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Sustainability challenges for the social-environmental systems
across the Asian Drylands Belt

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Supplementary material for this article is available [online](#)

Abstract

This paper synthesizes the contemporary challenges for the sustainability of the social-environmental system (SES) across a geographically, environmentally, and geopolitically diverse region—the Asian Drylands Belt (ADB). This region includes 18 political entities, covering 10.3% of global land area and 30% of total global drylands. At the present time, the ADB is confronted with a unique set of environmental and socioeconomic changes including water shortage-related environmental challenges and dramatic institutional changes since the collapse of

the Union of Soviet Socialist Republics. The SES of the ADB is assessed using a conceptual framework rooted in the three pillars of sustainability science: social, economic, and ecological systems. The complex dynamics are explored with biophysical, socioeconomic, institutional, and local context-dependent mechanisms with a focus on institutions and land use and land cover change (LULCC) as important drivers of SES dynamics. This paper also discusses the following five pressing, practical challenges for the sustainability of the ADB SES: (a) reduced water quantity and quality under warming, drying, and escalating extreme events, (b) continued, if not intensifying, geopolitical conflicts, (c) volatile, uncertain, and shifting socioeconomic structures, (d) globalization and cross-country influences, and (e) intensification and shifts in LULCC. To meet the varied challenges across the region, place-based, context-dependent transdisciplinary approaches are needed to focus on the human-environment interactions within and between regional landscapes with explicit consideration of specific forcings and regulatory mechanisms. Future work focused on this region should also assess the role of the following mechanisms that may moderate SES dynamics: socioeconomic regulating mechanisms, biophysical regulating mechanisms, regional and national institutional regulating mechanisms, and localized institutional regulating mechanisms.

1. Introduction

The Asian Drylands Belt (ADB) covers over 15 million km² of land area, including 30% of global drylands. Despite being mostly landlocked, this region contains several important migration and trade routes, including the Silk Road, which connects east Asia to the west (Chen *et al* 2015a, Gutman *et al* 2020). These connections mean the ADB has played a key role in human civilization and societal development (Banuazizi and Weiner 1994, Diamond 1997, Hansen 2012, Chen *et al* 2020). The ADB is also an ecologically, socioeconomically, and institutionally diverse region. From a biophysical perspective, the region contains different biomes (e.g. grassland, forest, desert, and tundra) and climates. Culturally, the ADB contains many ethnic groups with different traditions, languages, and livelihoods. Over time, the component countries of the region have experienced numerous major geopolitical and economic changes, including transition to market driven governance, widespread institutional shifts, armed conflicts, rapid urbanization, and intensified land use/conversions have collectively, dramatically and (in)directly changed the structure and function of the social, economic, and ecological systems (de Beurs and Henebry 2004, Schleussner *et al* 2016, Park *et al* 2017, Gutman *et al* 2020).

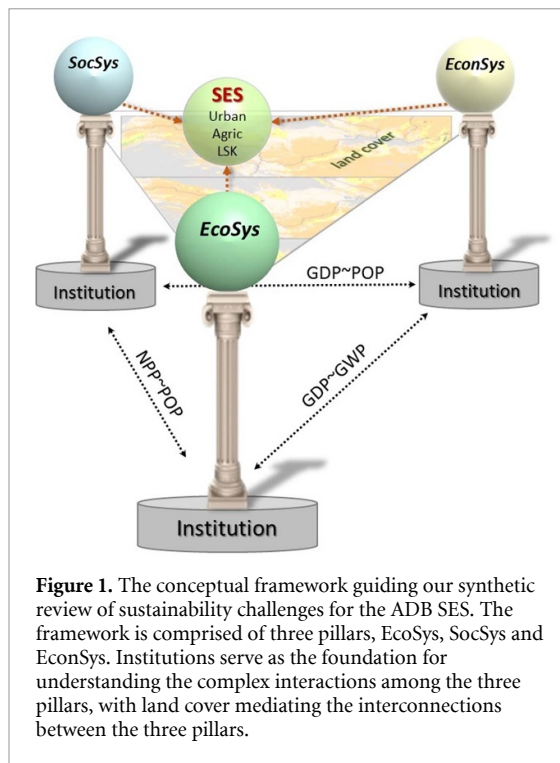
In recent decades, the ADB has experienced geopolitical, environmental, social, and institutional changes including several major geopolitical conflicts, rapid warming, drying trends (e.g. the desiccation of the Aral Sea), harsher winters (i.e. dzuds) affecting livestock mortality, international conflicts over water resources, and institutional shifts (e.g. from centrally-planned to open market economy). Many of these changes are rooted in climate change, which is generating new challenges in both the ecosystems (Thakur *et al* 2020) and the livelihoods of indigenous

pastoralists. These coinciding changes have introduced unique challenges to the social-environmental systems (SESS) in the region, with significant implications for future sustainability (table S2 available online at stacks.iop.org/ERL/17/023001/mmedia).

Given these changes, the goal of this synthesis paper is to review contemporary challenges to the sustainability of the ADB and outline areas for future research to overcome these challenges. To achieve this overarching goal, we examine the ADB as a macro system (i.e. national and regional scales) and apply the concept and principles of social-environmental (aka social-ecological) systems and sustainability science. In the following sections, we outline the organizing framework for the paper (section 2); next, we provide details on the unique biophysical, socio-economic and geopolitical context of the ADB (section 3); we then quantitatively examine the interconnections among selected features of the three pillars (section 4). Based on the historical changes and interdependencies of SES elements, we outline future research to examine five key threats to sustainability across the ADB (section 5).

2. Organizing framework: SESS

Figure 1 outlines the organizing framework for this paper, which is based on the three pillars of sustainability science: social system (SocSys), economic system (EconSys), and ecological/environmental system (EcoSys) (Wu 2013, 2021, Chen *et al* 2015a). Institutions (e.g. policy shifts, geopolitical conflicts) are the foundation of each of these pillars, which recognizes their direct or indirect influences on each of the elements of this tripartite framework (Ostrom 1986, North 1989, Chen *et al* 2015b). This is especially important to recognize for the ADB because of the continued intensive and widespread geopolitical conflicts across the region since WWII (table S2).



Examples of important geopolitical events include wars in Afghanistan, Iraq, Iran, and Syria, as well as the breakup of the former Union of Soviet Socialist Republics (USSR), which led to the formation of several newly independent states in Europe and Central Asia. Several studies find strong and distinctive relationships among SES variables at the national and provincial levels due to institutional shifts (Gutman and Radeloff 2016, Seto and Ramankutty 2016, Allington *et al* 2018, Chen *et al* 2018, Amartuvshin *et al* 2021).

Based on this framework, a SES is comprised of social, economic and ecological/environmental elements. It also includes the institutions and processes that impact each of these elements, as well as the feedback effects between each of the three pillars (Hansmann *et al* 2012, McGinnis and Ostrom 2014, Colding and Barthel 2019, de Vos *et al* 2019). In the analysis that follows, we will explore the dynamics of each pillar across the ADB, as well as the interactions between the component systems (Clark and Dickson 2003, Mensah 2017). In our analysis of the ADB SES, we consider land use and the corresponding land cover change (LCC) as mediating variables in modeling and understanding SES dynamics, because functional changes in macrosystems can be reflected in land use and LCCs (LULCCs) (Chen *et al* 2013, Gutman *et al* 2020).

3. State and changes of the ADB

The ADB region is in the heart of the Eurasian continent (approximately 30° N–55° N, 30° E–120° E) and covers 10.3% of global land area that extends

westward from Mongolia to the Mediterranean Sea (Qi *et al* 2017, Groisman *et al* 2018, Gutman *et al* 2020). It is home to more than 645 million people (8.6% of the global population). For the purposes of this review, we divided the ADB into 18 primary political entities (PEs): Afghanistan (AF), Kyrgyzstan (KG), Kazakhstan (KZ), Tajikistan (TJ), Turkmenistan (TM), and Uzbekistan (UZ) in Central Asia (CA); Mongolia (MN) and six Chinese provinces, namely, Gansu (GS), Inner Mongolia (IM), Ningxia (NX), Qinghai (QH), Tibet (TB), and Xinjiang (XJ) in East Asia (EA); and Iran (IR), Iraq (IQ), Jordan (JO), Syria (SY), and Turkey (TK) in the Middle East (ME) (figure 2 and table S1). The six Chinese provinces are treated as separate PEs because they are large in area and are distinct from the rest of China in terms of geography, climate, and economy (table S3) (Qi *et al* 2017, Groisman *et al* 2018, Gutman *et al* 2020). It is worth noting that IM, XJ and TB are autonomous regions; four neighboring PEs (i.e. Israel, Lebanon, Kuwait, and Pakistan) are not always considered part of the ADB but are included as separate PEs in this review.

3.1. Biophysical conditions

The ADB is bounded by a boreal forest biome to the north and high mountains (e.g. Himalayas) to the south (figure 2). In the southwest it borders the drylands of west Asia. The majority of the ADB is characterized by continental climate (i.e. hot summers and cold winters) due to its distance from the Pacific and Atlantic Oceans and its separation from the Indian Ocean by the Himalayas. Areas along the coasts of the Black Sea and Eastern Mediterranean Sea in Turkey, Syria, Lebanon, and Israel have a Mediterranean climate (i.e. dry summers and mild, wet winters). Because the region receives less moderating influences from the oceans (Groisman *et al* 2018), its spatial and temporal variations in climate are higher than in neighboring land areas. Extreme climatic events have been reported across this region (e.g. heatwaves, droughts, cold winters, sandstorms, flooding) (Mildrexler *et al* 2006, Groisman *et al* 2018, Chen *et al* 2020, Qu *et al* 2020). On average, the ADB region receives annual precipitation of 306 mm and loses 248 mm via evapotranspiration (ET), resulting in approximately 58 mm water to recharge its soils, streams, and groundwater (table S3). Due to this high fraction of evaporative water loss (~81%), drought events are common and widespread, as indicated by an average palmer drought severity index (PDSI) value of −0.47 (note that PDSI is a relative value to the long-term mean; Alley 1984).

The ADB also has exhibited signs of a warming climate over the past 140 years (figure 3). Annual surface air temperature anomalies during 1880–2020 in the ADB crossed the zero ordinate in 1950, which was 10 years before the crossing of the global annual temperature anomaly in 1960. The deviation to the

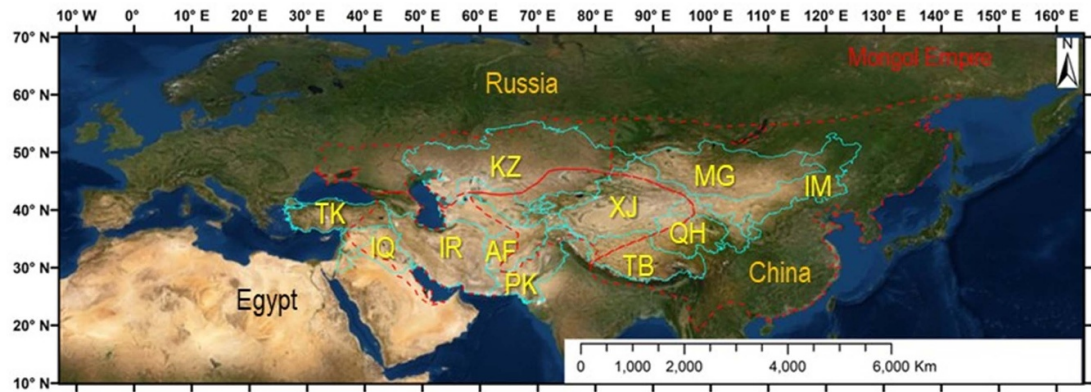


Figure 2. Distribution of PEs within the ADB. Solid cyan lines are the boundaries of PEs and dashed red lines show the territories of the Mongol Empire (www.arcgis.com/home/item.html?id=0d86d9cd628f4b4bb9ba647beb20470a; see table S1 for abbreviations). Note that not all PEs are labeled for their locations.

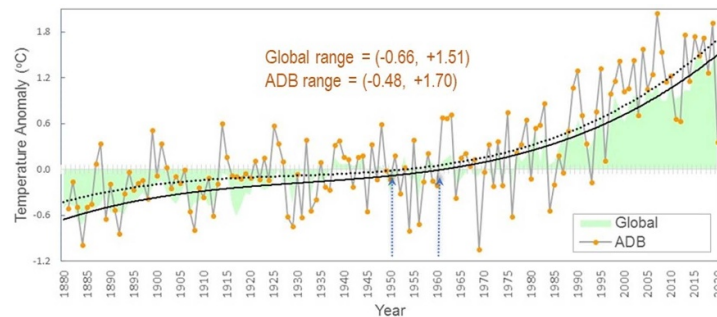


Figure 3. Change in anomalies of surface air temperature ($^{\circ}\text{C}$) for global land and the ADB during 1880–2020 (www.ncdc.noaa.gov/cag/). A cubic polynomial function was used to create the trend lines for the ADB (dashed line) and global (solid line) anomalies.

long-term mean in 1880 was -0.483°C for the ADB and -0.655°C for the globe, but 1.70°C and 1.51°C , respectively, in 2020, resulting in temperature anomalies of 2.17°C during the 140 year period. The difference in these warming trends appears to start in 1980, resulting in a warming rate of 0.244°C for the ADB and 0.215°C per decade for the globe. More importantly, interannual variations in temperature are much higher for the ADB region than for the rest of the world. Although three-quarters of the ADB area experienced no significant trend in mean annual precipitation (MAP), approximately 12.8% of the ADB lands experienced a drying trend and 8.8% of the lands showed a wetting trend (Groisman *et al* 2018, Chen *et al* 2020). There is high spatial variation in long-term changes in temperature and precipitation: only 7.1% of the lands in Tibet and northern Mongolia showed no significant changes in annual temperature during 1961–2016.

There are several major ‘hotspots’ of warming, including the Gobi Desert, the Taklamakan Desert spreading westward to the Caspian Sea, the Arabian Desert, and most countries in the Middle East. While over 90% of the land in East Asia and nearly 75% of Central Asia and the Middle East show no significant

changes in precipitation, the remaining lands in Central Asia show a tendency of increased MAP, and the Middle East shows a drying trend. There are hotspots of wetting in the northeast Mongolian Plateau, western Tibet, and coastal Mediterranean regions, and drying hotspots in central Tibet, Central Asia, and western Turkey. The phenology of grasslands is also generally moving under climate change. Ren *et al* (2018) revealed that during 2000–2015 the start of the growing season in typical steppes and desert steppes significantly advanced by 2.2–10.6 d, and the end of the growing season in desert steppes also significantly advanced by 6.8 d (see also Tang *et al* 2015, Bao *et al* 2019). In the Central and Western Tian Shan mountain ranges, Tomaszewska and Henebry (2018) found significant changes in snow seasonality since 2000 that were not unidirectional across the region, but longer snow cover was linked to higher pasture productivity in the subsequent growing season (Tomaszewska *et al* 2020).

3.2. Social context

From socio-demographic and sustainability perspective, the ADB is characterized by lower population density (POP_d), gross domestic product

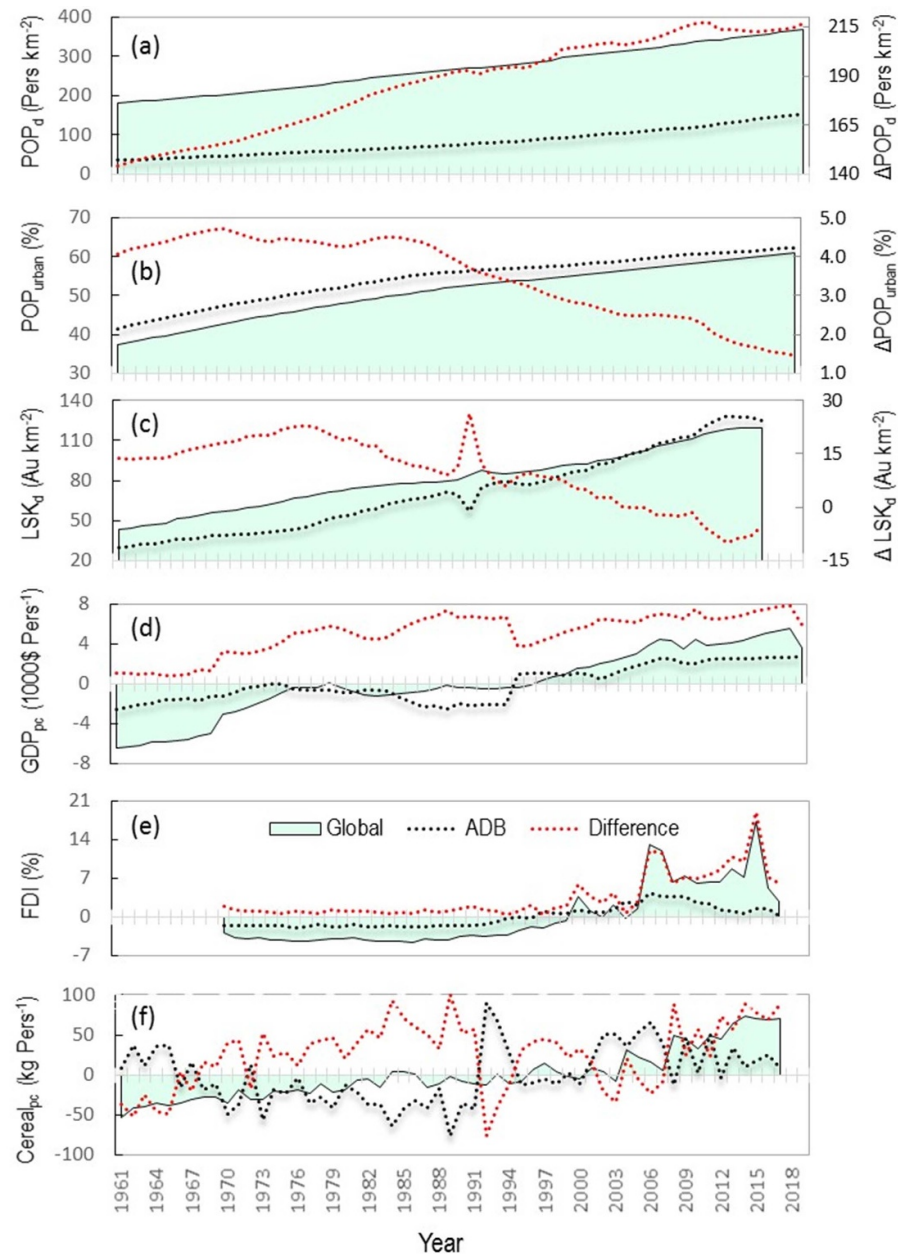


Figure 4. Long-term changes in socioeconomic indicators (means, anomalies, and the differences between the ADB and the world). The means and anomalies were calculated for the 12 PEs of the ADB (i.e. by excluding the six provinces in China due to a lack of historical data) and for 217 countries around the world (excluding Macão), which resulted in different values than reported in table S1. Data were downloaded from the World Bank (<https://databank.worldbank.org/home.aspx>) on 21 February 2021. The mean values are used for (a)–(c), whereas anomalies are used for (d)–(f).

per capita (GDP_{pc}), life expectancy index (LEI), and sustainability index than the global average (note that mean values of all countries for the globe and the ADB were used). The region does have a slightly higher than average urban population, but with large variation among the 18 PEs and the three subregions. Based on World Bank data (1961–2020), POP_d increased from 35.6 in 1961–152.5 $Pers\ km^{-2}$ in 2018 for 12 of the 18 PEs (excluding those in China). In contrast, the global average POP_d increased from 179.8 to 364.9 $Pers\ km^{-2}$ during this period, resulting in a narrower gap of 217.0 $Pers\ km^{-2}$ in 2018. During this period, the difference in POP_d between the

ADB and the global averages increased at a higher rate during 1961–1990 than during the last three decades (figure 4(a)). Interestingly, the percentage of urban population (POP_{urban}) within the ADB has been historically higher than the global average, ~4% higher before 1990, although the difference has declined since then to ~1.5% (figure 4(b)). LEI was 72 years in 2017 for ADB, compared to 72.4 years globally (table S3). Livestock density (LSK_d) as a proxy indicator of livelihood vitality for the nomadic community (Qi *et al* 2017) in the ADB was substantially lower than the global average until 2004. After 2004 the livestock density of the ADB exceeded the global average. In

the most recent decade (2010–2020), the LSK_d for the ADB was on average 4.5 Au km^{-2} higher than the global average (figure 4(c)).

3.3. Economic context

To better understand the dynamics in economic conditions, we explored long-term economic trends after adjusting purchasing power parity and inflation for GDP (see <https://data.worldbank.org/indicator/PA.NUS.PPP>). The average GDP_{pc} of the ADB was \$7048 per capita in 2017, 42.5% of the global average (\$16 588 per capita). This difference has been growing since 1961, when the ADB's average GDP_{pc} was 78.3% of the global average (figure 4(d)). The difference in GDP_{pc} was relatively stable ($\sim \$1000$) between 1961 and 1968 but was elevated to $> \$6700$ in 1994 and $\$7700$ in 2017. In terms of foreign direct investment (FDI), both the ADB and countries around the globe experienced an increase since 1994; the ADB exhibited a lower rate of increase, however (figure 4(e)). Over the last two decades, the average FDI was 10.6% for the globe and 3.7% for the ADB. Interestingly, during three years of global FDI peaks, in 2006, 2007, and 2017, the ADB exhibited no such spikes, showing decoupled trends. Finally, production has fluctuated over last six decades. In 1961 cereal production per capita was $225.1 \text{ kg Pers}^{-1}$ for the ADB, compared to the global average of $188.6 \text{ kg Pers}^{-1}$. This higher value in the ADB continued until 1965, when the global average started increasing steadily, with an accelerated increase in the past 15 years. Across the ADB, average cereal production per capita declined during 1966–1992, increased in the mid-1990s, and has declined since 2007, while the global average increased during 2007–2017. During this decade, the global and ADB average was 299.2 and $234.3 \text{ kg Pers}^{-1}$, respectively, yielding a net difference of $64.9 \text{ kg Pers}^{-1}$.

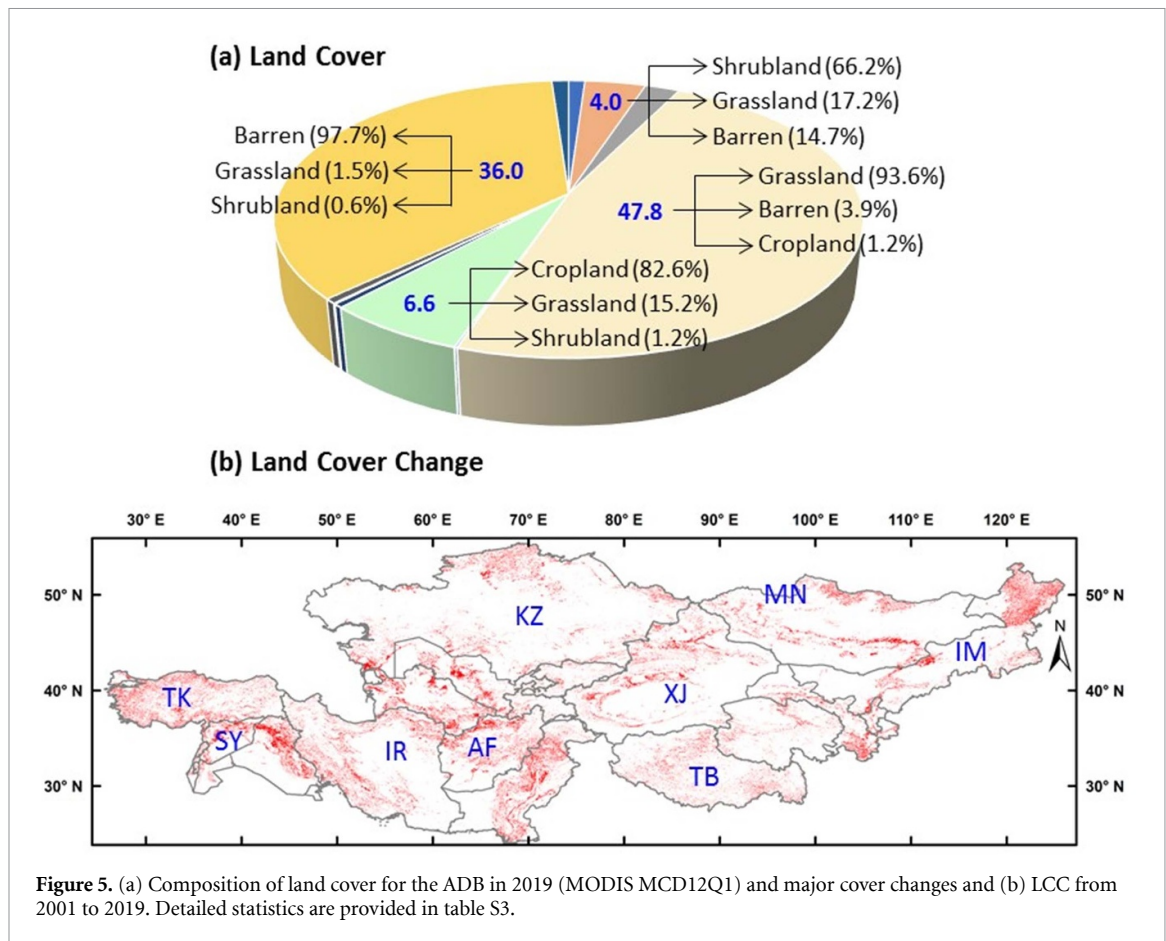
3.4. LCC

The land cover of the ADB in 2020 is primarily composed of grasslands (47.8%), barren land (36.0%), croplands (6.6%), and shrublands (4.0%), totaling 94.4% of $15.4 \text{ million km}^2$ (figure 5). Other cover types account for $< 1\%$ of the ADB (table S4). Among the four dominant types, shrublands experienced the most dramatic changes during 2001–2019 (i.e. 66.2% remains), followed by croplands (82.6%), grasslands (93.6%), and barrens (97.7%). Both the composition and changes varied substantially across the region and among the 18 PEs. More importantly, LCC needs to be viewed by cover type and country. For example, 15.2% of the croplands (total = $153 688 \text{ km}^2$) changed to grasslands, and 1.2% of the grasslands (total = $87 486 \text{ km}^2$) changed to croplands during the same period (figure 5(a)), resulting in a net grassland gain of $66 201 \text{ km}^2$ between the two cover types. The net gain/loss becomes more complicated when other cover types are included in

our analysis because, for example, substantial barrens and shrublands were converted to grasslands. When LCC is tallied for the ADB, $\sim 10.3\%$ of the lands ($1.22 \text{ million km}^2$) changed their cover type during the 18 year study period ($67 615 \text{ km}^2 \text{ year}^{-1}$). On average, 10.3% of the total land experienced cover change, with Kyrgyzstan experiencing $> 15\%$ of the cover change, whereas Qinghai, Kazakhstan, and Jordan showed $< 5\%$ of the changes. Across space, the LCC are more pronounced at transitional zones of biomes, such as the eastern end of the Gobi Desert, the border region of Turkey–Syria–Iraq, an intensively managed area with a major policy shift in northern Kazakhstan, and formerly irrigated farmlands in Turkmenistan and Uzbekistan (figure 5(b)).

3.5. Historical/geo-political context

From a geopolitical perspective, the ADB region is of great importance because of its geographic location between Europe, Russia and China (Grousset 1939, Lattimore 1940, Weiner and Banuazizi 1994, Golden 2011, Graham *et al* 2021). Due to its location, the region has been influenced economically, socially and politically by a variety of empires. The Achaemenid Persian Empire controlled the lands west of the Himalayas during the years 550–330 BCE, but the campaigns of Alexander the Great during 334–323 BCE took over control of these territories; they became the Seleucid Empire after Alexander's death in 323. Parthians later gained control of much of Central Asia and the Middle East, ruling an empire there from 247 BCE to 224 CE. The growing power of Rome around the Mediterranean put them into conflict with Parthia, but also brought them a greater knowledge of the lands and the goods of Asia. When the Roman Empire began its reign in 27 BC, it also had control over the western part of the ADB, but Parthia kept it from expanding further east. The Roman Empire lasted until 476 CE; it was brought low by waves of invasions, successive movements of people driven from northeast to southwest by climate change, in north Central Asia in particular. By this time Parthian territories were ruled by a different Persian dynasty, the Sassanids (224 BCE to 651 CE), until the mid-7th century when Islamic conquests began. Islamic conquests in Asia gained momentum during the Abbasid Empire, from 750 to 1258 CE. In the early 13th century the Mongol Empire began expanding and became the sole government that controlled the entire ADB and beyond for over 100 years; it is noteworthy that this wave of invaders from north Central Asia put an end to the lingering Abbasid Empire when it sacked Baghdad and ended the Islamic Golden Age. The Ilkhanate Empire (1256–1335 CE) was the subset of the Mongol Empire that controlled the Middle East, while the Timurid (founded in 1370 in Central Asia) ruled fluctuating boundaries and overlapped with the Ottoman Empire (1300–1919). This focused on modern-day Turkey and controlled the majority of



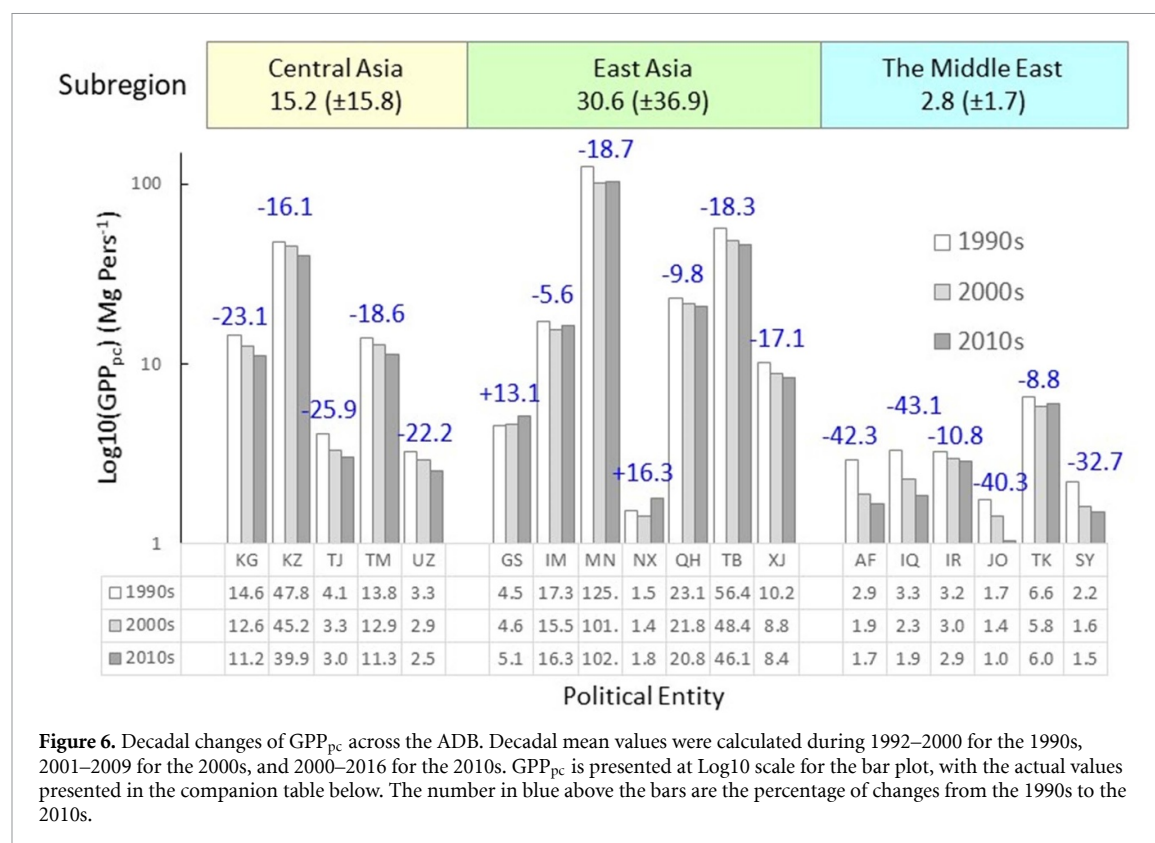
the ADB until the Russian Empire's expansion from the northeast (1721–1917).

By 1920 the current Central Asia and Middle Eastern portions of the ADB were divided into smaller Turkish and Iranian states, mandates of Italian, French, and British Empires. The 'Russian' portion of Central Asia was included in the USSR. From the east, the Chinese Empire started its growth in 138 BCE, by trading with early Persian empires through the establishment of the ancient Silk Road between the west and east, and by the 1st dynasty of Qin (221–206 BC), half of Rome's annual production was traded with the Chinese on this route (Beckwith 2009). Conflicts between the Han Chinese and other ethnic groups (e.g. Hsung-Nu, Mongols) flared for over 2000 years, and the Great Wall in northern China was constructed as a direct consequence of these conflicts. The rise of the Tibetan Empire in the 14th century added additional complexity among the Chinese, Ottomans, and others. Tibet, Qinghai, Xinjiang, Ningxia, Gansu, and Inner Mongolia have been provinces of China since 1644. In contrast, the five countries in Central Asia (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan) were republics of the USSR from the 1920s until it formally dissolved in 1991. In the west, Israel and Lebanon became independent after WWII, with ongoing conflicts between Israel and neighboring Islamic countries. In sum, the ADB served as a major commercial and cultural center and route

that influenced the civilizations of the region and the world (Frankopan 2018, Chen *et al* 2020). Today, one can find Christian churches, Muslim mosques, and Jewish synagogues next to each other in the western parts of the ADB, whereas between western China and Central Asia, Buddhism, Daoism, Islam, and even Russian Orthodoxy coexist in typical cultural landscapes. The settlement of Jewish migrants in Kaifeng of China during 960–1127 remains visible and influential in modern China (Beker 1998). In contrast, monuments in Mongolia remind us of the Turkish influence since the mid-7th century (Hanks 2010).

4. Interdependent dynamics of SocSys, EconSys and EcoSys

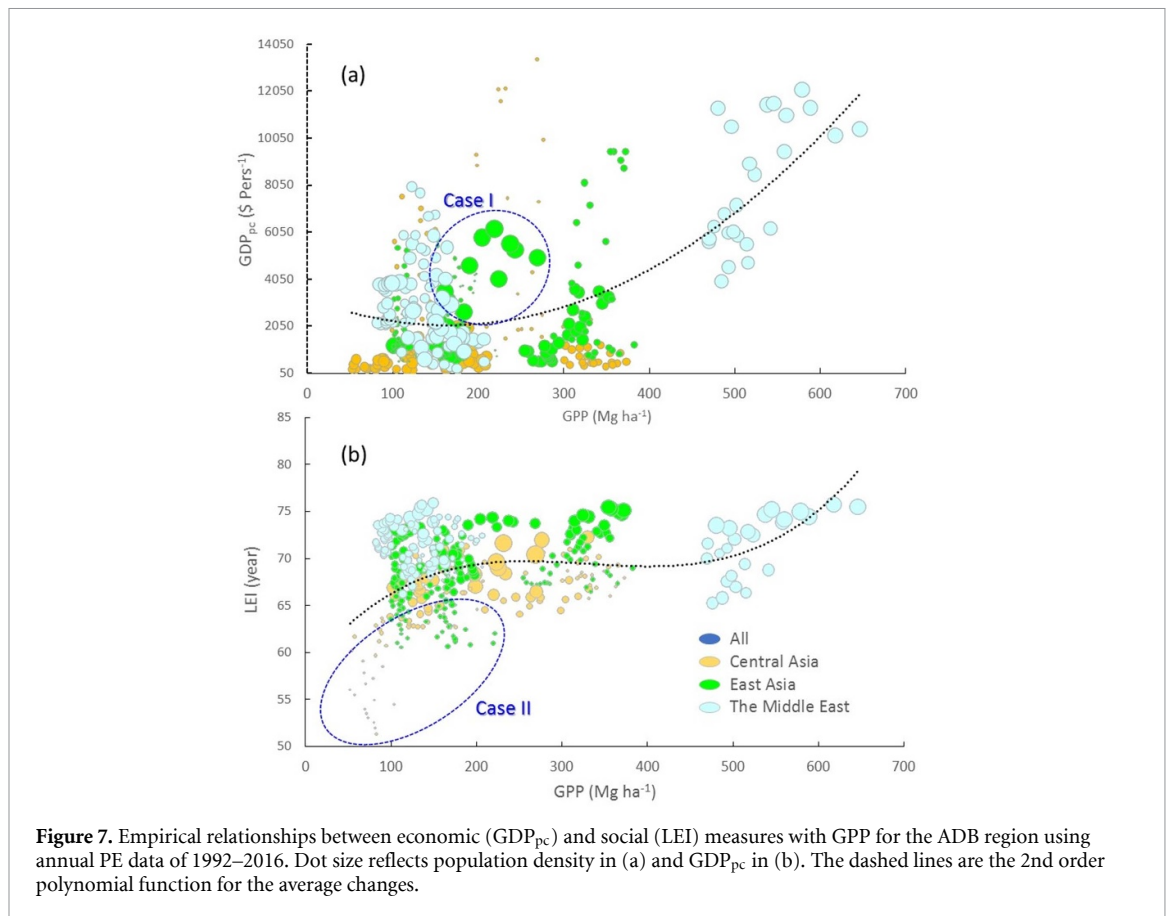
Classical measures of SocSys, EconSys, EcoSys, land use, and institutions reflect partial properties of a SES (table S3), but none can fully express system behavior. A few metrics have considered coupled information, such as GDP_{pc} and GPP per person (Vitousek *et al* 1986, Chen *et al* 2015b), and recent efforts have been made to include measures of all three system pillars (Hickel 2020, Chen *et al* 2021). Here we selected a few key variables from the three subsystems and explore their empirical changes, albeit strong correlations do not always indicate causal relationships. To understand the coupled dynamics of EcoSys and SocSys, we calculated the decadal GPP per capita between 1992



and 2016 by PE (figure 6). The mean ($\pm$ SD) GPP_{pc} of the ADB region over the 26 year study period was 17.2 ± 27.0 Mg Pers⁻¹. Among the three subregions, the mean ($\pm$ SD) GPP_{pc} was the highest for East Asia (30.6 ± 36.9 Mg Pers⁻¹), intermediate for Central Asia (15.2 ± 15.8 Mg Pers⁻¹) and the lowest for the Middle East (2.8 ± 1.7 Mg Pers⁻¹). However, GPP_{pc} of the PEs varied from 0.94 Mg Pers⁻¹ for Jordan in 2016–150 Mg Pers⁻¹ for Mongolia in 1994. Large differences within subregions are also evident. In Central Asia, Kazakhstan had the highest GPP_{pc} (44.3 Mg Pers⁻¹) while Uzbekistan and Tajikistan had significantly lower values (2.9 and 3.5 Mg Pers⁻¹, respectively). For East Asia, Mongolia, Tibet, and Qinghai had high GPP_{pc}, likely due to their lower population densities (table S3), whereas Ningxia's low GPP_{pc} was due to its low GPP. In the Middle East, Turkey had the highest GPP_{pc} (6.1 Mg Pers⁻¹), while others maintained at <3.3 Mg Pers⁻¹. Iraq, Afghanistan, and Jordan experienced $>40\%$ GPP_{pc} reduction from the 1990s to the 2010s, followed by Syria (32.7%). Cautiously, it is critical to see the large differences in GPP and GPP_{pc}, which suggests that examinations of their relationships with other SES measures may not truly reflect coupled dynamics. An alternative is to assess the relative changes over a specified time period using the earliest number as the reference when comparing the changes among PEs.

To further explore the socioeconomic dependencies on ecosystems within the ADB, we examined the relationships between our indicators of SocSys and EconSys with EcoSys. We found a weak correlation

between (SocSys and EcoSys) and (EconSys and EcoSys), but this varied by decade (i.e. 1990s, 2000s, 2010s) and organization level (i.e. region, subregion, PE, and provincial levels). Here we present the effects of changes of GDP_{pc} and LEI with GPP on the relationship between economic and environmental conditions (figure 7). There was a positive relationship between GDP_{pc} and GPP (figure 7(a)), indicating that economic development may be potentially dependent on natural conditions that are partially measured by GPP. A positive relationship was evident when data from each subregion was pooled. It appears that PEs with low population densities were more likely to be above the trend line. This perhaps indicates that PEs with fewer population pressures (e.g. high population density, low resources, or their combinations) are more likely to have higher GDP_{pc} for the same level of GPP. However, this trend is subject to large variation, as some PEs with high population densities were also observed to be above average, suggesting that the GDP_{pc} $\sim$ GPP relationship is further complicated by other physical and human processes. For example, several data points above the trend line with high population density (case I) are from Tibet and Xinjiang in the 2010s, when China promoted oil/gas industries or provided special economic incentive assistance to these provinces (Wang and Wei 2004). Similarly, there appeared to be an overall positive relationship between LEI and GPP amid high variations among subregions and PEs. This suggests that the natural conditions partially and positively influenced LEI of the ADB over the past three decades, although high



LEI can be achieved under low GPP and other physical and socioeconomic variables (figure 7(b)). However, it is evident that PEs with low GDP_{pc} had a much higher chance of being below average, as is illustrated by Afghanistan and Turkmenistan (i.e. case II), which experienced harsh geopolitical conflicts, climate change (figure 3), and/or LCC (section 5.1) during the study period.

The interdependencies of SocSys, EconSys and EcoSys also varied by organization scale (e.g. administrative levels). Here we demonstrate these differences by using the changes in livestock density (LSK_d) with GDP_{pc} and ET from three countries where we had collected provincial data from the 2016 annual statistics (figure 5). Strong exponential relationships were found showing that LSK_d decreased with GDP_{pc} but increased with ET, with a few exceptions, such as Orkhon, home of a large mining site, and Ulaanbaatar, the capital city, in Mongolia (case III). Advanced infrastructure in these two city-driven aimags promoted the livestock industry, and their populations account for nearly 50% of the national total (i.e. lowered GDP_{pc}) (Amartuvshin *et al* 2021). These unique combinations of economic and population density explain their outlier positions along the $LSK_d \sim GDP_{pc}$ gradient. Nevertheless, these results confirm that livestock has been decreasing in importance in the national economy, again with exceptions. Livestock density in Kazakhstan was much lower

than in Mongolia and Uzbekistan, suggesting a great potential to increase livestock density there, especially since Kazakhstan has a much higher portion of grasslands (85%) and GPP (255.9 Mg ha^{-1}) than Uzbekistan (40.4%, 129.4 Mg ha^{-1}) and Mongolia (63.5%, 181.9 Mg ha^{-1}). The overall higher economic stature (table S3) may devalue livestock development in Kazakhstan, but the accelerating demand for dairy products from neighboring Russia and China may promote its livestock economy (Qi *et al* 2017). Economic and environmental influences on livestock density are obvious in 2016 for these PEs, but it is not known yet if these influences are similar for other countries. If not, efforts are needed to build different models, with PE-specific regulatory mechanisms. In inner Mongolia, for example, the Chinese central government implemented a series of grassland conservation projects since 2000 to include all cover types (Xue *et al* 2021), which brought critical changes and challenges to rural livelihoods. For example, the comprehensive Subsidy and Incentive System for Grassland Conservation program (2011) was designed to reward herders, even in undegraded grasslands, as long as they maintained the balance of grassland carrying capacity and livestock (Liu *et al* 2019, Xue *et al* 2021). However, the compensation does not make up the loss of market value (Hu *et al* 2019), and local governments face increasing costs for administration (Liu *et al* 2019), which is generating conflicts

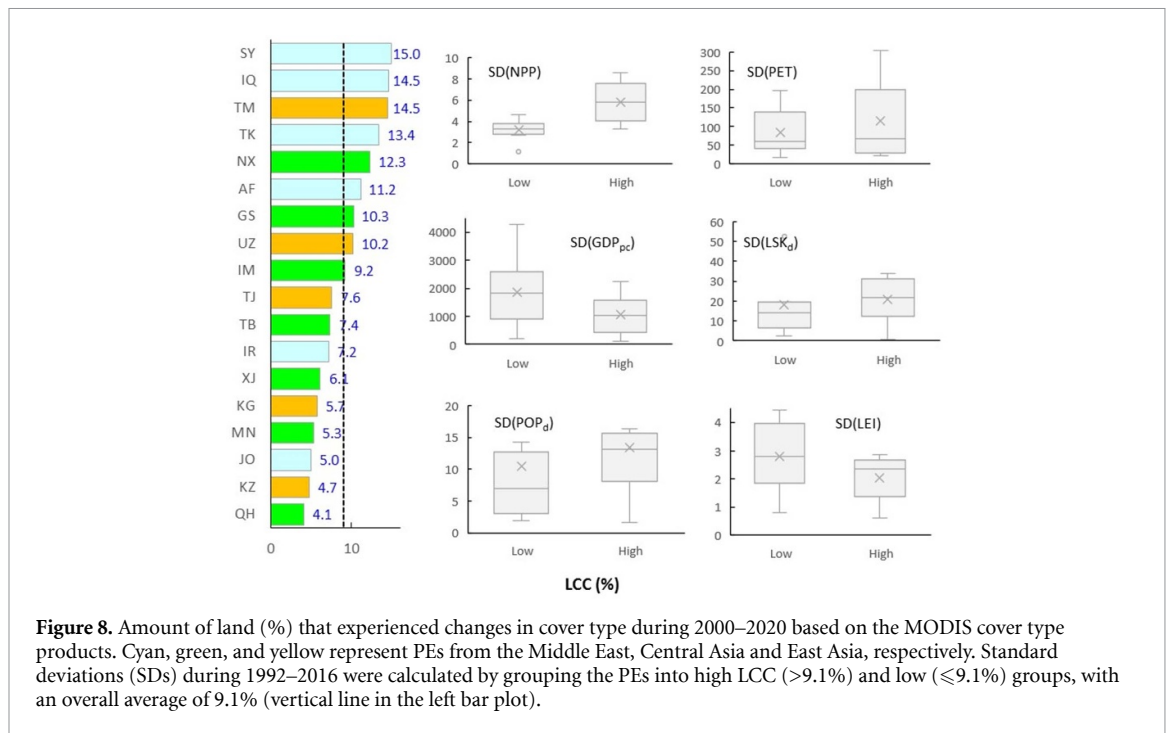


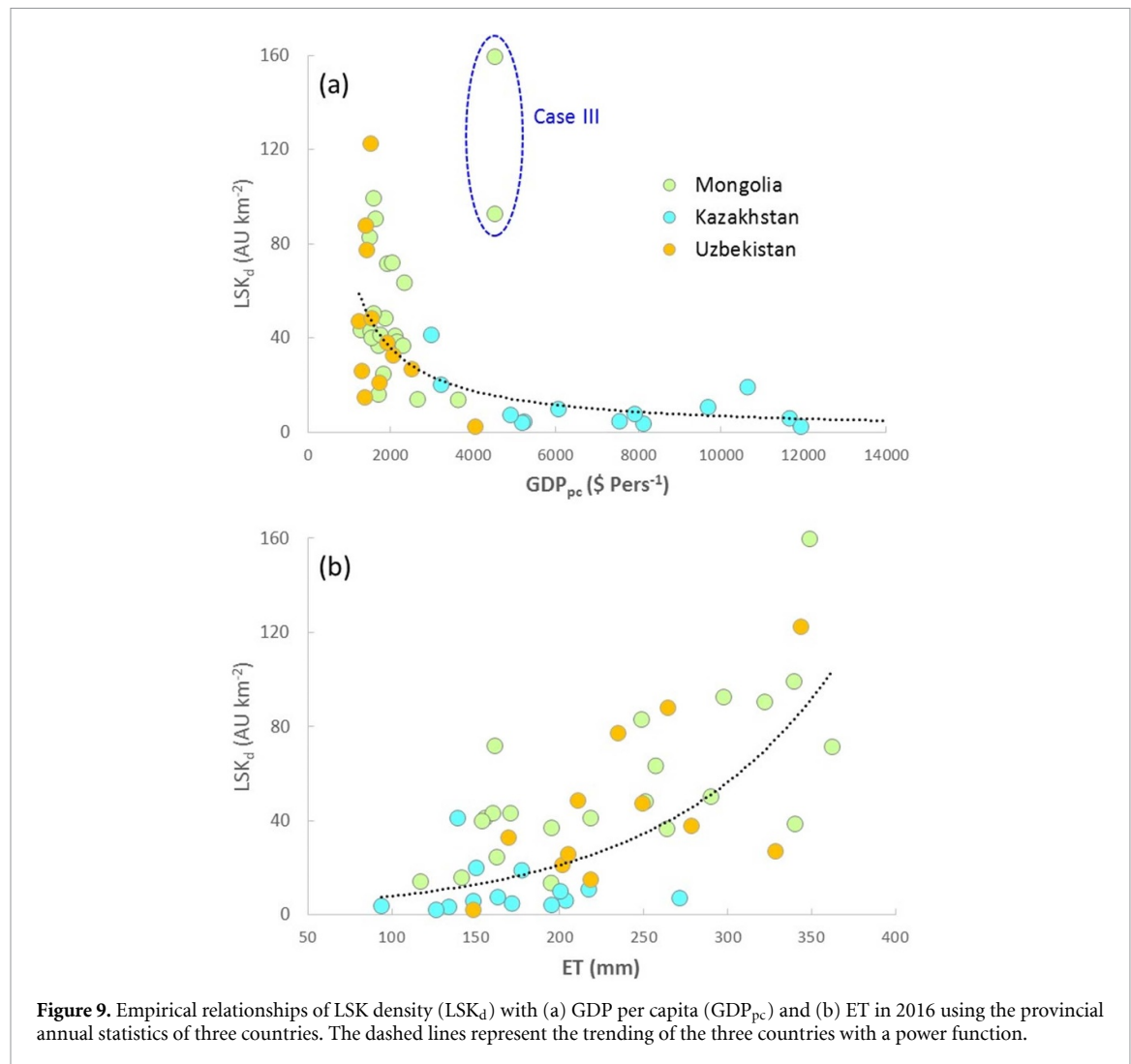
Figure 8. Amount of land (%) that experienced changes in cover type during 2000–2020 based on the MODIS cover type products. Cyan, green, and yellow represent PEs from the Middle East, Central Asia and East Asia, respectively. Standard deviations (SDs) during 1992–2016 were calculated by grouping the PEs into high LCC ($>9.1\%$) and low ($\leq 9.1\%$) groups, with an overall average of 9.1% (vertical line in the left bar plot).

between indigenous herders and grassland conservation strategies.

Another major focus of this synthesis is the impact of rapid LCC on ecosystem dynamics and how these changes are affecting societies as well as being affected by them (Groisman and Soja 2009, Klein *et al* 2012). Based on MODIS, during 2000–2020 an average of 9.1% of the ADB land changed cover type (figure 5). In the Middle East, Syria, Iraq, Turkey, and Afghanistan saw some of the largest changes in cover type, at 11.2% – 15.0% . These PEs were involved in major armed conflicts during the study period, including the US occupations of Iraq (2003–2011) and Afghanistan (2001–2021) and continued civil wars in Syria (2011 present), where Turkey, Iran, and Iraq played major roles. In Central Asia, Turkmenistan had the highest percentage change at 14.5% , and Uzbekistan showed a higher-than-average change. Understanding this change in Turkmenistan, in particular, is challenging because it is a relatively closed-off society, it has been developing infrastructure oil and gas production, and it is a hotspot of high interannual variation in weather and climate (Lioubimtseva *et al* 2012, Groisman *et al* 2018). In East Asia, Ningxia, Gansu, and Inner Mongolia showed the highest amount of cover change (9.2% – 12.3%). These provinces have been the focus of China's Three-North Shelterbelt program, which promotes increasing vegetation cover (Qiang *et al* 2014, Chen *et al* 2018), while the other three provinces considered here have received significantly less revegetation attention (Gerlein-Safdi *et al* 2020). The long-term variations in six major indicators of SES function suggest that these may be coupled with LCC (figures 7 and 8). The temporal variation of NPP

and PET under low LCC was lower than those under high LCC; for GDP_{pc} and LSK_d , their variation was higher and lower, respectively, under low LCC; for POP_d its variation was lower under low LCC.

The ADB experienced rapid transformations in land cover, such as grassland to cropland cover changes in Central Asia and East Asia, cropland to vacant land conversions after the collapse of the USSR (Lioubimtseva and Henebry 2009, Chen *et al* 2015b), increased grazing pressure following land privatization on the Mongolia Plateau (Chen *et al* 2015a, Amartuvshin *et al* 2021), and in response to changes in food demand (Gutman *et al* 2020). Between 2001 and 2012 shrublands and savannas showed a high turnover rate across the ADB region, at 38% and 73% , respectively. This turnover (77% and 89% , respectively) during the same decade in East and Central Asia at 47% and 88% , respectively. Barrens and water represent $\sim 35\%$ and 1% of total land cover, respectively, but 15% and 18% of those changed across the ADB (Chen *et al* 2020). Based on the levels of LCC during 2000–2020, high LCC is associated with higher variation in NPP, PET, LSK_d and POP_d , but lower variation in GDP_{pc} and LEI (figure 8). These land use changes are expected to worsen the stress on the environment and ecosystems in the area, as this water-limited region is predicted to experience a warming trend (longer, more intense, and frequent summer heatwaves) higher than the global mean (IPCC 2014), which would alter summer and winter precipitation patterns and increase the frequency of extreme climate events. Furthermore, the LULCC driven by climate/economic changes in this politically polarized region is expected to be significantly higher in the coming decades (IPCC 2014,



Kelley *et al* 2015), jeopardizing regional stability and sustainability. These changes, along with the region's geographic features (i.e. landlocked, arid), make it an important focal area for global change science and SES dynamics.

5. Scientific challenges in studying the SES of the ADB

Several unexpected relationships between SES elements are identified in ADB subregions (Heffernan *et al* 2014, Becknell *et al* 2015, Chen *et al* 2015a, 2015b, Tian *et al* 2018). Future efforts are needed to explore the interdependent dynamics within these subregions with a focus on regulatory mechanisms. As shown in figure 9(a), LSK_d decreases exponentially with GDP_{pc} —an example of a socioeconomic regulating mechanism; however, LSK_d increases with ET—evidence of biophysical regulating mechanism (figure 9(b)). These relationships appear valid when data are pooled from the three countries, but they are not the same within each country—an example of an institutional regulating mechanism (Gutman and Radeloff 2016, Seto and Ramankutty 2016, Allington

et al 2018, Chen *et al* 2018). Additionally, it is not known if these relationships also vary among the provinces within each country, or remain the same at the local scale where landowners (e.g. herders) maintain diverse practices that depend on their land size and quality (e.g. cover type, climate), LSK size, family needs and aspirations, technological support, etc—a localized regulating mechanism where social networks and familial households may play pivotal roles for the sustainability of the land and families (i.e. interaction order). This synthesis of changes in the ADB suggest five key areas for future research.

5.1. Reduced water quantity and quality under warming, drying, and escalating extreme events

Water is the foremost limiting resource for most of the ADB region. Both quantity and quality are increasingly affected by the warming climate, uneven distribution of precipitation, and increased intensity and frequency of extreme physical events, such as dust storms, heatwaves, dzuds, desertification, and drought (Kurnaz 2014, Rao *et al* 2015, John *et al* 2018, Qu *et al* 2020). Turkey—a country with relatively high precipitation (table S3)—is

experiencing drought effects, a threat to its agricultural industry, with increased frequency, and dzuds (extreme cold winters) have increased in frequency and severity, impacting livestock across the Mongolian Plateau and pushing populations into urban areas to find alternative livelihoods (Qi *et al* 2017, Vova *et al* 2020). Rapid shrinkage of glaciers due to the warming climate further increase drought effects on ecosystem productivity in the grasslands and agricultural lands that are major economic bases for rural communities, and this is exacerbated by excessive water use to support rapid urban expansion. Around the Aral Sea, escalated irrigation to meet increasing demand for grain production, combined with high ET in recent decades (Jung *et al* 2010) and reduced ground water recharge from glaciers, has caused not only shrinking of the sea but also large-scale soil salinization. Additionally, water quality has become a serious concern for many countries, partially due to less-developed water treatment systems and unregulated water use by mining industries (Amartuvshin *et al* 2021). Finally, transboundary water use, such as water withdrawal from the Karun River between Iran, Iraq, and Turkey (Beaumont 1996, Abdullah *et al* 2015) can lead to geopolitical conflicts that fuel uncertainty in SES dynamics. The latest armed conflict during 28–30 April 2021, between Kyrgyzstan and Tajikistan is the direct result of the struggle for control of water use from the Ak-Suu River (Reuters 2021). Indeed, transboundary water disputes plague much of Central Asia. Nearly all the significant rivers of Kazakhstan are sourced in its neighbors, including Russia and China. The collapse of the Soviet Union led to a serious breakdown in the previous water and energy sharing regime mediated by Moscow. Ongoing negotiations between Kazakhstan and China on sharing the Ili River and between Uzbekistan and Tajikistan on how to moderate the impact of the construction of the Rogun Dam largely remain unresolved (Graham *et al* 2017, ICG 2002 at www.crisisgroup.org/latest-updates/report, and the World Bank 2004 at www.worldbank.org/en/publication/wdr/wdr-archive).

5.2. Continued, if not intensifying, geopolitical conflicts

Armed and civil geopolitical events have persisted throughout the history of the ADB region (table S2). The region faces a number of challenges due to the predominantly arid environment, landlocked nature (i.e. self-sustained), diverse cultures, and overall scarcity of resources. A recent rise in nationalism (e.g. Gutman *et al* 2020, Graham *et al* 2021) will elevate geopolitical conflicts. Nevertheless, the area is a major base for energy exploration (e.g. oil, natural gas, minerals) and occupies a strategic position between the west and east. Armed conflicts have devastating effects on the environment, personal security, and livelihoods in dryland regions, where

access to natural resources, especially water, is often a root cause of such conflicts, which are likely to increase as water scarcity becomes more acute with the changing climate and intensified land use (FAO 2016). Recent decades have seen increased hegemonic influences from China, Iran and Russia in the region, while several developed countries (e.g. USA, EU, Australia, Japan, South Korea) also have growing interests. China's Belt and Road Initiatives (BRIs) will likely continue and cause unpredictable effects on different parts of SES (Zou 2018). The Islamic movement will not stop its momentum but can be expected to continue in new ways, internally and/or externally (e.g. militant Islam in multiple hotspots) that directly affect societal stability, economic development, and ecosystem dynamics, partially through indirect influences on institutions (e.g. governance, land use policy).

5.3. Volatile, uncertain, and shifting socioeconomic structures

Most PEs within the ADB have experienced dramatic social and economic changes since WWII, some more severe (e.g. Afghanistan, Iraq, Syria) than others (e.g. Jordan, China). The dissolution of the USSR in 1991 had devastating impacts on some countries in Central Asia that were ill-prepared for the transition to market-based economies (Batsaikhan and Dabrowski 2017, Graham *et al* 2021, United Nations 2021). Countries in the Middle East, Central Asia, and Mongolia are heavily natural resource-dependent (Felipe and Kumar 2010), making them vulnerable to fluctuations in commodity prices and presenting a need to diversify into other economic sectors including manufacturing and services (Batsaikhan and Dabrowski 2017). This vulnerability coupled with poorly functioning institutions also presents challenges to the provision of basic public services (e.g. education and medical care) in societies marked by high levels of educational and income inequality, a large informal sector, and high unemployment (Khitashvili 2016, Khouri 2019b, United Nations 2021). The transition to higher value-added activities is complicated by high levels of political and regional instability (e.g. Afghanistan, Pakistan, Russia, China, and Iran) (Batsaikhan and Dabrowski 2017; see also ICG 2005, Allouche 2007, Ziganshina 2009). It is commonly believed that a transition to a higher valued economy would have been possible by following recipes of a market economy and substantial external subsidies, however this assumes that there were no complicating circumstances like 'high levels of political and regional instability' (see Anderson *et al* 2018). Other scholars may see the transition into a state of a peripheral economy as a common trajectory (Chase-Dunn *et al* 2000). It should also be noted that some PEs with relatively high levels of social service provision before the transition have experienced degradation in public service provision in rural areas,

leading to rural–urban and interregional migration to large urban centers for education and health care opportunities in addition to having better economic prospects (Chen *et al* 2015b, Park *et al* 2017). The people and environment in the Middle East are especially affected by volatility because the region has experienced more frequent and intense conflicts than any other around the world since the mid-1900s, which has wrought devastating economic and social impacts (Rother *et al* 2016). Income inequality in the Middle East is among the highest in the world and is on par with other notably unequal countries (Assouad 2020). This situation is exacerbated by low levels of educational attainment, high levels of unemployment and a growing population (Khoury 2019a). When a government seems incapable of providing basic public services, it may steer discontented citizens to look to militias and terror groups for solutions (Khoury 2019a). Regime changes do matter and must be tracked as the agricultural modernization and diversification efforts in Uzbekistan attest (Starr and Cornell 2018).

5.4. Globalization and cross-country influences

All PEs are increasingly integrated into the global economy and at the same time influenced by global PEs through FDI, overseas development aid, and flow of migrants and remittance, which further complicate our understanding of the SES and policy development. Today, post-Soviet influences remain apparent in Central Asia and Mongolia while international investments (e.g. BRI) have started to pour into Central and East Asia to compete for resources (e.g. oil, mineral and dairy production) and political control/influence. The world's energy supply demand chains are largely influenced by ADB countries, as the oil industry is the major economic base in Iran, Turkmenistan and Xinjiang, and mineral extraction is key on the Mongolian Plateau (Allington *et al* 2018, Amartuvshin *et al* 2021). Furthermore, numerous cases have shown that international agreements and policies on trade and investments can have both immediate and lasting effects as well as teleconnections on the social, economic, and environmental systems in ADB countries. For example, economic sanctions placed on Russia by the United States and EU in response to the Russian-Chechen conflicts promoted the import of dairy products from Kazakhstan to Russia, which in turn stimulated a policy shift to increase Kazakhstan's livestock by several fold (Zharmagambetova 2014). Increasing energy and food demand due to China's economic and population growth have greatly affected the mining and livestock industries in Mongolia, with Australia, South Korea, Japan, Canada and other countries continuing their influences and investments in Mongolia (Kakinuma *et al* 2019, Amartuvshin *et al* 2021). One must also consider the impact of the volatility of oil prices for exporters in the region (but in a general downward

trend) that suggests the need for alternative development strategies (Brown 2015, Yergin 2020). At the household level, many ADB countries show significant migration from rural areas to urban centers or between countries, and these migrants often remit a portion of their earnings to their families back home. In some ADB countries, remittances can be a significant source of income, exceeding even the level of foreign aid (Ratha 2016, Mack *et al* 2021). This widespread phenomenon suggests both labor migration and remittances must be included in modeling SES dynamics.

5.5. Intensification and shifts in LULCC

During 1948–2008, the drylands in the Eastern Hemisphere became drier because of the weakened East Asian summer monsoons. Drylands in the ADB have expanded over the last 60 years and are projected to expand in the 21st century, which will lead to reduced ecosystem functions and services. Increasing aridity, enhanced warming, and rapidly growing populations will exacerbate the risk of land degradation and desertification in the near future (Huang *et al* 2017). Thus, human-induced changes in LCC will likely play a more critical role than climatic forcing, due to population growth and distribution, elevating demands for food and energy, and emerging complications from urbanization, infrastructure development (e.g. road networks), and other industries (e.g. mining, oil). Overall, land degradation will likely increase in the future, particularly where groups of people rely heavily on the land for their livelihoods. For example, livestock is expected to increase, and agriculture is expected to be intensified to meet increasing demands for food, which will result in the overgrazing of grasslands and more irrigated croplands. Meanwhile, infrastructure development will increasingly replace fertile lands with urban, roads, mines, oil fields, etc (Gutman *et al* 2020).

The five pressing issues identified above do not affect all PEs, nor do they place an equal amount of pressure on the SES. We emphasize that the relative strength of the coupling between SES dynamics often varies by country and period. For example, in a historical analysis, Marx *et al* (2018) noted that a cooling effect in the northeast Eurasian steppes preceded a massive migration from this region to the Mediterranean basin. Consequently, during the little Ice Age of 450–700 AD, a large migration was recorded from cooler areas to the European areas, and this timing lines up with the start of the downfall of the Western Roman Empire. However, it is likely that a combination of many additional factors explain the long-lasting decline and eventual collapse of that empire (Marx *et al* 2018). Other scholars also connected climate change with the fall of the Roman Empire (Harper 2018), the Dark Age of Greece (Cline 2014), and the collapse of the Eastern Mediterranean (Ellenblum 2012). In recent

decades, reversing this environmental-anthropologic influence, near the Israeli–Egyptian political boundary there is an example of desertification resulting from human impact on a fragile ecosystem. Although the sandfield in the northwestern Negev desert in Israel is an extension of the one in northeastern Sinai in Egypt, the Negev dunes have transformed into stabilized dunes since the establishment of the State of Israel in 1948, while the Sinai dunes have remained active (Karnieli and Tsoar 1995). Minimal human activity has occurred in that area on the Israeli side due to the strict conservation policy and restricted civilian activity in the vicinity of the border. This difference is among the many examples showing how contrasting institutional mechanisms may shape the natural ecosystems via differences in land use.

Another widely acknowledged land use example comes from the collapse of the USSR. Prior to 1991, the region's drylands were inhabited by semi-nomads, with grazing as the major source of employment, and by temporary farmers who migrated or were forcibly moved from Russia and Ukraine in the 1950s to the so-called 'Virgin Lands'. In 1980, 60% of the Kazakh rangelands suffered from varying degrees of degradation. Farmlands in Kazakhstan were productive, but after 1991 a large portion of this agricultural land was abandoned (Groisman *et al* 2018, Prishchepov *et al* 2021) and farmers migrated away to Russia, Ukraine, Germany, or nearby cities. Changes in the political system and the collapse of the national economy brought about a drastic decline in the livestock population, and unparalleled LULCC occurred in the region. On the one hand, the collapse promoted agriculture, and the need to be close to markets forced people to migrate closer to central villages and towns. This aggravated the ecological situation by causing overgrazing and the harvesting of vegetation in these sites. On the other hand, less human activity happened in remote areas. The centralized government subsidy programs were terminated, including guaranteed supplemental forage during cold winters and drought years. Farmers struggled to feed their livestock during the harsh winters, water wells were demolished, pumps were stolen or broken, and the means of transporting animals to the markets in the central cities were lost. Disengagement from Russia also led to a decline in the production of exports, including wool and meat. Due to rising meat, wool, and milk prices, the diets of Kazakh people changed, as people ate more carbohydrates than meat. For all these reasons, drastic declines in livestock populations were observed after 1991 that have resulted in lower grazing pressure and hence recovery of the natural vegetation and rehabilitation of the land (Karnieli *et al* 2008).

Finally, the Syrian Civil War since 2011 may provide important lessons in modeling SES dynamics. Prevailing opinion linked the Syrian civilian uprising with the sequential droughts that occurred in

2007–2010, but some studies show that the climatic conditions for winter–rainfed agriculture in Syria during the years before 2011 were similar and even more favorable to farmers than those affecting Turkish crops across the border. Simultaneously, summer-irrigated crops, heavily dependent on water from the Euphrates, notably declined in Syria while they flourished in Turkey. Furthermore, satellite altimeter data shows a dramatic increase in 2010 in the water level of the Turkish water reservoirs that dam the Euphrates flows, and a corresponding drop in the water level of the Syrian reservoirs. These findings are firmly supported by other datasets, such as Turkey–Syria transboundary surface and groundwater flows, water levels in the main water reservoirs of the two countries, and actual rainfed in contrast to irrigated winter and summer crop production. It is concluded that water policies and diversions from the Euphrates basin by Turkey were the main reason for the agriculture collapse and subsequent instability in Syria during the spring of 2011. It can be concluded that anthropogenic activities, rather than environmental drivers, were the main cause of the Syrian Civil War (Karnieli *et al* 2019).

6. Concluding thoughts

We have provided an overview of the current state and historical changes in the ADB from socioeconomic and environmental perspectives. This vast region, while facing all the water shortage-related environmental challenges of other global drylands, has experienced a particular set of environmental and socioeconomic changes driven primarily by dramatic shifts in institutional and political regimes, especially since the collapse of the USSR. These changes highlight the outstanding and longstanding problems of resource overexploitation, land degradation, poverty, conflicts, and social instabilities. Because it consists of nation states and geographic regions that have highly contrasting sociopolitical systems and histories, the ADB probably exhibits more diverse SES with greater geospatial heterogeneity than other drylands in the world. While the sustainability of the ADB is certainly affected by climate, globalization, rapid urbanization, labor migration, and other widespread environmental and socioeconomic changes, LULCC is a key direct driver for the sustainability of the ADB landscapes and the region as a whole. These complex dynamics of SES need to be understood through linking the biophysical, socioeconomic, institutional, and local context-dependent mechanisms.

Not yet explored are the impacts of urbanization and de-urbanization in the ADB, which have particular influence on regional water consumption in this drought-threatened region (Zhang *et al* 2020). The interference between local areas and high demand in any kind of ecosystem services and weaknesses how to feed them in abandoned or very sparsely settled

lands might be one of the huge challenges for this region, which is rich in resources but also characterized by huge spatial disparities in terms of access to them. People living traditional lifestyles and a young 'globalized' generation are faced with negotiating consensus over future sustainability and intra-/inter-generationally equitable land and resource use while ethnical and religious concerns provoke ongoing conflicts that might be worsened by the diverse spatial pattern of climate change impacts on water availability, the productivity of land, and the health and well-being of people.

No panacea exists for resolving the environmental, social, and economic challenges facing the ADB. Global sustainability requires local sustainability in regions across the planet, including the vast drylands. To meet these local and regional challenges, we need place-based, context-dependent transdisciplinary approaches to focus on the human–environment interactions within and between landscapes with explicit consideration of specific forcings and regulatory mechanisms (Kates 2012, Koschke *et al* 2012, Forman and Wu 2016, Opdam *et al* 2018, Wu 2019, Cumming and Epstein 2020). For example, the landscape sustainability science framework focuses on enhancing the dynamic capacity of landscapes to provide consistently ecosystem services essential for maintaining over the long term human well-being in a regional context and in the face of environmental and sociocultural changes (Wu 2013, 2021). Several landscape/regional approaches are available, including landscape ecology, landscape resilience, landscape governance, regional safe and just operating space, and integrated landscape approaches, among others. Such landscape-based approaches can help identify national and regional sustainability by placing more emphasis on local capacity building, landscape planning, and local governance, all in the context of global changes in climate, socioeconomic connections, and potential geopolitical conflicts. It remains to be seen if these approaches be implemented to connect the dots of EcoSys, SocSys and EconSys in real environmental and political settings, since those that outline and advocate for these frameworks are typically far from the funding and political power needed to address these complex challenges. Yet, the landscape-based approaches to SES should help us to understand more clearly the context dependence and contingent interactions, and asymmetrical interdependencies among key elements of human–environment cross-scale systems (Holling 1973, 2001).

In the long run, understanding sustainability in such highly socially and ethnically complex systems calls for the 4th axis of sustainability (i.e. cultural sustainability). Societal transformation, loss of cultural heritage and affiliation in combination with threats from climate change decrease the overall resilience of the SES in the ADB without providing any vision of how future SES could be conceived

in this highly vulnerable part of our Earth. Neither abandonment and full protection of ADB areas nor more intensive exploitation of local resources would be strategies that could help protecting the unique social-ecological heritage of this region. Most local residents were raised with an understanding of how to sustainably manage their environment, but this important cultural asset is more than ever threatened with extinction, thereby increasing the vulnerability of the ADB countries to globalization impacts and climate change. This paper thus, calls for protecting the entire SES in the ADB and calls for giving the bearers of social-cultural-environmental and economic knowledge still inherent in the local populations the opportunity to bring forth their rich knowledge to the ongoing challenges of sustaining life on our planet.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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