

UDC 528.235

DETERMINATION OF AN APPROPRIATE PROJECTION SYSTEM FOR FOREST AREAS IN TURKEY

Faruk YILDIRIM¹, Fatih KADI^{2*}, Adem KURTIPEK³^{1, 2}*Department of Geomatics, Engineering Faculty, Karadeniz Technical University, Trabzon, Turkey*³*Kütahya Regional Directorate of Forestry, Kütahya, Turkey*

Received 08 October 2019; accepted 03 June 2020

Abstract. Geometrical surfaces such as sphere and ellipsoid are considered as reference surfaces since there is no geometric shape that perfectly represents the earth when translating the earth into a map plane. Hence, on 3D reference surfaces, it is almost impossible to perfectly preserve the angle, direction and area properties and transfer them to a map plane without any deformations. The scaled topographic maps produced in our country under provision of map production regulations are conformal projections that do not preserve area properties but angle and shape properties. Area values calculated by projection coordinates cannot be considered the exact area values therefore, an area reduction is needed. Area values calculated by ignoring this situation in GIS based software do not represent the accurate area values on reference surfaces. The aim of this study is to determine the best area preserving projection for GIS applications in which area values are important. In this study, the real area values of 25 large-extent forest parcels are determined by employing the Danielsen method with geographical coordinates on ellipsoid surface. These parcels are also calculated by using the area-preserving projections available in ArcGIS software and are compared to their real area values.

Keywords: reference surface, map plane, conformal projections, GIS based software, Danielsen method, area-preserving projections, forest parcel.

Introduction

Nowadays, geographic information systems (GIS) – based applications use coordinate data as well as area data. Accuracy of a calculated area depends on the position accuracy of the coordinates used, map scale and selected map projection. The map scale and projection are the most effective ones in accurate computation of an area. Today's technological plotting, computation techniques and GIS software enable the conduction of applications in 1:1 scale, which attaches importance to the accuracy of the used coordinates and selection of a map projection.

Map projection is the reduction of measurements obtained from physical earth surface to a geometrically defined reference surface (such as ellipsoid, sphere etc.) and projection onto a map plane by means of geometrical and mathematical techniques. Projection from a 3D reference surface to a 2D plane (i.e. map) causes deformations in the area, angle and length of original shapes. It is not possible to eliminate all these deformations. Hence, one of the area preserving, angle preserving or length preserving projections is selected to preserve one of these deformations (Pearson, 1990).

Characteristics and extent of an area play a vital role in its accuracy. Relatively large-extent parcels have been used in various forestry, environment and agriculture applications. Large-scale (i.e. 1:1000, 1:2000, 1:5000 and 1:10000) base maps and cadastral maps are angle preserving conformal maps (i.e. shape preserving) that are used in engineering and cadastral applications. In GIS applications conducted in large-scaled areas, one should use an area preserving projection if area is important, and a length preserving projection if length is important (Yıldırım & Kaya, 2008; Yıldırım, 2012).

In forestry applications, it is seen that area preserving map projection is used in the related works for the assessment and mapping of forest parcels with large areas. Area preserving projections were used in the maps used to examine Asian regional raster data (Usery & Seong, 2000), to determine the stock increase in European countries (Päivinen et al., 2009), to examine the current status of the large-scaled forests in Northeast of China (Stantauf et al., 2012), to map the forests in Europe (Brus et al., 2012), to map the distribution of forest ownerships in Europe (Pulla et al., 2013), to map Leaf Area Index in heterogeneous

*Corresponding author. E-mail: fatihkadi@ktu.edu.tr

forests with terrestrial laser scanning techniques (Guang et al., 2013), to divide endangered species into ecological zones in Canada (Committee on the Status of Endangered Wildlife in Canada [COSEWIC], 2015), to planning European forests (Borkowski, 2016), and to monitor forest inventory of 50 states in conjunction with forest data published in the USDA Forest Service Field Inventory and Analysis Library (Vogt & Smith, 2017).

In our country, boundaries of forest parcels are measured in the Modified Universal Transversal Mercator Projection (MUTM, 3° wide longitude zones) through Global Navigation Satellite Systems (GNSS). Areas of forest parcels are calculated by the Gauss Area Method using MUTM projection coordinate data. The studies carried out by the Regional Directorate of Forestry revealed the fact that growing stock of forests is increasing year by year. With the completion of the forest cadastre, it will be possible to determine the exact forest area with high accuracy. While the forests covered an area of 20.2 million ha area in 1972 in Turkey, this amount increased up to 22.3 million ha in 2015, which makes about 28.6% of the whole country. In parallel to this increase, timber wealth increased from 0.9 billion m³ to 1.6 billion m³ in the same time period (Republic of Turkey General Directorate of Forestry, n.d.). In our country, 1/1000, 1/5000 and 1/10000 scale maps are produced in the Modified UTM projection system, whereas 1/25000, 1/50000, 1/100000 and 1/250000 scale maps are produced in the UTM (6° wide longitude zones) projection. The UTM projection is obtained from the Gauss-Kruger mapping. The Gauss-Kruger projection is a mapping of a reference ellipsoid of the earth onto a plane and some definition of the ellipsoid and various associated constants are useful. In the Gauss-Kruger mapping; x prime axis is the equator and y prime axis is the prime longitude. Turkey is located between 26–45° east longitudes and 36–42° north latitudes. This 19° longitude difference is divided into four 6° zones (zone numbers; 35, 36, 37, 38) in the UTM, whereas into seven 3° zones (central meridians 27°, 30°, 33°, 36°, 39°, 42°, 45°) in the MUTM (See Figure 1).

The UTM system is a conformal projection as it is derived from the Gauss-Kruger mapping. The area deformation in the UTM projection system depends on the size of the area and the distance from the prime longitude. Therefore, geographical coordinates are needed for the accurate determination of areas, rather than UTM coordinates.

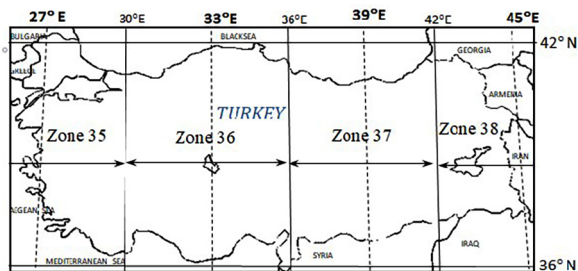


Figure 1. UTM and MUTM zones for Turkey

However, existing geodetic and GIS software are not able to compute areas using geographical coordinates, which forces the users to seek for alternative software and also to make extra calculations. Instead, area preserving projection is usually used to determine areas (Yıldırım & Kaya, 2008; Yıldırım, 2012).

As the forest areas calculated in the conformal projection system increase, they less represent the actual areas. In our country, forests cover a considerable amount of area. They also consist of large-scaled parcels. Hence, it would be more reasonable to determine the exact amount of forest areas with area preserving projections instead of conformal MUTM projection. Thus, selection of area preserving projections in large-extent GIS applications carried out by the General Directorate of Forestry will reduce the deformations in parcel areas.

1. Applications requiring parcel area information (surface area) in general directorate of forestry

The parcel areas in our country are calculated by Gauss area method using MUTM coordinates. Since the Gauss area method is based on map coordinates, it is applied on planes and hence, is not applied on original ellipsoid surface. Forest area information is used directly in many studies carried out by the General Directorate of Forestry. Direct or indirect studies on forest areas in the central and provincial organizations of the General Directorate of Forestry:

- Forest cadastre applications;
- Studies on rehabilitation and afforestation areas;
- Planning of forest and forest resources;
- Production and marketing of wood and non-wood forest products;
- Silviculture applications;
- Retained carbon quantity in forest areas;
- Studies on recreation areas;
- Studies on permissions given for forest areas;
- Pasture improvement and erosion control studies;
- Forest management planning;
- Studies on coniferous and deciduous species in coppice and high forests;
- Growing stock studies;
- Studies on regeneration areas.

Calculated forest areas play a significant role in forestry organizations, especially in forestry economy applications. In forestry organizations; plans, practices and outputs are mainly based on forest areas. Considering the extent of forest areas in forest organizations, accurate calculation of forest areas is a necessity to maintain the sustainability of forests and conduct aforementioned studies related to forest management.

2. Area calculations

Areas, which are calculated from the scale maps generated from the ellipsoid reference surface by the map projection method, have plane geometry. On the other hand, area

deformation increases as the area grows. Hence, accurate value of an area should be calculated from the ellipsoid surface by means of the geographical coordinates. Area deformation formulas (F-f) are derived based on each projection type. The magnitude of the deformation in these formulas is usually proportional to the size of the area and the distance to x or y axis (Grossmann, 1976).

$$F - f = -\frac{f}{R^2} y_m^2 \tag{1}$$

In the area deformation formula for MUTM; *F* is the original ellipsoid area, *f* is the map projection area, *R* is the Gauss average radius, and *y_m* is the average distance from the parcel to the y axis origin (prime meridian). In GIS applications, deformation formulas and geographical coordinates on the ellipsoid surface are not available for area calculation. Therefore, in such applications, an area preserving projection should be preferred, considering the geographical location and size of the study area, instead of conformal projections. In such cases, out of the area-preserving projections, the one that causes the minimum area deformation should be preferred. The most straightforward way to achieve this is to compare the area values on area preserving projections against the area values calculated from the ellipsoid geographic coordinates. In spite of the fact that the area-preserving projections are based on the principle to preserve area information, area deformation is inevitable to some extent (Snyder, 1987; Bugayevskiy & Snyder, 1995).

Many methods have been reported in the literature to calculate the area of any parcel using ellipsoidal geographical coordinates. Some of the most commonly used methods are; Kimerling (1984), Danielsen (1989), Gillissen (1993), Sjöberg (2006), Karney (2013) and Tseng (Tseng et al., 2015). Since the Kimerling method is a spherical solution, the edges are not geodetic line but the great circle in the sphere. For this reason, the accurate ellipsoid is not the solution. The Danielsen, Sjöberg, Karney and Tseng solution methods consider parcel edges as geodetic lines on ellipsoid and calculate the areas from the ellipsoidal area between this line and equator. The Gillissen method uses the Albers Equal Area Conic Projection to calculate the area of each part of the geodetic area divided by secants on the ellipsoid surface.

3. Application

Turkey is a large-scale country that extends in the East-West direction and its geographical boundaries do not fit into a single UTM gore (Figure 1). In Turkey, there are 28 Regional directorates of forestry in the General Directorate of Forestry. The Kütahya Regional Directorate of Forestry, which was chosen as study area in this study, is one of these directorates. The Kütahya Regional Directorate of Forestry, which covers an area of approximately 2 million hectares, consists of 6 forestry operation directorates and 40 forest sub-district directorates. The forest area covered by the Kütahya regional directorate of forestry is

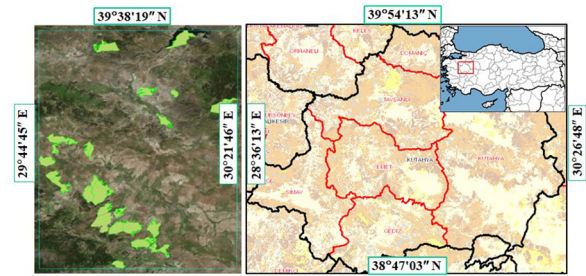


Figure 2. Satellite imagery of forest parcels (left) and geographical boundaries of the Kütahya regional directorate of forestry and forestry operation directorates in Itrf datum (right)

approximately 708,784.40 hectares, which is about 36% of the total area of the regional directorate of forestry in Turkey (Figure 2).

In this study, 25 forest parcels from the Kütahya regional directorate of forestry were used, whose areas ranged from 339 ha to 2857 ha (see Figure 2). As a first step, the areas of these forest parcels were calculated by using the MUTM coordinates in the ITRF datum. Then, the area deformation of these parcels were calculated by using the Equation 1 (*y_m* = 13 km and *R* = 6370 km). Finally, on the reference ellipsoid (GRS80) surface, the MUTM coordinates of these parcels were converted to geographical coordinates and accurate area values were calculated using the Danielsen method (Ellipsoid Geographical Area) (see Table 1).

The area deformation rates determined by two different methods (see Table 1) are shown in the Figure 3.

As seen in Figure 3, reduction rate from map coordinates (F-f) increased as did the size of the area, whereas the differences from the accurate area were found to vary with respect to the shape of the parcels. Comparisons between the actual area values and areas computed via the (F-f) reduction equations revealed the insufficiency of the reduction equations. The differences between the actual areas of the parcels and areas computed from the reduction equations were found to vary between 1 m² and 200 m², which made a total area difference of 1052 m² in all parcels. Deformation formulas; it does not match the actual field values when the area grows and is applied

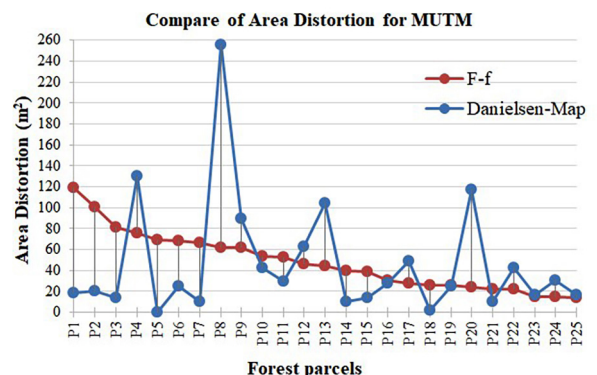


Figure 3. Comparison of the area distortion for MUTM

to smooth square or rectangular external shapes (concave polygon). Therefore, in large areas, it is necessary to compute the accurate area values by using the geographical coordinates on the ellipsoid surface, which minimizes the amount of the area deformation determined from maps.

Since the existing GIS software do not have the capability to calculate actual area values with reduction equations or geographical coordinates, six different area-preserving

projections (see Table 2) implemented in the ArcGIS 10.3 GIS software were used in this study to compute the parcel areas. The projection parameters used for the parcel areas are given in Table 2 (Kennedy & Kopp, 2000).

The areas of the forest parcels given in Table 1 were recalculated by using the area-preserving projection methods given in Table 2. The differences between these areas and Danielsen-derived areas are given in Table 3.

Table 1. MUTM map areas, area deformations and ellipsoid area values

Forest parcels	Map area MUTM (ITRF)		Ellipsoid geograpiical area (Danielsen)	Area distortion with equation 1	Area distortion with Danielsen method	Differences in absolute value
	Square meters (m ²)	Hectare (ha)	Square meters (m ²)	(F-f) [1] (m ²)	(Danielsen-map) [2] (m ²)	[2]-[1] (m ²)
P1	28570421.774	2857.042	28570403.642	118.994	18.132	100.862
P2	24240491.726	2424.049	24240471.391	100.960	20.335	80.625
P3	19454360.215	1945.436	19454374.205	81.026	13.990	67.036
P4	18201997.722	1820.200	18201867.804	75.810	129.918	54.108
P5	16730817.085	1673.082	16730816.942	69.683	0.143	69.540
P6	16398464.060	1639.846	16398439.169	68.298	24.891	43.408
P7	15951105.646	1595.111	15951094.999	66.435	10.647	55.788
P8	14809228.918	1480.923	14808972.997	61.679	255.921	194.242
P9	14780100.995	1478.010	14780011.170	61.558	89.825	28.267
P10	12920294.789	1292.029	12920252.149	53.812	42.640	11.172
P11	12718503.893	1271.850	12718473.882	52.972	30.011	22.961
P12	11067018.225	1106.702	11066955.840	46.093	62.385	16.291
P13	10550351.283	1055.035	10550247.366	43.941	103.917	59.976
P14	9498509.712	949.851	9498499.811	39.561	9.901	29.660
P15	9275762.399	927.576	9275748.557	38.633	13.842	24.791
P16	7246694.410	724.669	7246666.585	30.182	27.825	2.357
P17	6575866.610	657.587	6575817.915	27.388	48.695	21.307
P18	6190103.981	619.010	6190102.046	25.781	1.935	23.846
P19	6123019.112	612.302	6122994.177	25.502	24.935	0.567
P20	5774651.499	577.465	5774533.892	24.051	117.607	93.556
P21	5395186.747	539.519	5395176.547	22.471	10.200	12.271
P22	5301967.898	530.197	5302010.728	22.082	42.830	20.748
P23	3673397.840	367.340	3673381.412	15.299	16.428	1.129
P24	3563672.444	356.367	3563642.156	14.842	30.288	15.446
P25	3389657.603	338.966	3389640.706	14.118	16.897	2.780
Sum	288401646.586	28840.060	288400596.087	1201.173	1164.139	1052.731

Table 2. Projections and projection parameters used in the application

Map projection	I_0 Central Longitude (meridian)	B_0 Central Latitude (parallel)	B_1 Standard parallel	B_2 Standard parallel
Albers Equal Area Conic (AlbersEAC)	30° E	30.05° N	34.45° N	34.85° N
Equal Area Cylindrical (EAC)	30° E	30.05° N	-	-
Behrmann Equal Area Cylindrical (BehrmannEAC)	30° E	0° (Equator)	-	-
Bonne Equal Area (BonneEA)	30° E	0° (Equator)	-	-
Lambert Equal Area Azimuthal (LambertEAA)	30° E	30.05° N	-	-
Sinusoidal Equal Area (SEA)	30° E	0° (Equator)	-	-

Table 3. Danielsen ellipsoid geographical area with equal area projection differences

Forest parcels	Danielsen differences in accurate value (m ²)					
	AlbersEAC	EAC	BehrmannEAC	BonneEA	LambertEAA	SEA
P1	12.795	93.620	93.602	5.209	8.958	10.234
P2	42.682	489.671	489.914	31.609	35.908	171.051
P3	42.451	100.815	100.750	43.457	42.629	69.103
P4	25.802	147.748	147.698	37.897	30.597	126.803
P5	1.129	27.469	27.467	0.145	0.573	15.403
P6	8.829	111.727	111.608	0.242	4.233	9.219
P7	13.088	152.436	152.686	11.000	11.133	62.475
P8	3.811	43.418	43.441	5.315	4.488	26.596
P9	3.978	9.444	9.495	2.524	3.284	7.567
P10	65.392	290.955	290.727	79.121	71.626	216.072
P11	5.046	6.745	6.756	5.112	5.009	5.949
P12	3.069	48.192	48.207	5.584	4.566	6.415
P13	4.296	21.360	21.420	11.092	7.263	42.312
P14	33.750	300.017	300.197	33.660	33.180	138.509
P15	4.898	20.587	20.524	6.910	5.821	19.635
P16	4.014	9.815	9.728	4.224	4.152	7.481
P17	15.003	99.155	99.102	12.670	13.525	38.425
P18	1.274	2.652	2.682	2.335	1.875	4.642
P19	3.782	1.178	1.165	3.509	3.752	1.677
P20	13.656	135.512	135.407	15.865	14.120	72.084
P21	10.981	105.461	105.509	0.189	5.386	1.011
P22	28.232	99.940	99.953	41.509	35.202	36.554
P23	9.254	3.260	3.193	9.985	9.649	7.341
P24	3.357	4.154	4.162	3.496	3.429	4.244
P25	0.205	1.223	1.179	0.198	0.181	0.283
Sum	360.773	2326.554	2326.570	372.858	360.539	1101.086

Table 3 was used to determine the area-preserving projection that achieved the minimum area deformation value.

The area deformation rates of the area preserving projections are shown in Figure 4.

As shown in Figure 4 and Table 3, the AlbersEAC, LambertEAA and BonneEA were found to achieve the maximum area deformations of 65 m², 71 m² and 79 m², respectively. The difference between the actual area of the

forest parcels and AlbersEAC – and LambertEAA – derived parcels were below 30 m² at a rate of 96%, whereas the difference with the BonneEA projection was below 30 m² at a rate of 92%. The areas of 21 parcels in the AlbersEAC, 20 parcels in the BonneEA and 20 parcels in the Lambert EAA projection were found to have a maximum of 15 m² difference with the actual parcel areas. In addition, 6 parcels in the AlbersEAC, 8 parcels in the BonneEA and 6 parcels in the LambertEAA projection were found to have an accuracy of 1 m². Since the AlbersEAC is a conic projection, it is a suitable projection method for Turkey. Conic projections are suitable for countries with a rectangular shape extending in middle latitudes and in the east-west direction. This, of course, enables the production of maps with a single coordinate system and less deformation all around the country. Currently, the MUTM projection is used for forest parcels in Turkey.

In case of using AlbersEAC instead of this projection, the MUTM in Table 1 and the AlbersEAC area deformations in Table 3 are shown in Figure 4.

Figure 5 revealed the fact that deformation differences caused by the selection of the MUTM and AlbersEAC projection were found to vary between 1 m² and 250 m². The

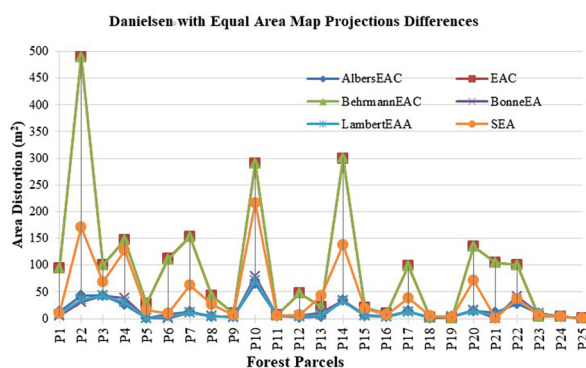


Figure 4. Danielsen ellipsoid geographical area with Equal area projection differences

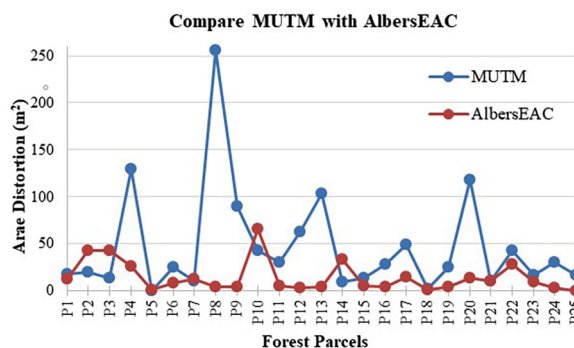


Figure 5. Comparison of the MUTM with the AlbersEAC in terms of area deformation

total area difference for all parcels was found about 0.1 ha (1000 m²). All forest areas of Turkey (22 342 935 ha) if we take into consideration; the total area deformation resulting from the projection selection is approximately 77 hectares. This value equals approximately 110 soccer fields.

Conclusions

In forestry operation directorates, forest areas play an important role in many studies carried out. In the Forest management, plans, practices and outputs are largely shaped by forest areas. When considering the size of forest areas in the forest general directorate, the accurate value of forest areas in terms of forestry management should be calculated with high precision. In addition, forest areas are very important for sustainable forest management and for the healthy implementation of plans and activities. All mapping applications including forest parcels in our country are produced in MUTM projection.

Projections can not represent the original surface (ellipsoid and sphere) perfectly. The angles (conform), distances and areas of shapes on an original surface are distorted when they are projected onto a map. Projection is done by preserving at least one of these three deformations. The MUTM projection is a conformal projection that is more deformed in terms of length and area. The area deformation in the MUTM projection varies according to the size and shape of the area, and to the distance from the prime longitude. Area deformation can be minimized by using geographical coordinates on ellipsoid surface instead of MUTM coordinates, by using projection area reduction equations (F-f) or by using one of the area-preserving projections. In this study, 25 forest parcels with areas ranging between 339 ha and 2857 ha were used to decide which method determines the parcel areas with minimum deformation. The accurate area values of these parcels were calculated by Danielsen method using the geographical coordinates on ellipsoid surface.

For forest application parcels, it can be seen that there are differences up to 200 m² when comparing the reduction values calculated from the area reduction equations and the accurate area values in the MUTM projection. The sum of these differences in all parcels was found 1052 m².

Area reduction equations are insufficient to determine the areas of large and concave-shaped parcels in the MUTM projection. Hence, exact area values should be computed with geographical coordinates. However, existing GIS and CAD-based geodetic software are not capable of computing areas with geographical coordinates, hence; additional software and workload are needed for such purposes. Workload can be reduced by using area-preserving projections.

In this study, the area values calculated with six different area-preserving projections available on ArcGIS 10.3 GIS software were compared against the areas computed using the Danielsen method with geographical coordinates to determine which projection provides the minimum area deformation for Turkey. The maximum deformations of 65 m², 71 m² and 79 m² were found with the AlbersEAC, LambertEAA and BonneEA projections, respectively. The AlbersEAC and LambertEAA projections were found to be the ones that achieved the minimum deformations (360 m²) in terms of the total area of all parcels. Since the AlbersEAC is a conic projection, it is suitable for Turkey. It is a well-known fact that the conic projections are suitable for countries in middle latitudes with a rectangular shape and lying in the east west direction. This also enables the production of maps with a single coordinate system, minimizing area deformations.

In our country, it was observed that the area deformation differences resulting from the selection of the MUTM and AlbersEAC projections varied between 1 m² and 250 m². For all application forest parcels (28840 ha), this difference was approximately 1000 m² (0.1 ha). Considering all forest parcel areas in Turkey, the total deformation area was found to be about 77 hectares.

Since the AlbersEAC projection is not used in Turkey, area deformation differences are expected to be very high, considering the total forest area in Turkey. These differences can be considered too much for forestry departments with very high economical outcomes.

Forest areas are calculated on the ellipsoid surface using the geographical Coordinates. Parcel corners have different elevation values in areas calculated with geographical coordinates on ellipsoid surface. In this context, accurate area value needs to be analysed and investigated by considering the topography of the area. Plenty of attention should be paid to interpret the actual area in sloping terrains. This was ignored in this study.

The optimum projection selection is important in GIS applications where accurate area information is needed. In addition, the users should pay attention to choose the optimum projection parameters (central meridian, initial longitude or central meridian, one or two standard parallels) in the areas close to study area to minimize the deformations. In this work, the errors due to the position and scale accuracy of the coordinates were ignored. In large forest area GIS applications, accuracy will be further reduced when the effects of errors resulting from the production of coordinates are taken into consideration.

The Albers EAC projection proposed for Turkey may not be suitable for other countries. For other countries, one of the area preserving projection types according to the geographical position and size of the country should be selected first. Thus, area values calculated using the geographical coordinates of the parcels should be determined by comparing them with the results obtained using the danielsen method.

References

- Borkowski, P. (2016). *Future of the forests a perspective of European State Forests (EUSTAFOR)*. Brussels.
- Brus, D. J., Hengeveld, G. M., Walvoort, D. J. J., Goedhart, P. W., Heidema, A. H., Nabuurs, G. J., & Gunia, K. (2012). Statistical mapping of tree species over Europa. *European Journal of Forest Research*, 131, 145–157. <https://doi.org/10.1007/s10342-011-0513-5>
- Bugayevskiy, L. M., & Snyder, J. P. (1995). *Map projections: A reference manual*. Taylor and Francis.
- Committee on the Status of Endangered Wildlife in Canada. (2015). *Applications for wildlife species assessment and un solicited wildlife species status reports*. COSEWIC.
- Danielsen, J. (1989). The area under the geodesic. *Survey Review*, 232, 61–66. <https://doi.org/10.1179/sre.1989.30.232.61>
- Gillissen, I. (1993). Area computation of a polygon on an ellipsoid. *Survey Review*, 248, 92–98. <https://doi.org/10.1179/sre.1993.32.248.92>
- Grossmann, W. (1976). *Geodätische Rechnungen und Abbildungen in der Landesvermessung*. Stuttgart.
- Guang, Z., Monika, M. L., & Soo-Hyung, K. (2013). Retrieval of effective leaf area index in heterogeneous forests with terrestrial laser scanning. *IEEE Transactions on Geoscience and Remote Sensing*, 51(2). <https://doi.org/10.1109/TGRS.2012.2205003>
- Karney, F. F. C. (2013). Algorithms for geodesics. *Journal of Geodesy*, 87(1), 43–55. <https://doi.org/10.1007/s00190-012-0578-z>
- Kimerling, J. A. (1984). Area computation from geodetic coordinates on the spheroid. *Surveying and Mapping*, 44, 343–351.
- Kennedy, M., & Kopp, S. (2000). *Understanding map projections*. ESRI Press.
- Päivinen, R., Brusselen, J. V., & Schuck, A. (2009). The growing stock of European forests using remote sensing and forest inventory data. *Forestry*, 82, 479–490. <https://doi.org/10.1093/forestry/cpp017>
- Pearson, F. (1990). *Map projections: Theory and applications*. CRC Press.
- Pulla, P., Schuck, A., Verkerk, P. J., Lasserre, B., Marchetti, M., & Green, T. (2013). *Mapping the distribution of forest ownership in Europe*. (EFI Technical Report 88). European Forest Institute.
- Sjöberg, L. E. (2006). Determination of areas on the plane, sphere and ellipsoid. *Survey Review*, 38(301), 583–593. <https://doi.org/10.1179/sre.2006.38.301.583>
- Snyder, J. P. (1987). *Map projections – A working manual*. United States Government Printing. <https://doi.org/10.3133/pp1395>
- Stantaurf, J., Madsen, P., & Lamb, D. (2012). *A goal-oriented approach to forest landscape restoration*. Springer. <https://doi.org/10.1007/978-94-007-5338-9>
- Tseng, W. K., Guo, J. L., & Liu, C. P. (2015). The geometric algorithm of inverse and direct problems with an area solution for the great elliptic arcs. *Journal of Marine Science and Technology*, 23(4), 481–490.
- Republic of Turkey General Directorate of Forestry. (n.d.). URL-1. Retrieved June 11, 2019, from <https://www.ogm.gov.tr/Sayfalar/Ormanlarimiz/TurkiyeOrmanVarligi.aspx/>
- Usery, E. L., & Seong, J. C. (2000). A comparison of equal-area map projections for regional and global raster data. In *Proceeding of 29th International Geographical Congress*. Seoul, Korea. <https://pdfs.semanticscholar.org/b02c/f48d02e4e53ca1775758737a064ae6a53336.pdf>
- Yıldırım, F., & Kaya, A. (2008). Selecting map projections in minimizing area distortions in GIS applications. *Sensors*, 8, 7809–7817. <https://doi.org/10.3390/s8127809>
- Yıldırım, F. (2012). Selecting suitable map projections in minimizing distance distortions in GIS-based applications: A case study from Turkey. *Fresenius Environmental Bulletin*, 21(10), 2916–2921.
- Vogt, J. T., & Smith, W. B. (2017). *Forest inventory and analysis fiscal year 2016 business report*. United States Department of Agriculture, USDA.