Spatiotemporal dynamics of ecosystem services provision in a degraded ecosystem: a systematic assessment in the Lake Urmia basin, Iran

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Abstract

Lake Urmia has experienced severe environmental degradation, mainly characterized by the enormous reduction of its surface area and water level. This issue has been mainly attributed to land-use and land-cover changes, in particular related to agricultural expansion and intensification. In this study, we used the DPSIR framework (D: driving forces, P: pressures, S: states, I: impacts, and R: responses) to systematically describe the ecosystem service dynamics related to anthropogenic activities and climatic parameters in the region. We reviewed the literature and used remote sensing, agricultural, climatic and hydrological data together with expert knowledge to assess the main driving forces and pressures, resulting land-use transitions and their spatiotemporal impacts on ecosystem services and biodiversity using a matrix-based assessment approach. We identified population growth, economic incentives and climate change as the most important driving forces, leading to altered agricultural activities, numerous dam constructions and droughts. Since 1987 cropland areas doubled at the expense of bare soils and natural vegetation, the lake hast lost more than half of its surface area, urban and freshwater areas increased threefold and by 50%, respectively. This favored crop and freshwater provision, while all other ecosystem services remained nearly constant or decreased, though spatial patterns were heterogeneous. For example, regulating and cultural services, and biodiversity mainly decreased at the shorelines of the lake, while provisioning services increased along the major rivers and close to cities. To address the land-use transitions with the most profound impact on ecosystem service provision, we recommend the following measures: increase the water supply to the lake, reduce cropland expansion, manage existing croplands more sustainably and protect natural vegetation. Our study provides a comprehensive overview of the regional ecosystem service dynamics and a valuable baseline for future research and environmental management in the basin.

Keywords: Land-use transitions, DPSIR framework, cropland expansion, environmental management, climate change, lake shrinkage, salinization.

1. Introduction

Lake Urmia, located in northwestern Iran, is one of the largest natural permanent hyper saline lakes in the world, covering around 6,000 km^2 before 1989 (Torabi Haghighi et al., 2018). The lake provides important cultural, economic, aesthetic, recreational and scientific values (Abbaspour et al., 2012; Ahmadi et al., 2016). Due to the important role of the lake for biodiversity, it has been designated as a UNESCO Biosphere Reserve and a national park (Khatami & Berndtsson, 2013). In recent decades, the lake has been threatened by multiple anthropogenic activities, including expansion and intensification of agriculture, urban expansion, extensive construction of dams and other infrastructure (e.g. the 16 km long Kalantari causeway in the middle of the lake), as well as severe climate change-induced droughts (Alborzi et al., 2018). As a consequence, Lake Urmia faces a similar tragedy as the Aral Sea in Central Asia, which lost 90% of its water volume mainly due to the expansion of cotton cultivation (Micklin, 2007, 2010) with major impacts on the region's human capital. Today, the Aral Sea region has one of the highest rates of infant mortality in the world (Franz & Fitzoy, 2006). Likewise, the area of Lake Urmia decreased by more than 5,000 km^2 in the last two decades and the water level dropped from 1,277 m to 1,270 m above sea level (Tabari et al., 2012). During an extended drought period in the 2000s, the lake's water level even dropped below 1,270 m above sea level and more than 40% of the lake's bed was exposed (Lotfi, 2012). These changes and the underlying drivers have direct implications for the provision of ecosystem services (ES) and biodiversity in the entire basin.

Most existing studies on Lake Urmia have assessed the hydrological situation and ongoing changes in the water balance of the lake, including the anthropogenic and climatic factors of lake depletion related to human land and water resources management (e.g. AghaKouchak et al., 2015; Alizade Govarchin Ghale et al., 2018). Moreover, there is an ongoing debate whether the shrinkage of Lake Urmia is mainly driven by climate change or human overexploitation. Recent studies suggest that changes in precipitation and temperature alone cannot explain the dramatic decline of the lake's water level since 2000 (Khazaei et al., 2019) and that unsustainable agricultural practices are the main cause of lake shrinkage (Chaudhari et al, 2018). However, an in-depth assessment of the other related land-use transitions and their spatiotemporal implications for ES provision and biodiversity is missing. Historical data that would allow the calibration of models for multiple ES (including provisioning, regulating and cultural ones) for the past, however, are not available. At the same time, knowledge of the spatiotemporal patterns and changes of ES is urgently needed for land-use planning, environmental impact assessments and biodiversity conservation. A straightforward and rapid assessment strategy in such situations is the matrix-based assessment approach proposed by Burkhard et al (2009), which focuses on the known capacities of land-use/cover classes to provide ES. We also opted for the matrix-based approach here because it allows the integration of multiple views of experts and is often easier to explain to stakeholders or decision-makers. Despite its simplicity, the approach has proven its ability to target priorities and highlight management hotspots (Campagne et al., 2017).

Here, we provide a systematic overview of the socio-environmental dynamics, their impacts on ES provision, and potential strategies to address these impacts using the DPSIR framework (D: driving forces, P: pressures, S: states, I: impacts, and R: responses). In particular, we (i) reviewed the literature to identify the major driving forces and pressures of land-use and land-cover (LULC) change; (ii) used LULC data to describe the current state, (iii) linked this information to ES provision and biodiversity to assess spatiotemporal impacts, and (iv) identified the most profound LULC transitions that need to be addressed through various management strategies to foster a more sustainable provision of ES.

2. Data and Methods

2.1. Study region

The Lake Urmia basin is located in a mountainous area of northwestern Iran, encompassing the three provinces West Azerbaijan, East Azerbaijan and Kurdistan, at an altitude of 1,280 to 4,886 m above sea level. The basin covers 51,876 km^2, of which previously around 10% were covered by the lake (AghaKouchak et al., 2015; Hossein Mardi et al., 2018). The lake is fed by 17 major rivers, 12 seasonal rivers and 39 floodways passing through urban, agricultural and industrial areas (Hashemi, 2012). The annual average precipitation and evaporation rate ranges from 1,973 to 2,011 mm and 352 to 1,150 mm/year, respectively. The average air temperature varies between -20 to 0º C in the cold season and reaches up to 40 ºC in the warm season. Currently, the basin is inhabited by around 6 million people. Agriculture, horticulture, and animal husbandry are the most important economic sectors in the region (Delju et al., 2013). Cultivated products in the basin mainly include alfalfa, wheat, sugar beet, apples and grapes, while livestock includes sheep and cattle. Crop production in the basin relies on both rainfall and irrigation, thus farmlands are mainly located along the major streams (Faramarzi, 2012). Due to an exceptional richness in biodiversity, the lake has been designated as a UNESCO Biosphere Reserve in 1978 and a National Park in 2010 (Garousi et al., 2013).

2.2. The DPSIR framework

The driving forces, pressures, states, impacts and responses (DPSIR) framework conceptually incorporates the causal links that describe the interaction between environment and society (Stanners et al., 2007). Changes in the state of ecosystems, e.g. driven by global change processes that exert pressures on the environment, lead to responses that then feedback to driving forces and pressures (Kelble et al., 2013; Smeets, 1999). The DPSIR framework has often been used to identify cause-effect relationships between social, economic and environmental components of a system. It is also frequently applied as a management tool for complex environmental issues (Bradley & Yee, 2015). In this study, we used the framework to systematically describe drivers, pressures, states, impacts and responses related to LULC change, ES provision, and biodiversity in the Lake Urmia basin.

2.2.1. Driving forces and pressures

Driving forces or drivers are various natural or human-induced factors that force the system to change and that intentionally or unintentionally exert pressures on the environment. Direct drivers mostly refer to human demand for goods and services. Indirect drivers include the general social and economic situation (Burkhard and Müller, 2008). In this study, we identified the major demographic, socioeconomic and climatic driving forces in the basin, as well as the resulting pressures, based on existing studies (Gari et al., 2015; Smeets, 1999), regional statistical data and our own knowledge. To assess climatic driving forces, we calculated the Standard Precipitation Index (SPI) designed by Mckee et al. (1993) and the Streamflow Drought Index (SDI) developed by Nalbantis and Tsakiris (2009), using precipitation data provided by the Islamic Republic of Iran Meteorological Organization (IRIMO) and streamflow data provided the by Iranian Water Resource Management Company, respectively. For calculating drought indices we used the spi function in the R package SPEI (Beguería & Vicente-Serrano, 2017).

2.2.2. *State*

We focused on LULC change as the major indicator of the environmental state, as it affects most parts of the system (Liu et al., 2018; Song & Deng, 2017). Due to data and time limitations, we used existing LULC data covering five time steps (1987, 1998, 2006, 2011, and 2016) with a 30 m resolution to analyze temporal changes (Chaudhari et al., 2018). This data has been generated from Landsat 5-TM and Landsat 8-OLI imagery using an unsupervised classification approach (ISODATA algorithm) to differentiate seven LULC classes (water, shallow water, natural vegetation, clouds, cropland, bare soil, and urban areas). Finally, classified scenes were clipped with the watershed boundary. Chaudhari et al. assessed the overall accuracy of the 2016 classification using a confusion matrix at 82%, which corresponded to a kappa coefficient of 0.76. To better differentiate between cropland and natural vegetation, they used Landsat imagery acquired during the harvesting season in September (Chaudhari, 2017; Chaudhari et al., 2018). For our study, we slightly adapted the original water categories (water bodies and shallow water) to differentiate between the actual lake and other water bodies (Table A.1). More specifically, all water bodies within the combined lake boundary of all five time steps including a buffer of 2 km were assigned to the 'lake' class, while all remaining water bodies were assigned to 'other water bodies'. We then assessed temporal LULC changes and transitions as a basis for our impact assessment.

2.2.3. *Impact*

For assessing the impacts on ES and biodiversity resulting from LULC change, we followed the matrix-based assessment approach proposed by Burkhard et al. (2009). We focused on three provisioning ES (crop provision, livestock provision, freshwater provision), two regulating ES (water regulation, local climate regulation) and one cultural ES (recreation and ecotourism) as well as biodiversity (Table A.2), because these are particularly relevant for the study region. Due to variety of definitions for ES categories we compared our literature-based definitions with the newest version of CICES V5.1(Haines-Young & Potschin, 2018). Based on the literature (e.g., Burkhard and Maes, 2017), and specially expert opinions we estimated the relative capacity of each LULC class to provide various ES and biodiversity from 0 (no capacity) to 5 (maximum capacity). Therefore, we sent a questionnaire (by email) to 15 local experts (from local NGOs, institutions and universities). To derive a first matrix, we averaged their values assigned to each class and service. We finally sent the primary proposed matrix to five local experts, all holding a Ph.D. degree in environmental science (mostly with a focus on ecosystem services), to review and adjust the values to local circumstances. We used the median values resulting from the expert opinions of our second assessment (Table 1). Some of the weights we used are very specific to the situation in Lake Urmia. For example, the capacity of natural vegetation for crop provision relates to the use of alternative products (e.g. local medicinal herbs or acanthus harvesting) by locals. Since bare land also include vegetation and the new margins of the lake, these areas are also valuable for recreation and ecotourism. In addition, experts assigned the maximum value to the lake for climate regulating services because it moderates the temperature extremes. We then linked these values to the land-use data to derive ES provision for each time step and assessed the relative temporal changes. To identify spatial hotspots, we first subtracted the cell-specific ES values in 1987 from the values in 2016. In a second step, we spatially aggregated this difference by a factor of 100 taking cell sums and determined the 2.5% and 5% quantiles, i.e. the most negative values, as hotspots of losses and the 95% and 97.5% quantiles, i.e. the most positive values, as hotspots of gains. Finally, we calculated the effect of each LULC conversion on ES provision and biodiversity between 1987 and 2016 to identify the most critical transitions. Based on this, we discuss potential management strategies that affect these underlying land-use transitions. All analyses were performed in the statistical software package R 3.5.1 (R Core Team 2018).

Table 1. Matrix indicating the capacity of different LULC classes to provide selected ES and biodiversity based on literature, own and expert knowledge. 0 = no capacity, 1 = very low capacity, 2 = low capacity, 3 = medium capacity, 4 = high capacity and 5 = very high capacity.

	Crop provision	Livestock provision	Freshwater provision	Water regulation	Local climate regulation	Recreation and ecotourism	Biodiversity
Lake	0	0	0	3	5	5	4.5
Other water bodies	0	0	5	3	3	4.5	4
Natural vegetation	2	5	0	5	3	3	5
Cropland	5	3.5	0	3	2	2.5	2
Bare land	0	3.5	0	2	1	2	2.5
Urban	1	0	0	1	1.5	1	1.5

3. Results

3.1. Driving forces and pressures

We identified four major driving forces shaping the social-ecological dynamics in the Lake Urmia basin (Fig. 1). First, population constantly grew in the last decades from 2,664,069 in 1976 to 7,357,434 in 2016. One third of this strong increase can be attributed to the past ten years. Population growth was highest in the urban areas (Statistical Center of Iran, 2016). Second, many people recently migrated from rural to urban areas to seek better economic opportunities and welfare. For example, between 2011 and 2016 the annual average population growth rate in West Azerbaijan was 1.17% in urban and -0.33% in rural areas, while in East Azerbaijan growth rates were 1.72% and -0.8%, respectively (Statistical Center of Iran, 2016). Third, economic incentives, in particular related to agriculture, changed substantially in the past years. In this regard, the sugar beet industry increased its processing capacity from 700-1800 tons/day in 1996 to 1800-3500 tons/day in 2016 (Iranian Sugar Factories Syndicate, 2016). At the same time, the importance of other industries like fishing, shipping, ecotourism and health tourism decreased (Zarrineh & Azari Najaf Abad, 2014). Fourth, the regional climate substantially changed in the last decades. Annual mean precipitation dropped by 40% between 1967 and 2006, and the mean annual temperature has increased by about 1 ºC since 1998 (Ghale et al., 2018). Evaporation is strongly correlated with temperature. Accordingly, mean annual evaporation was at 1,319 mm in 1989 and reached a maximum amount of 1,338 mm in 2000 (Alizade Govarchin Ghale et al., 2018).

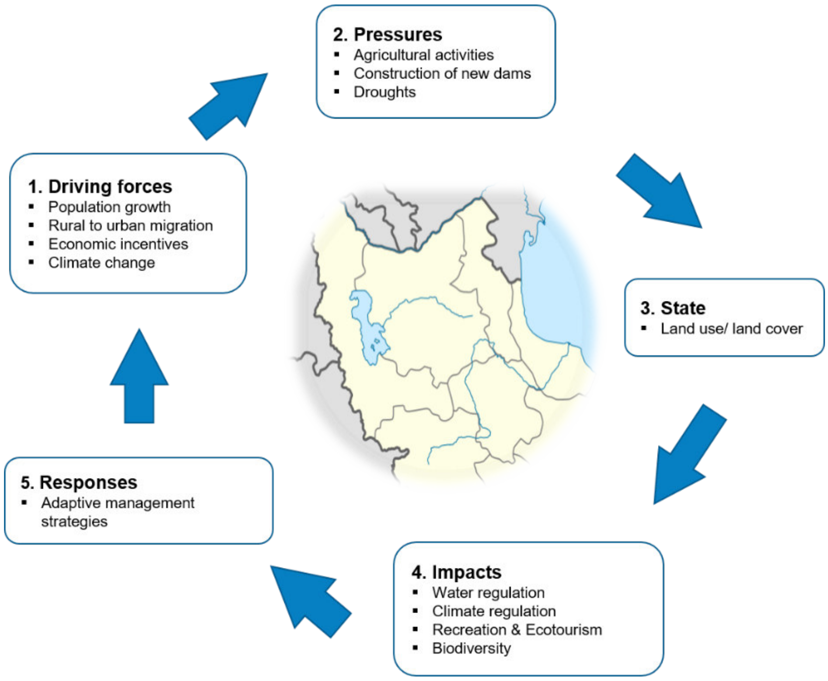

Figure 1: Driving forces, pressures, states, impacts and responses related to the provision of ecosystem services in the Lake Urmia basin (map source: Wikipedia).

The driving forces described above have led to three major pressures regarding regional land-use and climatic patterns. First, agricultural activities have substantially changed. The cultivation of water-intensive crops like sugar beet in West Azerbaijan increased around fivefold compared to 1987 (Fig. A.1). Water-intense horticultural products such as apple rose by around 53,158 ha from 2008 to 2015. The regional average net irrigation water requirement of sugar beet and apple is 639,300 and 592,300 m^3/km^2, respectively (Agricultural organization of Iran, 2016) and the production expansion therefore led to a substantial increase in water demand for irrigation. Second, 56 dams were constructed in the past decades, 9 are under construction and 37 are in planning to meet the rising water demands for agriculture (c. 75% of reservoir volume) as well as for drinking water production and industrial usage (c. 25% of reservoir volume) (Iranian Water Resources Management, 2018). Third, most climatic stations in the basin registered recurrent severe droughts since 1998. SPI values indicate severe droughts for the years of 1998-2002, 2008, and

2017 (Fig. A.2a). Due to some delay in hydrological dynamics following climatic events (low precipitation), streamflow was substantially reduced in 2000, 2001, and 2010, with the lowest value observed in 2016 (Fig. A.2b).

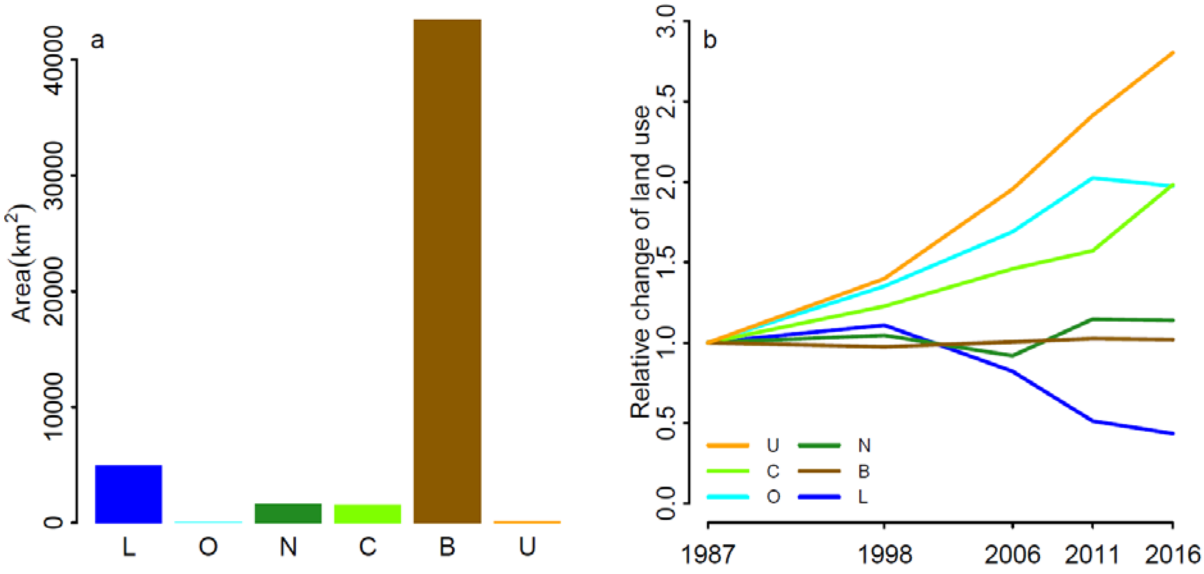

Figure 2: LULC in the Lake Urmia basin. (a) Area of different LULC classes in 1987 and (b) temporal changes of these classes relative to the area in 1987 (L = lake, O = other water bodies, N = natural vegetation, C = cropland, B = bare land, U = urban areas) (own calculations based on the data of Chaudhari et al., 2018).

3.2. State: LULC changes since 1987

Between 1987 and 2016, the urban area almost tripled from 132.8 to 372.3 km^2, while the highest rates of increase where observed from 1998 onwards (Fig. 2; Table A.3). This increase was mainly at the expense of bare lands in all periods (Fig. 3). Cropland nearly doubled in the study period and covered 3,102.4 km^2 in 2016, thus becoming the second most abundant LULC class (Fig. 2; Table A.3). The annual rate of increase was highest in the past five years (128.8 km^2), i.e. three to four times higher compared to the previous time periods (Table A.3). New cropland mainly originated from bare lands and natural vegetation (Fig. 3). Between 2011 and 2016, around one third of the existing natural vegetation was converted to cropland, reflecting substantially higher losses than in the previous time periods. In contrast, considerable amounts of cropland area degraded into bare lands; this concerned, for example, more than 20% of the croplands between 2006 and 2011. After a 10.9% increase between 1997 and 1998, the lake area subsequently decreased to 2,147.9 km^2, which is only 43.4% of its area in 1987 (Fig. 2; Table. A.3). The former lake area almost exclusively changed to bare lands (Fig. 3). Other water bodies doubled between 1987 and 2011 and slightly decreased in the past five years, but with 85.6 km^2 in 2016 represent the least abundant LULC class overall (Fig. 2; Table. A.3). The increment was mainly at the expense of bare lands and to a minor extent of other classes, e.g. natural vegetation (Fig. 3). Bare lands, covering 85.5 % of the basin in 2016, remained relatively constant in total area, but changed substantially in spatial location (Figs. 2 and A.3; Table. A.3). Changes between time periods mainly occurred between bare lands and natural vegetation, croplands and lake area (Fig. 3). Natural vegetation slightly increased over the entire study period, although there was a drop between 1998 and 2006 (Fig. 2; Table A.3). Gains between time periods resulted mainly from succession on bare lands and, to a minor extent, from the abandonment of croplands (Fig. 3).

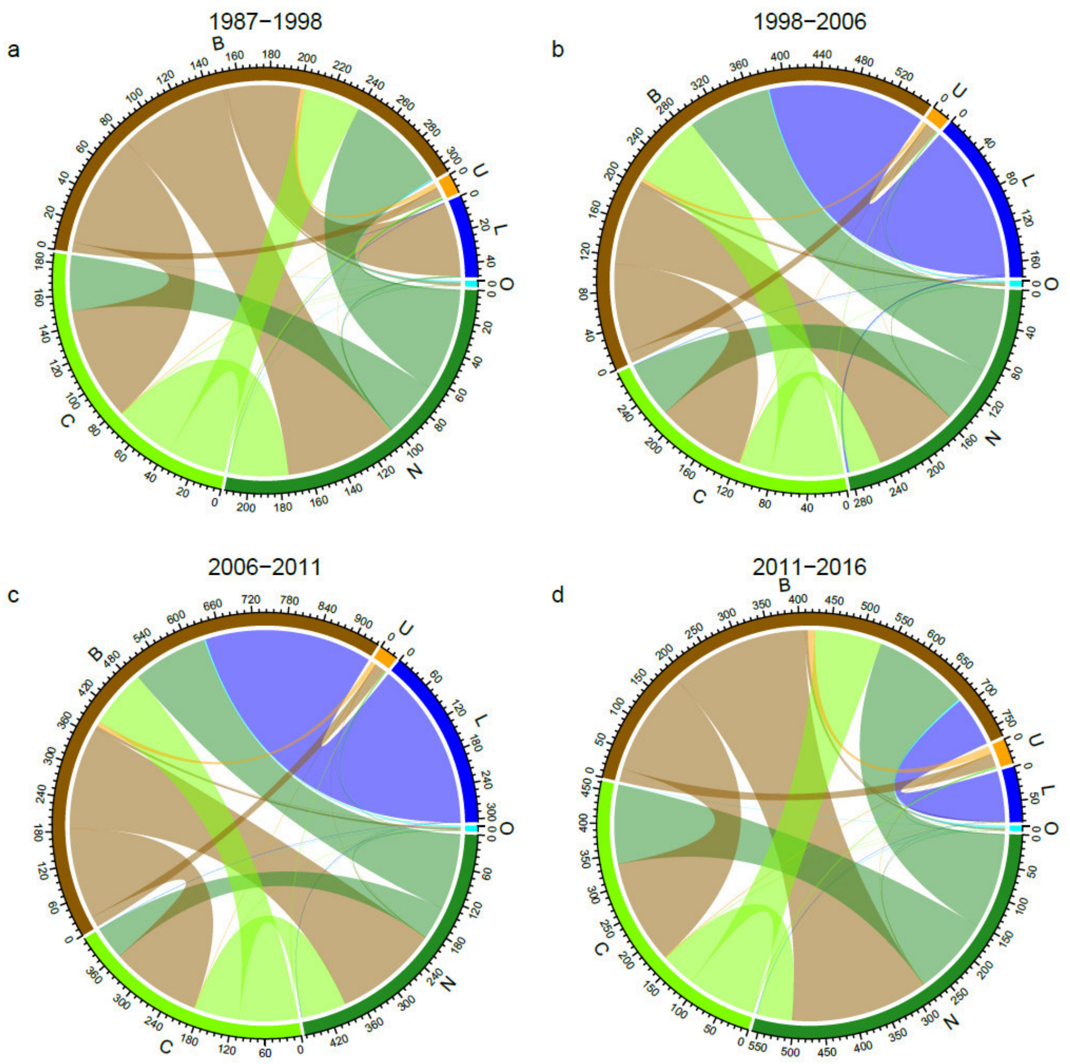

Fig. 3 Average annual transitions between different classes of LULC. Transitions are shown for (a) 1987-1998, (b) 1998-2006, (c) 2006-2011 and (d) 2011-2016 in km^2. Colors of the transition relate to the class of origin, e.g. a dark green transition indicates a change from natural vegetation to other classes (L = lake, O = other water bodies, N = natural vegetation, C = cropland, B = bare land, U = urban areas).

3.3. Impacts: changes in ecosystem service provision

The total capacity of crop provision in the Lake Urmia basin increased about 75% during the study period (Fig. 4). Freshwater provision nearly doubled, but slightly decreased within the last five years. All other services and biodiversity remained nearly constant during all time steps, except climate regulation experiencing a slight decrease since 1998. Spatial patterns of ES losses and gains, however, were highly variable (Fig. 5).

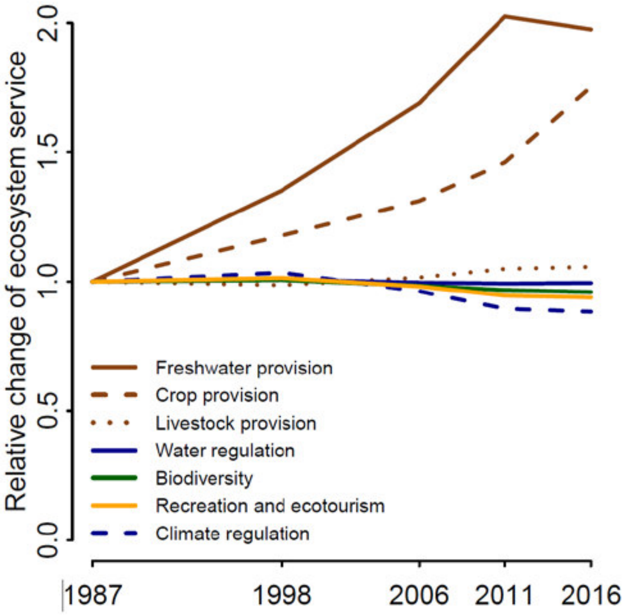

Fig. 4 Temporal change of total ecosystem service provision and biodiversity relative to 1987. Colors indicate ES category (brown = provisioning service, blue = regulating service, yellow = cultural service, green = biodiversity). For spatial variation of losses and gains see Fig. 5.

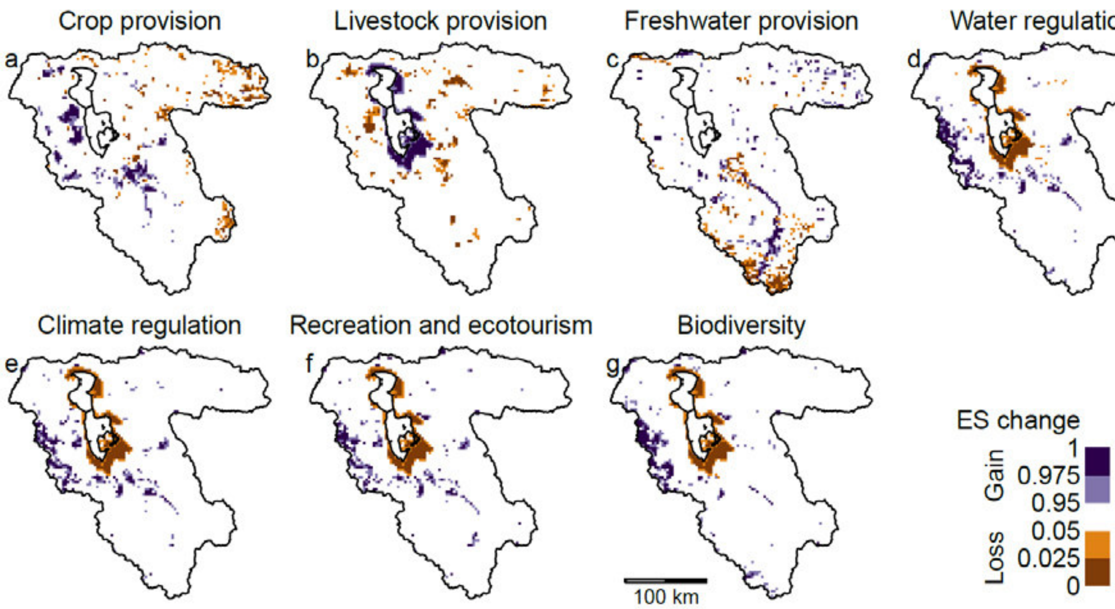

Fig. 5 Hotspots of gains and losses of ecosystem services and biodiversity in the Lake Urmia basin between 1987 and 2016. Hotspots were derived from the cell-specific ES values in 2016 minus the ES values in 1987. This difference was aggregated by a factor of 100 (3x3 km² cell size) taking pixel sums, and 2.5% (dark orange) and 5% (light orange) quantiles, i.e. the most negative values, were defined as hotspots of losses and the 95% (light purple) and 97.5% (dark purple) quantiles, i.e. the most positive values, as hotspots of gains. The lake boundary refers to the year 2016.

Crop provision largely increased along the western margins of the lake and close to Urmia city. Other hotspots of gain occurred in the central part of the basin and along its major rivers and other water bodies such as reservoirs (Fig. 5a). These gains were mainly at the expense of livestock provision, as the potential for livestock is lower in croplands than in natural areas (Fig. 5b; Table 1). The potential for livestock provision mainly increased along the southern margins of the lake, i.e. where the lake turned into bare land. The availability of freshwater provision substantially decreased in the very southern part of the basin, but increased in particular along the Zarrinehrood River and in other areas where new reservoirs were constructed (Fig. 5c). This river is the most important freshwater source in the region. All other services and biodiversity experienced substantial losses around the lake, as they are heavily dependent on it (Fig. 5e-g; Table 1). The gains show a high spatial overlap in particular in the western and central part of the basin, which is mainly due to the increase of natural vegetation and croplands.

Several LULC transitions negatively affected the provision of ES (Fig. 6). The transition from lake to bare land was responsible for more than 80% of the losses of recreation and ecotourism and climate regulation, as well as for around 55% and 41% of the losses of biodiversity and water regulation, respectively. The loss of natural vegetation and degradation to bare land yielded substantial losses for all services except freshwater provision. For the latter, the transition from other water bodies to bare land was most problematic. The conversion of natural vegetation to cropland was responsible for 29% of the loss of area for livestock provision and for 17% of the losses for both water regulation and biodiversity. In turn, the conversion of cropland to bare land was responsible for 50% of the reduction of crop provision. The bare land to urban transition was responsible for nearly one quarter of losses in the area for livestock provision. All other transitions were of minor relevance or only affected single services. Gains in water regulation were mainly related (61%) to the conversion from bare land to natural vegetation (Fig. A.4). The transition from bare land to other water bodies, finally, contributed to 87% of the gains in freshwater provision, while the transition from lake to bare land accounted for about 80% of the capacity gains for livestock provision. The conversion from bare land to croplands contributed to 62% of the gains in crop provision.

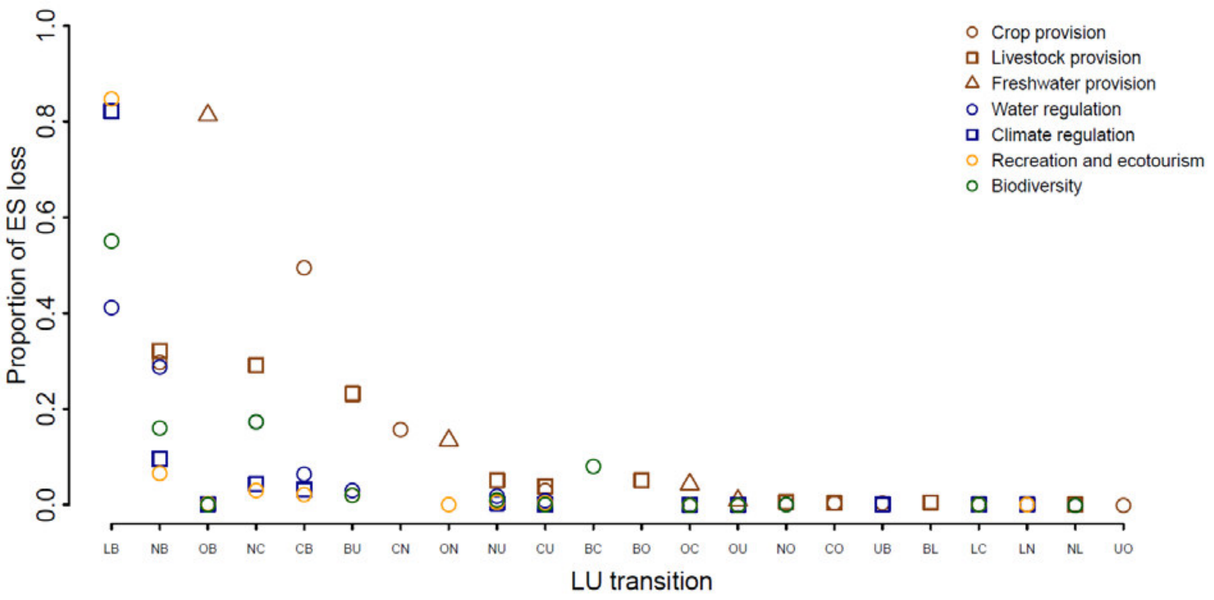

Fig. 6 The contribution of different LULC transitions to ES losses relative to total losses between 1987 and 2016 in the Lake Urmia basin. Transitions are ordered by the highest cumulative impacts across services (L = lake, O = other water bodies, B = bare land, N = natural vegetation, C = cropland, U = urban areas; the first letter indicates the LULC class in 1987 and the second letter the class in 2016, e.g., LB indicates a transition from lake to bare land).

4. Discussion

4.1. Unsustainable agricultural expansion and intensification

Agriculture plays a central role for ES dynamics in the Lake Urmia basin. On the one hand, croplands nearly doubled (Chaudhari et al., 2018), which negatively affected livestock provision and biodiversity that both rely on natural vegetation. This was triggered by population increases (Chaudhari, 2017) and because agriculture offered an important development opportunity after the Iran-Iraq war ended in 1988 (Rouw, 2017). On the other hand, unsustainable agricultural practices leading to excessive amounts of water use for irrigation are the main cause of the shrinking of Lake Urmia (Chaudhari et al., 2018), which in turn affects other ecosystem services (see below).

While this gain in crop production provides important economic benefits in the short term, it jeopardizes the long-term resilience of agricultural production due to its reliance on scarce water resources which is accelerated through climate change (Brodt et al., 2011), and will exacerbate environmental, social and economic problems. Similar issues have been observed in the Aral Sea basin, where vast increases in irrigated lands for cotton production have reduced the lake surface area to less than 20% of its former area (Micklin, 2007; White, 2013). Community level approaches including awareness raising are important strategies to address these problems and to advance environmental restoration (Ataniyazova, 2003). Thus, exchange and mutual learning from these experiences on the scientific, political and societal level would be beneficial for both the Lake Urmia and Aral Sea regions.

4.2. Impacts on other ES, biodiversity and human well-being

While we found that most ecosystem services and biodiversity remained constant over the entire region, we identified substantial spatial changes. Most importantly, the shrinkage of Lake Urmia is a major problem for the long-term provision of ES and biodiversity conservation in the basin. As a consequence, regulating services, recreation and ecotourism as well as biodiversity decreased where lake turned into bare land. The lake is a moderator of local and regional climate and essential for water regulation. Further degradation and LULC will thus have unforeseeable environmental consequences on a large scale. For example, altered evaporation may accelerate droughts and increase maximum temperatures, and different LULCs affect the surface albedo and therefore the regional climate and water cycle (Chaudhari, 2017; Fu, 2003; Sagan et al., 1979). The attractiveness of the lake for recreational activities, as well as the regional flora and fauna is directly linked to the ecological state of the lake (Stone, 2015). For example, increased salinity negatively influences *Artemia Urmiana* regeneration, a brine shrimp that provides a major food source for migratory birds. Furthermore, this restricts fishing and aquaculture activities in the region (Zarrineh & Azari Najaf Abad, 2014). In addition, the natural habitat of most species is severely threatened due to the growing area of salty soil and resulting emissions of dust and salt (Stone, 2015; Zarrineh & Azari Najaf Abad, 2014). The increase of dust and salt emissions also significantly affects human health, the quality of water resources and agricultural products (Hossein Mardi et al., 2018). Grazing along the shores of the lake as well as salt harvesting activities further intensify this problem (Alizade Govarchin Ghale et al., 2017). Similar cascading effects of lake shrinkage have been observed elsewhere. For example, a sharp reduction of the surface area of the Inle lake, the first Biosphere Reserve in Myanmar (Karki et al., 2018), due to deforestation and agricultural development, has negatively affected 44 ecosystem services and local livelihoods (ICIMOD and MONREC, 2017; Karki et al., 2018). Likewise, human activities around Lake Mead, the largest manmade reservoir in the United States, caused significant impacts on wildlife, biodiversity and recreation (Rosen et al., 2012).

The decrease of the lake area only positively affected livestock provision, as more potential areas for grazing became available. Although these areas are salty and temporarily flooded, they have already attracted local livestock keepers (Alizade Govarchin Ghale et al., 2018; Hossein Mardi et al., 2018; Zarrineh & Azari Najaf Abad, 2014).

Gains for regulation services, recreation and ecotourism, and biodiversity were mainly found in the western parts of the basin, because of the conversion of bare land to natural vegetation and cropland. Khazaei et al. (2019) argue that this might be related to CO_2 fertilization.

4.3. Management recommendations

Based on our identification of the most detrimental land-use transitions regarding ES provision, we suggest a set of general management strategies to address these changes (Table 2). These strategies provide a baseline with the aim to integrate a more comprehensive ES perspective into existing management programs, e.g. by the Urmia Lake Restoration National Committee (ULRC) that has, up to now, mainly focused on streamflow and water availability (ULRC, 2015).

Table 2. Recommended management strategies to address the most critical LULC transitions regarding their effects on ES.

Land-use transition addressed	Strategies to address these land-use transitions	ES positively affected	Specific effects on ES (examples)
Lake to bare land	I. Increase water supply of lake a. Avoid expansion of croplands (see below) b. Increase irrigation efficiency on the farm level c. Stop drilling new and deeper agricultural wells d. Consider the cultivation of less water demanding crops, e.g. damask rose, barberry, saffron e. Adapt water levels in reservoirs to account for seasonal water needs of the lake f. Stop new plans for dam construction g. Improve water circulation between north and south part of lake through channels in the Kalantari causeway h. Develop water and waste water treatment plans to reuse water II. Introduce drought and salt tolerant plants to increase vegetation cover at the margins of the lake (preventing salt and dust storms and diffusion to other parts of the basin) III. Develop protection plans for satellite wetlands around the lake	Recreation and ecotourism Local climate regulation Biodiversity Water regulation	- Maintenance of cultural values of the lake - Moderation of climatic parameters - Maintenance of natural habitat for wild life (e.g. migratory birds) - To maintain the balance of water resources
Natural vegetation to bare land	I. Prevent excessive livestock grazing (especially on lake shorelines)	Livestock provision Crop provision	- Increase of available biomass for livestock - Long-term maintenance of non-cultivated food provision

	II. Prevent illegal resource extraction such as excessive harvesting of subsidiary products (e.g. acanthus and local underground mushrooms) III. Define pasture and forest reserve plans in the southwestern, southeastern and southern parts of the basin IV. Control water harvesting from agricultural wells to sustain soil humidity (see above)	Water regulation Biodiversity Climate regulation Recreation and ecotourism	- Increase availability of water resources - Moderation of climatic parameters - Maintenance natural attraction of the system
Other water bodies to bare land	I. Improve irrigation efficiency II. Prevent human manipulation (expansion of farmland and construction of dams) in riversides III. Proper management of flood waters in streambeds IV. Plan comprehensive watershed management projects in Zarrinehrood and Siminehrood river basins V. Wetland preservation (see above)	Freshwater provision Recreation and ecotourism Biodiversity Water regulation Climate regulation	- Increase availability of water resources - Maintenance of the natural attraction of the system - Maintenance of natural habitat for wild life (e.g., aquatic specious) - To maintain the balance of water resources
Natural vegetation to cropland	I. Avoid expansion of croplands a. Zoning and strict enforcement of conservation and agricultural areas b. Increase long-term productivity of existing croplands c. Increase resilience of existing croplands e.g. through crop diversification (to reduce future demand for croplands) a. Develop non-agricultural industries in the basin (e.g. ecotourism)	Livestock provision Biodiversity Water regulation Climate regulation	- Increase of available biomass for livestock - Maintenance of natural habitat for wild life - To maintain the balance of water resources - To moderate climatic parameters - Maintenance of the natural attraction of the system

		Recreation and ecotourism	
Cropland to bare land	I. Monitor and improve soil quality in croplands, e.g. through cultivation of legumes II. Prevent soil erosion through more sustainable agricultural practices III. Prevent illegal and unsustainable land use changes to cropland at the margins of the lake IV. Decentralize welfare and services from cities to prevent migration to cities and thus land abandonment	Crop provision Water regulation Climate regulation Recreation and ecotourism	- Long-term maintenance of food production - To maintain the balance of water resources - To moderate climatic parameters - Maintenance of the natural attraction of the system
Bare land to urban areas	I. Prevent extensive migration to cities by decentralizing welfare and services from cities and by developing non-agricultural industries in the basin II. Reduce poverty to prevent illegal marginalization and spontaneous settlement at the urban margins III. Improvement of soil texture and infiltration of water to soil (e.g. increasing vegetation cover and carbon sequestration plans)	Livestock provision Water regulation Recreation and ecotourism Biodiversity	- Increase of grazing area for livestock - To maintain the balance of water resources - Maintenance of the natural attractions of the system - Maintenance of natural habitat for wild life (e.g. migratory birds)

4.3.1. Adoption of new agricultural practices

To increase the water supply to the lake and thus prevent the change from lake to bare lands, halting agricultural expansion is crucial. Positive further consequences of curbing agricultural expansion would be the maintenance of natural vegetation and the prevention of further biodiversity loss. Another highly relevant factor lies in unsustainable practices of irrigation. The efficiency of irrigation in Iran (33-37%) is clearly below the average for developing (45%)s and developed countries (60%) (Abbas Keshavarz et al., 2005). This is mainly related to surface irrigation of wheat, barley and alfalfa which dramatically increases evaporation. Due to this low efficiency, the agricultural sector uses almost 80% of the water resources in the basin while water use for the industrial sector is neglectable (A Keshavarz et al., 2003). Therefore, irrigation efficiency should be increased and the construction of new and deeper wells avoided. A recent development is the expansion of water-intensive sugar beet cultivation around Lake Urmia driven by the sugar industry which guarantees purchase. This change in cultivation seems to have similar negative consequences as the substitution of traditional crops by cotton and rice in the Aral Sea basin (Micklin, 2007). In this regard, a way forward would be to switch to the cultivation of less water-intensive crops (for examples see Table 2 Id). A further important factor shown by our analysis is that lake shrinkage increases the area available for grazing. However, grazing strategies need to be adapted to avoid overuse leading to land degradation and potentially to irreversible changes due to soil erosion (see also Notenbaert et al., 2012 on suitable policies to ensure biodiversity protection in East African grazing lands and Godde et al., 2018 on globally relevant trends in grazing systems with respect to grazing expansion and intensification).

4.3.2. New economic incentives and industries

Economic needs have forced farmers to expand their cultivation area to the margins of the lake. Therefore, identifying new and also alternative jobs for farmers according to the potentials of this region is urgently needed. There are innovative ideas for developing non-agricultural industries to stop the expansion of croplands and thus protect the lake and the natural vegetation, e.g. by using algae of the lake as biodiesel, bioethanol and methanol (Najafi et al., 2011), developing legal and eco-friendly salt harvesting and medicinal plant industries with sustainable harvesting and restoration. A further option could be the development of health tourism related to the medical value of the lake's mud, and ecotourism based on the unique landscape and culture of the region (Khatami & Berndtsson, 2013). By developing small industries, increasing recreational services, and improving educational opportunities in rural areas, new income sources could be generated. Apart from halting agricultural expansion, this could encourage people to stay in the countryside rather than migrating to urban areas.

4.3.3. Environmental restoration

The construction of channels in the Kalantari causeway is essential to improve the water circulation between the northern and southern part of the lake and to improve the environmental state of the lake and the basin (Karimzadeh et al., 2018; Zeinoddini et al., 2009) (Fig. A.5).

The establishment of riparian vegetation around the lake would limit the negative impact of storms in the shallow parts of the lake. Satellite wetlands around the lake could be better protected through monitoring and awareness raising. Moreover, artificial ponds and wetlands could be created, as it has been proposed for the delta and dry bed of the Aral Sea (Micklin, 2007).

We have to acknowledge that this set of proposed management strategies is rather general and formulated from our scientific perspective based on the results presented above. An important next step would be to specify these measures, ensure acceptance by the diverse set of local stakeholders, and to discuss their practicability and appropriateness. As experiences in other case studies on transforming systems to ensure sustainable resource use have shown, only a joint transdisciplinary endeavor which includes all relevant stakeholders such as local resource users, local authorities, and industry beside the scientists may lead to solutions which are accepted and fit the specific context. Guidelines on how to conduct such processes have been developed and experiences from good practice case studies can be taken up (e.g. Lang et al., 2012, Brandt et al, 2013). It would be a crucial next step, even though outside of the scope of this paper, to develop a plan for such a transdisciplinary process. The use of models and role-playing games can be helpful tools in this regard (cf. Whitfield and Reed, 2012 for an example of participatory environmental assessment in drylands and Lamarque et al, 2014 on the use of role-playing games to explore farmers' cognition on ecosystem services in a French case study).

4.4. Limitations and future research

We used general LULC classes to assess spatiotemporal dynamics and their implications for ES provision, which fail to fully discriminate different land-use practices. Using a wide range of LULC classes would lead to more differentiated results, although optimal classification schemes, e.g. for lakes, rivers and wetlands, are difficult to obtain (Ma et al., 2012). The matrix approach is suited to detect general trends for multiple ES directly linked to LULC. However, the following shortcomings have to be acknowledged: processes beyond LULC are not included; there are no standardized units/scale for the ES values, which hampers comparability with other studies; and the quality of the results depends on the quality of regional data and the experience of experts (Burkhard et al., 2009; Montoya-Tangarife et al., 2017). In our study, the ES values assigned to different LULC classes are based on a limited number of experts. To confirm our results, the matrix could be reevaluated by other experts (Montoya-tangarife et al., 2017; Vihervaara et al., 2010) and additional services could be included. This would also ensure the integration of different disciplines (e.g. ecology, engineering and social sciences) and viewpoints. For future studies, we also recommend to use alternative and more comprehensive approaches to assess ES dynamics in the region. Models like InVEST (Raudsepp-Hearne et al., 2010), MIMES (Boumans et al., 2015) and ARIES (Villa et al., 2009) are promising ways forward in this regard. Biodiversity assessments should differentiate effects across taxa and need to include information about landscape configuration (e.g. fragmentation). The economic valuation of ES dynamics identified and the impacts on human wellbeing merit future attention. As agriculture directly or indirectly affects the environmental and socio-economic dynamics in the region, potential ways to reduce the dependency on the agricultural sector and to improve its resilience need to be investigated. Finally, the identification of leverage points by engaging relevant stakeholders is urgently needed for awareness raising and to facilitate the detection of suitable ways to support a more sustainable management of ES in the region in the long term.

5. Conclusion

To our knowledge, our study provides the first comprehensive overview of the most important spatial and temporal changes of ecosystem service provision and their underlying forces in the Lake Urmia basin. It is hence a valuable baseline for future research and environmental management in the area. Agricultural production plays a central role in the environmental and socio-economic dynamics of the Lake Urmia basin. Population growth and economic incentives have increased the demand for agricultural products. This is reflected in the doubling of the cropland area between 1987 and 2016, as well as altered agricultural activities, including intensification and widespread cultivation of water-intensive crops. This, in turn, alters the system dynamics in three ways. First, it directly reduces natural vegetation and thus negatively affects biodiversity, recreation and ecotourism. Second, it reduces the water supply to the lake contributing to the enormous reduction of the surface area. This has heavily degraded regulating and cultural services and biodiversity. Third, it undermines the long-term resilience of agricultural production, which heavily depends on scarce water resources. Given the dependency of the region on the agricultural sector, this may entail devastating socio-economic consequences in the future. Consequently, sustainable management of the basin depends on profound changes of the agricultural sector, which should be a top priority for decision makers in the region. In particular, we recommend (i) reducing cropland expansion, (ii) increasing irrigation efficiency, and (iii) incentivizing the cultivation of less water-demanding crops alongside with environmental restoration. If implemented, the proposed strategies will support a more comprehensive management plan for the region and will pave the way for ensuring the sustainable provision of multiple ecosystem services.

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Appendix:

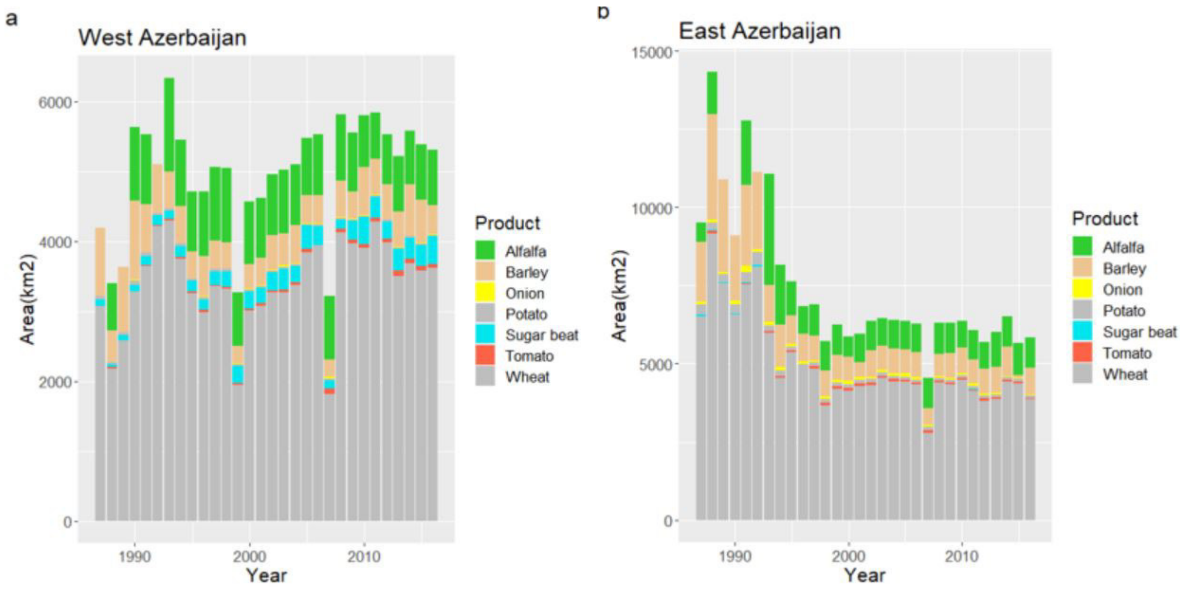

Fig. A.1 Agricultural products cultivated in the Lake Urmia basin. The area is shown for West (a) and East (b) Azerbaijan (km2) in 1987-2016 (data source: Agricultural organization of Iran, 2016). Note that the area includes the totally cultivated area including dry farming and irrigated lands.

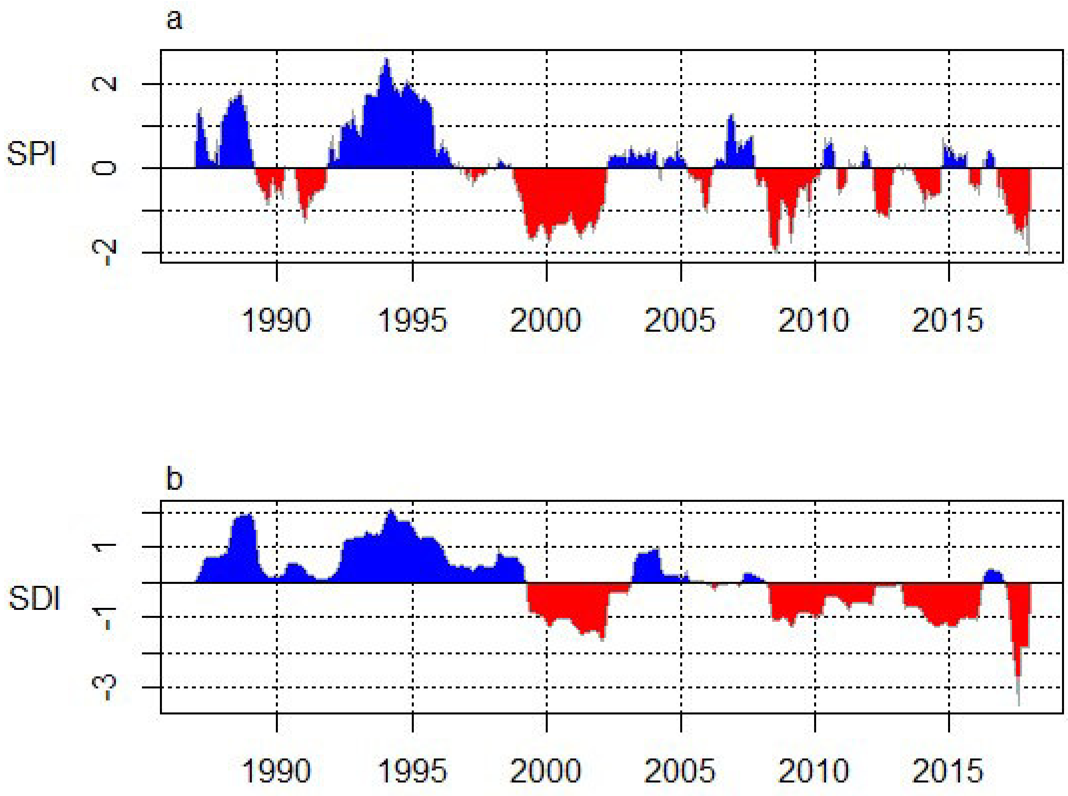

Fig. A.2 Climatic driving forces in the Lake Urmia basin. (a) Standard Precipitation Index (SPI) (data source: Islamic Republic of Iran Meteorological Organization (IRIMO), 2017). (b) Streamflow Drought

Index (SDI) between 1986 and 2017 (data source: Iranian Water Resource Management Company, 2017).

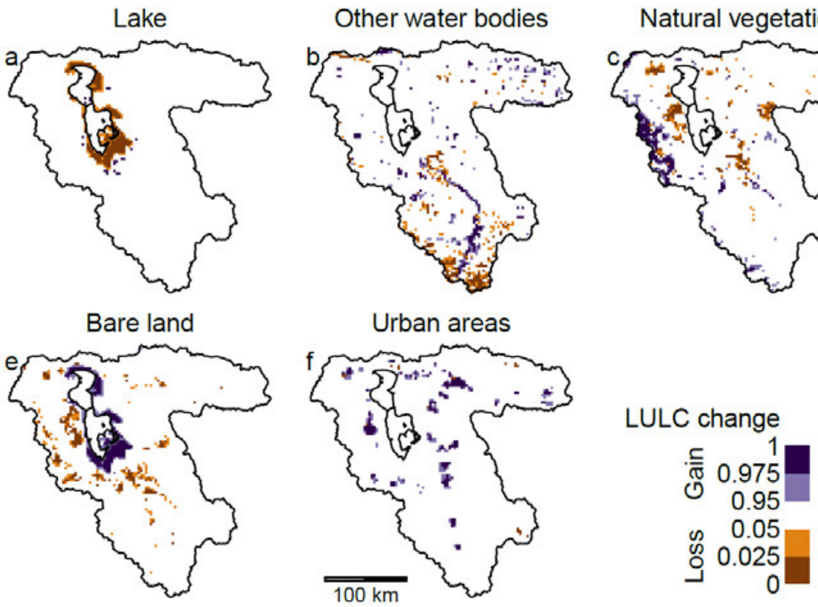

Fig. A.3 Hotspots of gains and losses of LULC classes in the Lake Urmia basin between 1987 and 2016. Hotspots were derived from the cell-specific ES values in 2016 minus the ES values in 1987. This difference was aggregated by a factor of 100 (3x3 km² cell size) taking pixel sums, and 2.5% (dark orange) and 5% (light orange) quantiles, i.e. the most negative values, were defined as hotspots of losses and the 95% (light purple) and 97.5% (dark purple) quantiles, i.e. the most positive values, as hotspots of gains. The lake boundary refers to the year 2016.

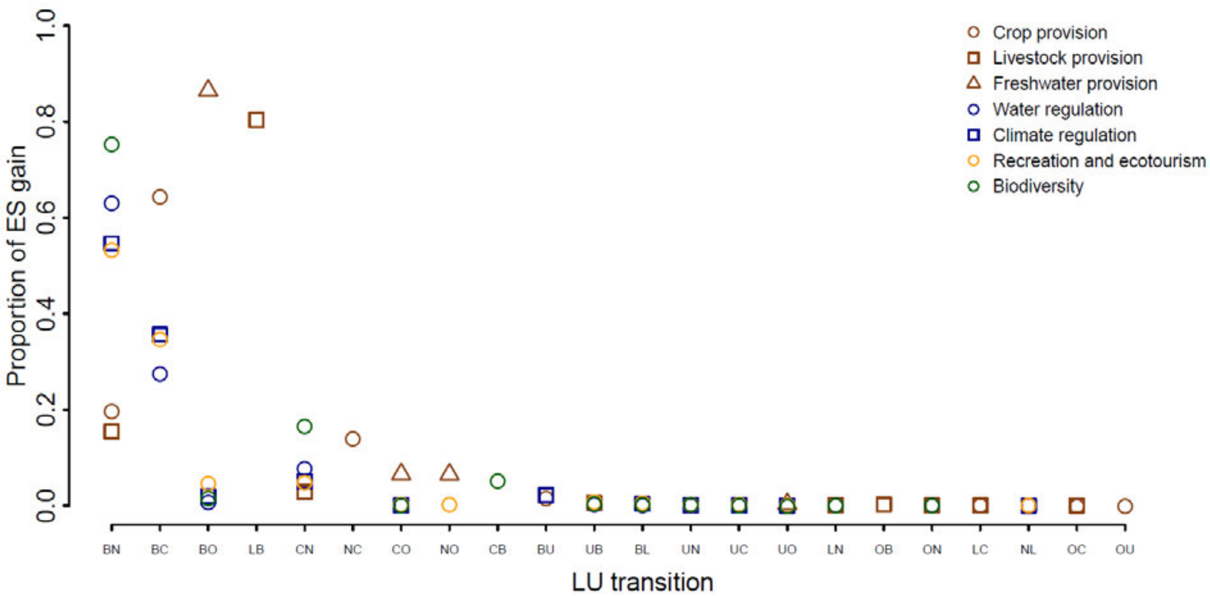

Fig. A.4 The contribution of different LULC transitions to ES gains relative to total gains between 1987 and 2016 in the Lake Urmia basin. Transition are ordered by the highest cumulative impacts across services (L = lake, O = other water bodies, B = bare land, N = natural vegetation, C = cropland U = urban areas; the first letter indicates the LULC class in 1987 and the second letter the class in 2016, e.g., BN indicates a transition from bare land to natural vegetation).

Fig. A.5 Lake Urmia and the Kalantari causeway. (a) Satellite image of Urmia lake in 2016 (figure source: https://earthobservatory.nasa.gov/images/88395/red-lake-urmia) (b) Location of the causeway in the middle of the lake (figure source: https://earthobservatory.nasa.gov/images/88395/red-lake-urmia) (c) Kalantari causeway (figure source: http://www.nasrnews.ir/News/tabid/243/ArticleID/33687/).

Table A.1 Description of adopted LULC classification and original classes in Chaudhari et al (2018).

LULC Type (used in this paper)	**Original classes in** (**Chaudhari, 2017**)	**Description**
Lake	Water bodies / shallows within total lake boundary plus a buffer of 2 km	Total saline water of lake
Other water bodies	Water bodies / shallows outside the lake area	Inland waters excluding the lake and including streams and reservoirs
Natural vegetation	Natural vegetation	Natural vegetation and rangelands with good vegetation cover
Cropland	Croplands	Irrigated croplands and orchards
Bare land	Bare soil	Mainly areas with poor vegetation cover including rangelands and dry farming
Urban areas	Urban areas	Human settlements and industrial areas

Table A.2 Description of ecosystem services considered and biodiversity. Our classification was adapted from CICES V5.1.(Haines-Young & Potschin, 2018)

Category	Short name	Description in the context of this study	CICES code	CICES definition
Provisioning	Crop provision	The provision of agricultural products (e.g. food, fodder and bioenergy) from managed agricultural systems and, to a minor extent, food harvested from unmanaged systems (e.g. wild plants)	1.1.1.1	Cultivated terrestrial plants including any crops and fruits growing by humans for provide food or from unmanaged systems
	Livestock provision	The provision of fodder for livestock from vegetation that is harvested or from land that is directly grazed (e.g. rangelands)	1.1.3.1	Livestock raised in housing and/or grazed outdoors
	Freshwater provision	The provision of various freshwater resources that are used by humans (e.g. as drinking water or for irrigation)	4.2.1.1	Surface water including various freshwater resources that are used by humans (e.g. as drinking water or for irrigation)
Regulating & Maintenance	Water regulation	The natural regulation of the water cycle and the prevention of floods by ecosystems (e.g. by forests)	2.2.1.3	Regulation of baseline flows and extreme events including hydrological cycle and water flow regulation(flood control, and coastal protection
	Local climate regulation	The regulation of local climatic parameters (e.g. temperature, precipitation, radiation and wind) by an ecosystem (e.g. cooling effects of water bodies)	2.2.6.2	Micro and regional regulation of atmospheric composition and condition including regulation of temperature and humidity
Cultural	Recreation and ecotourism	The natural features (e.g. a lake) that provide opportunities for recreation and ecotourism	3.1.1.1 3.1.1.2	Characteristics of a natural system which provide opportunities for enjoyment and promoting community health through active or passive (observational) interactions with natural system
NA	Biodiversity	The provision of natural habitat for biodiversity (e.g. wetlands for migratory birds)	NA	NA

Table A.3 Area of different land use classes in different years (km^2).

LULC	1987	1998	2006	2011	2016
Lake	4946.30	5486.06	4065.33	2535.59	2147.87
Other water bodies	43.34	58.58	73.25	87.79	85.59
Natural vegetation	1586.79	1659.39	1457.94	1819.54	1807.25
Cropland	1563.94	1918.96	2283.13	2458.37	3102.37
Bare land	43449.44	42352.82	43667.56	44544.57	44287.91
Urban areas	132.78	185.69	259.71	320.53	372.31