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RESEARCH ARTICLE

Mapping ecoregions under climate change: a case study from the biological 'crossroads' of three continents, Turkey

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Abstract
Context Besides climate change vulnerability, most ecosystems are under threat from a history of improper land-use and conservation policies, yet there is little existing long-term ecological research infrastructure in Turkey. In regions with no ecological networks across large landscapes, ecoregion concept offers opportunities for characterizing the landscape under changing climate.

Objectives Aim is to develop contemporary and future quantitative ecoregions for Turkey based on climate model outputs, to identify climate change-sensitive areas of biodiversity and conservation significance, and to provide a framework for a comprehensive ecological observatory network design.
Methods Using Multivariate Spatio-Temporal Clustering and climate data contemporary and projected future distributions of Turkey's ecoregions are delineated at several division levels.
Results Turkey's contemporary ecoregions generally show a northward shift by the end of this century and the lengthening of the growing season across

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the country, especially eastward and northward. The increase in growing season length, along with the shift in precipitation seasonality and increasing growing season precipitation, shape future conditions within the climate change-sensitive areas. Apart from transboundary ecological and socioeconomic significance, these potentially vulnerable ecosystems also constitute the majority of Turkey's biodiversity hotspots.
Conclusions Our study marks the first 'ecoregionalization' study for Turkey based on both contemporary and future climate scenarios. For countries like Turkey, where large-scale ecological networks have not been established, using such quantitative methodology for delineation of optimal ecoclimatic regions, and for mapping environments at risk from climate change provides an invaluable perspective for conservation planning strategies, and a framework for a comprehensive ecological observatory network design.

Keywords Biodiversity conservation · Climate change · Ecoregions · Ecological observatory network · Multivariate Spatio-Temporal Clustering · Regional climate modelling

Introduction

Forming a biological 'crossroads' of three continents, and containing diverse combinations of physiognomy and geomorphology, Turkey represents an especially important gradient of habitats. Turkey encompasses three overlapping biodiversity hotspots: Irano-Anatolian, Mediterranean, and Caucasian, sheltering over 20,000 recorded animal species and about 11,000 native vascular plants, one-third of which are endemic (Atay et al. 2009) (https://www.iucn.org/content/biodiversity-turkey). Turkey is a major center for genetic diversity for several cultivated plants and agricultural crops. Sekercioglu et al. (2011) highlighted Turkey's biodiversity, and suggested a need for ecoregional analysis upon which to base conservation planning under climate change.

Despite this important status, few ecoregionalizations have been produced for Turkey. Turkey's conventional geographic regions (hereafter CGR), were drawn considering topography, climate, vegetation as well as social and economic factors at the 1st Turkish Geographical Congress in 1941, but are often mistakenly regarded as seven climate zones (Fig. 1). Climate zones of Turkey were quantitatively defined for the first time by Unal et al. (2003) using temperature and total precipitation data at Turkish State Meteorological Service (TSMS) stations, using several hierarchical clustering methods. Their results were largely consistent with the CGR. Evrendilek and Berberoglu (2008), using comparative quantitative analyses like hierarchical and non-hierarchical clustering with several environmental variables, found the CGR to be insufficient representations of their seven quantitative climatic zones. Recently, Iyigun et al. (2013) developed twelve and fourteen climate zones (hereafter I12 and I14, respectively) for Turkey by applying hierarchical clustering on air temperature, total precipitation, and relative humidity measured by TSMS stations. Their climatic zonation simply splits the Eastern Anatolia region into four regions, while dividing the Black Sea region and the Mediterranean region down the middle. In a more recent study, fourteen Holdridge life zones were estimated for Turkey by applying spectral clustering on air temperature and total precipitation data from TSMS (Tatli and Dalfes 2016). These existing regionalizations for Turkey are all relatively coarse and may fail to distinguish among rare habitats for conservation, sampling and monitoring programs. They are also restricted to present-day conditions, and do not consider future projections of climatic change.

As discrete generalizations, ecoregions assist us to distinguish, locate, map, and track different combinations of environmental conditions across space and through time. Such mapped representations are of immense practical use, and often form the basis for designing monitoring and sampling programs, and even for prioritizing ecological triage. In the past, ecoregions have been drawn manually using human expertise, making them qualitative, subjective and difficult to replicate. However, the use of multivariate statistical methods has made it possible to delineate quantitative ecoregions. These quantitative methods

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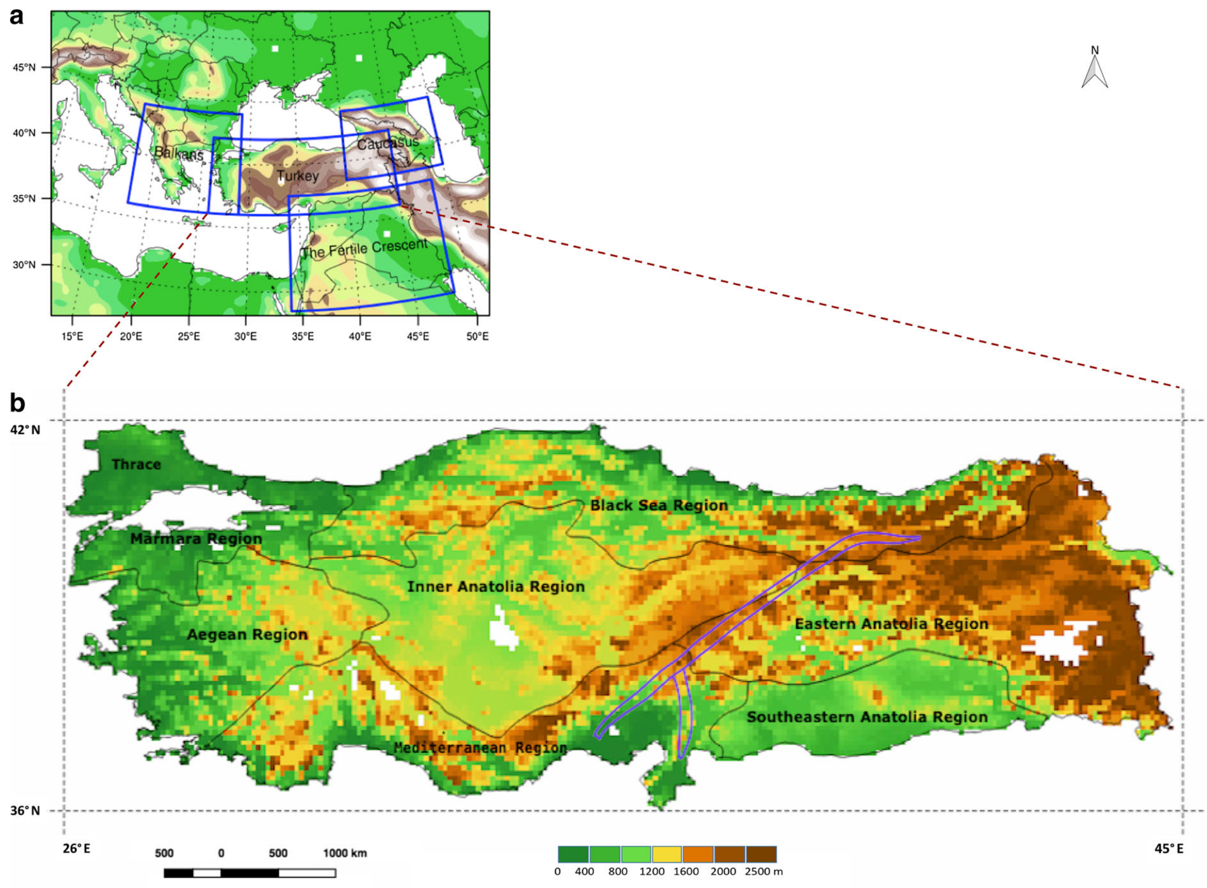

Fig. 1 **a** The model domain and regions of interest (adapted from Bozkurt et al. 2012). The innermost blue box shows the extent of data used in the creation of quantitative ecoregions for Turkey. **b** Turkey's conventional geographic regions (CGR) shown as black outlines superimposed on a topographic (Hydro1K, USGS) map. Purple outline shows the approximate location of the anecdotally recognized "Anatolian Diagonal" (see details in "Contemporary ecoregions" section)

(e.g. ecoregions for United States (Hargrove and Hoffman 1999, 2004), environmental domains for New Zealand (Leathwick et al. 2003), European environmental stratification (Metzger et al. 2005), bio-climatic map of the world (Metzger et al. 2013) provide ecoregions that are more explicit and objective. Such quantitative regions are both defensible, in that the methods used to obtain them are transparent and open to examination by others, and repeatable, in the sense that others can produce the same results using the same input data.

Hargrove and Hoffman's (2004) Multivariate Spatio-Temporal Clustering (MSTC) method also allows the statistical creation of a consistent set of ecoregions through time, allowing comparison of present conditions with those of the past or future. They demonstrated the comparison of present and global climate simulated future ecoregions across space and time for United States. Ecoregions delineated through MSTC analysis may shift across the landscape, may grow and shrink, or new unique regions may even be created, while others may disappear entirely in the future (Hoffman et al. 2013). MSTC method has proven useful in interpreting impacts of climate change, specifically for the comparison of alternative future global climate model predictions (Hoffman et al. 2005); mapping environments at risk from climate change (Saxon et al. 2005) and ecoregions for the People's Republic of China for historical and future climates (Baker et al. 2010).

This MSTC methodology has been successfully used for designing sampling networks, and can also quantify how well samples or data collected at one location represent conditions across the entire network. Using the same quantitative representativeness techniques, MSTC can be used to scale-up local measurements across greater spatial and temporal extents. Hargrove et al. (2003) used MSTC to calculate the representativeness of AmeriFlux Network across the United States, and to delineate the U.S National Ecological Observatory Network (NEON) domains. NEON is the first comprehensive ecological network that has been statistically designed before deployment (Keller et al. 2008). Hoffman et al. (2013) recently applied MSTC as a downscaling approach for offering a framework for up-scaling measurements that provides model-inspired insights into optimal sampling strategies.

According to the IPCC AR4 (IPCC 2007) and also spotlighted by AR5 (IPCC 2014), Turkey is projected to be one of the regions that is most vulnerable to climate change in the Mediterranean basin, yet there is little existing long-term ecological research and monitoring infrastructure in the country to help address current and future threats to biodiversity. Although forecasts of future temperature and precipitation regimes are well-studied for Turkey using global and regional climate model results (Bozkurt et al. 2012; Önol et al. 2014), as well as past and present regimes using station time-series (Türkeş et al. 2002; Tayanç et al. 2009), there still exists a large gap for long-term ecological studies across regional and national levels. Such large-scale studies will be necessary to understand and act upon the impacts of climate change on Turkey's ecosystems and biodiversity.

We present a multivariate representation of ecoclimatic regions for Turkey at several levels of division, and map both their contemporary and their projected future distributions under the SRES A2 emissions scenario, based on the simulations of the ECHAM5 model. We also provide a quantitative comparison of contemporary ecoregions with available existing climatic regionalizations for Turkey. Finally, our study marks the first 'ecoregionalization' study for Turkey that creates both present and future climate scenarios, allowing us to track the spatio-temporal shifts in ecoregions under climate change and quantify the magnitude of change to identify those regions most sensitive to change. Mapping environments at risk from climate change provides an invaluable perspective for conservation planning strategies. This national analysis also provides a framework, which could act as the statistical foundation for the design of an ecological observatory network for Turkey.

Methods

Study area and existing regionalization maps

Turkey (36°–42°N, 26°–45°E) is a fairly mountainous peninsula surrounded by the Black Sea, the Aegean Sea, and the Mediterranean Sea, and is located across the Mediterranean Basin of Western Asia, called *Anatolia* and also partly in Southeastern Europe, named *Thrace* (Fig. 1b). All map analyses are kept slightly larger than the country itself, defined by a bounding box at 35.5°–42.6°N, 25.4°–45.3°E.

Contemporary ecoregions for Turkey generated in this study are compared with the aforementioned existing regionalization maps (CRG, I12 and I14) using MapCurves method (Hargrove et al. 2006). We also provide comparison with terrestrial ecoregions of world map (Olson et al. 2001) (hereafter WWF), Holdridge life zones (Holdridge 1967) and International Geosphere-Biosphere Programme (hereafter IGBP) (http://www.igbp.net) regions for these quantitatively produced ecoregions of Turkey.

Climate model outputs and input layers

For the eastern Mediterranean-Black Sea region, global climate models (GCM) and NCEP/NCAR Reanalysis I prediction data (NNRP) (Kalnay et al. 1996) have been dynamically downscaled to a 27 km resolution using a regional climate model, ICTP-RegCM3 (Bozkurt et al. 2012) (Fig. 1a). Their study indicates that the performance of RegCM3-driven simulations over Turkey and the surrounding region are reasonably good. It is also reported that ECHAM5 is good at simulating both winter and summer precipitation and temperature in the region. However, ECHAM5 tends to overestimate the precipitation over mountainous areas, as does the reanalysis simulation. In this study, outputs from the regional model driven with ECHAM5 simulations by Max Planck Institute for Meteorology are used to generate climate attributes for the continents (2041–2070) under A2 emission scenario, while NNRP 30-year daily climatology data are used for the historical reference period (1961–1990).

Since the climate model outputs are at a coarse resolution of 27 km and edaphic factors are available at a much finer resolution (1 km), we opted for a resolution of 9 km as a common ground. We applied a 'delta' approach to produce a finer resolution (9 km) daily time-series for both historical and future periods (i.e. model outputs). This simple 'delta' approach is widely used for generating regional projections from GCM outputs and local observations (e.g. Hay et al. 2000; Mote and Salathé 2010). Differences between GCM-generated future and historical periods (i.e. NNRP-driven) are calculated (i.e. the 'delta'), and these differences are simply added (for temperature) or multiplied (in the case of precipitation) to historical monthly or daily observations in order to simulate the future conditions.

In this study, anomalies or 'deltas' are calculated as differences for the temperature variables and as mean ratios for precipitation between the 30-year historical period (1961–1990) of ECHAM5 A2 scenario and its future period (2041–2070). The anomaly for each variable was interpolated to a finer resolution 9 km grid using NCAR Command Language's bilinear interpolation method, using the adiabatic lapse rate correction for the temperature values. The interpolated anomalies were then added back to the daily climatology of NNRP reference period (1961–1990) to generate a finer resolution future daily time-series (2041–2070). Available water capacity and elevation variables from Harmonized World Soil Database v.1.2 (http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/) and HYDRO1k database of USGS (https://lta.cr.usgs.gov/HYDRO1K) respectively, were also resampled to 9-km resolution grid to match all other input layers used in this study.

We compiled and calculated over forty climatic variables (including WorldClim's bioclimatic variables), twelve of which are similar to U.S NEON input layers and based on a 'growing season' approach. We used European Climate Assessment and Dataset (http://eca.knmi.nl/indicesextremes/index.php) definition for the 'growing season length' as a period between first 6 consecutive days greater and less than 5 °C threshold. Then, we applied a principal component analysis and a factor analysis (equamax rotation) to statistically select the variables contributing the most distinct information to the analysis. We selected ten ecoclimatic variables (Table 1), including climatic factors as well as topographic and edaphic attributes.

Multivariate Spatio-Temporal Clustering (MSTC)

Cluster analysis groups a set of objects, using a quantitative set of multivariate characteristics, in such a way that objects in the same cluster are more similar to each other than to those in any other cluster. Hargrove and Hoffman (2004) developed a Multivariate Geographic Clustering based on a non-hierarchical *k*-means clustering algorithm (Hartigan 1975), to form a user-defined number of clusters of map cell locations that are similar in composition with regard to a series of environmental characteristics. Hoffman et al. (2005) extended the algorithm to develop MSTC to create quantitative ecoregions through time to analyse the climate change predictions from General Circulation Models. Kumar et al. (2011) further extended the algorithm, to develop a decentralized fully distributed massively parallel MSTC tool for analysis of very large datasets. Using ten ecoclimatic variables generated in this study (Table 1), we applied this MSTC method to quantitatively delineate ecoclimatic regions for both contemporary and future periods for Turkey.

Similarity color maps

Interpretation of maps based on high dimensional data is often a challenge. We develop similarity color maps in which the colors of each ecoregion are generated statistically to reflect the combination of environmental conditions within each ecoregion in order to provide a visual comparison of the degree of similarity between different ecoregions, both spatially and temporally. Similarity color maps were produced by assigning the Red–Green–Blue (RGB) color triplet to the values of the first three principal components after applying equamax rotation (Table 1). Based on the relative loading of each of the ten environmental factors, blue represents non-growing season precipitation and cold (Factor1), green reflects precipitation in the growing season (Factor 2), and red indicates available soil water capacity (Factor 3).

MapCurves analysis

The MapCurves method allows the quantitative comparison of multiple categorical maps (Hargrove et al.

Table 1 Ecoclimatic variables used in the Multivariate Spatio-Temporal Clustering and their factor loadings (with equamax rotation)

	Factor 1	Factor 2	Factor 3
Available water capacity of soil—AWC (mm/m)	− 0.02542	0.17813	**0.97465**
Number of days with measurable precipitation during growing season	− 0.06889	**0.93791**	0.16749
Number of days with measurable precipitation during non-growing season	**0.94772**	− 0.22680	− 0.07893
Precipitation sum during growing season (mm)	− 0.06686	**0.87846**	0.12639
Precipitation sum during non-growing season (mm)	**0.79285**	− 0.14087	− 0.16504
Total solar insolation during growing season (W/m^2)	− 0.96335	− 0.15144	0.02110
Total solar insolation during non-growing season (W/m^2)	**0.86653**	− 0.44755	− 0.13150
Number of cold days during non-growing season	**0.87553**	− 0.39320	− 0.09976
degree-day heat sum during growing season (°C)	− 0.97641	0.08881	0.10828
Number of hot days during growing season	− 0.68416	− 0.40313	0.17902

Bold values indicate the greatest loading for that variable on a particular Factor, helping with interpretation. Non-growing season precipitation and cold are loaded on (Factor 1); Precipitation in the growing season is loaded on (Factor 2) and the available soil water capacity is loaded on (Factor 3)

2006). Using MapCurves Analysis, each level of Turkey's ecoregion maps that we created were compared with two existing climatic regionalizations, the expert-delineated Turkey CGR map (Fig. 1b) and the I12 and I14 maps. Comparison with some other global regionalization datasets (e.g. WWF, Holdridge zones) was also conducted (Table 2).

MapCurves, a quantitative goodness-of-fit method, was used to determine the degree of similarity/concordance between our ecoregionalizations and each of the existing maps, and also among the existing maps themselves. The method empirically determines the degree of spatial overlap, or positive spatial correlation, between two or more maps with the same spatial extent by using a goodness-of-fit (GOF) algorithm, according to the equation:

$$\text{Goodness - of - fit} = \sum\left[\left(\frac{C}{B+C}\right)\left(\frac{C}{A+C}\right)\right]$$

where C is the amount of overlapping spatial intersection of a category shared in common between the two maps, B is the total area of the category on a reference map, and A is the total area of the category on the compared map. Since MapCurves GOF scores are standardized and largely eliminate the effects of different numbers of categories in the maps being compared, it permits a quantitative ranking of scores (given in percentages) for comparisons of different maps (Hargrove et al. 2006).

Magnitude of change maps

To quantify the magnitude of changes in contemporary ecoregions under future climate change, we calculated the Euclidean distance in multi-dimensional environmental data space (Table 1) between conditions during present and future periods, and mapping the shifts as "magnitude of change maps". These maps enable us to quantify and visualize the shifts in environmental conditions under climate change which can guide us when identifying most sensitive regions. Magnitude of change maps were generated to quantify shifts within each ecoregion, and also for each individual cell. To quantify shifts in the ecoregions, the Euclidean distance between centroids of the cluster during the present and the future period were calculated. To quantify location-specific shifts, Euclidean distance between environmental conditions during present and future conditions at each cell were calculated to quantify the magnitude of change.

Results

Quantitative regionalization can be customized for specific purposes based on the quantitative method itself and the availability, selection and formulation of the input layers. Some ecoregion uses may favour particular levels of division, but some divisions are likely to be more 'natural,' while others are more

Table 2 MapCurve analysis—GOF (goodness-of-fit) table

Number of quantitative ecoregions delineated (k)												
		10 k(9)	11 k(10)	12 k(11)	13 k(11)	14 k(12)	15 k(12)	16 k(12)	17 k(14)	18 k(16)	19 k(15)	20 k(17)
Ecoregions[a]	CGR	14.13	15.78	18.62	10.11	15.49	15.5	13.8	12.48	11.15	11.42	11.23
WWF	28.57	10.72	9.45	9.25	7.42	7.57	7.78	7.96	7.72	6.88	6.89	6.94
I12	30.41	10.16	11.78	12.18	8.45	10.34	9.53	9.41	7.82	7.74	7.53	7.25
I14	28.83	10.08	11.41	11.74	8.36	9.96	8.98	8.75	7.06	7.15	7.09	7.17
Holdridge	13.22	9.33	8.62	8.71	6.84	7.02	6.68	6.60	6.32	6.44	6.21	5.97
IGBP	10.33	8.38	8.57	8.41	7.25	7.06	6.51	6.39	6.17	6.06	5.95	5.63

Comparison of contemporary ecoregions from 10 to 20 levels (k) with available regionalization maps and also the comparison of the Conventional Geographic Regions (CGR) of Turkey with the given maps. GOF values are given in percentages. Numbers in parentheses indicate the number of regions created within the borders of Turkey itself

[a]WWF: terrestrial ecoregions of world map (Olson et al. 2001); Holdridge life zones (Holdridge 1967); I12 and I14: twelve and fourteen climate zones for Turkey, respectively (Iyigun et al. 2013); IGBP: International Geosphere-Biosphere Programme

forced or artificial. While no level of division is incorrect, ‘better’ divisions will result in tighter clusters in data space that have smaller within-group variance. Statistical metrics like mean distance to centroid and the Pseudo-F test using for these within-group variance evaluations, with decreasing values indicating better ecoregion results.

After exhaustively calculating and comparing sequential levels of division from 10 to 40 ecoregions (Appendix S1 in Supplementary Material), 12 quantitative ecoregions were determined to be the most suitable and useful within Turkey, indicating local depressions in the Pseudo-F statistic at 16 and also 22 clusters (k). Interestingly, requesting higher number of ecoregions (like k = 14, 15 or 16) within our study area consistently produced only 12 ecoregions within the national borders of Turkey. This consistent result suggests some robustness within Turkey at this level of division. Only a quantitative statistical ecoregionalization provides this kind of feedback about the ‘naturalness’ of the division; no such information is available for qualitative expert ecoregions. Higher levels of division reveal additional details in the landscape mosaic. Along with the Magnitude of Change maps, which show the size of changes expected under forecasts of climatic change, these detailed visualizations can provide a quantitative foundation for regional and national sampling and monitoring programs for a variety of ecological applications including biodiversity conservation.

Contemporary ecoregions

As a peninsula bridging three continents, Turkey has a complex geography and a high diversity of climate types. The Anatolian peninsula consists of a high central plateau with narrow coastal plains and lies between the Northern Anatolian Mountains to the north and Taurus Mountains to the south. Anatolian highlands show considerable variability and heterogeneity toward the east. All of our contemporary ecoregions, from 10 to 150 ecoregions (Fig. 2), successfully reflect these main intuitive physiographic characteristics of Turkey. Each of these maps (Fig. 2) distinguishes and represents the Anatolian plateau (Inner Anatolia) and surrounding low-altitude mountains, the Aegean and Mediterranean plains (especially the alluvial plains), the southeast Anatolian plains, and the high-altitude mountain ranges behind them.

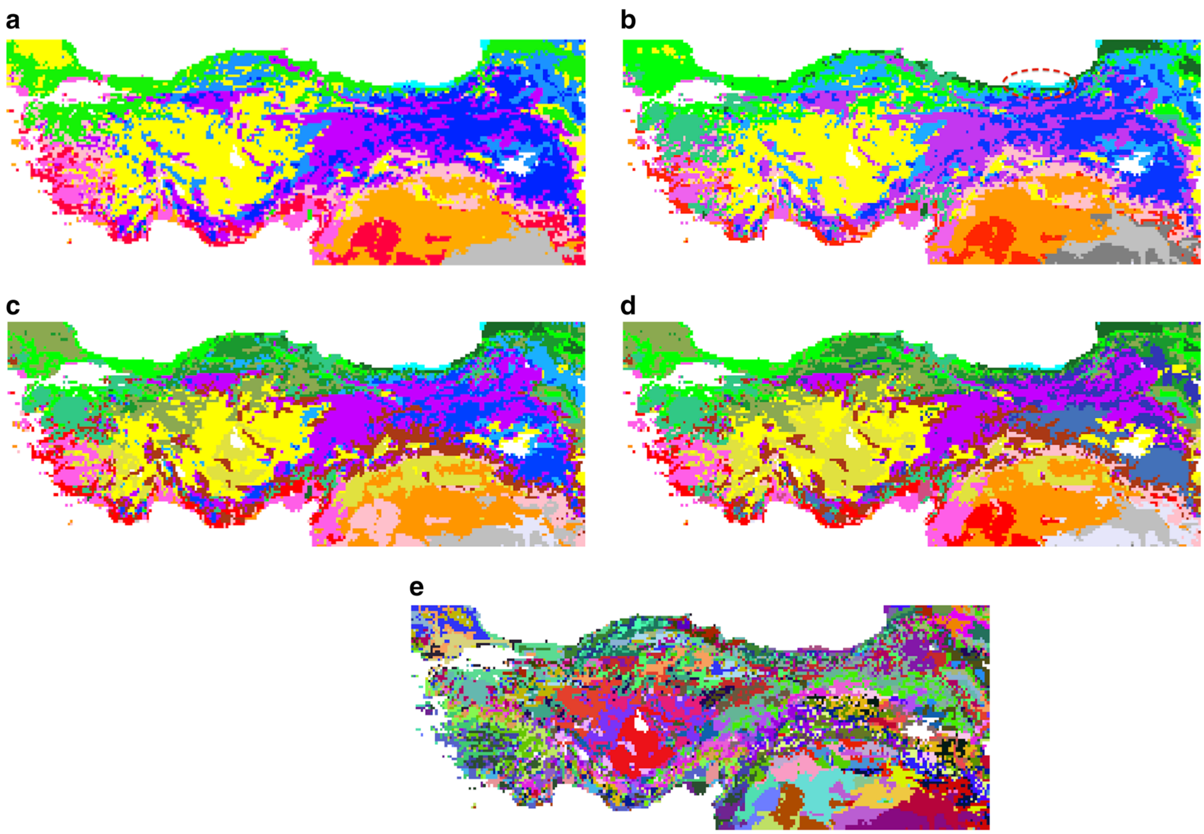

Fig. 2 Contemporary ecoregion maps (twentieth century) for Turkey with **a** 10, **b** 12, **c** 16, **d** 17, and **e** 150 levels (k-cluster), shown in random colors. Additional ecological distinctions emerge as the level of statistical division increases, but all levels of division represent the 'Caucasus hotspot,' a unique biodiversity microclimate along the Eastern Black Sea coastline of the Trabzon-Rize provinces (red dashed area in Map **b**), which gets the greatest annual precipitation in Turkey and experiences floods, and hailstorms. At lower levels of division (**a**–**d**), the statistical ecoregions are intuitively recognizable and understandable, but at the highest level of division (**e**), there are too many regions for easy visual interpretation. Nevertheless, map (**e**) would serve well as the basis for a network or observatory sampling design or a representativeness analysis for Turkey

Since our quantitative characterization of ecoregions is based on a combination of several environmental factors, these contemporary maps provide further resolution beyond the existing conventional regionalizations, the representation of unique biodiversity hotspots like the 'Caucasus hotspot', a unique microclimate at the Eastern Black Sea coastline of the Trabzon-Rize provinces (red dashed area, Fig. 2b). This Caucasus hotspot, which gets the highest annual precipitation in Turkey and frequently experiences extreme weather events like floods and hailstorms, is a distinct ecoregion that is visible at every level of our quantitative regionalizations (Fig. 2).

Our contemporary ecoregions also delineate and capture the typical Mesopotamian hot and semiarid environments in southeastern Anatolia, particularly the upper Tigris and middle Euphrates basins, comprising one of the most important waterways in the world that arises in the highlands of eastern Turkey. These quantitative ecoregions are resolved by differences in their soil available water capacity which represent maximum plant available water soil can provide. The ecosystems of countries bordering Turkey to the south, like sand dunes and semi-arid steppes, are also well represented. Our contemporary ecoregions also separate the different Mediterranean climate elements at the south and west coasts, the central Anatolian steppes and plateaus, the high plateaus and mountains of eastern Anatolia, and ecoregions penetrating from the Balkans through Thrace.

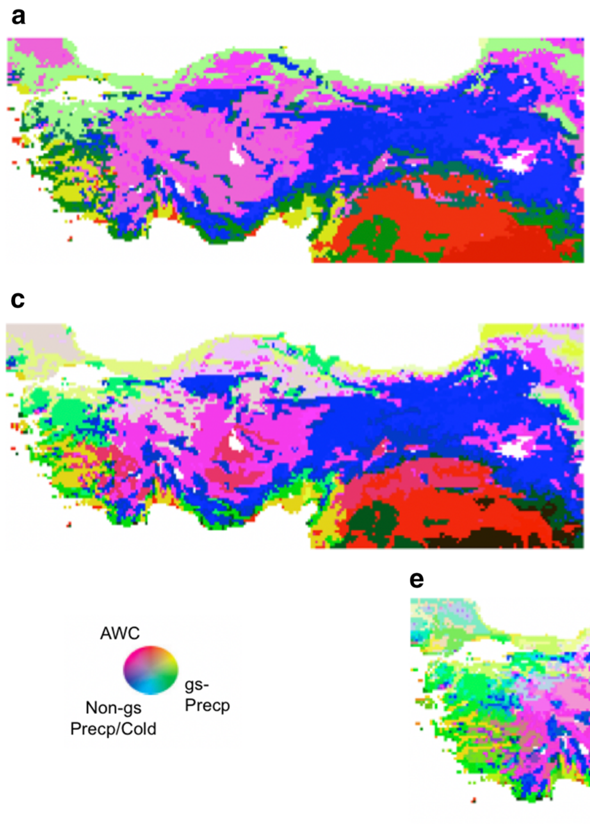

Fig. 3 Contemporary ecoregion maps for Turkey with **a** 10, **b** 12, **c** 16, **d** 17, and **e** 150 levels (k-cluster), shown using similarity colors. The statistically assigned colors now visually shows the combination of ecological conditions occurring within each region. Blue represents non-growing season precipitation and cold (Non-gs Precp/Cold); green reflects precipitation in the growing season (gs-Precp); red shows available soil water capacity (AWC)

Through the finer levels of division from 10 to 20 ecoregions, more detailed depiction of Turkey's ecoregions, marking diverse climatic zones with their characteristic vegetation and landscape structures, are achieved. For example, alpine meadows become distinguished from the alpine steppes of eastern Anatolia and Mediterranean region, southeastern plateaus split apart from the inner Anatolian plateaus, Thracian steppes separate from middle Black Sea plains, and western Black Sea fir forest ecosystems are resolved from the alluvial plains of southern Marmara, respectively (Figs. 2, 3a–d). Greater levels of division also distinguish the middle Anatolian mountain steppes from prairie steppes.

The contemporary quantitative ecoregion maps using similarity color (Fig. 3) clearly show the predominance of non-growing season precipitation and cold (largely 'winter snow') over eastern Anatolia and the eastern Black Sea mountains running through the 'Anatolian Diagonal' (purple outline, Fig. 1b) from the northeast up to the high elevations of the Taurus mountains in the Mediterranean. The Anatolian diagonal is an empirically observed dividing line that represents a change in the floral continuum between inner and eastern Anatolia, first realized by Cullen and named by Davis (1971).

Quantitative ecoregions along the Aegean and Mediterranean coasts and plains are dominated by growing season precipitation and by non-growing season precipitation and cold through Marmara and Thrace. Both available water capacity and non-growing season precipitation/cold dominate and define the Inner Anatolian steppes. Some ecoregions occurring through the inner Aegean region and below Lake Tuz are distinguished mainly by available water capacity. Almost equal contributions of all three factors can be seen in northeastern coastlands ecoregions of the Black Sea Region.

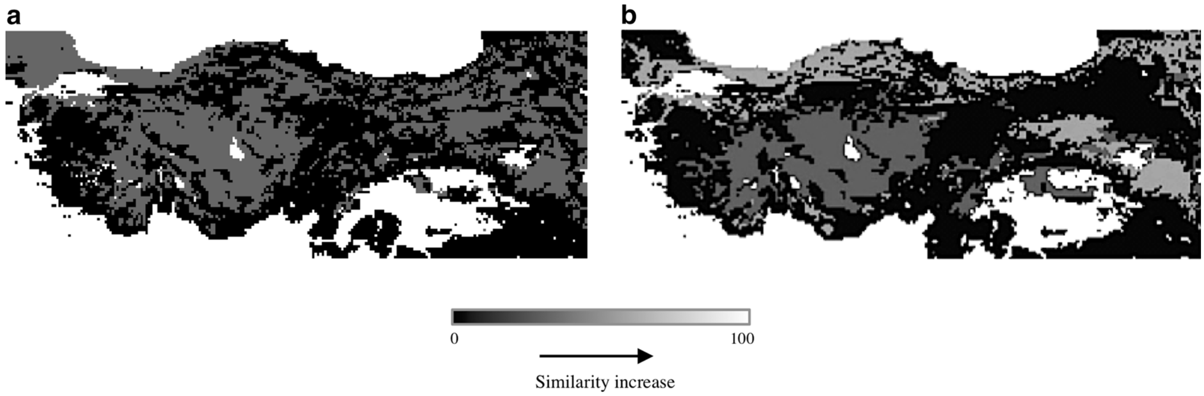

Fig. 4 MapCurves comparison of **a** 12, and **b** 16 level (k-cluster) quantitative ecoregions with Turkey Conventional Geographic Regions (CGR). CGR's Southeastern Anatolia region shows the greatest commonality with our quantitative ecoregions. But the similarities are weakening at the higher level of divisions, specifically after 16 cluster level. Central and Northeastern Anatolia, and the Lake Van area are showing a good match with CGR at both levels of division, and the Black Sea coast is well-matched by the 16-level ecoregion version, but both versions of the quantitative ecoregions are substantially different from the CGR map. Main reason for this can be explained by the fact that our quantitative ecoregions are based on more recent climatic factors in addition to edaphic factors that are generated statistically

Northern Mesopotamian hot and arid environments, and some parts of southeastern Anatolia are defined mainly by available water capacity, along with growing season precipitation. These orange–reddish quantitative ecoregions also have more than 130 hot days within the growing season, and where the growing degree day heat sum exceeds 6000 °C. The utility of including precipitation in the non-growing season as an environmental characteristic can be seen in defining the Euphrates–Tigris river basins of southeastern Anatolia.

MapCurve analysis results

MapCurve analysis shows that our quantitative eco-climatic regions for Turkey, while intuitive and recognizable, are quite different from the existing Turkey's Conventional Geographic Regions (Fig. 4); from the existing global WWF map, and from other prior regionalizations for Turkey (Table 2). This can be explained by the fact that our quantitative ecoregions are based on more recent climatic and edaphic factors that are generated statistically. Despite these differences, CGR shows relatively larger goodness-of-fit values (15.5–18.6) with our quantitative ecoregions than any of the other maps that were compared (Table 2). CGR's Southeastern Anatolia region shows the greatest commonality across every level of our quantitative regionalizations (Fig. 4). Comparison of CGR with WWF, I12, and I14 maps shows 28.6–30 GOF scores. MapCurve analysis suggests that Turkey's existing ecoreginalization maps are not so different from each other, and may not provide detailed understanding of Turkey's unique ecoregions for long-term monitoring studies. Above all, they cannot provide insights into relative future climate change impacts.

Potential future ecoregions

We also present a multivariate representation of predicted future ecoclimatic regions for Turkey under the A2 emissions scenario, and map their projected future distributions at several levels of division. Here we discuss changes in the environmental conditions of ecoregions; their spatial changes are covered in the next section. In the future, under ECHAM5 A2 scenario, it is predicted that the growing season will become longer across Turkey, especially in the east and the north (Fig. 5). This is consistent with the climate change A2 scenario projections for Turkey, in which the temperatures are projected to increase 1.0–2.5 °C by the mid-twenty first century (Önol et al. 2014).

Furthermore, our findings indicate that in the mid-twenty first century, growing season precipitation will profoundly affect the regions that are currently delineated at present by non-growing season

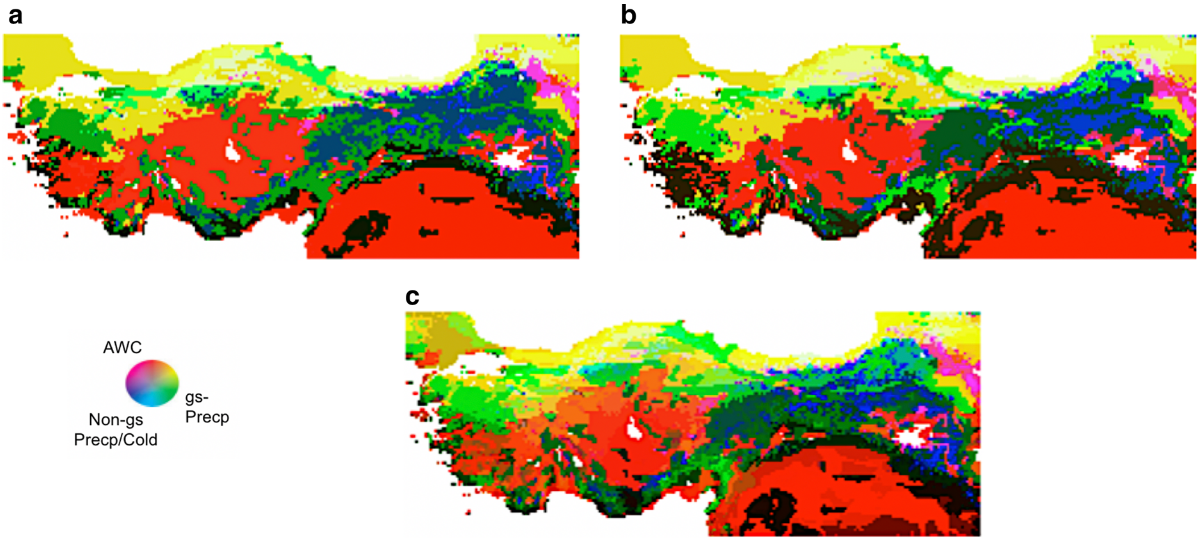

Fig. 5 Potential future quantitative ecoregion maps for Turkey in the mid-twenty-first Century divided into **a** 12, **b** 16, and **c** 150 levels (k-cluster), shown in similarity colors. The statistically assigned colors now visually show the combination of ecological conditions occurring within each region. Blue represents non-growing season precipitation and cold (Non-gs Precp/Cold); green reflects precipitation in the growing season (gs-Precp); red shows available soil water capacity (AWC). Central Anatolia becomes much drier (redder) than shown under present conditions (Fig. 3), while northeastern Anatolia becomes warmer and more gs-Precp mediated (less blue, more green)

precipitation/cold. These changes are not uniformly distributed across Turkey, as is the case with the increasing temperatures, according to A2 scenario projections. This shift in precipitation seasonality is projected to be more pronounced through the eastern Anatolian highlands. Other examples of this seasonal shift in precipitation can be seen in the Koroglu Mountains (in the inner western Black Sea region), in the high plateaus of the east of Central Anatolia, and also in the higher elevations of the Taurus Mountains.

One dramatic spatial shift in the future quantitative ecoregions is the penetration of northern Mesopotamian hot and arid ecoregions into Anatolia toward the west and the north. The southeastern Anatolian ecoregion grows into these directions and reduces the extent of the central Anatolian ecoregion. This makes central Anatolia becomes much drier than its present conditions (It can be seen increasing amount of red areas while comparing for example, Figs. 3b or e with 5b or c). Our results suggest that available water will become increasingly critical factor shaping ecoregions in southeastern Anatolia and the Inner Anatolian steppes, and also throughout eastern Anatolia the shift in growing season precipitation will be instrumental in conforming ecoregions. Regions distinguished by heat in the growing seasons are also shown in blackish colors. Together with the influence of water capacity, growing season precipitation will also govern the Marmara region, particularly in Thrace and the central Black Sea region. Especially in Thrace, changing environmental conditions in the future will sharpen and narrow the transitional ecoregions between the Balkans and the Mediterranean regions.

Spatial shifting of ecoregions through time

The most remarkable spatial shift in quantitative ecoregions is observed in eastern Anatolia, in which the largest contemporary ecoregion will shrink significantly and be fragmented into smaller patchy ecoregions in the future. One of these future ecoregions is novel, meaning that it has no analog conditions in the present for Turkey. This novel quantitative ecoregion extends from the highlands of the Mediterranean to eastern Anatolia through the Anatolian diagonal (It can be seen as dark green areas while comparing for example, Figs. 3b or e with 5b or c). A few other patchy ecoregions are predicted to be scattered around Lake Van in the future, but these are not novel. Another newly emerged ecoregion will be dispersed across the coastal Aegean Sea and the upper southeastern belt of the Mediterranean Sea region. Scattered ecoregions in the middle Black Sea region disappear, thus reducing the diversity in environmental conditions and creating more spatially compact ecoregions. For instance, one quantitative ecoregion that presently extends from the Bosphorus strait through the middle Black Sea region also extends in the future over the coastal part of the eastern Black Sea region. The second largest contemporary ecoregion (central Anatolia) is projected to disappear, and to be replaced by the current southeastern Anatolia ecoregion, which is forecast to also penetrate into the Aegean Sea region, becoming the largest quantitative ecoregion occurring in future Turkey. The shifting of the central Anatolian ecoregion into southeastern Anatolia ecoregion in the mid-twenty-first century can be seen as conversion of pinkish areas into reddish while comparing for example, Figs. 3b or e with 5b or c.

Under predicted future climate, the relative degree of changes forecast between present and future quantitative ecoregions can be examined, for both regions and cells, in the magnitude of change maps (Fig. 6). These maps provide a basis for identifying the quantitative ecoregions that are most sensitive to predicted climate change. High elevation mountainous regions of Turkey, along with the Anatolian diagonal and its surroundings, are prone to climate change in future under the ECHAM5 A2 emissions scenario (Fig. 6). Particularly large changes are observed around the northeastern Black Sea mountain range, e.g. the Kackar Mountains, the high mountain ranges of eastern Anatolia and the Mediterranean Taurus, the alpine meadows and alpine steppes of eastern Anatolia (especially around Lake Van), and the Euphrates–Tigris river basins of southeastern Anatolia.

Discussion

Spatio-temporal delineation of quantitative ecoregions for Turkey illustrates both the contemporary and the predicted future distribution of ecoregions at multiple levels of division under simulated climate change. Present quantitative ecoregions generally show a northward shift in future, consistent with a warming climate by the end of this century, as projected by models using the A2 emissions scenario (Önol et al. 2014). Predicted future warming causes lengthening of the growing season across Turkey, especially eastward and northward. This lengthening of growing season, along with the shift in precipitation seasonality and amount of growing season precipitation, together shape future conditions within the climate change sensitive areas. Recent studies (Ulbrich et al. 2012; Navarra and Tubiana 2013) report that the Mediterranean region, including southern Europe and non-European Mediterranean countries, are highly vulnerable to climate change, and also point out an observed increase in both the duration and the intensity of droughts and heat waves. Sen (2013) also projected similar future trends in climate change impacts report for Turkey, based on ECHAM5 A2 scenario for Turkey and the surrounding (Bozkurt et al. 2012; Önol et al. 2014). These changes will have consequences for species composition, migration, and ecosystem dynamics, as well as for ecosystem services that are provided.

This shift in the precipitation regime, along with increasing heat that lengthens the growing season emphasize the significance of growing season precipitation and water stress for the region. Based on ECHAM5 A2 scenario for Turkey, the model projections suggest that there will be significant reductions in precipitation especially in the southern regions. It is also projected that there will be 16% and 27% reductions in the water potentials in Turkey by 2050 and 2075, respectively. According to detailed study on the climate change impacts in the Euphrates–Tigris basin, Bozkurt and Sen (2013) suggest that the annual surface runoff is projected to decrease by 26–57% in Turkey by the end of the present century. They also noted that lands of Turkey and Syria within the basin are most vulnerable to climate change and ultimately Iraq may suffer more as they rely primarily on the water released by the upstream countries. Considering the actual water release to Iraq and Syria from Turkish dams is a matter of constant dispute among these countries and Turkey, and these changes will have important implications for countries in the basin as available water diminishes during the twenty-first century. These are critical future changes, especially in the river basins and agricultural zones of central and southeastern Anatolia. For example, the Euphrates–Tigris river basin, a climate sensitive agricultural site, is at moderate climate risk. One of the most important waterways in the world, the Euphrates–Tigris basin has an important role for future water availability in the Middle East. Moreover, the Southeastern Anatolia Project, (abbreviated as GAP in Turkish), a major

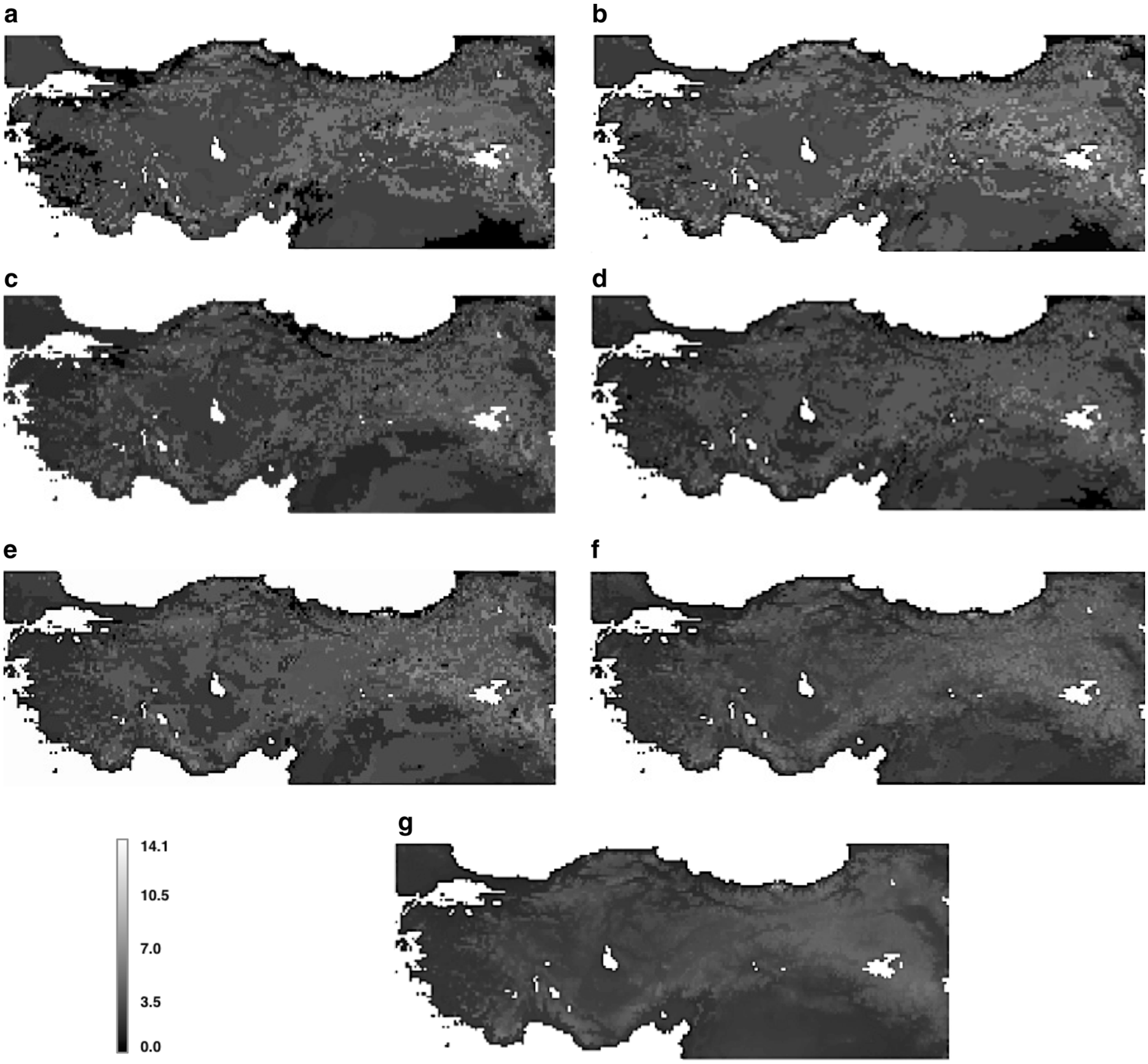

Fig. 6 Magnitude of change maps for Turkey with **a** 10, **b** 12, **c** 15, **d** 18, **e** 20, and **f** 150 levels of clusters and also for **g** cell-by-cell comparison. These maps show the degree of change predicted, from present to future conditions, in terms of all ten included ecological metrics, in each location across Turkey. In maps **a**–**f**, each entire ecoregion has the same uniform color, while every cell location has a unique color in map **f**. Black areas show little change. Northeast Anatolia, Tigris–Euphrates basin, and Lake Van area are forecast to experience the greatest environmental changes in the future, along with the Mediterranean and Black Sea coastal areas

regional development project of Turkey, is located within the Euphrates–Tigris basin (http://www.gap.gov.tr/en/what-is-gap-page-1.html). The GAP includes the construction of 22 dams, 19 hydropower plants and irrigation networks covering 1.8 million hectares of land in the Euphrates–Tigris basin. With 27 billion kWh annual energy production, total installed capacity of hydraulic power plants would be 7490 MW. This large land consolidation operation (2.4 million hectares) resulted in the construction of 19 dams, 13 hydropower plants and about a thousand miles of main irrigation canals until 2015. Euphrates and Tigris rivers are about 30% total water potential of Turkey and also vitally important for Syria and Iraq. On the Euphrates river, Keban, Karakaya, Atatürk (largest holding capacity of 48.7 km^3), Birecik and Karkamış dams and hydropower plants form a continuous series of reservoirs through the downstream country Syria. Key dams, namely, Tishrin (Teshreen), Tabqa (At-Thawra, largest holding capacity of 11.7 km^3) and Baath (Al-Baath) are sited on the mainstream Euphrates in Syria. The major dams on the Tigris basin of Turkey are Kralkızı, Dicle and Batman dams. On the main Tigris river in Iraq, another downstream neighbor, the largest dam Mosul (holding around 13 km^3 of water) is located besides the Bekme, Dokan and Dibbis dams on the tributaries of Tigris. The project area covers nine provinces with 867 million people on 75,000 km^2 lands of the Euphrates–Tigris basin and upper Mesopotamia plains. These figures correspond to approximately 10% of geographical and 10.7% of population size of Turkey based on 2017, Address-Based Population Registry System of Turkey. Through GAP irrigation projects, Harran and Ceylanpinar plains in the region have become important agricultural zones of Turkey. Potential impacts of future climate change on Euphrates–Tigris river basin will be likely to have transboundary ecological and socioeconomic aspects.

The inner Anatolian steppe ecosystems are both at the origin and at the center of genetic diversity for many important staple agricultural crops, including cereals like wheat and barley, many legumes, and wild relatives of fruit trees. Many of these Anatolian agricultural diversity center ecoregions show sensitivity to future climate changes. For example, the central Konya basin produces most of Turkey's cereal, salt, and sugar beets, while the Seyhan basin, farther southeast, is another important water and agricultural resource that provides water for the Cukurova plain, the main cotton production zone of Turkey.

Apart from their agricultural and socioeconomic significance, these potentially vulnerable ecosystems also constitute the majority of the Important Plant Areas (IPAs), Important Bird Areas (IBAs) and biodiversity hotspots of Turkey, sheltering thousands of plants and animals. Specific examples include: (1) the Caucasian mixed temperate rain forest and high alpine meadows along the northeastern Black Sea mountains, like Artvin-Borcka-Macahel, (2) the unique 'Caucasus biodiversity hotspot' located along the Eastern Black Sea coastline of the Trabzon-Rize provinces (also the only site in country and the northern limiting zone where tea (*Camellia sinensis*), an economically important plant, grows), (3) important bird areas in Kars and Igdir, (4) Kure Mountains National Park, a forest biodiversity hotspot, (5) Mediterranean forests and high alpine ecosystems of the Taurus mountains, including the Bolkar Mountains, (6) the salt marshes of Lake Tuz, and (7) the Irano-Anatolian phytogeographical ecoregions in eastern Anatolia, like the Munzur Mountains National Park. Ecozones surrounding the Anatolian diagonal have a large degree of endemism about 1200 endemic plant species (https://www.cepf.net/our-work/biodiversity-hotspots/irano-anatolian/), and show as greatly vulnerable to climate change. On the other hand, future environmental conditions are predicted to create several new ecoregions, increasing environmental diversity in eastern Anatolia, especially near the Lake Van ecoregion, which is currently considered among the most biodiverse wetlands in Turkey. Only 7.2% of Turkey's habitats are currently under protection as existing reserves or preserves (https://www.iucn.org/nl/node/17020); these potentially climate-vulnerable ecosystems have insufficient monitoring and/or biodiversity conservation capacities.

Conclusion

We applied a categorical ecoregion concept using climate model outputs with the MSTC technique to statistically develop potential contemporary and future quantitative ecoregions for Turkey, and to demonstrate climate change-sensitive areas for the purpose of emphasizing the need for a comprehensive national-scale observatory network design for long-term ecological monitoring and climate impact studies that is vital for biodiversity conservation. For countries like Turkey, where national/large scale ecological networks have not been established, using this well-proven explicit multivariate statistical methodology for delineation of optimal quantitative ecoclimatic regions, and for showing the most representative sampling network sites, can provide a framework for ecological observatory network design. Currently most of Turkey's ecosystems are under threat from a series of insufficient land-use and conservation management actions. The utility and necessity of such controls could have been demonstrated using such a conceptual framework based on ecoclimatic regions under climate change.

In Turkey, national and international projects on forest health and agricultural monitoring remain in the formative infrastructure phase, but a growing number of studies on climate change are being conducted by academia and non-governmental organizations. For Turkey, now more than ever, it is essential to ensure the representativeness of these new ecological observations over a broad range of spatio-temporal scales and to establish a national-scale ecological observatory in order to address the environmental challenges and biodiversity threats that will emerge under changing environments and climate. Such national-scale monitoring networks are expensive and lasting large-scale infrastructure, and represent a substantial investment. Rather than growing incrementally in an ad hoc, organic way, it is prudent to statistically design the final overall structure of such networks a priori, even if the construction itself is to be incrementally phased.

This study marks the first empirical 'ecoregionalization' study for Turkey, a global biodiversity and connectivity 'hotspot,' based on both contemporary and future climate scenarios by statistically integrating quantitative data on environmental factors. It also demonstrates the utility of providing a quantitative framework with addressing biodiversity conservation perspectives, which could act as the statistical foundation for a national 'ecological observatory network' for Turkey.

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References

Atay S, Byfield A, Özhatay N (2009) Turkey. In: Radford EA, Odé B (eds) Conserving Important Plant Areas: investing in the Green Gold of South East Europe. Plantlife International, Salisbury, pp 69–74

Baker B, Diaz H, Hargrove WW, Hoffman F (2010) Use of the Köppen-Trewartha climate classification to evaluate climatic refugia in statistically derived ecoregions for the People's Republic of China. Clim Change 98:113–131

Bozkurt D, Sen OL (2013) Climate change impacts in the Euphrates-Tigris Basin based on different model and scenario simulations. J Hydrol 480:149–161

Bozkurt D, Turuncoglu U, Sen OL, Onol B, Dalfes HN (2012) Downscaled simulations of the ECHAM5, CCSM3 and HadCM3 global models for the eastern Mediterranean-Black Sea region: evaluation of the reference period. Clim Dyn 39:207–225

Davis PH (1971) Distribution patterns in Anatolia with particular reference to endemism. In: Davis PH, Harper PC, Hedge IC (eds) Plant life of south-west Asia. The Botanical Society of Edinburgh, Edinburgh, pp 15–27

Evrendilek F, Berberoglu S (2008) Quantifying spatial patterns of bioclimatic zones and controls in Turkey. Theor Appl Climatol 91:35–50

Hargrove WW, Hoffman FM (1999) Using multivariate clustering to characterize ecoregion borders. Comput Sci Eng 1(4):18–25

Hargrove WW, Hoffman FM (2004) Potential of multivariate quantitative methods for delineation and visualization of ecoregions. Environ Manag 34:S39–S60

Hargrove WW, Hoffman FM, Hessburg PF (2006) Mapcurves: a quantitative method for comparing categorical maps. J Geogr Syst 8(2):187–208

Hargrove WW, Hoffman FM, Law BE (2003) New analysis reveals representativeness of the AmeriFlux Network. Eos Trans AGU 84(48):529–535

Hartigan JA (1975) Clustering algorithms. Wiley, New York

Hay LE, Wilby RL, Leavesley GH (2000) A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States. J Am Water Resour Assoc 36:387–397

Hoffman FM, Hargrove WW, Erickson DJ, Oglesby RJ (2005) Using clustered climate regimes to analyze and compare predictions from fully coupled general circulation models. Earth Interact 9(10):1–27

Hoffman FM, Kumar J, Mills RT, Hargrove WW (2013) Representativeness-based sampling network design for the State of Alaska. Landscape Ecol 28:1567

Holdridge LR (1967) Life zone ecology. Tropical Science Center, San Jos, Costa Rica

IPCC (2007) Climate change 2007: synthesis report. In Contribution of Working Groups, I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change

IPCC (2014) Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects. Europe. In Contribution of Working Group II to the IPCC fifth assessment report of the intergovernmental panel on climate change

Iyigun C, Türkeş M, Batmaz I, Yozgatligil C, Purutcuoglu V, Koç EK, Ozturk MZ (2013) Clustering current climate regions of Turkey by using a multivariate statistical method. Theor Appl Climatol 114:95

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Leetmaa A, Reynolds R, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Jenne R, Joseph D (1996) The NCEP/NCAR 40-year reanalysis project. Bull Am Meteorol Soc 77:437–471

Keller M, Schimel DS, Hargrove WW, Hoffman FM (2008) A continental strategy for the National Ecological Observatory Network. Front Ecol Environ 6:282–284

Kumar J, Mills RT, Hoffman FM, Hargrove WW (2011) Parallel k-means clustering for quantitative ecoregiondelineation using large data sets. In: Sato, M, Matsuoka S, Sloot PM, van Albada GD, Dongarra J (eds)Proceedings of the international conference on computational science (ICCS 2011), volume 4 of ProcediaComput. Sci. Elsevier, Amsterdam, pp 1602–1611.

Leathwick JR, Overton JM, McLeod M (2003) An environmental domain classification of New Zealand and its use as a tool for biodiversity management. Conserv Biol 17:1612–1623

Metzger MJ, Bunce RGH, Jongman RHG, Mücher CA, Watkins JW (2005) A climatic stratification of the environment of Europe. Global Ecol Biogeogr 14:549–563

Metzger MJ, Bunce RGH, Jongman RHG, Sayre R, Trabucco A, Zomer R (2013) A high-resolution bioclimate map of the world: a unifying framework for global biodiversity research and monitoring. Global Ecol Biogeogr 22:630–638

Mote PW, Salathé EP (2010) Future climate in the Pacific Northwest. Clim Change 102:29

Navarra A, Tubiana L (2013) Regional assessment of climate change in the Mediterranean. In: Navarra A, Tubiana L (eds) Case studies, vol 3. Springer, Dordrecht, p 225

Olson DM, Dinerstein E, Wikramanayake ED, Burgess ND, Powell GVN, Underwood EC, D'Amico JA, Itoua I, Strand HE, Morrison JC, Loucks JC, Allnutt TF, Ricketts TH, Kura Y, Lamoreux JF, Wettengel WW, Hedao P, Kassem KR (2001) Terrestrial ecoregions of the world: a new map of life on earth. BioScience 51:933–938

Önol B, Bozkurt D, Turuncoglu UU, Sen OL, Dalfes HN (2014) Evaluation of the twenty-first century RCM simulations driven by multiple GCMs over the Eastern Mediterranean-Black Sea region. Clim Dyn 42:1949–1965

Saxon E, Baker B, Hargrove WW, Hoffman FM, Zganjar C (2005) Mapping environments at risk under different global climate change scenarios. Ecol Lett 8:53–60

Sekercioglu CH, Anderson S, Akcay E et al (2011) Turkey's globally important biodiversity in crisis. Biol Conserv 144:2752–2769

Sen OL (2013) A holistic view of climate change and its impacts in Turkey. Mercator-IPC Report: Istanbul Policy Center, Sabancı University. http://ipc.sabanciuniv.edu/new/a-holistic-view-of-climate-change-and-its-impacts-in-turkey/?lang=en

Tatli H, Dalfes HN (2016) Defining Holdridge's life zones over Turkey. Int J Climatol 36(11):3864–3872

Tayanç M, Im U, Dogruel M, Karaca M (2009) Climate change in Turkey for the last half century. Clim Change 94:483–502

Türkeş M, Sümer UM, Demir İ (2002) Re-evaluation of trends and changes in mean, maximum and minimum temperatures of Turkey for the period 1929–1999. Int J Climatol 22:947–977

Ulbrich U, Lionello P, Belušić D et al (2012) Climate of the Mediterranean: synoptic patterns, temperature, precipitation, winds, and their extremes. In: Lionello P (ed) The climate of the Mediterranean region: from the past to the future. Elsevier, London, UK and Waltham, MA, USA, pp 301–346

Unal Y, Kindap T, Karaca M (2003) Redefining the climate zones of Turkey using cluster analysis. Int J Climatol 23:1045–1055