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Under the mantra: ‘Make use of colorblind friendly graphs’

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Abstract
Colorblindness is a genetic condition that affects a person’s ability to accurately perceive colors. Several papers still exist making use of rainbow colors palette to show output. In such cases, for colorblind people such graphs are meaningless. In this paper, we propose good practices and coding solutions developed in the R Free and Open Source Software to (i) simulate colorblindness, (ii) develop colorblind friendly color palettes and (iii) provide the tools for converting a noncolorblind friendly graph into a new image with improved colors.

KEYWORDS
colorblindness, colors, R software, science dissemination, scientific graphs

'I'll try out the pencils sharpened to the point of infinity which always sees ahead.' Frida Kahlo[1]

1 | A GENTLE INTRODUCTION TO COLORBLINDNESS

Colors are related to the reflectance of light in different wavelengths of the electromagnetic spectrum. However, they are not innate; we are used to give names to colors based on external imprinting. With colorblindness we refer to the inability to see some of the windows of the electromagnetic spectrum.

Colorblindness is a mostly genetic condition that affects a person's ability to accurately perceive colors. The main issue arises from the reduced or altered functioning of the cone photoreceptors in the retina, which are responsible for color perception. These cones are categorized into three types: L (long), M (medium), and S (short), which correspond to the colors red, green, and blue, respectively (Deeb, 2005). In individuals with colorblindness, there may be a deficiency or abnormality in one or more of these cone types, resulting in difficulties in distinguishing colors (Neitz & Neitz, 2000). The severity of this color perception abnormality can range from a mild difficulty in discerning shades to a complete inability to perceive colors (Gegenfurtner, 2003; Gordon, 1998; Viénot et al., 1995).

Colorblindness is typically inherited and is more common in men than in women (Simunovic, 2010). This is because the gene responsible for colorblindness is linked to the X chromosome. Women have two X chromosomes and therefore need two copies of the altered gene to exhibit colorblindness, whereas men, with only one X chromosome, require just one copy (Birch, 2012).

The most common types of colorblindness are related to the inability to detect differences between red and green: in *protonopia* people cannot perceive electromagnetic radiation at 560 nm (red) while in *deuteranopia* a higher frequency (530 nm, green) cannot be recognized. Beside these major severe types of colorblindness, *tritanopia* hampers people to distinguish a very high frequency radiation type at 420 nm (blue). The inability to recognize specific color palettes, particularly those with gradients from blue to green or yellow to red, can greatly impact the perception of maps and other visual materials for colorblind individuals. For example, the use of rainbow color palettes in various contexts can pose challenges for those with colorblindness (Crameri et al., 2020). The problem with rainbow color palettes is exacerbated by the fact that they often feature smooth transitions between colors that are particularly difficult to distinguish by colorblind individuals, such as green and red. This can lead to misinterpretation of visual information, as shades that appear distinct to someone with normal color perception may appear indistinguishable or very similar to a colorblind person (Silva et al., 2011).

In most cases, under normal human vision, we are used to distinguish colors in a straightforward way. For instance, a person can distinguish blue from yellow. However, this is dependent on the distance of colors (wavelengths) in the electromagnetic spectrum. In other words, while the discrimination between blue and yellow would be simple, that between very light green and light yellow would not be immediate. Now, imagine what would happen if this issue might include the discrimination between green and red. In most of the color deficiency problems, this is the case.

The accessibility to scientific graphs is a crucial issue in science. The use of colors that are indistinguishable to those with colorblindness still persists in scientific graphs and maps, particularly when representing continuous variables or contrasting factors. The aim of this paper is to provide a showcase of solutions developed in the R Free and Open Source Software (hereafter also referred to as FOSS). We will focus on (i) colorblindness simulation, (ii) colorblind friendly color palettes and (iii) the tools for converting a non-colorblind friendly graph into a new image with improved colors.

2 | ACCESSIBILITY TO SCIENTIFIC GRAPHS

A certain amount of limitations can be associated with scientific graphs (Burrough et al., 2015), since they imply an abstraction of reality (Palmer et al., 2008). This is necessary to simplify the data and improve comprehension, but it can also introduce potential ambiguities and misunderstandings, e.g., color interpretation can be highly subjective. Different individuals, influenced by their color perception, may draw divergent conclusions when examining the same graph

[1]From the English re-edition of the diary of Frida Kahlo: Kahlo, F., Lowe, S. M., Fuentes, C. (2005). *The diary of Frida Kahlo: An intimate self-portrait*. Publisher: Harry N. Abrams Inc, New York (USA).

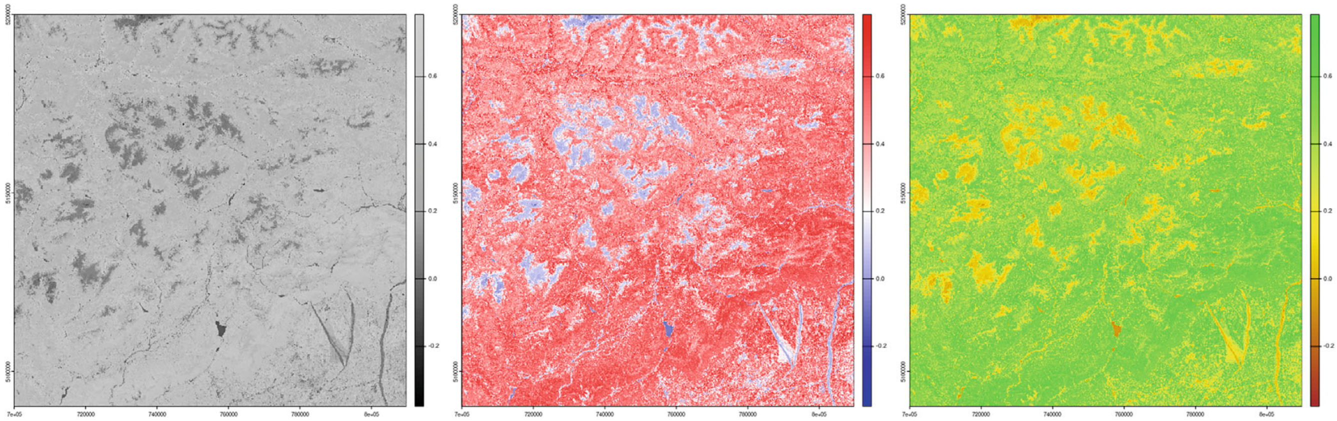

FIGURE 1 NDVI of Eastern Alps in Italy. The perception of spatial differences in a variable can be influenced by the choice of color palette.

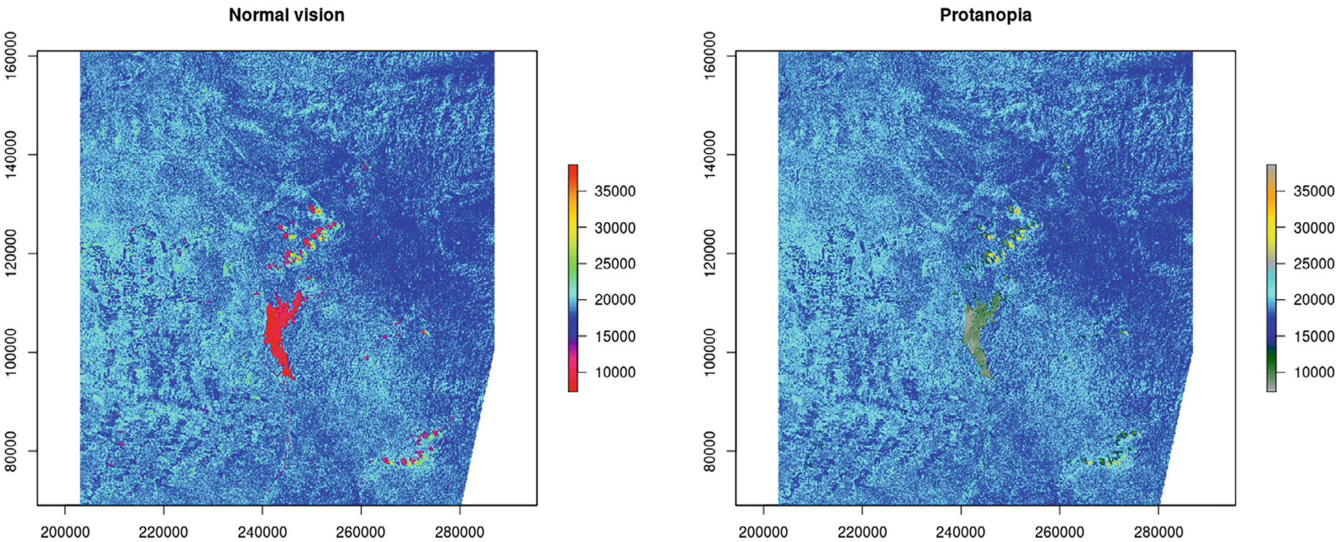

FIGURE 2 The Amazon forest between Boa Vista and Caracaraí (Brazil), band 8 of a Santinel-2 image (near infrared) plotted with a rainbow color palette (left). A simulation of the vision with protanopia or deuteranopia is provided on the right image. It shows the blurring effect that can occur with colorblindness.

(Popelka et al., 2012). A simple example is provided in Figure 1 in which different color palettes enhance different aspects of the same variable.

When plotting scientific graphs, in most cases green and red are confounding colors for colorblind people (Figure 2). This is a well known, but often unconsidered, problem.

In several cases, rainbow color palettes are still being used to represent the variability of patterns in space, with, generally, the blue/green color representing minima and the red color representing maxima (Figure 2).

Many researchers use rainbow color palettes to represent ecological patterns or processes. Several examples exist in the literature that use such a color scheme, related to a wide range of scientific themes like: from the measurement of diversity by satellite imagery (Rocchini et al., 2021) to the prediction of spatio-temporal patterns of species assemblages (Guisan & Rahbek, 2011), from the mapping process of plant strategy types (Schmidtlein et al., 2012) to Bayesian geostatistical modelling of discrete-valued processes (Zheng et al., 2023).

3 | R SOLUTIONS

To ensure replicability under any software and condition, it is best practice to propose FOSS solutions to the problem at hand. Moreover, FOSS guarantees high reproducibility and robustness, giving the ability to enter the code of a computational process, test it, and potentially improve it. Among the different solutions based on FOSS, R (R Core Team, 2023) represents one of the most widely used software worldwide, providing for both official packages (e.g. the Comprehensive R Archive Network, CRAN, https://cran.r-project.org/) and additional packages in external repositories (e.g. GitHub, https://github.com/). A complete history of management of colors in R is provided by Zeileis and Murrell (2023).

Instead of constraining the user to import and export images and make the rendering in a dedicated internet site, it would be preferable to allow users to see scientific graphs in a proper way under a unique coding workflow. From this point of view, R is the perfect solution due to its wide usage by several users attaining to very different communities.

There are different R based solutions for: (i) checking graphs for potential colorblind unfriendliness, (ii) providing colorblind friendly palettes, and (iii) redrawing images using colorblind friendly colors.

3.1 | Simulation of colorblindness

It is impossible to fully understand the sensations of someone else (Viénot et al., 1995). This said, simulations of color vision offer a valuable tool for researchers involved in the creation of scientific graphs to understand the potential use of them, also considering color vision impairments. Packages are devoted to simulating both (i) color palettes and (ii) entire graphs for the different types of colorblindness previously described.

In the first case, packages such as `colorspace` (Zeileis et al., 2020), and built upon it, `colorblindcheck` package (Nowosad, 2019), allow a direct comparison of different color palettes. The `colorblindcheck` package provides the ability to simulate the vision of a color palette and to calculate the distances between colors inside a palette for each type of colorblindness. Here, as an example, we use the R function `rainbow` that generates a rainbow color palette with a given number of colors. The palette can be checked using the `palette_check` function as follows:

```
rainbow_pal <- rainbow(7)
colorblindcheck::palette_check(rainbow_pal, plot=TRUE)
```

This code will generate the rainbow color palette as it is seen by different color vision impairments (Figure 3) and a summary data frame.

```
          name n tolerance ncp ndcp  min_dist mean_dist  max_dist
1       normal 7  12.13226  21   21 12.132257  61.06471 107.63470
2 deuteranopia 7  12.13226  21   19  2.572062  44.29065  85.87461
3   protanopia 7  12.13226  21   17  3.647681  47.63882  83.28286
4   tritanopia 7  12.13226  21   20  2.025647  47.41585  83.77189
```

The original rainbow palette with seven colors has 21 pairs of colors (`ncp`), with a minimum distance of 12.13, a mean distance of 61.06 and a maximum distance of 107.63 for normal vision. All pairs in the original palette are differentiable (`ndcp`, the number of pairs of colors with a distance greater than the tolerance level, `n`). The default tolerance is set as the minimum distance between two colors in the original input palette; however, it can be set to a different value. The versions of the palette for the different types of colorblindness exhibit, in general, lower distances between colors, which means that they are less differentiable. Most importantly, the minimum distances between colors are much lower for the different types of colorblindness, suggesting that the colors are less differentiable for people with

FIGURE 3 Simulation of the vision of a color palette by the different types of colorblindness described in section 1.

these conditions. Thus, we can summarise that the original rainbow palette is not suitable for people with color vision impairments.

Concerning simulations of entire graphs, the `colorblindr` (https://github.com/clauswilke/colorblindr) package allows one to check for problems in rainbow color based graphs. As an example, once the dependency package `ggplot2` has been installed, a default plot can be generated by:

```
library(ggplot2)
explot <- ggplot(iris, aes(Sepal.Length, fill=Species)) +
geom_density(alpha=0.7)
```

Hence, the `cvd_grid()` function would plot how the `explot` graph is seen by colorblind people (Figure 4), with different colorblind related diseases:

```
colorblindr::cvd_grid(explot)
```

3.2 | Colorblind friendly color palettes

One of the very first attempts to create an open access colorblind friendly palette was performed by Smith and van der Walt (2021) (see van der Walt, 2024). Starting from a closed source color palette called "parula" from *Parula americana* bird, they developed the first version of the viridis color palette, which, ranging from blue to yellow is a first example of colorblind friendly gamut. The name, meaning "green" in latin, come out from several animal species like the snake *Dendroaspis viridis*, the fish *Chromis viridis* and the bird *Tersina viridis*. The viridis color palette was then implemented in an R package called `viridis` (Garnier et al., 2023).

The palettes developed in the `viridis` package were designed or adjusted from previous palettes maintaining three basic principles: (i) colorfulness, covering a broad range of options in order to enhance the visibility of distinctions; (ii) perceptual uniformity, with values in close proximity exhibiting similar colors and far values displaying more distinct

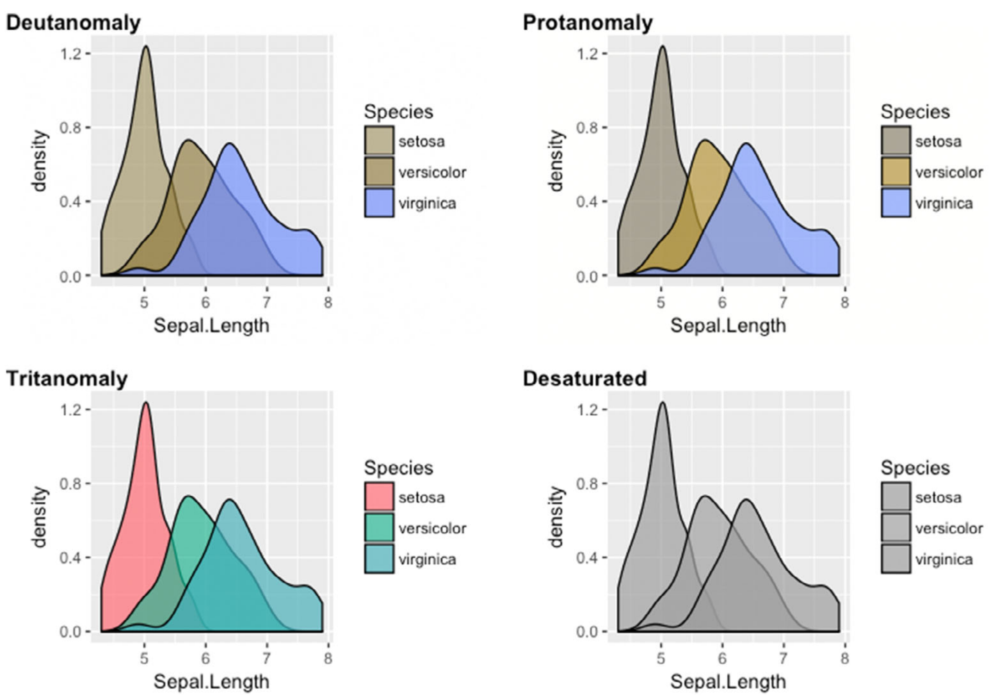

FIGURE 4 The `colorblindr` package allows users to check for the color friendliness of their graphs simulating the vision of people with different kinds of colorblind impairment. Simulation of the vision of a color palette by the different types of colorblindness described in section 1.

colors; (iii) robustness to colorblindness, so that the aforementioned characteristics are valid for individuals with typical types of color vision impairment.

Several R tools provide colorblind-friendly color palettes, including built-in functions such as *hcl.colors* and *palette.colors* (R Core Team, 2023; Zeileis & Murrell, 2023). The `RColorBrewer` and `rcartocolor` packages are also popular choices (Neuwirth, 2022; Nowosad, 2018). The previously mentioned `colorblindr` package offers a similar color palette called `scale_color_OkabeIto`, which is comparable to the `cividis` palette of the `viridis` package. Another useful tool is the `cols4all` package, which allows users to check the properties of various color palettes, including colorblindness simulation. Finally, the `colorBlindness` package provides a colorblindness simulator and offers color palettes specifically designed for colorblind individuals.

3.3 | Creating graphs with improved color palettes

The above described packages provide possibilities to create colorblind friendly palettes. However, they alone are not able to rerender existing graphs. For this reason, the `cblindplot` package has been developed. It is currently available in GitHub at https://github.com/ducciorocchini/cblindplot, and also being under evaluation in the Comprehensive R Archive Network (CRAN, https://cran.r-project.org/). It allows users to directly input an image and a colorblind disease type, and plots a new image with an improved color palette (Rocchini et al., 2023).

The first method developed in `cblindpot` is based on a reduction of the dimensionality of the input image by a Principal Component Analysis (PCA) and a rescaling of the colors on the first PC. For each type of colorblindness disease, an appropriate legend following Viénot et al. (1995) is then applied, based on the `viridis` package. As an example, a person affected by protanopia could make use of the founding function (`cblind.plot()`) as:

```
rainbowinput = "rainbow.png"
cblindpot::cblind.plot(rainbowinput, cvd= "protanopia")
```

The above code leads to a colorblind-friendly image like the one reported in Figure 5.

This method is straightforward, but (i) it only works for cases where the input color palette is sequential (its luminance changes linearly), and (ii) there is no control on colors of minima and maxima in the output, due to uncontrolled rescaling of the original values by Principal Component Analysis.

An alternative second method is based on the legend sampling. It requires one more input argument, an image of the original image color legend (it can be, for example, cropped from the original image using an external graphic editor, such as GIMP). Legend sampling involves regularly selecting the colors from the input legend (e.g., from the top to the bottom), and then replacing the original input colors in the provided main image with colors from a colorblind friendly palette.

```
my_image = "my_image.png"
my_legend = "my_legend.png"
cblindplot::cblind.plot(my_image, legend=my_legend)
```

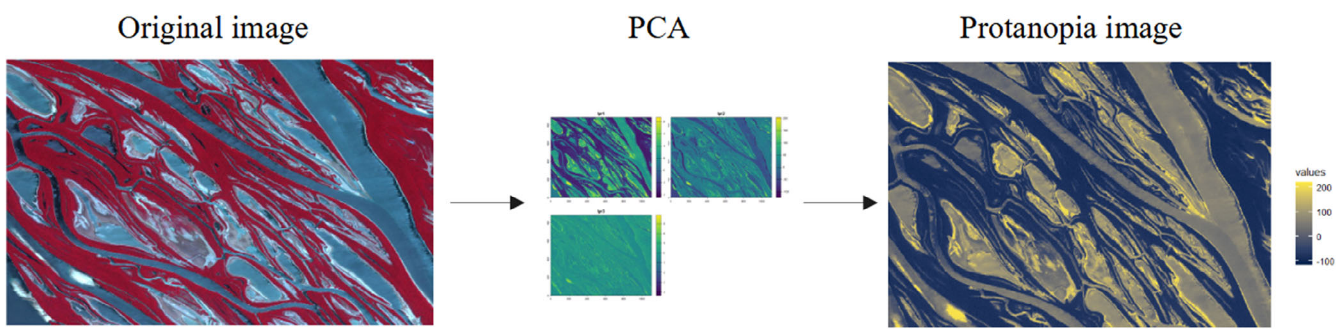

FIGURE 5 An image of the Rio Negro (Amazon forest, at Manaus, Brazil), using the ASTER satellite. *Source*: https://photojournal.jpl.nasa.gov/catalog/PIA26196). We provide an example considering protanopia. Using the `cblindplot` package the original image, which is poorly visible for colorblind people, is rescaled to a single layer with Principal Component Analysis, and a meaningful color palette is applied.

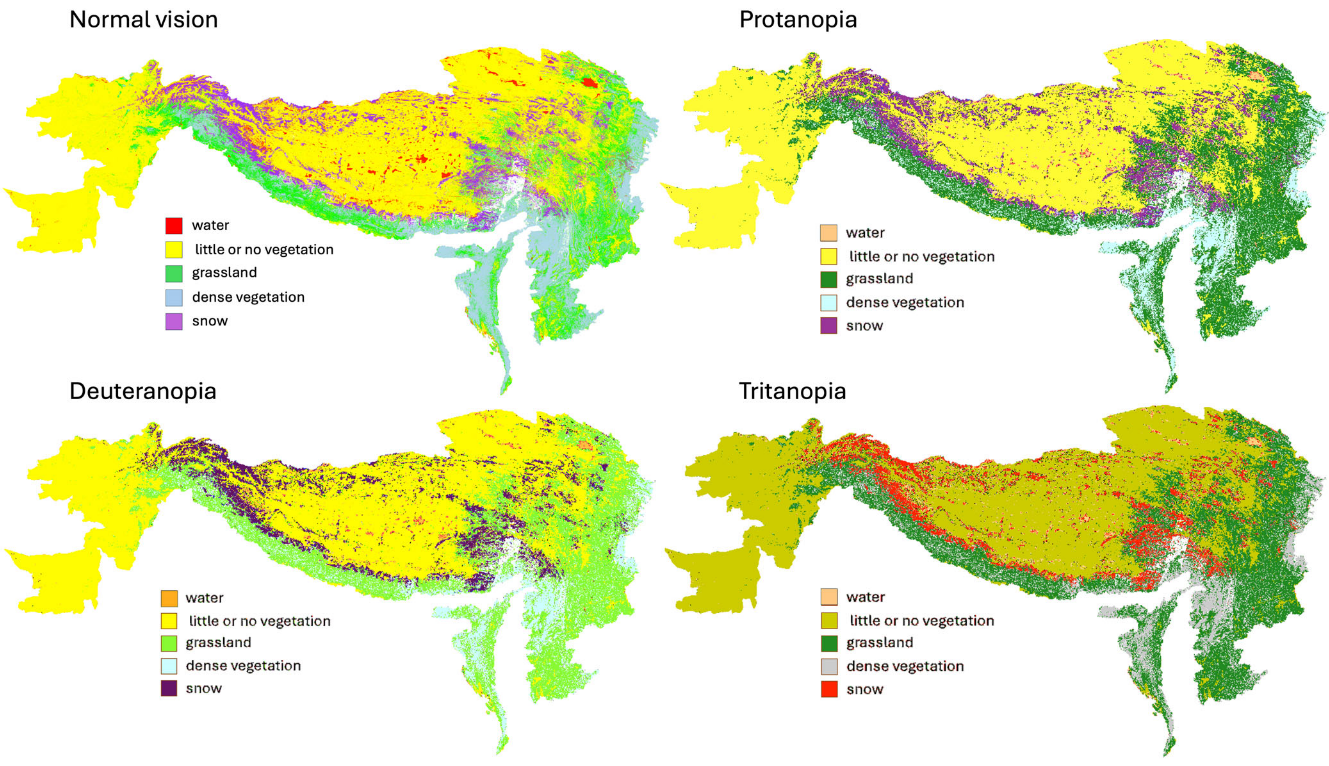

FIGURE 6 A classified map of the Himalaya region with rainbow colors in normal vision, and the colorblind-friendly maps created by the `nncblind()` function for protanopia, deuteranopia and tritanopia.

Additional methods for legend sampling could be based on a classification of colors by making use of neural networks (e.g., by the `nncblind()` function):

```
my_image = rast("my_image.png")
nncblind(my_image)
```

Initially, the neural network categorizes colors in the image into thirteen classes: white, red, brown, orange, yellow, light green, green, light blue, blue, pink, violet, grey, and black. Subsequently, the identified colors are substituted with a colorblind-friendly palette meticulously curated by ophthalmologists and orthoptists from Luigi Sacco Hospital (Milan, Italy). This specialized palette is tailored to the specific colorblind condition, ensuring an enhanced visual experience for users. Although there is a limited number of colors to be classified, this method has proved its efficiency in creating readable maps for colorblind people, especially when categorical maps are transformed, as in Figure 6.

4 | CONCLUSION

The main goal of data visualisation is to make it easier to identify patterns, trends and outliers in large data sets. The choice of colors can significantly impact how people interpret and interact with the data. A very good example is provided by the `ggplot2` R package and its derivatives (see https://www.cedricscherer.com/2019/08/05/a-ggplot2-tutorial-for-beautiful-plotting-in-r/ for an impressive and colorful tutorial).

Color vision impairment presents a notable obstacle in the visualization and comprehension of data, especially in the realm of ecology. It is essential to accurately interpret maps and graphs to understand complex ecological processes, ranging from the distribution of species to the dynamics of ecosystems. Yet, for individuals with colorblindness, conventional visual displays can frequently lead to misinterpretation or confusion. This paper highlighted the importance of developing tools and approaches that take into account the unique needs of individuals with color vision impairments in data visualization. The suggested R packages offer practical remedies to improve the clarity of maps and graphs intended for people with color vision impairments.

While the use of colorblind-friendly palettes is guided by the principle of inclusivity, caution is needed when using multiple palettes within a single visualization. The use of different palettes may lead to color overlap or hue merging, even if they are color-blind friendly. Therefore, it is essential to verify palette compatibility using the packages shown in Box 1 to ensure that colors do not blend across the various layers of a visualization.

In mapping contexts, where polygons often delineate political or ecological boundaries using distinct colors, introducing a second palette to represent an ecological/environmental gradient at several study sites can lead to color overlap for color-blind individuals. Specifically, some points might merge with the background, becoming indistinguishable to those with color vision impairments. In these cases, adopting a grayscale gradient for the background is an effective way to address this problem. Grayscale gradients, which rely on luminance rather than hue, offer a scale of differentiation that is universally discernible, making them useful in complex visualizations requiring clear distinctions between different data layers. However, when the visualization includes many classes, even grayscale gradients may lack discernibility for everyone. In such scenarios, the use of different textures can facilitate the necessary distinction.

We provided several R examples to face the colorblindness issue during data analysis in streamed pipelines. Additional packages exist to (i) simulate vision deficiencies and to (ii) apply colorblind-friendly palettes. For space and narrative reasons, we decided to include them in Box 1.

Moreover, we also encourage publishers to embed a tool in their systems so that someone viewing a graph/image online could literally click a button and change the visualisation, as in many colorblind simulator sites like *Coblis* (https://www.color-blindness.com/coblis-color-blindness-simulator/) or *Pilestone* (https://pilestone.com/pages/color-blindness-simulator-1). This would represent an enhancement for people to be able to easily change the graph/image into an accessible form.

Finally, as ecology continues to evolve, the tools and methodologies used to communicate research findings must keep pace. Adopting a higher awareness of the needs of colorblind people represents an important step in fostering inclusivity and accessibility.

Box 1- Packages related to colorblindness available in R

Simulation of colorblindness

- `colorspace` contains tools for manipulating and assessing colors, it also has functions for simulating color vision deficiencies (Zeileis et al., 2020);
- `colorblindcheck` simulates colorblindness of a given color palette, it also provides numerical summaries of the pairwise distances between colors inside a palette (Nowosad, 2019).
- `colorblindr` simulates colorblindness for R graphic objects, including `ggplot2` (McWhite & Wilke, 2023);
- `colorBlindness` contains palettes for colorblind people and a color vision impairment simulator (Ou, 2021);

Colorblind-friendly color palettes

- `RColorBrewer` provides color palettes for R, including colorblind-friendly palettes (Neuwirth, 2022);
- `viridis` provides color palettes for R, including colorblind-friendly palettes) (Garnier et al., 2023);
- `rcartocolor` provides color palettes for R, including colorblind-friendly palettes (Nowosad, 2018);
- `cols4all` provides a selection of color palettes designed to be accessible to people with normal color vision and color vision impairments (Tennekes, 2023).

Creating graphs with improved color palettes

- `cblindplot` allows to convert any rainbow color graph into a meaningful graph for colorblind people just digitising the type of colorblindness (Rocchini et al., 2023)

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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