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A global inventory of lakes based on high-resolution satellite imagery

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Key Points:
- Earth has 117 million lakes > 0.002 km^2
- Large and intermediate lakes dominate the total surface area of lakes
- Power law-based extrapolations do not adequately estimate lake abundance

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Abstract An accurate description of the abundance and size distribution of lakes is critical to quantifying limnetic contributions to the global carbon cycle. However, estimates of global lake abundance are poorly constrained. We used high-resolution satellite imagery to produce a GLObal WAter BOdies database (GLOWABO), comprising all lakes greater than 0.002 km^2. GLOWABO contains geographic and morphometric information for ~117 million lakes with a combined surface area of about 5×10^6 km^2, which is 3.7% of the Earth's nonglaciated land area. Large and intermediate-sized lakes dominate the total lake surface area. Overall, lakes are less abundant but cover a greater total surface area relative to previous estimates based on statistical extrapolations. The GLOWABO allows for the global-scale evaluation of fundamental limnological problems, providing a foundation for improved quantification of limnetic contributions to the biogeochemical processes at large scales.

1. Introduction

Lakes comprise a small fraction of the Earth's land surface but are sites of intense biogeochemical activity [*Cole et al.*, 2007]. Lakes are an important source of atmospheric carbon dioxide and methane to the extent that they are thought to offset a majority share of the terrestrial carbon sink [*Bastviken et al.*, 2011; *Raymond et al.*, 2013]. They are also a major component of continental carbon burial [*Dean and Gorham*, 1998]. However, estimates of stocks and fluxes of elements are poorly constrained in part because they are based on incomplete or inaccurate information of the global occurrence of lakes [*Lewis*, 2011]. Hence, the question, "how many lakes are there on Earth, and how big are they?," remains one of the most important unanswered questions in the study of inland water biogeochemistry [*Seekell et al.*, 2013].

Current understanding of the global abundance and size distribution of lakes comes from two sources: map compilations and statistical extrapolations based on abundance-size relationships. Map compilations, such as the Global Lake and Wetland Database (GLWD) compiled by *Lehner and Döll* [2004], are based on digitized inventories, registers, archives, and remote sensing data from various sensor types. This compilation includes most of Earth's large lakes (e.g., > 10 km^2) but underrepresents small lakes that are typically omitted from maps [*Downing et al.*, 2006]. To overcome this deficiency, statistical extrapolations based on power law abundance-size relationships have been used to estimate the number of small lakes not covered by mapping [e.g., *Downing et al.*, 2006; *Minns et al.*, 2008]. Such analyses have revealed that the global abundance of lakes is much greater relative to previous estimates and that small lakes dominate the total surface area of lakes [*Downing et al.*, 2006], a result with wide-ranging implications for upscaling of biogeochemical fluxes [e.g., *Lewis*, 2011; *Bastviken et al.*, 2011; *Raymond et al.*, 2013]. However, recent analyses have found that statistical extrapolations of lake abundance are error prone and that they likely overestimate abundance of small lakes [*Seekell and Pace*, 2011; *McDonald et al.*, 2012; *Seekell et al.*, 2013]. Further, the map compilations these extrapolations are based on encompass the full variety of errors and uncertainties characteristic of the different types of source data [*Lehner and Döll*, 2004]. It is likely that the only way to accurately resolve the global abundance and size distribution of lakes is through analysis of high-resolution satellite imagery [*Seekell and Pace*, 2011].

Recent advances in remote sensing technology and the development of automated methods for extracting lakes from satellite imagery make it feasible to enumerate all of Earth's lakes [*Verpoorter et al.*, 2012]. We applied a previously validated lake extraction algorithm to high-resolution satellite imagery to enumerate

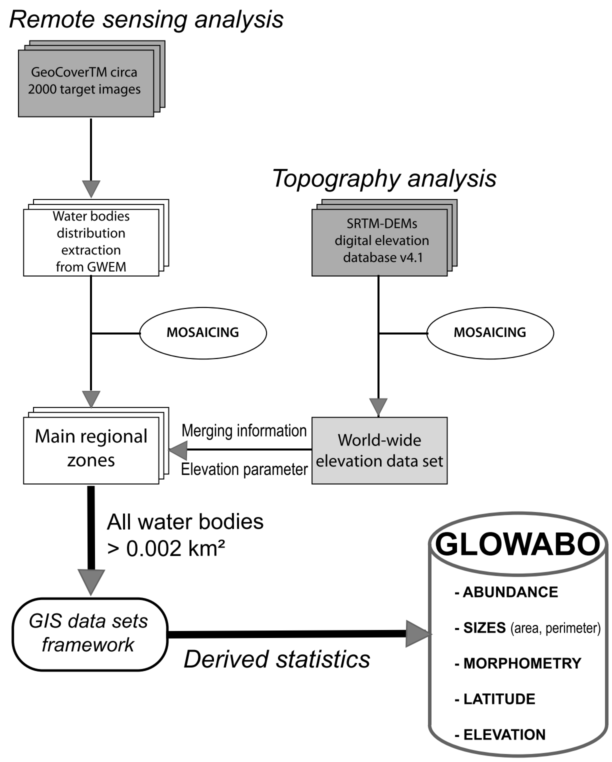

Figure 1. Overview of GLOWABO computations showing the data set inputs used (grey boxes), the data set outputs generated (white boxes), and the methodology used (GWEM).

and measure Earth's lakes, including their abundance, size (i.e., area and perimeter), geographical distribution, elevation, and morphometric characteristics such as the shoreline development index (SDI). Here we summarize the characteristics of this GLObal WAter BOdies database (GLOWABO). Overall, we answer the fundamental question "how many lakes are on Earth?" and provide the foundation for improved quantification of limnetic contributions to the biogeochemical processes at large scales, including emissions and burial of carbon.

2. Methods and Database Contents

We previously developed and validated an automated algorithm called GWEM (GeoCover^{TM} Water bodies Extraction Method) for extracting lakes from high-resolution satellite imagery [*Verpoorter et al.*, 2012]. The GWEM algorithm extracts lakes from the GeoCover^{TM} circa 2000 data set based on spectral characteristics and eliminates false detections due to mountain shadows by considering local elevations and the position of the sun at the time the of imaging. The GeoCover^{TM} data set is mostly cloudless, minimizing false lake identification due to cloud shadows [*Verpoorter et al.*, 2012]. When validated against a high-resolution map of Sweden [*Verpoorter et al.*, 2012], an area comprising nearly all difficult targets (cloud and mountain shadows, dark forest that can be mistaken as water, as well as turbid lakes, shallow lakes, and ice that are prone to be detected as land), the method yielded a performance index [*Bagli and Soille*, 2004] of 91% for lake area, and the lake count deviated by less than 3% from the lake data of the high-resolution map. Metrics of lake shape, like the shoreline development index (SDI) can also be calculated in high accuracy based on the GWEM algorithm extractions [*Verpoorter et al.*, 2012]. Detailed descriptions of the GWEM algorithm and its application to the GeoCover^{TM} data set are found in *Verpoorter et al.* [2012].

To create the GLOWABO database, we applied the GWEM algorithm to the global coverage of the GeoCover^{TM} circa 2000 image data set. GeoCover^{TM} circa 2000 is built from imagery of the Enhanced Thematic Mapper Plus (ETM+) sensor on board the Landsat 7 satellite collected in year 2000 ± 3 years. It is a static product, and it is delivered through https://zulu.ssc.nasa.gov/mrsid/. The Landsat imagery (about 8500 scenes) was pan sharpened to have 14.25 m spatial resolution and is mosaicked into 882 nearly cloud-free tiles containing three spectral bands (ETM + 2, ETM + 4, and ETM + 7) [*Koeln et al.*, 1999; *Lillesand and Kiefer*, 1999]. When applying the GWEM algorithm, we used digital elevation data from the Shuttle Radar Topography Mission digital elevation model (SRTM-DEM) database v4.1 from the Consortium for Spatial Information of the Consultative Group for International Agricultural research [*Jarvis et al.*, 2008]. We filtered out all objects smaller than 9 pixels corresponding to a cutoff value of ~0.002 km^2 (0.2 ha) in size (i.e., 9 × 14.25 × 14.25 m pixels) because water bodies smaller than this size are difficult to verify relative to image noise [*Verpoorter et al.*, 2012]. Islands in lakes were considered land in the GLOWABO computation and coastal lagoons were not included in the analysis using a well-defined coastline polygon as a mask. We analyzed the complete global imagery with the exception of Antarctica and the glaciated areas of Greenland. Application of the GWEM algorithm resulted in a GLOWABO, covering all lakes larger than 0.002 km^2 (Figure 1). Elevation [*McVicar and Korner*, 2013] is provided for all lakes between 60°N and 56°S, where digital elevation data are available via the Shuttle Radar Topography Mission.

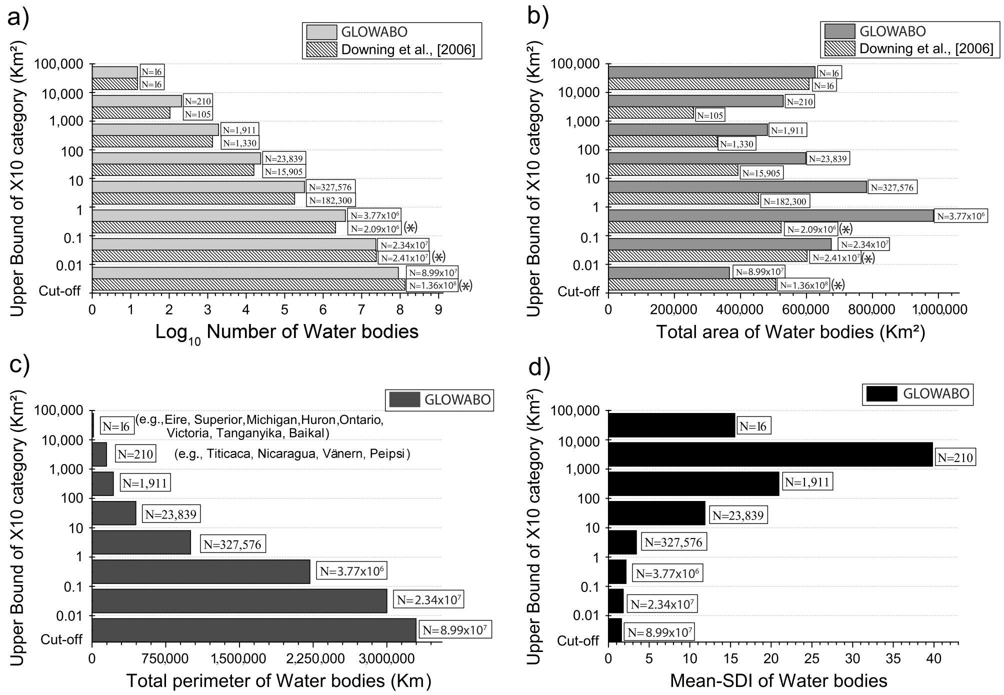

Figure 2. The (a) number, (b) total area, (c) total perimeter, and (d) mean SDI of water bodies of the GLOWABO (excluding the Caspian Sea). Numbers on *y* axis are the lower/upper boundary of decadal size classes. GWEM results are shown with grey bars while dashed bars are number as reported from *Downing et al*. [2006] and used here for comparison (excluding the Caspian Sea). Note that for the smaller-size category that GWEM data are ranged between 0.01 and 0.002 km^2 were recalculated using the statistical extrapolation approach detailed by *Downing et al*. [2006]. Below 10 km^2 (asterisk), data are extrapolated from canonical data set (GLWD, *Lehner and Döll* [2004]) using the power law abundance-size relationship.

3. Global Abundance and Distribution of Lakes

The database contains about 27 million water bodies larger than 0.01 km^2 with a total surface area of 4.76×10^6 km^2 excluding Caspian Sea (Figure 2). This is approximately 3.5% of Earth's nonglaciated land surface area. About 22 million water bodies larger than 0.01 km^2 are located between 60°N and 56°S, where elevation data are available. These lakes have a total surface area of 1.89×10^6 km^2, 1.4% of nonglaciated land surface area. Hence, about 5 million lakes north of 60°N or south of 56°S, where there are no digital elevation data, make up a substantial fraction of the global lake area. There are about 117 million lakes greater than 0.002 km^2, covering a total area of 5.0×10^6 km^2, which corresponds to 3.7% of Earth's nonglaciated land surface. Accordingly, about 90 million lakes in the smallest size bin (0.002 to 0.01 km^2) make up only 0.27% of the nonglaciated land surfaces, which is mostly dominated by lakes larger than 0.01 km^2.

The highest concentration, area, and perimeter of water bodies appear at boreal and arctic latitudes (45°–75°N). Water body abundance is lower at southern latitudes where the continental area is also lower. The general pattern is consistent with previously published map compilations [*Lehner and Döll*, 2004], albeit with more variability (Figures 3a, 3c, and 3e). Size distribution of water bodies decreases drastically across elevation where 85% of lakes, 50% of lake area, and 50% of total lake perimeter are located at elevations lower than 500 m above sea level (Figures 3b, 3d, and 3f).

The total area contributed by decadal water body size categories increases with the decreasing size down to an area of 0.1 km^2 (Figure 2a). This pattern is consistent with previously reported results based on map compilations and statistical extrapolations [*Downing et al*., 2006]. However, the area of lakes < 0.1 km^2 is less and does not follow the pattern of larger lakes. This result is inconsistent with prevailing knowledge derived from statistical extrapolations. Water bodies smaller than 0.1 km^2 are numerous, but they contribute only

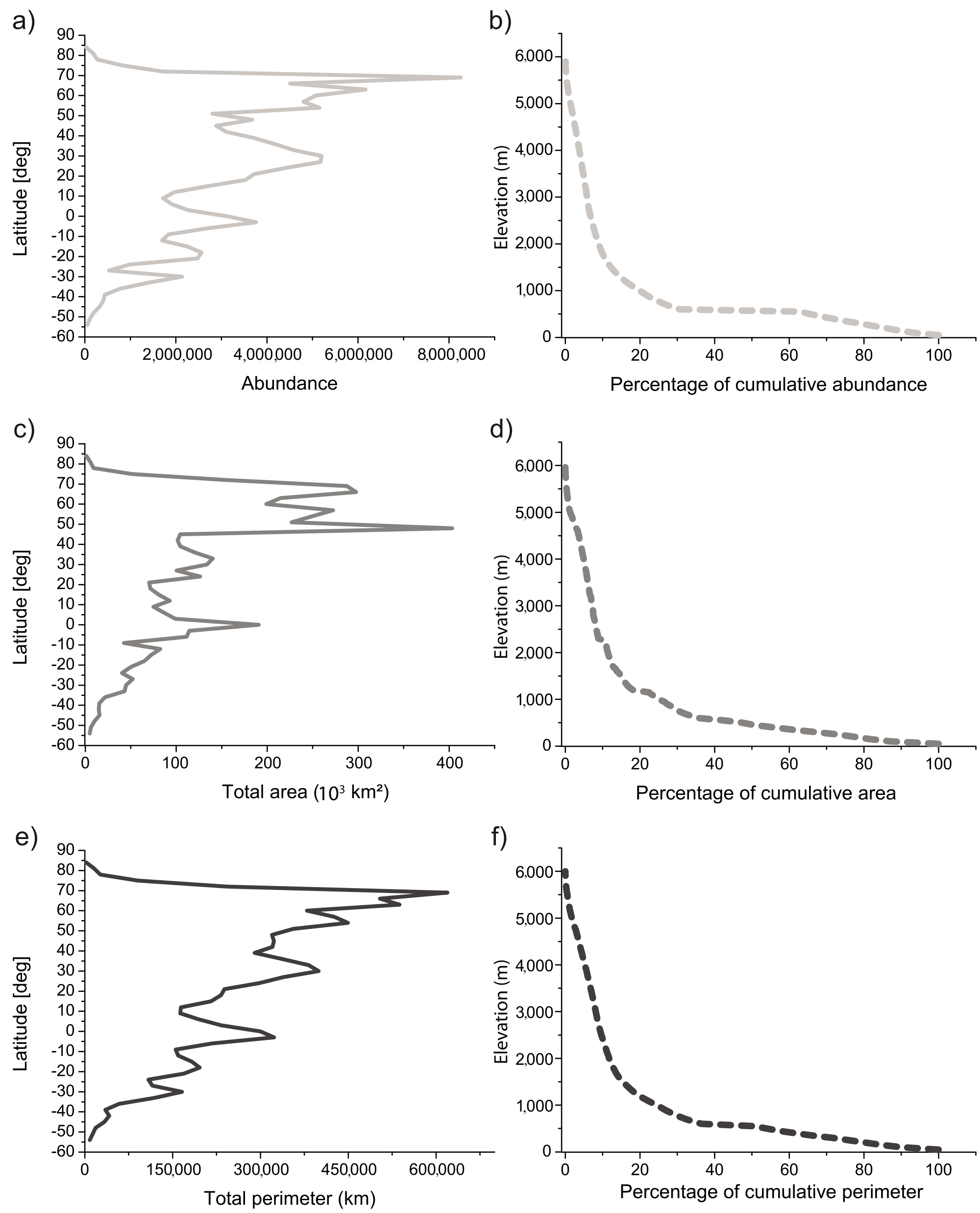

Figure 3. Latitudinal and elevation distribution of the GLOWABO database for all size categories (excluding Caspian Sea). The latitudinal distribution of water bodies of (a) abundance, (c) total area, and (e) total perimeter. Numbers were aggregated in steps of 3° latitude (see full lines). The elevation distribution of water bodies of (b) percentage of cumulative abundance, (d) percentage of cumulative area, and (f) percentage of cumulative perimeter. Numbers were cumulated in steps of elevation of 50 m (see dashed lines).

marginally to the total limnetic area (Figure 2b). Still, the smallest lakes comprise a major fraction of the total global lake perimeter, i.e., the global continental interface between lakes and land (Figure 2c). The SDI, a measure of roundness, decreases with decreasing lake size indicating that smaller lakes are rounder with less convoluted shorelines than large lakes (Figure 2d).

We compared the size distribution of lakes in the GLOWABO data set to estimates of global lake abundance based on statistical extrapolations of abundance-size relationships. Specifically, we compare our results to those of *Downing et al*. [2006], with the exception that we have adjusted estimates of their smallest size class (0.001–0.01 km^2) to have a higher minimum size (0.002–0.01 km^2) such that the estimates are directly comparable to the GLOWABO data.

The total abundance of lakes $> 0.002\ km^2$ differs substantially between the statistical extrapolation approach (163 million) and our direct count by remote sensing (117 million). This discrepancy is mainly explained by differences in the abundance of small lakes (0.002–0.01 km^2), which are overestimated by 46 million compared to our direct remote sensing approach. The previously reported extrapolation by *Downing et al*. [2006] revealed the number of lakes between 0.002 and 0.01 km^2 is 136 million with a total surface area of 506,685 km^2 (or 0.37% of global land mass). Nearly half of the total number of lakes estimated by *Downing et al*. [2006] are smaller than 0.002 km^2, i.e., below the detection limit of our remote sensing method. Despite this, the differences in lower threshold have no bearing on the key results when comparing our results with those of *Downing et al*. [2006] in that intermediately sized lakes dominate the total surface area of lakes and that lakes do not follow a power law abundance-size relationship. With an improved spatial resolution of GLOWABO, allowing a lower threshold, the deviation between the two approaches will most likely increase.

Previously published extrapolations found that small lakes dominate the global extent of lakes, but the remote sensing-based GLOWABO demonstrates that global areal extent of lakes is dominated by medium and large lakes (Figure 2b). Despite finding less lakes overall, the GLOWABO reveals more total surface area, with a total surface area of $5.0 \times 10^6\ km^2$ greater than 0.002 km^2 while the statistical extrapolation approach count for ~$3.6 \times 10^6\ km^2$ (excluding Caspian Sea). The discrepancy is highest for lakes with areas 0.1–1 km^2, where we report a global coverage of 984,650 km^2 (19% of the total area estimated), which is 46% higher than the result of statistical extrapolation. These differences have two origins. (1) The distribution of lake sizes does not conform to a power law distribution, resulting in an overestimation of small lakes [*Seekell and Pace*, 2011; *Lewis*, 2011; *Seekell et al*., 2013] and (2) the base data used to calibrate the extrapolations is incomplete for certain regions of the world.

4. Discussion and Conclusions

There are 117 million lakes $> 0.002\ km^2$ covering 3.7% of Earth's nonglaciated land area. These values represent the first direct, global count of lakes by satellite-based remote sensing. The GLOWABO database constitutes a substantially improved answer to the question addressed by scientists for almost a century, on "how many lakes are there on Earth?" [*Halbfass*, 1922; *Thienemann*, 1925; *Downing et al*., 2006]. As previously shown at subcontinental scale [*McDonald et al*., 2012], the size distribution of lakes reported here based on direct remote sensing is inconsistent with the prevailing view based on statistical extrapolations of the abundance of small lakes and their proportional contribution to total lake surface area [*Downing et al*., 2006; *Minns et al*., 2008; *Lazzarino et al*., 2009; *Hendriks et al*., 2012]. This has important implications for global-scale limnological understanding, specifically for the relative contributions of small versus large lakes to the global carbon cycle.

Lake abundance is changing rapidly in some regions, and changes in the relative abundance of large and small lakes may reflect important characteristics of regional hydrologic and geomorphic processes [*Zhang et al*., 2009; *Englund et al*., 2013; *Liu et al*., 2013]. The GLOWABO database derives from a static remote sensing imagery and does not capture these changes. At the global-scale, cloudless data sets are composites of images taken over a multiyear periods. Because of time required to compile global cloud-free imagery, regional-scale analyses are better suited to tracking changes in lake abundance. The influence of such changes is unknown, and the disappearance of lakes in some regions [e.g., *Liu et al*., 2013] may be balanced out by the creation of both natural and man-made lakes in other regions [e.g., *Englund et al*., 2013]. Future development of Landsat imagery is likely to allow the study of dynamics of abundance and size of lakes at the decadal scale. The GLOWABO can also be combined with a large variety of data sets, archives, registers, or other remote sensing data in order to ameliorate the global information on lakes. For example, the Advanced Spaceborne Thermal Emission and Reflection Radiometer global digital elevation model data set may be used to fully represent the altitudinal size distribution of lakes even at high latitude where the SRTM-DEM data are missing.

Our results constitute a valuable source of data on lake abundance and size distribution, to aid upscaling of biogeochemical fluxes, in particular, regarding processes that can be scaled to lake area, distribution, and perimeter. Such processes, currently estimated based on less well-constrained information on lake abundance, include emission of carbon dioxide [*Raymond et al*., 2013] and methane [*Bastviken et al*., 2011], sediment burial of carbon and other elements [*Einsele et al*., 2001], and primary production [*Lewis*, 2011]. These results may also be a valuable for comparing to lakes on other planetary bodies such as Mars or Titan [*Seekell and Pace*, 2011; *Sharma and Byrne*, 2011]. Because differences in size distributions or in fractal dimensions may correspond to the influences of different hydrologic regimes, geometric constraints, or geomorphic processes, such comparisons with Earth are one of the best ways to make inferences about the physical processes that have shaped the surfaces of other planetary bodies [e.g., *Zhang et al*., 2009; *Sharma and Byrne*, 2011; *Seekell et al*., 2013].

Although we report a lower abundance of small lakes than statistical extrapolations suggest, we do find that most of the global land-lake interface (perimeter) is in small lakes. This zone harbors some of the most productive habitats on Earth [*Wetzel*, 1992]. The land-water gradient with its associated littoral vegetation can extend through a large fraction of the lake area [*Wetzel*, 1992] and is a site of intense production of invertebrates and fish [*Downing*, 2010] as well as a hot spot for the emission of methane [*Bastviken et al*., 2011]. Hence, while small lakes may be important for their contributions to global aquatic elemental fluxes, biodiversity, and productivity, this importance does not derive from a dominance of the total lake surface area [*Seekell et al*., 2013].

Given the significant role of inland waters in global biogeochemical cycles [*Tranvik et al*., 2009; *Ciais et al*., 2013] accurate accounting for the abundance, area, and distribution of lakes is crucial for landscape and continental-scale assessments of biogeochemical cycles. Our analysis removes a major source of uncertainty in these estimates and provides a springboard for the accurate evaluation of fundamental and applied limnological problems at the global scale [e.g., *Downing*, 2010; *Seekell et al*., 2013].

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Erratum

In the originally published version of this article, Figure 2 contained errors. The figure has since been corrected, and this version may be considered the authoritative version of record.

