

## Hal Shelton Revisited: Designing and Producing Natural-Color Maps with Satellite Land Cover Data

*Tom Patterson*  
*US National Park Service*

*Nathaniel Vaughn Kelso*  
*National Geographic*

This paper examines natural-color maps by focusing on the painted map art of Hal Shelton, the person most closely associated with developing the genre during the mid twentieth century. Advocating greater use of natural-color maps by contemporary cartographers, we discuss the advantages of natural-color maps compared to physical maps made with hypsometric tints; why natural-color maps, although admired, have remained comparatively rare; and the inadequacies of using satellite images as substitutes for natural-color maps. Seeking digital solutions, the paper then introduces techniques for designing and producing natural-color maps that are economical and within the skill range of most cartographers. The techniques, which use Adobe Photoshop software and satellite land cover data, yield maps similar in appearance to those made by Shelton, but with improved digital accuracy. Full-color illustrations show examples of Shelton's maps and those produced by digital techniques.

**Keywords:** Adobe Photoshop, Blue Marble, Hal Shelton, Jeppesen Map Company, Library of Congress, MODIS Vegetation Continuous Fields, National Geographic Society, natural-color maps, National Land Cover Dataset, raster land cover data, satellite images, shaded relief, The Living Earth, Tibor Tóth, US Geological Survey.

### INTRODUCTION

Natural-color maps are some of the most admired physical maps. The combination of land cover colors and shaded relief brings to the printed map a colorized portrait of the landscape that closely approximates what people see in the natural world around them. Green represents forest, beige represents desert, and white represents ice and snow, and so forth. By basing map colors on the colors humans observe everyday in nature, the goal is to create physical maps that, despite their complex content, are easy to understand and more universally accessible to diverse audiences.

A discussion of American natural-color maps by necessity must start with the pioneering work of retired USGS (US Geological Survey) cartographer Hal Shelton for the Jeppesen Map Company during the 1950s and 60s. The first half of this paper offers a retrospective on Shelton's career and cartographic output, which, nearly fifty years later, still stands as some of the finest natural-color maps ever made (Figure 1). That he painted many natural-color maps with the apparent detail and realism of satellite images—years before the launching of the first satellites—is a visualization accomplishment worthy of our attention today.

The second half of the paper fast-forwards to the present day. Drawing upon Shelton's work as inspiration, we examine how to make natural-color maps digitally from raster land cover data derived from satellite imagery. We work with USGS National Land Cover Dataset and MODIS Vegetation Continuous Fields, produced by NASA and the University of Maryland. These two products detect, model, and classify land cover

differently, which in turn affects the use of these data for cartographic presentation. Step-by-step instructions and illustrations show how to create polished natural-color maps from raw data. The design focus is on small-scale continental maps similar to those made by Shelton.

### HAL SHELTON AND NATURAL COLOR MAPS

Shelton's development of natural-color mapping evolved over several decades and was not, in his words, "part of a grand design." Nor was his entry into the cartographic profession.

#### The accidental cartographer

Shelton was born in 1916 in New York State and moved with his family at an early age to southern California, where he grew up. Today he lives in the Rocky Mountain foothills above Denver, Colorado. His cartographic career began in 1938 after he graduated from Pomona College, California, with a degree in scientific illustration. Launching a career during the Great Depression with a background in art posed a challenge for Shelton. The only work that he could find was with a USGS field topography team conducting plane table surveys, starting out as a rod man. Although Shelton enjoyed mapping and working outdoors, he had other career aspirations. After one year with the USGS, he went back to college, received a Master of Arts degree in education, and took a teaching position with the San Diego school district. Shelton's brief mapping career would have ended unnoticed at this point had it not been for the start of WWII (Shelton, 2004).

Because of his field mapping experience, during the WWII years Shelton found himself again employed by the USGS, mapping areas considered strategically important in the western United States. It was in the remote Jarbridge Mountains of northeastern Nevada that Shelton, now a full-fledged USGS topographic engineer, first began thinking about the presentation of terrain on maps, a process that would eventually lead him to natural colors (Shelton, 1985). Seeking place name information from the local residents, Shelton discovered that they could not read the contour map that he had just made. However, when he pointed across the valley to the rugged silhouette of the Jarbridge Mountains, the residents—there were seven in all—could readily identify Red Mountain, Old Scarface, and the other peaks. This experience convinced Shelton that the conventional symbology used on topographic maps was inadequate for depicting the landscape in a manner easily understandable by general audiences. The map symbology that he encountered was specialized and anachronistic even by 1940s standards. For example, the USGS manual at that time specified using a green tint for vegetation only for areas where you could hide a small detachment of troops or nine mules. Shelton—the artist, teacher, and by now a committed US government cartographer—was determined to find a better way.

#### Becoming a terrain artist

Shelton's subsequent government assignments took him away from the field and to Washington, DC, Kansas, and finally to Colorado, where he spent the remainder of his career. Working indoors now, he began experimenting with shaded relief presentation, an effort that eventually paid off with his appointment as Chief Cartographic Engineer for the USGS Shaded Relief Map Program. Under Shelton's direction the quantity and quality of shaded relief usage on USGS maps increased. His early shaded



Figure 1. A portion of Hal Shelton's 1:5,000,000-scale New Europe map painted ca. 1968. The original measures 107 x 137 centimeters. Drainages and water bodies are photomechanical additions to the original art. Courtesy of Rand McNally & Company. (see page 69 for larger color version)

*"Seeking place name information from the local residents, Shelton discovered that they could not read the contour map that he had just made."*

relief work included large-scale maps of Yosemite Valley, California, and Valdez, Alaska. These maps emphasized topographic form and relative elevation by combining brown shaded relief with a green lowland tint, overlaid with lightly printed contours. His relief presentation style during this time was strictly conventional.

Shelton's first attempt at natural-color mapping occurred while on temporary duty with the US Air Force. His primary assignment was designing aeronautical charts for use in airplane cockpits in low light conditions. Of greater relevance to our story was another assignment redesigning an aeronautical chart of a remote corner of the Sahara (for use under full lighting). The replaced chart used conventional symbology—a dense network of blue lines portrayed intermittent wadis and a green tint filled lowland areas all but devoid of vegetation. According to Shelton, using this chart “would tempt a pilot to land and go trout fishing.” Referring to the realism of aerial photography, Shelton redesigned the chart to appear appropriately arid mimicking the view seen by a pilot flying over the area. Because lines rarely occur in nature (Shelton firmly believes in avoiding the use of lines on maps wherever possible), the new chart depicted wadis as light streaks across the brown desert floor. Shelton also depicted volcanic rocks with rough-textured dark tones. The original chart based on conventional symbology lacked a way to depict these areas, so its author resorted to a label stating “area of dark rocks.” According to Shelton, such text labels are evidence of a map's failure to communicate. Nor is he keen about legends, which he views as unnecessary on a properly designed map. He defines a map as

*“According to Shelton, such text labels are evidence of a map's failure to communicate. Nor is he keen about legends, which he views as unnecessary on a properly designed map.”*

“A graphic instrument of communication that transfers information from the awareness of a person with information to the awareness of a person without that information.”

Shelton thinks of map-making as a two-step process, each of roughly equal importance. The first step involves the accurate gathering of data. The second step is the depiction of that data using a “cartographic language or vocabulary” (1985, videotape interview) —terms he uses often and interchangeably—that others can easily understand. Map making is also an expression of Shelton's feelings for the land, especially wild places

*“Aviation and aeronautical charting played a central role in Shelton's early thinking about natural-color maps.”*

“It smells different on top of a mountain than it smells down in the valley, it sounds different at the top. As you climb... you're getting a tremendous amount of information.” (1985, videotape interview)

To Shelton a successful map was one that permitted another person to

“...to smell the mountain and hear the wind.” (1985, videotape interview)

Shelton would often fly over the western states with his brother, who was a geologist and a pilot. These flights gave Shelton a firsthand impression of the land from above, a view unimpeded by the graphical filtering of maps. Aviation and aeronautical charting played a central role in Shelton's early thinking about natural-color maps. In the next phase of his career it became even more important.

## The Jeppesen Natural-Color Map Series

Shelton began his natural-color map career with a USGS colleague by making freelance recreational maps of Colorado. These maps attracted the attention of Elrey Borge Jeppesen, a United Airlines pilot who had started a company that published aeronautical charts and other navigational information for pilots (NAHF, 2002). He also wanted to publish general maps catering to the ever-increasing numbers of air travelers. For the first time the public at large was seeing Earth from directly above and Jeppesen believed that Shelton's natural-color maps would provide passengers with more relevant information than conventional maps. Jeppesen and Shelton teamed up in the early 1950s. Their business association spanned two decades and yielded more than 30 titles in what was to become *The Jeppesen Natural-Color Map Series*. The contract work for Jeppesen provided an outlet for Shelton's creative talents and a public forum for his cartographic art, which received worldwide acclaim. The USGS never published any of his natural-color maps.

Jeppesen paid Shelton by the square inch for painting natural-color base maps. Depending on the complexity of an area, not all square inches were equal. Any given square inch might take anywhere from one hour to one day to complete. Initially Shelton used a Paasche AB airbrush to apply colors, but he thought the results looked too smooth and unnatural. Painting with 00 and 000 brushes, although slower, brought a more natural texture to his work. However, he still used the airbrush in splatter mode to speckle his maps with tiny green dots to represent widely dispersed trees and brush, such as the pinyon-juniper vegetation that typifies the Colorado Plateau. Because vegetation doesn't generally transition abruptly in nature, Shelton sought to depict these boundaries with soft edges on his maps.

Since this was the era of photomechanical reproduction, painting base maps on a stable material proved essential. One problem was seeing underlying compiled line work after applying the first layer of paint. The zinc plates used by the printing industry provided the solution. By etching line work 0.05 millimeters (0.002 inches) into the plates the compilation remained faintly visible (when illuminated obliquely) even when covered with paint, and the etchings did not interfere with reproduction. He would start painting by applying a white base coat to the zinc plate. He preferred acrylics because they yielded bright white and vivid colors. Next he painted swaths of flat color blending into one another to represent the land cover. At this point the map was ready for the application of shaded relief, achieved by painting light and dark tones based on each of the underlying land cover colors. Shelton painted the land tones extending well into water bodies with the idea that a water plate produced separately would clip these tones at the coastline later. Lastly, the map underwent a "balancing step" to give topographic features appropriate emphasis in relation to one another.

Large quantities of geographic information went into making natural-color maps that were easy-to-read and informative. Land cover, vegetation, topography, geology, and climate all factored into his interpretation of the landscape. Shelton was by no means alone in this effort. Jeppesen hired a team of geographers to compile base line work, which guided Shelton's painting. Shelton and the geographic team devised a standardized classification and colors for depicting land cover worldwide (Figure 2). Considerable discussion ensued over classifications and terminology—one person's scrubland was another's shrub land, or is brush a better term? Is chaparral a type of forest or should it be an entirely separate

*"The contract work for Jeppesen provided an outlet for Shelton's creative talents and a public forum for his cartographic art, which received worldwide acclaim."*

*"Considerable discussion ensued over classifications and terminology—one person's scrubland was another's shrub land, or is brush a better term?"*

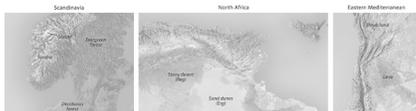


Figure 2. Shelton's standardized palette of natural colors captured the character of disparate geographic regions worldwide. Courtesy of Rand McNally & Company. (see page 69 for larger color version)

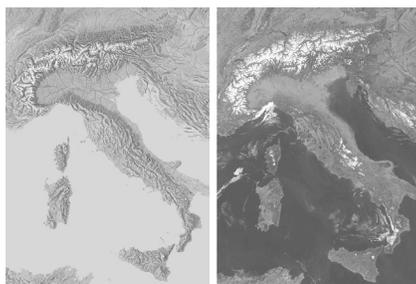


Figure 3. (left) Excerpt of a natural-color map painted by Hal Shelton ca. 1968. (right) NASA MODIS satellite image taken in 2003. Map on left courtesy of Rand McNally & Company. (see page 70 for larger color version)

*“At this conference Imhof praised Shelton's natural-color maps . . . However, the two men did not see completely eye to eye.”*

category? The questions were as varied as the world itself. They settled on ten categories:

Ice and snow	Shrub land
Tundra	Farmland (irrigated)
Evergreen forest	Lava flows
Deciduous forest	Sand dunes
Grassland	Tropical forest

This mix of mostly vegetation zones and physiographic formations may seem eclectic at first glance. All of the categories, however, are well suited for distinctive depiction on a map. The goal after all was making readable and informative maps as opposed to classifying world land cover in a scientifically consistent manner. Thinking that too many colors might overwhelm the reader, Shelton favored using fewer categories but the other team members convinced him otherwise. Judging by the readability of the finished plates, his concerns did not materialize, no doubt because of the artistic skill he applied to the task. In a classification dominated by nature, the inclusion of farmland is noteworthy because it acknowledges the impact of humans on the land—a fact plainly obvious to anyone flying over the checkerboard fields of the US Midwest. With crosshatched brush strokes Shelton represented these field patterns on his maps. Built up areas are the one major land cover category conspicuously absent from Shelton's painted bases. Admittedly, however, urban sprawl was not nearly as widespread then as it is today. To depict urban areas on the Jeppesen maps, bright yellow area tones were applied photo mechanically in a second step for final printing.

Shelton/Jeppesen maps covered all areas of the globe. Uses included wall maps and textbook maps for schools and colleges, commercial promotion, and passenger maps for many airlines (Library of Congress, 1985). Because of their detail and realism, NASA used these maps to locate and index photos of Earth taken on early space missions (Figure 3).

In 1961, Elrey Jeppesen sold his firm to the Times Mirror Publishing Company of Los Angeles but remained as president. Shelton also continued working for the new owners until the late 1960s. In 1985, the HM Gousha Company, a subsidiary of the Times Mirror Publishing Company, donated 29 original plates painted by Shelton to the US Library of Congress. The Shelton Collection, as it is now called, has grown to some 33 plates and miscellaneous other materials. Rand McNally & Company in 1996 acquired the assets of HM Gousha, which no longer exists, thereby inheriting copyright ownership of Shelton's plates housed at Library of Congress (see Appendix A). The Shelton Collection can be viewed by appointment in the Map Reading Room.

### Cartographic contemporaries

Shelton's colleagues in the cartographic profession influenced his thinking about natural-color maps, particularly those from the Alpine countries of Europe. The famous Walensee Map painted by Eduard Imhof in 1938, which masterfully combines land cover colors and shaded relief, directly influenced Shelton. Shelton and Imhof met in 1958 at the 2<sup>nd</sup> International Cartographic Conference in Chicago, the so-called “Rand McNally” conference. At this conference Imhof praised Shelton's natural-color maps saying, “there is nothing more that I can contribute.” However, the two men did not see completely eye to eye. Afterwards Imhof visited Shelton at his studio in Golden, Colorado, for about a week.

According to Shelton, they politely agreed to disagree on the use of color on physical maps. Imhof favored using color exclusively for modeling topographic forms and depicting altitude, arguing that combining land cover colors with shaded relief only weakens the presentation of topography. Discussing Shelton's work in his 1982 text, *Cartographic Relief Presentation*, Imhof states

"At the small scale, however, the relief forms and the ground cover mosaic are so finely detailed and often have so little relation to one another that in certain areas great complexity and distortions of the relief are unavoidable. As a result of the flatness and spaciousness of the "models," distinct aerial perspective hypsometric tints can scarcely be achieved by such combinations." (344-45)

Imhof's point is valid—if one's sole aim is portraying topography on a physical map. Shelton's approach to physical mapping, however, is more holistic. Shelton regarded the physical world not as a cartographic abstraction, such as elevation above sea level, but as the colors and forms processed by his mind from reflected light observed outdoors. What was on the terrain surface mattered as much as the terrain surface itself. If a landscape looked arid and sun bleached, so too should its depiction on a map.

Shelton's closest cartographic soul mate from Europe was, perhaps, Heinrich Berann of Austria. Like Shelton, Berann came from an art and illustration background and painted panoramic maps lavishly adorned with colors depicting land cover and vegetation (Patterson, 2000). Shelton departed from Berann's technique in using natural colors on plan maps viewed from directly above. Although Shelton never met Berann, he admired his work. He once had a German-speaking neighbor on vacation call on Berann to obtain his color formulas. A page and a half of detailed instructions on paint mixing resulted from the visit. However, Shelton found Berann's palette to be based more on artistic considerations than observed nature, so he devised his own. One of Berann's colors that did find its way into Shelton's palette, however, was yellow-green for depicting humid grasslands, pastures, and meadows. Bright and decidedly unnatural, this green occasionally detracts from Shelton's otherwise balanced colors, at least according to the authors' tastes. The primitive color printing of that time only exacerbated this problem. To be fair to Shelton, nearly all terrain artists from that era relied on this particular shade of green; such was the dominant influence of Heinrich Berann.

On this side of the Atlantic, Richard Edes Harrison was a contemporary of Shelton's in the arena of cartographic relief presentation. He was renowned for creating artistic "over-the-horizon maps" for *Fortune* magazine, and shaded relief plates containing fine physiographical detail. Both men were similar in that they came to cartography from illustration backgrounds, and they were both innovators and cartographic populists. Harrison colored his maps in a conventional manner, which offered no guidance to Shelton's development of natural colors. However, Harrison's monochromatic portrayal of textured lava flows, sand dunes, and other physiography influenced Shelton's mapping style, which gained in detail over the years (Shelton, 2004).

### Why natural colors?

In terms of willingness to experiment with color, Shelton fell somewhere between the conventional colors preferred by Imhof and Harrison, and the

*"Shelton regarded the physical world not as a cartographic abstraction, such as elevation above sea level, but as the colors and forms processed by his mind from reflected light observed outdoors."*

*"In terms of willingness to experiment with color, Shelton fell somewhere between the conventional colors preferred by Imhof and Harrison, and uninhibited end of the color spectrum preferred by Berann."*

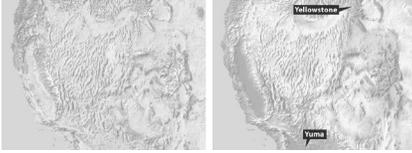


Figure 4. (left) A shaded relief map of southwestern United States combined with natural colors. (right) The same map with blended hypsometric tints. Although hypsometric tints are attractive and show topography clearly, they can mislead readers about the character of the land. Forests cover the Yellowstone region and Yuma, Arizona, is an extreme desert environment. (see page 70 for larger color version)

*“Creating a tabloid-sized map of moderate complexity required two to three weeks of work with the constant worry that the airbrush could splatter without warning and ruin everything.”*

uninhibited end of the color spectrum preferred by Berann. A half-century ago the key players in the field of relief presentation strongly espoused differing styles. Shelton was in the middle of this fray. The central point of debate then—which continues today but with considerably less fervor—was over appropriateness of hypsometric tints (colors assigned to elevation zones). Shelton regarded hypsometric colors as “arbitrary” and as bearing little relation to the actual color of the land, such as a green lowland tint filling parched desert basins, and red applied to uplands where forests grow. Classic hypsometric tints inverted the sequence of elevation-influenced natural colors observed by Shelton in the landscapes of the US West (Figure 4, right).

Based on the large quantities of maps that display hypsometric tints, an anthropologist a thousand years from now might conclude that our society was elevation-centric. However, the current popularity of hypsometric tints has more to do with production ease and pretty colors than it does with our interest in elevation. Making competent hypsometric tints requires mere minutes to accomplish with a digital elevation model and freeware software. Even the photomechanical techniques of yesteryear were relatively straightforward, albeit much slower. With hypsometric tints, the end result is often a map with pleasing colors that blend softly into one another in an orderly fashion, a design trait that people find attractive, even if they don’t necessarily know or care about elevations. To the average reader the elevation zone between 750 and 2,000 meters in California, for example, which can assume any color in the rainbow on a hypsometric tint map, is artificial, abstract, and, to use Shelton’s favorite term, arbitrary.

By contrast, natural colors on a map are less susceptible to misinterpretation. For example, color-sighted humans tend to associate green with the color of vegetation, brown with aridity, and white as the color of snow (at least people living in the mid and high latitudes). The Nevada residents interviewed by Shelton 60 years ago had named Red Mountain because of its distinctive cast. Recent psychological research suggests that bright colors attract our attention—not really a surprise—and that our memory retention improves on images comprised of natural colors compared to false colors or black and white (Gegenfurtner et al., 2002). Considering the potential for natural-color maps to easily, and perhaps lastingly, communicate geographic information to the user, why then are they so rare? The short answer: they are tremendously difficult to make.

The making of natural-color maps manually requires that a cartographer possess singular artistic talent, broad knowledge of physical geography, and patience—combined traits that are in short supply, particularly where costs are determining factors. Natural-color maps are handcrafted and expensive products. One occasionally sees gaudy, unrefined attempts at natural-color mapping published in tourist brochures, proof that not everyone qualifies for the job title: artist/cartographer. Working with colored pencils, airbrush, watercolors, and acrylics, one of the authors of this article tried over the course of many years to create such maps, but met with only limited success. Creating a tabloid-sized map of moderate complexity required two to three weeks of work with the constant worry that the airbrush could splatter without warning and ruin everything. Shelton was considerably faster in applying pigments to maps. Providing that he had a clear and accurate base to work from, a typical large natural-color map would take about 40 hours to paint (Shelton, 2004).

We must also bear in mind that natural-color maps are not appropriate for all types of general or even physical mapping. The merging of shaded relief and land cover, regardless of how delicately done, creates a level

visual weight and background complexity that may detract from other classes of information depicted on the map. Nothing good comes from printing area colors, such as polygons showing property ownership, on top of natural-colors, or on hypsometric tints for that matter.

Natural-color bases are suited for use with uncluttered general reference maps and thematic maps where the surface environment and interconnectedness matters most. They are most appropriately used at small and medium-scales where the natural colors combine with shaded relief to create textures that appear organic and plausibly realistic. Larger map scales, however, require supplementary bump map textures (a type of 3D embossment) to achieve similar results (Patterson, 2002). Although some cartographers may be loath to admit this as a valid use, natural-color maps make outstanding wall decorations. Even today the airline route maps published by Jeppesen are still one of the best uses ever found for natural-color maps.

**Moving forward**

Today, the foremost practitioner of natural-color mapping is Hungarian-born Tibor Tóth, formerly an employee of National Geographic, and now working freelance. Readers of the *National Geographic Atlas of the World* would quickly recognize Tóth’s work. Showcased prominently, his painted plates of the physical world and continents are associated by many with the distinctive look and feel of National Geographic maps. Toth, a talented artist and cartographer in his own right, consulted with Shelton at his Colorado studio in early 1971. Tóth then developed a natural-color mapping style modified and distinct from Shelton’s, which he first applied to a map of Africa later that same year (Tóth, 1986). Instead of showing existing land cover as Shelton did, Tóth’s maps use color to show potential vegetation based on biogeographer AW Küchler’s data. Potential vegetation shows readers a more abstract interpretation of the landscape without human influences. Imagine if you will, untrammelled North America before the first humans arrived from Asia.

Tóth—before switching to digital production—painted and airbrushed his maps from a standardized palette formulated by carefully mixing paints drop by drop (Tóth, 1973) (Figure 5). The National Geographic tradition in natural-color mapping continues today thanks to Tóth’s successor, John Bonner (Tóth also continues to work freelance for NG). Bonner’s magnum opus was a 3.35-meter-wide globe airbrushed and painted with natural colors that was on display at Explorers Hall in Washington, DC, for more than a decade, up until 2000.

In 1985 the Library of Congress, Geography and Map Division interviewed Shelton on videotape. During the 51-minute interview, Shelton stated his hope that new people and techniques would continue the process of natural-color mapping into the future. He concluded the interview with the advice:

“...that we can be flexible enough to recognize change, and be wise enough to understand those things that don’t change so much, which is the need to have human beings to communicate.”

Turning now to the digital part of this paper, we attempt to follow his advice.

*“Natural-color bases are suited for use with uncluttered general reference maps and thematic maps where the surface environment and interconnectedness matters most.”*

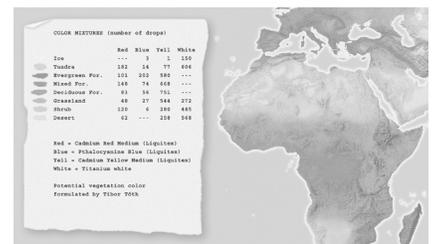


Figure 5. (left) Tibor Tóth’s color formulas. (right) His colors applied to a map. Courtesy of National Geographic. (see page 71 for larger color version)

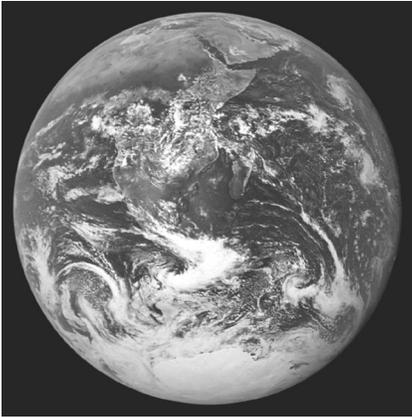


Figure 6. NASA's "Blue Marble" photograph shows Earth from a distance of nearly 48,000 kilometers (30,000 miles). Dominated by the Sahara and Kalahari deserts, Africa is usually the most cloud-free continent. Antarctica is also visible in this image for the first time (NASA, 2002). (see page 71 for larger color version)

*"But more than just a technical means to an end, space imagery has forever changed how people visualize Earth in a realistic context from afar."*

#### SATELLITE IMAGES—SEEING THINGS DIFFERENTLY

If the growth of commercial aviation compelled Shelton to paint natural-color maps, going higher still, the advent of space flight largely defines the genre today as we settle into the digital era. The digital solutions offered in this article for making natural-color maps employ raster land cover data derived from satellite images. But more than just a technical means to an end, space imagery has forever changed how people visualize Earth in a realistic context from afar. The aptly named "Blue Marble" photograph taken by the Apollo 17 crew heading to the moon in 1972 gave us the first full view of oasis Earth set against the emptiness of outer space (Figure 6). Embraced as a symbol of environmental awareness, the "Blue Marble" has become one of the world's most recognized images. And as a natural-color geographical image with pop culture cachet, it is a rarity.

Starting with the launch of Landsat (originally called ERTS—Earth Resources Technology Satellite) in 1972, remotely sensed images of Earth in both natural and false colors have become increasingly abundant with each passing year. The sheer volume of remotely sensed data collected by a multitude of platforms and sensors is difficult to comprehend. A Google search in early 2004 using the key words "satellite images" yields 4,810,000 hits, a coarse, but nevertheless telling barometer of current popularity. Satellite images have also replaced maps as the dominant method of depicting natural color on geospatial products. However, as we shall discuss shortly, quantity and quality are not always directly related. Off-the-shelf satellite images are less than ideal for the presentation of natural color on maps.

Intended primarily for scientific, military, and economic use, satellite images find secondary (and sometimes gratuitous) application in television and print news, posters, coffee table books, and even silk screened on coffee mugs and t-shirts. That atlases sometimes use satellite images and space shots of Earth as cover art points to their marketing potential. These colorful images attract a buyer's attention and deliver a subliminal message that the contents within are scientifically based, accurate, environmentally concerned, and global in scope. Perhaps for similar reasons, a satellite image appears on the cover of the Spring 2002 issue of *Cartographic Perspectives*. Satellite images also serve as fine art. The traveling exhibit "Our Earth as Art" prepared by the Library of Congress, NASA, and USGS is currently showing in museums and other public venues. The 41 images in the exhibit (selected from 400,000 taken since 1999) treat audiences to eye-catching views of Earth from above that appear both surreal and abstract (Stenger, 2002). Trying to identify the images without reading the captions is a pleasurable challenge.

Several popular products containing global satellite data in natural color are available today. "The Living Earth" is one of the older and better-known commercial images (Figure 7, left). The original image derives from 1.1-kilometer-resolution AVHRR (Advanced Very High Resolution Radiometer) data, which NASA began collecting in 1978. While technically sophisticated when first introduced, AVHRR products are beginning to show their age. Contrary to what the name suggests, AVHRR images, judged by contemporary standards, appear coarse, with too much contrast, and contain tonal variations seemingly unrelated to land cover and vegetation. The Living Earth, Inc. now sells updated and improved natural-color images made from Landsat 5 and 7 data. They also have other promising products under development.

Another notable product is NASA's new "Blue Marble," named after the famous photograph taken by the Apollo 17 crew. The "Blue Marble"

derives from MODIS (Moderate Resolution Imaging Spectro-radiometer) data collected at 500-meter resolution and distributed to the public at one-kilometer resolution (Figure 7, right). The “Blue Marble” portrays arid regions with convincing natural colors but is less effective in humid regions, which appear as monotonous green tones. Meteorological interference in the form of snow cover and sea ice in the polar regions is visible, and areas of shallow water appear to have been arbitrarily added and appear discordant with rest of the image.

The “Blue Marble” comes pre-composited with shaded relief generated from GTOPO30 (Global 30-Arc-Second Elevation Data Set) that employs standard cartographic illumination from the northwest. “The Living Earth” image discussed previously also contains shaded relief made from GTOPO30. While the inclusion of shaded relief is a step in the right direction, its legibility diminishes at scales smaller than 100 percent of original size, and, with more significant reduction, disappears entirely. Shaded relief is not nearly as tolerant of reduction as the underlying color tones found in satellite images. While colors tend to blend pleasingly into one another when reduced, shaded relief becomes an unattractive dark smudge. These shortcomings aside, the “Blue Marble” is a remarkable dataset and is invaluable for making 3D visualizations and animations. It is also free.

### Pictures vs. maps

Based on the popularity of satellite images, many of which appear in natural color, it would appear that Shelton’s idea about depicting Earth more realistically has finally taken hold. Well, not quite. The graphical merging of satellite images and maps, two closely related geospatial products, has not happened to any great extent. It is a rare map that uses a satellite image as a raster base in conjunction with other map information, such as labels, lines, area tones, and point symbols. In the cartographic context, satellite images are perhaps most common in atlases as stand-alone thematic insets, decorative introductory pages, and the aforementioned cover art.

The lack of satellite images used as cartographic backdrops, in the same manner as shaded relief or hypsometric tints, has a simple explanation: they are not maps. Remotely sensed images contain traits that are incompatible with basic cartographic design conventions (Figure 8). Dense, detailed, colorful, and contrasting, satellite images tend to dominate all other classes of map information to the point of illegibility. Just as photographic snapshots often contain undesirable visual elements—a jet contrail in the sky above the Grand Canyon—satellite images are similarly afflicted. For example, clear-cut forests in the US Pacific Northwest appear on satellite images as a mottled pattern that distracts from everything else.

Other common problems with satellite images include:

- Meteorological interference — Because clouds on average cover 64 percent of Earth’s surface (54 percent of land areas) at any given time, the odds of finding satellite images completely free of clouds and their shadows are slim at best (Warren, 1995). Even one small cloud on an image requires a cartographer to make a difficult choice—an exercise in cartographic situational ethics. Is it best just to leave the unsightly blemish on the image, or is it proper to quickly remove it with the Clone Stamp (Rubber Stamp) tool in Photoshop? After all, who would ever notice or object? Other meteorological interference encountered on satellite images includes snow-covered ground, frozen water bod-

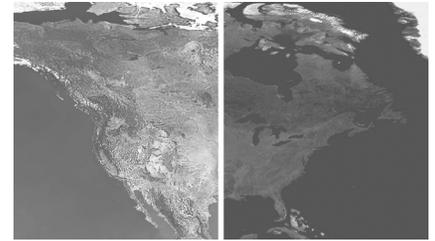


Figure 7. (left) “The Living Earth.” (right) NASA’s new “Blue Marble.” (see page 72 for larger color version)

*“Even one small cloud on an image requires a cartographer to make a difficult choice—an exercise in cartographic situational ethics.”*

*“When using satellite images as backdrops on maps, boring is better.”*

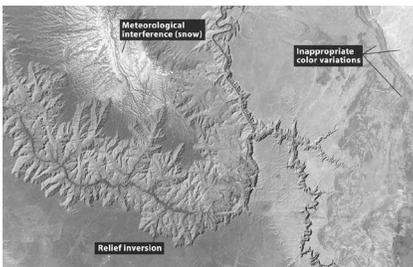


Figure 8. A natural-color Landsat image of the Grand Canyon made from bands 2, 4, and 7. Even the handsomest satellite images contain graphical elements inconsistent with cartographic design goals. Courtesy of the USGS. (see page 72 for larger color version)

ies, smog, smoke plumes from wildfires, and lowland flooding. Such undesirable traits plague many of the satellite images available online for free, which are provided by organizations that monitor the environment and natural disasters. When using satellite images as backdrops on maps, boring is better.

- **Inappropriate color variations** — It is typical for natural color satellite images to contain at least some colors that are decidedly unnatural. Despite appearances, natural-color satellite images are not truly photorealistic. They typically consist of “bands” of electromagnetic radiation data from outside the visible spectrum. By inserting these data, in the form of 8-bit grayscale images, into the red, green, and blue channels of, say, a TIF image, the results are a concocted scene with ersatz natural colors—if the mixing and matching of data and colors are done correctly. The inappropriate color variations flagged in Figure 8 are in an area of uniform desert shrub. The cause of these pronounced variations, which are invisible to humans on the ground, might be differing mineral or moisture content in the exposed soil—information only of interest to a few people in specialized fields. Regardless of what the colors represent, they are too prominent compared to other colors on the image and do not belong on a general-purpose map.
- **Relief inversion** — The southeast lighting (lower right) found on most high-resolution satellite images when north-oriented causes an optical illusion known as relief inversion, whereby mountains appear as valleys, and vice versa. Because being able to tell up from down is so fundamental, the presence of relief inversion is completely unacceptable on maps. Removing the embedded shadows that cause relief inversion on satellite images is technically difficult and yields poor results, especially in areas of high, sharp relief where shadows are entirely black. Substituting neutral colors and textures to replace the shadows, whether by automated means or the Clone Stamp tool in Photoshop, is an inelegant solution at best. On another tack, overprinting the satellite image with shaded relief generated from a DEM (digital elevation model) using standard northwest illumination only serves to flatten and darken the topography. The shadows, based on opposing light sources, cancel each other out.

### Land cover—cartographically friendly data

In contrast to satellite images, raster land cover data derived from satellite images is well suited for making natural-color maps. Raster land cover data with its classified structure and generalization brings order to the tonal anarchy of satellite images. The product of sophisticated image processing techniques and often multiple data sources, raster land cover data is generally free of the problems that afflict raw satellite images, such as relief inversion. The result is reconstituted data that facilitates the production of natural-color maps. A satellite image distilled into a land cover classification of, for instance, a dozen categories is merely the raster equivalent of the polygons etched into zinc plates that guided Shelton’s painting. Shelton colored his maps with brushes and acrylic paints. We will use software and pixels. Although the means of production has changed, the process remains essentially the same today as it was a half century ago—a cartographic version of painting by the numbers.

Next, we will examine how to make natural color maps from two different types of raster land cover data. Both are in the public domain and available online for free. Our primary software for manipulating the data is Adobe Photoshop. We will begin with National Land Cover Dataset.

### NATIONAL LAND COVER DATASET

Produced by the USGS, National Land Cover Dataset (NLCD) is available for the 48 contiguous states at 30-meter resolution (Figure 9). It derives from Landsat Thematic Mapper imagery taken during the early to mid 1990s with 1992 as the oldest collection date. Coverage ends abruptly at the borders with Canada and Mexico and seaward at the 12 nautical-mile limit of US territorial waters.

NLCD is a type of categorical land cover data, which is the most common variety of raster land cover data available. With categorical land cover data, each pixel represents a sampled area on the ground and receives a classification as one type of land cover or another. For example, if the contents of a 30 x 30-meter sample of NLCD were 51 percent shrub and 49 percent evergreen forest, then the sample receives the shrub assignment entirely—the winner takes all. What categorical land cover lacks in subtlety, it makes up for in quantity. The millions of pixels that comprise these data when reduced in scale blend land cover colors together smoothly, a desirable trait on natural-color maps. The effect is much like Shelton’s airbrush technique of spraying atomized color droplets.

NLCD uses a modified form of the USGS’s Anderson Land Use and Land Cover Classification System (Anderson et al., 1972). The full Anderson classification system consists of four hierarchical levels and more than one hundred categories of land cover (occupying the two uppermost levels) and land use (occupying the two bottommost levels). The distinction between land cover and land use is an important one. For example, forest is a land cover category and bird watching or fire wood collecting are uses that occur in a forest. Because determining detailed land use information is impossible on a national dataset made from 30-meter-resolution Landsat imagery, the NLCD classification does away with land use altogether. It instead consists of a two-level system with nine level-one land cover categories and 21 level-two categories (Figure 10, left).

The USGS developed NLCD for scientific and analytical tasks. Therefore, to make natural-color maps, which are at heart artistic products, requires a change in thinking about what the NLCD classification does. Taking a cue again from Shelton, we next will transform the scientific NLCD classification into an artist’s color palette (figure 10, right).

### From classification to palette

The first step was reducing NLCD categories from 21 to 15 so as not to overwhelm the reader with too much information. Because every pixel is accounted for with categorical land cover data, reducing the number of NLCD categories required methods other than simple deletion to avoid the appearance of null areas on the final map.

Aggregation, a method that combines several categories as a single generic category, was the method most commonly used. For example, *cropland* in the color palette represents the aggregation of *row crops*, *small grains*, and *fallow* from the NLCD classification. These detailed and temporally sensitive agricultural categories do not contribute to our geographic understanding on a small-scale map of the US. Reclassification was an-



Figure 9. NLCD mosaic of the 48-contiguous states, using the USGS suggested color scheme. (see page 73 for larger color version)

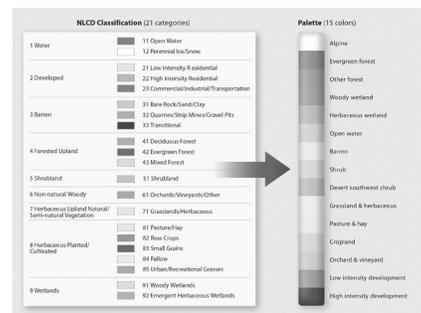


Figure 10. (left) The NLCD classification with USGS assigned colors. (right) The derivative color palette used for natural-color mapping. (see page 73 for larger color version)

other helpful method. For example, the NLCD category *transitional* mostly represents clear-cut and burned forestlands in the western US. Working under the optimistic assumption that the trees will eventually grow back, the palette reclassifies and groups *transitional* with *evergreen forest*. Similarly, the NLCD category *urban/recreational grasses* represent golf courses, schoolyards, and other open areas found in urban environments. Reclassifying this as *low intensity development* in the palette rather than as a subset of *herbaceous planted/cultivated* gave discontinuous urban areas on the final map a more concentrated appearance.

The transformation of NLCD into a palette also required the creation of new categories. On natural-color maps the appearance of white (snow) in lofty mountain areas tells readers that these areas are higher and colder than adjacent lowlands. In the continental US, however, the NLCD category *perennial ice/snow* occupies only scattered tiny areas in the Cascades and northern Rockies. To give high western mountains the emphasis they deserve, the palette contains a new category called *alpine*. It encompasses all areas above timberline and slightly lower in select places, such as the snowy and rugged Wasatch Range of Utah that barely reaches timberline. Because the elevation of timberline varies depending on latitude, continentality, and other factors, a DEM and biogeography references proved essential for delineating *alpine* areas. The procedure involved reclassifying all *perennial ice/snow*, *barren*, *shrubland*, and *herbaceous/grassland* as *alpine* for areas above the documented timberline elevation of each mountain range (Arno and Hammerly, 1984).

Another new palette category was *desert southwest shrub*. In the NLCD classification *shrubland* is the largest single category, representing 18 percent of the total area of the continental US and dominating vast tracts of the intermountain West to the exclusion of all else. The creation of the *desert southwest shrub* category recognizes that not all shrublands are the same and brings needed graphical variation to these otherwise monotonous regions. Using a DEM to subdivide the *shrubland* category by elevation zone, *desert southwest shrub*, which is depicted with a blush of red, represents the hot, low-elevation Sonoran, Mojave, and Chihuahuan Deserts of the southwestern US. The remaining area in the *shrub* category primarily represents the cold sagebrush steppes of northern Nevada and Wyoming.

Choosing colors for the palette was an exercise in subtlety. The USGS appropriately assigned bright colors to each of the 21 NLCD categories to make their patterns as distinct as possible. By contrast, the colors chosen for the natural-color palette were complementary and representative of natural environments to the greatest degree possible. With some categories, however, graphical pragmatism dictated using conventional map colors, such as blue for *open water*. The only colors in the palette not inspired by nature are the muted purples assigned to *low* and *high intensity development*—unnatural colors for unnatural information. The overarching goal was to achieve a soft impressionistic portrayal of land cover that could serve as an unobtrusive backdrop on general maps. Even though the palette contains 15 colors, compared to ten used by Shelton, the additional colors were not problematic because they represented land cover categories only slightly different from one other. For example, the similar yellowish colors depicting *grassland & herbaceous* and *pasture & hay* reflect land cover categories with similar characteristics. If these colors happen to merge together indistinctly in places, it is the small price that one must pay for creating cartographic art. Not all categories deserve equivalent strength on a natural-color map. Because trees are the most conspicuous vegetation—they are bigger than we are—the green depicting forest on a

*“The only colors in the palette not inspired by nature are the muted purples assigned to low and high intensity development—unnatural colors for unnatural information.”*

*“If these colors happen to merge together indistinctly in places, it is the small price that one must pay for creating cartographic art.”*

map deserves more prominent treatment than grassland, shrub, and other diminutive vegetation categories. Also worthy of prominent color treatment are land cover categories that are unique or important to humans, such as the developed land where we dwell. In the color palette, the emphasized colors/categories cluster at either end of the scale with muted background colors falling in between.

Some color choices in the palette were compromises. For instance, the light beige given to the *barren* category serves well at representing desert salt flats, pale Colorado Plateau sandstones, and sand dunes, but it is misrepresentative of lava flows comprised of dark basaltic rocks. Because lava occupies relatively small areas that are scattered in the continental US, this inappropriate color is barely noticeable on our map. Nevertheless, on a future update the map needs to depict lava in a more representative fashion. In the western US (where all the lava flows are found) sagebrush sometimes grows abundantly on flows, which the NLCD classification detects as *shrub*, obscuring their extent. The question arises: on a natural-color map is it better to show lava, a geologic feature, or the vegetation that grows on it? Considering the uniqueness of lava and ubiquity of sagebrush, lava is perhaps the better answer. Even choosing an appropriate color with which to portray lava presents problems—the logical choice, gray, is easily confused with shaded relief. A possible solution is dark red gray coupled with subtle 3D embossment and a hint of rough surface texture.

The grouping of colors in the palette attempts to acknowledge the non-hierarchical and interrelated character of the natural world. Although it looks like a conventional legend, further macro level groupings exist within the palette (Figure 11). The highest division is between the *natural* and *human* environments. Below this level the overlapping groups contain common colors to infer inter-categorical relationships. For example, the group *water* consists of *woody wetland*, *herbaceous wetland*, and *open water*, all of which contain blue in varying amounts. The color groupings, which are invisible to the reader, bring natural order to the underlying data and produce more harmonious colors on the final map (Figure 12).

### Using NLCD in Adobe Photoshop

Having discussed what to do with NLCD, we now discuss how to do it.

First you will need to obtain NLCD, which is downloadable from two sites maintained by the USGS (see Appendix B for URLs). The USGS Seamless Data Distribution System provides unprojected data (sometimes called the Geographic or Latitude/Longitude projections) for user-selected areas in either ESRI (Environmental Systems Research Institute) compatible GRID format or as a GeoTIF. The USGS also maintains an FTP (File Transfer Protocol) site accessible with a web browser containing individual GeoTIF files for the 48 contiguous states in the Albers Equal-Area Conic projection. The 30-meter-resolution data on both sites is otherwise identical and tend to be large. To produce the map shown in Figure 12, we used a mosaic of NLCD data of the entire contiguous US at 240-meter resolution in the Albers Equal-Area Conic projection, an unpublicized product. The USGS kindly gave us this 19,322-pixel-wide TIF image via FTP in response to an email request sent from the link on their website.

Opening NLCD in GeoTIF format in Photoshop reveals an image with a kaleidoscope of colors similar to those shown in Figure 8. Although NLCD may look like an ordinary RGB (Red-Green-Blue) or CMYK (Cyan-Magenta-Yellow-Black) image, it is in indexed color mode, which is less familiar

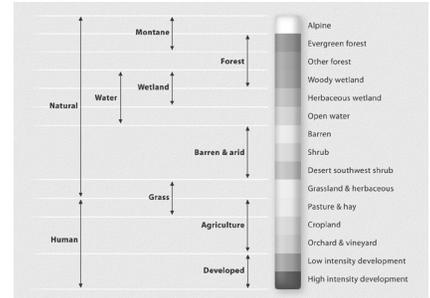


Figure 11. Color groupings in the palette. (see page 74 for larger color version)



Figure 12. California and the southwestern US depicted with colorized NLCD and shaded relief. (see page 74 for larger color version)

to many cartographers. The advantage of indexed color mode over, say, RGB color mode, is its compact file size, no larger than an 8-bit grayscale image, and the ability to manage colors, such as those representing land cover categories, via a color table. An indexed color table may contain up to 255 colors.

Going to the drop menu and Image/Mode/Color Table, accesses the Color Table dialog, where you can explore and modify the color palette. Toggling between the presets in the Color Table (Spectrum, Mac OS System, Windows System, etc.) vividly demonstrates how changes to the Color Table can change the appearance of NLCD. Although the jumble of multi-colored squares in the Color Table may look confusing at first, their positions correspond to the numbered categories in the NLCD classification. For example, NLCD category 11 is open water, which occupies the 12<sup>th</sup> color square in the top row of the Color Table (counting the first square as zero); category 43 evergreen forest occupies the 44<sup>th</sup> square; and, so forth. If you can count, you can manage indexed NLCD colors in Photoshop.

Changing colors in the Color Table is as simple as clicking on a square and specifying a new color in the Color Picker or using the Eyedropper tool to select a color from any open Photoshop image. Use the Eyedropper tool technique to select natural colors from other maps, scanned art, digital photographs, or any image found on-line. Stuck for a color with which to portray desert southwest shrub? A Google photo search using the keyword "Arizona" will yield a spectrum of choices. Or maybe a snapshot of your golden retriever might contain the ideal color. Hint: you may need to click the okay button to confirm your color table changes before the Eyedropper tool works as expected between uses. Once you have chosen new colors that you like, the modified Color Table is savable and loadable for use with later projects and sessions (Figure 13). The Color Table used in this project is available with the online version of this article (see Appendix B).

*"If you can count, you can manage indexed NLCD colors in Photoshop."*

Other tips for working with NLCD include:

- If you plan on reprojecting NLCD with GIS or cartographic software (NLCD is formatted to decimal degrees) use data downloaded from the Seamless Data Distribution System. For reprojecting in GIS, GRID (the default) or GeoTIF formats work equally well. After reprojecting is complete, save NLCD in TIF format (with no compression) to bring it into Adobe Photoshop. Should you find yourself with a standard grayscale or RGB image after reprojecting NLCD, in Photoshop going to Image/Mode/Indexed Color allows you to convert the data back to indexed color mode. However, be aware that Photoshop randomly generates new positions for the colors in the Color Table upon returning to indexed color mode. Therefore, it is best to apply the final colors via the Color Table prior to reprojecting NLCD.
- Indexed color mode images in Photoshop may interpolate incorrectly on screen with a jittery appearance at some zoom levels. If you are not seeing what you expected, zoom in or out until the image appears smoother.
- When resampling (changing the pixel dimensions) NLCD in Photoshop, it is key to use "nearest neighbor" interpolation to preserve the purity of colors assigned to land cover categories. Using "bicubic" (the Photoshop default) or "bilinear" interpolation for image resampling

and other transformations yields intermediate colors, which do not respond to Color Table manipulations.

- Photoshop's functionality is limited in indexed color mode (layers and filters, for example, are disabled). Therefore it is necessary to switch from indexed color mode to RGB or CMYK color modes for the final production of natural-color maps. Do this only after the application of final colors in the Color Table in indexed color mode.
- As a last step before compositing NLCD with shaded relief to make the final map, apply a slight amount of Gaussian blur (Filter/Blur/Gaussian Blur) to the data. Set the blur radius to 0.5 pixels as a starting point. Applying blur softens the harsh grainy appearance of NLCD, a condition that commonly afflicts images processed with nearest neighbor interpolation. Because making color changes to NLCD with the Color Table is impossible after applying Gaussian blur, as a precaution you should use a duplicate file for this final step. Also, excluding the open water category from blurring will preserve crisp, well-defined shorelines and drainages.

The USGS is currently revising NLCD based on 2001-era Landsat 7 Enhanced Thematic Mapper Plus imagery. Limited areas of the US are now available in the same classification system as the 1992 NLCD just discussed. These upgraded land cover datasets are better able to accommodate mixed spectral signatures across image mosaics and multiple time captures of vegetation, which means that besides being newer, they are more accurate. Perhaps the new NLCD will include Alaska and Hawaii, too.

#### MODIS VEGETATION CONTINUOUS FIELDS

MODIS VCF (Vegetation Continuous Fields) is the second type of land cover data that we examine. It consists of three data layers representing forest, herbaceous, and bare land cover. Although three land cover categories may seem scant, VCF data possesses unique qualities that are amenable to making generalized natural-color bases. Afterwards, color modifications and additional data are applicable to the VCF bases as needed.

#### Fuzzy data

VCF is the product of two organizations. Like the "Blue Marble" discussed earlier, it originates from the MODIS sensor aboard NASA's Terra satellite platform, which traverses the entire Earth every one to two days in a polar orbit. The University of Maryland, Global Land Cover Facility created VCF from raw MODIS data collected by NASA in 2000 and 2001. The final 500-meter-resolution land cover data derives from monthly composites (they use seven bands of spectral information with emphasis given to bands 1, 2, and 7) processed to remove clouds and cloud shadows (Hansen et al., 2003).

Coverage includes all terrestrial areas of the planet except Antarctica and the polar fringes of Canada, Greenland, and Siberia north of 80 degrees latitude. VCF land cover layers for each continent (up to several hundred megabytes apiece) are downloadable for free from the University of Maryland website in either the Geographic or the Interrupted Goode Homolosine projections. If you plan on reprojecting these data, choose the

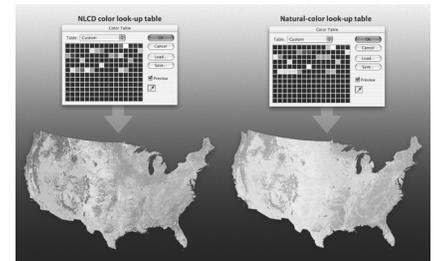


Figure 13. Using the Color Table in Adobe Photoshop with NLCD in indexed color mode to convert USGS colors (left) to natural colors (right). (see page 75 for larger color version)

*“Although three land cover categories may seem scant, VCF data possesses unique qualities that are amenable to making generalized natural-color bases.”*

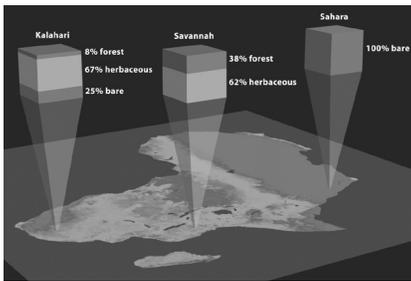


Figure 14. Blended lands cover categories in MODIS VCF. The combined values for any sampled pixel on the map are 100 percent. (see page 75 for larger color version)

Geographic projection, which is better suited for use with most GIS and cartographic software. MODIS VCF data layers, provided in BIL (Band Interleaved by Line) format, readily open in Photoshop or GIS software. Note: Photoshop only opens single-channel (i.e. grayscale) BIL files in “Raw” file format, so make sure to note the row and column dimensions (in pixels) prior to opening the file. Downloads also include metadata and projection information (see Appendix B).

Unlike hard categorical land cover data such as NLCD, MODIS VCF consists of a matrix of continuous tone values. For any given 500 x 500-meter sample of Earth’s surface, grayscale pixels represent the three land cover categories as percentages. Together they add up to 100 percent. For example, Figure 14 shows forest, herbaceous, and bare land cover for Africa loaded into the Red, Green, and Blue channels of an RGB image—a quintessentially scientific choice of colors. A sample selected from the relatively lush savannah of East Africa shows the content as 38 percent forest and 62 percent herbaceous. By comparison, a sample from the Sahara registers as 100 percent bare, as one would expect, given the extreme aridity of that region. Elsewhere in Africa the three land cover categories blend softly with one another much as vegetation does in nature. They also combine to form intermediate categories. Bare desert gradually transitions to semi-desert, semi-desert to herbaceous grassland, herbaceous grassland to savannah, and savannah to forest. Compared to categorical land cover data, this model better represents nature and Shelton’s painted art where there are few stark boundaries between vegetation types.

Given the global extent, 500-meter resolution, and general nature of MODIS VCF land cover data, this product is most appropriate for making natural-color maps at small and medium-scales. Next, we will make a natural-color map of North America. With diverse natural environments ranging from tropical rainforests to ice caps, North America is a rigorous test of the capacity of VCF for natural-color map design.

### Using MODIS VCF in Photoshop

Having downloaded, decompressed, and, perhaps, reprojected VCF, you will next need to open it in Photoshop as a raw raster file from the File/Open dialog. Note: to open Eurasian VCF layers that are more than 42,000 pixels wide requires Photoshop CS (v. 8.0) or later. North America and the other smaller VCF tiles are accessible to earlier versions of Photoshop, which are limited to a maximum file width of 30,000 pixels. When opened in Photoshop, VCF land cover appears as an ordinary 8-bit grayscale image. White areas on the image represent open water, so in effect VCF provides you with a bonus fourth category of information. The forest, herbaceous, and bare information appear as grayscale values with lighter values representing greater densities. They are analogous to photographic negatives. This trait makes VCF amenable for use as layer masks for modulating colors in Photoshop. After opening each VCF data layer as a separate Photoshop file, combine them into one multilayer image as follows:

- 1) Create a new Photoshop document with exactly the same pixel dimensions as the VCF data you just opened.
- 2) Create five new layers by selecting Layer/New Fill Layer/Solid Color in the drop menu or by clicking the “Create a new layer” button in the Layers palette.

*“With diverse natural environments ranging from tropical rainforests to ice caps, North America is a rigorous test of the capacity of VCF for natural-color map design.”*

- 3) Name the layers white background, herbaceous, forest, bare and water respectively from bottom to top.
- 4) Fill each layer with an exploratory color. Use white for the background, green for forest, yellow-green for herbaceous, beige for bare, and blue for water (these colors can be fine-tuned later in the design process).
- 5) Create a layer mask for each of the layers by selecting Layer/ Add Layer Mask/ Reveal All, or by clicking the "Add layer mask" button in the Layers palette.
- 6a) To insert the VCF land cover data into their respective layer masks, copy and paste the data. Tip: you need to Option-click (Mac) or Alt-click (PC) on the Layer mask thumbnail to open the Layer mask itself for the pasting to occur.
- 6b) Alternatively, you can use the Apply Image dialog (Image/ Apply Image) to insert the VCF land cover data into Layer masks (all VCF files intended for insertion must be open). First click the Layer mask thumbnail to activate it. Then open the Apply Image dialog and choose one of the VCF files as the source image. The target is by default the Photoshop file you are currently working in. Set blending to normal and opacity to 100 percent. Repeat these steps to insert for the two remaining VCF data files.
- 7) To color the land cover layers at the full intensity as chosen in step 4, activate the VCF layer mask for each layer mask as described in 6b above. Then use the Levels dialog (Images/ Adjustments/ Levels) to convert the grayscale data into a high contrast mask by adjusting the Input Levels settings to 0, 1.00, and 100 respectively from left to right.
- 8) To prepare the water layer, insert any one of the three VCF data files into the Layer mask on that layer. First, activate the Layer mask. Then use the Brightness/ Contrast dialog (Image/ Adjustments/ Brightness/ Contrast) to convert the grayscale data into a high contrast land/ water mask by setting the contrast slider to plus 100. Lastly, invert the mask so that water areas appear white (Image/ Adjustments/ Invert).

### Color adjustments

When finished you should have a Photoshop file that looks similar to Figure 15 (left side). Although preparing MODIS VCF for use in Photoshop is complex, the resulting file permits the easy application of colors to the data. We will start by globally colorizing the vegetation colors. Double clicking the foreground color in the Tool palette brings up the Color Picker and using the Fill command (File/ Fill) delivers the new color to the layer (remember to click on the Layer thumbnail before filling). Assigning new colors to the forest, herbaceous, bare, and water layers takes only minutes. Changing the master opacity (keep the blending mode as normal) or manipulating the VCF grayscale data in the layer masks permits even finer global color adjustments. For example, to bring more emphasis to low-density forests use Curves (Image/ Adjustments/ Curves) to increase the value of these areas. In the North American example, employing this technique made the arctic tree line more distinct.

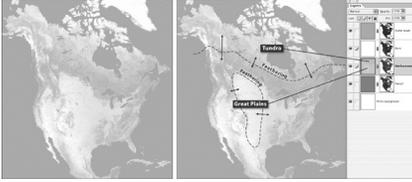


Figure 15. (left) MODIS VCF in Photoshop presented as uniform colors. (right) With environmental color adjustments applied to the herbaceous layer. (see page 76 for larger color version)

*“Fixing this problem involved three steps—and two days of work.”*

Another even more powerful option is to locally adjust colors based on environmental factors. Doing this creates new land cover categories and adds geographically relevant color variations to the map. For example, in Figure 15 (left side) herbaceous land cover appears as the same yellow-green whether it shows cornfields in Iowa, rangeland in Montana, or tundra in Nunavut. Contrast this with Figure 15 (right side), where local color adjustments depict rangeland as yellow-gold and tundra as light gray-green. Applying local color adjustments is technically simple—just draw a selection boundary with the Lasso tool, apply feathering (Select/Feather) to taste, and fill with a new color. A more critical concern, however, is where the color adjustments are applied and the colors used. For accomplishing this task biogeography and climatic references are a must. Returning to the example of North American tundra, we considered a number of geographical definitions of the arctic for delineating this environmental zone. The 10-degree-centigrade isotherm for July average temperature, for example, generally defines the northern limit of trees worldwide. This definition, however, proved inadequate for subarctic regions, such as Labrador, where tundra-like muskeg and spruce-lichen woodland extend southward for hundreds of kilometers. To bring tundra coloration to these deserving areas we drew the diffuse southern boundary of the tundra zone to include the northern third of the boreal forest zone. Because the tundra coloration applies only to herbaceous land cover, the green forests remained undisturbed.

We applied similar environmental color adjustments to the bare VCF layer to accentuate the polar desert of the high arctic (muted purple), alpine areas (light gray), and the hot southwestern deserts (light red brown). Many other local adjustments are possible. For instance, according to the Köppen climate classification system, the 18-degree-centigrade isotherm for January average temperature defines tropical areas in the northern hemisphere. A slight increase in saturation for all land cover categories within this area (delineated by a diffuse boundary) would increase the vibrancy of tropical areas—bringing the colors on the map closer to our perceptions of geographic reality. Considering that tropical areas in North America account for a small percentage of the total area, as an added benefit (and depending on the design goals of the map) brighter natural colors could bring needed emphasis to the tropics.

### Accessorizing MODIS VCF

MODIS VCF is not a complete data solution for making natural-color maps. While the natural manner in which it blends colors into one another is highly effective, it lacks important land cover categories one would expect to find on a map. To bring a natural-color map based on VCF to final completion requires supplemental data. For example, in VCF the “bare” category does not differentiate between sand, rock, and permanent ice and snow, etc. Any surface without biomass receives the bare classification, be it a gravel bar in Alaska or the concrete skyscrapers of Manhattan. Looking again at the map of North America, glaciers in northern Canada and Greenland appear with the same white color as the surrounding bare ground, rendering them invisible (Figure 15, left and right). Fixing this problem involved three steps—and two days of work. First, using the color adjustment technique discussed previously, we assigned a muted purple tint to all bare areas (including the glaciers) in the high arctic to depict polar desert. Next, we reprojected, rasterized, and imported DCW (Digital Chart of the World) vector data at 1:2,000,000-scale as white polygons, which contrasted with purple background in VCF to show glacier

shapes. As a final touch, in Photoshop we overprinted the white glaciers with gray-blue shaded relief to bring tonal modulation to their surfaces (Figure 16).

Although not applicable to our map of North America, large deserts completely devoid of vegetation, such as the Sahara and the Rub al Khali in Arabia, expose another problem with VCF data for the bare category. Completely lacking in tonality, these areas appear flat and homogenous when colorized. Furthermore, the addition of shaded relief to these areas is often not enough to break the monotony. To bring tonal variation to the deserts, selectively swap in the “Blue Marble” image discussed earlier in this paper. Also derived from MODIS, the “Blue Marble” is a close kin to VCF and merges easily with it. For best results lighten and recolorize the entire “Blue Marble” image as desert beige using the Hue/Saturation dialog (Image/Adjustments/Hue/Saturation). Then copy and paste the recolorized “Blue Marble” image to replace the flat bare color in the layered VCF file, retaining the bare VCF data as a mask. The Sahara will now appear as a mosaic of textured dune fields and rocky areas.

Cities are another category requiring outside help on MODIS VCF. Although VCF depicts large urban areas mostly as bare, they appear indistinctly. For the North America map we used the USGS’s one-kilometer-resolution Global Land Cover based on AVHRR as an add-on (see Appendix B for URL). Placing the AVHRR city data in layer mask with an associated layer color permitted easy adjustments to color, opacity, and blending. Looking elsewhere, the water layer extracted from MODIS VCF may also require replacement. While it is reasonably good for delineating oceans and lakes, all but the widest rivers appear as discontinuous strings of pixels. Replacing open water areas and rivers with rasterized vector data from sources such as DCW is advisable in most cases. Doing this also requires the removal of the embedded water from the VCF land cover to prevent it from conflicting with the new water. We discuss a semi-automated Photoshop technique for removing embedded water in the next section. The portrayal of open water areas on natural-color maps also deserves consideration. The North America map in Figure 16 portrays open water with hypsometric tints and shaded relief derived from ETOPO2 (2-minute Worldwide Bathymetry/Topography) data. It is ironic that a mapping style that so stridently eschews hypsography for terrestrial areas happens to work so well with hypsography in water areas. On the other hand, since no human has ever seen the ocean basins without water, portraying them with blue hypsometric tints and shading is the closest approximation of natural colors that we have.

New MODIS VCF products are in the production pipeline based on more recent data. The University of Maryland, Global Land Cover Facility plans to expand the forest and herbaceous categories. Forest (woody vegetation, more precisely), will include needleleaf and broadleaf, and evergreen and deciduous subcategories. Herbaceous will include new subcategories for crops and shrubs. These new data will give cartographers even more tools to make refined natural-color maps.

#### DESIGN AND PRODUCTION TIPS

This last section provides design and production tips for making natural-color maps and managing land cover data. Because of space limitations and the ever-changing nature of software, the intent of Photoshop tips described here is to give you design ideas and point you in the right procedural direction. The website for this article contains additional resources related to the discussed tips (see Appendix B). Prior experience with

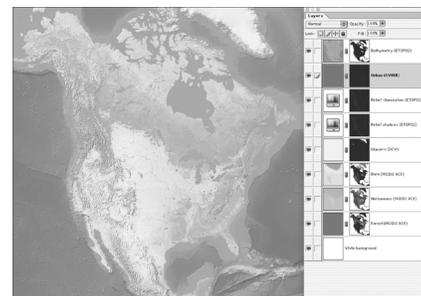


Figure 16. (left) The final map primarily based on MODIS VCF data. (right) The top five Photoshop layers contain supplemental data added to the MODIS VCF base. (see page 76 for larger color version)

*“It is ironic that a mapping style that so stridently eschews hypsography for terrestrial areas happens to work so well with hypsography in water areas.”*

Adobe Photoshop is helpful. And given the large files involved, so too is a graphics workstation with large amounts of physical RAM, scratch disk space, and file storage.

### Tip 1: Combining shaded relief and land cover data

Shaded relief is an essential component on all natural-color maps (Figure 17). However, the textures in shaded relief and those found in land cover, if clumsily combined, have the potential to become heavy and messy. The following will help you use shaded relief more effectively with land cover data:

*“Excessive topographic detail at small map scales only pollutes the background landcover colors and detracts from our understanding of major topographic structures.”*

- Show shaded relief and land cover with roughly equal emphasis. Despite the considerable effort that goes into transforming raw land cover data into a natural-color base, for the greater graphical good, do not to print these colors too boldly. The same rule applies to shaded relief. The relative visual prominence of shaded relief and land cover varies on a map depending on viewing distance. Up close the shaded relief appears more dominant as a dimensional texture. By comparison, when viewed from farther away land cover colors on the map become the more noticeable feature, appearing as broad generalized zones.
- Generalize shaded relief at reduced scales. Although land cover colors reduce to smaller sizes with no visible harm, shaded relief is not as elastic. Excessive topographic detail at small map scales only pollutes the background land-cover colors and detracts from our understanding of major topographic structures. Repurposing a natural-color map from, for instance, wall map size to textbook size requires replacing the shaded relief with a more generalized version. As a general rule the resolution of a DEM used to generate shaded relief should be equal to or less than that of the land cover. For example, if a land cover image is 10,000 pixels wide, the DEM used to generate the shaded relief might be 7,000 pixels wide. The resulting shaded relief is then upsampled (or rendered) to 10,000 pixels wide for final compositing with the land cover. The need for generalized shaded relief applies to all maps and not just those with natural colors.
- Remove shaded relief tones from flat areas. A typical shaded relief contains tonal values of 10 to 20 percent density in flat lowland areas. They serve as a neutral base upon which other topographic features, modeled by light and shadows, project upward or downward in a three-dimensional manner. While tones in flat areas are desirable for stand-alone shaded relief, the overall image becomes too dark when merged with land cover colors. A cleaner and brighter alternative is to let the land cover colors themselves do double duty as a base tone for the shaded relief. To do this use Curves (Image/Adjustments/Curves) or Levels (Image/Adjustments/Levels) to clip the tonal range of the shaded relief just enough to remove tones from the flat areas. This procedure works best with a shaded relief possessing a full tonal range including fine detail in the brightest highlighted slopes and densest shadowed slopes. Be careful not to remove too much tone, or the shaded relief will lack body and appear spindly. Using the Eyedropper tool and the Info palette permits the removal of tones with numerical precision.

*“A cleaner and brighter alternative is to let the land cover colors themselves do double duty as a base tone for the shaded relief.”*

- Show illumination. The illuminated slopes on a shaded relief are almost as important as shadowed slopes. They enhance the apparent three dimensionality of a shaded relief, giving it an embossed look and also lightening the image. To add supplemental illumination to a shaded relief, first create a Hue/Saturation adjustment layer (Layer/New Adjustment Layer/Hue/Saturation). Next, copy and paste the grayscale shaded relief into the adjustment layer's layer mask. Then, in the layer mask, use Curves to choke the shaded relief tonal range so that all areas except illuminated slopes are black. For the final step double click on the adjustment layer icon to open the Hue/Saturation dialog and move the Lightness slider to the right until the illuminated slopes look appropriately bright. In Figure 16, the third layer from the top shows an illumination adjustment layer in Photoshop. A low-resolution version of this file is available on the website of this paper for you to download and examine.

The adjustment layer technique also works well for displaying shaded relief shadows. The advantage is that the darkening preserves the varying colors below. For example, forest green becomes a darker green, desert beige becomes a darker beige, and so forth. The final result is a natural-color map with more pure natural colors. Creating shadows with a Hue/Saturation adjustment layer is similar to the illumination technique described above. But this time invert the shaded relief (shadowed slopes should be lightest) and move the Lightness slider to the left (start with settings between  $-55$  and  $-30$ ).

### Tip 2: Legend design

Despite Shelton's misgivings about their usefulness, legends do play an important role even on well-designed maps. Readers expect to find legends on maps, and cartographers are partial to displaying them. If a legend is a little redundant, that is a lesser problem than having no legend and uniformed map-readers. Having said that, the design of legends on natural-color maps is worthy of reexamination. The traditional map legend explains natural colors with small, rectangular color filled boxes arranged neatly in a row and separated from one another. Typically a black casing line bounds these boxes. Such a portrayal disassociates the legend colors from one another and, of greater concern, from their counterparts on the map. If the map uses shaded relief and the legend does not, the communication disconnect is even greater.

To improve the design of traditional legends on natural-color maps, consider doing the following: remove the black casing lines, place the colored boxes in a contiguous row, include shaded relief, and, perhaps, blend the colors (Figure 18, examples 1-4). The idea is for the legend to mimic colors on the map as closely as possible while still maintaining order. For another step toward this goal think about using a natural legend (Figure 18, example 5). Placing legend labels on an icon of the map itself communicates the meaning of colors directly and unambiguously to readers. Compared to traditional legends, the disadvantages of natural legends are that they require more space and are less tidy.

### Tip 3: Mapping urban extents

Besides the making of natural-color maps, land cover data is a useful product for mapping urban areas as a stand-alone category on general

*"Despite Shelton's misgivings about their usefulness, legends do play an important role even on well-designed maps."*

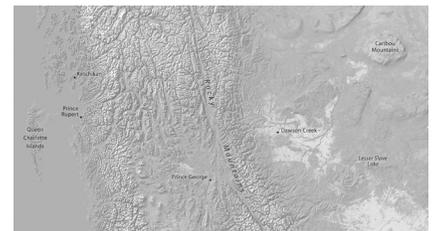


Figure 17. Shaded relief merged with a natural-color base made from MODIS VCF data. (see page 77 for larger color version)

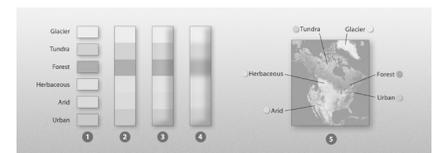


Figure 18. (1-4) Variants of the traditional legend. (5) A natural legend. Legend portrayal becomes less abstract and more cartographically realistic from left to right. (see page 77 for larger color version)



Figure 19. Using the Median filter to generalize urban land cover data. (see page 78 for larger color version)

maps. Isolating urban areas from the other categories in NLCD (and other categorical land cover data) is simple to do with the Magic Wand tool. Hint: set the tolerance to zero and do not choose the antialiasing and contiguous options. Having selected the urban areas, invert the selection (Selection/Inverse) and fill all of the other land cover categories with white. The image should now look something like Figure 19 (upper left). The next potential issue is one of generalization. Because the urban categories in NLCD include transportation, depending on the scale of your data, discontinuous roads and other stray pixels make for a noisy image. The Median filter (Filter/Noise/Median) in Photoshop permits the removal of unwanted pixels below a threshold of interest (Figure 19, upper right). Moving the radius setting to the right increases the amount of generalization. Be sure to apply the Median filter using nearest neighbor interpolation (Preferences/General/Image Interpolation) to prevent the urban colors from blurring.

#### Tip 4: Shoreline buffering

Any cartographer who has worked with data from two or more sources on the same map is familiar with the problem of misregistration, especially when merging raster images and vector linework. For example, matching raster land cover data to vector water bodies often reveals unwanted fringing pixels and data gaps—the stair-stepped pixel boundaries don't match smooth-edged vector shapes. This problem is solved by growing the land cover pixels outward—a process called buffering in GIS applications—so that they fall under the edges of vector water bodies (Dunlavy, 2002). A similar procedure is also available in Photoshop if you know what buttons to click:

- 1) To start, open your land cover image in RGB or CMYK color mode and double check that Photoshop is set to use nearest neighbor interpolation (Preferences/General/Image Interpolation).
- 2) Select and delete all water pixels so they are now transparent (Figure 20, upper left).
- 3) Duplicate the land cover layer.
- 4) Select the Move tool in the Tool palette. Then on the keyboard press the up arrow cursor once. The image will move up one pixel.
- 5) Merge the copied layer with original below.
- 6) Duplicate the merged layer and repeat steps 4 and 5. But this time nudge the copied layer to the right.
- 7) Repeat this process two more times, nudging the copied layer down and then to the left respectively.

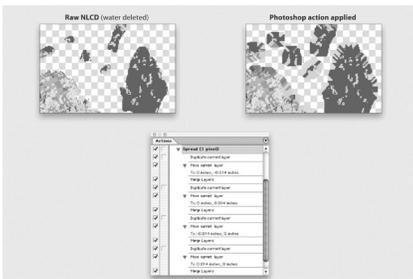


Figure 20. Using the Actions palette in Photoshop to spread shoreline pixels outward. (see page 79 for larger color version)

Each cycle of copying, nudging, and merging the image grows edge pixels outward by one pixel. Apply the steps repeatedly as needed until all misregistration gaps disappear. Alternatively, record your steps in the Actions palette and the save the results for one-click replays (Figure 20, bottom). We have built a Photoshop action that automates this process. It is available on the article website for both Mac and PC.

#### Tip 5: Land cover removal

Just because a category for land cover exists doesn't mean that you have to accept it. For example, the pixelized depiction of rivers and lakes is often too noisy and irregular for display on a map, requiring removal

from the raster land cover data and showing it instead with vector lines in a drawing software application. Beyond issues of accuracy, considering that hundreds of thousands of pixels might be water on a land cover image, manually replacing them with the Clone Stamp tool is not a realistic option. The Dust & Scratches filter offers a quicker and more accurate solution. It reads the tonal contrast in an image and replaces pixels beyond a specified threshold with nearby unaffected pixels. In Figure 21, for example, the green forest color that dominates the image replaces the black lakes. Follow these steps to remove imbedded water from an image:

- 1) Select all water pixels and fill them with black.
- 2) Use the Dust & Scratches filter (Filter/Noise/Dust & Scratches) to infill the black-filled water bodies. (Be sure to use nearest neighbor interpolation.) Experiment with different radius and threshold settings until the black water bodies disappear. The settings will vary depending on the contrast range in your image.

It is the authors' hope that this paper spurs renewed interest in natural-color mapping. The digital procedures presented in this paper, we believe, will permit many more cartographers to make natural-color maps. The combination of Adobe Photoshop software and raster land cover data now provides a means of producing attractive natural-color maps that, dare we say, rival those made by Shelton. But good looks are only part of the story. Compared to manual methods, digital production yields maps of much greater accuracy. Map-readers can confidently assume that the pixels representing forests, fields, and fells are where they should be. New land cover data, such as MODIS VCF, which blends land cover categories into one another, provides readers with insights about the indistinct vegetative boundaries found in nature. For example, the colors representing forest and herbaceous land combine in Africa to form a third category: savannah. The amount of blending between, say, green forest and tawny grassland allows readers to gauge intuitively the relative vegetative content for any given area. And the use of shaded relief provides additional insights about the relationship of topography and vegetation. Making complex geospatial information such as this easy for inexperienced map-readers to grasp is what cartographic communication is all about. That natural-color maps are also visually pleasing and attract and hold our attention only adds to their effectiveness, in the words of Shelton, as "instruments of communication."

Digital production has largely removed the economic and time disincentives that have been associated with the making of natural-color maps in the past. Most of the data discussed in this paper is in the public domain and available online for free (see Appendix B). Adobe Photoshop, although relatively expensive, is already part of the software toolkit on many cartographers' computers. Most of the time needed for making natural-color maps digitally is spent in tedious data management chores: finding and downloading large data files, converting obscure formats, and reprojecting and registering shaded relief and land cover data. Compared to the manual era, however, the time needed for making a digital natural-color map now requires days rather than weeks or months. Once the data is ready, the procedures and examples we have described explain how to design and produce natural-color maps. Switching your thought processes from data management mode to a more creative mindset is a key to success. Because critical design decisions occur at the end of the project when time is often running short, one must resist the temptation to rush to completion.

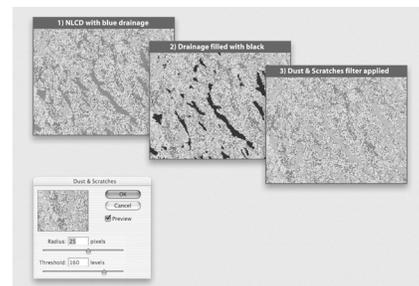


Figure 21. Removing drainages from NLCD with the Dust & Scratches filter. (see page 80 for larger color version)

## CONCLUSION

*"The combination of Adobe Photoshop software and raster land cover data now provides a means of producing attractive natural-color maps that, dare we say, rival those made by Shelton."*

While one no longer must be an accomplished artist/cartographer to make natural-color maps, good design sense and grounding in physical geography are still necessary prerequisites. Because of our tendency to overuse new design trends, cartographers must be mindful that natural-color maps are not applicable to all physical mapping situations. Shelton's claims of arbitrariness aside, hypsometric tints are acceptable, and they excel at showing elevation zones and topographic forms, if that is what one wants to emphasize on a map. Cartographic choice is a good thing.

### Hal Shelton revisited: returning to art

Because this article began with a discussion of Shelton's early years in cartography, it is fitting that it should end with a few words about his later career. Art has become increasingly important in his life. After easing out of his relationship with the Jeppesen Map Company, Shelton turned his attention to painting ski area panoramas. His work included many of the major resorts in North America and a panorama of Grenoble, France, used by ABC TV for the 1968 Olympics. For his most famous panorama, "Colorado: Ski Country USA," Shelton received a lifetime ski pass to all resorts in Colorado, which he has put to good use for decades.

Shelton now devotes his time to painting—a return to his early art interest before it was interrupted by some 40 years of cartography. When creating art, Shelton finds that he is

"responding to a broader spectrum of realities than I was able to do in cartography."

The artistic and cartographic careers of Shelton came full circle in 1985 with an unusual request from the U.S. Library of Congress. The Geography and Map Division commissioned him to paint a landscape using the techniques he learned as a natural-color cartographer. Having applied his art training to cartography for so many years, the idea was for cartography to give something back to art. The result was "Canyon Lands," a 1.9-meter-wide triptych displayed behind the reference desk in the Map Reading Room (Figure 22). Although at the time of this writing "Canyon Lands" no longer is on display, you may view it privately by asking one of the librarians. The effort is worthwhile. Shelton's "Canyon Lands" repays cartography's debt to art most generously.



Figure 22. "Canyon Lands" by Hal Shelton. Millard Canyon, Utah, dominates the center of the scene and the snowcapped LaSal Mountains are faintly visible on the right horizon. The vertical triptych joints do not appear because of digital compositing. Courtesy of Library of Congress. (see page 80 for larger color version)

### ACKNOWLEDGEMENTS

Just as the making of natural-color maps is a team effort, so too is the writing of an article about them. The authors wish to thank the following people for their kind assistance: John Hutchinson, USGS EROS Data Center; Marc Weinschenker, Angie Faulkner, Mark Muse, Melinda Schmitt, and Ed Zahniser, US National Park Service; Christine Bosacki, Nystrom; Bernhard Jenny, ETH Zürich; Linda Schubert, Rand McNally & Company; Jim Flatness and Ronald Grim, US Library of Congress; Tibor Tóth; and, most importantly, Hal Shelton and his wife Mary.

### REFERENCES

- Anderson, J. R., Hardy, E. E., and Roach, J. T., 1972. A Land-use Classification System for use with Remote-sensor Data. *U.S. Geological Survey Circular 671*.
- Arno, S. F. and Hammerly, R. P., 1982. *Timberline: Mountain and Arctic Forest Frontiers*. The Mountaineers, Seattle.

Gegenfurtner, K. R., Sharpe, L. T., Wichmann, F. A., 2002. The Contributions of Color to Recognition Memory for Natural Scenes. *Journal of Experimental Psychology*, American Psychological Association, Inc., Learning, Memory, and Cognition 2002, Vol. 28, No. 3: 509–520.

Dunlavey, P., 2002. GRASS - A Useful Tool for the Mountain Cartographer. *2002 ICA Mountain Cartography Workshop Proceedings*.  
[http://www.karto.ethz.ch/ica-cmc/mt\\_hood/abstracts/dunlavey.html](http://www.karto.ethz.ch/ica-cmc/mt_hood/abstracts/dunlavey.html)

Hansen, M. C., DeFries, R. S., Townshend, J. R. G., Carroll, M., Dimiceli, C., and Sohlberg, R. A., 2003. *MOD44B: Vegetation Continuous Fields Collection 3, Version 3.0.0 User Guide*. [http://modis.umiacs.umd.edu/documents/MOD44B\\_User\\_Guide\\_v3.0.0.pdf](http://modis.umiacs.umd.edu/documents/MOD44B_User_Guide_v3.0.0.pdf)

Imhof, E., 1982. *Cartographic Relief Presentation*, In Steward, H. J. and de Gruyter, B. (Eds) New York: 344-45.

Library of Congress. Circa 1985. Brochure announcing exhibit of the Shelton Collection.

NAHF (National Aviation Hall of Fame). Circa 2002. Website about Elrey Jeppesen. [http://www.nationalaviation.org/museum\\_enshrinee.asp?eraid=5&enshrineeid=375](http://www.nationalaviation.org/museum_enshrinee.asp?eraid=5&enshrineeid=375)

NASA. 2002. *Apollo 17 Anniversary: Celebrating thirty years of Earth-observing*. Goddard Space Flight Center. Website. <http://www.gsfc.nasa.gov/topstory/2002/1203apollo17.html>

Patterson, T., 2000. A View from on High: Heinrich Berann's Panoramas and Landscape Visualization Techniques for the U.S. National Park Service. *Cartographic Perspectives*. 36: 38-65.

Patterson, T., 2002. Getting Real: Reflecting on the New Look of National Park Service Maps. *Cartographic Perspectives*, 43:43-56.

Shelton, H., 1985. Video interview. Introduction by John Wolter, Chief, Geography and Map Division, Library of Congress. Interview conducted by Thomas K. Hinckley (BYU). Produced by TV Facilities of Motion Picture Broadcasting & Recorded Sound Lab, Library of Congress. 51 minutes.

Shelton, H., 2004. Personal communication with authors.

Stenger, R., 2002. *From distant eye, Earth becomes art*. CNN website. <http://www.cnn.com/2002/TECH/space/12/06/satellite.art/>

Tóth, Tibor. 1973. *Terrain Representation Manual*, Cartographic Division, National Geographic Society.

Tóth, T., 1986. Moving on! *Karlsruher Geowissenschaftliche Schriften*. Christian Hermann and Hans Kern (publishers).

Warren, S., Circa 1995. *Global Cloud Climatology from Surface Observations*. <http://www.gcric.org/ASPEN/science/eoc94/EOC1/EOC1-25.html>

## Appendix A: Shelton Collection, Library of Congress

<p><b>Africa</b> Acrylic on zinc (1961) Lambert Azimuthal Equal-Area Projection Scale: 1:6,336,000 163 x 131 cm</p>	<p><b>World: Eastern Hemisphere</b> Acrylic on zinc (undated) Parabolic Equal-Area Interrupted Projection Scale: 1:25,344,000 93 x 98 cm</p>	<p><b>Palestine</b> Acrylic on zinc (1965) Lambert Conformal Conic Projection Scale: 1:1,000,000 91 x 60 cm</p>
<p><b>Arizona</b> Acrylic on zinc (1955) Lambert Conformal Conic Projection Scale: 1:1,000,000 86 x 75 cm</p>	<p><b>World: East Asia Gore</b> Acrylic on zinc (1957) Parabolic Equal-Area Non-Conformal Proj. Scale: 1:25,344,000 91 x 65 cm</p>	<p><b>Nevada</b> Acrylic on zinc (undated) Lambert Conformal Conic Projection Scale: 1:1,000,000 92 x 65 cm</p>
<p><b>California</b> Acrylic on paper-covered zinc (1959) Lambert Conformal Conic Projection Scale: 1,000,000</p>	<p><b>Color Legend</b> Acrylic on zinc (1957) 18 x 29 cm</p>	<p><b>Reno Area</b> Acrylic on paper-covered zinc (undated) Lambert Conformal Conic Projection Scale: 1:250,000 72 x 58 cm</p>
<p><b>Colorado</b> Acrylic on zinc (1957) Lambert Conformal Conic Projection Scale: 1:1,000,000 48 x 65 cm</p>	<p><b>Los Angeles Area</b> Casein on paper-covered zinc (1949) Lambert Conformal Conic Projection Scale: 1:500,000 51 x 56 cm</p>	<p><b>Salt Lake City Area</b> Acrylic on paper-covered zinc (1950) Lambert Conformal Conic Projection Scale: unknown 53 x 39 cm</p>
<p><b>Eurasia</b> Acrylic on zinc (1961) Lambert Azimuthal Equal-Area Projection Scale: 1:9,504,000 122 x 150 cm</p>	<p><b>Middle East</b> Acrylic on zinc (1951) Lambert Conformal Conic Projection Scale: 1:5,000,000 102 x 123 cm</p>	<p><b>South America</b> Acrylic on zinc (undated) Parabolic Equal-Area Projection Scale: 1:5,000,000 183 x 118 cm</p>
<p><b>Europe</b> Acrylic on zinc (1957) Lambert Azimuthal Equal-Area Projection Scale: 1:12,038,400 51 x 61 cm</p>	<p><b>World</b> Acrylic on paper-covered zinc (1951) Mercator Projection Scale: 1:31,400,000 102 x 157 cm</p>	<p><b>Southern Hemisphere</b> Acrylic on zinc (1962) Polar Orthographic Projection Scale: 1:1,000,000 65 x 61 cm</p>
<p><b>New Europe</b> Acrylic on zinc (undated) Lambert Conformal Conic Projection Scale: 1:5,000,000 107 x 137 cm</p>	<p><b>North America</b> Acrylic on zinc (1956) Lambert Azimuthal Equal-Area Projection Scale: 1:6,336,000 145 x 119 cm</p>	<p><b>South Polar Area</b> Acrylic on zinc (1957) Polar Stereographic Projection Scale: 1:25,344,000 48 x 53 cm</p>
<p><b>Western Hemisphere</b> Acrylic on illustration board (1962) Global Projection Scale: unknown 58 x 44 cm</p>	<p><b>Northern Hemisphere</b> Acrylic on zinc (1963) Polar Orthographic Projection Scale: unknown 56 x 57 cm</p>	<p><b>United States</b> Acrylic on paper-covered zinc (1956) Lambert Conformal Conic Projection Scale: 1:3,000,000 102 x 175 cm</p>
<p><b>Eastern Hemisphere</b> Acrylic on illustration board (1957) Global Projection Scale: unknown 43 x 33 cm</p>	<p><b>New Mexico</b> Acrylic on zinc (undated) Lambert Conformal Conic Projection Scale: 1:1,000,000 79 x 71 cm</p>	<p><b>Utah</b> Acrylic on zinc (1956) Lambert Conformal Conic Projection Scale: 1:1,000,000 91 x 65 cm</p>
<p><b>Hawaiian Islands</b> Acrylic on zinc (1957) Lambert Conformal Conic Projection Scale: varies depending on island 65 x 89 cm</p>	<p><b>North Polar Area</b> Acrylic on zinc (1956) Polar Stereographic Projection Scale: 1:25,344,000 55 x 73 cm</p>	<p><b>Wyoming</b> Acrylic on paper-covered zinc (1953) Lambert Conformal Conic Projection Scale: 1:1,000,000 48 x 65 cm</p>
<p><b>World: Western Hemisphere</b> Acrylic on zinc (undated) Parabolic Equal-Area Interrupted Projection Scale: 1:25,344,000 93 x 75 cm</p>	<p><b>Pacific Northwest</b> Acrylic on paper-covered zinc (1962) Lambert Conformal Conic Projection Scale: 1:1,000,000 117 x 183 cm</p>	

## Appendix B: Internet Resources

### The website for this article

<http://www.nacis.org/cp/cp45/shelton/index.html>

### Satellite images

NASA "Blue Marble" (free)

<http://earthobservatory.nasa.gov/Newsroom/BlueMarble/>

Landsat images of the World (free)

<https://zulu.ssc.nasa.gov/mrsid/mrsid.pl>

NASA MODIS (free)

<http://modis.gsfc.nasa.gov/gallery/index.php#>

The Living Earth (commercial)

<http://livingearth.com/>

Worldsat International, Inc. (commercial)

<http://www.worldsat.ca/>

### Land cover data

University of Maryland, Global Land Cover Facility

MODIS Vegetation Continuous Fields (free)

<http://modis.umiacs.umd.edu/vcfdistribution.htm>

USGS National Land Cover Dataset (free)

<http://landcover.usgs.gov/natl/landcover.asp>

<http://seamless.usgs.gov/>

USGS Global Land Cover (free)

<http://edcdaac.usgs.gov/glcc/glcc.html>

European Commission Global Land Cover (free)

<http://www.gvm.jrc.it/glc2000/Products/fullproduct.asp>

Boston University Global Land Cover (free)

<http://duckwater.bu.edu/lc/mod12q1.html>

GAP Analysis Program (free)

<http://www.gap.uidaho.edu/Projects/FTP.htm>

### Elevation data

NOAA ETOPO2 Worldwide Bathymetry (free)

<http://www.ngdc.noaa.gov/mgg/image/2minrelief.html>

USGS GTOPO30 Global Topographic Data (free)

<http://edcdaac.usgs.gov/gtopo30/gtopo30.html>

SRTM - Shuttle Radar Topography Mission (free)

[http://www2.jpl.nasa.gov/srtm//pub\\_dist.htm](http://www2.jpl.nasa.gov/srtm//pub_dist.htm)

### Artist/Cartographers

Tóth Graphix Cartographic Art Studio

<http://www.tothgraphix.com/>