diverging color schemes were chosen in an attempt to accommodate the color-vision impaired. These schemes, along with diverging spectral color schemes, were tested for accuracy in map reading ability. Sequential schemes are used for showing ordered data by using changes in lightness, with dark representing more. Diverging schemes are used to show difference from a midpoint value (i.e., zero or the mean) using change in lightness of two hues with darker colors on the ends representing greater difference. Spectral schemes are those that use the full range of hues through the spectrum. The authors found through testing a general audience of normal color vision individuals that the schemes chosen were used effectively, and that spectral schemes were preferred. These spectral schemes can be designed to accommodate the color-vision impaired with diverging steps of lightness and with hues not located on the same confusion line. Other discussion of the use of spectral schemes on maps can be seen in Brewer (1997a) and Kumler and Groop (1990).

Both Olson and Brewer (1997) and Brewer et al. (1997) use the idea that selecting color schemes along logical paths through perceptual color space will best reveal the patterns and relationships within mapped data (Brewer, 1994b). A systematic understanding of color space leads to selection of colors that communicate most effectively and accommodate the color-vision impaired.

Accessibility and Design

Discussion of color-vision impairment in literature on color use for computer-based applications is common but limited. White (1990) talks about how color should be applied in the advent of the electronic age. Red and green are labeled as the most common problem colors for the color-vision impaired and should be used only in stronger, mid-range values where differentiation is more likely. Blue is described as a "universally recognizable" color, though this is not the case with several of the ColorBrewer color schemes, as will be explained in the Results and Discussion chapter. In general, the author states, vivid colors should be used for the color to serve its purpose.

Eckstein (1991) gets more in-depth about color-vision impairment in discussion of color use in the modern technological era. The author describes how there is no total color-blindness, but rather limited color perception and inability to perceive certain portions of the spectrum accurately. The three types of impairment, each involving one of the three photopigments, are mentioned briefly and problem colors given. Protanopia, says Eckstein, is explained as causing difficulty with reds, oranges, yellows, and greens, while deuteropia, in a poorly researched statement, is called an inability to distinguish gray from purple. Tritanopia is illustrated as leading to problems with blue/green, and gray/violet. Diminished color perception is described as "very prevalent" and the author warns that often we are not aware of differences between our own color vision and what others see.

In one of the best discussions of how color-vision impairment should be handled in computer-based color presentation and display, Jackson et al. (1994) talk about red-

green color-vision impairment also causing difficulty with colors such as cyan/brown, yellow-green/orange, and blue/purple. When color is used to differentiate classes of information, the authors state that the colors should be unambiguously different, such as complementary pairs. They describe how important applications should avoid using color for class differentiation or use color in combination with another visual variable. They also provide a maxim for colored page design, "Get it right in Black and White," which ensures appropriate brightness differences along with hue differences.

This same idea is seen throughout literature on accessibility of web pages. This literature is abundant due to the rapid growth of the internet and new federal regulations. With governments mandating public accessibility to information, such as U.S. Section 508 requirements, the color-vision impaired must be taken into account when designing a color graphic or web page to provide information. Though not a severe disability, color-vision impairment affects a significant portion of the population and can inhibit comprehension when a confusing color design is used.

Clark (2003) provides a guide to building an accessible website, and describes color-vision deficiency in depth in an attempt to promote appropriate color use. A thorough discussion of general facts about the nature and types of color-vision impairment, including the colors that are often confused, is presented. He states, "The range of hues you have to be concerned about, then, is actually pretty wide: Red, orange, yellow, beige, and green" (206). Red should also not be used in combination with black. The colors used are only important, though, where an "actual meaning" is attached to the color. It makes no difference if someone sees a color as something different than intended as long the color does not mean anything. Meaningful objects on a web page

are text, links, navigation, artwork that informs, and interface elements. These are the things that must be unambiguous, not a graphic design meant only for effect.

In choosing color combinations, Clark (2003) cites Brewer's work on color choices for maps, saying if colors work for maps where they represent actual data, then they will surely work for the web. Color pairs given as safe for web use, with the author citing Brewer (1996), are red/blue, orange/blue, orange/purple, yellow/purple, brown/blue, and yellow/blue. Shades of these hues that are clearly described by the color name should be used (blue not turquoise), as they are most likely to be perceived as that color. Also, lightness steps should be used when a range of items must be differentiated. The author then sums up web accessibility guidelines on color to mean, "Don't use colour by itself to convey meaning" (215).

Brinck et al. (2002) discuss how making a website usable by everyone "expands your audience significantly, increases user satisfaction" (46), avoids discrimination, and complies with legal regulations by providing accessibility to those with disabilities. They call for usability being placed ahead of style and that contrast in lightness be sufficient for those with visual impairments. People's ability to correctly distinguish colors cannot be taken for granted. Nielsen (2000) agrees with this, calling for use of high contrast colors in foreground and background, and avoiding anything that interferes with reading. He suggests getting feedback on designs from someone with red-green color-vision impairment. Vision impairment, overall, is described as causing severe accessibility issues due to the nature of the web as a visual medium.

Van Duyne et al. (2003) provide an example of just how important color differentiation is by describing a user filling in form data to make a purchase. Feedback

was then given by showing missing information marked in red while the remaining spots on the form were green. This color-deficient user could not understand what he did wrong and ended up giving up on a purchase at this stage.

In Mueller's (2003) book on understanding accessibility requirements of the Section 508 amendment to the Americans with Disabilities Act, he describes how this amendment ensures that all U.S. citizens have access to information technology distributed by U.S. government agencies and anyone associated with them. He says that we should "consider color one of the more problematic issues" (57) as visual perception is less reliable than most people think. It is also explained how the statistics show that an application will eventually be used by a color-vision impaired individual. He describes how accessibility can be achieved by not using color to indicate content, using high contrast color settings, and using a color-blindness checker. By doing this, the author claims that federal requirements will be met, productivity will increase, and more clients will be attracted. Mueller, along with Pring (2000), describe how use of color as a source of information also may not make sense due to aesthetic and cultural differences.

Both Mueller (2003) and Pring (2000) also discuss the use of Vischeck (http://www.vischeck.com) as a means of informal color vision testing and verifying compatibility with the design needs of the color-vision impaired. Mueller also provides his own desktop application for use in ensuring that an application is "colorblind friendly."

These suggestions on accessibility are echoed in Slatin and Rush (2003) who discuss how color can be an important tool in web design but must be used in a way to avoid unintended accessibility barriers. They cite Arditi (1997) who talks about how the

color-vision impaired are more likely to experience diminished perception across all three dimensions of color (hue, saturation, and lightness). Thus, the most effective pages are those where colors “differ dramatically” in all three dimensions.

Overall there has been a lack of research into the perception abilities of the color-vision impaired, especially related to cartographic design. Color vision research and research into the physiological nature of color-vision impairment are numerous, yet there have been few empirical studies evaluating difficulty of color differentiation for those with impaired color vision. This can be seen by the simplistic nature of the discussion in graphic and web design communities, where the advice focuses on staying away from red and green. These communities have recently become more interested in color-vision impairment due to accessibility requirements, but the conversation, for the most part, is very limited. Designers have not been provided with a full realization of how color perception ability can differ among individuals and what ranges of colors can be confused. More research on this topic is necessary, not only in cartography, but in the field of communication in general.

Chapter 3

Methods

In this chapter I discuss the methods used for this thesis research experiment. I first describe the subject gathering process followed by subject groups and map order, thematic map creation, production of materials needed for the experiment, the experimental procedure, and analysis of the data. This research uses a concurrent mixed method strategy involving quantitative and qualitative analysis of map reading and perception abilities of the color-vision impaired. Utilizing this strategy, I have collected subjects' responses to multiple-choice map reading questions and gathered subjects' answers to semi-structured interview questions concerning color scheme perception.

The experiments were conducted in 208 Walker Building on the Pennsylvania State University, University Park campus. Each subject was seated in front of a computer. A map using one of the ColorBrewer color schemes was shown to the subject as part of a PowerPoint slideshow. The subject then answered three multiple-choice map reading questions followed by a brief interview concerning on-screen and on-paper perception of the color scheme. This procedure was repeated until the subject had tested 17 of the ColorBrewer color schemes. With the subject's authorization, audio tape recording of interview responses was collected. Ten dollars compensation was used as motivation for subjects to participate and was given to subjects at the completion of the experiment. Prior to beginning experiments, I received a $300 Masters Thesis Research Grant from the Association of American Geographers Cartography Specialty group to be

used for subject compensation. The remaining $100 needed for compensation was provided by the Penn State University Department of Geography with money from the Ruby Miller Fund.

Subject Sample and Recruiting

An experimental group of 20 subjects with color-vision impairment was used, while 20 subjects with normal color vision made up the control group. The twenty subjects were split up into two groups of 10, with each testing 17 of 34 ColorBrewer color schemes. Twenty was chosen since it a manageable number for a thesis project given available funding.

Before beginning research, I gained Institutional Review Board (IRB) approval for the use of human subjects in this study, following the appropriate university procedures. I completed the IRB online training module, then provided the Social Science IRB with the Application for Use of Human Participants, an abstract of my proposed study, the informed consent form, and examples of advertising and other materials used during my research. See Appendix A for the Informed Consent form.

For my primary method of collecting participants, I posted flyers around campus (see Appendix E). The focus of these flyers was on the term “Colorblind” even though this term is not used in discussing my research. This is the term most commonly used by the general public, even though these individuals are not blind to color. The flyers ask for colorblind volunteers to participate in a Penn State Department of Geography experiment testing color schemes for map reading ability among the colorblind. The

experiment is open to any adults with no restrictions other than color-vision impairment for my experimental group and normal color vision for my control group. The offer of $10 compensation is set off to grab their attention. My phone number and email are provided for potential subjects. Initially only flyers looking for color-vision impaired subjects were posted. Flyers looking for individuals with normal color vision were posted after the majority of color-vision impaired subjects had been found. This was to decrease the confusion about which flyer a potential participant was responding.

Flyers were printed out on plain white paper and posted around Walker Building, Deike Building, Hammond Building, Earth and Engineering Sciences Building, Rec Hall, Intramural Building, dining commons, Pattee Library study areas, and the HUB-Robeson Center. An effort was made to place flyers in areas where men congregated, due to the prevalence of color-vision impairment in men. This method was successful. A large majority of my color-vision impaired subjects learned of this research through flyers around campus. Word of mouth to friends and acquaintances along with posting ads on http://psu.dailyjolt.com were also used to recruit subjects.

Flyers were also sent to optometrists' offices in the State College area along with a letter explaining my experiment and asking the optometrist to please post the flyer in their waiting area where it could be seen by patients. I did not gain any subjects who heard of the experiment through these postings, and only heard from one optometrist who agreed to post the flyer in his office. This method was unsuccessful.

To gather the subjects with normal color vision, the flyers were basically the same except looking for males with normal color vision. Word of mouth to friends and acquaintances was also used to recruit normal color vision males. I found one female

with color-vision impairment who agreed to take part in my experiment, so I only needed one female with normal color vision. That female was a personal contact, thus only males were needed and the advertising was geared as such. The large discrepancy in number of male and female participants was expected due to the very small number of women who are color-vision impaired.

The majority of individuals showing interest in this study contacted me by email after seeing a flyer. Fewer chose to contact me by phone. For email respondents, I sent them a reply that included information about the study, purpose, procedure to be followed, length of time, and compensation. I also told them to please contact me if interested so that I could answer any questions they have and set up a time to conduct the experiment. For those individuals who contacted me by phone, I provided them with all the same information as in emails, and asked them if they were interested. If so, I informed them of my schedule and worked out a time to meet for the experiment, making sure they knew that they could contact me at any time with questions or concerns.

For most of the email respondents who showed interest in setting up a time to meet, I emailed them a proposed weekend schedule of when I planned on conducting interviews, informing them of when I had open times. They then got to choose, on a first come-first served basis, the time slot that they wanted. Being at the National Geographic Society on an internship during the week limited my availability, but nearly all respondents were open to coming in on a weekend. The only information I collected from volunteers who agreed to set up a time to conduct the experiment was their name, phone number or email address, and whether or not they were color-vision impaired.

Subject Groups and Map Order

The group of 20 color-vision impaired subjects was split up into two groups of ten (groups AI and BI). Each group was tested on 17 maps, each using one the ColorBrewer color schemes. See Figures 7 and 8 for the color schemes tested with each group. Group A received eight sequential, five diverging, and four qualitative maps. Group B received nine sequential, four diverging, and four qualitative maps. The groups of ten were then divided into three subgroups based on the order of the maps to be shown during the experiment. Four subjects in each group were shown the sequential color scheme maps first (subgroups AIS and BIS), three subjects in each group were shown the diverging scheme maps first (subgroups AID and BID), and the remaining three subjects were shown the qualitative scheme maps first (subgroups AIQ and BIQ). This same distribution was used for the control group of 20 normal color vision subjects. See Table 1 for subgroup characteristics.

Table 1: Subgroup Characteristics. (S = Sequential, D = Diverging, Q = Qualitative)

Subgroup	**Number of subjects**	**Color vision**	**Order of maps shown**
AIS	4	Impaired	SDQ
AID	3	Impaired	DQS
AIQ	3	Impaired	QSD
BIS	4	Impaired	SDQ
BID	3	Impaired	DQS
BIQ	3	Impaired	QSD
ANS	4	Normal	SDQ
AND	3	Normal	DQS
ANQ	3	Normal	QSD
BNS	4	Normal	SDQ
BND	3	Normal	DQS
BNQ	3	Normal	QSD

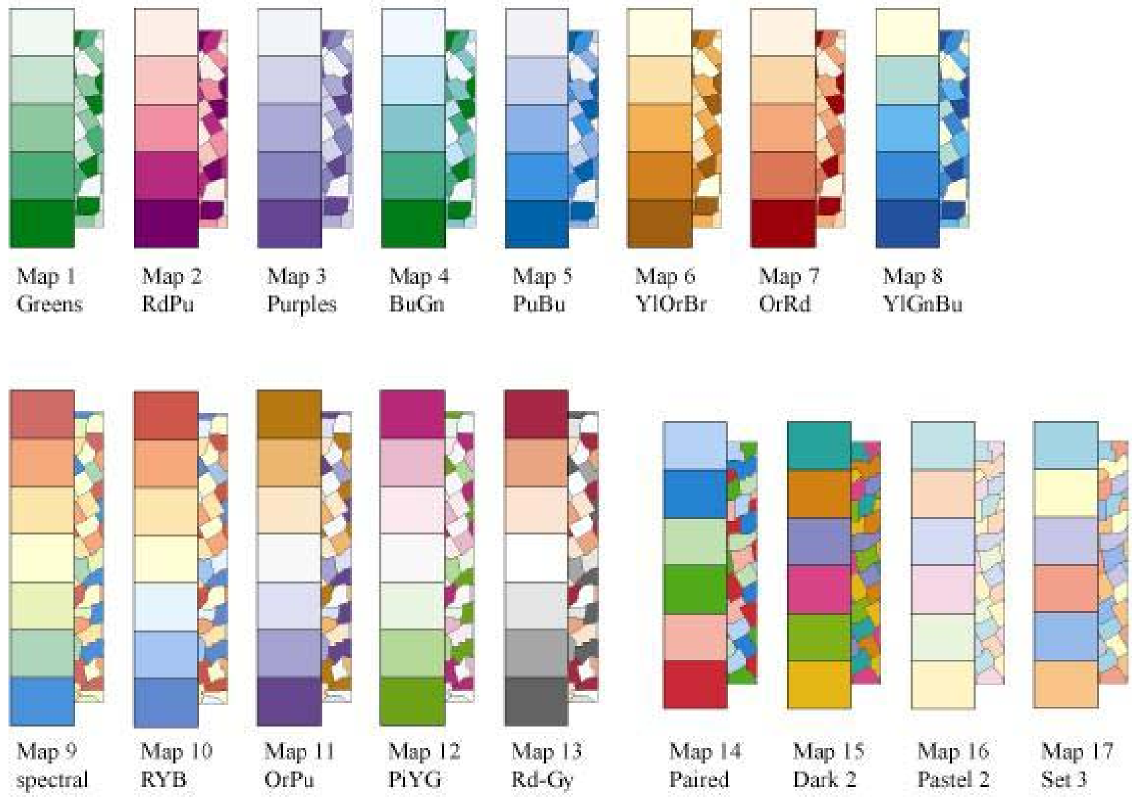

Figure 7: Group A color schemes with names and associated map number.

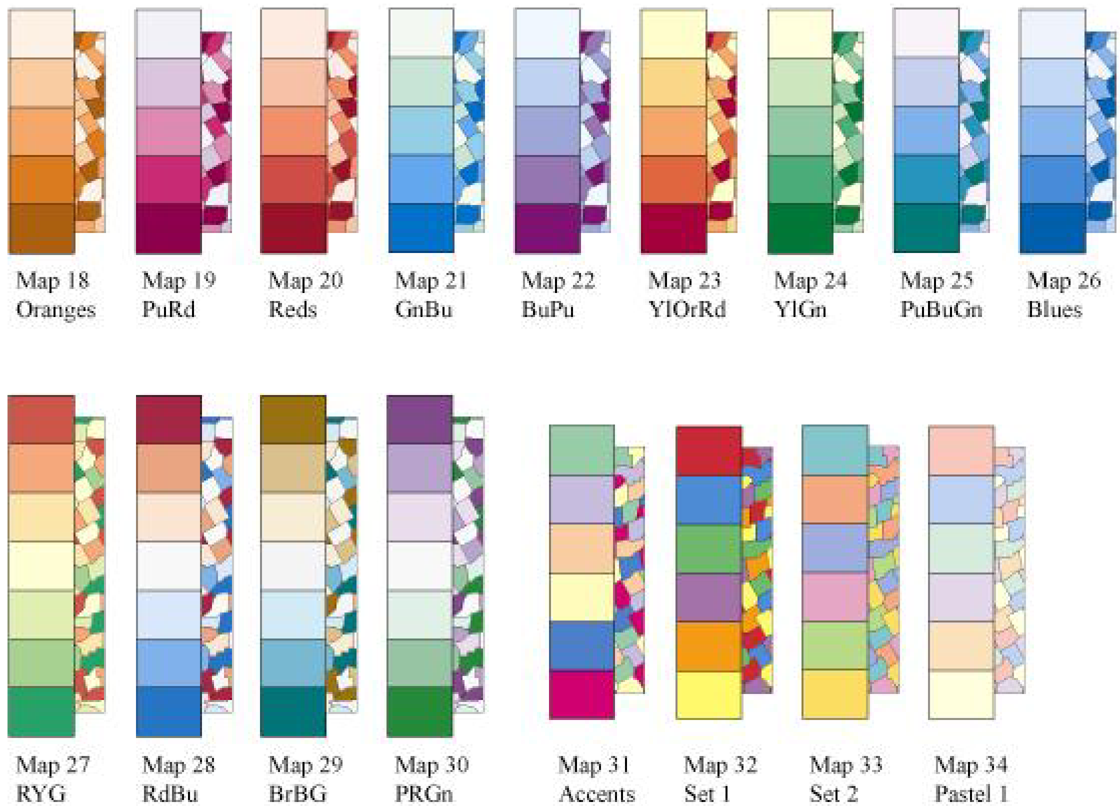

Figure 8: Group B color schemes with names and associated map number.

Map Production

After gaining approval from the IRB, I began producing the maps to be used for my experiments. Since ColorBrewer is an online tool designed to aid color choice for thematic mapping, I chose to create choropleth maps of varied socioeconomic statistics. Choropleth maps—maps in which the value associated with an area is symbolized based on classification of data values—are one of the most common types of thematic maps, and thus familiar to most people. Also, when using the tool, color schemes are shown on an example choropleth map. Thus, choropleth maps are most appropriate for this

research. Socioeconomic data, primarily from the US Census Bureau, were used to create the maps. These data had already been collected for previous work at Penn State with the National Park Service on their developing Socioeconomic Atlas series, and were readily available.

Maps were created using the ArcMap tool of ArcGIS 9. Data were classified into a different number of classes based on the type of data I was going to show. The maps showing sequential schemes used five classes, diverging schemes used seven classes, and qualitative schemes used six classes. These numbers of classes were chosen to represent the entire set of schemes due to their location in the lower to middle portion of the range of options for number of classes. My goal was to provide an overall feel for the scheme while not overwhelming the user. The five class sequential and seven class diverging are also common numbers of classes to be used for their specific data type. For the qualitative schemes six classes were chosen because I felt seven would be more complicated due to the larger number of different hues covering the map. Also with four of the eight qualitative schemes only going up to eight classes, six as a mid-range number seemed appropriate.

I chose to use choropleth maps of states or multi-state regions of the United States with counties as enumeration units. This was due to ready availability of Census data and ArcGIS shapefiles for US counties prepared for the National Park Service atlas project. This also allowed for creation of maps with similar size enumeration units which would eliminate scale as a factor affecting map reading ability. I chose to include US counties outside the specific region of interest but inside the neatline to provide a wider extent to symbolize in color.

Data were classified in ArcMap to the selected number of classes using the Natural Breaks (Jenks) Method of classification. This method uses an algorithm to find the natural breaks in a histogram of data, providing groups of like values. When data values were large and the Natural Breaks method provided numerically detailed class breaks, these break values were rounded to a number which would be easier to read and interpret but retained the overall pattern of the original natural breaks. For diverging choropleth maps, the Natural Breaks method was used initially, and then values were adjusted to include the US average value or a zero value as the break for the fourth (middle) class. This then provided a classification of values that diverged from the US average or zero, and could be appropriately symbolized with a diverging color scheme.

After the classification of the data and symbolizing the counties with one of the appropriate ColorBrewer color schemes, I searched for a state or region of the United States and its surroundings where counties were sized to be easily seen but were not too large, that contained a clear trend in values across the region, and that contained at least one county in all of the classes being mapped. I then created the proper size map focusing on that region and its surrounding counties and added a legend in a space that would not obscure the selected area. This was repeated with other socioeconomic statistics, attempting to keep sizes of counties as similar as possible, until 18 maps were created. These eighteen maps include nine sequential maps, five diverging maps, and four qualitative maps. See Table 2 for a listing of map topics and associated map regions.

Eight of the sequential maps were used with two different color schemes, four of the diverging maps were used with two different color schemes, and all four qualitative maps were used with two different color schemes. This provided me with 34 maps with

which to test the 34 ColorBrewer color schemes. Each experimental group, testing 17 of the color schemes, received only one version of the same map. Group A tested Maps 1 through 17 while group B tested Maps 18 through 34. One final map was created, using the sequential gray ColorBrewer color scheme, to be used as an example map.

Table 2: Map Topics and Regions. (S = Sequential, D = Diverging, Q = Qualitative)

Maps	**Data**	**Topic**	**Region of the U.S.**
Example	S	Rural Population	Wisconsin
1 & 18	S	Educational Attainment	Virginia
2 & 19	S	Elderly Population	Louisiana
3 & 20	S	Median Age	California
4 & 21	S	Median Household Income	Nebraska
5 & 22	S	Population Density	Kansas
6 & 23	S	Poverty	Ohio
7 & 24	S	Total Population	Pacific Northwest
8 & 25	S	Civilian Labor Force	Michigan
26	S	Urban Population	Mid-Atlantic Coast
9 & 27	D	Average Family Size	Idaho
10 & 28	D	Racial Diversity	Georgia
11 & 29	D	Recent Population Change	Arkansas
12 & 30	D	Unemployment	Alabama
13	D	Domestic Migration	Central Texas
14 & 31	Q	Foreign-born Place of Birth	Northern Plains
15 & 32	Q	Industry	Colorado
16 & 33	Q	European Ancestry	Lower New England
17 & 34	Q	Language Spoken at Home (excl. English)	Iowa

Following creation in ArcMap, maps were exported to Adobe Illustrator for editing. Each map was given a title based on the state or region and the socioeconomic statistic being mapped and given a unique number to be used during experimental testing.

For the three multiple-choice map reading questions, I chose to ask the subject two questions on specific areal unit values, and one question on a general trend across the region. For each map I then added the text “X” to one county and the text “Y” to one county. These are the counties about which specific areal unit questions were asked, i.e.,

"the value of county X is between." Also a line was added to the map along the general trend present in the region mapped, such as high values on one side to low values on the other. The text "R" was added to one end of the line while the text "S" was added to the other end. These letters were used for trend questions, i.e., "which of the following most closely describes the general trend in values across the region from R to S." Specific counties and the trend line were the same on repeating maps with different color schemes, since only one of the maps would be shown to each group. All maps are included at the back of this thesis (Appendix B).

Experimental Materials

When all the maps had been created and subject groups had been established, I then developed the multiple-choice questions to be included in the experimental test. I created each question so that the answer options included those colors/classes and trend determinations most likely to be confused by the color-vision impaired according to CIE 1931 confusion line theory and similar lightness. Each multiple-choice question contained four answer options, one of which was "cannot determine with the given colors" in case a subject could not distinguish between colors on the map and did not want to make a guess. The format for the questions is as follows:

i) The percentage of the population that is over 24 years old with some college or a college degree in county X is between

a. 13.9 – 27.3
b. 27.4 – 34.5
c. 34.6 – 41.5
d. cannot determine with the given colors

Correct answers were placed in choices a, b, and c randomly. To eliminate order effects, the order of questions was changed and the type of map (sequential, diverging, or qualitative) shown first was changed for different subgroups. One of three subgroups received the question concerning county X first, one subgroup received the question concerning county Y first, and the remaining subgroup received the question concerning the regional trend first. This order then also changed from question to question. These multiple-choice questions were presented in a set order for specific groups, creating six different test forms, one for each sub-group with the normal and impaired subjects using the same test form (e.g., AIS and ANS used the same test form; see Appendix C).

For the first page of my experimental test form, I created a form for conducting the Ishihara color vision test. More information on the Ishihara test will be provided later in this chapter. On this page I included twelve blanks for the subject to write in a number that they see for each of the twelve plates in the book to be shown. Also on the first page of the form were blanks for the subject number (a number assigned by myself to keep track of each subjects' data), the date, and the subject's group.

After completing the test form, I then created JPEG format images of all of my maps by exporting out of Adobe Illustrator. These JPEGs were added to successive slides in a PowerPoint slide show. I then edited the Powerpoint file to create six files, one for each combination of group and starting data type. The first slide of each file was the example map shown in the gray ColorBrewer color scheme. This scheme was not tested but rather used to explain the experimental procedure to subjects and for them to become familiar with the map format.

For the remaining experimental materials, I created an Interview Guide (see Appendix D) to use when conducting the semi-structured interview for each color scheme. These questions were typed out on a sheet of paper for my own personal use. The questions were not asked word for word from the paper and were not all asked for every color scheme, but rather used to guide the interview. This allowed me to follow up with other questions while being able to skip questions deemed unnecessary for the specific color scheme. A benefit of this semi-structured type of interview is the flexibility that it gives the interviewer while having more of a personal feel.

I also created an Interview Field Notes form used for note taking during the semi-structured interview. This form contained simply a series of blanks to fill in corresponding to the specific map (color scheme) number for which a subject was providing his or her thoughts. A space below each blank was left open for taking notes during the interview.

Then the paper versions of each color scheme were created. I had numerous offprints of “ColorBrewer in print: A catalog of color schemes for maps” (Brewer et al., 2003). I cut out each of the individual class variation ramps for each ColorBrewer color scheme from the offprints. I then pasted each of the class variations on the same paper in order from least number of classes to the greatest. This resulted in one sheet of paper with all of the ColorBrewer versions of the same color scheme. I did this for all of the color schemes; producing 34 sheets with the pasted cut out color ramps (see Figure 9 for an example). Finally, a tape recorder and audio tapes were acquired for use during the experiments, completing the needed materials for use during the experimental sessions.

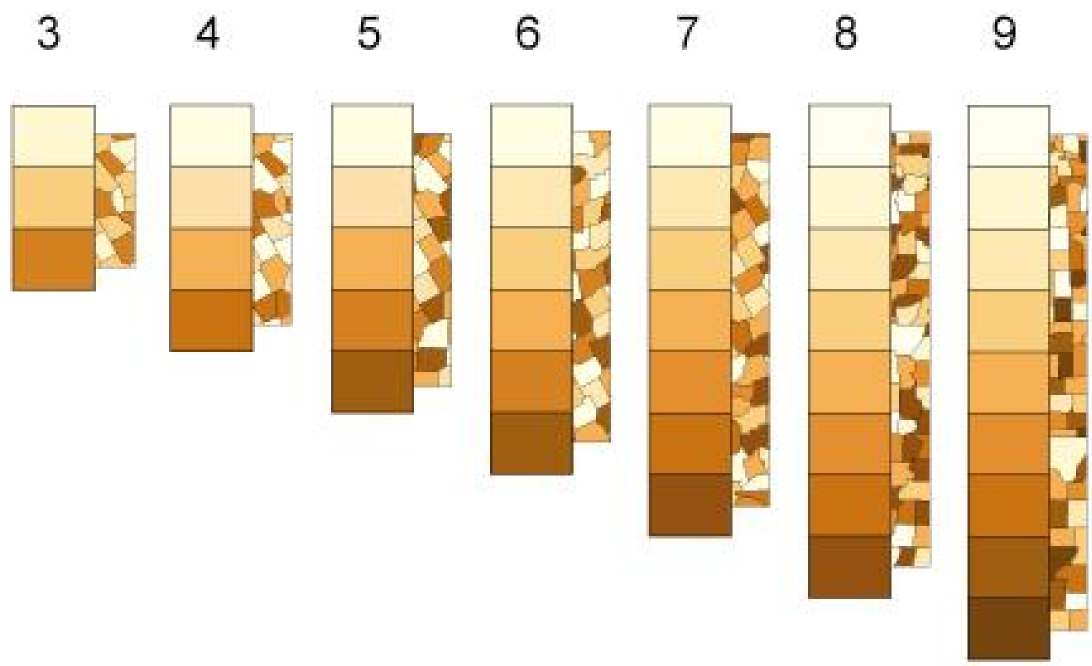

Figure 9: Example of cut out color ramps showing all class variations of a color scheme.

Experimental Procedure

Each experimental session was held in 208 Walker Building, a Geography Department computer lab on the University Park campus of Pennsylvania State University. The computers in the lab are all Dell Optiplex GX270 with a Dell LCD flat-screen monitor, Model No. 1901FP. Since nearly all of the experiments were conducted on weekends, I was able to use the same computer for nearly every experiment. Other experiments were conducted on other computers in the same lab. The color settings of the screen were set to the normal preset specifications of R 95, G 100, B 92, and the brightness was set to 70. This was determined after discussion with my advisor about which settings most closely approximated the color schemes on paper. When unable to

use the same computer, I adjusted the screen to match those same specifications, so that all subjects were viewing the same exact on-screen colors. The first ten subjects to take part were placed in group A while the last ten were placed in group B.

Upon the subject's arrival, I introduced myself and had the subject sit down at the computer. I sat down in the chair next to the subject. First, I thanked the subject for taking part and asked where they found out about this research. Then I briefly explained the research I am conducting and the procedure to be followed. I then had the subject read over the Informed Consent form, including marking whether or not they agreed to have their responses audio taped. This form also informed the subject of the purpose and procedure of the experiment, subject's rights, duration, and compensation. I made it clear that the subject was welcome to ask questions at any time. If the subject consented to this research, he or she then signed the second page of the form. I then signed below as the person obtaining consent. The same was done for a second copy of the form which was the subject's copy to keep.

After consent was obtained, the subject was given the experimental test form, and the color-vision test was completed. This was done through the Ishihara test for color vision (Ishihara, 1980). This book contains a series of plates with a circular image composed of small dots of different colors. Inside each circle, the dots of different colors form a number. For the majority of the plates, one number can be distinguished by individuals with normal color vision and a different number (or no number at all) is seen by individuals with color-vision impairment. These plates give a good determination of whether the individual taking the test is color-vision impaired. They also can show the type (red or green deficient) and severity (by number of questions missed) of color-vision

impairment. An example of an Ishihara plate can be seen in Figure 10. In this plate, an eight is seen by individuals with normal color vision, while a three is seen by individuals with red-green color-vision impairment.

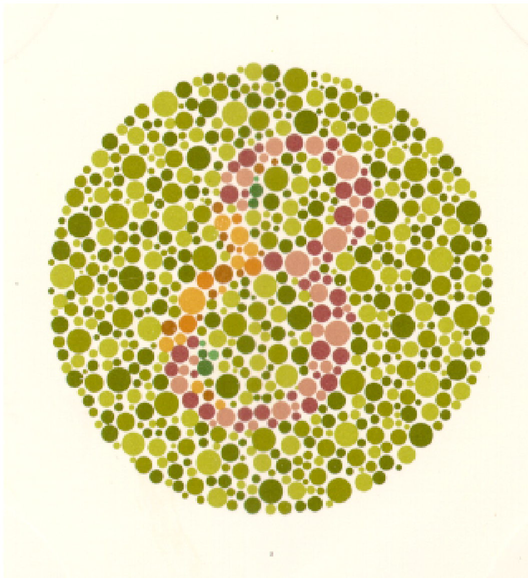

Figure 10: Example of an Ishihara Plate. Taken from http://www.digitalexposure.ca/BlindTest.html

After the Ishihara plates were explained, the subject was told to write down the number that he or she sees inside the circle, and if no number is seen then to leave it blank. This test was designed to be used with natural light, so I had the subject follow me to an area near a window where outdoor light was shining in. I then held up the book for the subject to see, beginning with the first plate, and turning the pages until each plate had been answered. I then examined the subject's answers quickly to determine if he or she was color-vision impaired, which was easily done due to the way the plates are set up in that normals will read one number while the impaired will read another number or nothing at all. If the subject's color-vision test results differed from his or her stated condition, the subject was informed at the end of the experiment. This happened for two

individuals who contacted me saying that they thought they were colorblind but were not and one individual who said he had normal color vision but test results showed that he was color-vision impaired. This latter individual was guided to seek verification from an eye care professional.

When the color-vision test had been completed, I led the subject back to the computer where the remainder of the experiment would take place. The lab was primarily lit from the ceiling using fluorescent light bulbs (Philips Econ-o-watt F40LW/RS/EW 34-watt bulbs), though some indirect sunlight was usually coming in the window between the blinds. After being seated, the PowerPoint slideshow was started, bringing up the example map in the gray color scheme. I then described how a choropleth map works, told the subject that each map would be similar in structure to the example, and explained the different letters on the map and how they relate to the multiple-choice questions to be asked. Then I discussed how after the three questions had been answered I would briefly ask the subject some questions on his or her perception of the color scheme, then have them view the scheme on paper and describe perception of the cut-out color scheme ramps.

After making sure the subject was clear on how each map would represent data and the procedure to be followed, I had the subject flip to the next page of the test form while I moved to the next slide. This was the first map to be tested. I had the subject examine the map and answer the three multiple-choice map reading questions. While the subject was doing this, I began the audio tape if the subject had agreed to be taped. I started the tape by saying the subject number, date, and group. The tape then ran continuously throughout the experiment.

When the subject had answered the three multiple-choice questions on the test form, I then began the semi-structured interview for this specific color scheme. I used the Interview Guide to gather thoughts from the subject on using this particular color scheme on screen. When I felt I had a complete answer, I then showed the subject the paper version of the color scheme by presenting the sheet of paper with all of the cut-outs of the same scheme. This allowed the subject to see all of the different variations of the scheme based on number of classes to be shown. I initially had the subject compare the same number of classes on paper to on screen (i.e. the five class scheme for sequential maps), describing any differences that were seen. Then the subject was asked to describe at which number of classes he or she started to have difficulty distinguishing the colors within the ramp and would have difficulty using them on a map. For example, the six class color scheme would cause problems because the second and third colors appear too similar causing difficulty differentiating them on a map.

While the subject was providing his or her thoughts, I was taking notes on my Interview Field Notes form. These notes captured most of the major thoughts of the subject, the number of the color and class variation where the subject had problems, and any quote-worthy phrases. I did not worry about writing down everything since I was using a tape recorder. On only one occasion did a subject not agree to be tape recorded, and for this subject I attempted to write down a summary of everything he said during the interview sessions.

This process was then repeated for the remaining sixteen maps, each using a different ColorBrewer color scheme. I would give a verbal signal that we were moving on and switch to the next slide of the PowerPoint presentation after I was satisfied with

the semi-structured interview. The subject turned the pages of his or her test form when necessary. As maps changed to a different type, I made sure to explain the new type and confirm that the subject understood the differences and how they pertained to the multiple-choice questions. No time limit was imposed for answering questions or for giving thoughts during the interview. Most experiments lasted between 45 minutes and one hour.

Upon completion of the final map, I gave the subject the opportunity to provide any overall comments or ask questions on the experimental process. I then stopped the audio recording, thanked the subject for their participation, made sure they had their copy of the informed consent form, and gave them the 10 dollars compensation. I marked on the audio tape the subject number and group. I used each tape for two subjects, one per side. For the Ruby Miller fund money, subjects needed to print their name and sign a sheet stating that they received the 10 dollars compensation. So I had my first ten subjects do this, and turned in this form to the Geography Department verifying that the $100 had been used for subject compensation.

Analysis

When grading the test forms, I first compared the subject's answers for the color-vision test to the key provided in the back cover of the book. This told me whether or not the subject can be included in the impaired group. I then graded the responses to the multiple-choice questions by using two keys that I had created, one for group A and one for group B. I went through each question, marking the answer if it was incorrect. To

keep track of questions missed, I created an Excel table of subjects and questions. Questions were labeled by map number and X, Y, or R, corresponding to the X value, Y value, and trend questions, respectively. So for each subject, I went through each of their 51 questions and put a check in the box for each question that was missed. Thus I had four different tables, group A impaired, group A normal, group B impaired, and group B normal. I added up all of the missed questions per map number (combining X, Y, and R) to come up with the total number of questions missed per color scheme for the impaired group and for the normal group.

This allowed me to do a Chi-Square Test of Significance for each color scheme based on the number of correct and incorrect answers. Each scheme had a total of thirty responses from impaired subjects and thirty responses from normal subjects. My independent variables were whether the group was color-vision impaired or had normal color vision, and my dependent variables were the total number of correct and incorrect answers to multiple-choice questions for a given scheme. This test for significance was done in Excel by entering the formula for finding the chi square value from cells containing the number of correct and incorrect answers for both the color-vision impaired and normal groups. These values were then compared to a Critical Values of Chi-square table (http://www.statsoft.com/textbook/sttable.html) for one degree of freedom and a probability of 0.05. Thus, I could say for each color scheme whether there was a statistically significant difference in ability to answer multiple-choice map reading questions between the color-vision impaired subjects and the normal color vision subjects.

A very important part of my data collection was the interview responses. These notes taken on the Interview Field Notes form were then enhanced by reviewing the audio tape of the entire experiment. When these notes were completed, they were then coded by color scheme (or map number). For each color scheme I looked at each of my notes for subjects with color-vision impairment. I then wrote down common themes, how common they were, and any unique thoughts or comments from individual subjects. This provided an overall view of the perception of the color-vision impaired on using that color scheme. This was then done for the same color scheme with the normal color vision group. The two were then compared and can be used along with the results of the chi square test to give a thorough understanding of the differences between the two groups in reading a map with one of the ColorBrewer color schemes. The same process was used for all 34 color schemes.

Chapter 4

Results and Discussion

In this chapter I will describe the results of my thesis research, discuss the meaning behind them, and give my recommendations for the accommodation icon in the ColorBrewer tool. The results are divided into quantitative and qualitative sections, with the qualitative results examined by data type and by overall themes. In the discussion section, I focus on integrating the quantitative and qualitative data into triangulated results. Finally, I take those results and use them to make recommendations for the class variations of each ColorBrewer color scheme, deciding whether each accommodates, possibly confuses, or definitely confuses the color-vision impaired.

Quantitative Results

The number of incorrect answers, out of thirty, recorded for the two vision groups, color-vision impaired and normal, are given in Table 3 for each specific color scheme. These numbers were then analyzed using a Chi-Square test of significance. The number of right and wrong answers for the impaired and normal groups produced a two-by-two chi-square table for each map and its associated color scheme. An example of the chi-square table can be seen in Table 4.

Table 3: Number of incorrect multiple-choice answers per group. (Thirty total questions) (S = Sequential, D = Diverging, Q = Qualitative)

Map	Data Type	Color Scheme	Scheme name	Impaired	Normal
1	S	Green	Greens	2	1
2	S	Red-Purple	RdPu	1	1
3	S	Purple	Purples	1	0
4	S	Blue-Green	BuGn	0	1
5	S	Purple-Blue	PuBu	4	4
6	S	Yellow-Orange-Brown	YlOrBr	0	0
7	S	Orange-Red	OrRd	0	0
8	S	Yellow-Green-Blue	YlGnBu	3	0
9	D	Spectral	spectral	5	1
10	D	Red-Yellow-Blue	RYB	5	1
11	D	Orange-Purple	OrPu	0	0
12	D	Pink-Green	PiYG	0	1
13	D	Red-Gray	RdGy	3	2
14	Q	Paired	Paired	0	0
15	Q	Dark 2	Dark 2	2	1
16	**Q**	**Pastel 2**	**Pastel 2**	**9**	**0**
17	Q	Set 3	Set 3	2	1
18	S	Orange	Oranges	0	0
19	S	Purple-Red	PuRd	1	3
20	S	Red	Reds	0	0
21	S	Green-Blue	GnBu	2	1
22	S	Blue-Purple	BuPu	0	0
23	S	Yellow-Orange-Red	YlOrRd	1	0
24	S	Yellow-Green	YlGn	2	0
25	S	Purple-Blue-Green	PuBuGn	2	0
26	S	Blue	Blues	2	1
27	D	Red-Yellow-Green	RYG	5	1
28	D	Red-Blue	RdBu	4	1
29	D	Brown-BlueGreen	BrBG	0	0
30	D	Purple-Green	PRGn	0	1
31	Q	Accents	Accents	0	0
32	Q	Set 1	Set 1	0	0
33	Q	Set 2	Set 2	1	1
34	Q	Pastel 1	Set 3	4	1

Table 4: Example of Chi-square table for Map 16.

		Group	
		Impaired	Normal
Outcome	Correct	21	30
	Incorrect	9	0

The formula for finding the chi-square value from this type of two-by-two table was entered into an Excel spreadsheet referencing cells that contained the numbers of correct and incorrect responses by each group for each color scheme. The resulting chi-square values describe the relationship between the normal and color-vision impaired groups. The chi-square values for each of the color schemes are listed in Table 5. To be statistically significant at the 0.05 level using one degree of freedom (two rows and two columns in the table), values must be greater than 3.84. This means that the odds of this difference between vision groups happening by chance are less than 5 percent. The only color scheme that produced a significant difference between the color-vision impaired and normal groups was Pastel 2 (Map 16). This scheme produced all 30 correct answers from the normal group, while the color-vision impaired answered only 21 correct. This led to a chi-square value of 10.588 which is statistically significant beyond the 0.005 level (odds of chance are less than five out of one thousand).

Table 5: Chi-square values for each color scheme. (S = Sequential, D = Diverging, Q = Qualitative)

Map	**Data Type**	**Color Scheme**	**Scheme name**	**Chi-square value**
1	S	Green	Greens	0.351
2	S	Red-Purple	RdPu	0.000
3	S	Purple	Purples	1.017
4	S	Blue-Green	BuGn	1.017
5	S	Purple-Blue	PuBu	0.000
6	S	Yellow-Orange-Brown	YlOrBr	0.000
7	S	Orange-Red	OrRd	0.000
8	S	Yellow-Green-Blue	YlGnBu	3.158
9	D	Spectral	spectral	2.963
10	D	Red-Yellow-Blue	RYB	2.963
11	D	Orange-Purple	OrPu	0.000
12	D	Pink-Green	PiYG	1.017
13	D	Red-Gray	RdGy	0.218
14	Q	Paired	Paired	0.000
15	Q	Dark 2	Dark 2	0.351
16	**Q**	**Pastel 2**	**Pastel 2**	**10.588**
17	Q	Set 3	Set 3	0.351
18	S	Orange	Oranges	0.000
19	S	Purple-Red	PuRd	1.071
20	S	Red	Reds	0.000
21	S	Green-Blue	GnBu	0.351
22	S	Blue-Purple	BuPu	0.000
23	S	Yellow-Orange-Red	YlOrRd	1.017
24	S	Yellow-Green	YlGn	2.069
25	S	Purple-Blue-Green	PuBuGn	2.069
26	S	Blue	Blues	0.351
27	D	Red-Yellow-Green	RYG	2.963
28	D	Red-Blue	RdBu	1.964
29	D	Brown-BlueGreen	BrBG	0.000
30	D	Purple-Green	PRGn	1.017
31	Q	Accents	Accents	0.000
32	Q	Set 1	Set 1	0.000
33	Q	Set 2	Set 2	0.000
34	Q	Pastel 1	Set 3	1.964

The other color schemes showed little difference between the two groups in the number of incorrect answers given and no statistically significant difference through chi-square testing. The chi-square values for the sequential yellow-green-blue, diverging spectral, diverging red-yellow-blue, and diverging red-yellow-green (Maps 8, 9, 10, 27) were higher than the rest but were not statistically significant at the 0.05 level and only exhibited a difference of three or four questions missed between the two groups. Based on confusion line theory, the diverging spectral and red-yellow-green were expected to cause errors but the yellow-green-blue and red-yellow-blue were not.

Considering there were multiple chi-square tests in this research (34 color schemes), the Bonferroni correction can be used to take into account the possibility that one of the 34 tests may show significant results by chance. When applied, this correction decreases the level of statistical significance needed to 0.0015. The Pastel 2 scheme (Map 2) is still statistically significant in this case ($p = 0.0011$).

Overall, the color-vision impaired answered a total of 61 questions incorrectly, missing 6.0% of all questions asked. This breaks down to 4.1% of the questions on sequential schemes, 8.2% of the questions on diverging schemes, and 7.5% of the questions on qualitative schemes. The normal color vision group, conversely, answered only 24 questions incorrectly, missing 2.4% of all questions asked. This group missed 2.4% of the sequential scheme questions, 3.0% of the diverging scheme questions, and 1.7% of the qualitative scheme questions.

Qualitative Results

The qualitative results produced some common themes throughout the color schemes. At the same time, there were many individual differences in the thoughts of the subjects as to how they perceived a specific color scheme and what, if any, difficulties they had. This was a good exercise to not only evaluate the perception of the color-vision impaired, but those individuals with normal color vision as well. With one female color-vision impaired subject volunteering for this study, only one female with normal color vision was included in the control group, and thus I did not make any generalizations about gender difference. Color perception varies from individual to individual, but the resulting commonalities can be used to improve ColorBrewer and advance knowledge of color use in cartography and design.

Sequential Schemes

Two sequential color schemes were found to be better than the rest based on overall interview results. The Yellow-Orange-Brown (Map 6) and the Yellow-Orange-Red (Map 23) schemes (see Figure 11) were described as good or easy by nearly all of the subjects. A very small number said that they saw some slight similarity between two of the colors on the on-screen five class map but had no difficulty with the five class scheme on paper. Many participants said that they liked these color schemes, found them well-defined, and labeled them as easier to use than the other sequential schemes. Subject 18 said how he “can easily distinguish between all these colors,” on Map 23. Subject 5 claimed to see a “sharp difference in all of them,” on Map 6. This was

consistent throughout the sample. When examining the different class variations on paper, the lighter end into the middle caused some difficulty with similarity of adjacent colors, but the dark end was fine. The two-three-four range of the seven and eight class variations is where participants most often said colors started to become close. Many, though, found the scheme accommodating through all nine classes. No difference in results was found between the color-vision impaired group and the normal group. These findings were consistent throughout both groups. These two schemes were clearly favored over the rest as most participants found them quick and easy, especially with the five class schemes.

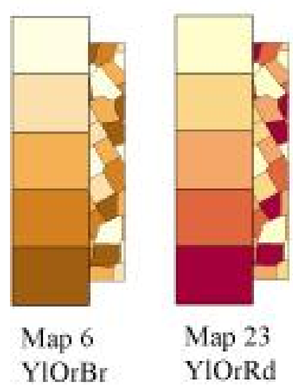

Figure 11: Yellow-Orange-Brown and Yellow-Orange-Red sequential schemes in five class formats.

The next group of sequential color schemes to show similarities are those where most subjects found the map “okay” with no difficulty in perception while some had minor difficulty differentiating adjacent colors on the map. These schemes include the Red-Purple (Map 2), Blue-Green (Map 4), Orange-Red (Map 7), Red (Map 20), and Green-Blue (Map 21). See Figure 12. These schemes are similar to the two previously discussed except that there were more individuals mentioning some closeness or

confusion between colors on the on-screen five class map. Still, the great majority of participants described them as good or okay to use. The phrase from subject 6 when asked about how the colors of Map 4 were perceived, “pretty well different,” can be applied for many subjects. Some subjects found similarity between pairs of middle colors, either the second and third or third and fourth, but could still distinguish them. When this similarity was seen, it caused subjects to do double-checking from map to legend until they were sure they had the right color. Thus it took the subject slightly longer to read the map and answer the multiple-choice questions.

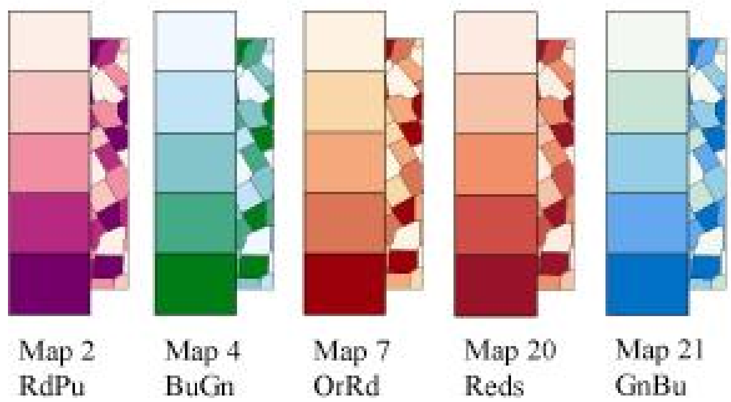

Figure 12: Red-Purple, Blue-Green, Orange-Red, Red, and Green-Blue sequential schemes in five class formats.

These schemes were slightly more difficult for some subjects, but overall these schemes were good with few problems being mentioned in the semi-structured interviewing. The responses about where in the range of class variations the subject started to have difficulty varied quite a bit, but the six class scheme in the second-third-fourth region was a common answer for these color schemes. Again, no difference was seen between the color-vision impaired group and the normal group, as was expected

because the sequential schemes use change in lightness from top to bottom. These findings were consistent for both groups.

Five of the sequential schemes showed the common theme of being nearly equal in the number of participants who had no difficulty with the five class on-screen map and those who described some slight difficulty due to similarity of colors on the same map. These five colors schemes are the Purple (Map 3), Yellow-Green-Blue (Map 8), Orange (Map 18), Purple-Red (Map 19), and Blue-Purple (Map 22). See Figure 13. These were hard to evaluate because of this discrepancy in responses of subjects. For the most part, those who said that they had some difficulty declared that colors were close but still distinguishable. Several, though, had more difficulty. Subject 14, when asked if he could distinguish the colors of Map 14 said, “not always.” The Purple scheme had a couple of subjects who mentioned confusing colors, and others took longer with close colors that were distinguishable but needed to be double-checked. The Purple, Orange, Purple-Red, and Blue-Purple schemes showed closeness between the second-third-fourth colors of the five class map. This was described by nearly half of the subjects.

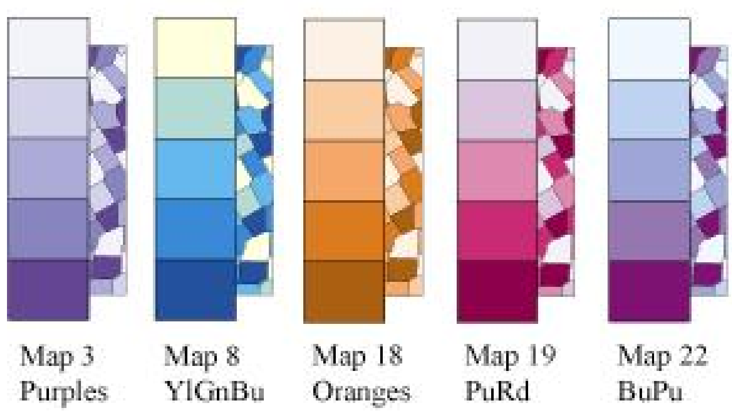

Figure 13: Purple, Yellow-Green-Blue, Orange, Purple-Red, and Blue-Purple sequential schemes in five class formats.

The Yellow-Green-Blue scheme showed similarity with nearly half of the participants in the on-screen five class map between the third and fourth colors. The Yellow-Green-Blue scheme was the only one of these five color schemes to be accommodating up to the eight and nine class variations, while the other four commonly start to show some difficulty in the lighter end of the six to seven class variations. The Yellow-Green-Blue scheme was much easier for subjects to use on paper than on screen.

The Orange and Purple schemes show no difference between the color-vision impaired and normal groups, but the others do show a difference. These three have a very small number of normal subjects who discussed any sort of difficulty with colors on screen looking similar, while nearly half of the color-vision impaired mention closeness or similarity of colors on screen though they can still distinguish them. Overall, all five of these color schemes worked for nearly all subjects involved, but about half of them took a little longer to distinguish pairs of colors in the middle ranges.

The next three sequential color schemes all show a majority of subjects describing some difficulty resulting from adjacent colors of the five class scheme looking similar but distinguishable. These schemes are the Green (Map 1), Yellow-Green (Map 24), and Purple-Blue-Green (Map 25). See Figure 14. On these, a large number of subjects were like subject 17 who said he was “not comfortable” with the colors on Map 25. The second to third and third to fourth both were mentioned as giving subjects difficulty when trying to match up colors on the map to the legend. The responses of those mentioning difficulty varied. Some said that two colors were slightly close or close with a little trouble distinguishing them, while others said certain pairs were “hard” (subject 14) and that they could “only tell a difference after staring for a while” (subject 25). The point on

paper where subjects started having trouble and would not be able to use a map with a certain class variation was wide-ranging. The five, six, and seven class schemes in the light to middle range were the most common responses as to where the schemes started to break down. Overall, the schemes were slightly easier to distinguish on paper than on screen, and also easier to distinguish on the map than on the legend. These characteristics were seen in both the normal and color-vision impaired groups, though the normal group had a moderately easier time with the Purple-Blue-Green.

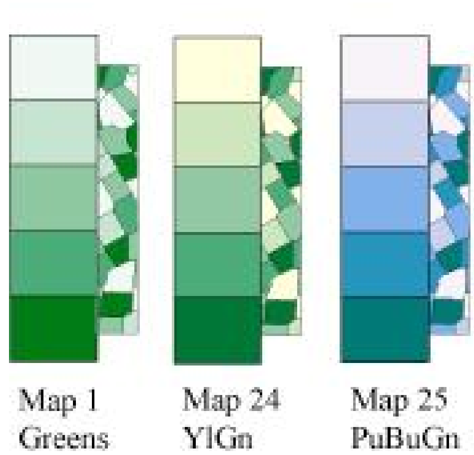

Figure 14: Green, Yellow-Green, and Purple-Blue-Green sequential schemes in five class formats.

The last two sequential color schemes produced responses that showed the most difficulty for schemes of this data type. These two color schemes are the Purple-Blue (Map 5) and Blue (Map 26). See Figure 15. All of the color-vision impaired and a majority of the normal group described one or more pairs of colors of the on-screen five class map that caused problems to some degree. Again, the second, third, and fourth colors in the range were the ones that caused difficulty. The first and fifth were fine and distinguishable from the others. Subject 5 when looking at Map 5 said he was “not a fan

of these colors." This could most likely be said for many of the subjects. Descriptions of these schemes include, "harder" (subject 9), "had to look at other colors to figure it out" (subject 5), and "not as clear" (subject 31). The majority of subjects could eventually distinguish the colors that caused them some problems, but several also had a more difficult time. This latter group explained their perception of these color schemes as really close, hard to distinguish, or difficult to match. The Purple-Blue scheme was clearly easier on paper than on screen for the participants to distinguish colors. The Blue scheme was the same on paper. The five and six class light to middle range is where the Blue scheme started to break down, while the Purple-Blue failed in the light to middle range of the six and seven class variations. A difference between the color-vision impaired and normal groups was seen in both schemes. For the normal group there were subjects who had no problems distinguishing the five class scheme, while others exhibited the same difficulties as discussed above that were seen to some degree in all of the color-vision impaired.

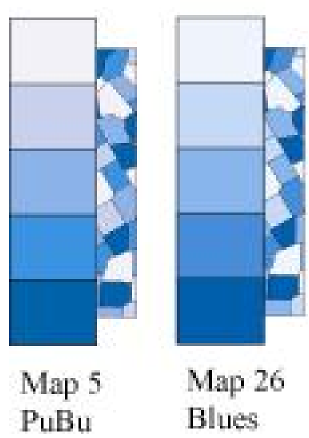

Figure 15: Purple-Blue and Blue sequential schemes in five class formats.

Diverging Schemes

Looking at the diverging color schemes, six schemes exhibited similar characteristics in that a large majority of the color-vision impaired subjects found the seven class map easy or okay to use, but some of them had to do a bit of double checking when comparing colors. The colors that caused this bit of difficulty were generally the lighter colors on either side of the middle compared to the middle itself, and also the light to middle shades of one of the hues. These schemes are the Red-Yellow-Blue (Map 10), Orange-Purple (Map 11), Red-Gray (Map 13), Red-Blue (Map 28), Brown-BlueGreen (Map 29), and Purple-Green (Map 30). See Figure 16**.** The terms "easier," "clearly distinguishable," and "no problem at all" came up many times.

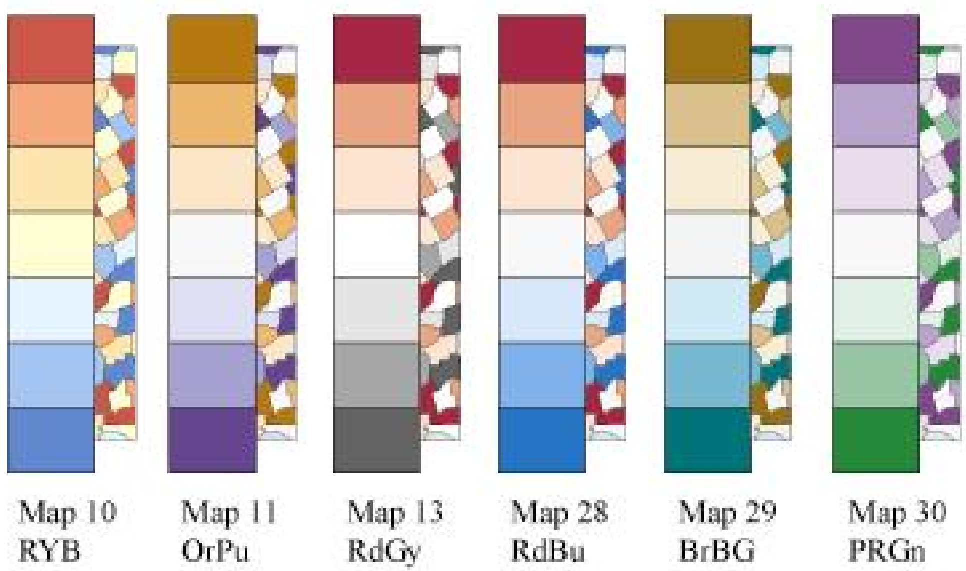

Figure 16: Red-Yellow-Blue, Orange-Purple, Red-Gray, Red-Blue, Brown-BlueGreen, and Purple-Green diverging schemes in seven class formats.

A few subjects took a little longer and had some difficulty distinguishing the third-fourth and fourth-fifth colors, specifically three-four on the Red-Yellow-Blue, four-five on the Orange-Purple, four-five on the Red-Blue, four-five on the Brown-BlueGreen, and three-four on the Purple-Green. Some subjects also mentioned closeness in the light and middle shades of the blue and purple ends of these schemes. Subject 5 said the purples on Map 11 were “way too close,” but this was not the norm. This subject also had difficulty distinguishing the two darker hues on either end of the Red-Gray scheme, saying “the extremes are too bloody close” leading to a double-take. This response is typical for protan- impairment, yet subject 5 was determined to be deuteran- impaired based on the color-vision test results. The others, many of whom also were determined to be deuteran-, thought this scheme contrasted very well.

Even fewer normal subjects had difficulty with these six schemes, but those that did described the same problems as seen in the color-vision impaired. The paper versions in general were a slight improvement over the on-screen map. The schemes commonly started to break down in nine, ten, and eleven class variations on the blue, purple, or gray side, though many subjects evaluated the schemes as distinguishable through eleven.

The Pink-Green diverging scheme (Map 12) (see Figure 17) was similar to the previous six but with a majority of color-vision impaired subjects describing some difficulty with adjacent colors. The lighter pinks into the middle were the most commonly given culprits that caused some similarity in perception for this group. The “two colors contrasted enough” as subject 6 declared about the pink and green, but the “pinks are more difficult.” This one was a “little bit harder” (subject 12) than the diverging schemes previously discussed. On paper, the third and fourth colors (light pink

and light gray) of the seven class variation caused greater difficulty than on screen, with over half the subjects saying that they had some difficulty with these colors on the on-screen map but that they were more similar on paper. Subject 8 called this scheme "unsure to green." The light pink clearly caused difficulty. The normal group did not have this problem. Only two normals mentioned difficulty with the seven class scheme and that was with the fourth and fifth colors (light gray and light green) looking similar but distinguishable. For the color-vision impaired, the scheme starts to break down with the seven class variation in the light pink to gray region. The normal group was fine into the nine, ten, and eleven class variations with difficulty commonly seen on the green side of the range.

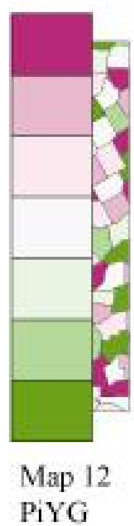

Figure 17: Pink-Green diverging scheme in seven class format.

The final two diverging schemes, the Spectral (Map 9) and Red-Yellow-Green (Map 27) (see Figure 18), are the first two schemes to show a serious difference between the color-vision impaired group and the normal group. For the color-vision impaired, there was serious difficulty with the three in the middle of the on-screen seven class map.

The third and fifth colors (light green and light orange) looked similar to all of the subjects, with many of them claiming they were very difficult and hard to distinguish. Subject 2 labeled Map 9 as, “kind of useless” because three and five “look like the exact same color.” Subject 18 described the third and fifth colors of Map 27 as looking “awful damn close.” Most of the subjects were like subject 37 who said three and five on Map 27 were “distinguishable, but barely.” It clearly took the color-vision impaired much longer to use this color scheme, with a few not even able to differentiate the colors in the middle and thus unable to answer the multiple-choice questions. Subject 5 points out a major flaw of this scheme with the color-vision impaired when he says he “might reference something above average as below average.” The fourth color, a light yellow, was also mentioned as being similar to the third and fifth. The differences in severity of color-vision impairment can be seen as well in that a few subjects said they had no difficulty and that all of the colors were clearly distinguishable.

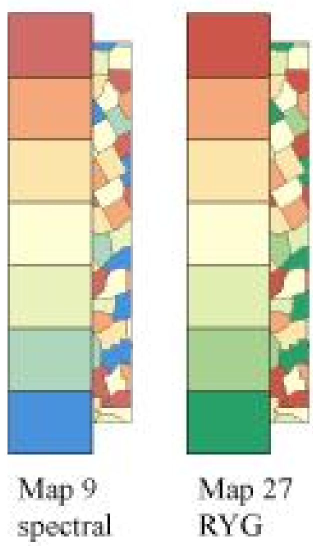

Figure 18: Spectral and Red-Yellow-Green diverging schemes in seven class formats.

Overall, for the color-vision impaired these two schemes, as subject 16 put it, "would cause serious problems." The scheme on paper only works up to the five class variation, then with six classes there starts to be serious difficulty with the third and fourth colors. These are then the third and fifth colors in the seven class variation. The normal color vision group had no difficulty at all with these schemes saying they were good or fine on screen with no problems at all. They were okay with the scheme up to the ten and eleven class variations where some of the lighter green colors started to appear similar, though several of them said that the schemes were good through eleven.

Qualitative Schemes

Two of the qualitative schemes found to be better at accommodating color-vision impaired subjects were Paired (Map 14) and Accents (Map 31). See Figure 19. A large percentage of the color-vision impaired subjects stated that the on-screen six class maps were good or okay with no problems resulting from colors appearing similar. One subject had some difficulty with the third and fifth colors of the Paired scheme on Map 14, but the rest of the subjects were fine. For Map 31 there were several subjects who had problems with the first and third colors (green and light orange) of the Accents, with one individual saying they looked "exactly the same" (subject 25). Most though did not have this problem or said they were close but distinguishable, and those that did declared one and three more distinguishable on paper. One subject even declared Map 31 "probably the easiest so far" (subject 20). The first and third colors were the only ones that caused some difficulty on paper. The rest of the colors in the full range of the

scheme were fine. For Map 14 several subjects could distinguish the light and dark pairs of hues all the way through the full range, but for half of them it started to break down with the seven class variation where they mentioned similarity between the third and seventh colors (light green and light orange). The light blue and light purple (first and ninth) were also mentioned by a couple subjects. With their use of many different hues, these schemes, as with all of the qualitative schemes, posed no problems for the normal color vision group with a large majority declaring the schemes as easy and accommodating up through the full range of the scheme.

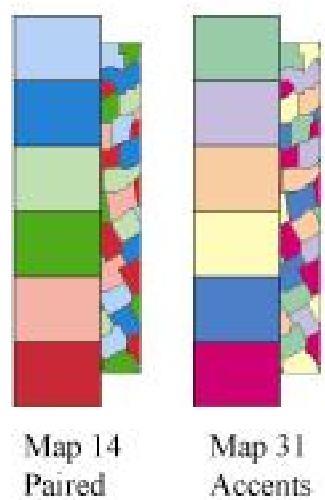

Figure 19: Paired and Accents qualitative schemes in six class formats.

The Dark 2 color scheme (Map 15) and the Set 1 color scheme (Map 32) (see Figure 20) are darker, more saturated schemes which led to an easier time distinguishing colors for the color-vision impaired, though there were still many subjects who mentioned some slight difficulty with specific pairs of colors in the schemes. For the Dark 2 scheme, many subjects discussed how two of the colors looked close but that they could distinguish them. Various combinations of the first, second, fourth, fifth, and sixth

colors were talked about as leading to double checking and extended time needed to read the map. Nearly all subjects had either no difficulty or only some slight hesitation with a certain pair of colors. As subject 5 stated, "green and orange are close" but he could distinguish them. The colors were described as better on paper with the second, fifth, and seventh (orange, green, brown) most commonly causing difficulty when trying to distinguish them. Several subjects were fine with all of the colors in the full range of the scheme. In Set 1, clearly the second and fourth colors (blue and purple) of the on-screen map took subjects a little longer, with over half of the subjects mentioning these two as looking similar. These two were easier on paper, though, with the majority of subjects being okay with the colors through the full range of the scheme. Again, the normal color vision subjects had no difficulty at all with any of these colors.

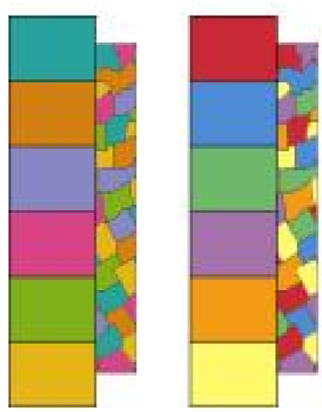

Figure 20: Dark 2 and Set 1 qualitative schemes in six class formats.

The next two qualitative schemes are of medium lightness: Set 3 (Map 17) and Set 2 (Map 33). See Figure 21. The color-vision impaired consistently described difficulty when attempting to distinguish pairs of colors in the blue-magenta-purple

range. These pairs are the third and fifth colors of Map 17 and the third and fourth colors of Map 33. Most subjects called these colors similar, or close, but distinguishable, and labeled them as better on paper. For several subjects, these were very hard to use. Subject 12, talking about the third and fifth of Map 17, said he “can’t tell which one’s which,” and that this was “frustrating.” Greens, yellows, oranges, and browns also caused difficulty. Thus, the more classes needed and the more hues necessary, the more difficulty the scheme will cause for the color-vision impaired. Subject 16 discussed Map 33 saying it was a “little harder because it was duller colors.” The darker color schemes were preferred over these and consistently called easier to use. The normal color vision group found both these schemes very easy to use with no difficulty except for the light gray and light green in the full range of Set 3. No general preference was given to darker or lighter colors by this group. A couple of them said that the lighter colors took a little longer to use. A few subjects thought the darker schemes were too strong and, as subject 29 described, “overwhelming.”

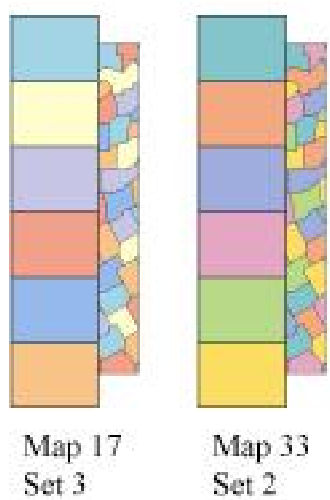

Figure 21: Set 3 and Set 2 qualitative schemes in six class formats.

The final two color schemes caused the most difficulty for the color-vision impaired of any of the schemes tested. These are the two pastel color schemes: Pastel 2 (Map 16) and Pastel 1 (Map 34). See Figure 22. This is clearly due to the difficulty of distinguishing lighter colors compared to darker colors. As subject 5 bluntly put it, “pastel colors are awful.” Nearly all subjects mentioned some difficulty with these color schemes.

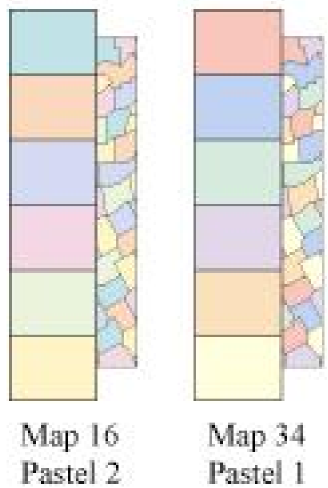

Figure 22: Pastel 2 and Pastel 1 qualitative schemes in six class formats.

Both schemes gave subjects great difficulty in distinguishing the light blue from the light purple (third and fourth colors on Map 16 and second and fourth colors on Map 34). To a slightly lesser degree, the light green, light orange, and light yellow also caused problems. Many subjects said the light blue and light purple looked like the same color or could only tell a very slight difference. When subject 20 was discussing these two colors in the Pastel 1 scheme on Map 34 he said, “they might even be the same color, I’m not sure.” The light green and light orange also caused serious difficulty for many subjects. With these two colors representing Spanish and German, subject 37 stated he

"can't tell on this map if there is any Spanish, or for that matter, any German." The problem that this difficulty in color differentiation produces is exemplified in subject 25 who errantly determined that on Map 34, Iowa was consistently German based on his "prior knowledge" that Iowa is predominately of German heritage even though the answer for most common language spoken at home (excluding English) was consistently Spanish. On Map 16, subject 12 felt the same about the Pastel 2 scheme saying about the light blue and light purple, "I'm guessing these two are different," while subject 2 "can't even tell a difference." For subject 5, the German and Irish (light blue and light purple) are "way too close." The light green, light yellow, and light brown (fifth, sixth, and seventh) also caused subjects confusion. Again, with a larger number of classes, many more confusions were described due to the use of many different hues.

It was obvious that the majority of subjects did not like these colors schemes and experiencing more confusion with these than other schemes. The blue and purple were the most difficult, but overall the lighter colors made it much harder to use for the color-vision impaired. Subject 6 described Map 16 as more difficult than the last one "because they are all light colors," which "make it difficult to read." Subjects 7 and 16 echoed this thought which was consistent among all subjects, when they said, respectively, "mild tones are harder to tell" and "brighter is way easier." While a few subjects had little or no difficulty in differentiation for these two schemes, generally the subjects agreed with subject 25 who labeled the pastel Map 34 as "terrible." These problems were only seen in the color-vision impaired, as the normal color vision group had an easy time with the pastel schemes and no difficulty in differentiating colors, though the much lighter colors did cause them to take slightly longer. See Table 6 for a qualitative summary table.

Table 6: Qualitative summary table listing general amounts of subjects in each group who encountered problems with the color scheme of each on-screen map.

Map	Data Type	Color Scheme	Scheme name	Impaired	Normal
1	S	Green	Greens	Many	Half
2	S	Red-Purple	RdPu	Few	Few
3	S	Purple	Purples	Half	Half
4	S	Blue-Green	BuGn	Few	Few
5	S	Purple-Blue	PuBu	All	Half
6	S	Yellow-Orange-Brown	YlOrBr	Few	Few
7	S	Orange-Red	OrRd	Few	Few
8	S	Yellow-Green-Blue	YlGnBu	Half	Few
9	D	Spectral	spectral	Many	Few
10	D	Red-Yellow-Blue	RYB	Few	Few
11	D	Orange-Purple	OrPu	Few	Few
12	D	Pink-Green	PiYG	Many	Few
13	D	Red-Gray	RdGy	Few	Few
14	Q	Paired	Paired	Few	None
15	Q	Dark 2	Dark 2	Many	Few
16	Q	Pastel 2	Pastel 2	Many	Few
17	Q	Set 3	Set 3	Many	None
18	S	Orange	Oranges	Half	Half
19	S	Purple-Red	PuRd	Half	Few
20	S	Red	Reds	Few	Few
21	S	Green-Blue	GnBu	Few	Few
22	S	Blue-Purple	BuPu	Half	Few
23	S	Yellow-Orange-Red	YlOrRd	Few	Few
24	S	Yellow-Green	YlGn	Many	Many
25	S	Purple-Blue-Green	PuBuGn	Many	Few
26	S	Blue	Blues	All	Many
27	D	Red-Yellow-Green	RYG	Many	None
28	D	Red-Blue	RdBu	Few	Few
29	D	Brown-BlueGreen	BrBG	Few	Few
30	D	Purple-Green	PRGn	Few	Few
31	Q	Accents	Accents	Half	None
32	Q	Set 1	Set 1	Many	None
33	Q	Set 2	Set 2	Many	None
34	Q	Pastel 1	Set 3	Many	Few

General Results

Many general themes ran through interview responses of both the color-vision impaired and the normal color vision groups. First, subjects consistently said that they preferred the map to the legend because the colors were easier to distinguish on the map. This was due to the format of the legend as showing the blocks of color with white space in between each. This space made it more difficult to differentiate colors that were similar in appearance by keeping them separate. On the map they were often right next to each other, only separated by a thin gray line, and could more easily be compared to each other. Subject 9 looking at Map 17 with a pastel scheme said he "had a hard time going map to legend" and that colors were "easier on the map where they are next to each other." Subject 2 similarly stated that it's "easier to judge one against another with no space in between." This was brought up more on schemes where there was a lot of similarity between colors.

When the subjects were comparing the sequential color schemes, those schemes that used a change in lightness through various hues were generally preferred and described as easier than those schemes that used simply a change in lightness of one hue (i.e., light green to dark green). Thus the schemes with different hues on either end and the schemes that progress through three different hues in their change from light to dark provided subjects with more difference between adjacent colors and subsequently an easier and quicker time reading the map. Subject 5 stated when describing why he likes the Yellow-Green-Blue scheme, "it incorporates greens and blues, not just shades of one specific color."

When looking at the schemes where colors were becoming close, as in the middle ranges of many of the sequential schemes, subjects described their method of determining the right color as looking for various shades that they could easily distinguish and working their way up or down from there. For example, they would look for the lightest color on the map, then look around it for the next lightest color, and work their way up to the specific color that they were interested in, such as the color for county X when answering the questions. So when they found the lightest color and found that county X was the third color in the lightness sequence by comparing county colors to each other, they would then find the third color in the legend and know that it was the correct answer. This definitely takes more time than looking at the map and seeing county X and its color, then looking to the legend and picking out that color. When colors were similar and the correct color could not clearly be distinguished on the legend, the subjects went through this process to make sure they had the right map-legend match. Many subjects of both the normal group and the color-vision impaired group described a similar process.

Finally, it was common for a slight difference to be seen in the color scheme on screen versus on paper. More often than not, the schemes on paper were either described as similar to or slightly easier than the on-screen scheme. The colors on screen were described as brighter and more vivid, while the on-paper versions were labeled duller and “washed out” yet slightly darker which led to an easier time distinguishing between adjacent colors. The five class schemes were much more commonly described as easier on paper than on screen. This could be due to the differences of perceiving emitted light versus reflected light, variations in computer monitors, and the difficulty of matching

print CMYK colors with on-screen RGB colors, though I verified that the maps used the RGB color values given for each scheme in ColorBrewer.

Discussion

By looking at the quantitative results, I can definitively say that there is a significant difference in the map reading ability of the color-vision impaired versus the normal color vision group when reading a map that uses the Pastel 2 color scheme. The chi-square test shows a statistically significant difference for this scheme in the number of incorrect multiple-choice responses from the two groups. The interview responses clearly support this finding by showing the difficulty that the color-vision impaired have when using schemes with lighter colors, especially the light blue and light purple.

For the other schemes no significant difference is seen in the accuracy of answers to multiple-choice questions. This tells us that in general, the color-vision impaired could distinguish the colors of the different ColorBrewer color schemes, match colors on the map to the legend, and correctly answer the map reading questions. This does not mean, though, that all these schemes are accommodating to the color-vision impaired. Qualitative data collected from subjects show that even though there is minimal difference in the number of multiple-choice questions missed there are still many schemes where the impaired describe difficulty in differentiation of colors and would not want to use a map with those problematic colors. It is clear that many of the schemes (besides the Pastel 2) caused impaired subjects to take longer when differentiating colors, needing to check back and forth from map to legend to make sure they had the correct

color and the correct answer. Though no time data was collected, for schemes where interview responses reveal difficulty, the impaired took anywhere from a few seconds to a few minutes longer than the normal color vision group to answer the multiple-choice questions. So while a very slight difference in perception and no time limit given often allowed subjects to come up with the correct answer, the qualitative data explain just how much difficulty this group had in performing these map reading tasks.

Another possible explanation for the minimal differences is subjects guessing the correct answers even though they may have had difficulty with matching colors to the legend. The subjects may have felt uneasy about selecting the answer option "cannot determine with the given colors." Also, the questions may not have been worded as clearly as possible or multiple-choice answers as definitive as they should have been, but this would apply to both the color-vision impaired group and the normal color vision group, therefore controlling the effect of this problem on response accuracy.

Looking at answers to multiple-choice map reading questions can be part of understanding a scheme's ability to accommodate, thus I chose to include it as part of this experiment. Yet, these data were only gathered as part of an effort to understand the overall map reading abilities of the color-vision impaired versus subjects with normal color vision. These quantitative results clearly tell us that the subjects, for the most part, could come up with the correct answer, but they do not take into account how the user arrived at the correct answer and any difficulties that came up in the process.

As cartographers our goal is communication, and it is evident through the interview responses that several of these schemes do not adequately communicate spatial data to the color-vision impaired. When pairs of colors are used that are too similar, not

only for the impaired but for everyone, we limit our communication capability by increasing the effort needed to understand the information being presented and by introducing the possibility of miscommunication if the reader incorrectly matches data on the map to the legend. Thus, I feel that the subjects' responses on their perception and use of the color scheme outweigh the quantitative data collected in this research study. These interview results should be given primary focus in an evaluation of whether the color scheme can be defined as accommodating for the color-vision impaired.

The sequential color schemes do not show a major difference between the color-vision impaired and the normal color vision group. The characteristics that are problems for these schemes are seen for both groups. All subjects could distinguish the colors of the on-screen five class map for all sequential schemes, though some contained pairs of colors in the middle of the range that were described as close, causing subjects to take longer reading the map and double-check to verify colors. The only difference found between the two groups was that, on average, the color-vision impaired started to describe difficulty with colors being similar at a slightly lower number of classes than did the normal group. With the sequential schemes being simply a change in lightness from light to dark, these schemes were not expected to show a difference between the two groups. Color-vision impairment primarily affects an individual's ability to differentiate hues while being able to distinguish shades of light and dark of whatever hues are being perceived. So the changes in lightness of these schemes allow the color-vision impaired to have the same ability to differentiate colors in the scheme even though they may not be seeing the same hue as someone with normal color vision.

The sequential schemes that worked well were the schemes that used two or three different hues in their change in lightness, such as the Yellow-Orange-Brown. This scheme starts with a light yellow then works it way to a medium orange and into a darker brown. Schemes such as this produce adjacent colors with more of a difference in perception than schemes that use only one hue for the entire range of the light to dark scheme. The subjects clearly favored this due to the easier time differentiating between colors, and thus less time needed to read the map. These schemes worked well for subjects when using a higher number of classes, commonly up to the seven or eight class variation. The schemes using only one hue commonly started causing difficulty in the five or six class variation. The lighter end of the scheme was more often described as becoming close than the darker end of the scheme.

The diverging schemes are similar to the sequential schemes in that they use a change in lightness, but they use a dark to light to dark change. These schemes are used when trying to show change from a central value. This value is placed in the middle with the lightest color and as values move away from the center, the colors become darker. These schemes, like the sequential, use the cartographic fundamental that dark is more. Thus, the two ends of the diverging schemes being darker represent more change from the central value, either above or below.

For these, the majority of schemes were like the sequential showing little if any difference between the color-vision impaired and the normal group. This is due to the change in lightness above and below the middle and clearly differentiable hues on either end. Again, the color-vision impaired started to describe difficulty with colors becoming close at a slightly lower number of classes than the normal group, but this was not

enough to declare a difference between the groups. The characteristics seen for the majority of the diverging schemes were seen for both groups.

Two diverging color schemes did show a major difference between the two groups. These are the schemes that used a change in hue from red to yellow to green: Spectral (Map 9) and Red-Yellow-Green (Map 27). These caused serious difficulty for the color-vision impaired in the middle of the range between the lightest color and the ones on either side. For both these schemes, a light orange and a light green are on either side of light yellow middle. This light orange and light green pair could not be differentiated, or could barely be differentiated. They also caused some difficulty when comparing these two to the light yellow. The medium oranges and medium greens were also similar but not to the extent of the lighter colors. These two schemes started to break down with the six class scheme where the third and fourth colors looked the same. The normal group had no difficulty with either of these schemes in differentiating the oranges, yellow, and greens, and generally preferred the many hues of the spectral scheme.

The qualitative schemes all showed a difference between the color-vision impaired and the normal group, though to varying degrees. Their use of many different hues led to greater difficulty for the color-vision impaired. These clearly caused more problems with colors looking similar than with the sequential and diverging schemes.

Overall, the lighter the color scheme, the more difficulty the color-vision impaired had differentiating colors. Thus, the two Pastel schemes, Pastel 1 (Map 34) and Pastel 2 (Map 16), caused a great amount of difficulty. The light blue and light purple colors of these schemes led to serious confusion as many subjects could not distinguish them. The same was seen for the light green and light orange. In general, the color-vision impaired

described their displeasure for lighter, pastel colors, and said that they would not want to use a map that used these colors.

For the same reason, the darker qualitative colors schemes worked much better for this group. The blue and purple, and green and orange, still caused some slight confusion though the majority of subjects had an easy time with them or only described them as somewhat close. The darker colors were much easier for the color-vision impaired to distinguish from each other and a clear preference was given to these over the pastels. The Paired (Map 14) and Accents (Map 31) schemes also worked well because of their use of both light and dark colors and staying away from blues and purples of similar shades and greens and oranges of similar shades. The Accents scheme (one planned for accommodating the color-vision impaired and used in an atlas for the U.S. Census Bureau (Brewer and Suchan, 2001)) saw some similarity with the green and light orange, but they were different enough in lightness for many subjects to differentiate easily. When more classes are added to the Paired scheme, these color combinations eventually show up, and thus cause more difficulty. Yet for the on-screen six class map these two schemes worked well. The normal color vision group showed no difficulty at all with any of the qualitative schemes. They sped right through them, easily differentiating all of the various hues.

Recommendations for ColorBrewer

With the similarities in responses from both groups concerning the sequential color schemes, and the inherent change in lightness that can be perceived by the color-

vision impaired, I recommend that all of the sequential schemes be identified as accommodating to the color-vision impaired. Currently, and possibly erroneously, the nine class Purple-Blue scheme is identified with an **X** over the ColorBrewer eye icon as not accommodating. I suggest this be removed.

All of the diverging color schemes except two—the Spectral (Map 9) and Red-Yellow-Green (Map 27)—also show similarity in responses between the two groups. For the other two schemes, which both use a red-orange-yellow-green progression, the difference between the color-vision impaired and the normal group is clear. The difficulty of distinguishing the light orange from the light green was regularly described as beginning with the six class variation with the third and fourth colors. Thus I recommend that for these two schemes, the six class variation and above be identified as definitely confusing for the color-vision impaired and have an **X** placed over the eye icon in ColorBrewer. A small number of individuals, who exhibited more severe impairment, described some difficulty with the reds and greens in the three through five class variations. Being unsure if any subjects were protan- impaired, and the fact that reds and greens of similar lightness fall on the same confusion lines for both types of impairment, I suggest these first three class variations be labeled as possibly confusing and have a **?** placed over the eye icon. See Figure 23 for a diagram of these schemes in their full range of class variations with the suggested symbols for ColorBrewer. This is a change from the current ColorBrewer configurations of accommodating for the first three variations of both of these schemes.

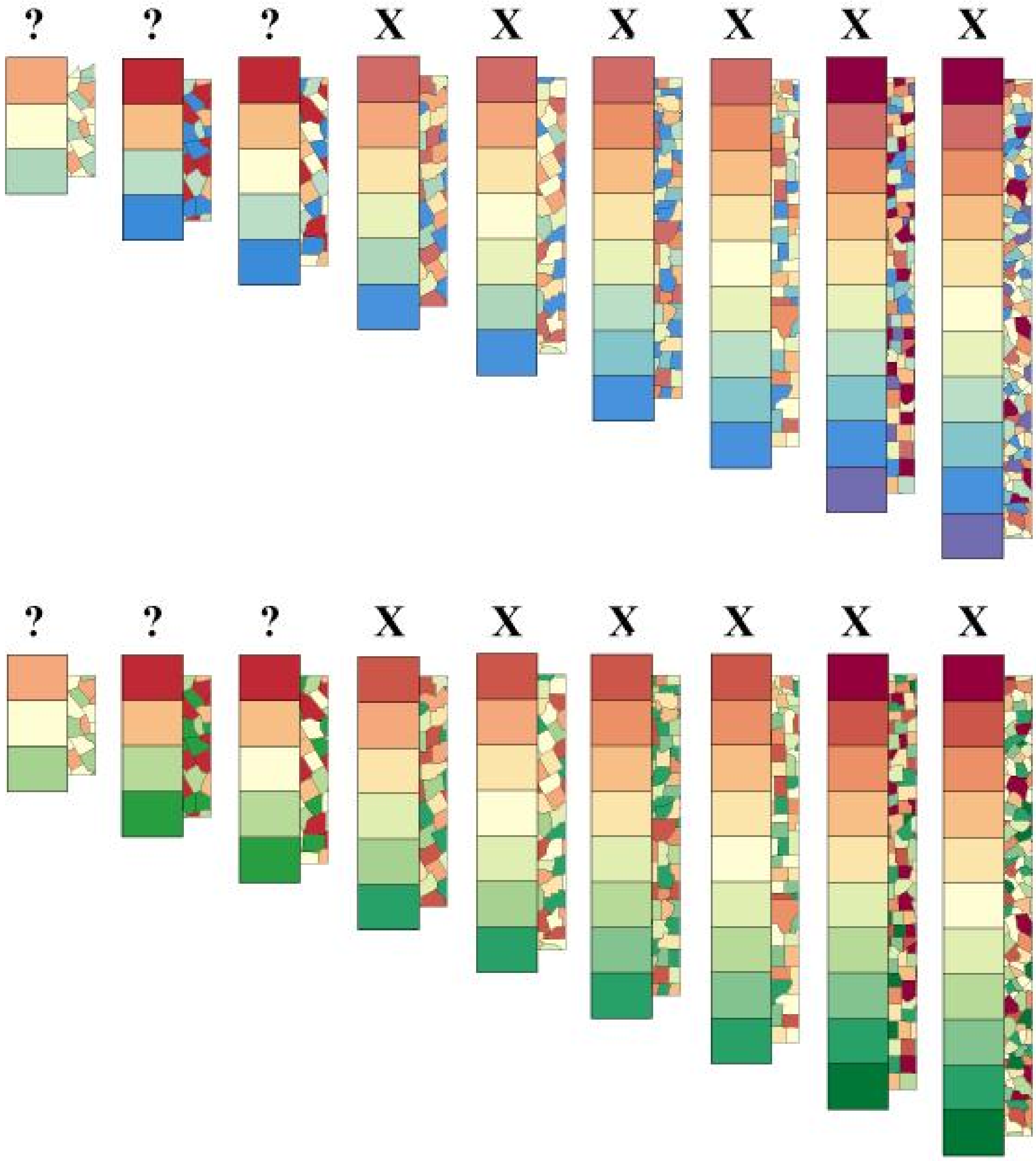

Figure 23: Spectral (top) and Red-Yellow-Green diverging schemes showing the full range of class variations with suggested symbolization in ColorBrewer.

An interesting finding concerning the Red-Gray (Map 13) diverging scheme was one severely impaired subject who mentioned great difficulty distinguishing the extremes of this scheme. This individual, based on the color-vision test, was determined to be

deuteran- impaired. This is remarkable due to the fact that confusion of reds with grays and blacks is commonly seen in protan- impairment. Taking both of these into consideration, along with the fact that I am unsure if any of my subjects were protan- impaired, I suggest that all variations of the of the Red-Gray scheme be defined as possibly confusing to the color-vision impaired and given a **?** over the eye icon. See Figure 24. Currently ColorBrewer has these schemes as accommodating.

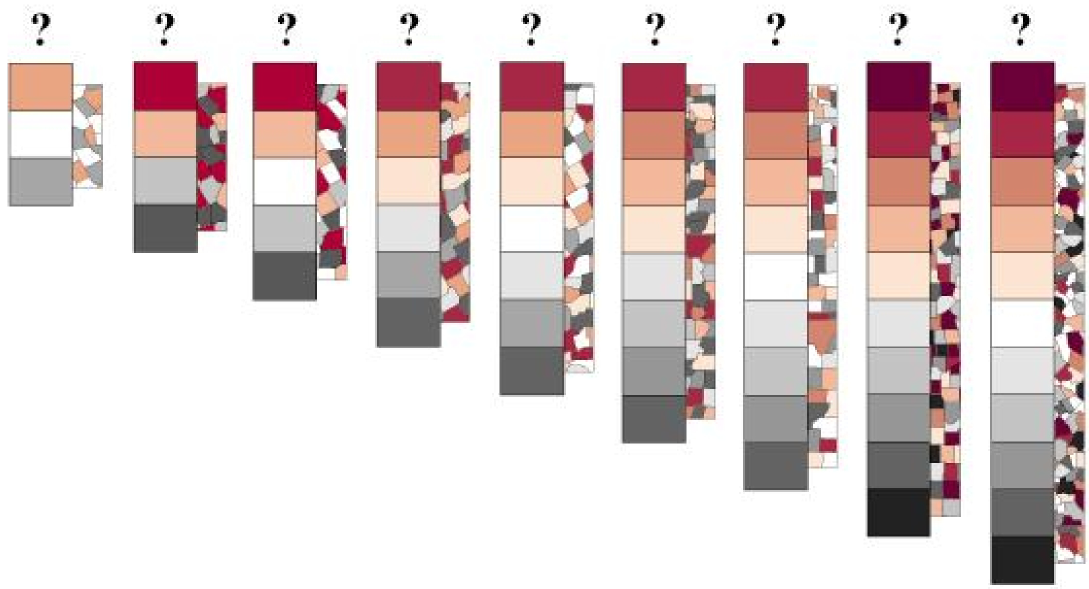

Figure 24: Red-Gray diverging scheme showing the full range of class variations with suggested symbolization in ColorBrewer.

For the qualitative schemes, there is more discrepancy over which will work and which will not due to the differences in responses of color-vision impaired subjects. There is a clear difference, though, between this group and the normal color vision group since all subjects with normal color vision had an easy time using all of the qualitative schemes. For the Paired scheme (Map 14) slight difficulty was commonly seen starting with the seven class variation where a light orange is added to the scheme which already

has a light green, yet this was still distinguishable. Several subjects also had difficulty with the reds when added in the fifth and sixth class. At nine classes when a light purple is added, nearly all subjects mention some difficulty, either with the light purple/light blue, oranges/greens, or reds/greens. Thus, for the Paired scheme, I suggest identifying the nine class variation and above as definitely confusing, and receiving an **X**. For the five through eight class variations, I suggest these be labeled as possibly confusing for the color-vision impaired and receive a **?** over the eye icon. The three and four class variations are accommodating. See Figure 25. For this scheme, I also recommend using the darker color of the hue pair as the first in the series due to the greater difficulty in differentiating lighter colors among the color-vision impaired. The purple hues could also be moved above the orange hues, since the blue/purple was slightly better than the green/orange. This is a change for the current ColorBrewer settings which are no symbol for the five and six class variations and an **X** for the seven and eight class variations.

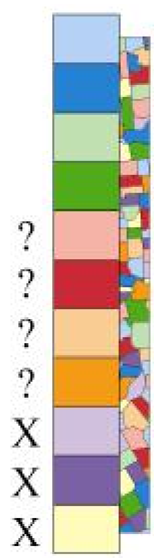

Figure 25: Paired scheme showing all eleven classes and suggested symbolization in ColorBrewer as each color is added.

For the Accents scheme (Map 31), the color-vision impaired subjects mention slight difficulty with the first and third colors (green and light orange). One individual said these colors looked exactly the same. All of the other colors were distinguishable. Since all of the variations use those two colors, I suggest that all of them be identified as possibly confusing and receive a question mark. See Figure 26. The scheme would be improved if either the green (first) or orange (third) hue was changed to a different lightness, or if one of them was moved to the last spot in the range. Right now ColorBrewer has all of the variations labeled with an **X**.

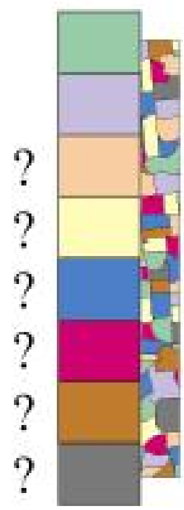

Figure 26: Accents scheme showing all eight classes and suggested symbolization in ColorBrewer as each color is added.

For the Dark 2 scheme (Map 15), a majority of color-vision impaired subjects describe difficulty on paper with the seven class variation. This seventh color (brown) causes some confusion with both the second color (orange) and fifth color (green), especially among those with more severe impairment. Some called these colors close while only a few described them as looking the same. The sixth color (yellow) caused

some difficulty for several subjects, but not as much when adding the seventh color. Thus for the seven and eight class variations, I recommend these be identified as definitely confusing for the color-vision impaired and given an **X** over the ColorBrewer eye icon. One of the more severely impaired subjects had difficulty distinguishing the first from the fourth color and also the second from the fifth color, while some others saw slight closeness. Thus, for the four through six class variations, I recommend these be identified as possibly confusing and receive a **?** over the eye icon. See Figure 27. Currently ColorBrewer labels all of these variations as accommodating. To improve this scheme, I suggest moving the gray (eighth) color up, and having the magenta (fourth) and two of the green-yellow-brown (fifth-sixth-seventh) series moved to the bottom.

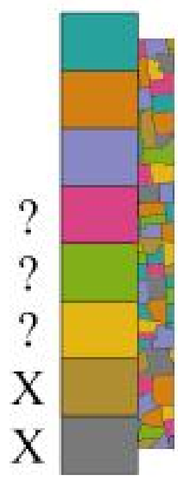

Figure 27: Dark 2 scheme showing all eight classes and suggested symbolization in ColorBrewer as each color is added.

For Set 2 (Map 33), the blue and magenta (third and fourth colors) caused slight confusion for some subjects and were more difficult for others. These were a little better on paper for a few subjects but still caused some difficulty due to their closeness. Several subjects were fine with these colors. While the third and fourth colors caused more

confusion than the same colors in the Dark 2 series, they were still generally distinguishable. The remaining colors produced results similar to the Dark 2 set. For this scheme I have the same recommendations as the Dark 2 set: possibly confusing for the four through six class variations, and definitely confusing for the seven and eight class variations. See Figure 28. The four, five, and six class variations in ColorBrewer are currently identified as not accommodating. For improving this scheme, I suggest the same as for the Dark 2 scheme, and place the magenta (fourth) at the end of the series.

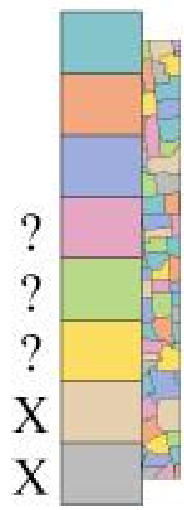

Figure 28: Set 2 scheme showing all eight classes and suggested symbolization in ColorBrewer as each color is added.

In Set 1 (Map 32), the second and fourth colors (blue and purple) are described by many subjects as similar but distinguishable. These two colors, which are more differentiable on paper, are the only pair regularly mentioned for this scheme. It generally took longer for subjects to distinguish the blue and purple, with a couple subjects having more difficulty with them. The first and third (red and green), along with the third and fifth (green and orange) are mentioned only a few times as appearing close,

yet these are likely to cause more difficulty for individuals with more severe impairment. Thus, I recommend that all of the class variations be labeled as possibly confusing and given a **?** over the eye icon. See Figure 29. This is contrary to the current settings which are that all variations accommodate. I suggest moving the green, purple, and orange (third, fourth, and fifth) colors to the end to allow for more accommodating variations.

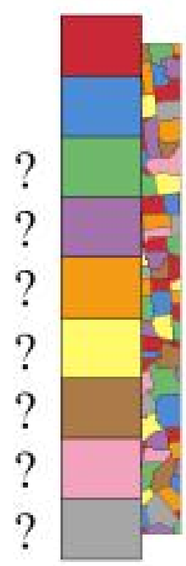

Figure 29: Set 1 scheme showing all nine classes and suggested symbolization in ColorBrewer as each color is added.

Similarly for Set 3 (Map 17) the blue and purple colors (third and fifth colors) caused some degree of difficulty for nearly all of the color-vision impaired with many of them having great difficulty. These were slightly better on paper, though still close. A small number of the more severely impaired subjects also had difficulty distinguishing the first and third colors, especially on paper. Taking this into consideration, I recommend that the three and four class variations of the scheme be identified as possibly confusing for the color-vision impaired, and the five class variation and above be

identified as definitely confusing for the color-vision impaired. See Figure 30. This is very similar to what is now in ColorBrewer, except that the three and four class variations are currently labeled as accommodating. I recommend that the third color (purple) be moved to the bottom of the series due to its confusion with other colors. The first or fifth, sixth or seventh, and ninth or eleventh could also be moved to the bottom due to confusions of these pairs of colors.

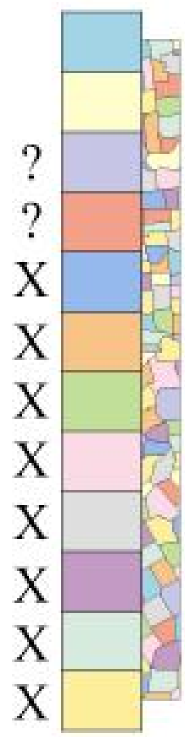

Figure 30: Set 3 scheme showing all twelve classes and suggested symbolization in ColorBrewer as each color is added.

Looking at Pastel 1 (Map 34), again the light blue and light purple (second and fourth colors), along with the light green and light orange (third and fifth), cause serious difficulty for the color-vision impaired. These lighter colors are much more problematic than the moderate and darker colors. A majority of the subjects talked about the second

and fourth colors (light blue and light purple) looking the same or very similar leading to confusion and extended time needed to read the map. Some could not distinguish these pairs of colors at all, or were unsure if they were able to distinguish them. The same characteristics were seen with the third and fifth colors (green and orange). With these two pairs causing such great difficulty, I recommend that the four class variation and above be identified as definitely confusing for the color-vision impaired. The three class variation, using light red and light green, produced some minimal confusion, but may cause problems for an individual with more severe impairment. Thus, I identify this variation as possibly confusing. See Figure 31. Again, this is very similar to what is currently listed in ColorBrewer except that the three class variation is listed as accommodating. To improve this scheme, I strongly recommend moving the green (third) and purple (fourth) to the end of the series. Switching the gray (eighth) and brown (sixth) would also help.

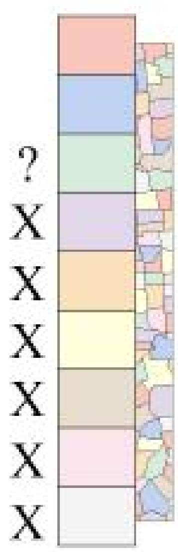

Figure 31: Pastel 1 scheme showing all nine classes and suggested symbolization in ColorBrewer as each color is added.

Pastel 2 (Map 16) is extremely similar to Pastel 1. With the six class on-screen map producing a significant difference between the color-vision impaired and normal color vision groups in the number of correct responses to multiple-choice map reading questions, the six class variation clearly does not accommodate. This is due to the great amount of difficulty the color-vision impaired had in differentiating both the third and fourth colors (light purplish-blue and light magenta) and the fifth and sixth colors (light green and light yellow). The third and fourth colors were very hard to differentiate, with many subjects describing them as too close or not differentiable. Differentiation of the fifth and sixth colors was not as severe but very hard for a few subjects. Again, the lighter pastel colors make this scheme more difficult for the color-vision impaired. Thus, I suggest identifying the four class variation and above as definitely confusing for the color-vision impaired. To be safe, I recommend labeling the three class variation as possibly confusing since one of the more severely impaired subjects described confusion between the first and third colors (aqua and light purplish-blue). See Figure 32.

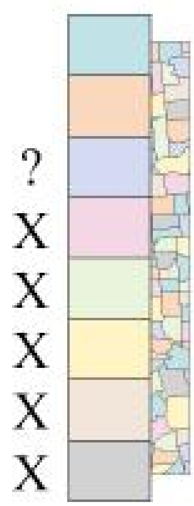

Figure 32: Pastel 2 scheme showing all eight classes and suggested symbolization in ColorBrewer as each color is added.

These recommendations for the Pastel 2 scheme are the same as what is currently listed in ColorBrewer except for the three-class variation which is currently labeled as accommodating. To improve this scheme, I recommend moving one of the colors in the third/fourth pair (light purplish blue and light magenta) to the end. The first and fifth colors (light aqua and light green) could also be moved to the end since these were occasionally confused with other colors. See Table 7 for an overview of each scheme and its accommodation recommendations.

I have tried to separate those schemes and variations where there were differences between colors being described as slightly close from those where there was serious difficulty among a majority of the subjects. I have recommended the current ColorBrewer use of the **?** and the **X** as the difference between these two types, though the question mark could give the impression that the scheme has not been tested and we are unsure of results. The question mark in this context means that the scheme may accommodate some color-vision impaired individuals but not others. Many of these recommendations are the same as what is currently displayed over the eye icon in the ColorBrewer tool, yet some of them are different. These differences are primarily due to the suggestion of using the **?** symbol for certain class variations since that symbol is not currently used for the accommodation icon. Now, though, there are recommendations for ColorBrewer which are based on experimentally tested results, looking at the thoughts and abilities of a group of color-vision impaired individuals.

Table 7: Recommendations for ColorBrewer accommodation icon.

Map	Data	Color Scheme	Name	Number of Classes									
				3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	S	Green	Greens										
2	S	Red-Purple	RdPu										
3	S	Purple	Purples										
4	S	Blue-Green	BuGn										
5	S	Purple-Blue	PuBu										
6	S	Yel-Orange-Brown	YlOrBr										
7	S	Orange-Red	OrRd										
8	S	Yellow-Green-Blue	YlGnBu										
9	D	Spectral	spectral	**?**	**?**	**?**	**X**	**X**	**X**	**X**	**X**	**X**	
10	D	Red-Yellow-Blue	RYB										
11	D	Orange-Purple	OrPu										
12	D	Pink-Green	PiYG										
13	D	Red-Gray	RdGy	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**	
14	Q	Paired	Paired			**?**	**?**	**?**	**?**	**X**	**X**	**X**	
15	Q	Dark 2	Dark 2		**?**	**?**	**?**	**X**	**X**				
16	Q	Pastel 2	Pastel 2	**?**	**X**	**X**	**X**	**X**	**X**				
17	Q	Set 3	Set 3	**?**	**?**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
18	S	Orange	Oranges										
19	S	Purple-Red	PuRd										
20	S	Red	Reds										
21	S	Green-Blue	GnBu										
22	S	Blue-Purple	BuPu										
23	S	Yel-Orange-Red	YlOrRd										
24	S	Yellow-Green	YlGn										
25	S	Purple-Blue-Green	PuBuGn										
26	S	Blue	Blues										
27	D	Red-Yellow-Green	RYG	**?**	**?**	**?**	**X**	**X**	**X**	**X**	**X**	**X**	
28	D	Red-Blue	RdBu										
29	D	Brown-BlueGreen	BrBG										
30	D	Purple-Green	PRGn										
31	Q	Accents	Accents	**?**	**?**	**?**	**?**	**?**	**?**				
32	Q	Set 1	Set 1	**?**	**?**	**?**	**?**	**?**	**?**	**?**			
33	Q	Set 2	Set 2		**?**	**?**	**?**	**X**	**X**				
34	Q	Pastel 1	Pastel 1	**?**	**X**	**X**	**X**	**X**	**X**	**X**			

Chapter 5

Conclusion

This study examined the differences in map reading ability and color perception between individuals with impaired color vision and individuals with normal color vision when reading thematic maps using the ColorBrewer color schemes. Results show that the majority of the ColorBrewer color schemes use colors that accommodate map reading by the color-vision impaired. Some of the color-vision-impaired subjects had little difficulty with a scheme while others had a much harder time distinguishing those same colors. The nature of color-vision impairment, as a condition with varying levels of deficiency based on lack of or weakness in types of cones in the retina, makes it difficult to predict accommodation for all of the impaired, yet consistencies in subjects' responses allow recommendations to be made for this group overall.

Generally, the quantitative portion of the experiment did not produce significantly different results in the ability of the two groups to answer multiple-choice map reading questions. Only Map 16 with the Pastel 2 color scheme exhibited a significant difference (beyond the 0.005 level). For this scheme, the group of ten color-vision impaired subjects missed nine of 30 multiple-choice questions, while the group of ten normal color vision subjects answered all questions correctly. The remaining 33 schemes all produced five or fewer incorrect answers by the color-vision impaired group and this level of accuracy was much closer to that of the normal color vision group. This leads to the conclusion that most color-vision impaired individuals can differentiate between the

colors enough to answer the multiple-choice questions that were asked. Yet this does not take into account the amount of difficulty a subject had when attempting to differentiate colors on the map in order to answer the questions.

The semi-structured interviewing session after each set of multiple-choice questions provided some intriguing responses regarding subjects' experiences using each of the ColorBrewer color schemes. Based on interview responses, qualitative color schemes and the diverging schemes that used a red-green range clearly caused problems. I have concluded that for five schemes, three qualitative and two diverging, the majority of the variations would definitely not accommodate map reading among the color-vision impaired: Pastel 1 (Map 34), Pastel 2 (Map 16), Set 3 (Map 17), Spectral (Map 9), and Red-Yellow-Green (Map 27). These schemes all caused serious difficulty when subjects were attempting to differentiate colors of the scheme. All subjects mentioned some difficulty, while many of them could barely differentiate certain pairs of colors or could not differentiate them at all. This led to increased time needed when using the map, and great uncertainty when answering the questions. The two diverging schemes both use a red to orange to yellow to green color ramp. This caused great difficulty in differentiating the light green and light orange on either side of the center.

The remaining five qualitative schemes also have colors similar in perception for this group, causing problems and leading to more time being needed when reading the maps. There was a difference, though, between these and the first three qualitative schemes in that the numbers of subjects mentioning difficulty were fewer and the degree of difficulty mentioned for differentiating colors was lower. In general, these schemes have colors that were described as close but distinguishable. The Paired (Map 14), Dark

2 (Map 15), and Set 2 (Map 33) schemes, were determined to be possibly confusing to the color-vision impaired in most class variations, except for the higher numbers of classes which become definitely confusing. The final two qualitative schemes, Accents (Map 31) and Set 1 (Map 32), were determined to be possibly confusing in all class variations. In addition, all variations of the Red-Gray diverging scheme were determined to be possibly confusing. I have suggested using the same convention currently in ColorBrewer by placing an **X** over the eye icon for class variations that are definitely confusing and question mark over the eye icon for those variations that are possibly confusing.

For all of the sequential schemes and the diverging schemes not using a red-to-green ramp, there was no difference between the color-vision impaired and the normal color vision groups. Schemes using a blue or purple generally seemed to cause slightly more difficulty in differentiation. The sequential schemes that use more than one hue in their transition from light to dark are generally preferred over those that simply use light to dark of one hue because of the greater contrast between adjacent colors. These allowed for differentiation of colors through a higher number of classes than the single hue schemes which regularly caused difficulty in the six class variation.

Responses from subjects in both groups included describing how, for close pairs of colors, they had to go back and forth from map to legend several times to make sure they were correct. They used a process of working their way from shade to shade starting at the lightest or darkest and comparing colors until they were sure of which color in the range they were looking at. Also, they had a much easier time differentiating colors on the map as opposed to the legend. The legends were created using the ArcGIS 9 ArcMap

default of having space in between the colors of the legend. This white space gave subjects more difficulty with similar colors in the legend than on the map where the counties were right next to each other only separated by a thin line. They would have preferred a legend with colors right next to each other, making colors easier to differentiate. In general, this white space making a difference means that the colors are likely too similar in the first place.

Another common theme was the greater difficulty color-vision impaired subjects had when using maps with lighter, pastel color schemes. This group definitely preferred darker, brighter colors. For pairs of hues that were confusing, seeing them in a lighter shade amplified the amount of difficulty. Thus, the two Pastel color schemes are ones that clearly do not accommodate. In general, the lighter shades of all of the schemes were more difficult for subjects from both groups. When subjects were evaluating the different variations of the scheme on paper, the lighter end was regularly described as the point where subjects started to have difficulty with colors becoming similar. Also, as can be expected, as more classes are added there is greater difficulty in differentiation for both the color-vision impaired and normal color vision individuals. This is caused by the decreased difference between adjacent colors when using a greater number of classes to move through the same range of color.

The length of time needed to read the map by differentiating colors is an important part of how well a color scheme accommodates an individual. Yet, this experimental research did not time subjects when answering the multiple-choice questions. For those schemes in which pairs of colors looked similar or the same, increased time was needed to compare the map to the legend, going back and forth and

double-checking to make sure an answer was correct. This extra time needed by subjects was not recorded and would have been a useful indicator in determining a scheme's accommodation ability in comparison to other schemes. Though in this mixed method experiment, it may have been difficult to collect accurate response times due to the conversational nature of the testing. Thus, in the future, the ColorBrewer color schemes could be tested for length of time needed for subjects of all capabilities to read the map by timing them when answering multiple-choice questions.

Also, the color-vision test did not provide an adequate determination of the type of color-vision impairment (deuteranope, deuteranomalous, protanope, or protanomalous). The last two Ishihara plates use two numbers each, one confusing to protan- and one confusing to deuteran- types of impairment. This test, though, does not determine whether an individual is a dichromat or an anomalous trichromat. Answers for many of the subjects showed them to be deuteran-, which was expected since deuteranomaly is the most common form of impairment, but the remaining subjects all showed inconclusive results. I was unsure if I had any protanopic or protanomalous subjects in my sample. It is possible that all of the color-vision impaired subjects in the sample were deuteran- impaired. Had the type of impairment for each subject been clearly known, comparisons of responses for the different types would have produced a more thorough understanding of what colors are confused by what type of impairment. This knowledge would have made it easier to make recommendations for ColorBrewer if the one subject who had difficulty with one of the schemes had a different type of color-vision impairment. With more time and funding I would have recruited a larger sample of subjects and found a more rigorous test for color-vision impairment.

Clearly, through this research, seven, eight, and nine classes of the sequential schemes using one hue were found to cause serious difficulty for subjects when attempting to distinguish adjacent colors. Further study could be done, focusing on where different types of color schemes commonly start to cause difficulty for the majority of the population when used for an increasing number of classes. The differences between schemes could be studied in more depth to determine which are better than others for communicating larger numbers of classes

The findings of this research now give ColorBrewer an experimentally tested basis for the information provided on whether a specific color scheme accommodates red-green color-vision impairments. The recommendations given can be integrated into the “colorblind friendly” usability icon of the online ColorBrewer tool, giving users confidence about the accommodation ability of their chosen scheme. This research also adds to the limited amount of literature on the topic of use of color for accessibility in cartography, thus improving communication by disseminating knowledge of which color schemes work for the greatest number of people. Nearly eight percent of men have some degree of color-vision impairment. Too often this group may be disregarded as insignificant, but if a map or graphic is to be distributed to a large number of people, the number of color-vision impaired who may have a difficult time reading it can become significant. With the Federal government now requiring that public information be accessible to all people, an understanding of color-vision impairment is imperative. In addition, a more thorough understanding of thematic map reading processes and appropriate color scheme use for the portion of the population with normal color vision has been collected.

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Appendix A

Informed Consent Form

ORP USE ONLY:
The Pennsylvania State University
Office for Research Protections

Approval Date: 12/10/04 M. Becker

Expiration Date: 11/29/05 M. Becker

Social Science Institutional Review Board

INFORMED CONSENT FORM FOR SOCIAL SCIENCE RESEARCH

The Pennsylvania State University

Title of Project: Map-Use Testing of the ColorBrewer Color Schemes for Accommodation of the Color-Vision Impaired

Principal Investigator: Steven D. Gardner, Graduate Student
302 Walker Building
University Park, PA 16802
(814) 441-1647; sdg150@psu.edu

Advisor: Dr. Cynthia Brewer
302 Walker Building
University Park, PA 16802
(814) 865-5072; cbrewer@psu.edu

1. **Purpose of the Study:** The purpose of this research study is to learn more about color use on thematic maps and which color schemes communicate effectively by accommodating map reading ability in that portion of the population which is color-vision impaired. This study will evaluate the color scheme options offered in ColorBrewer <http://www.colorbrewer.org>, an online tool designed to aid color selection for maps and graphics.

2. **Procedures to be followed:** You will be seated in front of a computer with an LCD computer screen. You will be asked to initially take a color-vision test, then examine and

answer questions on a series of PowerPoint slides showing thematic maps, each using a different color scheme. A first thematic map will be shown using one of the ColorBrewer color schemes. You will then be asked to answer three multiple-choice questions about areas and patterns on the map. This will be followed by interview questions in which you will be asked about your ability to read the map and perceive the given color scheme. This procedure will then be repeated for sixteen other ColorBrewer color schemes. In the event that abnormal color-vision test results are obtained based on your previously stated condition, you will be made aware of the results immediately after the experiment and recommended to contact your private medical care provider for follow up.

3. **Audio Recording:** Your responses to interview questions will be recorded on audio tape. Tapes will be stored in the Principal Investigator's office (337 Walker Building) through December 2005, after which time the tapes will be destroyed. Only the Principal Investigator and Advisor will have access to the tapes. If you do not wish to have your responses taped, please inform the person conducting the experiment and check the appropriate space below.

   ______ I give my permission to be *(audio)* taped.

   ______ I do not give my permission to be *(audio)* taped.

4. **Discomforts and Risks:** There are no risks in participating in this research beyond those experienced in everyday life.

5. **Benefits:** You may benefit by learning about spatial data patterns of various U.S. regions through reading the maps. Society will benefit from the knowledge of appropriate color schemes for accommodating the color-vision impaired leading to improved cartographic design and effective map communication.

6. **Duration:** It will take about one hour to complete the experiment.

7. **Statement of Confidentiality:** Only the person in charge, and his/her assistants, will know your identity. Your name or signature will not be associated with your multiple-choice answers or verbal interview responses. The data will be stored and secured in 337 Walker Building, a locked graduate student office, or on the Geography Department server in a password protected user account assigned to the PI. The Office for Research Protections and the Social Science Institutional Review Board may review records related to this project. In the event of a publication or presentation resulting from the research, no personally identifiable information will be shared.

8. **Right to Ask Questions:** You can ask questions about this research. Contact Steven Gardner at (814) 441-1647 with questions. If you have questions about your rights as a research participant, contact The Pennsylvania State University's Office for Research Protections at (814) 865-1775.

9. **Compensation:** Participants will receive 10 dollars in cash as compensation for participating in the experiment.

10. **Voluntary Participation:** Your decision to be in this research is voluntary. You can stop at any time. You do not have to answer any questions you do not want to answer.

You must be 18 years of age or older to take part in this research study. If you agree to take part in this research study and the information outlined above, please sign your name and indicate the date below.

You will be given a copy of this signed and dated consent for your records.

______________________________ ______________

Participant Signature Date

______________________________ ______________

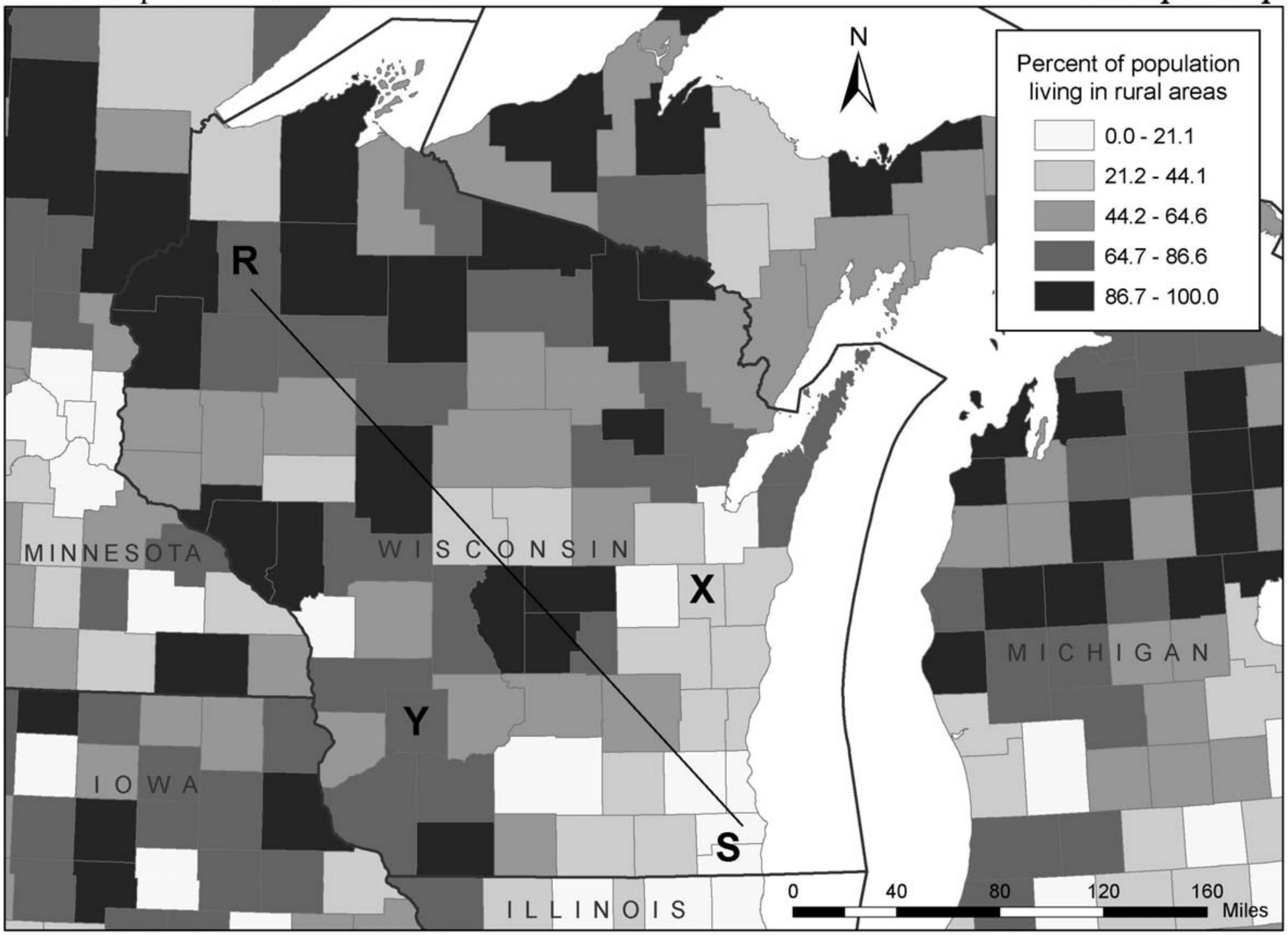
Person Obtaining Consent Date

Appendix B

Experimental Maps

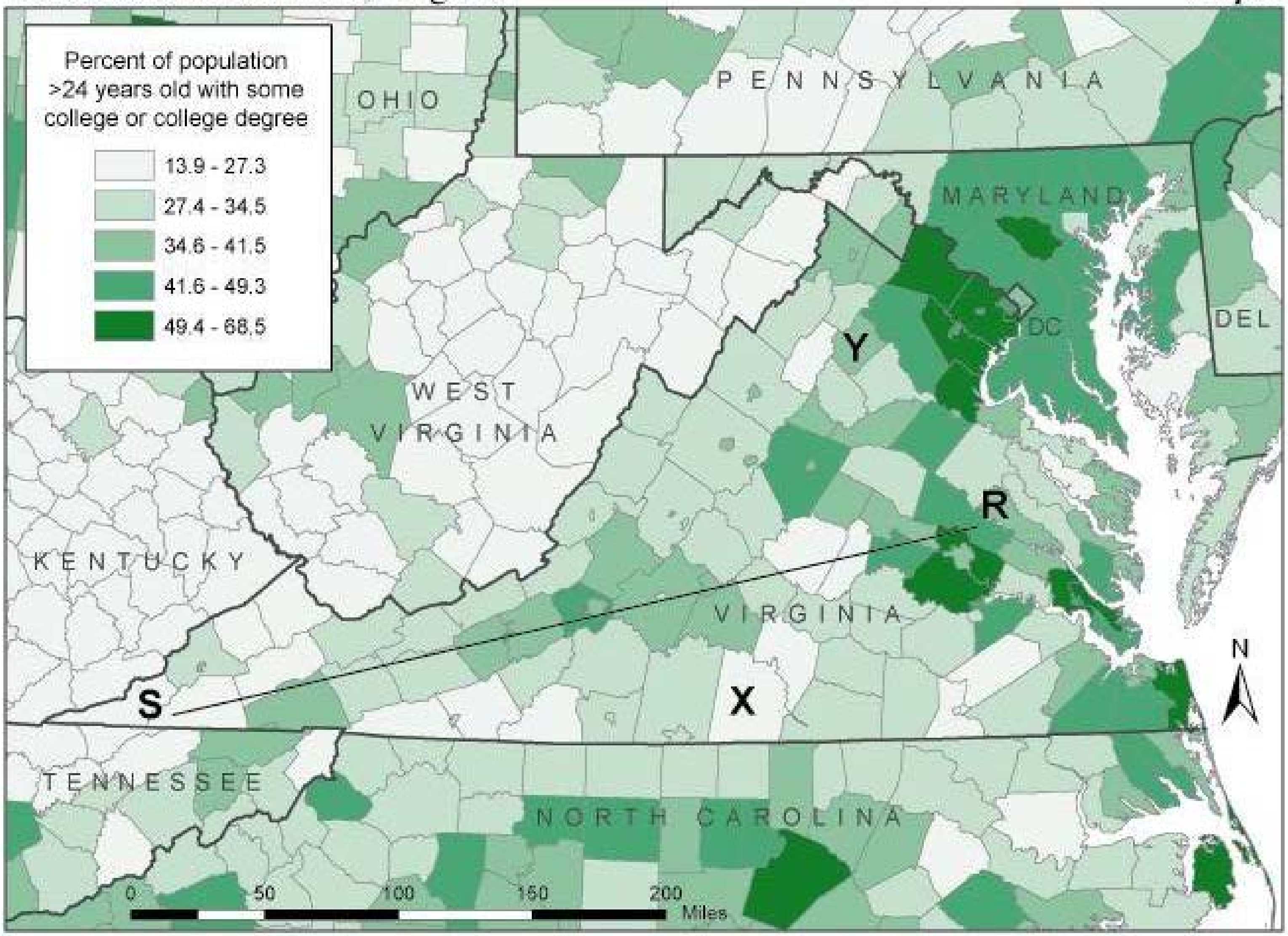
Rural Population, Wisconsin

Example Map



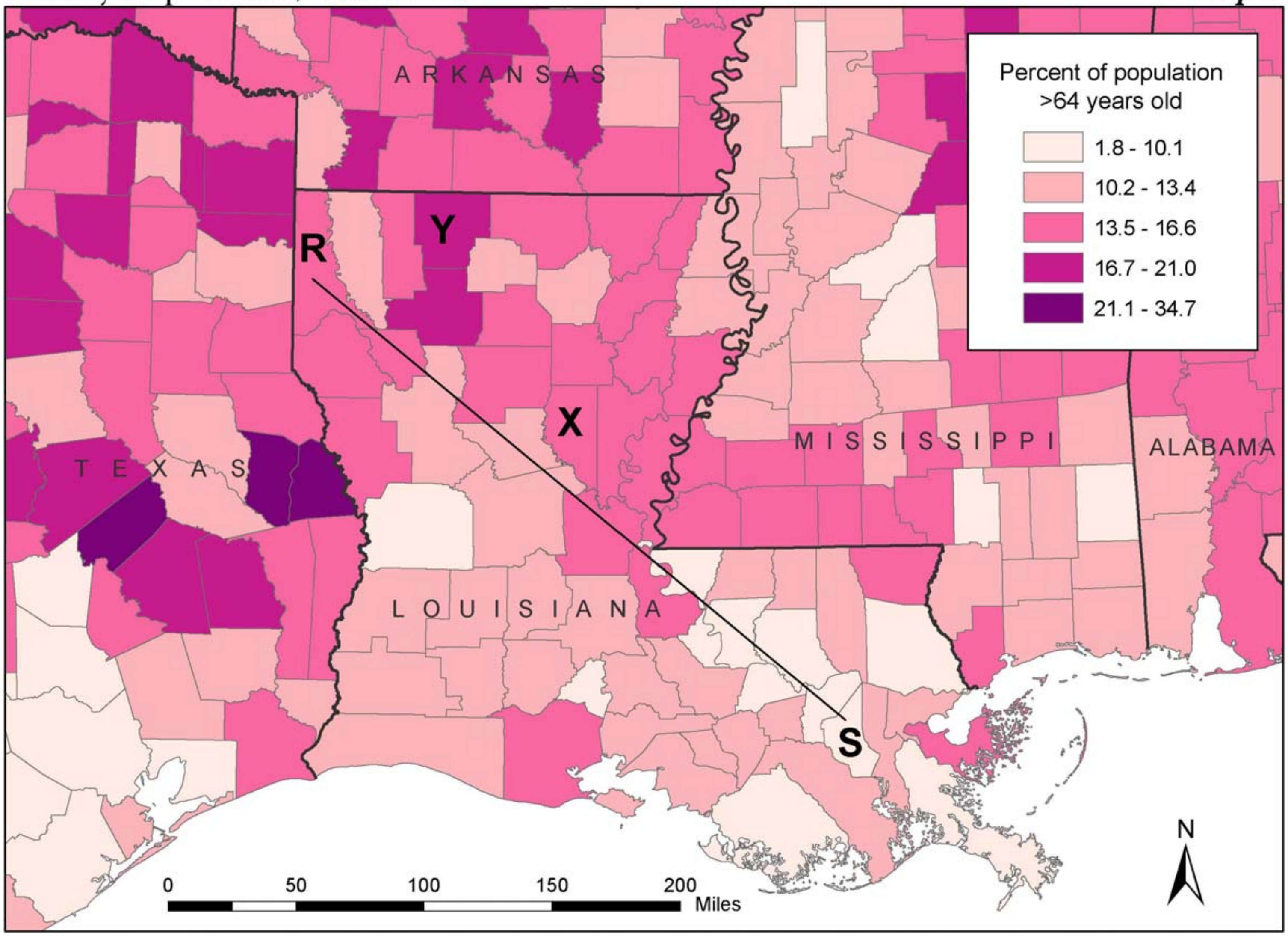
Educational Attainment, Virginia

Map 1

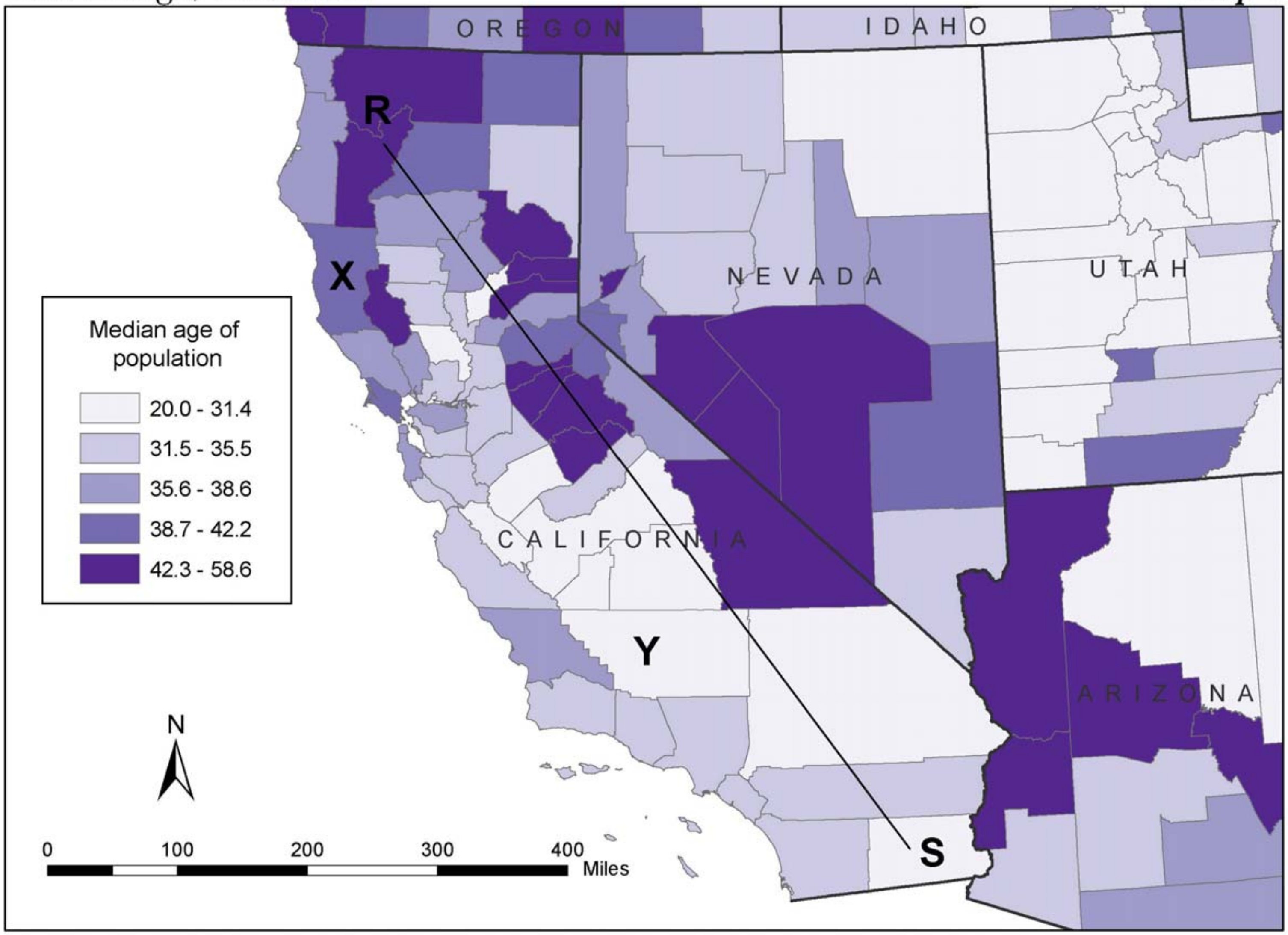


Elderly Population, Louisiana

Map 2

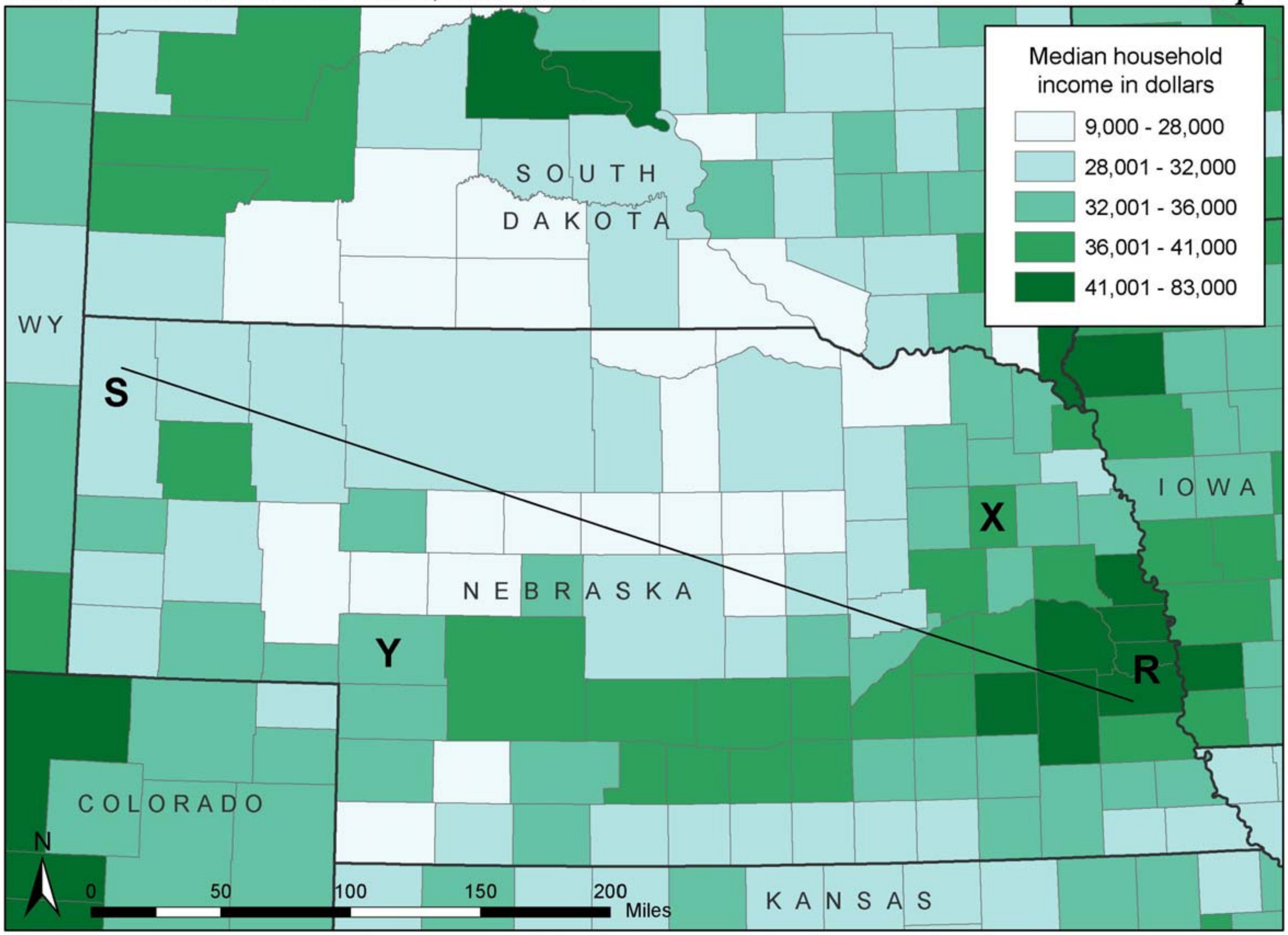


Median Age, California **_Map 3_**



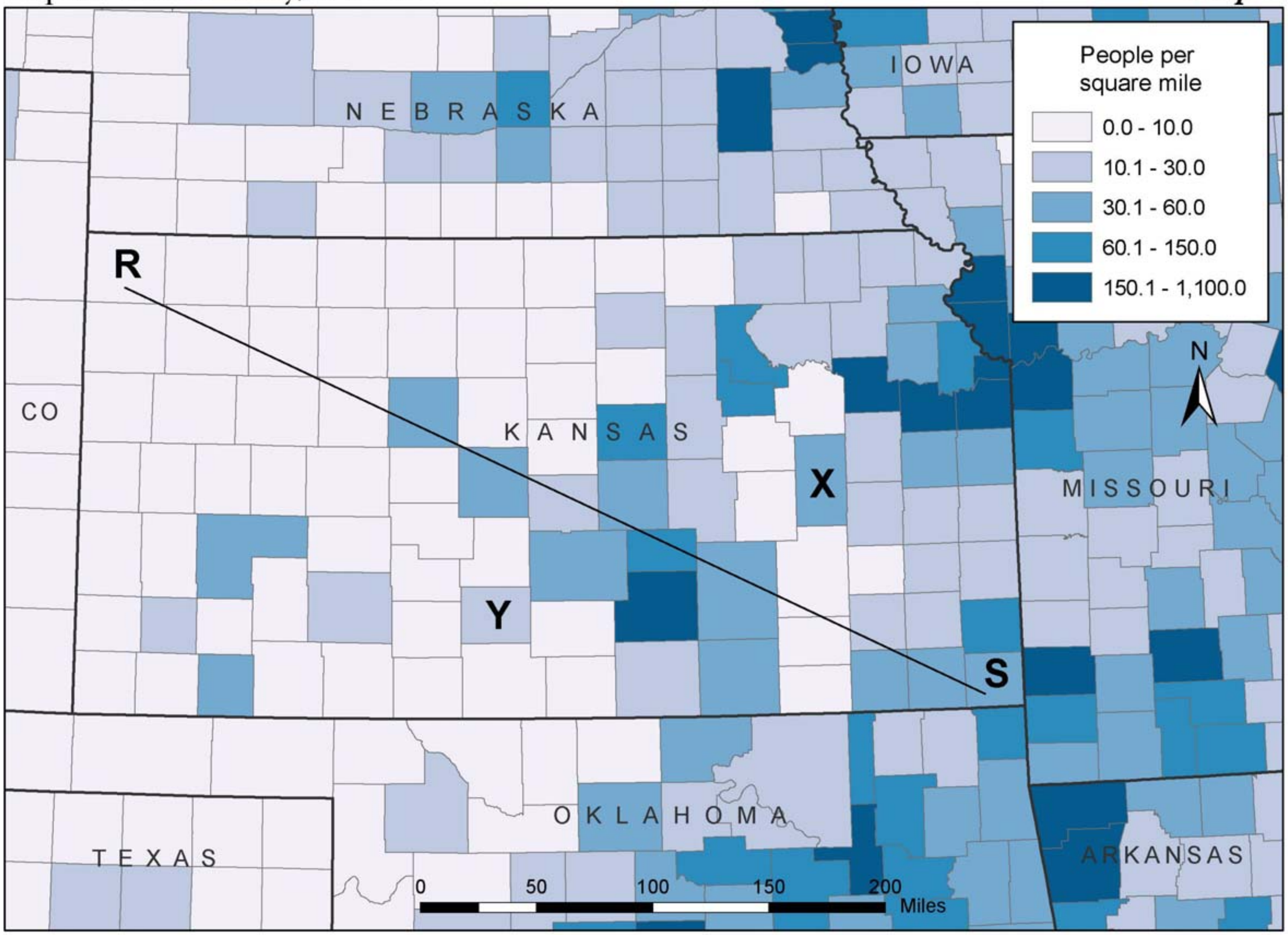
Median Household Income, Nebraska

Map 4



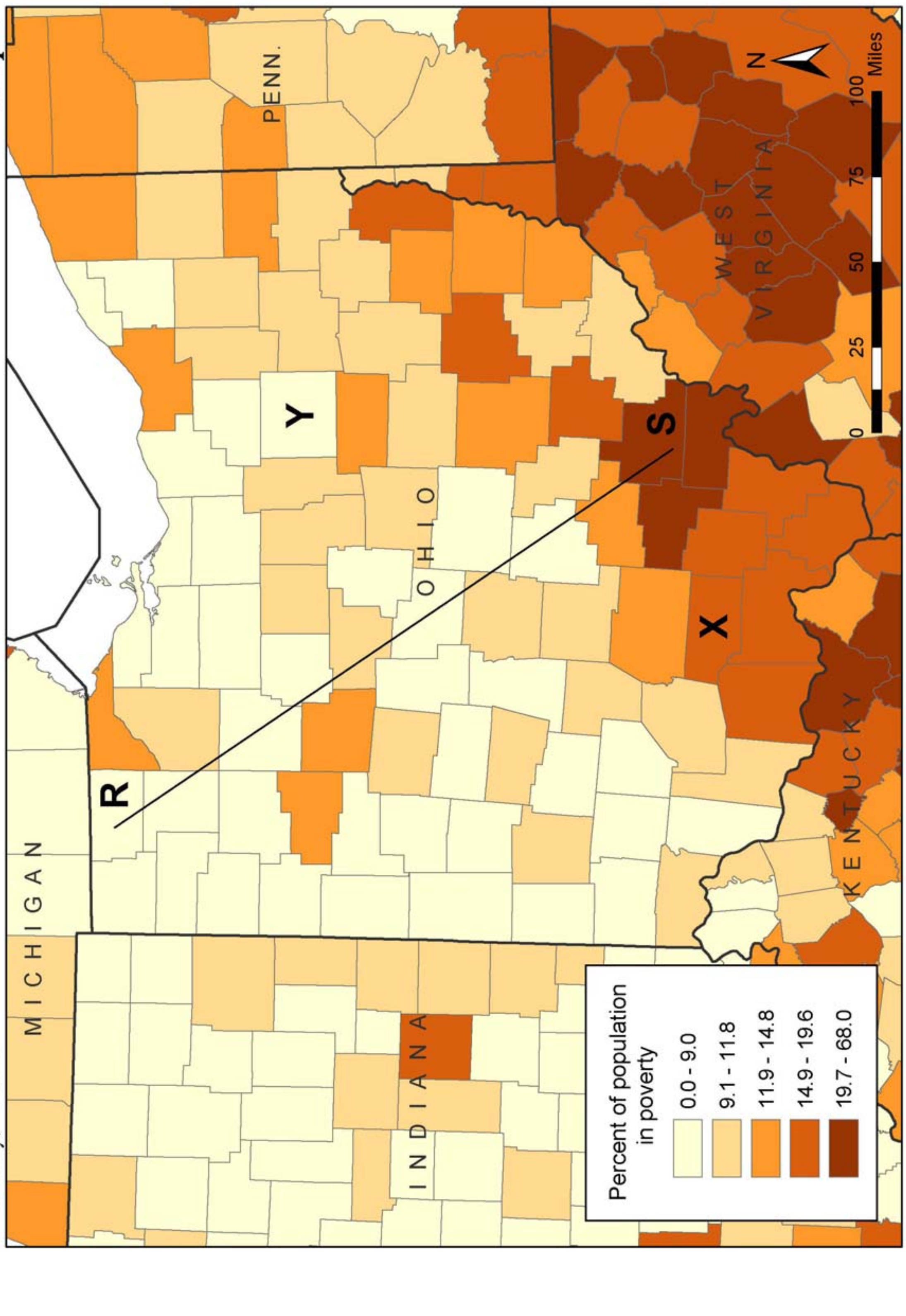
Population Density, Kansas

Map 5



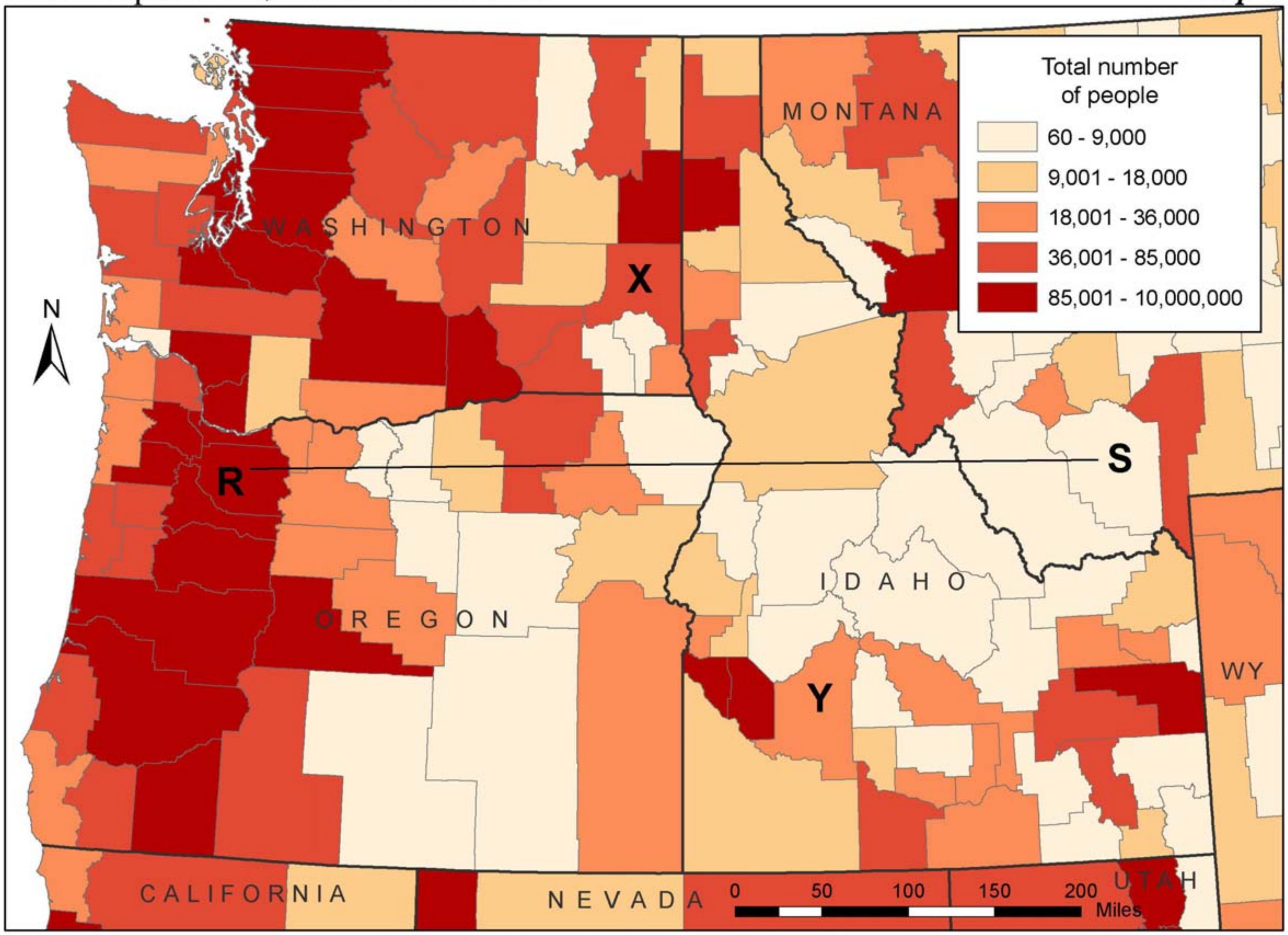
Poverty, Ohio

Map 6



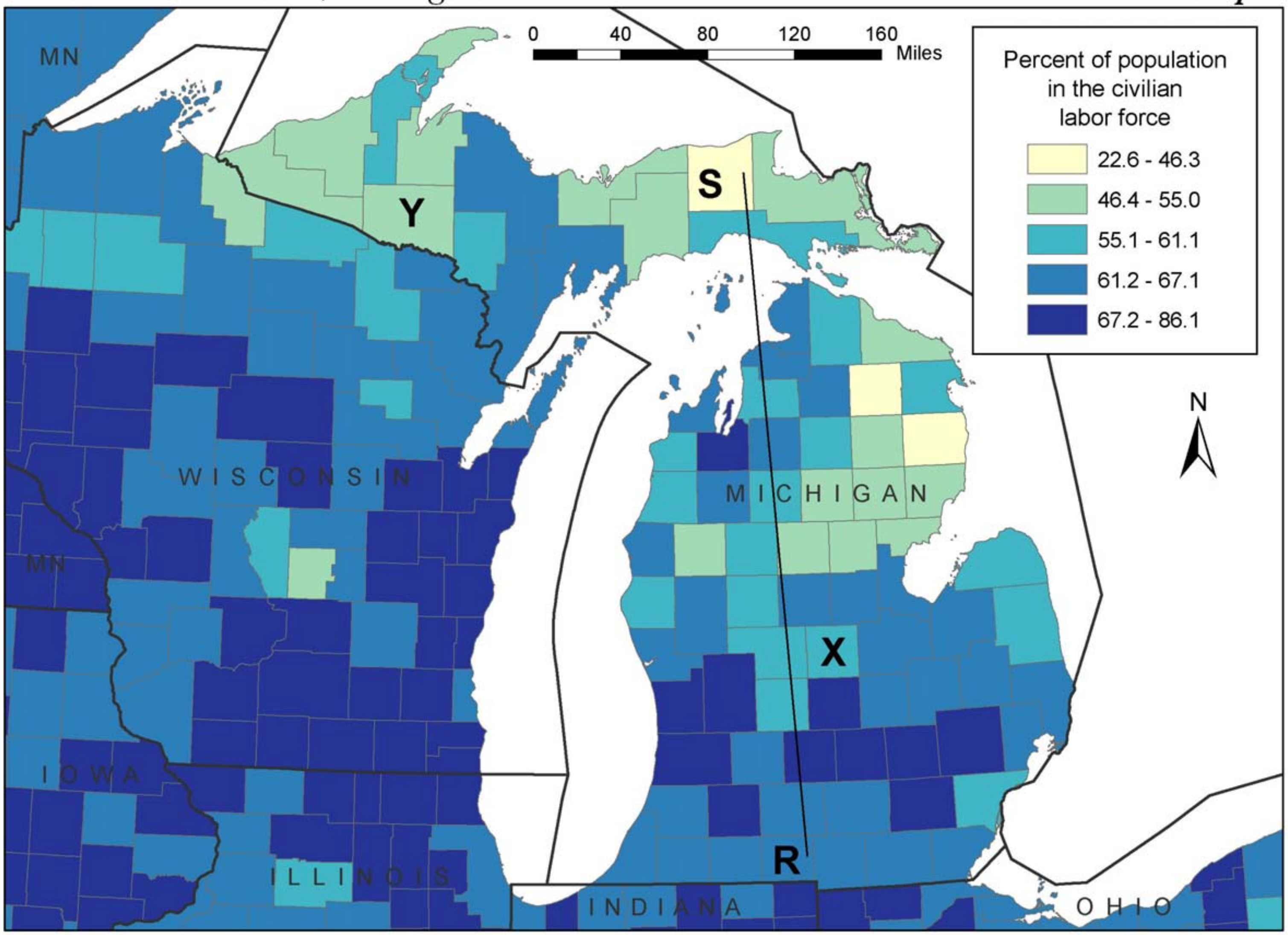
Total Population, Pacific Northwest

Map 7



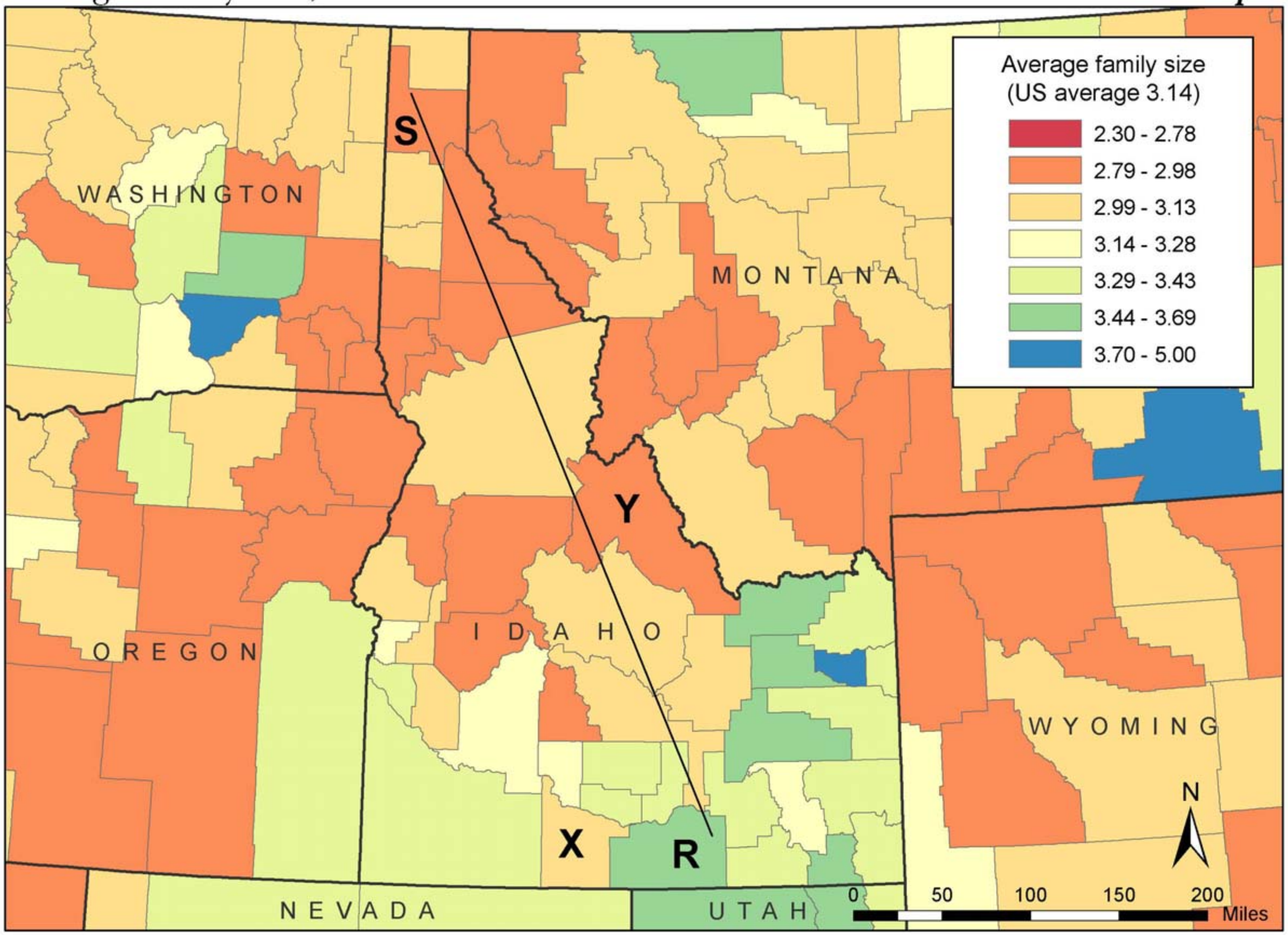
Civilian Labor Force, Michigan

Map 8



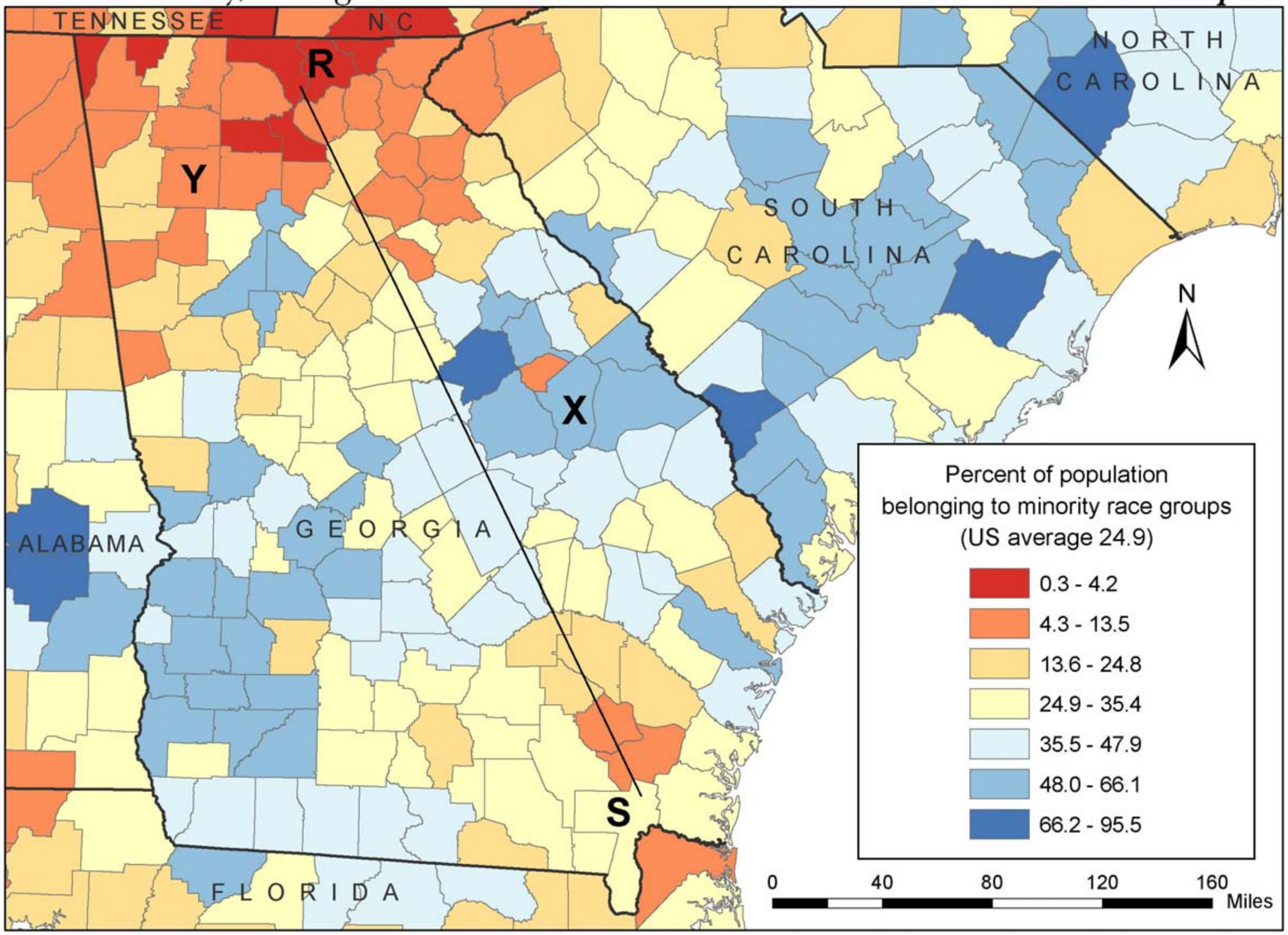
Average Family Size, Idaho

Map 9



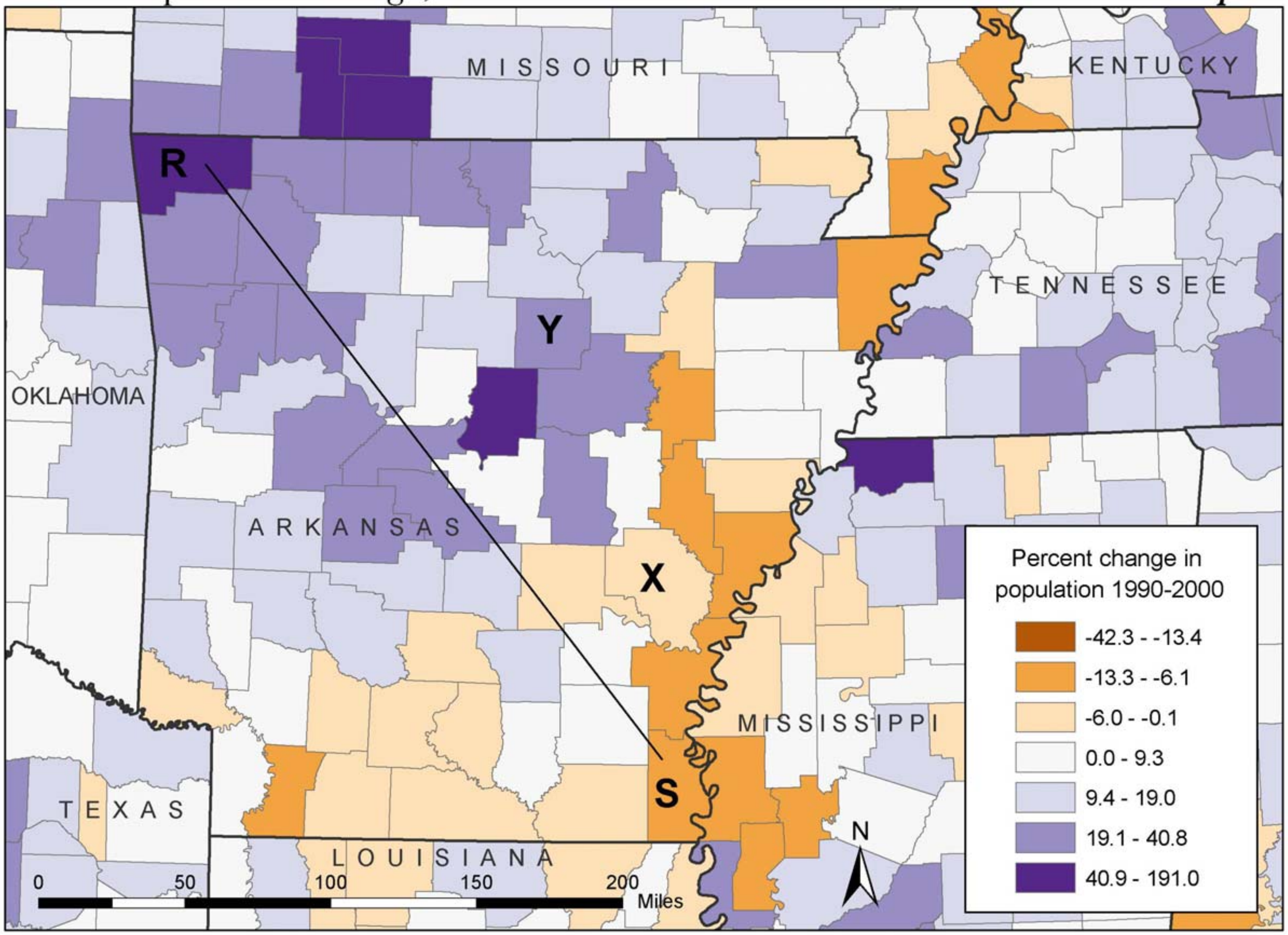
Racial Diversity, Georgia

Map 10



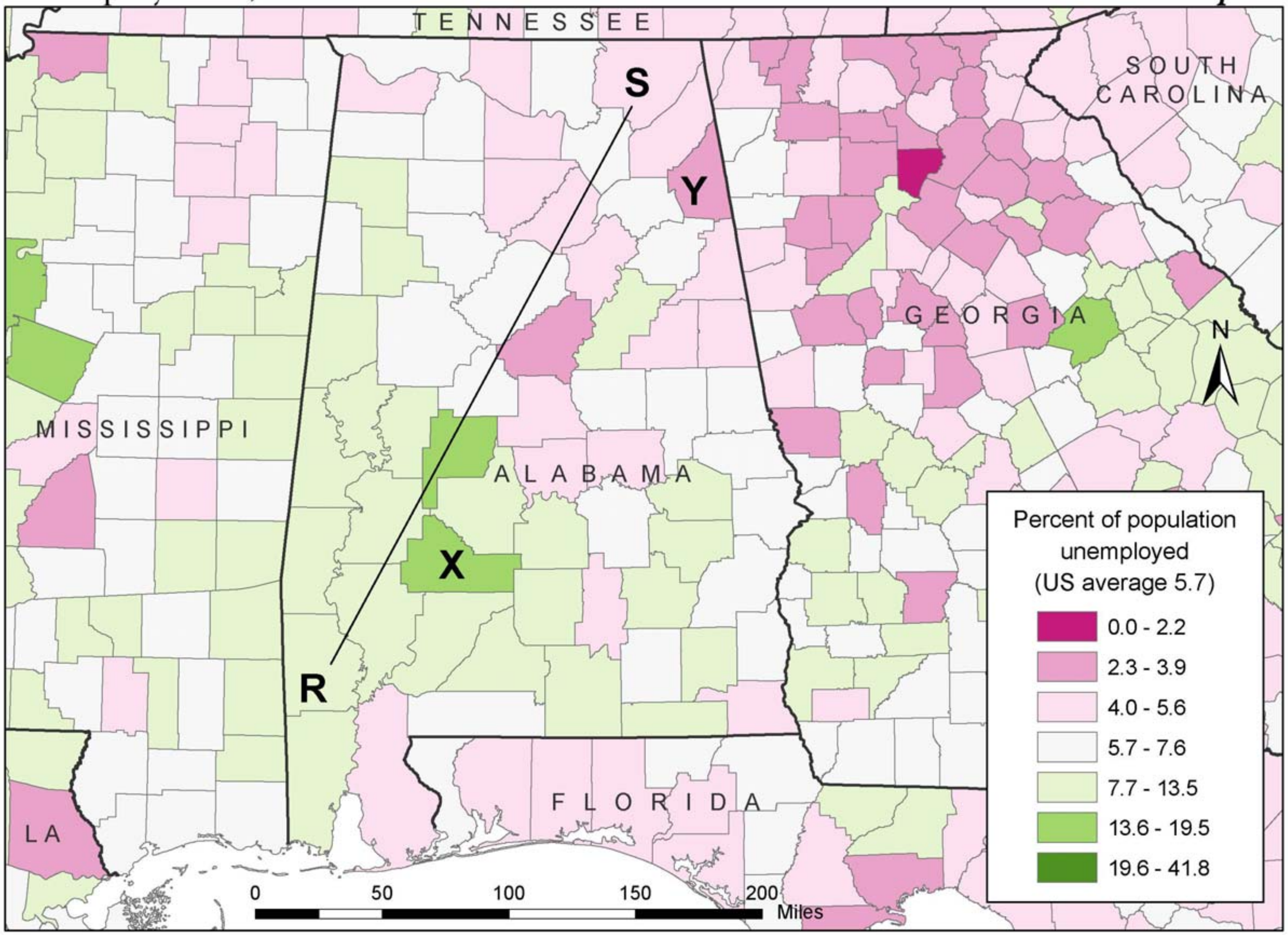
Recent Population Change, Arkansas

Map 11



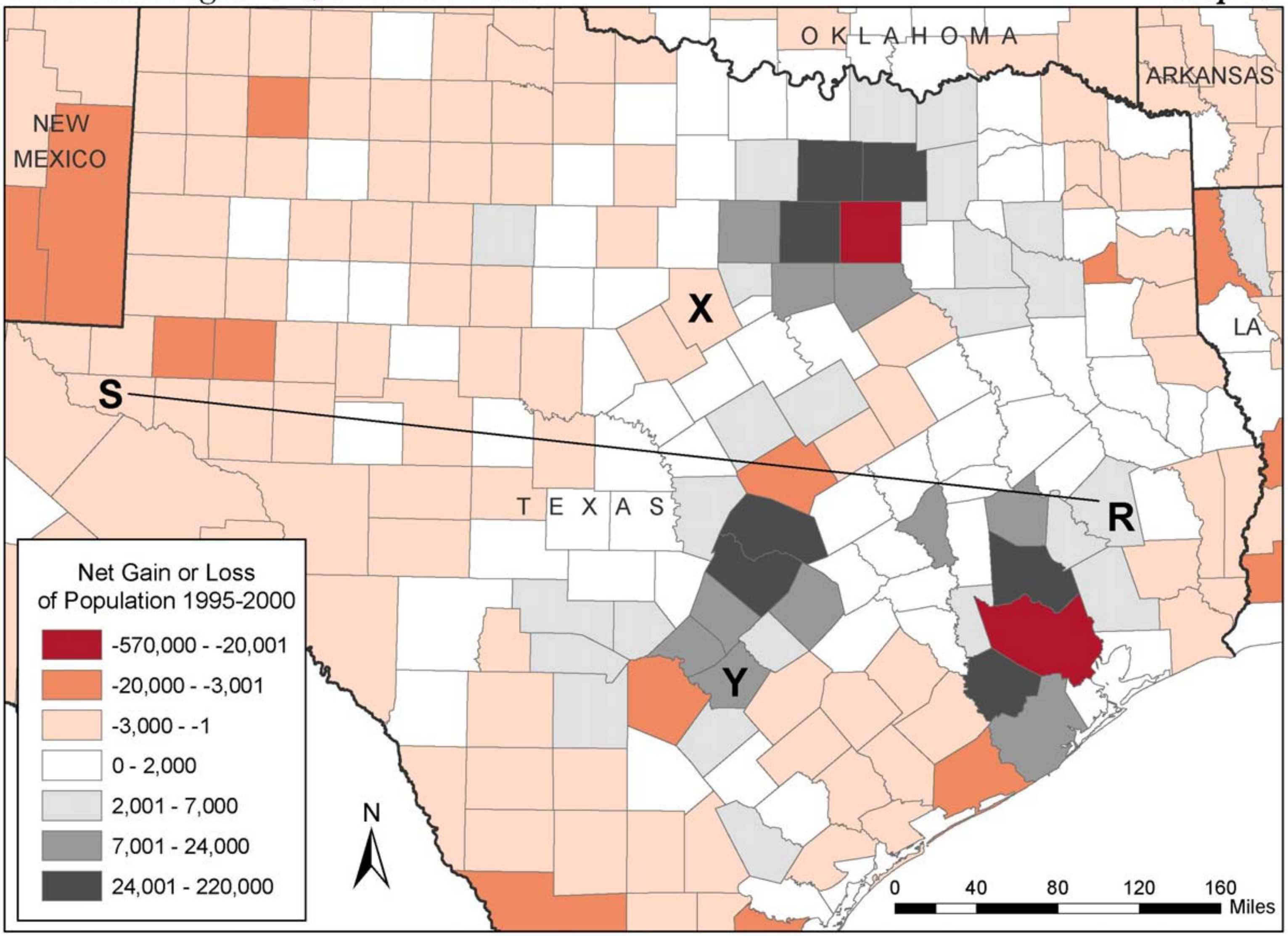
Unemployment, Alabama

Map 12



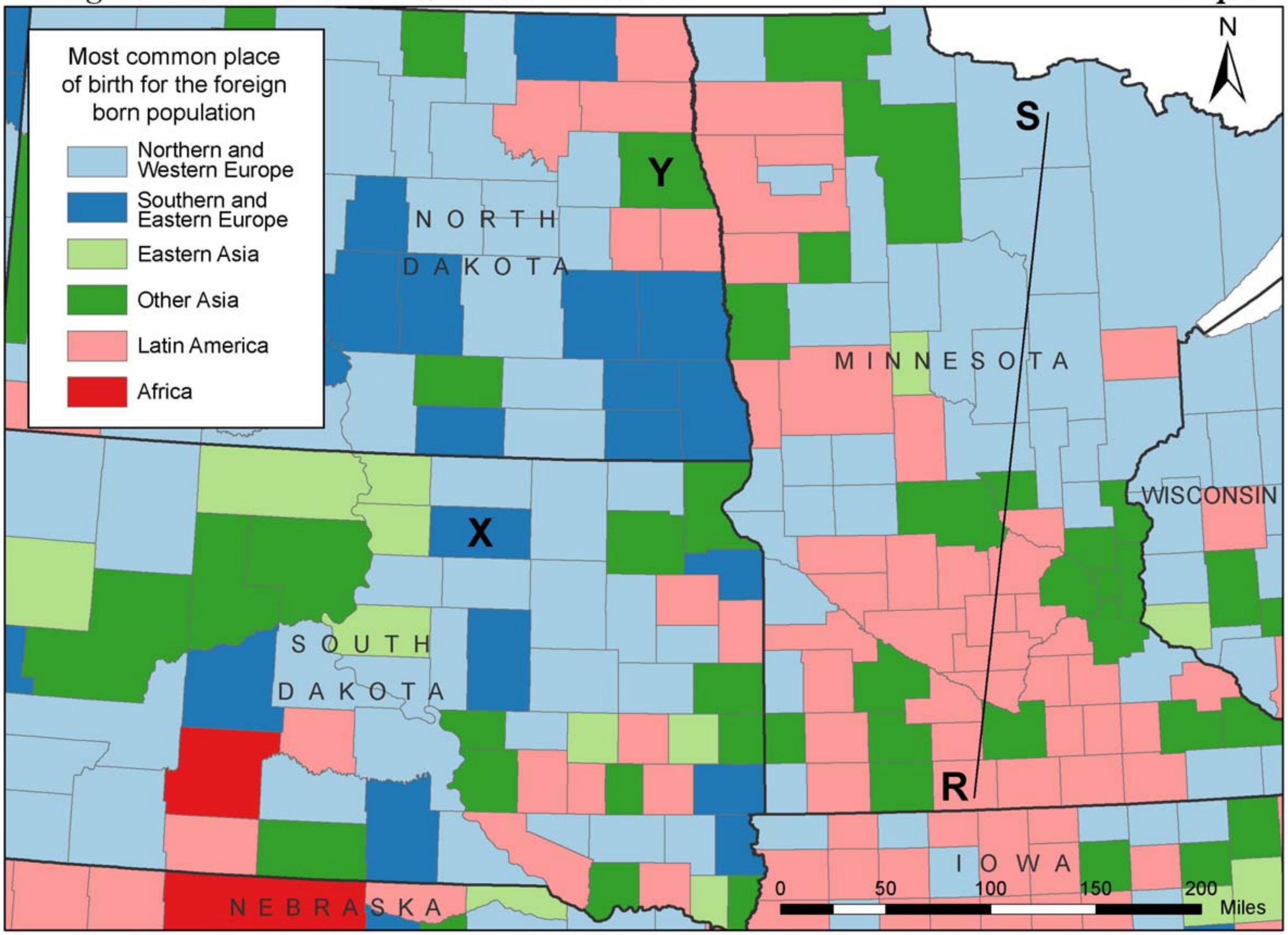
Domestic Migration, Central Texas

Map 13



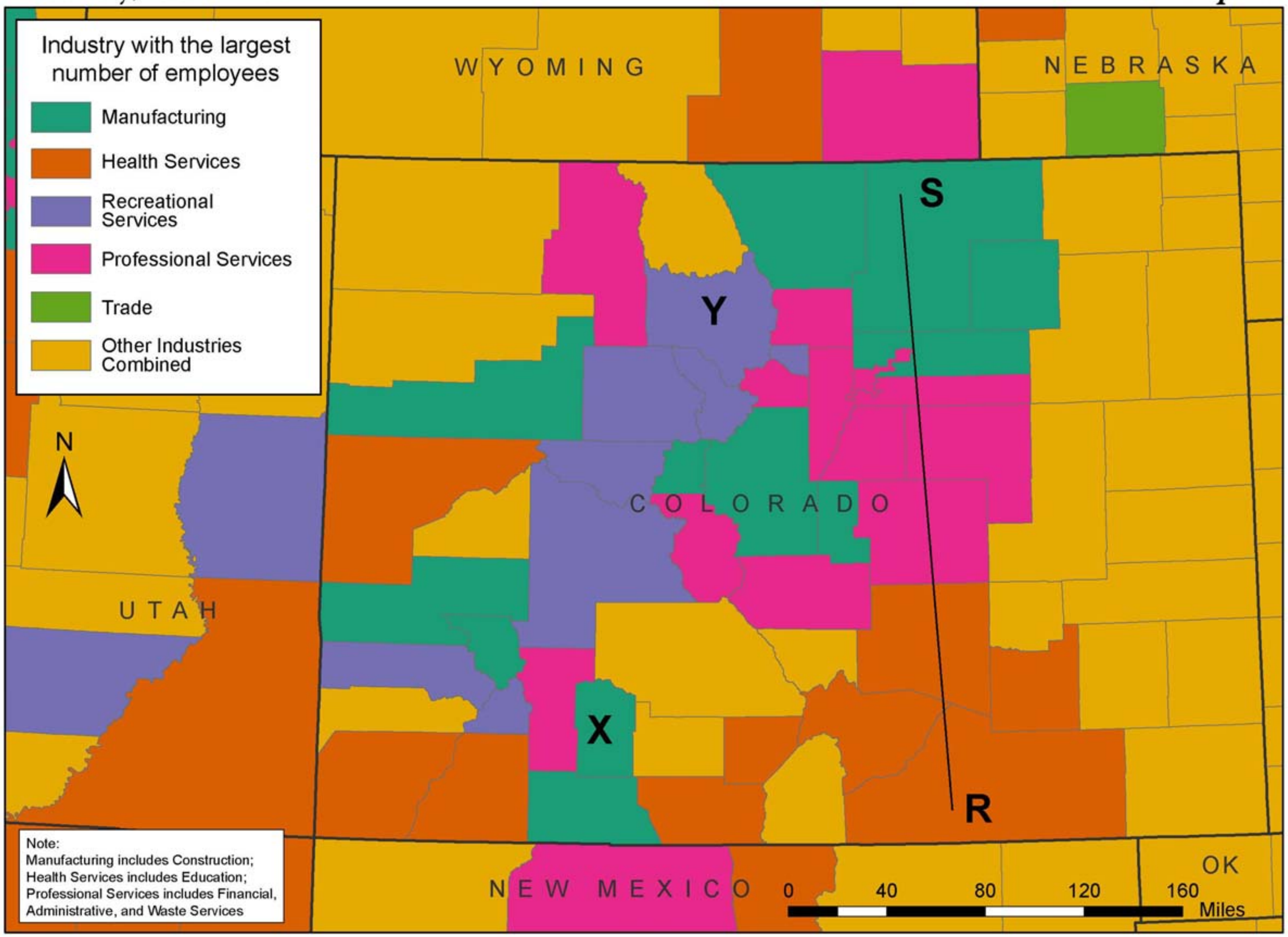
Foreign-born Place of Birth, Northern Plains

Map 14

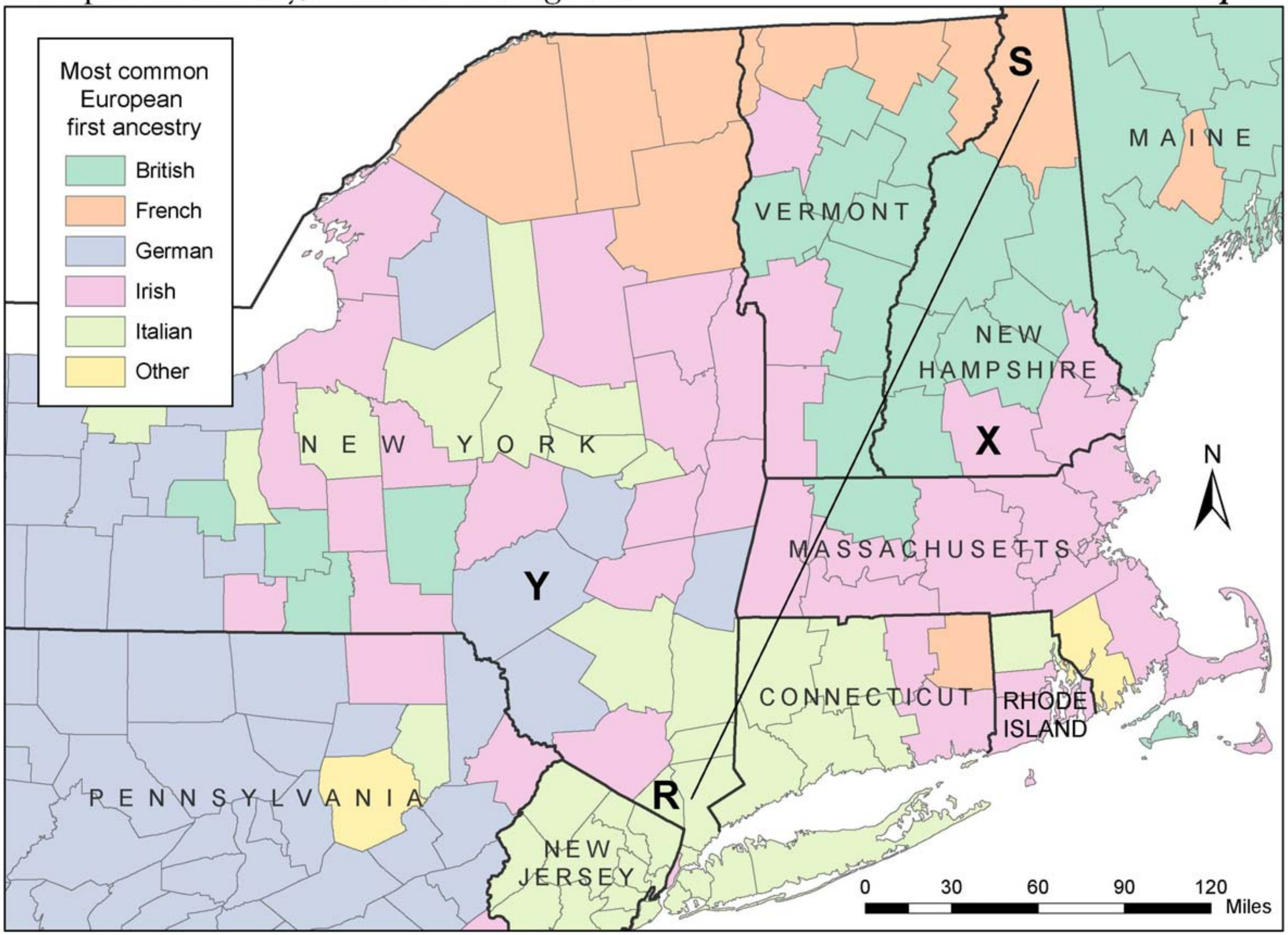


Industry, Colorado

Map 15

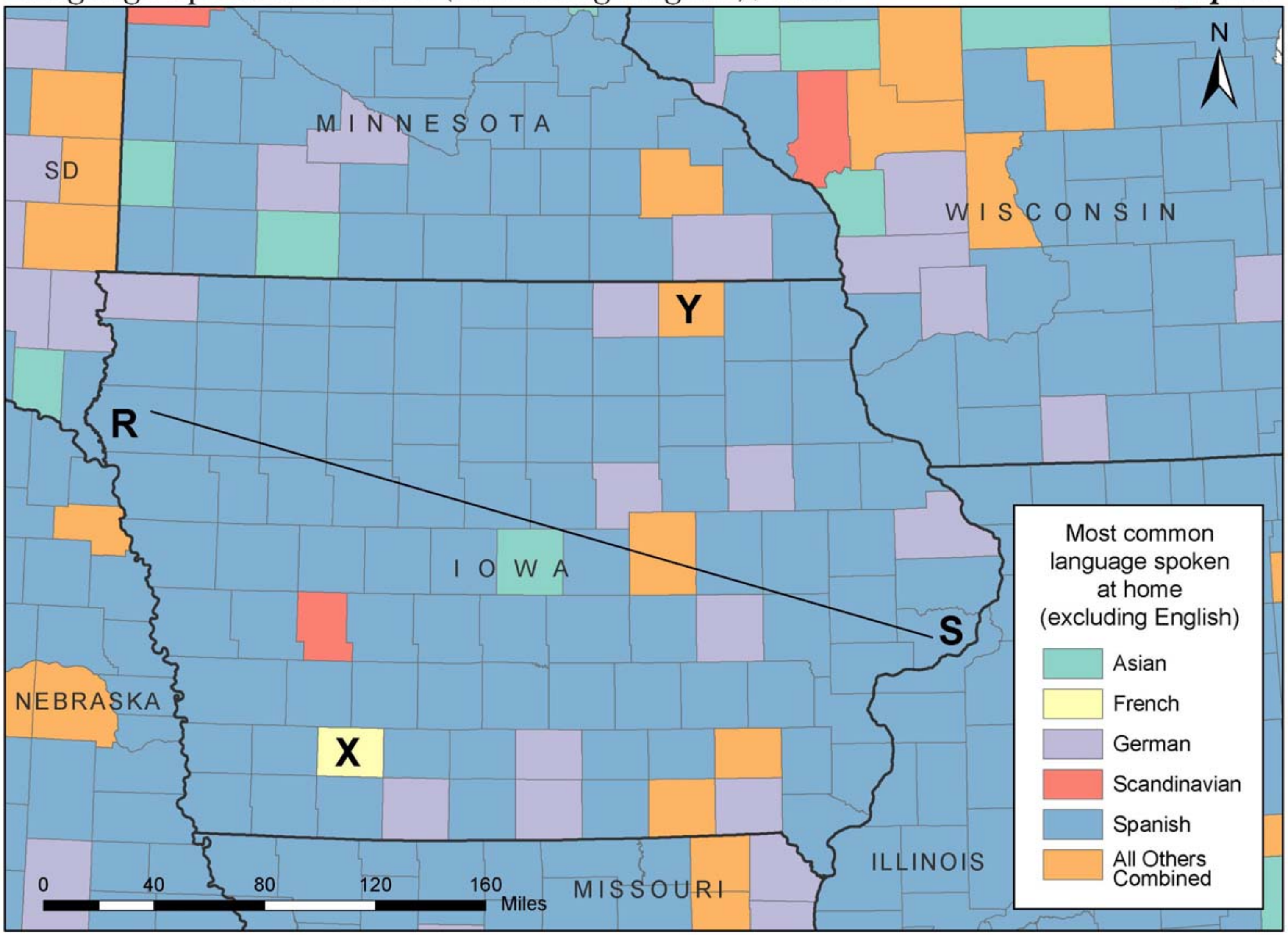


European Ancestry, Lower New England **_Map 16_**



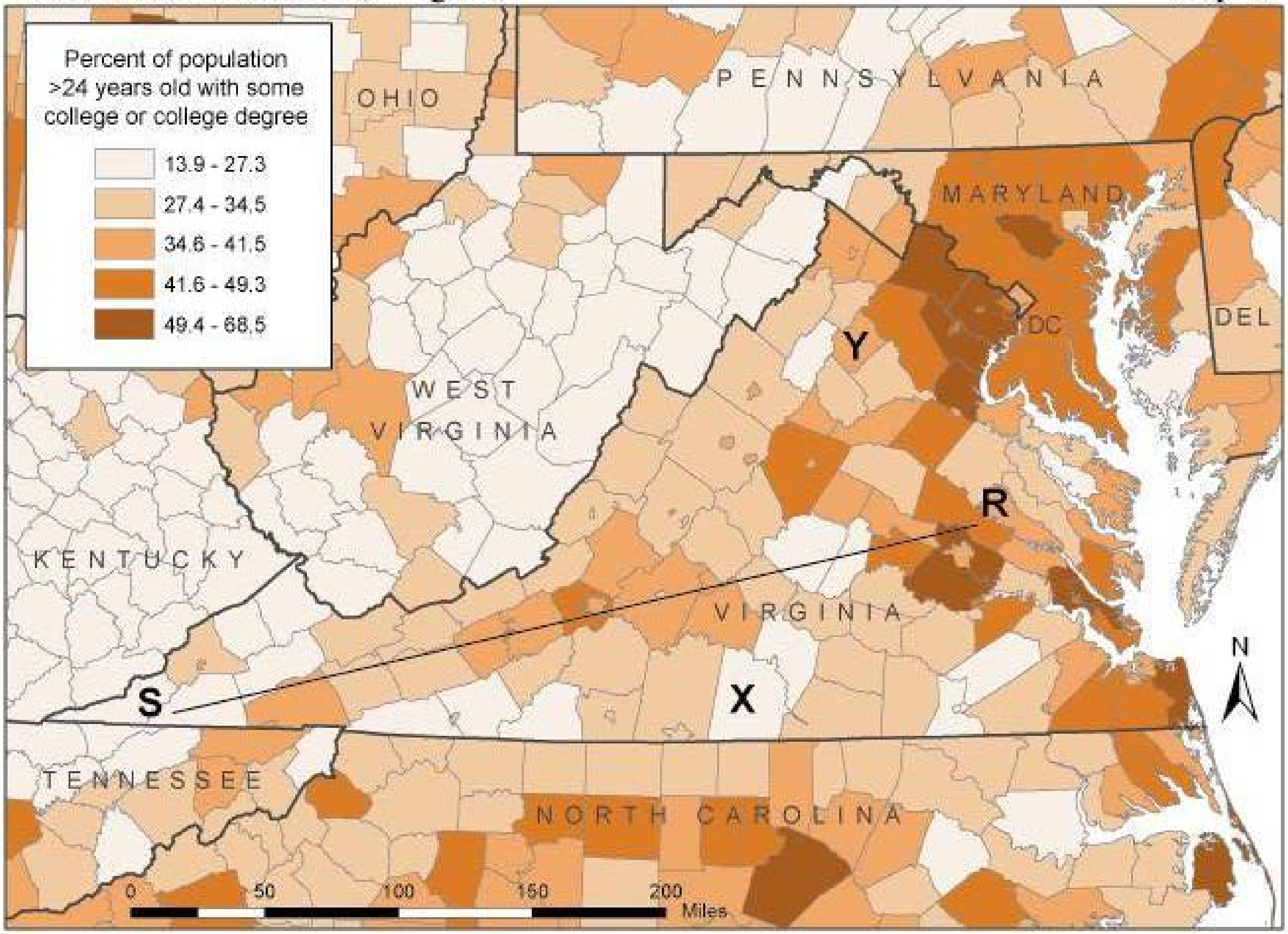
Language Spoken at Home (Excluding English), Iowa

Map 17



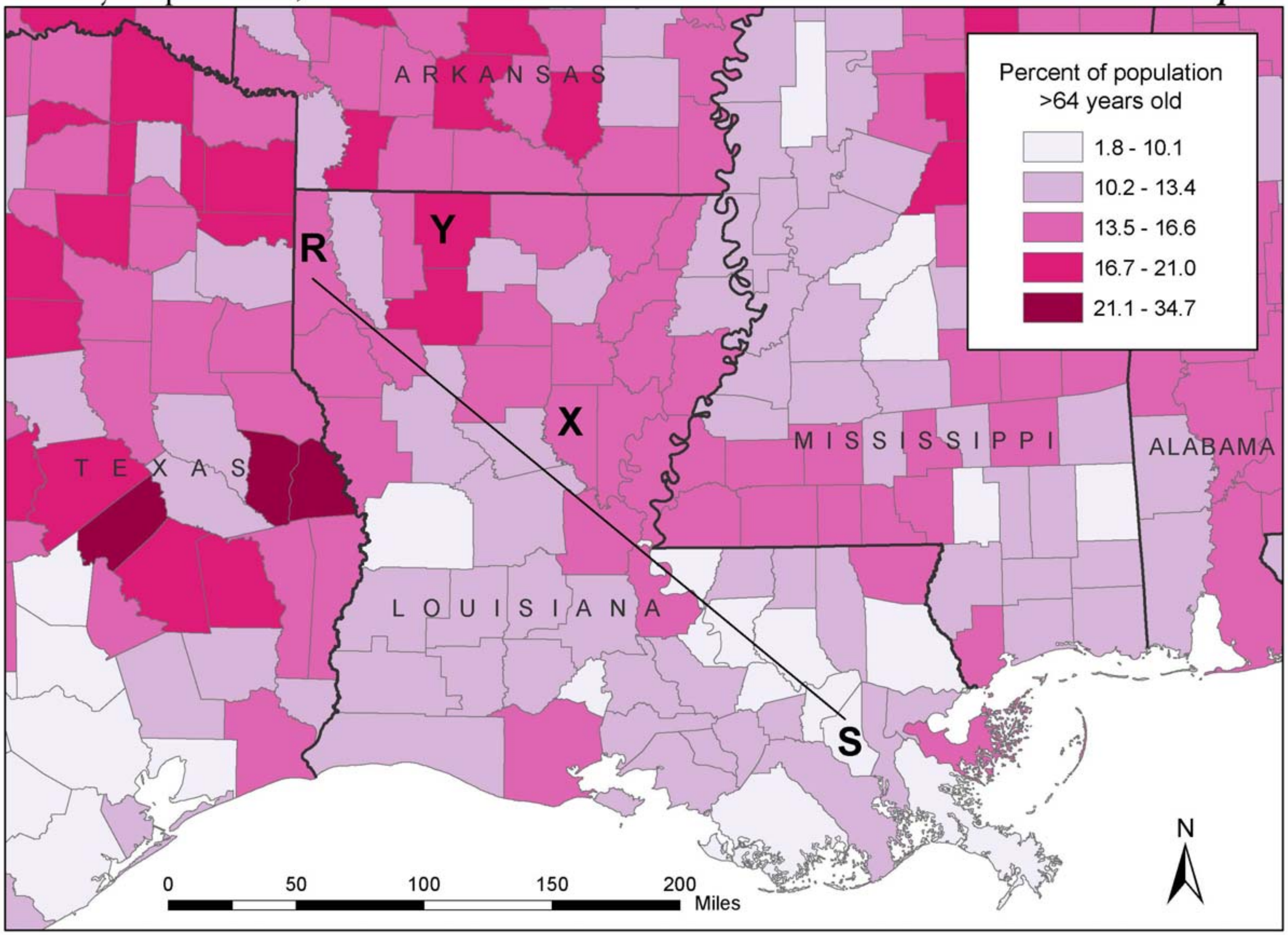
Educational Attainment, Virginia

Map 18



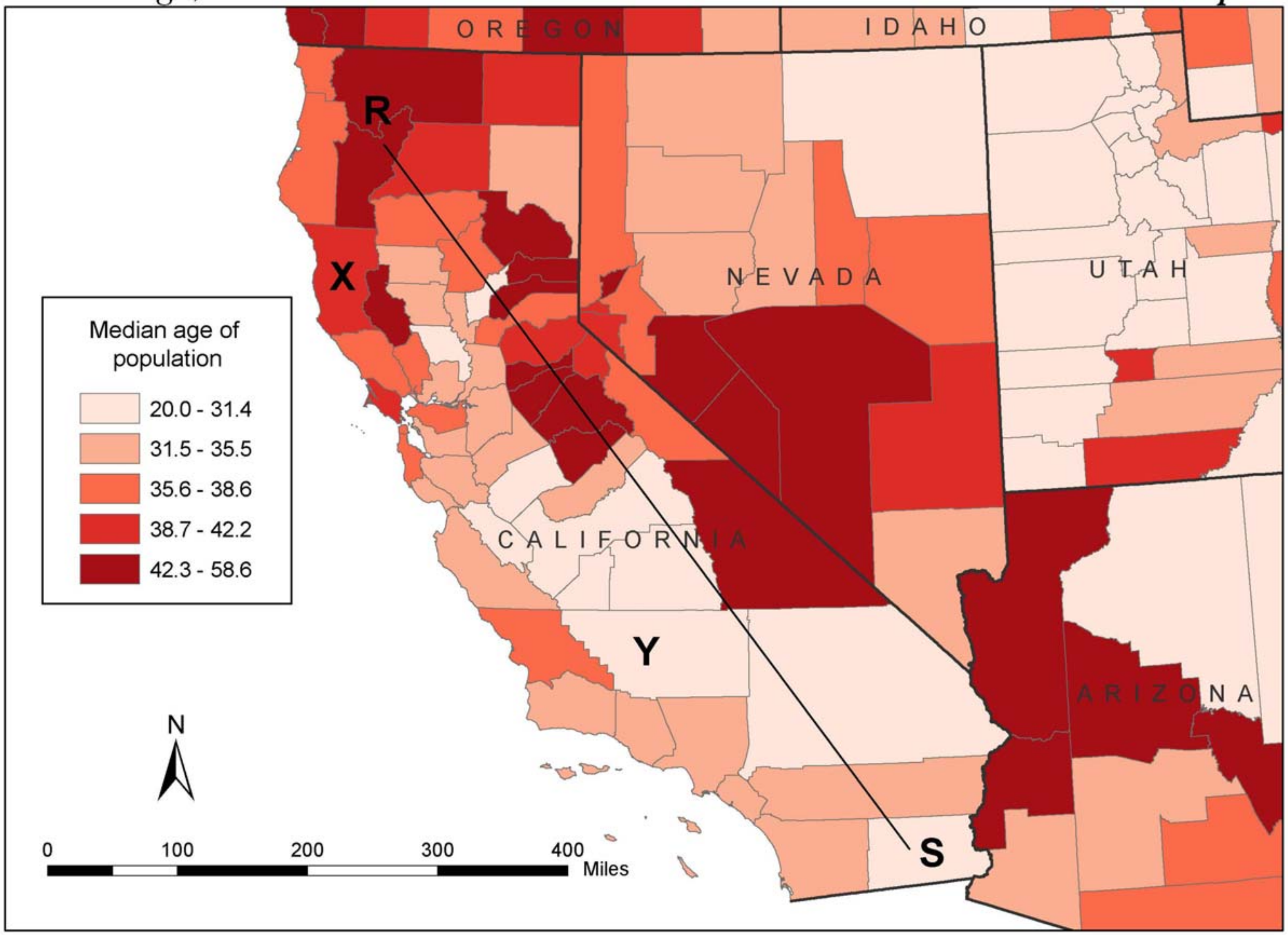
Elderly Population, Louisiana

Map 19



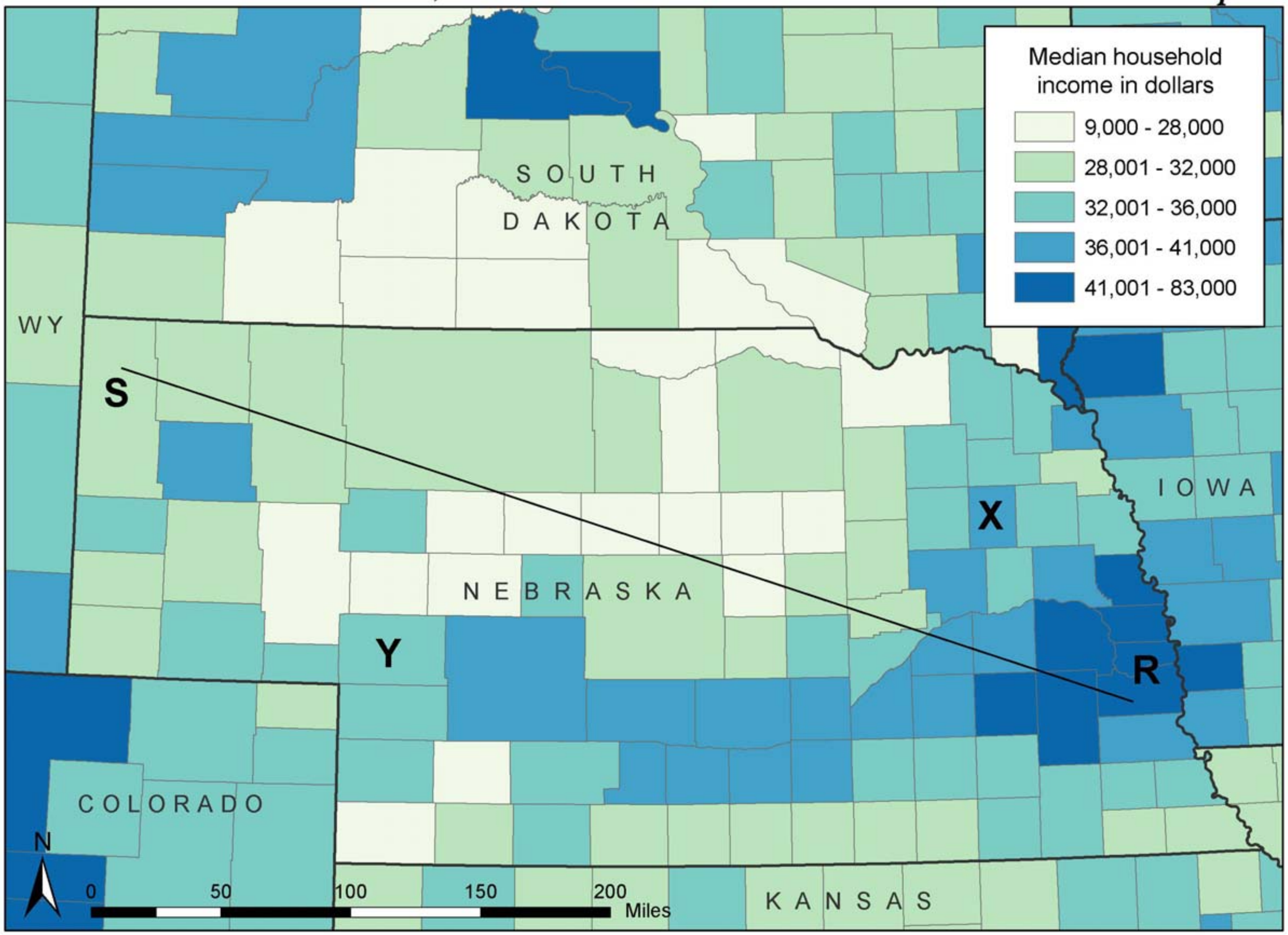
Median Age, California

Map 20



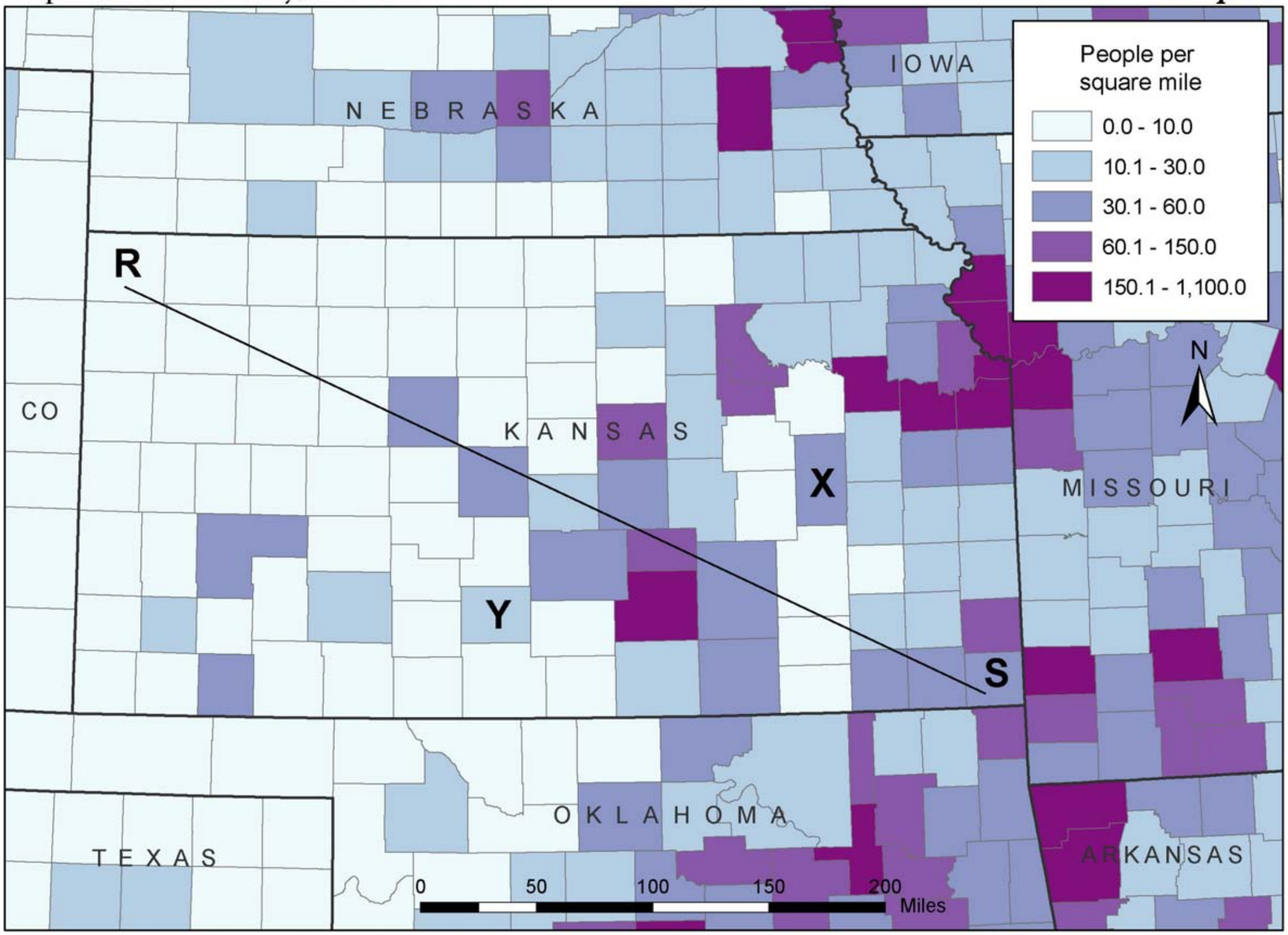
Median Household Income, Nebraska

Map 21



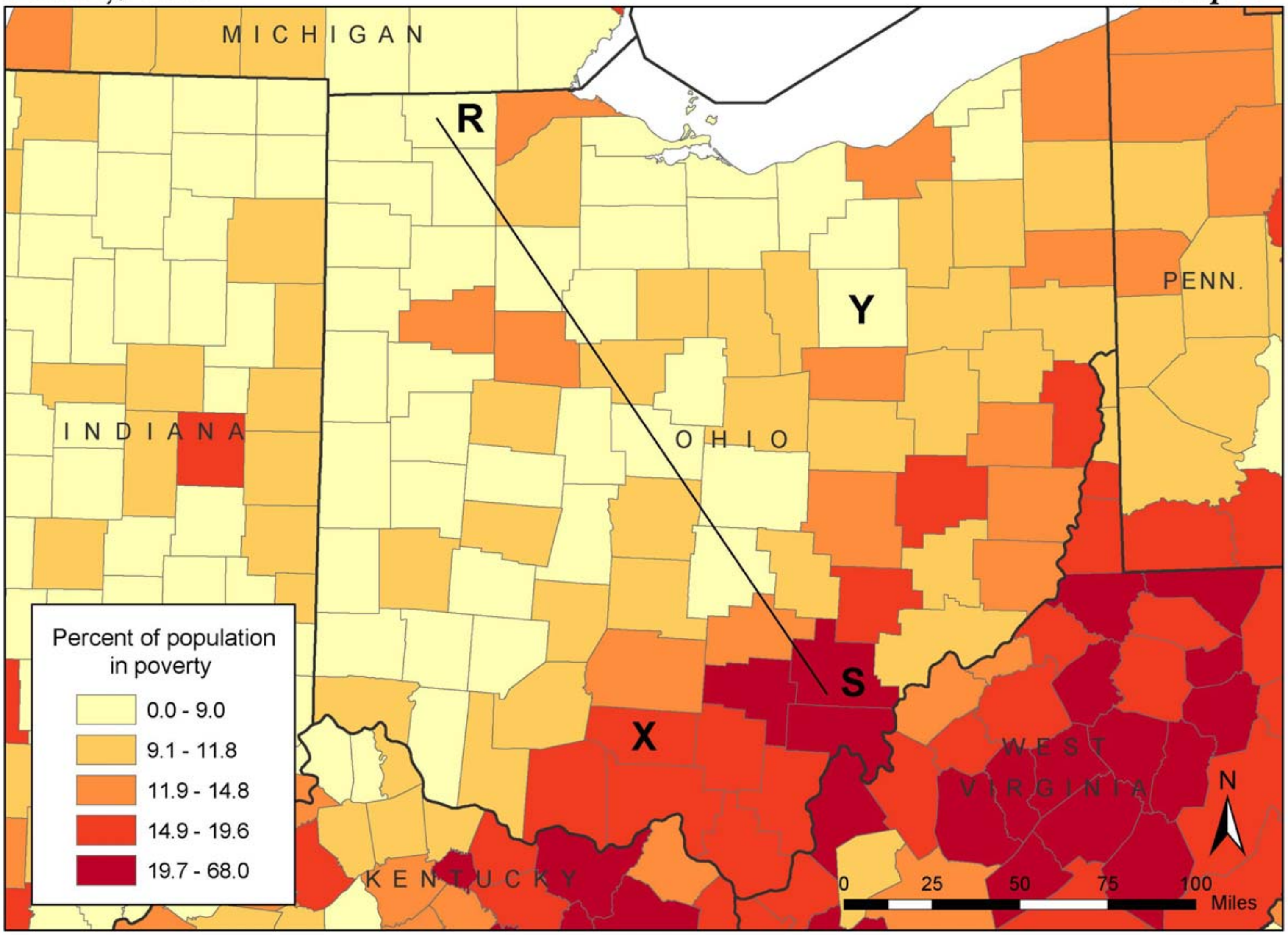
Population Density, Kansas

Map 22



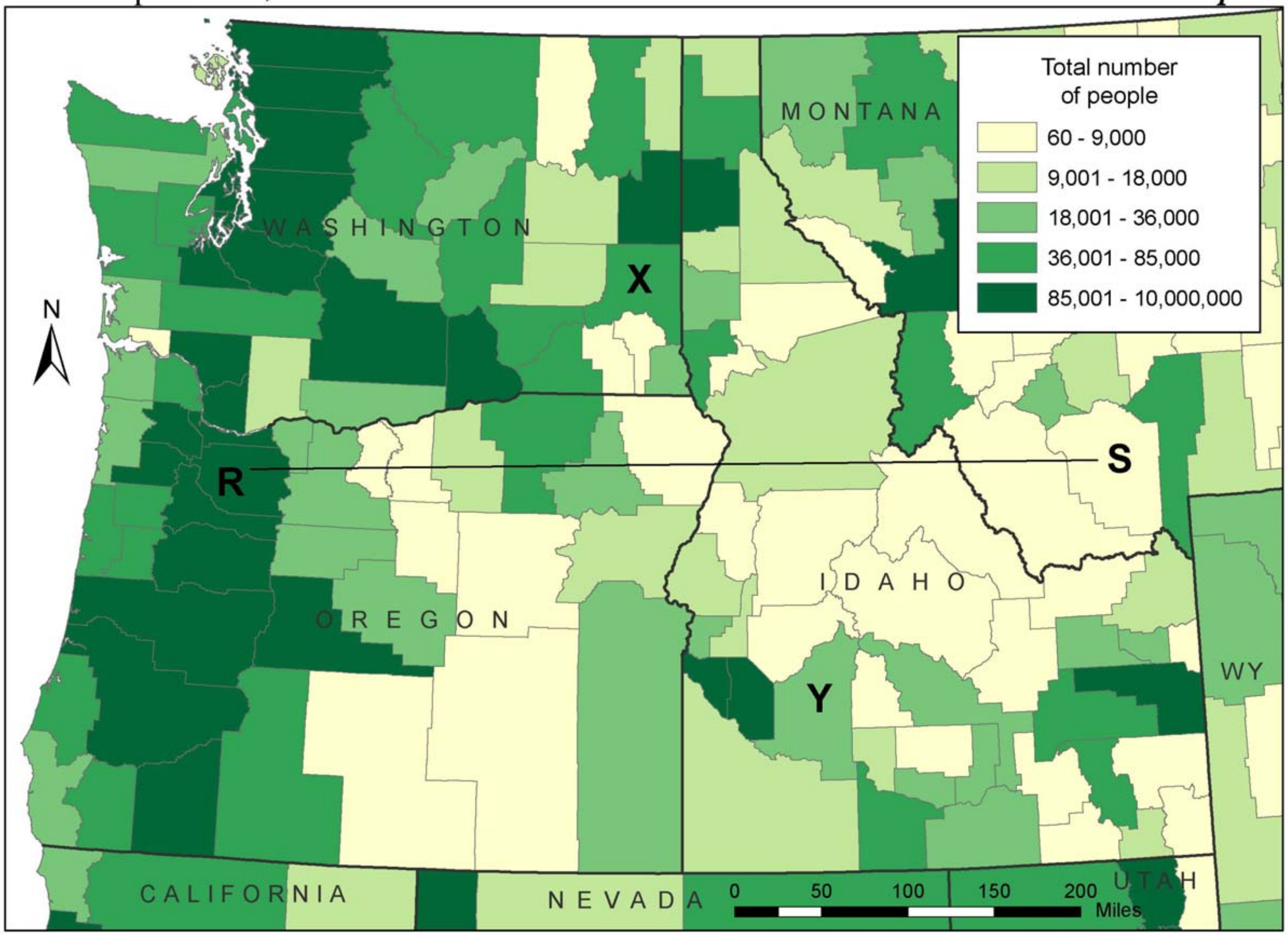
Poverty, Ohio

Map 23



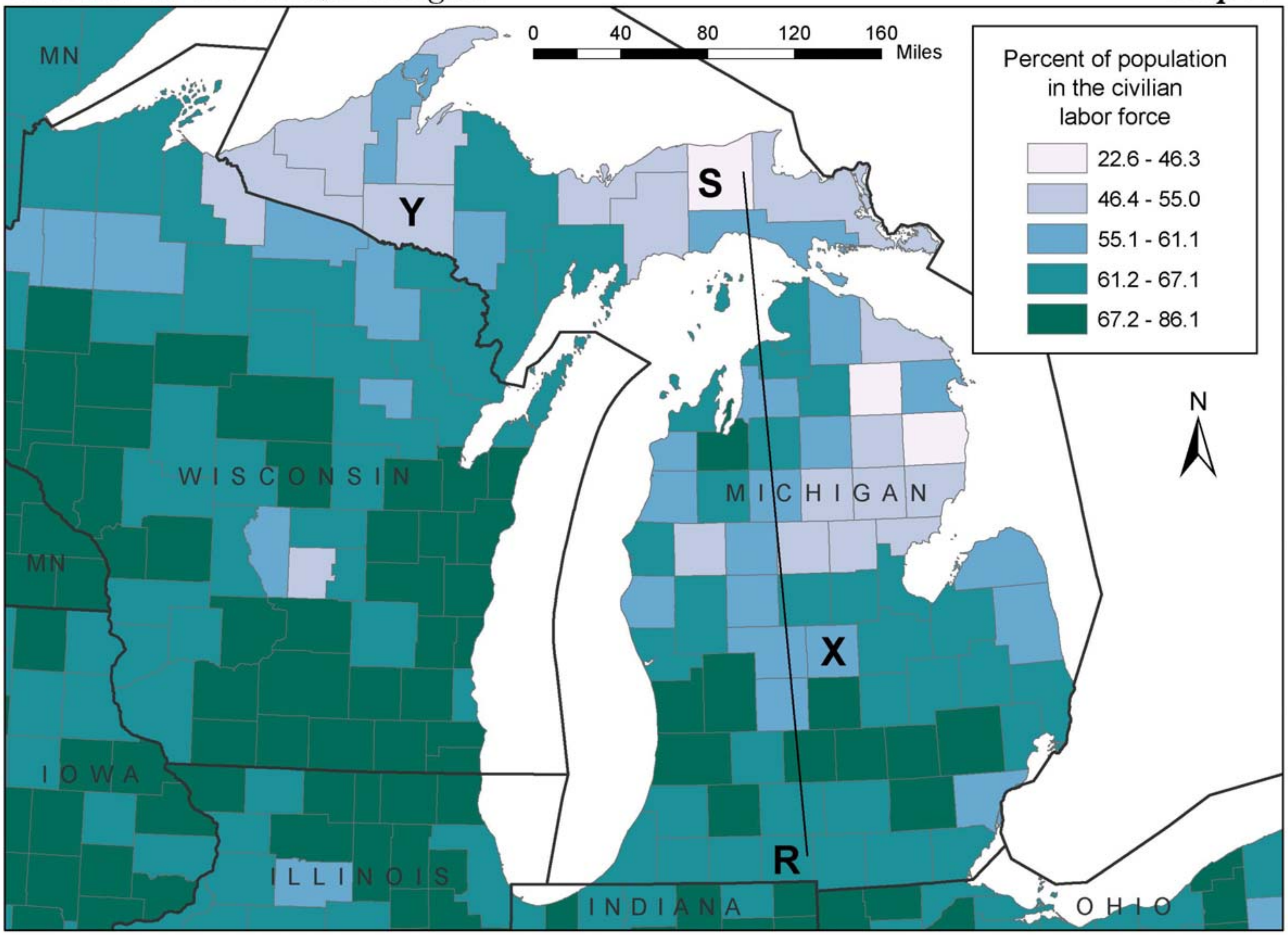
Total Population, Pacific Northwest

Map 24



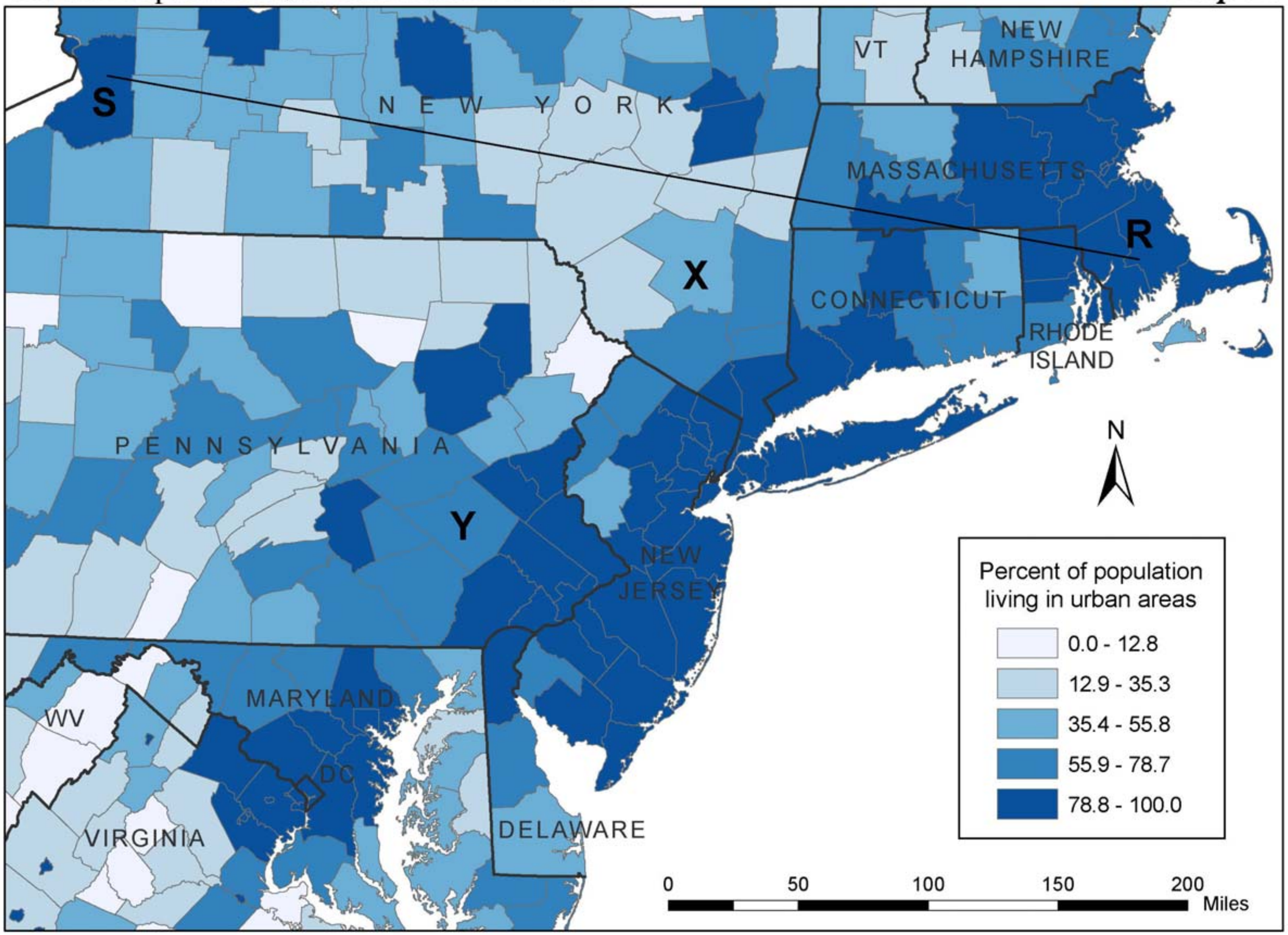
Civilian Labor Force, Michigan

Map 25



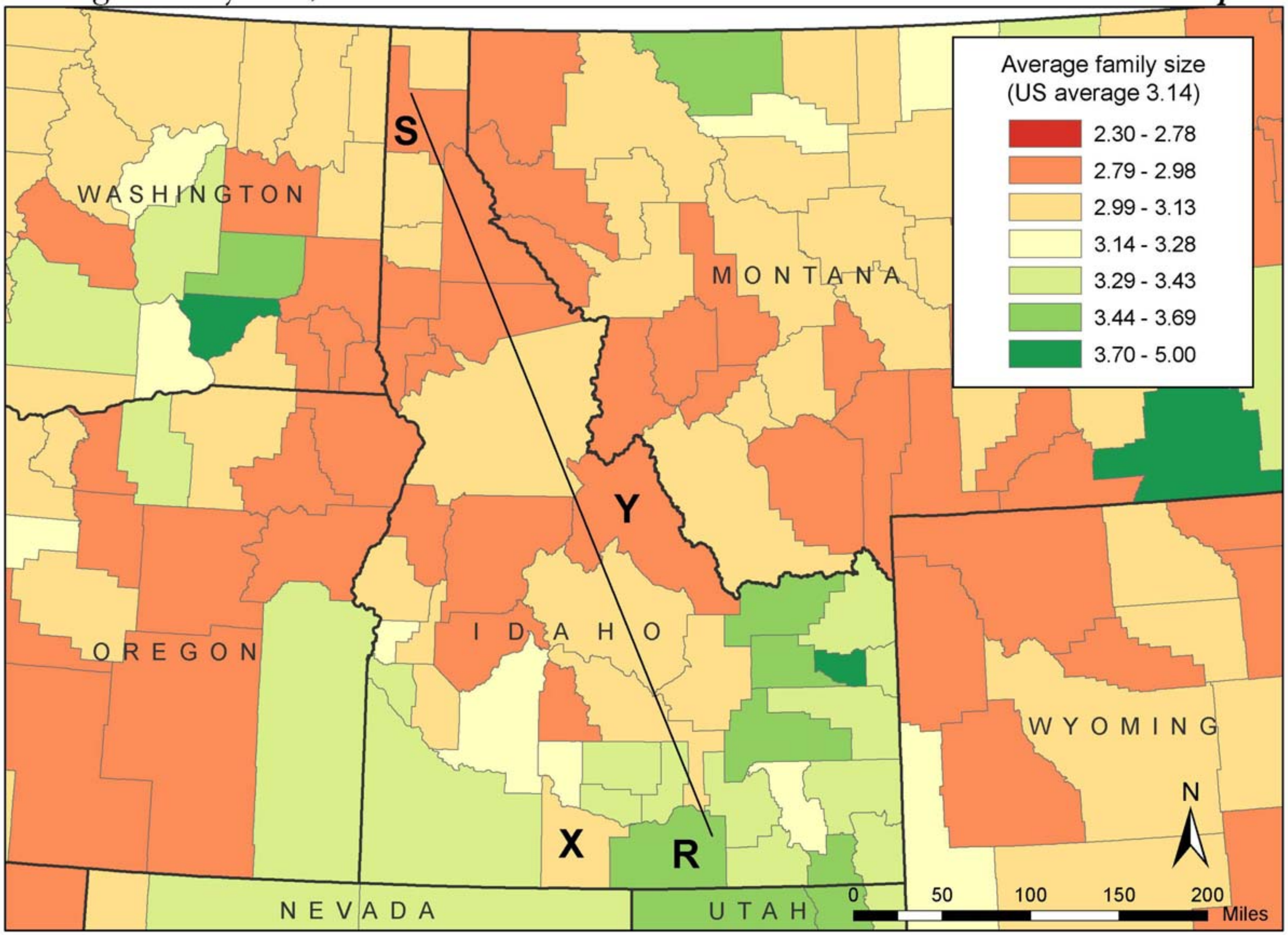
Urban Population, Mid-Atlantic Coast

Map 26



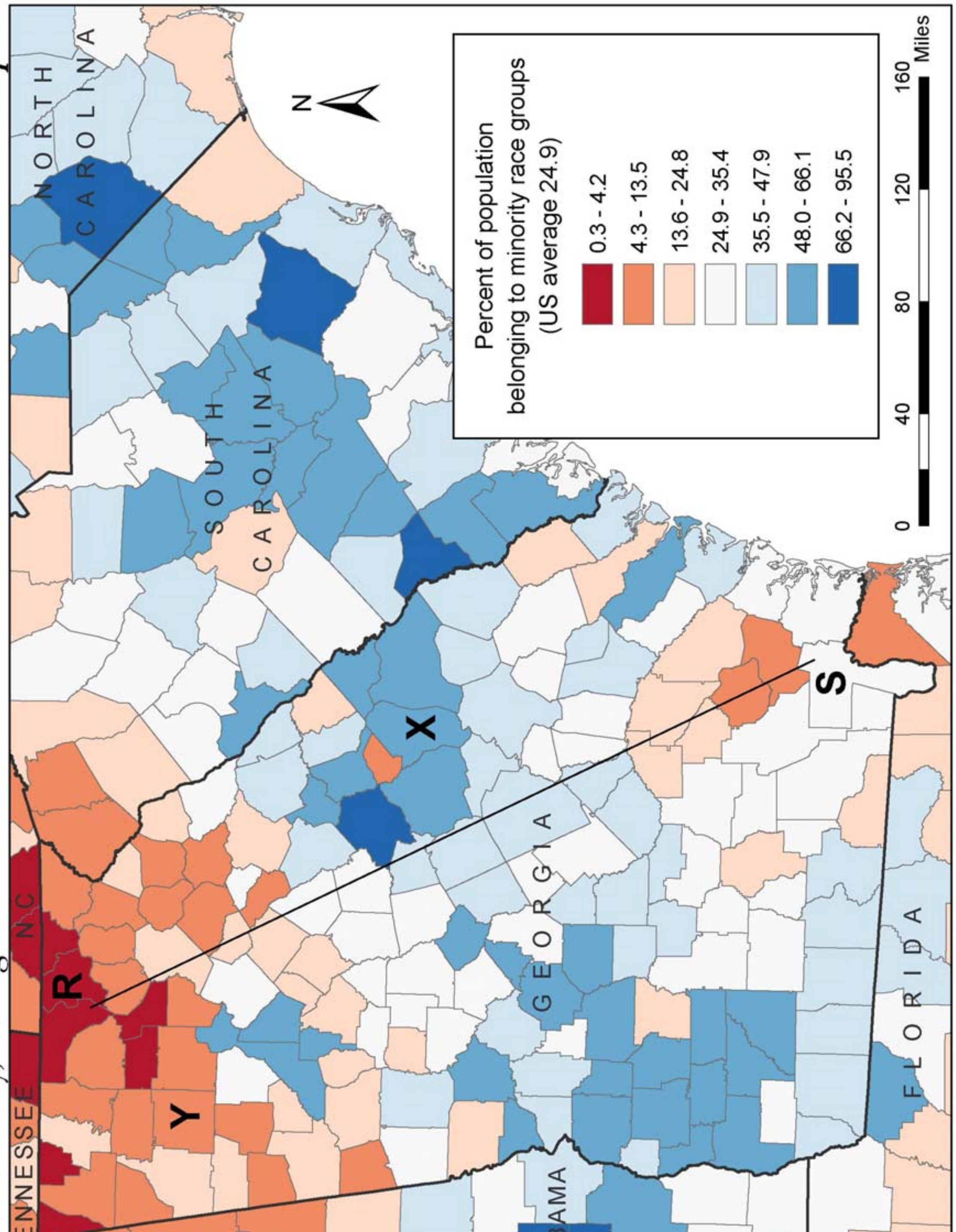
Average Family Size, Idaho

Map 27



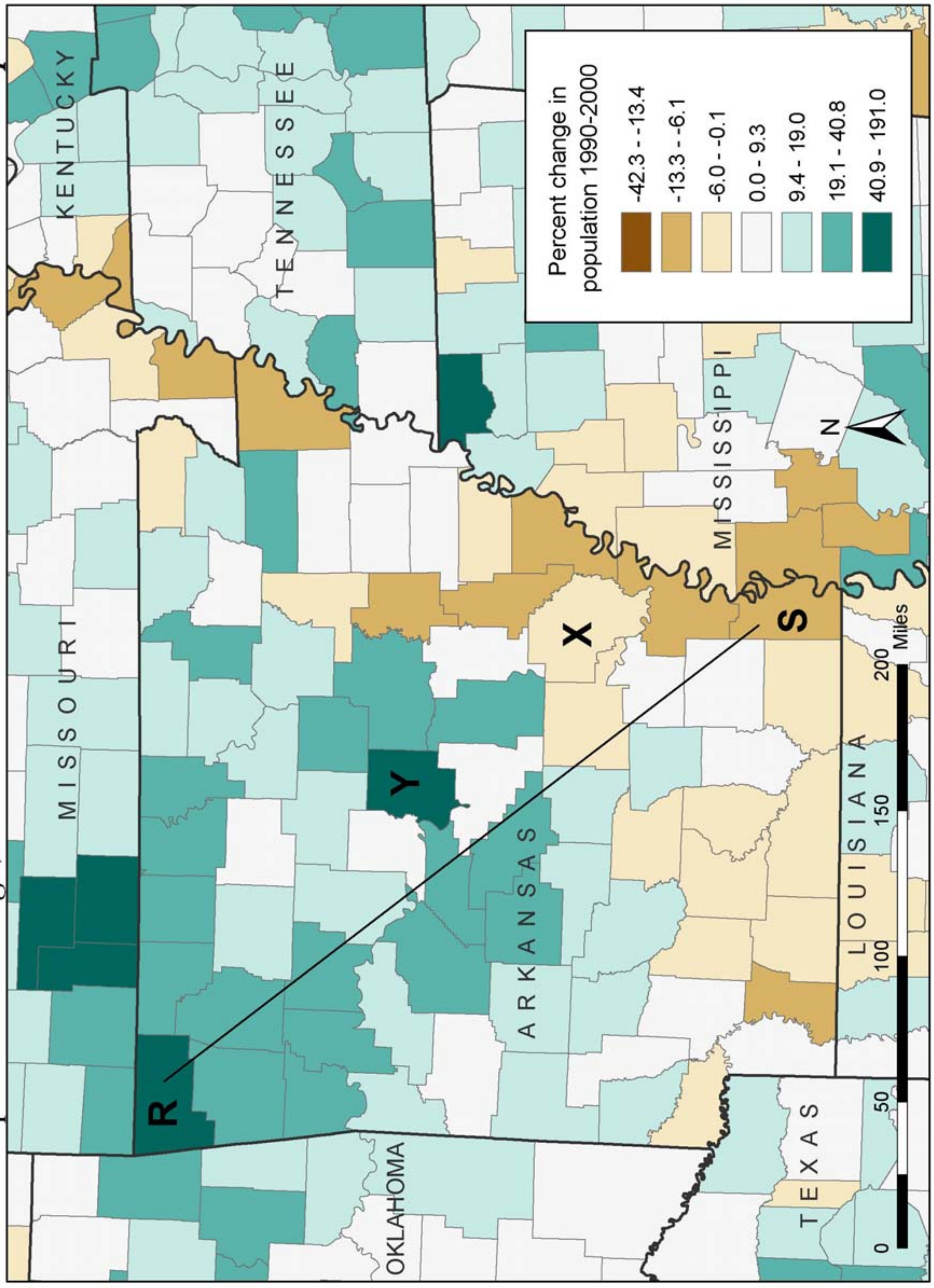
Racial Diversity, Georgia

Map 28



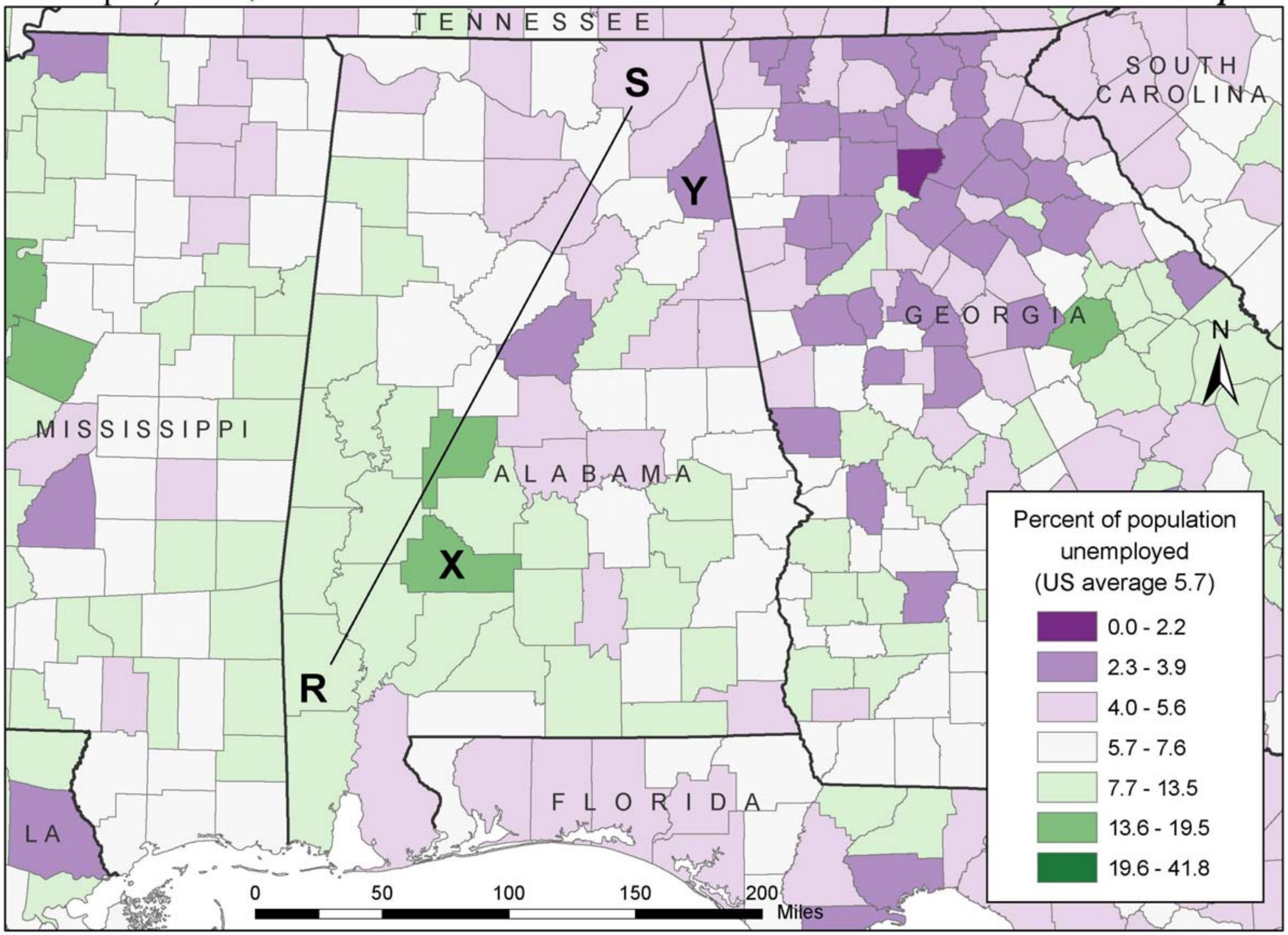
Recent Population Change, Arkansas

Map 29



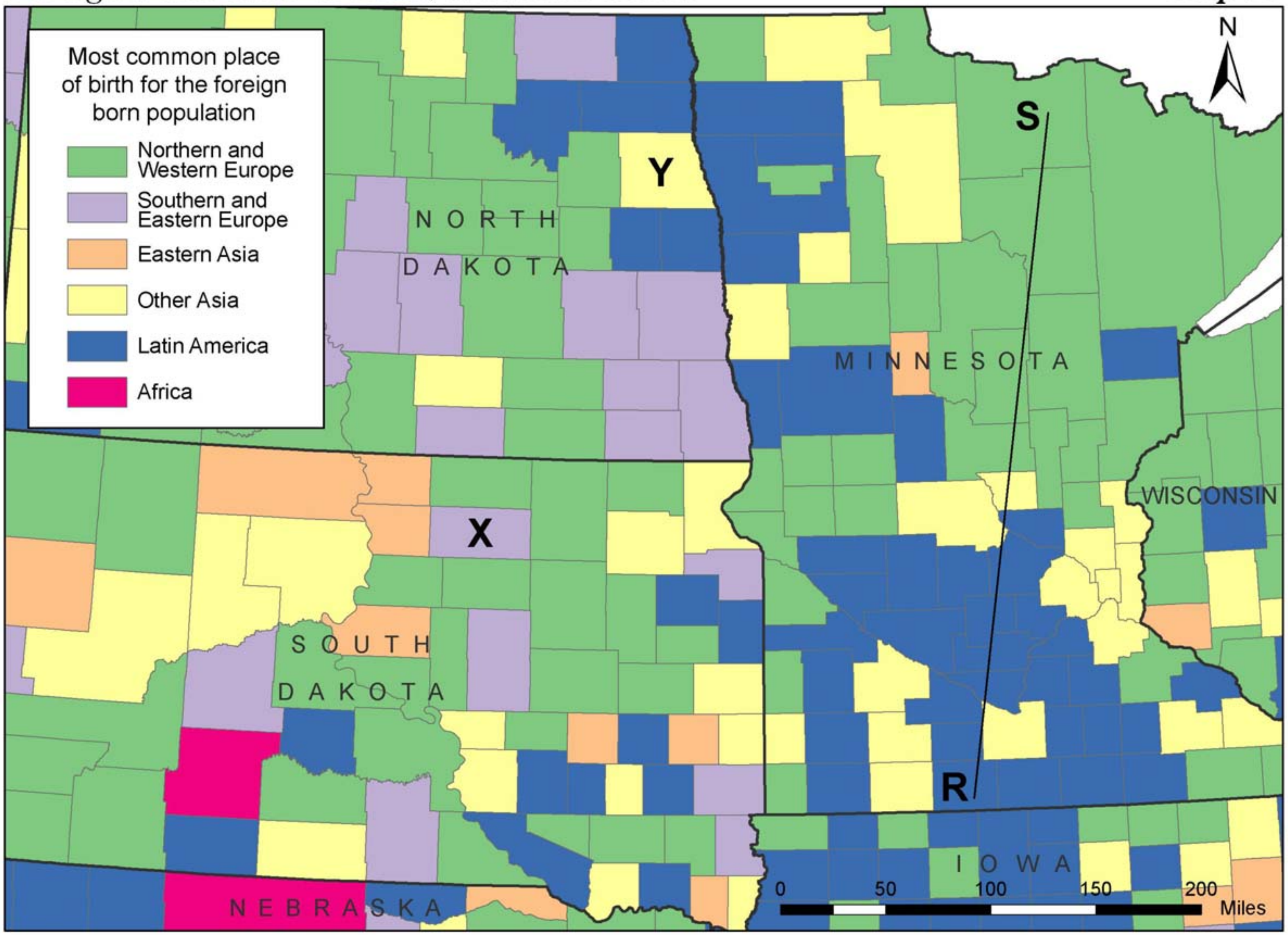
Unemployment, Alabama

Map 30



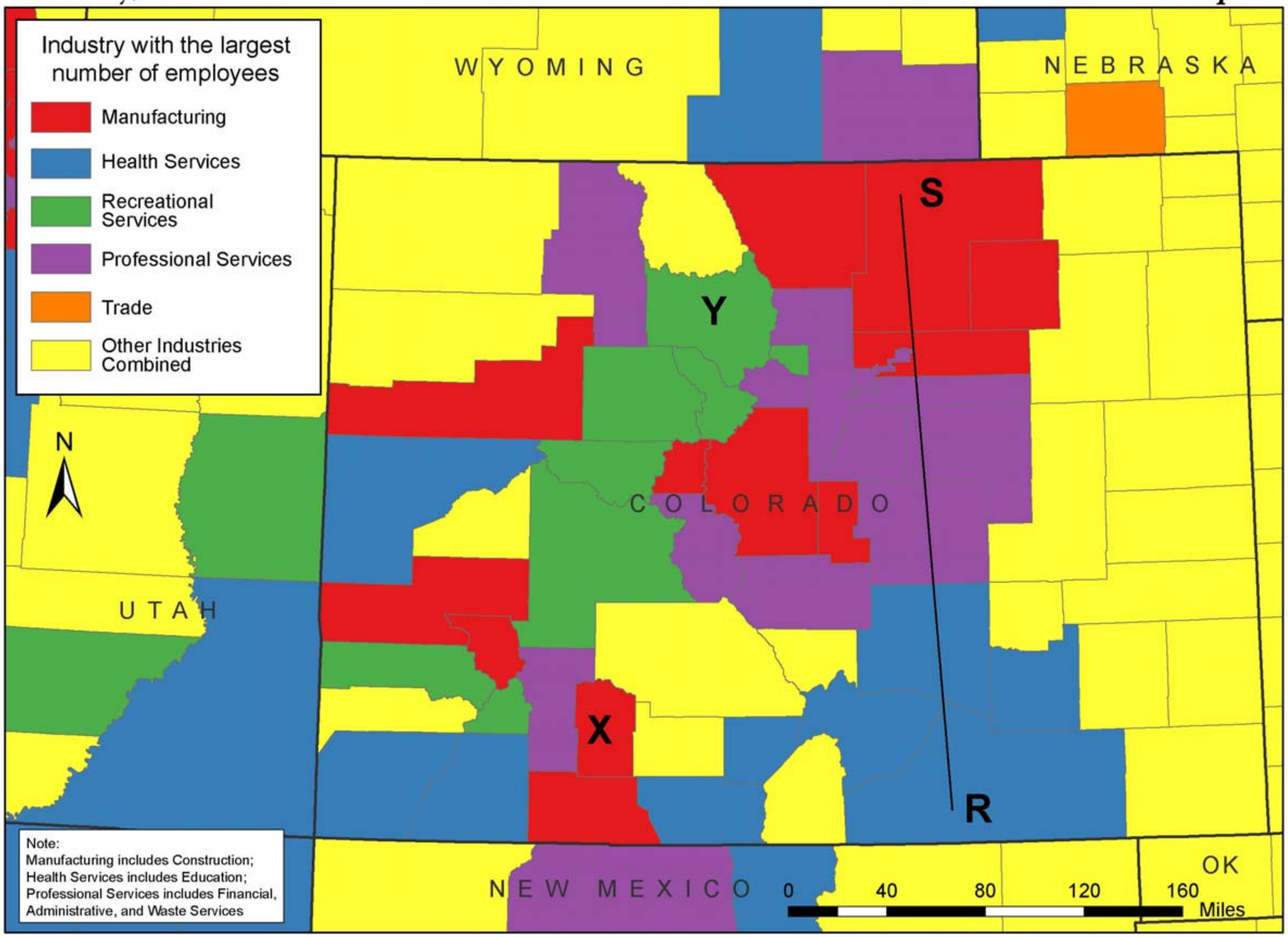
Foreign-born Place of Birth, Northern Plains

Map 31



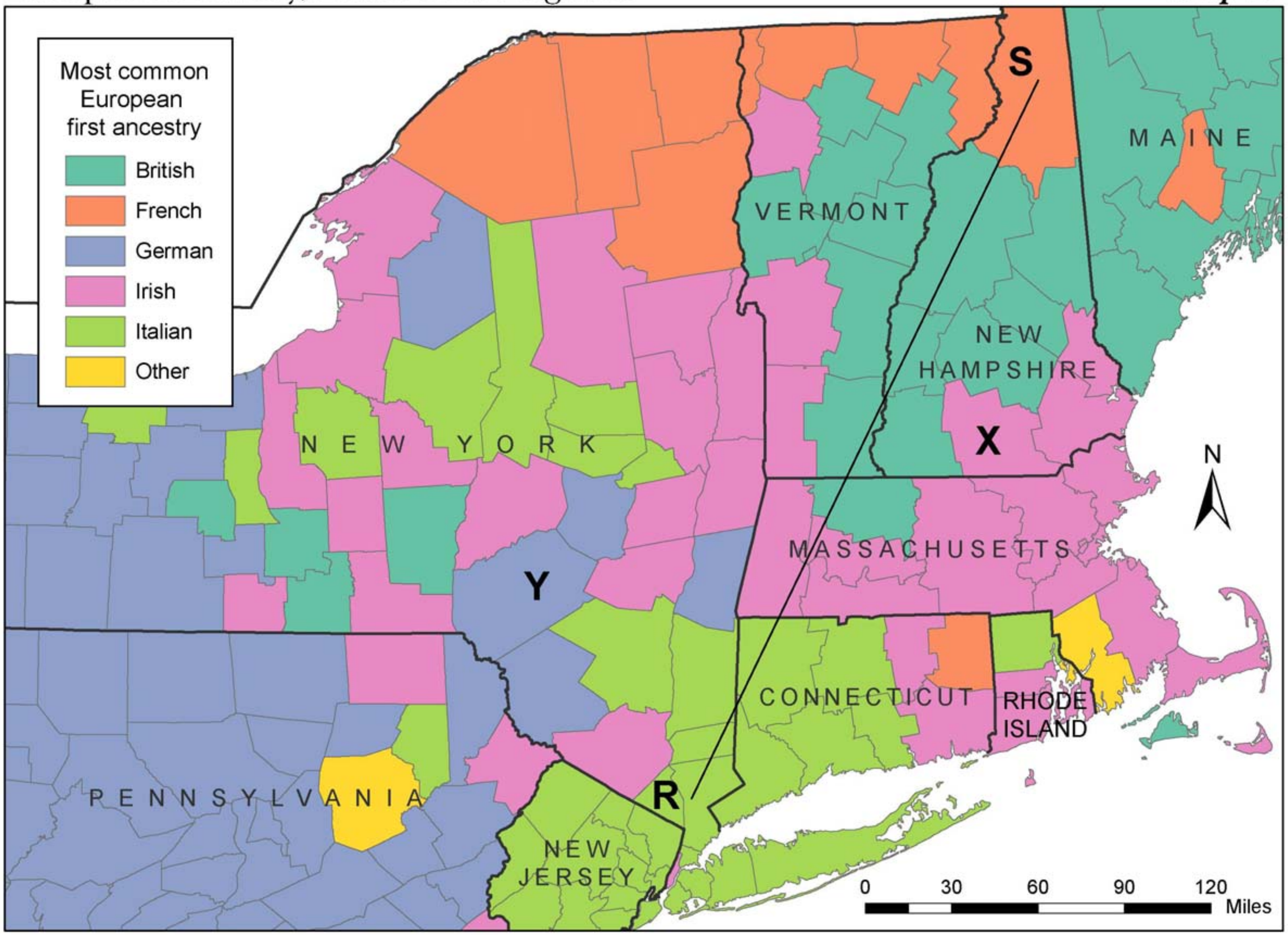
Industry, Colorado

Map 32



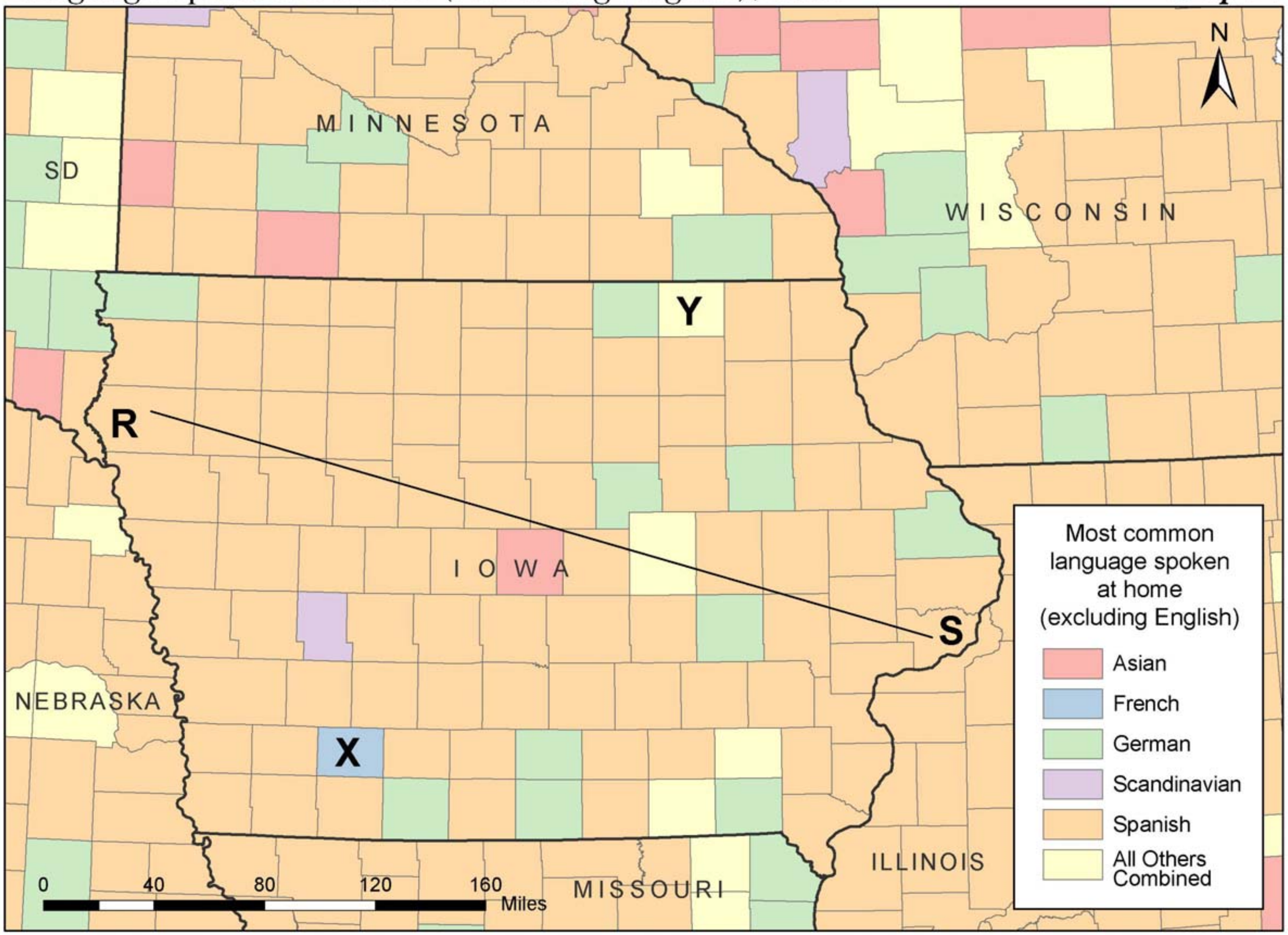
European Ancestry, Lower New England

Map 33



Language Spoken at Home (Excluding English), Iowa

Map 34



Appendix C

Test Form

Subject No.____________
Group___A___S___
Date____________

What number (if any) do you see on the following Ishihara plates?

Plate 1_________

Plate 2_________

Plate 3_________

Plate 4_________

Plate 5_________

Plate 6_________

Plate 7_________

Plate 8_________

Plate 9_________

Plate 10________

Plate 12________

Plate 13________

Map 1

i) The percentage of people over 24 years old with some college or a college degree in county X is between

e. 13.9 – 27.3
f. 27.4 – 34.5
g. 34.6 – 41.5
h. cannot determine with the given colors

ii) The percentage of people over 24 years old with some college or a college degree in county Y is between

a. 27.4 – 34.5
b. 34.6 – 41.5
c. 41.6 – 49.3
d. cannot determine with the given colors

iii) Which of the following most closely describes the overall trend of educational attainment levels across the state from R to S?

a. high to low
b. low to high
c. medium to high
d. cannot determine with the given colors

Map 2

i) The percentage of the population that is over 64 years old in county Y is between

a. 13.5 – 16.6
b. 16.7 – 21.0
c. 21.1 – 34.7
d. cannot determine with the given colors

ii) Which of the following most closely describes the overall trend of the percent of people that are over 64 years old across the state from R to S?

a. high to low
b. medium to low
c. medium to high
d. cannot determine with the given colors

iii) The percentage of the population that is over 64 years old in county X is between

a. 1.8 – 10.1
b. 10.2 – 13.4
c. 13.5 – 16.6
d. cannot determine with the given colors

Map 3

i) Which of the following most closely describes the overall trend in median age across the state from R to S?

a. high to low
b. medium to low
c. low to high
d. cannot determine with the given colors

ii) The median age of the population in county X is between

a. 42.3 – 58.6
b. 38.7 – 42.2
c. 35.6 – 38.6
d. cannot determine with the given colors

iii) The median age of the population in county Y is between

a. 31.5 – 35.5
b. 35.6 – 38.6
c. 20.0 – 31.4
d. cannot determine with the given colors

Map 4

i) The median household income in county X is between

a. 41,001 – 83,000
b. 32,001 – 36,000
c. 36,001 – 41,000
d. cannot determine with the given colors

ii) The median household income in county Y is between

a. 32,001 – 36,000
b. 28,001 – 32,000
c. 36,001 – 41,000
d. cannot determine with the given colors

iii) Which of the following most closely describes the overall trend of median household income across the state from R to S?

a. high to medium to low
b. high to low to medium
c. medium to low to high
d. cannot determine with the given colors

Map 5

i) The number of people per square mile in county Y is between

a. 30.1 – 60.0
b. 10.1 – 30.0
c. 0.0 – 10.0
d. cannot determine with the given colors

ii) Which of the following most closely describes the overall trend of population density across the state from R to S?

a. low to high
b. medium to high
c. low to medium
d. cannot determine with the given colors

iii) The number of people per square mile in county X is between

a. 30.1 – 60.0
b. 60.1 – 150.0
c. 150.1 – 1,100.0
d. cannot determine with the given colors

Map 6

i) Which of the following most closely describes the overall trend in poverty across the state from R to S?

a. low to high
b. medium to high
c. high to low
d. cannot determine with the given colors

ii) The percent of people in poverty in county X is between

a. 11.9 – 14.8
b. 14.9 – 19.6
c. 19.7 – 68.0
d. cannot determine with the given colors

iii) The percent of people in poverty in county Y is between

a. 0.0 – 9.0
b. 9.1 – 11.8
c. 11.9 – 14.8
d. cannot determine with the given colors

Map 7

i) The total number of people in county X is between

a. 85,001 – 10,000,000
b. 36,001 – 85,000
c. 18,001 – 36,000
d. cannot determine with the given colors

ii) The total number of people in county Y is between

a. 18,001 – 36,000
b. 9,001 – 18,000
c. 60 – 9,000
d. cannot determine with the given colors

iii) Which of the following most closely describes the overall trend in total number of people in counties across the region from R to S?

a. low to high
b. high to low
c. consistently high
d. cannot determine with the given colors

Map 8

i) The percent of people in the civilian labor force in county Y is between

a. 61.2 – 67.1
b. 46.4 – 55.0
c. 55.1 – 61.1
d. cannot determine with the given colors

ii) Which of the following most closely describes the overall trend of the percent of people in the civilian labor force across the state from R to S?

a. low to medium
b. medium to high
c. high to low
d. cannot determine with the given colors

iii) The percent of people in the civilian labor force in county X is between

a. 61.2 – 67.1
b. 46.4 – 55.0
c. 55.1 – 61.1
d. cannot determine with the given colors

Map 9

i) The average number of people per family in county Y is between

a. 3.44 – 3.69
b. 2.79 – 2.98
c. 2.30 – 2.78
d. cannot determine with the given colors

ii) Which of the following most closely describes the overall trend of average family size across the state from R to S as compared to the U.S. average?

a. above average with an abrupt change to below average
b. below average with a gradual change to above average
c. consistently below average
d. cannot determine with the given colors

iii) The average number of people per family in county X is between

a. 2.99 – 3.13
b. 3.29 – 3.43
c. 3.14 – 3.28
d. cannot determine with the given colors

Map 10

i) Which of the following most closely describes the overall trend in the percent of the population belonging to minority groups across the state from R to S as compared to the U.S. average?

a. greatly below average to above average to below average
b. above average to average to greatly above average
c. below average to above average
d. cannot determine with the given colors

ii) The percent of the population belonging to minority groups in county X is between

a. 35.5 – 47.9
b. 4.3 – 13.5
c. 48.0 – 66.1
d. cannot determine with the given colors

iii) The percent of the population belonging to minority groups in county Y is between

a. 13.6 – 24.8
b. 4.3 – 13.5
c. 48.0 – 66.1
d. cannot determine with the given colors

Map 11

i) The percent change in population from 1990 – 2000 in county X is between

a. -6.0 – -0.1
b. 9.4 – 19.0
c. 19.1 – 40.8
d. cannot determine with the given colors

ii) The percent change in population from 1990 – 2000 in county Y is between

a. -13.3 – -6.1
b. 19.1 – 40.8
c. 40.9 – 191.0
d. cannot determine with the given colors

iii) Which of the following most closely describes the overall trend in population change from 1990 – 2000 across the state from R to S?

a. very low to high to very high
b. very high to high to low
c. high to low to very high
d. cannot determine with the given colors

Map 12

i) The percent of the population that is unemployed in county Y is between

a. 0.0 – 2.2
b. 2.3 – 3.9
c. 19.6 – 41.8
d. cannot determine with the given colors

ii) Which of the following most closely describes the overall trend in unemployment across the state from R to S?

a. greatly below average to greatly above average
b. slightly above average to slightly below average
c. slightly below average to slightly above average
d. cannot determine with the given colors

iii) The percent of the population that is unemployed in county X is between

a. 2.3 – 3.9
b. 19.6 – 41.8
c. 13.6 – 19.5
d. cannot determine with the given colors

Map 13

i) Which of the following most closely describes the overall trend in net gain or loss of population across the state from R to S?

a. major losses to minor gains
b. moderate gains to minor losses
c. minor gains to major losses
d. cannot determine with the given colors

ii) The net gain or loss of population in county X is between

a. 7,001 – 24,000
b. 0 – 2,000
c. -3,000 – -1
d. cannot determine with the given colors

iii) The net gain or loss of population in county Y is between

a. 7,001 – 24,000
b. 24,001 – 220,000
c. -20,000 – -3,001
d. cannot determine with the given colors

Map 14

i) Which of the following most closely describes the overall trend across the region from R to S of the most common place of birth for foreign born people?

a. Africa to Northern and Western Europe
b. Latin America to Northern and Western Europe
c. Other Asia to Latin America
d. cannot determine with the given colors

ii) The most common place of birth for the foreign born population in county X is

a. Latin America
b. Northern and Western Europe
c. Southern and Eastern Europe
d. cannot determine with the given colors

iii) The most common place of birth for the foreign born population in county Y is

a. Eastern Asia
b. Other Asia
c. Africa
d. cannot determine with the given colors

Map 15

i) The industry with the largest number of employees in county X is

a. Manufacturing
b. Health Services
c. Trade
d. cannot determine with the given colors

ii) The industry with the largest number of employees in county Y is

a. Professional Services
b. Recreational Services
c. Other Industries combined
d. cannot determine with the given colors

iii) Which of the following most closely describes the overall trend across the state from R to S of industries with the largest number of employees

a. Health Services to Professional Services to Manufacturing
b. Trade to Recreational Services to Manufacturing
c. Health Services to Professional Services to Recreational Services
d. cannot determine with the given colors

Map 16

i) The most common European ancestry in county Y is

a. British
b. Italian
c. German
d. cannot determine with the given colors

ii) Which of the following most closely describes the overall trend across the region from R to S of most common European ancestry?

a. Italian to German to British
b. Other to German to British
c. Italian to British to French
d. cannot determine with the given colors

iii) The most common European ancestry in county X is

a. French
b. Irish
c. German
d. cannot determine with the given colors

Map 17

i) Which of the following most closely describes the overall trend in most common household language other than English across the state from R to S?

a. Spanish to German
b. Consistently Spanish
c. Consistently German
d. cannot determine with the given colors

ii) The most common non-English language spoken at home in county X is

a. German
b. Scandinavian
c. French
d. cannot determine with the given colors

iii) The most common non-English language spoken at home in county Y is

a. Spanish
b. German
c. All others combined
d. cannot determine with the given colors

Appendix D

Interview Guide

For the on-screen map:

- How confusing was it for you to use this color scheme?
- Do any of the colors of this scheme look similar to you? Explain.
- What name would you give to this color scheme?
- Do you feel you took more or less time to read the map using this color scheme?
- Did you have any other problems with or thoughts about this color scheme?

For the printout version showing all of the variations of the color scheme based on number of classes:

- Which of these variations of the color scheme do you have trouble with?
- At which number of classes do you start to have trouble perceiving difference between the colors?
- For qualitative schemes, when confusing colors in a set number of classes are found, is there a color or colors that could be moved into the set to replace a confusing color?
- How does the color scheme viewed on paper compare to the color scheme viewed on screen?

Appendix E

Recruitment Flyers

Are You Colorblind???

Colorblind volunteers are needed for a Penn State research experiment testing color schemes for map reading ability

$10 compensation provided
for one hour of your time

If interested please contact

Mr. Steven Gardner
Department of Geography,
Pennsylvania State University
phone: (814) 441-1647
email: sdg150@psu.edu

Men with normal color vision

Make an easy $10

Male volunteers are needed for a
Penn State Geography research
experiment testing color schemes for
map reading ability.

$10 provided for 45 minutes of your time.

For more information, please contact

Mr. Steven Gardner
Department of Geography,
Pennsylvania State University
phone: (814) 441-1647