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What Is the Impact of Tectonic Plate Movement on Country Size? A Long-Term Forecast

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Abstract: The Earth's surface is under permanent alteration with the area of some nations growing or shrinking due to natural or man-made processes, for example sea level change. Here, based on the NUVEL 1A model, we forecast (in 10, 25, and 50 years) the changes in area for countries that are located on the border of the major tectonic plates. In the analysis we identify countries that are projected to gain or lose land due to the tectonic plate movement only. Over the next 50 years, the global balance of area gains (0.4 km^2) and losses (12.7 km^2) is negative. Thus, due to the movements of lithospheric plates, the land surface of the Earth will decrease by 12 km^2 in 50 years. Overall, the changes are not that spectacular, as in the case of changes in sea/water levels, but in some smaller countries, projected losses exceed a few thousand square metres a year, e.g., in Nepal the losses exceed 10,000 m^2 $year^{-1}$. Methodologically, this paper finds itself between metric analysis and essay, trying to provoke useful academic discussion and incite educators' interests to illustrate to students the tectonic movement and its force. Limitations of the used model have been discussed in the methodology section.

Keywords: tectonics; plate movement; area; country size

1. Introduction

Land worldwide is a critical and limited resource that is subject to a variety of natural and/or anthropogenic processes and phenomena that cause modifications in areal extent [1]. A recent analysis using the Aqua Monitor tool, determined that between 1985 and 2015, the Earth's surface gained 115,000 km^2 of water and 173,000 km^2 of land, with coastal areas gaining 20,135 km^2 of water and 33,700 km^2 of land. Thus, during that 30-year period, the global net change of dry land was positive: 58,000 km^2 globally; 13,565 km^2 in coastal areas [2]. Important anthropogenic contributors to these changes were the creation of artificial islands, coastal reclamation, and the desiccation of natural water bodies (e.g., Aral Sea), all of which increased land area; increases in water were often associated with the building of large reservoirs or major shifts in large rivers.

With respect to natural processes, sea level change has been of one of the most significant determinants in land losses and gains over time. For example, at the peak of the last Ice Age (~20,000 years ago), sea level was 120–130 m lower than today, exposing

vast tracts of land worldwide. Coastal low areas were then flooded as the climate warmed gradually, raising sea levels an average of ~1.2 cm per year for 10,000 years until it levelled off at the beginning of Holocene (10^4 years) ~10,000 years ago to the approximate current day height [3]. Of growing contemporary concern is the extent to which more land will be lost from sea level rise through ice cap melt and nonlinear thermal expansion of the oceans as a result of anthropogenic global warming, for example in the Netherlands and tropical islands [4,5]. Furthermore, isostatic adjustment occurring since the last ice age will continue to cause various land masses to rise or sink until equilibrium is achieved [6].

Tectonic activity, which refers to the movement of the lithospheric plates that comprise the Earth's lithosphere, inherently results in changes in the land surface area [7–10]. The configuration of the continents, as well as the creation of most major landforms, is related to tectonic activity over geologic time. Most volcanoes occur at the boundaries of tectonic plates that are either converging or diverging; others occur over hotspots. Volcanism both creates new lands, but also many places formed in the past by volcanic activity lose surface area yearly through erosion [11] and/or during the formation of a caldera itself. Coastal erosion and accretion are two other natural processes with a profound effect on land areas [12]. Coastal processes are also often altered by human activity.

At a timescale related to management, tectonic plate movement has a marginal impact on the administrative borders in tectonically stable regions. Nevertheless, these small changes may still be noticeable. A pressing need is to understand the impacts in unstable areas where plate movements are substantial [13–15]. Overall, existing models of tectonic plate velocity is based on data from the globally distributed GNSS stations [16,17]. Furthermore, satellite techniques using GNSS observations allow for the determination of velocities at mm precision [18,19]. In this work, we use publicly available data to determine the influence of the tectonic plate movements on areal changes worldwide in the coming decades. This information augments the rate of change projections for sea level rise, volcanism, coastal erosion, and anthropogenic activity.

2. Methods and Limitations

To determine the impact of tectonics on country area we focused on the 15 large plates whose motion was described by the NUVEL-1A poles (Africa, Antarctica, Arabia, Australia, Caribbean, Cocos, Eurasia, India, Juan de Fuca, Nazca, North America, Pacific, Philippine Sea, South America), which are part of the digital model of plate boundaries presented by [20]. We use the plate motion calculator [13] to calculate rigid plate motions at specified locations on Earth using the NUVEL 1A plate motion model 1A [21–23] and the Eurostat (2020) administrative map of the globe [24]. Based on the literature, it should be assumed that the velocity determination error is 1 mm/year [25]. This is mainly due to the techniques used to determine the plates' velocities (GNSS and VLBI). It should also be noted that this is currently the most accurate technique for observing this type of phenomena and provides as accurate as possible velocities. Our focus is on changes occurring at terrestrial border locations, now and in the future. Motion is either divergent (spreading), convergent (subduction), or transform (lateral sliding), as shown in Figure 1.

This research has several limitations. We calculated a yearly velocity at the intersection points of the tectonic plates and countries borders. We do not account for changes in sea level (Figure 2). The subject of this research was only to determine the impact of tectonic plate movement on the administrative area of countries. It is not the only factor that causes surface changes, other factors include, e.g., earthquakes, volcanic eruptions, melting glaciers, or even man-made phenomena. However, the influence of plate movement is a mathematical factor that can be precisely defined, while the remaining phenomena are stochastic—their impact is purely random and also might significantly affect the phenomenon of tectonic plate movement.

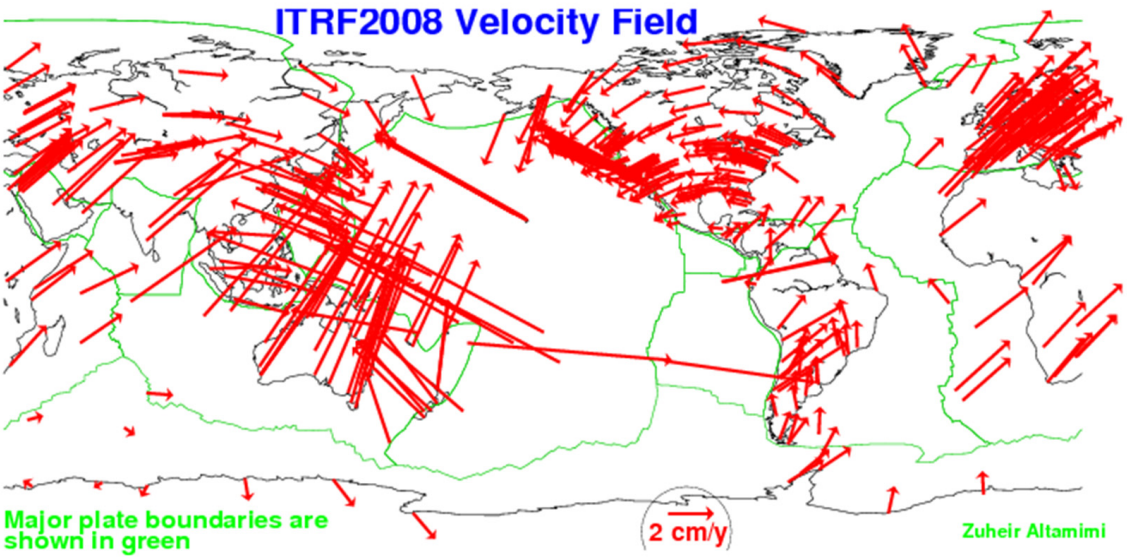


Figure 1. ITRF2008 velocity field, Mercator projection [https://itrf.ign.fr/ITRF_solutions/2008/ITRF2008.php, accessed date: 11 September 2021].

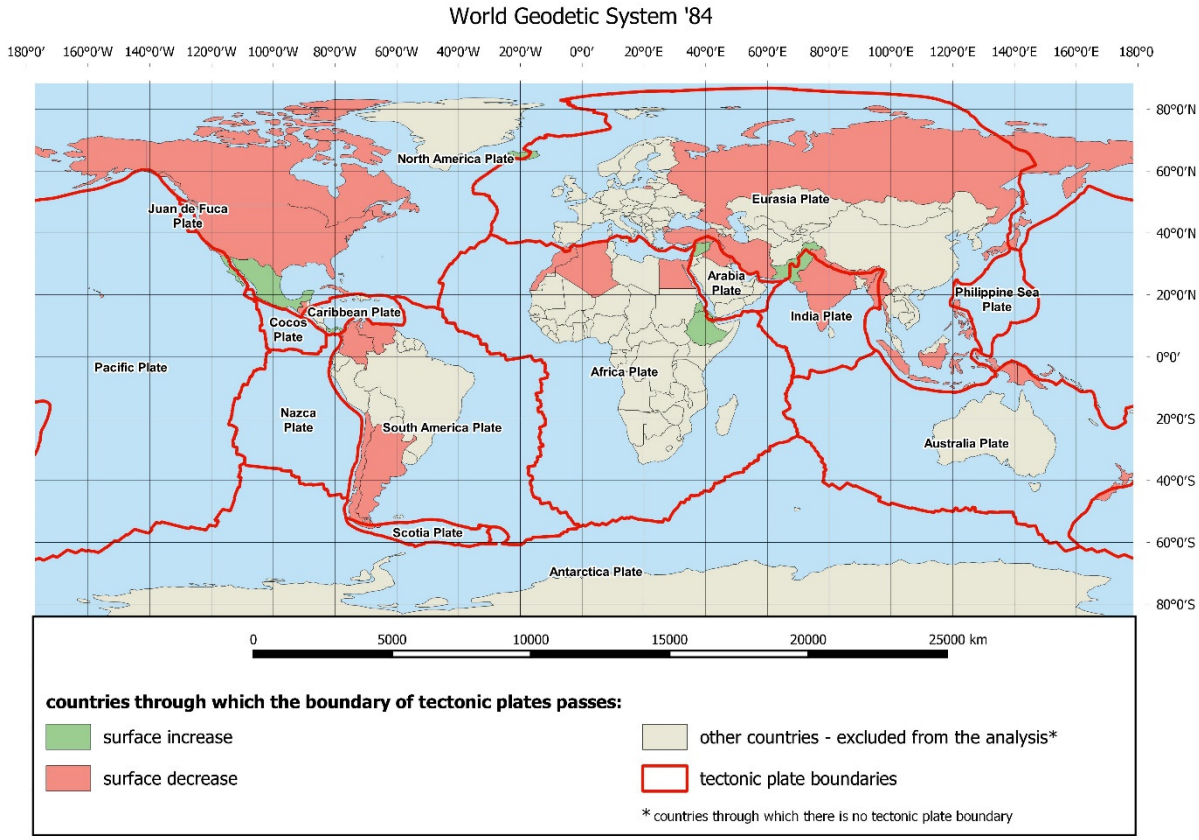


Figure 2. Map showing which countries have gained (green) and lost (red) land. For detailed map showing direction of plate movement and average velocity see, e.g., [20], Licence: EN: © EuroGeographics for the administrative boundaries.

To show the phenomenon on a global scale the authors simplified the processes occurring at tectonic margins. For example, the subduction zone of Nepal is very much a grossly oversimplified representation if reflected by a single line. This tectonic zone spans thousands of kilometres and shows a stepwise movement of thrust faults to the south. These faults are still active and act differently in various places [26,27]. Furthermore, the

movement along faults comes down to how much of the strain energy has been released. Not all faults result in a total release of the strain, for example in some areas a strong earthquake happened every few decades [28]. In subduction zones, an accretionary prism is observed, whereby the scraping of the upper surface of the downgoing plate accretes onto the overriding plate. This adds landmass to the overlying plate. For example, India subducting beneath Nepal should actually add landmass to Nepal, or at least to the foothills of the Himalayas. In addition, co-seismic movement exists (up, down, and laterally—often all three), then post-seismic movement occurs as plates reconfigure due to the weight of the plate edges with respect to the asthenosphere (see, e.g., [29,30]).

Moreover, more detailed studies (focusing on smaller areas) should use models that include the effects of earthquakes as new research found that GNSS velocities (of which plate motion models are calculated) include biases and need to be corrected for the effect of earthquakes (both co-seismic and post-seismic motions), so that more realistic crustal motions are obtained. Usually, for the large events, the post-seismic deformation equals or exceeds the co-seismic one [31]. The majority of earthquakes in the world (90% and 81% of the largest) occur within a 40,000 km horseshoe-shaped zone known as the Pacific Ring of Fire, which largely constrains the expansion of the Pacific Plate [32]. Massive earthquakes also happen along other plate boundaries, such as along the Himalayas [33]. Each of those places (and others as well) host a strong earthquake (see Gutenberg–Richter law). For example, in the case of large earthquakes (M > 8), Nepal will move towards India (the convergent boundary). This can happen within a few decades because of large seismic gaps along the Himalayas. The same can happen in California, New Zealand, or in Indonesia, and this dramatic change affects the areal calculations. Thus, this must be taken into consideration in further, detailed study.

In this study, the movement of plates is represented as an average movement along an individual fault line, but even along an individual fault zone, those rates vary depending on a host of factors, including rheology, orientation, and roughness. However, similarly to [2] this project uses several a priori assumptions.

In order to minimize errors (as much as possible), the following assumptions were made. A digital map of country borders (7710 points; 50–70 km average distance between consecutive points, minimum 10 km) was superimposed on the plate border map (6150 points; 50–70 km average distance between consecutive points, minimum 20 km). As a result of the intersection, 36 countries were selected, within which there were 4022 points. Within these countries, there were 608 points.

The areas of the analysed countries were calculated based on vector data models automatically generated within the GIS (geographical information systems) software-QGIS ver. 3.16.11 LTR Hannover, licence GNU GPL). The analyses were carried out in the WGS-84 coordinate system (World Geodetic System 1984), geographic coordinates, and ellipsoid surface. Based on Plate Motion Calculator, the coordinates of the intersection points between national borders and the tectonic plates after one year was calculated. Annual plate velocity for each country border point was calculated based on the Eurostat map [24], then the country areas were calculated before and after the NUVEL1A model application [21–23]. In a similar way, the coordinates of these intersection points after 10 years, 25 years, and 50 years were also calculated. The calculated coordinates were then imported into the QGIS software (version 3.10.0-A Co-ruña) and used to digitize the borders of the analysed countries, and then to calculate their area in the adopted time intervals. The speed of the point's location change was calculated for each point separately.

Importantly, the adopted generalization scale (number of points) was chosen to show the scale of the phenomenon and not its accuracy. However, increasing the number of points (reducing the generalization) will only slightly change the results—it is not the number of points, but rather the speed between them that changes the phenomenon.

3. Results and Discussion

Increases (green) and decreases (red) in 36 countries associated with 15 major tectonic plates over the period 2020 to 2050 are shown in Table 1. Plate border length for the 36 countries varied from 80 km (Trinidad and Tobago) to 3600 km (Russia), depending on the country size and shape. Area gains/losses related to the projected tectonic movements depend on the direction and velocity amplitudes of the tectonic plate movement. Based on the motion estimates for the next 50 years, 10 countries will increase in area and 26 will reduce in area (Table 1).

Table 1. Forecast of country size changes in 10, 25, and 50 years.

#	Country	Area * [km^2]	Plate Border Length [km]	Area Change [m^2] After 10 Years	After 25 Years	After 50 Years
1	Algeria	2,381,740	379	−36,810	−97,691	−198,668
2	Argentina	2,736,690	129	−4948	−4324	−6211
3	Bhutan	38,117	301	−92,220	−230,263	−460,291
4	Canada	9,093,510	213	−15,299	−27,806	−51,226
5	Chile	743,532	185	−23,445	−64,963	−132,276
6	Colombia	1,109,500	104	−76,446	−190,891	−380,949
7	Cuba	106,440	178	−1421	−1467	−1776
8	Djibouti	23,180	136	9086	22,725	45,720
9	Egypt	995,450	136	−2268	435	6756
10	Eritrea	101,000	132	2502	6053	11,909
11	Ethiopia	1,000,000	473	3779	7076	12,951
12	Guatemala	107,160	287	−4940	−12,459	−24,680
13	Iceland	100,250	476	56,598	140,186	279,317
14	India	2,973,190	1440	−575,659	−1,440,931	−2,882,874
15	Indonesia	1,811,570	494	−30,600	−75,692	−157,201
16	Iran	1,628,550	1547	−140,679	−353,301	−707,640
17	Iraq	434,320	396	−15,813	−37,491	−72,812
18	Israel	21,640	299	−18,467	−47,167	−94,828
19	Japan	364,555	335	−67,176	−161,376	−310,598
20	Lebanon	10,230	165	−2520	−6627	−13,445
21	Mexico	1,943,950	172	13,265	33,167	64,839
22	Morocco	446,300	425	−1486	−75	2565
23	Myanmar	653,290	1375	−55,878	−147,914	−299,340
24	Nepal	143,350	878	−391,615	−979,922	−1,960,880
25	New Zealand	263,310	535	−122,850	−306,878	−605,524
26	Pakistan	770,880	1774	−132,438	−331,018	−660,850
27	Panama	74,340	180	1938	3122	5527
28	Papua New Guinea	452,860	488	−115,344	−295,920	−594,725
29	Philippines	298,170	152	−121,255	−303,453	−607,910
30	Russia	16,376,870	,592	−31,186	−96,717	−213,285
31	Syria	183,630	159	1062	2057	4148
32	Taiwan	35,410	382	−236	171	2917
33	Trinidad and Tobago	5130	82	−639	−4964	−12,244
34	Turkey	769,630	904	−181,182	−454,212	−908,848
35	USA	9,147,420	1495	−210,355	−536,560	−1,085,144
36	Venezuela	882,050	227	−46,416	−117,708	−237,105

* [34].

The largest increases in area are for Mexico and Djibouti. Both these countries, after ten years, will increase their area by 13,000 and 9000 m^2, respectively. After half a century, their area will increase by 65,000 and 45,000 m^2. India, Nepal, and the USA are among the countries that will lose the most area due to plate movement. After just ten years, they will lose 575,000, 390,000, and 210,000 m^2, respectively. In 50 years, they will decrease in area by almost 3 km^2, 2 km^2, and more than 1 km^2, respectively. Collectively, the balance profits (0.4 km^2) and losses (12.7 km^2) are negative over the next 50 years.

Overall, it is easy to believe that the size of the Earth's dry land is increasing due to plate movement (e.g., land elevation and new volcanoes emerging). It is easier to fathom the 'increase' in land than its 'disappearance'. Supplementary Material shows interactive maps demonstrating the main types of plate motion, which include spreading (divergent), subduction (convergent), and lateral sliding (transform), and the change in size of land due to plate movement. For example, the North America Plate is moving west versus the Eurasian Plate, which is moving east. Thus, the distance between NYC and London is increasing slowly each year (approx. 25 mm year^{-1}), and Iceland will increase in size by 280,000 m^2 in the next 50 years (Table 1, Videos in Supplementary Files). An opposite situation can be noted in the subduction zone. For example, the India tectonic plate is moving towards Central Asia at a speed of 29–36 mm year^{-1} [20]—the reason for repeated earthquakes. The Himalayas are rising, but India (−2883,000 m^2) and Nepal (−1961,000 m^2) are shrinking (Table 1, Videos in Supplementary Files).

4. Conclusions

For the majority of the countries analysed, multiyear tectonic plate movement has a very small or even negligible impact on area size. However, when considered at small management scales, such as districts or states, etc., these changes are significant, for example, the San Andreas fault in California, USA (Videos in Supplementary Files) [35]. Even if the tectonic plate movement has a marginal impact on country area size, this small and insignificant impact on the changes of points in some areas is still noticeable—and potentially catastrophic. We have noted that due to the movements of lithospheric plates, the land surface of the Earth will decrease by 12 km^2 in the next 50 years. The size of the change depends strongly on the length of the tectonic border as well as the plate velocity and movement direction that vary globally.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/rs13234872/s1, Video S1: California, Video S2: Iceland, Video S3: Nepal.

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