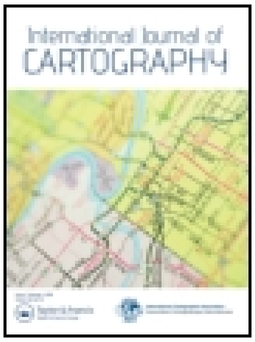

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The Natural Earth II world map projection

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ABSTRACT
The Natural Earth II projection is a new compromise pseudocylindrical projection for world maps. The Natural Earth II projection has a unique shape compared to most other pseudocylindrical projections. At high latitudes, meridians bend steeply toward short pole lines resulting in a map with highly rounded corners that resembles an elongated globe. Its distortion properties are similar to most other established world map projections. Equations consist of simple polynomials. A user study evaluated whether map-readers prefer Natural Earth II to similar compromise projections. The 355 participating general map-readers rated the Natural Earth II projection lower than the Robinson and Natural Earth projections, but higher than the Wagner VI, Kavrayskiy VII and Wagner II projections.

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Natural Earth II projection; map-reader preference; world projection; Natural Earth projection; Flex Projector

1. Introduction

This article introduces the Natural Earth II projection (Figure 1), a new compromise pseudocylindrical projection for world maps. Pseudocylindrical projections, such as the popular Robinson projection, are characterized by straight parallels and curved meridians. The Natural Earth II extends the work done on the Natural Earth projection (Jenny, Patterson, & Hurni, 2008; Šavrič, Jenny, Patterson, Petrovič, & Hurni, 2011), which applies moderate rounding to the four corners where bounding meridians and pole lines meet. This concept was taken one step further by eliminating all indication of corners on a world map for the Natural Earth II projection. At high latitudes, the bounding meridians bend steeply inward toward the central meridian and join seamlessly with relatively short pole lines. The result is a pseudocylindrical projection with a more rounded form resembling an elongated globe (Figure 1).

The design process, polynomial equation and characteristics of the Natural Earth II projection are described in the following section. A user study was conducted to evaluate whether map-readers prefer the Natural Earth II projection to similar compromise projections with straight parallels. The design of the user study, statistical significance tests and results are presented. The article concludes with a short discussion of our findings.

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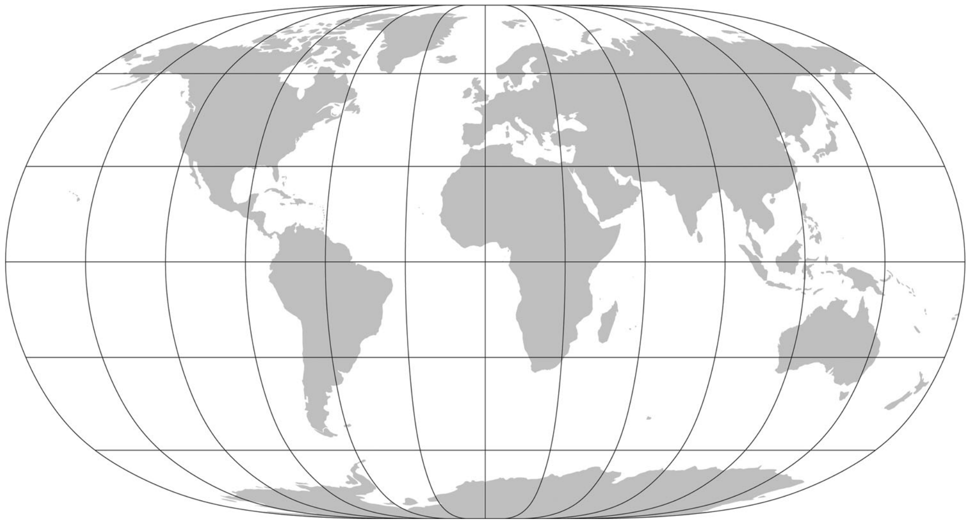

Figure 1. The Natural Earth II projection.

2. Natural Earth II

2.1. *Design and polynomial equations*

The Natural Earth II projection (Figure 1) is a compromise pseudocylindrical projection designed by Tom Patterson. Flex Projector, a freeware application for the interactive design and evaluation of map projections (Jenny & Patterson, 2014), was used to design Natural Earth II. For developing projections, Flex Projector takes a graphic approach that was first introduced by Arthur H. Robinson during the design of his well-known, eponymous projection (Jenny & Patterson, 2013; Jenny et al., 2008; Jenny, Patterson, & Hurni, 2010; Robinson, 1974). In Flex Projector, the user adjusts the length, shape, and spacing of parallels and meridians for every 5° of latitude and longitude. The Natural Earth II projection was designed by adjusting the relative length of parallels and the relative distance of parallels from the equator, while spacing of meridians remained constant and no bending was applied to parallels. The design process required trial-and-error experimentation and visual evaluation of the resulting map projection. By shortening the relative length of the pole lines, smoothly rounded corners of the bounding meridians were created, which resulted in a rounded graticule resembling an elongated globe.

When the Natural Earth II projection design was completed, the least squares adjustment method was used to develop a polynomial expression of the projection. Šavrič et al. (2011) detail the derivation of the polynomial expression for the Natural Earth projection, a similar projection designed by Tom Patterson (Jenny & Patterson, 2014). The graphical design in Flex Projector defined the Natural Earth II projection with 37 control points distributed over the complete range of the bounding meridian for every 5°. Each point defined the relative length of parallels and the relative distance of parallels from the equator. Control points were used to approximate the graphical design with two polynomials. To ensure the symmetry about the *x* and *y* axes, the *x* coordinate contains only even powers of latitude φ, and the *y* coordinate consists of only odd powers of latitude φ. By multiplying the even powers of the latitude with longitude λ, the meridians remained equally spaced curves. Details on polynomial derivations are presented by Canters (2002, p. 133).

Three additional constraints were used in the least square adjustment. The first two constraints enforced the distance of the pole line from the equator and the length of the equator to the values selected in Flex Projector. The third constraint fixed the slope of the y coordinate equation to 0° at poles, which ensured smoothly rounded corners where bounding meridians meet the pole lines. Šavrič et al. (2011) detail how constraints are applied and included in the least square adjustment method. Equation (1) is the resulting polynomial equation for the Natural Earth II projection.

$$\begin{aligned} x &= R \cdot \lambda \cdot (A_1 + A_2\varphi^2 + A_3\varphi^{12} + A_4\varphi^{14} + A_5\varphi^{16} + A_6\varphi^{18}) \\ y &= R \cdot (B_1\varphi + B_2\varphi^9 + B_3\varphi^{11} + B_4\varphi^{13}) \end{aligned} \tag{1}$$

where x and y are the projected coordinates, λ and φ are the latitude and longitude in radians, R is the radius of the generating globe, and A_1 to A_6 and B_1 to B_4 are polynomial coefficients given in Table 1. The polynomial expression for the Natural Earth II projection consists of 10 coefficients, 6 for the x coordinate and 4 for the y coordinate. With an appropriate factorization, the polynomial equation can be simplified to 15 multiplications and 8 additions per point. To convert Cartesian coordinates to spherical coordinates, the Newton–Raphson method is used to find the latitude φ from the y equation; longitude λ is computed by inverting the x equation.

2.2. *Projection characteristics*

The Natural Earth II projection has short pole lines that are 0.226 times as long as the equator. The smoothly rounded corners of the bounding meridians give the graticule a rounded appearance. The graticule is symmetric about the central meridian and the equator. The length of the equator is 0.847 times the circumference of a sphere. The central meridian is a straight line 0.535 times as long as the equator. Other meridians are equally spaced polynomial curves and the smoothness of their ends at the pole line decreases toward the central meridian. The parallels are straight and unequally spaced. The ratio between the lengths of pole lines and the equator as well as the ratio between the length of the central meridian and the equator are a result of the projection design and the derivation of the polynomial equations.

As a compromise projection, Natural Earth II is neither conformal nor equal area, but its distortion characteristics are comparable to other established projections. The distortion values of Natural Earth II fall between those of the Kavraiskiy VII, Robinson, Winkel

Table 1. Coefficients for the polynomial expression Equation (1) of the Natural Earth II projection.

x Equation		*y* Equation	
A_1	0.84719	B_1	1.01183
A_2	−0.13063	B_2	−0.02625
A_3	−0.04515	B_3	0.01926
A_4	0.05494	B_4	−0.00396
A_5	0.02326		
A_6	0.00331		

Tripel, Wagner VI and Natural Earth projections. Table 2 compares the weighted mean error in the overall scale distortion index D_{ab}, the weighted mean error in areal distortion index D_{ar}, and the mean angular deformation index D_{an} of the Natural Earth II projection to other compromise and equal-area projections commonly used for small-scale mapping (for details on how indices are defined, see Canters & Decleir, 1989, pp. 42–43 and Canters, 2002, p. 48). The local linear scale along meridians and parallels, areal scale and distortion of angles can be computed from the Gaussian fundamental quantities (for details on equations, see Canters, 2002, pp. 9–16).

As with all compromise projections, the Natural Earth II projection exaggerates the size of high-latitude areas. Figure 2 illustrates the distortion characteristics of Natural Earth II. In the top image, Tissot's indicatrices are placed at the intersection of the 30° meridians and parallels that make up the graticule. The area of indicatrices increases toward the poles, indicating an exaggeration of the size of high-latitude areas.

The middle and bottom images of Figure 2 show isocols of area distortion and maximum angular distortion. Areal distortion increases with latitude, but does not change with longitude. Therefore, all isocols of areal distortion are parallel to the equator. Isocols of maximum angular distortion increase with latitude, which follows the general pattern common to most pseudocylindrical projections.

Compared to the Natural Earth projection, Natural Earth II has a larger height-to-width ratio, shorter pole lines and a rounder appearance (Figure 3). It has a similar overall scale distortion index D_{ab}, a slightly better weighted mean error in areal distortion index D_{ar} and a larger mean angular deformation index D_{an} (Table 2). Unlike the Natural Earth projection which has standard parallels at 33°18′ N/S, the Natural Earth II projection has standard parallels at 37°4′ N/S.

Besides the Natural Earth projections, there are several other compromise pseudocylindrical projections with rounded corners. Winkel II is one example that is similar in appearance, commonly used and available in many GIS and mapping applications. The Winkel II projection with standard parallels at approximately 29°41′ N/S (Figure 3) has the same height-to-width ratio as the Natural Earth II projection. Winkel II also has a

Table 2. The weighted mean error in the overall scale distortion index D_{ab} the weighted mean error in areal distortion index D_{ar} and the mean angular deformation index D_{an} for the Natural Earth II projection and other world map projections.

Projection	D_{ab}	D_{ar}	D_{an}
Kavrayskiy VII	0.23	0.279	19.15
Natural Earth	0.251	0.194	20.54
Natural Earth II	**0.254**	**0.175**	**21.43**
Winkel Triple	0.256	0.179	23.28
Wagner VI	0.263	0.342	20.41
Robinson	0.265	0.275	21.26
Winkel II ($\varphi_S \cong 29^\circ 41'$)	0.268	0.194	21.49
Plate Carrée	0.285	0.571	16.84
Wagner II	0.315	0.116	26.88
Eckert IV	0.363	0	28.73
Miller Cylindrical	0.393	1.303	32.28
Mollweide	0.394	0	7.63

Note: Lower values indicate better distortion characteristics. The Natural Earth II projection is marked in bold.

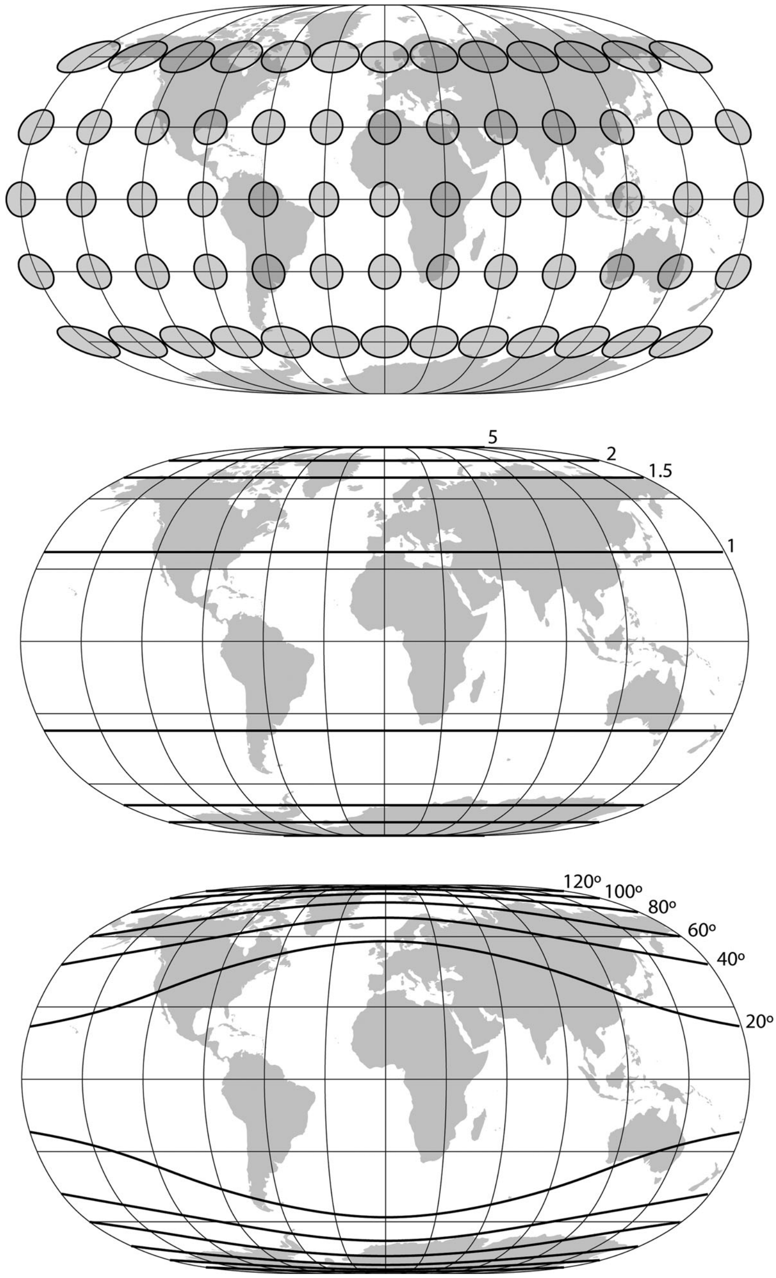

Figure 2. Tissot's indicatrices (top), isocols of area distortion (middle) and isocols of maximum angular distortion (bottom) for the Natural Earth II projection.

similar mean angular deformation index D_{an}, but Natural Earth II has a better overall scale distortion index D_{ab} and weighted mean error in areal distortion index D_{ar} (Table 2). Because the Natural Earth II projection has shorter pole lines and a rounder appearance, areas near the poles are stretched less in the east-west direction than with the Winkel II projection.

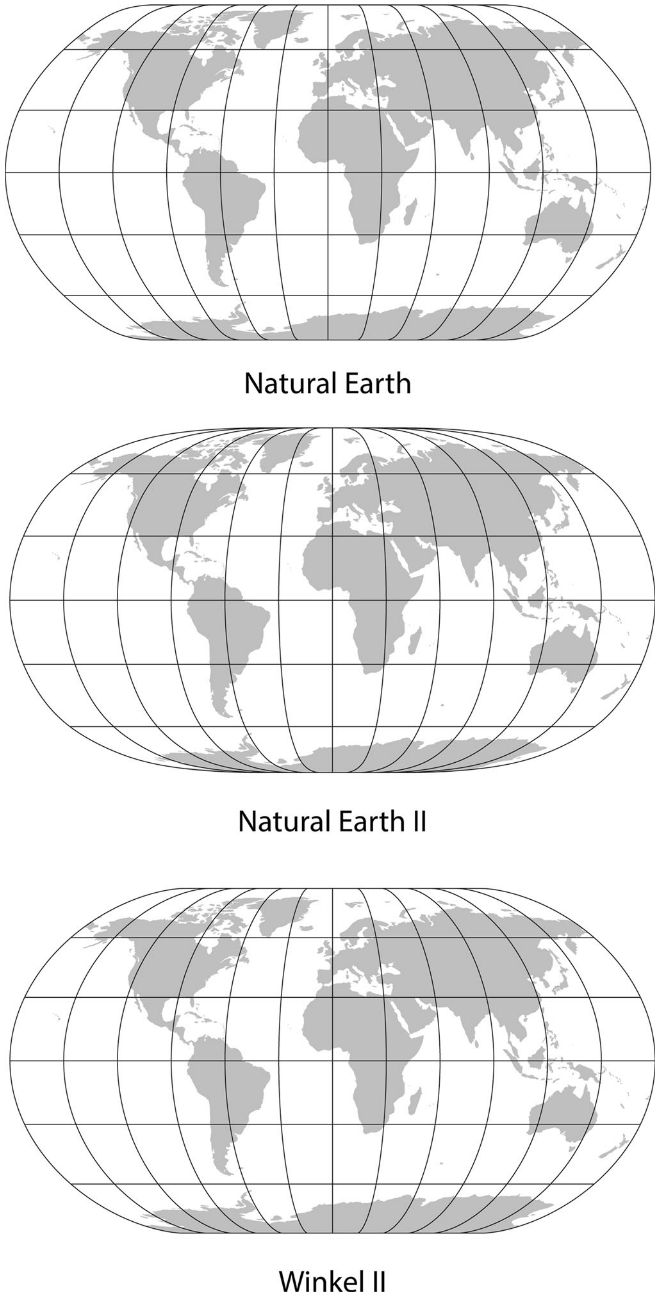

Figure 3. Comparing the Natural Earth II projection with the Natural Earth projection and the Winkel II projection with standard parallels at 29°41′ N/S.

3. User study

In a previous study of world map esthetics, student test subjects strongly preferred elliptical map graticules to rectangular ones (Gilmartin, 1983). We conducted a user study to test whether the highly rounded shape of the Natural Earth II projection (which is not elliptical) appeals to map-readers. Participants compared the Natural Earth II projection to five commonly used compromise projections with straight parallels. The study was part of a larger user study about map-readers' preferences for world map projections Šavrič, Jenny, White, & Strebe, 2015; Jenny, Šavrič, & Patterson, 2015.

3.1. *Design, process and statistics*

The user study used a paired comparison test to evaluate map-readers' preference for the Natural Earth II projection. The paired comparison test compared each map projection with every other map projection in the set. The set contained the Kavrayskiy VII, Natural Earth, Robinson, Wagner II, Wagner VI and Natural Earth II projections (Figure 4). All projections in the set have compromise distortion and straight parallels. The difference

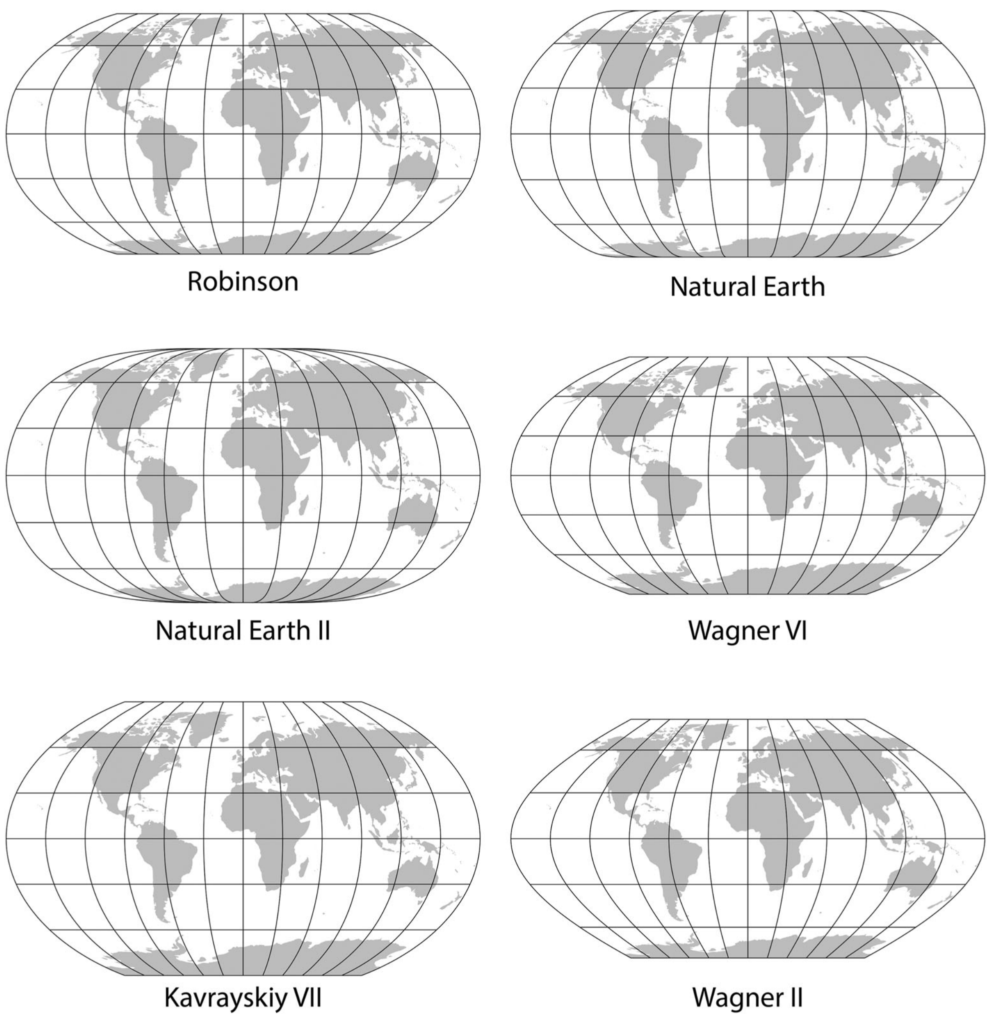

Figure 4. The six small-scale map projections used in the user study. They are arranged in descending order, from top left to bottom right, based on general map-reader preference.

between the projections lies mostly in the shape of meridians, height-to-width ratio, length of pole lines and the representation of pole line corners.

The study contained all 15 possible projection pairs. Participants of the online study were recruited through Amazon's Mechanical Turk, online forums and social networks. Participants were categorized into two groups of subjects: (1) *general map-readers* with limited or no map-making experience, and (2) *experts in map projections, cartographers or experienced GIS users*. Each participant evaluated all pairs of map projections by selecting the map in a presented pair that he or she personally preferred. Study participants were also asked demographic questions regarding their gender, age, education level, cartographic experience and how often they use maps. Details about the user study survey process, recruiting, selection of valid responses and participants' demographics can be found in Šavrič et al., 2015.

For the statistical analysis of the paired comparison study, two non-parametric tests of significance, proposed by David (1988), were used. The overall test of equality (David, 1988) determined which map projections were significantly different from each other based on how many times users selected a projection from the set. In the post hoc analysis, the multiple comparison range test (David, 1988) identified which graticules were significantly different from each other based on which graticules participants preferred. The χ^2 test for the $2 \times C$ table, where C represents the number of categories for each participant's demographic characteristics, evaluated the influence that demographic characteristics and frequency of map use had on participants' preferences. The χ^2 test was used on all 15 map projection pairs separately. The overall test of equality, multiple comparison range test and χ^2 test were performed separately for both groups of subjects.

3.2. *Results*

A total of 448 participants submitted valid responses. Participants were categorized into two groups: (1) *general map-readers* with 355 participants, and (2) *projection experts*, *cartographers or experienced GIS users* with 93 participants.

General map-readers selected the Robinson and Natural Earth projections more often than any other projection. Following the Robinson and Natural Earth projections were the Natural Earth II, Wagner VI and Kavrayskiy VII projections. Wagner II was the least preferred projection. The six projections are arranged according to general map-readers' preferences in Figure 4. Table 3 shows results of the pairwise preference

Table 3. Pairwise preference by general map-readers for six pseudocylindrical compromise projections.

	1	2	**3**	4	5	6
(1) Robinson		47%	**58%**	57%	62%	85%
(2) Natural Earth	53%		**52%**	57%	61%	86%
(3) Natural Earth II	**42%**	**48%**		**52%**	**55%**	**80%**
(4) Wagner VI	43%	43%	**48%**		48%	86%
(5) Kavrayskiy VII	38%	39%	**45%**	52%		84%
(6) Wagner II	15%	14%	**20%**	14%	16%	

Note: Names of projections are arranged in both rows and columns according to the total scores. Each row shows the percentages of participants that prefer the projection in the row to other projections listed in the column. The Natural Earth II projection is marked in bold.

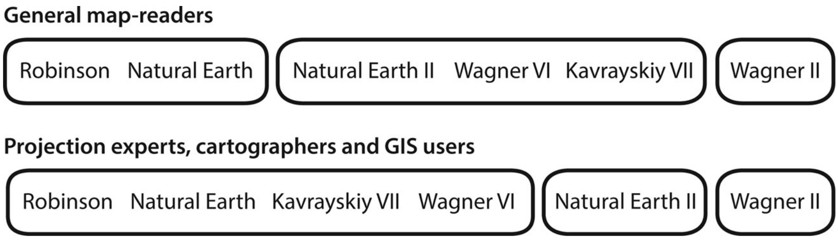

Figure 5. Projection preference summary. Projections are arranged with the most preferred on the left. Preference differences are significantly greater between outlined groups than within.

as a percentage for general map-readers. Of the 355 general map-reader participants, 58% preferred Robinson and 52% preferred Natural Earth to the Natural Earth II projection. Natural Earth II was preferred to Wagner VI by 52%, to Kavrayskiy VII by 58%, and to Wagner II by 80% of participants. An overall test of equality (χ^2_5, 0.01 $=$ 15.09, $D_n = 877.8$) showed statistically significant differences in general map-readers' preferences. Results from a post hoc multi comparison range test are displayed in Figure 5. Projections are arranged left to right according to user preference and any projection that is not outlined by the same line is significantly different based on user preferences.

Of the 93 participants that made up the group of projection experts, cartographers or experienced GIS users, 74% preferred the Natural Earth II projection to the Wagner II projection. Sixty-seven percent preferred Robinson, 62% preferred Kavrayskiy VII and Natural Earth, and 61% preferred Wagner VI to Natural Earth II. The Robinson and Natural Earth projections were selected most frequently, followed by Kavrayskiy VII and Wagner VI. Natural Earth II ranked second to last and Wagner II was the least preferred projection. The overall test of equality (χ^2_5, 0.01 $=$ 15.09, $D_n = 284.04$) showed statistically significant differences in map-readers' preferences for projections. Figure 5 shows results from the post hoc multi comparison range test (Table 4).

The χ^2 tests on the 15 map projection pairs did not show any differences in user preference due to gender, age, education level, background in cartography or cartographic experience for either group of participants. There were no differences attributable to participants' frequency of using web or virtual globe maps, or related to the type of map most often utilized by participants.

Table 4. Pairwise preference by projection experts, cartographers or experienced GIS users for six pseudocylindrical compromise projections.

	1	2	3	4	**5**	6
(1) Robinson		51%	57%	63%	**67%**	88%
(2) Natural Earth	49%		62%	52%	**62%**	86%
(3) Kavrayskiy VII	43%	38%		52%	**62%**	94%
(4) Wagner VI	37%	48%	48%		**61%**	89%
(5) Natural Earth II	**33%**	**38%**	**38%**	**39%**		**74%**
(6) Wagner II	12%	14%	6%	11%	**26%**	

Note: The table has the same ordering and units of measure as Table 3. The Natural Earth II projection is marked in bold.

4. Conclusion

The method for creating Natural Earth II involved three steps: (1) using the graphical user interface of Flex Projector to design a rough draft projection with a desired look; (2) developing the polynomial equation that approximates the Flex Projector draft; and (3) fine tuning the polynomial equation for projection appearance, distortion characteristics and computational efficiency. The resulting Natural Earth II projection is a rounder pseudocylindrical projection with compromise distortion characteristics similar to other projections in its class.

Creating the Natural Earth II projection was partially motivated by the idea that map-readers would prefer a pseudocylindrical projection with rounded corners that more closely resembles the spherical shape of Earth. However, the user study found that participants did not have a strong preference for the Natural Earth II projection. Preferences for the Natural Earth projection, which has slightly rounded corners, and the Robinson projection, which has more defined corners, were too close statistically to assume that either projection was preferred to the other. Both the Natural Earth and Robinson projections were preferred to the highly rounded Natural Earth II projection.

Wagner II was the least preferred projection. Wagner II differs from the other projections included in the set because meridian lines have a more sinusoidal shape, which results in the bulging of areas along the equator. Šavrič et al. (2015) found that map-readers generally dislike meridians that strongly bulge outwards at the equator. Our user study confirms these findings.

Projection experts, cartographers and experienced GIS users strongly preferred four map projections – Robinson, Natural Earth, Karayskiy VII and Wagner VI – all of which look more similar to the Robinson projection than to the Natural Earth II and Wagner II projections. In contrast, general map-readers liked the Natural Earth II projection, preferring it immediately behind the Robinson and Natural Earth projections. The discrepancy between the two groups is possibly due to different exposures to the Robinson projection. We speculate that mapping professionals who routinely use the Robinson projection may regard it as the standard against which all other pseudocylindrical projections are measured, thereby favoring projections most similar to it. General map-readers who are less familiar with the Robinson projection may presumably be more open to projections with alternative shapes.

The popularity of world map projections changes over time and varies according to the taste of publishers. For those looking for a new pseudocylindrical projection with acceptable distortion characteristics, Natural Earth II is available as an option.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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