Using gross ecosystem product (GEP) to value nature in decision making

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Gross domestic product (GDP) summarizes a vast amount of economic information in a single monetary metric that is widely used by decision makers around the world. However, GDP fails to capture fully the contributions of nature to economic activity and human well-being. To address this critical omission, we develop a measure of gross ecosystem product (GEP) that summarizes the value of ecosystem services in a single monetary metric. We illustrate the measurement of GEP through an application to the Chinese province of Qinghai, showing that the approach is tractable using available data. Known as the "water tower of Asia," Qinghai is the source of the Mekong, Yangtze, and Yellow Rivers, and indeed, we find that water-related ecosystem services make up nearly two-thirds of the value of GEP for Qinghai. Importantly most of these benefits accrue downstream. In Qinghai, GEP was greater than GDP in 2000 and three-fourths as large as GDP in 2015 as its market economy grew. Large-scale investment in restoration resulted in improvements in the flows of ecosystem services measured in GEP (127.5%) over this period. Going forward, China is using GEP in decision making in multiple ways, as part of a transformation to inclusive, green growth. This includes investing in conservation of ecosystem assets to secure provision of ecosystem services through transregional compensation payments.

gross ecosystem product | ecosystem services | natural capital | environmental–economic accounting | GDP

The global economy, as conventionally measured by gross domestic product (GDP), more than doubled between 1990 and 2015 in constant dollar terms (1). At the same time, however, the world's stocks of ecosystem assets (such as forests, grasslands, wetlands, fertile soils, and biodiversity) and the flows of ecosystem services they provide have come under increasing pressure. The loss and degradation of ecosystem assets has raised widespread concern about the resilience and sustainability of ecosystem services and the consequent threat to the economic activity and human well-being that they support (2–8). The contrast between economic growth and environmental degradation is particularly striking in China. Over the past quarter century the economy has expanded 10-fold (1). The size of the Chinese economy is currently second only to the United States and accounts for roughly 15% of world GDP (1). However, this rapid economic growth has been accompanied by environmental degradation in many regions of China (9–11).

There is by now widespread recognition of the need to move beyond measures of GDP so that decision makers also pay attention to important ecological and social determinants and dimensions of well-being (12–14). China is of global significance, with its combination of rapid economic growth alongside escalating threats to its ecological wealth, and is driving innovative work to bring ecological information into decision making. The need to protect and restore ecosystem assets in order to maintain and enhance the flow of important ecosystem services has been acknowledged at the highest levels of the Chinese government. In a widely cited speech to the 19th Communist Party of China National Congress, President Xi Jinping said that "lucid waters and lush mountains are invaluable assets" (15).

Here we focus on the development of gross ecosystem product (GEP), a measure that translates ecosystem contributions to the economy into monetary terms. Much of the power of GDP comes from its simplicity as a single monetary metric readily understood by decision makers. Although the economy is incredibly complex, with hundreds of thousands of goods and services, GDP uses market prices and surrogates for market prices to combine the accounting value of goods and services into a measure of aggregate income. Just like the economy, ecosystems are incredibly complex and contribute to human well-being in myriad ways. Analogous to GDP, GEP uses market prices and surrogates for market prices to calculate the accounting value of ecosystem services and aggregate them into a measure of the contribution of ecosystems to

Significance

To achieve sustainable development, there is a pressing need to move beyond conventional economic measures like gross domestic product (GDP). We develop gross ecosystem product (GEP), a measure that summarizes the value of the contributions of nature to economic activity. We illustrate the calculation of GEP in Qinghai Province, China, to show that the approach is tractable both across China and globally. Known as the water tower of Asia, Qinghai is the source of the Mekong, Yangtze, and Yellow Rivers and nearly two-thirds of GEP derives from water-related values. GEP was greater than GDP in Qinghai in 2000, and was three-fourths as large as GDP in 2015. China is using GEP to guide investments in ecosystem conservation and restoration.

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the economy. The power of GEP is enhanced by using similar methods for its construction as those underpinning GDP.

To become as influential as GDP in decision making, GEP must be readily calculable from available data. A wealth of biophysical data exist on which to develop ecological measures. Ouyang et al. (10) used multiple metrics from China's National Ecosystem Assessment (16) to summarize the change in ecological conditions and ecosystem services between 2000 and 2010. One problem with using only biophysical measures, however, is the involvement of multiple noncommensurate metrics, which pose a substantial challenge for incorporation within conventional decision making. For example, how can we compare changes in water quality measured in milligrams per liter of nitrogen with changes in greenhouse gas emissions assessed in tons of carbon equivalent? Furthermore, how can we compare these metrics to the costs of investment in restoration or the value of alternative investments? Here, we use data on market prices where available, and develop methods to estimate surrogate prices where market prices do not exist for ecosystem services. We then combine the values of different ecosystem services into an aggregate measure of GEP.

We illustrate the development and application of GEP in a case study of Qinghai Province, China, a region rich in endowments of ecosystem assets. For Qinghai, we first calculated the value of a suite of important ecosystem services. Limitations of data—and, more fundamentally, of scientific understanding—preclude valuing all known ecosystem services (there or anywhere). This case confirms, however, the potential for successful development and application of a GEP measure using existing data for a reasonably complete set of important services. Second, given policy concerns over the relatively low GDP per capita in Qinghai, we also examine the implications for income redistribution of potential ecosystem asset protection payments between regions. Devoting resources to protecting ecosystem assets can thereby serve the dual goals of environmental sustainability and poverty alleviation.

Our work to develop GEP builds on prior work to develop integrated environmental–economic accounts, including work led by the United Nations Statistics Division to develop the System of Environmental–Economic Accounting (SEEA) (17), whose definition of accounting value we follow, and the SEEA Experimental Ecosystem Accounting (EEA) (18). SEEA EEA is currently under revision (refs. 19–22 discuss recent advances) with the objective to elevate it to an international statistical standard on par with the System of National Accounts (23). There are several global initiatives to build environmental–economic accounts using the SEEA framework, including the United Nations Statistics Division's Natural Capital Accounting and Valuation of Ecosystem Services project, and the Wealth Accounting and Valuation of Ecosystem Services partnership led by the World Bank. This approach has been applied recently at a country scale (e.g., refs. 24 and 25). There are also related efforts by the World Bank to measure the *Changing Wealth of Nations* (26) and by various groups to measure inclusive/comprehensive wealth (e.g., refs. 27–34).

Our work applies spatially explicit integrated ecological–economic modeling that predicts the flow of ecosystem services and then applies economic valuation methods to estimate the value of ecosystem services (35–38). Much of the work on spatially explicit ecosystem services modeling advances particular applications, ranging from analysis of specific policy interventions or scenarios at local (e.g., refs. 39–41) to national levels (e.g., refs. 10, 42, and 43). Following Ouyang et al. (44), a number of papers have applied spatially explicit integrated ecological–economic modeling to estimate the value of ecosystem services in China, including ecosystem services from forests (45–49), wetlands (50–53), croplands, and grasslands (54–58) (see refs. 59 and 60 for reviews).

Our work on GEP contributes to the existing research in two main ways. First, GEP is a novel aggregate measure of the value of ecosystem services, which summarizes the contributions that nature makes to the economy (61–63). Second, we combine recent advances in ecosystem services modeling approaches with an integrated environmental–economic accounting framework consistent with the SEEA to demonstrate how to make progress on empirical measures with existing data.

The government of China is now actively working to develop and implement GEP. The National Development and Reform Commission, in coordination with the Ministry of Ecology and Environment, has launched pilot studies of GEP at provincial, municipal, and county levels. These pilots are aimed at developing GEP for evaluating government performance in key regions (officially designated as "key ecological function zones"), and for assessing the effectiveness of policy to sustain cross-regional flows of ecosystem services and improve livelihoods through compensatory transfer payments between areas (63) (see *SI Appendix*, section S2 *GEP Application in China*, and Tables S8 and S9 for a list of ecological compensation programs and projects in China).

Measuring GEP

We constructed GEP using methods that parallel those used to calculate GDP. A measure of aggregate income, GDP is equal to the sum of the value added (value of outputs less value of inputs) of all goods and services produced by economic units in a given region in an accounting period. Tracking real GDP over time provides information about the growth or decline in income for an economy. GEP is a measure of the aggregate monetary value of ecosystem-related goods and services (hereafter "ecosystem services") in a given region in an accounting period. Ecosystem services can be classified into material services (the contribution of nature to the provision of food, water supply, and so forth), regulating services (the contribution of nature to carbon sequestration, flood mitigation, soil retention, sandstorm prevention, and so forth), and nonmaterial services (the contribution of nature to ecotourism, nature experience for mental health, and so forth) (5).

In cases where market prices for ecosystem services do not exist, we used a variety of nonmarket valuation techniques to generate ecosystem service accounting prices. When an ecosystem service is an input into a marketed good or service (e.g., pollination of agricultural crops), we can use the value of the marketed good net of the value of inputs other than ecosystem services (e.g., labor, machinery, commercial fertilizer, and so forth). We can also use the value of marginal product: That is, the increase in the market value of marketed goods generated by input of the ecosystem service. Examples of the value of marginal product approach from the literature include the impact of water flows upon hydropower production (64), pollination services boosting the production of coffee and other agricultural production (65, 66), and the impact of climate regulation upon agricultural production (67).

Accounting prices for other ecosystem service values can be proxied using measures of avoided cost or replacement cost, such as when ecosystems filter nutrients, providing clean water to downstream users. The value of this service can be calculated using the (avoided) cost of removing nutrients via water treatment plants. Such cost-based methods are only valid, however, when certain conditions are met, including that the replacement method is the lowest cost alternative and that people would be willing to pay the cost of replacement to provide the service (68). Other approaches for estimating the economic value of ecosystem services, using revealed and stated preference methods, are also useful (69).

By using readily calculable ecosystem service accounting prices, GEP provides a tractable approach to bringing ecosystem services, including those that are not marketed, into decision making. The methods used for estimating the quantity and the accounting value for each ecosystem service are detailed in the first section of *SI Appendix*.

It is important to note that some ecosystem services are inputs into marketed goods and services that are included in GDP. For example, the ecosystem service of pollination enhances the value of agricultural outputs. Therefore, there is overlap between GEP and GDP and one cannot simply add the two measures together. GEP and GDP measure different things. GEP counts the value of inputs from nature but not the entire value of all final goods and services in an economy. GDP, on the other hand, includes many final goods and services not counted in GEP. However, some benefits from nature are not included in the final goods and services measured in GDP. Given this distinction, the two measures together provide vital and complementary information for decision makers.

Both GEP and GDP use accounting measures to estimate the value of goods and services, rather than a measure of economic welfare. Accounting measures equivalent to income suffer from well-known problems, such as an increase in value when supply declines and demand is inelastic; in contrast, welfare necessarily declines with a contraction of supply. Accounting measures, however, are typically far easier to calculate, do not require estimating elasticities, and do not require more extensive (and sometimes inaccessible) data for calculating welfare measures.

While GEP and GDP are useful measures of current flows of value, they are not adequate indicators of sustainability as neither considers the capital stocks (natural or man-made) upon which they rely. Current income can be increased through the nonsustainable use of ecosystem assets, for example by harvesting a stock above its replacement or renewal rate. Measures of sustainability should be tied closely to measures of the value of assets (28, 34). In principle, changes in the value of ecosystem assets could be used to calculate net ecosystem product by incorporating the change in the value of stocks of ecosystem assets into GEP. The value of an ecosystem asset should, in principle, equal the present value of the flow of all ecosystem services generated by the ecosystem asset, which offers a way to estimate its values. There have been several attempts to measure stocks of ecosystem assets in monetary terms (27–33). These efforts have excluded consideration of many types of ecosystem assets, however, generally including only the value of assets closely tied to market values (minerals, oil and gas, timber, fish). In practice, estimating ecosystem asset values is difficult, and China along with most applications of the SEEA EEA framework currently measure ecosystem assets in biophysical rather than monetary terms. Alongside GEP, China is tracking change in the stocks of ecosystem assets to account for the depreciation or appreciation of assets (70).

Case Study: GEP of Qinghai Province

Qinghai Province. Qinghai Province is located in western China (Fig. 1), on the northeastern part of the Tibetan Plateau, with an area of 722,000 km^2 and a population of 5.8 million. Because of its high altitude and inland location, Qinghai has cold winters (with lows of −7 to −18 °C in January), mild summers (highs of 15 to 21 °C in July), and a large diurnal temperature variation. The pattern of precipitation also varies both spatially and temporally across the province, decreasing from southeast to northwest and being very low in winter and spring but substantial in summer.

Qinghai provides a crucial store of natural capital and ecosystem service flows for much of China. Known as the "water tower" of East and Southeast Asia, Qinghai is the source of three major rivers: The Yellow River originates in the central part of the province, while the Yangtze and Mekong Rivers originate in the southwest. Qinghai provides 47.0 billion m^3 of water annually for other parts of China and Southeast Asian counties (71).

The dominant ecosystem type in Qinghai is grassland, including meadows and steppe. Grasslands occupy 52.5% of the region, mostly distributed in the central part of the province (Fig. 1). There is a single growing season per year from April to October, with peak growth occurring during July and August.

Qinghai is also a global hot spot for biodiversity. It is the home of many endangered species, such as Tibetan antelope (*Pantholops hodgsonii*), snow leopard (*Uncia uncial*), wild yak (*Bos mutus*), Bactrian camel (*Camelus ferus*), Asiatic wild ass (*Equus hemionus*), Black-necked Crane (*Grus nigricollis*), and Snowcock (*Tetraogallus tibetanus*). Qinghai has 11 nature reserves, covering 21.77 million ha, about 30% of the total area of the province.

Since 1970, rapid population increases and overgrazing have caused grassland degradation and desertification, resulting in loss of biodiversity and ecosystem services (72). Ecosystem degradation became a key concern for the Chinese government in early 2000. Qinghai is a high-priority area for conservation and ecosystem restoration and the Chinese government has implemented a number of regional eco-compensation programs to restore overgrazed and degraded grasslands, conserve forests, and wetlands, and restore watershed ecosystem services. These programs have also

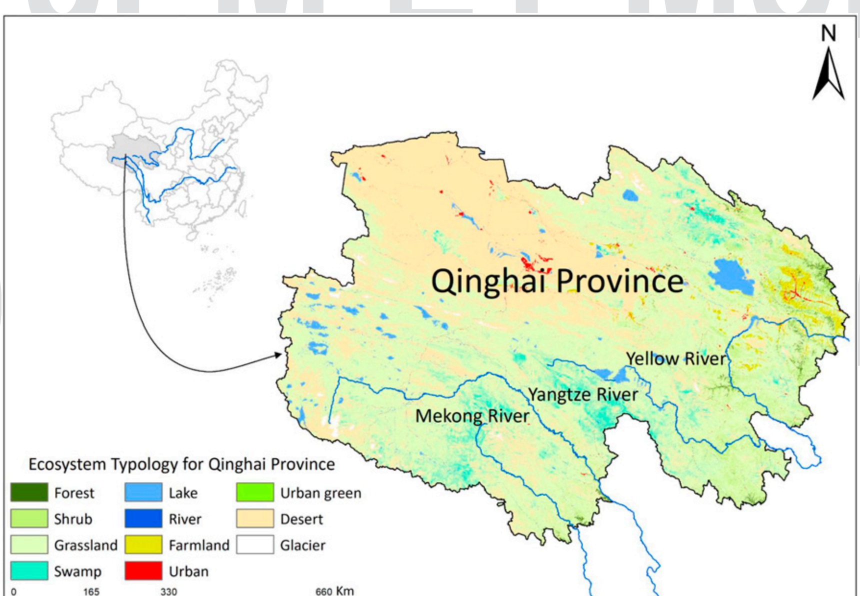

Fig. 1. The distribution of ecosystem types across Qinghai Province, and depiction of the headwaters of the Mekong, Yangtze, and Yellow Rivers.

embodied significant poverty alleviation objectives. During 2010 to 2015, the central government budgeted 45.819 billion Yuan ($7.4 billion) for different eco-compensation programs to improve ecosystems and human well-being in the province (63) (see *SI Appendix*, section S3 *Eco-Compensation in Qinghai Provence* and Table S10 for a list of eco-compensation programs in Qinghai.).

Methods for Calculating GEP in Qinghai. We assessed the biophysical quantities and monetary value of ecosystem services in Qinghai using a variety of data and models. The value of GEP is defined as

$$GEP = \sum_{i \epsilon I} \gamma_i p_i q_i,$$

where I is the set of ecosystem services, γ_i is the proportion of accounting value attributable to nature, p_i is the accounting price of ecosystem service i, and q_i is the quantity provided of ecosystem service i. For regulatory ecosystem services, the entire value of the services is attributable to nature ($\gamma_i = 1$). For other services, including many material services, there is a contribution from human labor and human-made inputs, so that $\gamma_i < 1$. We had information to allocate the contribution between nature and human inputs for agriculture and animal husbandry, but we lacked such information for other provisioning services (forestry, fisheries, and nursery products), all of which make up a small proportion of GEP in Qinghai.

We provide detailed descriptions of data sources and methods in *SI Appendix*. For material services, we relied primarily on published data on production and prices (*SI Appendix*, section S1.1, *Material Services*). For regulating services, we relied on biophysical data from government sources and use the InVEST suite of models (73) to calculate the provision of services (*SI Appendix*, sections S1.2–S1.8). We then applied a variety of market and nonmarket valuation methods to convert provision of services into monetary estimates of value. For nonmaterial services, in this case ecotourism, we applied travel cost methods using a survey on visitation and trip expenditures (*SI Appendix*, section S1.8 *Nonmaterial Services*). We also accounted for the monetary value of the ecosystem services generated in Qinghai to different beneficiaries (in Qinghai Province, other provinces in China, and globally).

Results: GEP Accounting in Qinghai. The GEP of Qinghai in 2015 was 185.4 billion Yuan, an increase of 127.5% over GEP for 2000 (Table 1). As befits the "water tower" of Southeast and East Asia, water supply was the single most important ecosystem service, contributing over half of the total value of GEP in 2015 (57.6%). Overall, material services, which include water supply, contributed 64.7% of the total value of GEP. The other main material services included husbandry products (3.1%) and agricultural products (3.0%). Regulating services contributed 23.7% of the total. The most important regulating service was sandstorm prevention (17.1%). Other important regulatory services were soil retention (3.8%) and carbon sequestration (2.5%). The value of nonmaterial services, represented here solely by ecotourism, contributed 11.7% of GEP in Qinghai.

The change in the value of GEP from 2000 to 2015 can be attributed to changes in supply, changes in price (value per unit), and other changes that affect use of ecosystem services. Despite the fact that the volume of water supply actually fell from 45.25 to 39.56 billion m^3 between 2000 and 2015, the value of this supply actually increased from 47.8 to 106.7 billion Yuan over the same period. Some of this change in value resulted from increases in prices (14.4 billion Yuan). However, the majority of the increase in the value of water supply occurred because of changes in the use of water, such as the increase in the number of hydroelectric dams downstream, which increased power generation from 21.3 to 92.0 billion kwh between 2000 and 2015.

For agricultural production, while the total tonnage produced in Qinghai almost doubled between 2000 and 2015 (1.7 to 3.1 million tons), its value increased by 482% (1 billion Yuan to 5.6 billion Yuan). A small portion of this increase was due to higher prices for agricultural products (0.4 billion Yuan), while the vast majority of the increase in value (4.2 billion Yuan) was due to changes in composition of the production as well as the increase in tonnage. Production in Qinghai shifted toward medicinal plants, melons, and vegetables that command a much higher price per ton than the cereals that made up the majority of output in 2000. Overall, the increase in GEP between 2000 and 2015 due to changes in supply and use was 75.5 billion Yuan, while changes in prices accounted for 28.4 billion Yuan. The precipitation gradient in Qinghai increases from west to east. Ecosystem services related to water (e.g., water supply, flood mitigation) generally show higher values in eastern Qinghai compared to western Qinghai (Fig. 2). Population density is also higher in eastern Qinghai, generating higher value for air purification and sandstorm prevention (Fig. 2).

Many of the ecosystem services produced by Qinghai provide benefits to people living outside the province (Fig. 2). For example, water supply primarily benefits people living downstream, sandstorm prevention primarily benefits people living downwind, and carbon sequestration provides global benefits. We attributed the value of all other services based on where the majority of benefits accrue. Accordingly, we attributed the value of domestic and industrial water use and hydroelectric generation in Qinghai to local benefits, and the rest of water-supply benefits to downstream users. We attributed the value of material services except for water supply (agricultural, forestry husbandry, fishery, and nursery production) because producers in Qinghai either gain value by selling products in the market or by consuming the products themselves. We also attributed the value of air purification and ecotourism to local benefits. We attributed the majority of the value of water supply, along with regulating services except air purification and carbon sequestration (i.e., soil retention, sandstorm prevention, flood control, water purification) to regional benefits, and carbon sequestration to global benefits.

With this classification, less than one-third of ecosystem services generated in Qinghai benefit residents of Qinghai, the remainder being exported out of the province. The large majority of these benefits accrue regionally to other provinces within China with only a small percentage accruing globally (2.5% for carbon sequestration).

Discussion

GEP can provide decision makers with clear and compelling evidence of the monetary value of ecosystem services. The Qinghai results demonstrate that it is feasible to produce an estimate of GEP with available data and methods: That is, that there is a tractable approach to producing estimates of GEP, not just in Qinghai but all across China, and indeed for all countries in the world.

GEP converts ecosystem services into a common monetary metric that is easy to interpret. Widely publicizing GEP can provide visibility and give prominence to the values of nature and their contributions to human well-being, just as GDP has provided visibility and given prominence to economic performance. Having measures of GEP can help to overcome the bias in public and private sector decision making, currently dominated by considerations of economic growth to the exclusion of important ecosystem services and the conservation of ecosystem assets.

GEP can contribute to achieving important societal objectives, such as sustainable development, by bringing the value of ecosystem services and trends in ecosystem assets into public and private sector decision making and investment planning. Recent experience in Zhejiang Province shows that providing government leaders with information about ecosystem assets and the goods and service they provide advances investments and other progress toward sustainable development (74). A tractable measure

Table 1. GEP accounting in Qinghai (2000 to 2015)

			2000			2015			2000–2015 (2015 constant price)		2000–2015 (Current price)		
Types of service	Category of ecosystem services	Accounting items	Biophysical quantity	Monetary value (billion Yuan)	Percent of total value, %	Bio-physical quantity	Monetary value (billion Yuan)	Percent of total value	Amount of change (billion Yuan)	Percent change, %	Amount of change (Billion Yuan)	Percent change, %	Valuation method
Material services	Production of ecosystem goods	Agricultural crop production ($\times 10^3$ *t*)	1652.1	1.0	1.2	3091.2	5.6	3.0	4.2	310.6	4.6	482.1	Market prices
		Animal husbandry production ($\times 10^3$ *t*)	458.7	1.1	1.4	724	5.8	3.1	4.2	266.4	4.7	419.4	
		Fishery production ($\times 10^3$ *t*)	1.2	0.01	0.01	10.6	0.3	0.1	0.3	2351.5	0.3	3375.0	
		Forestry production ($\times 10^3$ *t*)	19.5	0.2	0.2	10.4	0.7	0.4	0.5	247.1	0.6	392.1	
		Plant nursery production ($\times 10^9$ plants)	0.3	0.2	0.2	11	0.7	0.4	0.5	190.8	0.6	312.2	
	Total production of ecosystem services			2.5	3.0		13.1	7.1	9.7	284.1	10.7	444.5	
	Water supply	Water use in downstream agricultural irrigation ($\times 10^9$ m^3)		11.8	14.5		15.0	8.1	−1.5	−9.3	3.2	26.8	Market prices for water
		Water use in households ($\times 10^9$ m^3)		5.3	6.5		13.8	7.4	6.4	86.5	8.5	160.4	
		Water use in industry ($\times 10^9$ m^3)		19.4	23.8		29.2	15.8	2.2	8.1	9.8	50.5	
		Hydropower production ($\times 10^9$ kwh)	21.3	11.3	13.9	92	48.8	26.3	37.5	331.6	37.5	331.6	Market prices for electricity
	Total water supply			47.8	58.7		106.7	57.6	44.5	71.6	58.9	123.3	
Regulating services	Flood mitigation	Flood mitigation ($\times 10^9$ m^3)	0.07	0.02	0.03	0.07	0.03	0.02	0.001	2.3	0.01	45.0	Avoided water storage costs
	Soil retention and nonpoint pollution prevention	Retained soil ($\times 10^9$ *t*)	0.4	4.8	5.9	0.4	7.0	3.8	0.13	1.9	2.1	44.5	Avoided treatment costs
		Retained N ($\times 10^3$ *t*)	9.8	0.01	0.01	10	0.02	0.01	0.0003	1.9	0.01	103.9	
		Retained P ($\times 10^3$ *t*)	0.7	0.002	0.002	0.7	0.002	0.001	0.00004	2.0	0.00004	2.0	
	Water purification (wetland)	COD purification ($\times 10^3$ *t*)	33.2	0.02	0.03	104.3	0.1	0.1	0.1	214.0	0.1	528.0	
		NH-N purification ($\times 10^3$ *t*)	3.5	0.003	0.004	10	0.02	0.01	0.01	186.8	0.01	473.6	
		TP purification ($\times 10^3$ *t*)	—	—	—	0.9	0.003	0.001	—	—	—	—	
	Air purification	SO_2 purification ($\times 10^3$ *t*)	32.0	0.02	0.02	150.8	0.2	0.1	0.1	370.9	0.2	841.8	Avoided air filtration costs
		NO_x purification ($\times 10^3$ *t*)	—	—	—	117.9	0.1	0.1	—	—	—	—	
		Dust purification ($\times 10^3$ *t*)	105.5	0.02	0.02	246	0.04	0.02	0.02	133.3	0.02	133.3	
	Sandstorm prevention	Sand retention ($\times 10^9$ *t*)	0.3	21.4	26.2	0.5	31.7	17.1	1.5	4.9	10.3	48.2	Avoided health costs
	Carbon sequestration	Carbon sequestration ($\times 10^9$ *t*)	0.01	2.0	2.4	0.02	4.7	2.5	1.9	67.4	2.7	137.3	Afforestation cost
Total regulating services				28.3	34.7		43.9	23.7	3.9	9.8	15.6	55.3	
Nonmaterial services	Ecotourism	Tourists ($\times 10^6$ persons)	3.2	3.0	3.7	23.2	21.6	11.7	17.4	408.8	18.6	621.3	Travel expenditures
Grand Total				81.5	100.0		185.4	100.0	75.5	68.8	103.9	127.5	

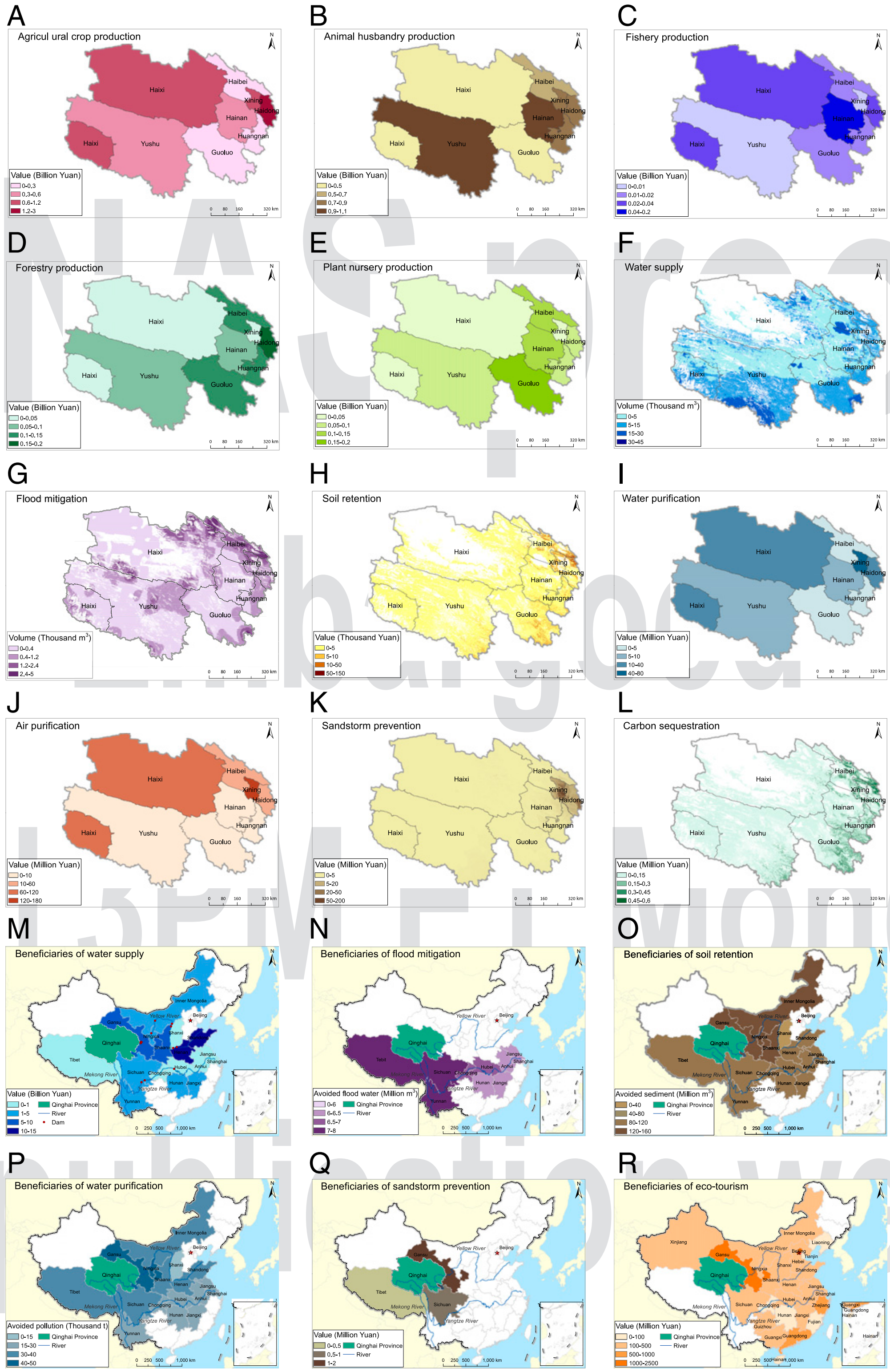

Fig. 2. Spatial distribution showing where ecosystem services are produced within Qinghai (*A*–*L*), and the location of beneficiaries in recipient provinces (*M*–*R*). (*A*–*E*) Value of material production services reported at the district level. (*F*) Origin of water supply in biophysical terms in Qinghai modeled at fine spatial level. Water supply contributes to material production services within Qinghai (*A*–*E*), and industrial, domestic, agriculture, and hydropower downstream (*M*). (*G*) Flood mitigation services in biophysical terms, with their value captured by downstream beneficiaries (*N*). (*H*–*L*) Value of regulating services shown by the district in Qinghai where they are produced. Beneficiaries of these services include people in Qinghai, people in other provinces of China, and, in the case of carbon sequestration, people globally. (*O*–*Q*) Value of regulating services to beneficiaries outside Qinghai reported at the provincial level. (*R*) Value of ecotourism shown by visitor's home province. White indicates zero value or volume. Details of methods are in *SI Appendix*.

of GEP can be widely applied for both planning and evaluation purposes, including the evaluation of government policy and performance, and land use and infrastructure planning. GEP can also provide the basis for determining financial compensation for the provision of ecosystem services (Fig. 3).

By facilitating commensurate measurement of ecological and economic performance, GEP also enables evaluation of the performance of government officials and policies that includes ecological as well as economic considerations. The government of China now requires the integration of ecological benefits into local governments' performance evaluation criteria (75). In China, 672 counties covering 49.4% of the country have been identified as Ecological Functional Conservation Areas, delineated to sustain ecosystem services for the entire country (10). Within these regions, GEP provides a crucial complement to GDP for joint evaluation of the economic and ecological performance of local government.

The results from Qinghai Province show how important it can be to incorporate the value of nature into decision making. In Qinghai, GEP was higher than GDP in 2000 (81.5 billion Yuan for GEP vs. 26 billion Yuan for GDP). Even with rapid economic development resulting in an 8.2-fold increase in GDP in Qinghai between 2000 and 2015, GEP was still approximately three-fourths as large as GDP in 2015 (185.4 billion Yuan for GEP vs. 242 billion Yuan for GDP). Part of the reason that GEP is large relative to GDP is that GEP measures the value of nonmarketed ecosystem services excluded from GDP (carbon sequestration, sandstorm prevention, soil retention, water purification).

However, the main reason that GEP is large relative to GDP is that Qinghai "exports" ecosystem services, which show up in GDP in other provinces of China or in other countries, but for which Qinghai currently does not receive credit. The share of exported value of GEP was 70.1% in 2015. The largest source of value in this regard is water supply, which provided vital inputs into downstream hydroelectric power generation, agriculture, industry, and domestic use. By measuring the value and location of the production and use of ecosystem services, GEP provides a basis for financial compensation across regions. Such eco-compensation programs can play an important role in conserving ecosystem assets necessary for the provision of ecosystem services (76, 77). Eco-compensation can also play an important role in poverty alleviation. Many regions, such as Qinghai Province, are rich in ecosystem assets but relatively poor in conventional economic measures (per capita GDP). The provinces that benefit from the ecosystem services generated in Qinghai tend to be far wealthier in conventional economic terms. Through eco-compensation mechanisms, such as water funds in which downstream water users pay for protection of upstream watersheds (76, 78), it is possible to conserve ecosystem assets, and in many cases like Qinghai, also help alleviate poverty and promote sustainable economic development.

Trends in GEP can also highlight the impacts of changing the quality and quantity of ecosystem assets. In Qinghai, large-scale investment in restoration resulted in improvements the flows of ecosystem services measured in GEP (127.5%) between 2000 and 2015. Increasing the value of GEP requires investment in ecosystem assets, much like producing marketed goods and services requires investment in manufactured and human capital. The results from Qinghai show that investment in ecosystem assets can generate a high rate of return in the form of increased value of ecosystem services.

Our measure of GEP for Qinghai is lower than several prior estimates of the value of ecosystem services in Qinghai. The major reasons why this is so are that some prior studies assigned much larger values to "climate regulation" that included a large value for oxygen production in addition to valuing CO_2 sequestration (79–82) or used benefit transfer methods based on an ecosystem classification to assign a value per hectare that aggregated to a large total estimate (83, 84).

Limitations and Next Steps. The measurement of GEP is at an early stage of development. Integrated ecological–economic accounts like GEP will likely take some years to reach maturity. This is to be expected; it took several decades between the initial attempts to develop systematic accounting of economic activity in the 1930s and 1940s (85) and the adoption of GDP by governments around the world, and the eventual worldwide adoption of the System of National Accounts (23). However, the development of GEP is aided by the extensive work on SEEA and the broad international agreement that exists regarding many of the core principles of integrated ecological–economic accounting.

The effort here represents a start toward systematic accounting of the value of ecosystem services into GEP, but much work remains. First, with existing data, it can be difficult to separate nature's contribution from the contribution of anthropogenic

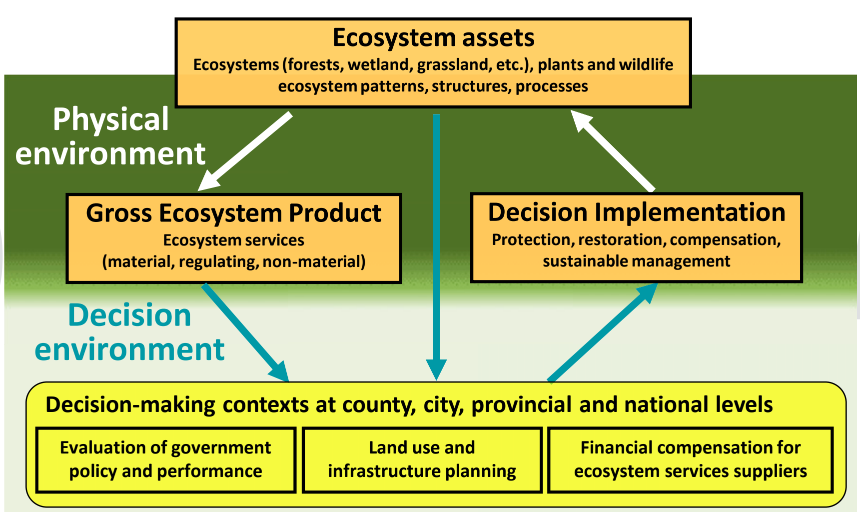

Fig. 3. Relationships among ecosystem assets, GEP, and decision making. The condition of ecosystem assets determines the output of ecosystem services and GEP. Then, GEP can be used in evaluation of government policy and performance, in planning, and in the determination of eco-compensation. Policy, finance, and management decisions, in turn, affect the condition of ecosystem assets.

assets and human labor. In general, the contribution of nature can be found by subtracting the costs of other inputs (labor cost, machinery, purchased inputs, and so forth) from accounting value. In some cases, national accounts used to compute GDP provide information on intermediate inputs, labor, and capital. Alternatively, it may be possible to estimate the value of inputs from nature directly by estimating the value of marginal product (e.g., pollination, improved soil quality, and so forth). At present, however, data do not always exist to implement such approaches. In Qinghai, we had information to do this separation for agricultural crop production and animal husbandry, but lacked data for other services (forestry, fisheries, nursery products, hydropower, and ecotourism). For example, in calculating the value of ecotourism in Qinghai, we lacked data on the cost of infrastructure, so that all of the accounting value is attributed to nature rather than some fraction of that total value. In such cases, our figures will overestimate the contribution of nature.

Second, even when we can clearly identify the contribution of nature, limitations in data or models give rise to imprecise estimates of the accounting value of ecosystem services. An important function of GEP, especially in the early stages of development, is to provide a roadmap of the biophysical monitoring necessary to underpin estimates of quantity, and the economic monitoring necessary to underpin estimates of price. Improved monitoring to provide accurate information, taking account of the scale, resolution, and temporal frequency of data collection, is important for creating a comprehensive and accurate accounting of GEP. With improvements in remote sensing and monitoring, data limitations are receding. Yet they are still substantial, especially for ecosystem services that cannot be remotely sensed and require on-the-ground measurement.

Third, for many ecosystem services, there are large gaps between where ecological modeling stops (e.g., the amount of nutrients in water supply) and where the valuation of ecosystem services begins (e.g., human health impacts). Advances in integrated ecological–economic modeling—focused on tracking cause and effect from human actions through changes in ecosystems, the goods and services provided, and ultimately to impacts on human well-being—will help to close these gaps (86, 87).

Fourth, although we included a large number of ecosystem services in the Qinghai example, this still represents an incomplete set of ecosystem services. We did not include several important ecosystem services because we lacked detailed data or understanding necessary to quantify provision and estimate its value. For example, forests, grasslands, and wetlands absorb water during and after precipitation events and store and release this water slowly, evening out the flow of rivers and the availability of water. For Qinghai, we lacked detailed soil and hydrological information to estimate adequately this ecosystem service of water retention and its value. We also did not include estimates of ecosystem services related to climate regulation through temperature moderation and impacts on local and regional precipitation patterns. Perhaps the biggest gap in the current set of ecosystem services is the lack of inclusion of nonmaterial ecosystem services beyond ecotourism. In addition, there are likely to be values of nature that we currently do not characterize and that will become clear only with greater understanding of ecosystems and how they contribute to human well-being.

Fifth, GEP is a measure of flow value and does not consider changes in the stocks of ecosystem assets. Future flows of ecosystem services depend upon maintaining the stock of ecosystem assets. A complete environmental–economic accounting system, as envisioned in SEEA, would include measures of the value of both ecosystem stocks and flows. In principle, the value of ecosystem assets should be equal to the present value of the ecosystem services that they generate. With improved monitoring and modeling, it may be possible to value ecosystem assets in this manner. Valuing assets was beyond the scope of this paper.

Finally, there is a need for agreement on standardized definitions and methods to compute GEP (88). On-going work led by the United Nations is working toward adoption of an international agreement on a system of environmental-economic accounts (89). International agreement on the System of National Accounts has facilitated its widespread adoption and use along with a more systematic approach to improving methods and data.

Conclusions

The large-scale loss of natural capital and the consequent reduction in the flow of ecosystem services around the world points to the urgent need for better metrics of ecological performance, and the integration of this information into societal decision making. Such integration can be facilitated by providing decision makers with easily understandable summary statistics of ecological performance. Just as GDP provides a useful summary statistic of the aggregate value of economic activity, GEP provides a useful summary statistic of the aggregate value of the contributions of nature to society. The development of GEP within China in pilot projects—including Qinghai Province, Zhejiang Province (74), and numerous municipalities and counties across China (10)—and its incorporation into government operations, is a promising step in this direction. Results from Qinghai Province demonstrate that GEP is a tractable approach with currently available data and methods. By setting out the data and methods in a clear and transparent manner, we hope to provide a useful template to account for the value of nature in countries worldwide, one that can be improved through time as data and methods improve.

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