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Concept Paper

Towards a Single Integrative Metric on the Dynamics of Social-Environmental Systems

Jiquan Chen [1,2,*], Ranjeet John [3], Changliang Shao [4], Zutao Ouyang [5], Elizabeth A. Mack [2], Geoffrey M. Henebry [1,2], Gang Dong [6], Ginger R. H. Allington [7], Amber L. Pearson [2], Fangyuan Zhao [4], David P. Roy [1,2], Peilei Fan [1,8], Gabriela E. Shirkey [2], Li Tian [9], Maira Kussainova [10], Jingyan Chen [11], David E. Reed [12] and Michael Abraha [1]

1 Center for Global Change and Earth Observations, Michigan State University, East Lansing, MI 48823, USA; henebryg@msu.edu (G.M.H.); roydavi1@msu.edu (D.P.R.); fanpeile@msu.edu (P.F.); abraha@msu.edu (M.A.)
2 Department of Geography, Environment, and Spatial Sciences, Michigan State University, East Lansing, MI 48824, USA; emack@msu.edu (E.A.M.); apearson@msu.edu (A.L.P.); shirkeyg@msu.edu (G.E.S.)
3 Department of Biology, University of South Dakota, Vermillion, SD 57069, USA; Ranjeet.John@usd.edu
4 National Hulunber Grassland Ecosystem Observation and Research Station, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100875, China; shaochangliang@caas.cn (C.S.); fangyuanyale@163.com (F.Z.)
5 Earth System Science Department, Stanford University, Stanford, CA 94305, USA; ouyangzt@stanford.edu
6 School of Life Science, Shanxi University, Taiyuan 030006, China; dongg@sxu.edu.cn
7 Department of Geography, George Washington University, Washington, DC 20052, USA; gallington@email.gwu.edu
8 School of Planning, Design, and Construction, Michigan State University, East Lansing, MI 48824, USA
9 Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; tianli@igsnrr.ac.cn
10 Sustainable Agriculture Center, Kazakh National Agrarian University, Almaty 050010, Kazakhstan; maira.kussainova@kaznaru.edu.kz
11 Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China; jychen@ibcas.ac.cn
12 Department of Environmental Science, University of Science and Arts of Oklahoma, Chickasha, OK 73018, USA; dreed@usao.edu
* Correspondence: jqchen@msu.edu

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Abstract: Integrating the dynamics and interconnections of natural and human system properties into a single measure would make it simpler to reliably and repeatedly assess and compare different social-environmental systems (SES). We propose a novel metric to assess the magnitudes and variations in SES dynamics by integrating longitudinal gross domestic product, population, and ecosystem net primary production. We use annual public data across the Asian Drylands Belt (ADB) from 1992 through 2016 for 18 political entities as our testbed for assessing the efficacy of the metric. We perform cross-comparisons with existing natural and social science metrics to demonstrate the validity of the proposed metric, including the Human Development Index and the Palmer Drought Severity Index. The new metric demonstrates notable and meaningful differences in trends among the political entities that reflect major social, economic and environmental events over the 25-year period. It provides unique perspectives about the three pillar components (social, economic and environmental systems) in each of the 18 political entities (PE) of the ADB. The metric also shows meaningful associations with key economic and environmental indicators and great potential for broader application and evaluation, given additional testing in other countries, regions, and biomes.

Keywords: Asian Drylands Belt; social-environmental system; quantitative measure; sustainability

1. Introduction

1.1. Need for Integrative Indicators

The concept of integrated social-environmental systems (SES) is becoming a dominant paradigm to understand the complex interactions of humans and nature. A prevailing

thought within this concept is that an SES is composed of three major pillars: social, economic, and ecological systems [1–5]. Understanding the connections, forcing mechanisms, and feedbacks among the properties of each pillar within the system is central in SES and is an ongoing research challenge [6]. Here, the development of quantitative metrics that integrate information from social, economic and ecological aspects are needed so that an SES can be reliably and repeatedly assessed with quantitative measures [7–12], ideally with a single measure [13].

Many SES metrics have been developed in the diverse disciplines of social, economic and environmental science. These include population size (POP) and POP density (POP_d, pers km^{-2}) for human demography, gross domestic product (GDP, USD yr^{-1}) and GDP per capita (GDP_{pc}, USD $pers^{-1}$ yr^{-1}) for economic development and standard of living, and net primary production (NPP, Mg m^{-2} yr^{-1}) and evapotranspiration (ET, mm yr^{-1}) for ecosystem functions. These metrics are well established because they can be measured or estimated, have physical units, and can be understood by policymakers and scientists. Integrated measures are an area of emerging research [13] and increasingly need academic and non-academic contributions to obtain the best available knowledge for each case (i.e., problem-based approach) for decision making [14]. We contend that a single metric on SES status that uses annual public data available for countries around the world has yet to be derived. Filling this gap is important from both scientific and policy perspectives if we are to effectively analyze the inter-connectivity among the SESs, understand system trajectories, and support sound regulatory processes in a cost-effective approach. This new integrative metric would provide a better understanding of SES dynamics and SES tipping points.

Most works to date exploring the interconnections among SES metrics have considered pairs of indicators. For example, the indicator GDP per capita cannot characterize societal advancement or economic contributions of a country alone but can be used as an indicator of social welfare if the GDP estimates are undertaken within a cost–benefit analysis framework [15–17]. Human appropriation of net primary production (HANPP) is one early attempt to integrate ecosystem production with human population size for different countries [18–22]. Similar metrics were applied for urban development (NPP:POP) [23,24], among administrative units of a region (NPP:GDP_{pc}) [25,26] and at global scales [22,27,28]. In an updated review of the UN's original concept of sustainability (e.g., the Brundtland Report [1]), Holden et al., (2014) compared changes between the ecological footprint, the human development index (HDI), Gini Coefficient and the ratio of renewable energy to total energy [5]. They found different tight correlations at a global scale that can be used by national and international policymakers in their decisions about sustainable development. The aforementioned studies considered metrics from the perspectives of ecosystems and human demography (e.g., NPP:POP) or ecosystems and economic status (e.g., ET:GDP_{pc}). A few also examined the changes due to institutional shifts [29,30]. The HDI is calculated as the geometric mean of a life expectancy index, an education index, and a gross national income (GNI) index but does not include environmental aspects [31]. Böhringer and Jochem (2007) examined the consistency and meaningfulness of 11 popular sustainability indices, including HDI, Ecologic Footprint, and Living Planet Index (also see [7]) [32]. They concluded these indices had limited explanatory power, and thus were not useful, if not altogether misleading, for policy development and evaluation. More recently, Hickel (2020) pointed out deficiencies in ecological indicators and derived a Sustainability Development Index (SDI), which is comprised of HDI, total CO_2 emissions at the national level, and the material footprint of countries [13]. While this is an important step forward, the use of CO_2 emissions in the SDI calculation only considers energy consumption and does not include emissions arising from ecosystem processes. Thus, while a plethora of indices exist, none were able to reliably represent all three SES pillars in a way that would contribute to impact assessments or policy [33–35].

In seeking a new, integrated metric on SES (IMoSES), we applied the following criteria: (1) quantitative metrics for each of the three sustainability pillars (social, economic, and

ecological systems), and (2) annually available data to facilitate comparisons through time. Ecosystem production (e.g., NPP), GDP and POP are among the most widely recognized and applied measurements in ecosystem science, macroeconomics, and the social sciences, respectively (Table 1). IMoSES is an integration of GDP, POP, and NPP in the context of land area (A, km^2) with critical resource input (e.g., evapotranspiration) as the regulator (i.e., the denominator in Equations (3)–(5)). We calculate IMoSES across the Asian Drylands Belt (ADB) as a proof of concept to demonstrate its use and interpretation in understanding SES dynamics. The ADB region is used because of (1) data availability after QA/QC in our labs and (2) the dramatic shifts in recent decades in social, economic, and ecological systems. Countries in the ADB include the Newly Independent States (NIS) formed by the breakup of the Soviet Union. Many of them have experienced periods of armed conflict and/or profound social changes that have initiated a series of economic changes and shifts in livelihoods. Physically, the region has also experienced higher-than-global average warming and reduction in water vapor influx [36], more frequent climatic extremes such as severe winters/*dzuds* [37], heatwaves [38], and large-scale dust storms [39].

Table 1. Variable names and data sources for IMoSES calculations and verifications. GDP in 2020 USD is deflated to constant 2011 USD using the consumer price index (CPI) from the Bureau of Labor Statistics. Daily carbon price is available. We used the average carbon price of 9.966 EUR per ton of CO_2 and currency exchange rate of 0.7875 USD per EUR during 2009–2020 due to a lack of price data before 26 October 2009. Livestock was converted to animal unit (AU) equivalents following conversion from livestock to sheep by the FAO (http://www.fao.org/3/y4176e/y4176e04.htm). More databases are provided in the tables for potential uses of IMoSES (e.g., livestock, CO_2 emission). All data accessed between June and August 2020.

Variable (Unit)	Source	Webpage
Political Entity (PE) level (1992–2016)		
NPP (g m^{-2} yr^{-1})	AVHHR	http://glcf.umd.edu/data/glopem/
NPP (g m^{-2} yr^{-1})	MODIS	https://earthdata.nasa.gov/
PET (mm)	CRU, UEA	http://www.cru.uea.ac.uk/data
GDP (USD)	SNA, UN	https://unstats.un.org/unsd/snaama/Basic
POP (pers)	UN	https://population.un.org/wpp/Download/Standard
PDSI (−10, 10)	CRU, UEA	http://www.cru.uea.ac.uk/data
LSK (Au km^{-2})	FAOSTAT	http://www.fao.org/faostat/en/#data/QA
HDI (0–1)	WB	https://datacatalog.worldbank.org/
SDI (0–1)	SDI Team	https://www.sustainabledevelopmentindex.org/
LEI (yr)	WB	https://datacatalog.worldbank.org/
CO_2 and N_2O emission	WB	https://datacatalog.worldbank.org/
Prefecture level (2016)		
NPP (g m^{-2} yr^{-1})	MOD17A3	https://earthdata.nasa.gov/
ET (mm)	MOD16A3	https://earthdata.nasa.gov/
GDP (USD yr^{-1})	Yearbooks	https://unstats.un.org/unsd/snaama/Basic
POP (n)	Yearbooks	http://data.stats.gov.cn/easyquery.htm?cn=E0103
LSK (Au)	Yearbooks	http://data.stats.gov.cn/easyquery.htm?cn=E0103
Others		
Temperature (°C)	CRU4.04	https://crudata.uea.ac.uk/cru/data/hrg/
Precipitation (mm)	CRU4.40	https://crudata.uea.ac.uk/cru/data/hrg/
Carbon Price (USD Mg CO_2)	Markets Insider	https://markets.businessinsider.com/

1.2. Integrative Indicator for SES Dynamics

Let IMoSES be the product of economic and ecosystem production efficiency:

$$\frac{Economic\ Production}{Resource\ Input} \cdot \frac{Ecosystem\ Production}{Resource\ Input} \quad (1)$$

where economic production may be any of the widely used indicators for economic development, such as GDP, energy production, agricultural production, etc.; whereas ecosystem production may be GPP, NPP, grain yield, livestock production, etc. Resource input is the amount of resources that are consumed for an SES to produce and function, such as water or energy input. This generic model needs to consider additional parameters to have different weighing factors when the same resource input is used for both economic and ecosystem production. The parameter (κ) is introduced to reflect the calculation of the two efficiencies:

$$IMoSES = \frac{[Economic\ Production]\cdot[Ecosystem\ production]}{[Resource\ Input]^{\kappa}} \tag{2}$$

where κ is a regulatory parameter and varies from neutral linear (κ = 0), to negative linear (κ = 1), or positive linear ($\kappa < -1$) regulations on the magnitude of IMoSES. Where the unit and weight of economic production and ecosystem production are the same, we would use the sum of these efficiencies. For example, GDP as the most popular indicator of economic systems has a unit of USD yr^{-1}, whereas NPP as a widely used measure of ecosystem production has a unit of Mg ha^{-1} yr^{-1}. Additionally, the proposed IMoSES needs to consider the land area (A) and population size (POP), so a large country can be compared with a small one, or an SES with high POP can be compared with a less dense one. For example, when GPD is used for economic development, GDP per capita (GDP_{pc}) is recognized to reflect social contributions. Similarly, HANPP (i.e., NPP·A/POP) is appropriate to represent the ecosystem production of an SES.

Using evapotranspiration (ET, mm yr^{-1}) as the resource maintaining an SES, IMoSES can be expressed as:

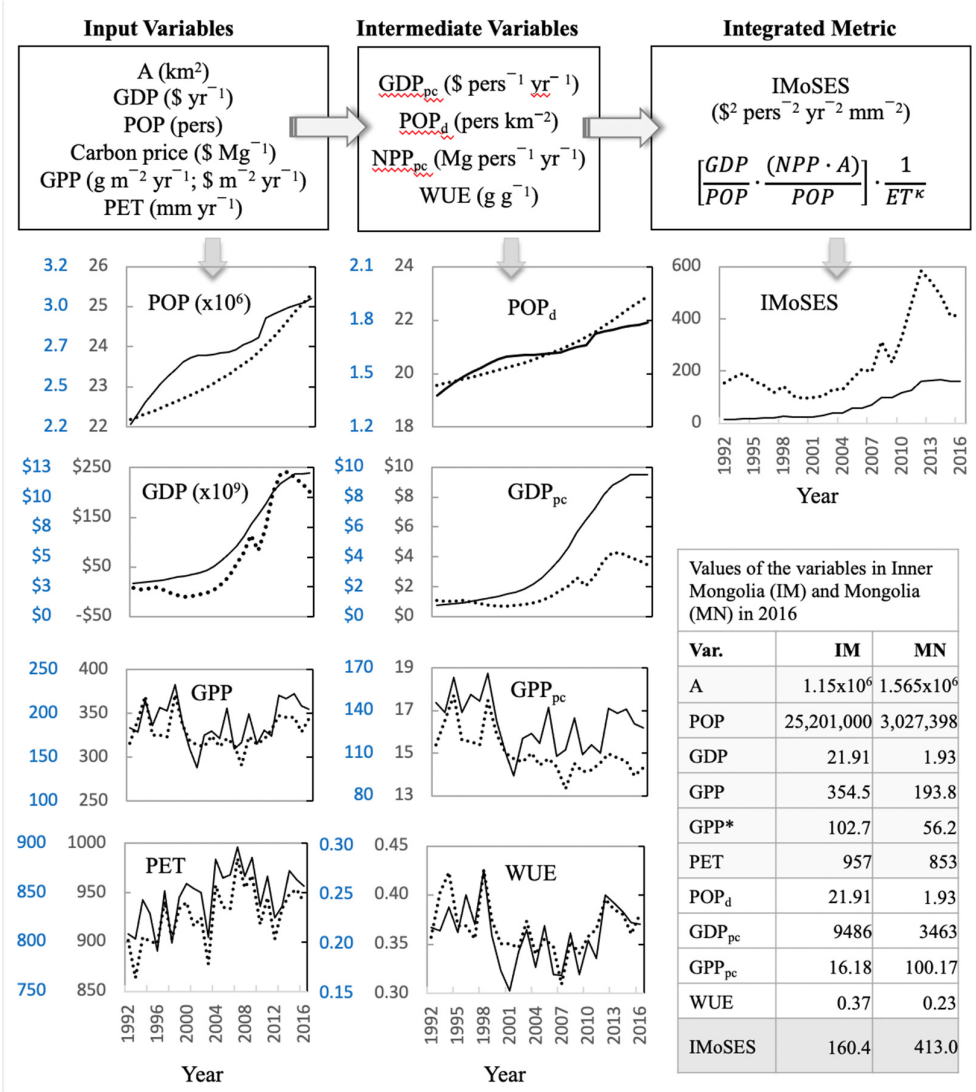
$$IMoSES = \left[\frac{GDP}{POP}\cdot\frac{(NPP\cdot A)}{POP}\right]\cdot\frac{1}{ET^{\kappa}} \tag{3}$$

This calculation can have multiple expressions and several intermediate variables to emphasize different aspects of SES properties and dynamics, including:

$$= \frac{GDP}{POP}\cdot\frac{1}{POP/A}\cdot\frac{NPP}{ET^{\kappa}} \tag{4}$$

$$= \frac{GDPpc}{POPd}\cdot WUE \quad \text{when } \kappa = 1 \tag{5}$$

where A (km^{-2}) is the land area of an SES, (NPP·A, Mg yr^{-1}) is the total NPP of the SES, and κ is a sole parameter determining the strength of ET regulations; GDP/POP is known as GDP per capita (GDP_{pc}, USD $pers^{-1}$ yr^{-1}), POP/A is population density (POP_d, pers km^{-2}), (NPP·A)/POP (Mg $pers^{-1}$ yr^{-1}) is called HANPP [22], and NPP/ET is known as water use efficiency (WUE, mg g^{-1}) in ecosystem studies [40,41]. Using carbon stock information, the unit for NPP can be converted to USD yr^{-1} based on monetary valuations of ecosystem services [42], resulting in a unit of USD^2 $pers^{-2}$ yr^{-2} mm^{-2} for IMoSES when κ = 2. To make this unit more meaningful, one can consider the use of the square root of IMoSES (i.e., $\sqrt{\text{IMoSES}}$) that will have a unit of USD $pers^{-1}$ yr^{-1} mm^{-1}. In this case, $\sqrt{\text{IMoSES}}$) can be interpreted as water use efficiency of SES performance. Notably, energy consumption can be used as an alternative resource input for ET; IMoSES then becomes a measure of energy use efficiency, with a unit of USD $pers^{-1}$ yr^{-1} W^{-1}. Other resource use efficiencies [43] can be further explored to substitute for WUE (Figure 1). Additionally, the strength of ET regulations (i.e., water limitations) can be adjusted by the value of κ. It can vary from no control (κ = 0), to negative linear (κ = 1), positive linear ($\kappa < -1$) or nonlinear control on the magnitude of IMoSES when $\kappa \neq +1$ or -1. To introduce the approach, we primarily draw on IMoSES when assessing and illustrating it implications (Table 2, Figures 2–6), with one case (Figure 4) using $\sqrt{\text{IMoSES}}$ for demonstration purposes. We argue that both IMoSES and $\sqrt{\text{IMoSES}}$ can be used for real world applications so long as the units are consistently presented.



Values of the variables in Inner Mongolia (IM) and Mongolia (MN) in 2016

Var.	IM	MN
A	1.15×10^6	1.565×10^6
POP	25,201,000	3,027,398
GDP	21.91	1.93
GPP	354.5	193.8
GPP*	102.7	56.2
PET	957	853
POP_d	21.91	1.93
GDP_{pc}	9486	3463
GPP_{pc}	16.18	100.17
WUE	0.37	0.23
IMoSES	160.4	413.0

Figure 1. Calculations of the intermediate variables and IMoSES from six input variables using the algorithms of Equations (3)–(5). Historical data during 1992–2016 from Inner Mongolia (IM) and Mongolia (MN) are used to illustrate the changes of input variables, intermediate variables and IMoSES. Because of the large differences between the two jurisdictions, independent vertical axes are used for MN (leftmost labels, blue) and IM (rightmost labels, grey). The vertical axes are scaled for easy visualization of the changes over time.

Table 2. Changes in IMoSES (USD^2 yr^{-2} pers^{-2} mm^{-1}) during 1992–2016 for the 18 political entities (PEs) across the Asian Drylands Belt (ADB). IMoSES is calculated with $\kappa = 1$ (Equations (3)–(5)).

Year	AF	KG	KZ	TJ	TM	UZ	GS	IM	MN	NX	QH	TB	XJ	IQ	IR	JO	SY	TK
	Central Asia						East Asia							The Middle East				
1992	1.08	12.68	141.16	2.85	12.56	3.09	2.88	14.29	154.21	1.32	22.10	42.94	9.87	1.05	6.57	2.50	2.25	42.18
1993	0.66	10.97	141.02	2.21	10.98	2.66	3.06	15.45	177.61	1.47	24.97	39.47	10.94	0.77	7.22	2.23	2.61	43.97
1994	0.43	8.81	109.81	1.67	9.61	2.52	2.70	17.19	192.73	1.41	25.07	42.95	11.56	0.57	6.46	2.30	2.02	30.42
1995	0.52	7.31	81.26	1.29	7.18	1.98	2.76	17.05	160.31	1.25	22.37	40.89	11.17	0.47	6.31	2.14	2.10	38.40
1996	0.44	9.05	85.81	1.08	6.70	1.72	3.64	20.70	146.42	1.92	25.38	43.62	11.48	0.70	6.39	1.86	2.10	38.78
1997	0.38	7.92	102.29	0.88	7.72	2.20	3.59	20.94	118.24	1.55	25.61	48.46	12.16	0.66	5.15	1.85	2.31	40.68
1998	0.51	7.90	73.00	1.50	9.37	2.26	4.03	26.10	141.77	1.81	26.91	57.86	14.01	1.05	5.72	2.16	1.94	40.81
1999	0.33	5.41	63.83	0.99	9.94	2.07	4.25	23.98	103.55	1.78	31.23	62.81	13.95	1.09	4.65	1.78	1.30	33.80
2000	0.28	4.91	80.41	0.51	11.02	1.22	4.18	23.37	94.13	1.23	31.31	73.25	14.18	0.95	3.90	1.75	1.22	31.16
2001	0.23	4.89	84.64	0.55	12.74	0.73	4.21	23.74	100.20	1.53	31.19	76.71	14.92	1.24	4.26	1.90	1.78	21.72
2002	0.33	6.18	123.13	0.88	22.11	1.25	5.18	30.19	104.22	2.60	36.83	82.87	17.62	1.08	5.46	1.95	1.57	26.60
2003	0.40	6.94	132.11	1.08	30.77	1.20	5.72	38.52	129.91	2.89	38.29	91.77	18.51	0.94	5.35	2.05	1.64	30.44
2004	0.33	6.84	145.28	1.31	29.52	1.27	6.40	40.88	130.98	3.06	46.21	104.89	18.41	1.63	6.74	2.09	1.81	40.68
2005	0.48	8.25	195.97	1.70	35.47	1.53	7.88	56.81	169.59	3.00	59.56	114.33	22.12	1.81	7.98	2.11	1.81	50.17
2006	0.35	7.17	220.29	1.34	30.10	1.36	8.36	59.44	208.28	3.12	62.40	110.17	21.58	2.52	8.39	2.08	1.77	50.92
2007	0.57	9.69	337.98	1.85	36.22	1.80	9.78	70.58	197.96	4.47	65.28	107.62	23.94	3.21	10.73	2.22	1.87	55.25
2008	0.34	9.71	281.03	1.61	30.19	1.75	10.44	97.34	312.55	4.56	74.75	128.72	22.02	3.13	9.51	2.40	1.77	57.01
2009	0.70	12.95	294.41	2.72	36.75	2.95	10.91	97.85	233.34	4.92	86.90	123.02	23.78	3.46	10.95	2.35	2.24	57.27
2010	0.74	13.26	278.06	3.16	37.46	2.86	13.54	118.26	328.08	8.10	105.10	137.92	30.34	3.93	14.01	2.50	2.48	62.48
2011	0.53	13.26	422.21	1.83	35.81	2.19	14.28	126.75	459.92	7.72	108.36	159.43	33.15	4.17	13.69	2.12	2.73	70.65
2012	0.87	13.54	394.43	3.09	51.88	3.12	17.25	162.22	585.27	11.43	123.85	171.72	35.00	4.53	14.29	2.07	1.78	60.82
2013	0.78	15.12	557.10	3.07	54.91	3.45	18.59	164.52	542.40	10.51	123.27	195.01	40.42	5.57	12.87	2.10	1.24	67.70
2014	0.66	12.85	420.82	3.13	48.14	3.26	20.01	166.32	489.88	11.17	127.00	203.23	37.98	5.42	9.55	2.12	0.86	60.33
2015	0.68	10.23	410.30	2.62	53.08	3.61	17.99	161.18	413.46	9.61	122.23	272.19	39.64	3.79	8.44	2.24	1.02	65.36
2016	0.60	11.60	365.35	2.25	48.04	3.75	18.28	160.38	413.05	10.74	124.76	279.65	45.53	3.75	9.59	1.93	0.49	57.43
Mean	0.53	9.50	221.67	1.81	27.13	2.23	8.80	70.16	244.32	4.53	62.84	112.46	22.17	2.30	8.17	2.11	1.79	47.00
Min	0.23	4.89	63.83	0.51	6.70	0.73	2.70	14.29	94.13	1.23	22.10	39.47	9.87	0.47	3.90	1.75	0.49	21.72
Max	1.08	15.12	557.10	3.16	54.91	3.75	20.01	166.32	585.27	11.43	127.00	279.65	45.53	5.57	14.29	2.50	2.73	70.65
SD	0.21	3.01	143.16	0.85	16.43	0.86	5.91	57.32	152.31	3.64	39.92	68.88	10.83	1.64	3.13	0.20	0.54	13.94

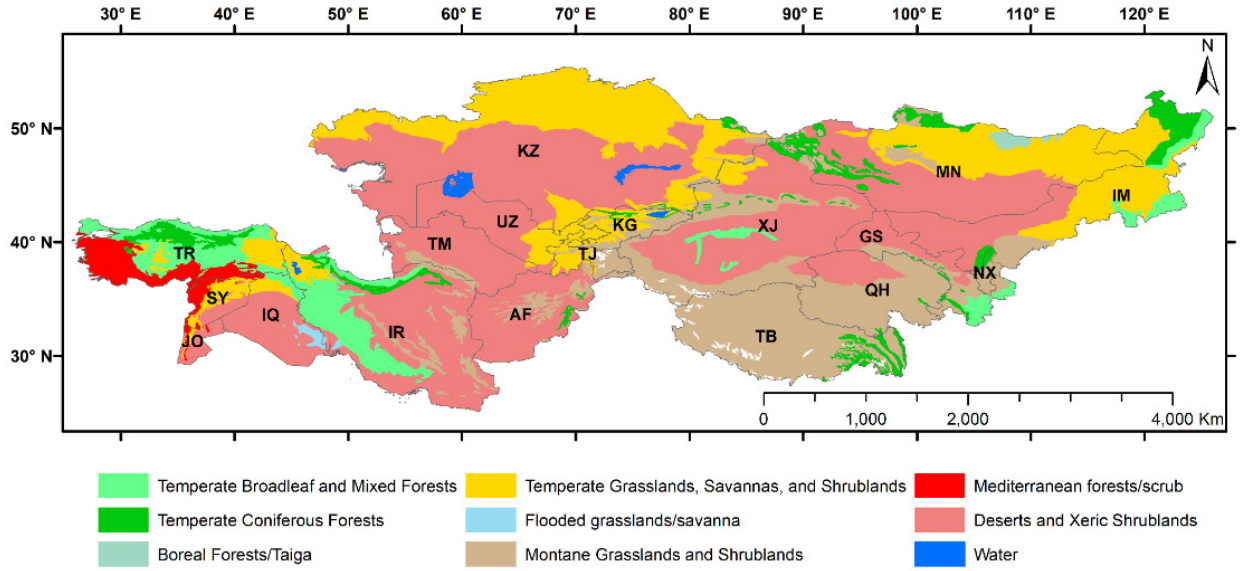


Figure 2. Spatial locations of 18 political entities (PEs) across the Asian Drylands Belt (ADB). PE boundaries are overlaid on the ecoregions of the World Wildlife Fund (https://www.worldwildlife.org, accessed on 10 July 2020). JO—Jordan; TR—Turkey; SY—Syria; IQ—Iraq; IR—Iran; TM—Turkmenistan; AF—Afghanistan; UZ—Uzbekistan; KZ—Kazakhstan; TJ—Tajikistan; KG—Kyrgyzstan; XJ—Xinjiang; TB—Tibet; QH—Qinghai; GS—Gansu; NX—Ningxia; MN—Mongolia; IM—Inner Mongolia.

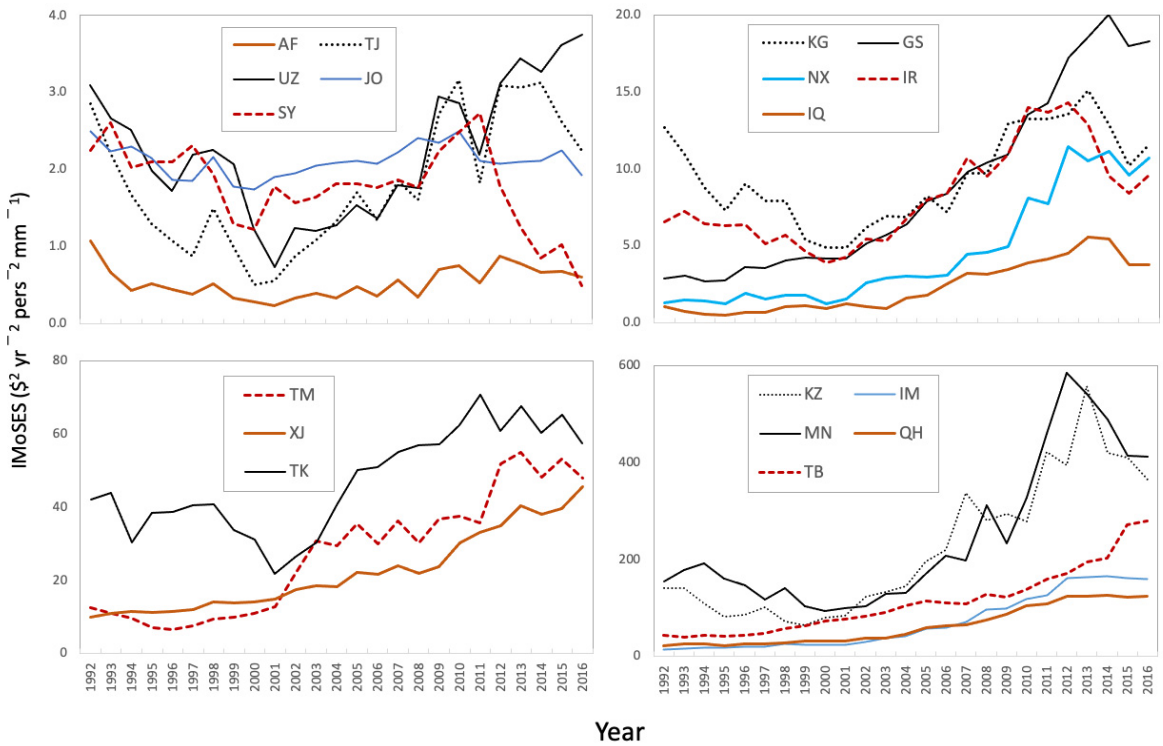


Figure 3. Changes in IMoSES for 18 political entities (PEs) in the Asian Drylands Belt (ADB) from 1992 through 2016. These PEs are arranged in four panels based on their maximum IMoSES values for easier visualization of the IMoSES dynamics. The abbreviations match those in Figure 2.

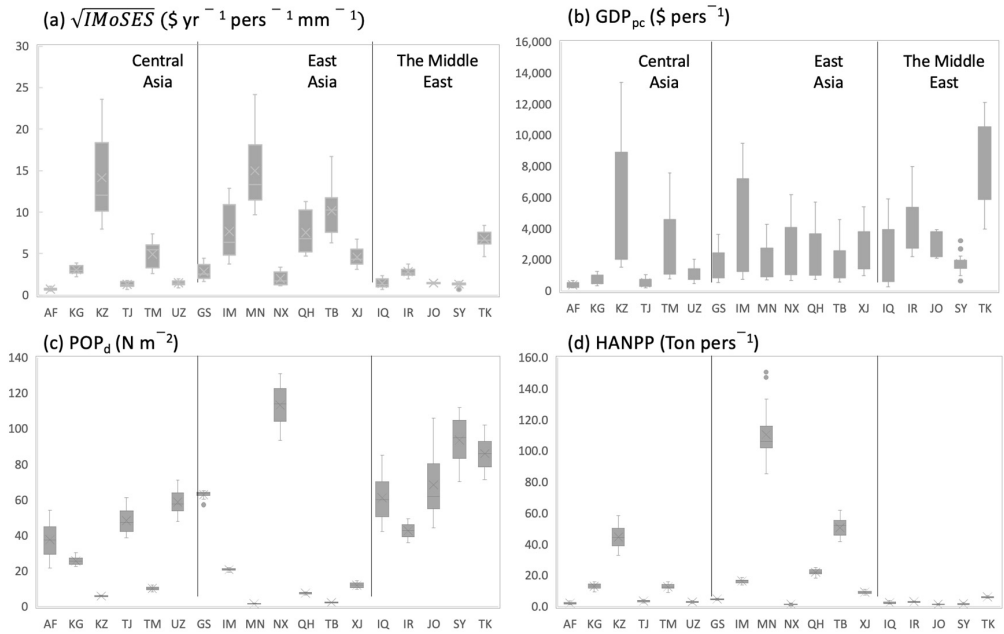


Figure 4. Boxplots of IMoSES (**a**) and its three components, GDP$_{pc}$ (**b**), POP$_d$ (**c**), and HANPP (**d**) for the 18 political entities (PEs) during 1992–2016. κ = 1. Because there are large differences in IMoSES among the PEs, the square root transformation of IMoSES is presented in panel (**a**) to show per capita relationships. See Figure 2 for PE locations and abbreviations.

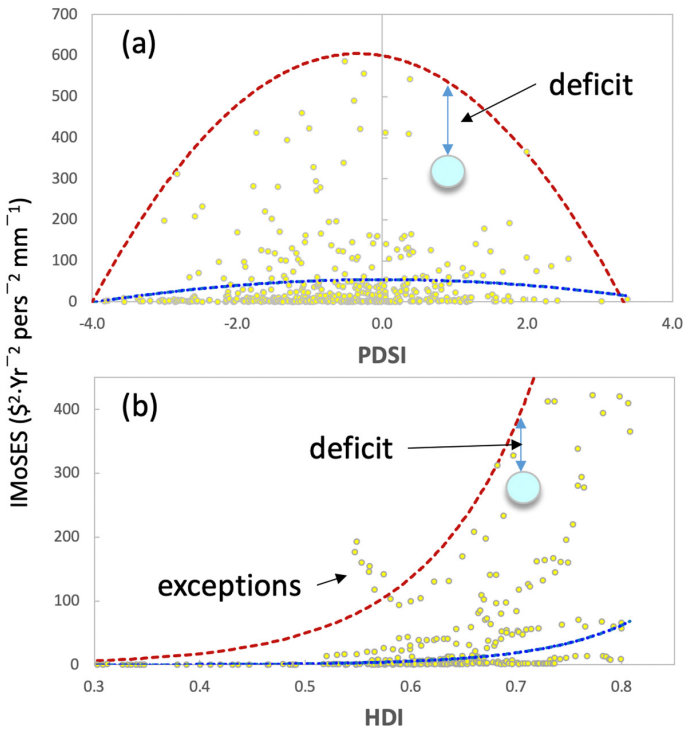


Figure 5. Changes of IMoSES with the Palmer Drought Severity Index (**a**) and the Human Development Index (**b**) for the 18 political entities during 1992–2016. IMoSES is calculated with κ = 1 (Equations (3)–(5)). The dashed blue lines are the predicted mean values from a quadratic and exponential model, respectively. The red lines define the upper limits of IMoSES—the historical potentials for different PDSI or HDI levels. The difference between IMoSES and its potential is called the IMoSES deficit. A few exceptional values greater than the regional maximum are apparent, which may be driven by other forces (e.g., global influences).

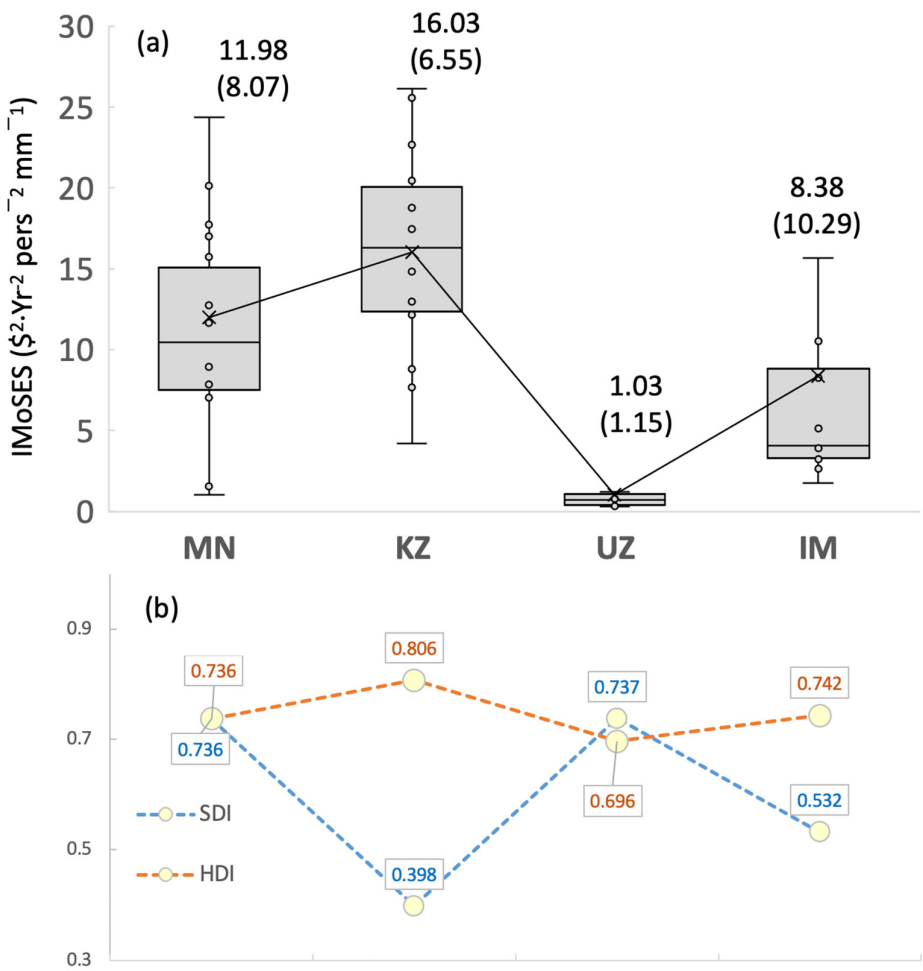


Figure 6. Boxplots of IMoSES at the prefectural level for the four political entities (PEs) in 2016 (**a**) and the PE mean values of HDI and SDI in 2015 (**b**). Note the similar values between IM and MN but different values between KZ and UZ.

1.3. IMoSES Calculation and the Intermediate Variables

IMoSES and associated intermediate variables are based on six input variables: land area (A) of the administrative unit (e.g., country), GDP, POP, carbon price (USD Mg), GPP, and PET (potential evapotranspiration) associated with the administrative unit. Multiple intermediate variables can be calculated to reflect synchronized SES functioning, such as GDP_{pc}, GPP_{pc}, POP_d and ecosystem water use efficiency (WUE). We used the historical input data (1992–2016) of Mongolia and Inner Mongolia for the calculations and values of IMoSES and the intermediate variables (Figure 1).

Mongolia (1.57 million km^2) and Inner Mongolia (1.15 million km^2) are jurisdictions with similar ecological systems but contrasting socioeconomic systems on the Mongolian Plateau. The political separation of the two in the 1920s, coupled with Chinese and Soviet influences, has caused a significant divergence in their human demographic and socioeconomic conditions [20]. The divergence of these SESs was attributed to the collapse of the USSR in 1991 and the rapid economic development of China since the mid-1990s [20,25,34,39]. During 1992–2016, the population and GDP of Inner Mongolia (IM) and Mongolia (MN) grew similarly, with approximately 10-fold and 7-fold higher levels in IM, respectively. The GPP and PET of IM are much higher than those of MN, though the patterns of interannual variation are similar. As a result of these differences, the population density of MN is ~8% of IM. Interestingly, the GDP_{pc} of MN before 1996 was higher than that of IM, but the relatively slow growth in MN resulted in a difference of 6486 USD lower than IM in 2016. Due to the high population density, GPP_{pc} of IM is ~16% of MN. Finally,

the ecosystem water use efficiency of IM is much higher than that in MG. In 2016 WUE was 0.37 for IM and 0.23 for MN. When the input variables are applied for calculating IMoSES for IM and MN, consistently higher values appear for MN than IM. In 2016, IMoSES of MN was 413.0 USD^2 $pers^{-2}$ yr^{-2} mm^{-2} versus 160.4 USD^2 $pers^{-2}$ yr^{-2} mm^{-2} for IM. More importantly, the differences in temporal changes of IMoSES for the two SESs seemed very different from those of all input and intermediate variables (Figure 1). If higher IMoSES values indicate better SES functioning, then MN had been performing consistently higher than IM, with the difference growing in the most recent decade. However, this conclusion could not be made from any input and intermediate variables.

1.4. The Uses of IMoSES

These models (Equations (3)–(5)) are based on assumptions that GDP is an appropriate measure of economic production (Equation (1)). GDP, the value of the final goods and services produced in a country, has been widely used to indicate how a nation's economy is doing [44]. Inflation is considered to produce an adjusted standard for cross-country comparison (https://data.worldbank.org/indicator/PA.NUS.PPP, accessed on 10 July 2020). Nevertheless, due to its exclusive focus on production, GDP has a limited capacity to represent progress and well-being [45]. Simon Kuznets has argued that the welfare of a country cannot be judged by GDP alone [46], and others have called GDP an overly simplistic monetary measure that represents economic growth rather economic development and noted that it does not represent well-being and other aspects of human development [45,47,48]. For these reasons, other indicators of economic strength, such as purchasing power parity (PPP), foreign direct investment (FDI), grain production, livestock production, have emerged. These alternative variables can be used effectively to indicate the achievement of certain goals (e.g., sustainability of agricultural systems). Still, GDP values have been widely reported by countries since the 1950s, while these other indicators may be limited by a lack of available data until recent years or some countries. Similar challenges may also exist for the selection of a sound measure for ecosystem production in our conceptual model (Equations (1) and (2)). As our first task in this paper, we used ecosystem primary production (i.e., GPP or NPP) to demonstrate the overall concept, partially because of its availability across countries and over long time periods. However, other metrics for measuring ecosystem functioning, such as net ecosystem production (NEP), carbon storage, species diversity, and valuations of other ecosystem services [9,49] could be used in Equations (3)–(5). Here, we focus on the conceptual foundation (Equation (1)) and the potential usefulness of IMoSES as an integrated measure of the SES function. We propose to include a set of input variables (e.g., Area, GDP, GPP, POP, etc.) and intermediate variables (e.g., POP_d, GDP_{pc}, GPP_{pc}, WUE, etc.) (Figure 1). Like any physical and social system, one cannot rely solely on a single metric to quantify system function, even an integrated metric. Similar practices of both integrative and specific property measures are very common in studying weather systems (e.g., temperature and precipitation), social systems (e.g., age structure vs. HDI), and ecosystem (e.g., NEP vs. carbon allocation) and can elucidate new understanding of system functions. In sum, applications of IMoSES should be made in the context of all conventional measures of each pillar of the system, as well as the intermediate variables (e.g., HANPP).

1.5. Practical Questions

Here we challenge ourselves with a fundamental question: Is the new metric meaningful and useful in modeling SES functioning? We tackle this important question by answering three specific questions: (1) Is IMoSES sensitive to the differences among the PEs and to time at the annual or decadal scale? If not, IMoSES will not be a useful metric describing SES function and dynamics. (2) Does IMoSES provide any new insights from its three components that describe social, economic, and environmental systems? We expect that the changes of IMoSES over time and among the SESs are different from its components (i.e., GDPpc, NPP, HANPP, POPd, WUE, etc.). (3) Is IMoSES meaningful when

compared with other independent measures of SES properties (e.g., HDI, PDSI, SDI, etc.)? We expect that IMoSES can indicate similar but different aspects of SES functioning.

2. IMoSES of the Asian Drylands Belt

To illustrate this new metric, we used information in a database from Chen et al., (2020) [50] for the countries in the Asian Drylands Belt (ADB) to calculate IMoSES and its terms for two purposes. First, we examine if IMoSES provides new insights for the SESs over those obtained using traditional measures, such as GDP_{pc} and HANPP, and other metrics used in the natural and social sciences (cf. Table 1). Second, we compare the magnitude and dynamics of IMoSES among the political entities (PEs). Here, we designate the ADB to include 18PEs, covering 14,380,099 km^2 (approximately 30° N–55° N; 30° E–120° E): Afghanistan (AF), Gansu (GS), Inner Mongolia (IM), Iran (IR), Iraq (IQ), Jordan (JO), Kazakhstan (KZ), Kyrgyzstan (KG), Mongolia (MN), Ningxia (NX), Qinghai (QH), Syria (SY), Tajikistan (TJ), Tibet (TB), Turkey (TR), Turkmenistan (TM), Uzbekistan (UZ), and Xinjiang (XJ). In this database, six Chinese provinces are treated as separate PEs due to their large land areas, positions in arid and semiarid regions, and unique cultures and economic conditions compared to other provinces of China. The database spans a time period of 25 years (1992–2016) (Figure 3). To demonstrate the utility of IMoSES at finer administrative levels, four PEs with annual provincial statistics during 2000–2016 were used. (Note: Provinces are equivalent to oblasts in KZ, vilayets in UZ, aimags in MN, and prefectures in IM).

Since IMoSES is a newly proposed metric for SES function and dynamics, we first compare the magnitude and variation of IMoSES with its major components in Equations (3)–(5) that reflect major economic, environmental, and social aspects. We then explore the variation of IMoSES with a few selected metrics that have been widely applied in studies of drylands SES: Palmer Drought Severity Index (PDSI), HDI, and SDI. HDI is among the few social indicators of social systems; whereas PDSI provides an integrative measure of drought severity—the most important forcing for the drylands regions.

Water rather than energy is the most limiting resource in the ADB countries and is consequently used as the "resource input" in calculating IMoSES in this paper (Equations (3)–(5)). While the total precipitation of a country is typically used as a proxy for water supply, we argue that total water loss through evapotranspiration (ET, mm yr^{-1}) in drylands better reflects the available water supporting the social, economic and ecological systems (i.e., the three pillars), particularly because the long-term changes in precipitation across the global terrestrial biosphere have been stable since 1880 [51,52].

3. Empirical Evidence for IMoSES Applications

The overall mean (and SD) of IMoSES for the 18 PEs over the 25-year study period is 47.19 (90.09) $USD^2\ yr^{-2}\ pers^{-2}\ mm^{-1}$, with the lowest value of 0.23 $USD^2\ yr^{-2}\ pers^{-2}\ mm^{-1}$ for Afghanistan in 2001 and the highest of 585.27 $USD^2\ yr^{-2}\ pers^{-2}\ mm^{-1}$ for Mongolia in 2012 (Table 2). Ten PEs (AF, TJ, KG, UZ, GS, NX, IQ, IR, JO and SY) have IMoSES of < 10.0 $USD^2\ yr^{-2}\ pers^{-2}\ mm^{-1}$; whereas three PEs (KZ, MN, and TB) have IMoSES of > 100.0 $USD^2\ yr^{-2}\ pers^{-2}\ mm^{-1}$. Among the three sub-regions of the ADB, IMoSES is the lowest for the Middle East (12.27 ± 18.70 $USD^2\ yr^{-2}\ pers^{-2}\ mm^{-1}$) and the highest for East Asia (75.04 ± 103.15 $USD^2\ yr^{-2}\ pers^{-2}\ mm^{-1}$). However, these sub-regional IMoSES are highly skewed by a few comparatively more affluent PEs. For example, other than Kazakhstan, all other countries in Central Asia have IMoSES of < 27.13 $USD^2\ yr^{-2}\ pers^{-2}\ mm^{-1}$. Similarly, the IMoSES for East Asia is skewed by Mongolia and Tibet; whereas Turkey's high IMoSES elevates the overall mean value for the Middle East. While this paper is not designed to assess all the nuances of performance of SES among countries of the ADB region, numerous publications indicate that Afghanistan, Iraq, and Syria have been hindered in their SES development by frequent geopolitical conflicts, whereas Turkey, Kazakhstan, Mongolia, and some parts of China experienced steady growth of their SES [39,53]. The large ranges of IMoSES values indicate that this new integrative metric is sensitive to

PE and varies in time – a promising sign because a lack of sensitivity would point to an indicator of little practical value for tracking SES dynamics. However, future efforts are needed to calculate IMoSES for a broader range of countries and different time periods so we may examine the relative positions of countries and regions in a global context.

To answer the first question (i.e., Is IMoSES sensitive to the differences among the PEs and to time at the annual or decadal scale?), we can examine the magnitude and variation of IMoSES among the 18 PEs across the ADB region. There appears to be a general increase in IMoSES over the 25-year study period for all 18 PEs, albeit with temporal variation (Figure 4). IMoSES values in all PEs, except Iraq and six provinces of China, decreased during the 1990s. Although it is beyond the scope of this study to detail the causal underlying mechanisms driving the observed changes, the decreasing and rebounding of IMoSES values for the five countries in Central Asia and Mongolia are likely due to the formal disintegration of the Soviet Union in 1991 and the profound socio-economic and biogeophysical consequences of this profound shift in institutions [50,54]. For example, Kazakhstan is heavily reliant on trade with Russia, so the decline in IMoSES after 2013 likely reflects the impacts of international sanctions on Russia following the invasion of Crimea in 2014. For Iraq, Afghanistan, and Iran, we can speculate that a period of intensifying violence in Iraq related to the Islamic State (BBC 2018; https://www.bbc.com/news/world-middle-east-14546763), accessed on 1 June 2020), as well as the Gulf Wars (1990–1991) and Iraq–Iran conflicts (1980–1988) that may have degraded the functioning of their SES. Syria presents an interesting case: it showed decreases in the early 1990s—comparable to other Middle East countries—but exhibited stable and increasing IMoSES values during 2001–2011. A sharp decrease appeared after 2011 (Figure 4a), which corresponds well to the beginning of the civil war from 2011 onwards. As expected, the steady increases in IMoSES for the six PEs in China corresponded well to the accession of China to the World Trade Organization (WTO) in 2001 [25,30]. The differences among Chinese PEs might be further explained by various policies of the central government, including the drive to promote economic development in China's western regions [55,56]. Clearly, institutional changes (including new policies, cross-country geopolitical conflicts, etc.) can have strong and lasting effects on IMoSES [29,30,57]. More importantly, the sensitivity of IMoSES to institutional changes further suggests IMoSES is a useful measure for quantifying SES dynamics.

For the second question (i.e., Does IMoSES provide any new insights from its three components that describe social, economic, and environmental systems?), we can compare IMoSES with three dominant components at PE and sub-region levels: GDP_{pc}, POP_d and HANPP (Equations (3)–(5)). In this regard, we compared the long-term mean (SD) of IMoSES with GDP_{pc}, POP_d and HANPP for the 18 PEs (Figure 4). The means and variations of IMoSES are very different from those of any three components among the PEs. By definition, IMoSES has a positive relationship with GDP_{pc} and HANPP, but a negative relationship with POP_d (Equations (1)–(4)). These relationships appear consistent, albeit with large differences among the PEs. Overall, Turkey, Kazakhstan, and Mongolia are the top three PEs for their IMoSES, which matches well with their relatively high HANPP (Figure 4d) and low POP_d (Figure 4c). However, the high IMoSES for Kazakhstan is due to high GDP_{pc} and low POP_d; whereas Mongolia and Turkey have relatively low GDP_{pc}. Among the PEs with low IMoSES, GDP_{pc} and HANPP are comparatively lower while POP_d is high. Increased IMoSES values can arise from rising GDP_{pc} and HANPP and declining POP_d over long time periods, except in times of armed conflict or a pandemic. In conclusion, we are convinced that IMoSES provides insights that none of the three components alone do. More importantly, the metric provides policymakers with some idea about the dynamics of each of the pillars, which can be used to identify SES dimensions requiring additional research and perhaps policy attention to move PEs toward improved and more sustainable IMoSES. For example, lessons from the different rebounding processes of Central Asian countries and Mongolia could identify constraining mechanisms in slowly recovering countries after the collapse of the USSR (Figure 3).

To address the utility of IMoSES in our third question (i.e., Is IMoSES meaningful when compared with other independent measures of SES properties?), we examine its relationships with other integrative measures of SES: (1) PDSI, which is an effective measure of environmental stress, and (2) HDI, which is a robust indicator of social conditions (Figure 5). We caution that PDSI is calculated with some common variables (e.g., temperature and precipitation), suggesting that IMoSES is not completely independent of PDSI. Overall, IMoSES increases with PDSI in dry-to-normal conditions (PDSI < 0) and decreases in normal-to-wet conditions (PDSI > 0) (Figure 5a). The changes in IMoSES with PDSI are similar to the environmental Kuznets curve depicting the relationship between environmental degradation and economic development [58]. IMoSES rises to its peak where water stress is minimal (i.e., not too dry or wet), after which, IMoSES declines as conditions become wetter (Figure 5a). This behavior suggests that deviations from the average PDSI for a region are negatively associated with SES functioning. More importantly, we used a quadratic model to estimate the upper envelope of values in the scatterplots—the potential maximum IMoSES for ADB countries. Each data point (i.e., a country or PE in a specific year) defines its current position and deficit from IMoSES potential for improvement. By comparing the theoretical potentials with the actual IMoSES values, it is clear that some PEs may have reached their potentials in the past, while the majority of PEs had much lower values regardless of drought severity (i.e., high deficits), suggesting that there is room for most countries to improve.

IMoSES exhibits an exponential relationship with HDI (Figure 5b); this strong relationship demonstrates its new potential to reflect the human dimensions of SES. However, GDP_{pc} is a large portion of GNI_{pc} that was used to calculate HDI, indicating that the relationship is not completely independent. Nevertheless, the clear exponential relationship between IMoSES and HDI suggests that IMoSES reflects some values of HDI; otherwise, the relationship would not exist. We also built an exponential model for the upper envelope of IMoSES values as the historical maximum (i.e., the potentials). IMoSES deficit—the difference from maximum IMoSES—would then indicate the improvement level that could be achieved if the goal is to reach a high IMoSES. Based on the historical data, some exceptional values appear that may have resulted from policy shifts, unique SES structure, global influences, and other driving forces (also see Figure 3).

To demonstrate the use of IMoSES at other administrative levels, we calculated IMoSES using the provincial statistics of four PEs and compared them with HDI and SDI (Figure 6). Provincial statistics from two pairs of PEs in 2016, with one from East Asia (IM and MN) and one from Central Asia (KZ and UZ), were collected. Among the four PEs, the highest mean (SD) $USD^2\ yr^{-2}\ pers^{-2}\ mm^{-1}$ of 16.03 (6.55) was found for Kazakhstan and the lowest of 1.03 (1.15) for Uzbekistan. Between Mongolia and Inner Mongolia, a higher IMoSES was found for Mongolia than for Inner Mongolia, which is likely due to the much higher (> 10×) population density in Inner Mongolia. POP_d in Uzbekistan is 11.4 times that of Kazakhstan (Figure 4c). One of the reasons for its comparatively low IMoSES however is that Kazakhstan has higher revenues from mining and oil and gas production than Uzbekistan (https://databank.worldbank.org, accessed on 1 June 2020). More importantly, IMoSES mirrors positive and negative patterns with HDI and SDI, respectively (Figure 6b), displaying that the correlations are not linear (see Figure 5). Both SDI and HDI in Kazakhstan are lower than in Uzbekistan, making IMoSES different from HDI and SDI. Future efforts are needed to examine the changes in IMoSES with other integrative measures, such as the Gini Coefficient and renewable energy/total energy, environmental sustainability index, etc. [5,10,59].

Our empirical evidence from the ADB region suggests that IMoSES is a truly integrative measure of SES function and dynamics. Despite widespread adoption of the concept of SES as a framework for studying coupled systems, more often systems are studied via uncoupled metrics. IMoSES is a product of GDP_{pc} and HANPP, rather than the linear sum of three components that is applied in other integrative indicators (e.g., HDI). The square root converts IMoSES into a measure of SES performance per capita

(USD^2 yr^{-2} $pers^{-2}$ mm^{-1}). With a unit of mm yr^{-1} for ET, IMoSES represents the water use efficiency of the SES. The use of the κ parameter provides an option for emphasizing the strength of ET regulations. An alternative expression is about SES performance (i.e., the product of GDP_{pc} and POP_d) that is regulated by ecosystem WUE. Our equations also address the lack of an environmental regulatory function in the HDI formula [13]. Other energy or natural resources could replace ET as the ecological foundation for an SES.

Historical data based on 18 PEs across the ADB (1992–2016) and on subnational scales in four countries for 2016 show that the IMoSES captures different aspects of SES function and dynamics. Although the IMoSES values and changes over time will be different when more countries are included, the unit of USD^2 yr^{-2} $pers^{-2}$ mm^{-1}, or USD yr^{-1} $pers^{-1}$ mm^{-1}, will remain the same and permit direct comparisons between PEs. An effort to calculate IMoSES for all countries globally will tell us about their magnitudes, differences, changes over time, and potentials. However, attention is needed to identify the appropriate values of κ and apply them consistently for comparisons among countries and over time. PDSI, HDI and SDI are used as the two independent metrics to demonstrate the effectiveness of IMoSES. The strong correlations with PDSI indicate that IMoSES changes with environmental conditions, similar to the idea behind the environmental Kuznets curve.

These results present several avenues for future research. First, it is necessary to investigate why other environmental indicators in place of PDSI, HDI and SDI (e.g., temperature, precipitation, CO_2 emission, N_2O emission, land use, etc.) exhibit different relationships with IMoSES, in order to explore how well IMoSES aligns with various indicators of environmental vitality [60]. Second, research on the relationship between IMoSES and other social indicators (e.g., life expectancy, educational attainment, gender equality) would increase understanding of the alignment between GDP and aspects of social well-being that together encapsulate the idea of economic development. Three, the metric we developed may be useful for the assessment of progress towards the Sustainable Development Goals (SDGs; https://sdgs.un.org/goals, accessed on 1 June 2020) by tracking the temporal trajectories of IMoSES across countries during the recent past to reveal how this concept maps onto SDG progress for specific countries. Specifically, our metric can be related to a number of goals, including ending poverty and promoting decent work and economic growth, human wellbeing, and climate action. Relatedly, more efforts are needed to explore if integrated metrics, including IMoSES, can be used in policy development and decision making. Here, lagging components of the metric can be selected for additional analysis and policy development. For example, stagnant or declining GDP relative to the other two-pillar components may suggest a need for policy action to raise domestic income. Stagnant or declining NPP relative to the other two indicators may indicate a need for policies to improve the environmental conditions of PEs. Future research could also extend the calculation and analysis of IMoSES to other countries, regions, biomes, or development stages (e.g., higher-income countries vs. lower-to-middle income countries) [61]. A potential revision of the proposed IMoSES is to standardize its values through normalization for a given scale (e.g., by region, continent, or time period). These steps would enable us to group countries by IMoSES in a way that is akin to "convergence clubs" in economics—by identifying countries that exhibit similar growth trajectories [62]. We provided preliminary evidence that "IMoSES clubs" are likely, as distinct over- and under-performers were evident within the three regional categories of ADB PEs (East Asia, Central Asia, and the Middle East). Among the Middle Eastern countries, Turkey had higher IMoSES than other countries in its group. In Central Asia, Kazakhstan had the highest IMoSES. From a global perspective, it would be important to identify countries with similar IMoSES trajectories, which are indicative of similar dynamics among the three pillars of sustainability.

4. Conclusions

Fostering sustainable development involves navigating and responding to a myriad of hazards and limiting exposure to high-risk events and consequences. At the same time,

political entities need to foster and support human development in the face of environmental variation and extreme events. IMoSES offers a new lens to assist in balancing these complex, contingent tradeoffs between various ecosystem services, economic productivity, wealth creation and distribution, and their latent impact on human health and well-being. We used public data from ADB countries to illustrate the utility of the IMoSES—an integrative metric as the product of economic and ecosystem production efficiency, although we do not know how well this metric captures SES dynamics elsewhere and at different spatial (e.g., global, continental, biome) and temporal (e.g., annual, years, and decades) scales. Future research will extend calculation and analysis of IMoSES to other countries, regions, biomes, or development stages economic status (e.g., global south vs. developed countries higher-income countries vs. lower to middle-income countries) [61]. A potential revision of the proposed IMoSES is to standardize its values through normalizations for a given scale. These steps would enable us to group countries by IMoSES in a way that is akin to "convergence clubs" in economics—by identifying countries that exhibit similar growth trajectories [62].

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