Gross Ecosystem Product (GEP):
A Tractable Approach for Bringing Ecological Information into Decision-Making

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Abstract: *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 3/4th 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 trans-regional compensation payments.*

Significance Statement: *To achieve sustainable development, there is a pressing need to move beyond conventional economic measures like 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 3/4th as large as GDP in 2015. China is using GEP to guide investments in ecosystem conservation and restoration.*

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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 ten-fold (1). The size of the Chinese economy is currently second only to the U.S. 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. Though 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 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 exists 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 non-commensurate 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? Further, 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 calculate 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 (UNSD) to develop the System of Environmental-Economic Accounting (SEEA) (17), whose definition of accounting value we follow, and the System of Environmental-Economic Accounting Experimental Ecosystem Accounting (SEEA EEA) (18). SEEA EEA is currently under revision (19-22 discuss recent advances) with the objective to elevate it to an international statistical standard on par with the System of National Accounts (SNA) (23). There are several global initiatives to build environmental-economic accounts using the SEEA framework, including the UNSD'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., 24-25). 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., 27-33).

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 (34-37). 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., 38-40) to national levels (e.g. 10, 41-42). Following (43), 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 (44-48), wetlands (49-52), croplands and grasslands (53-57) (see (58-59) 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 (60-62). 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 (NDRC), 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 (62) (see Supplementary Information (SI) Section S2, Tables S8-S9 for a list of ecological compensation programs and projects in China).

Measuring GEP

We construct 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, etc.), regulating services (the contribution of nature to carbon sequestration, flood mitigation, soil retention, sandstorm prevention, etc.), and non-material services (the contribution of nature to ecotourism, nature experience for mental health, etc.) (5).

In cases where market prices for ecosystem services do not exist, we use a variety of non-market 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, etc.). We can also use the value of marginal product, i.e., 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 (63), pollination services boosting the production of coffee and other agricultural production (64-65), and the impact of climate regulation upon agricultural production (66).

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 (67). Other approaches for estimating the economic value of ecosystem services, using revealed and stated preference methods, are also useful (68).

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 Supplementary Information (SI Section S1).

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; by 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 non-sustainable 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, 33). In principle, changes in the value of ecosystem assets could be used to calculate Net Ecosystem Product (NEP), 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 (27-32). 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 (69).

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 thousand 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 -18ºC in January), mild summers (highs of 15 to 21ºC 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.

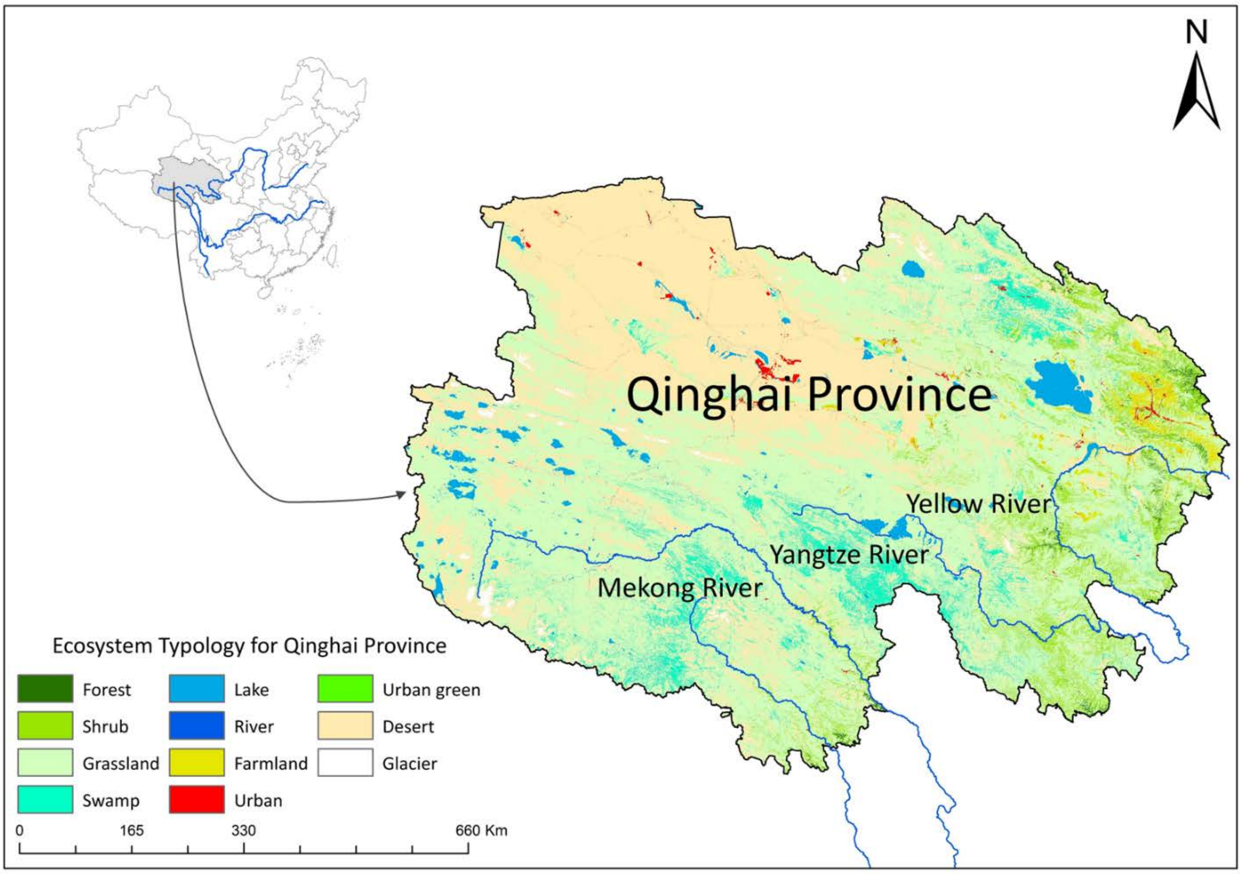


Figure 1. The distribution of ecosystem types across Qinghai Province, and depiction of the headwaters of the Mekong, Yangtze, and Yellow rivers.

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 (70).

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 uncia*l), 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 (71). 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 embodied significant poverty alleviation objectives. During 2010-2015, 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 (62). (See SI Section S3 Table S-10 for a list of eco-compensation programs in Qinghai.)

Methods for calculating GEP in Qinghai

We assess 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 (γ_i = 1). For other services, including many material services, there is a contribution from human labor and human-made inputs, so that γ_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 the on-line Supplementary Information (SI). For material services, we rely primarily on published data on production and prices (SI Section S1.1). For regulating services, we rely on biophysical data from government sources and use the InVEST suite of models (72) to calculate the provision of services (SI Sections S1.2 – S1.8). We then apply a variety of market and non-market valuation methods to convert provision of services into monetary estimates of value. For non-material services, in this case ecotourism, we apply travel cost methods using a survey on visitation and trip expenditures (SI Section S1.9). We also account 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 includes 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 non-material 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 580% (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 towards 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 79.3 billion Yuan, while changes in prices accounted for 24.6 billion Yuan.

Table 1 GEP accounting in Qinghai (2000 - 2015)

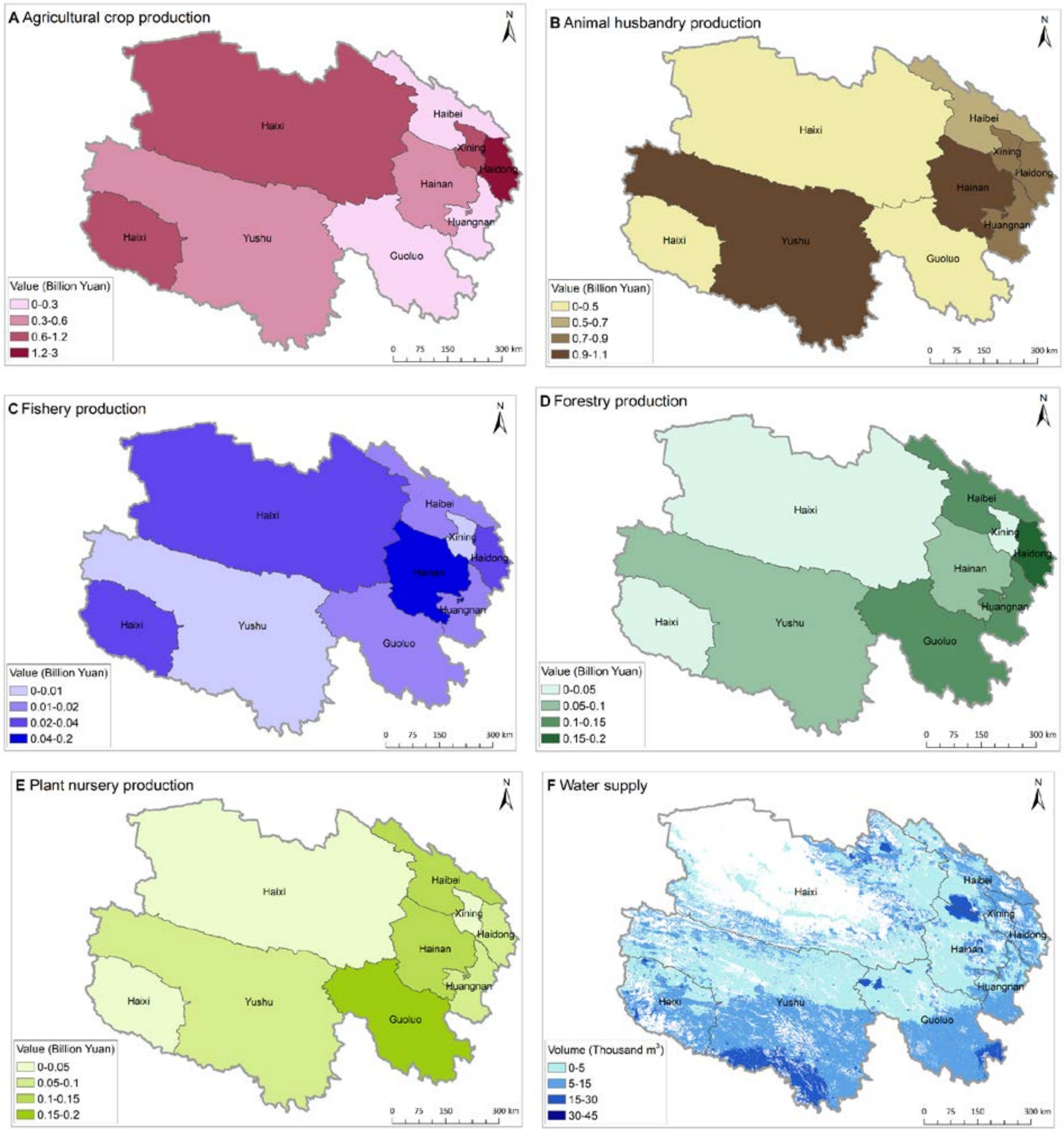
Types of service	Category of ecosystem services	Accounting items	2000			2015			2000-2015 (constant price)		2000-2015 (current price)		
			Bio-physical quantity	Monetary value (Billion Yuan)	% of total value	Bio-physical quantity	Monetary value (Billion Yuan)	% of total value	Amount of change (Billion Yuan)	% change	Amount of change (Billion	% change	Valuation method
Material services	Production of ecosystem goods	Agricultural crop production ($x10^3t$)	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 ($x10^3t$)	458.7	1.1	1.4	724	5.8	3.1	4.2	266.4	4.7	419.4	
		Fishery production ($x10^3t$)	1.2	0.01	0.01	10.6	0.3	0.1	0.3	2351.5	0.3	3375.0	
		Forestry production ($x10^3m^3$)	1800	0.2	0.2	825	0.7	0.4	0.5	247.1	0.6	392.1	
		Plant nursery production ($x10^9$)	0.3	0.2	0.2	11	0.7	0.4	0.5	190.8	0.6	312.2	
		Total		**2.5**	**3.0**		**13.1**	**7.1**	**9.7**	**284.1**	**10.7**	**444.5**	
	Water supply	Water use in downstream agricultural irrigation ($x10^9$ 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 ($x10^9m^3$)		5.3	6.5		13.8	7.4	6.4	86.5	8.5	160.4	
		Water use in industry ($x10^9m^3$)		19.4	23.8		29.2	15.8	2.2	8.1	9.8	50.5	
		Hydropower production ($x10^9$ 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		**47.8**	**58.7**		**106.7**	**57.6**	**44.5**	**71.6**	**58.9**	**123.3**	
Regulating services	Flood mitigation	Flood mitigation ($x10^9m^3$)	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 non-point pollution prevention	Retained soil ($x10^9$ 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 ($x10^3$ t)	9.8	0.01	0.01	10	0.02	0.01	0.0003	1.9	0.01	103.9	
		Retained P ($x10^3t$)	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 ($x10^3$ t)	33.2	0.02	0.03	104.3	0.1	0.1	0.10	214.0	0.1	528.0	
		NH-N purification ($x10^3$ t)	3.5	0.00	0.004	10	0.02	0.01	0.01	186.8	0.01	473.6	
		TP purification ($x10^3$ t)	-	-	-	0.9	0.003	0.001	-	-	-	-	
	Air purification	SO_2 purification ($x10^3$ t)	32.0	0.02	0.02	150.8	0.2	0.1	0.15	370.9	0.2	841.8	Avoided air filtration costs
		NO_x purification ($x10^3$ t)	-	-	-	117.9	0.1	0.1	-	-	-	-	
		Dust purification ($x10^3$ t)	105.5	0.02	0.02	246	0.04	0.02	0.02	133.3	0.02	133.3	
	Sandstorm prevention	Sand retention ($x10^9t$)	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 ($x10^9$ t)	0.01	2.0	2.4	0.02	4.7	2.5	1.9	67.4	2.7	137.3	Afforesta-tion cost
		Total		**28.3**	**34.7**		**43.9**	**23.7**	**3.9**	**9.8**	**15.6**	**55.3**	

Types of service	Category of ecosystem services	Accounting items	2000			2015			2000-2015 (constant price)		2000-2015 (current price)		
			Bio-physical quantity	Monetary value (Billion Yuan)	% of total value	Bio-physical quantity	Monetary value (Billion Yuan)	% of total value	Amount of change (Billion Yuan)	% change	Amount of change (Billion	% change	Valuation method
Non-material services	Eco-tourism	Tourists（x10^6 persons）	3.2	**3.0**	**3.7**	23.2	**21.6**	**11.7**	**21.2**	**4988.4**	**18.6**	**621.3**	Travel expendi-tures
Grand Total				**81.5**	**100.0**		**185.4**	**100.0**	**79.3**	**74.9**	**103.9**	**127.5**	

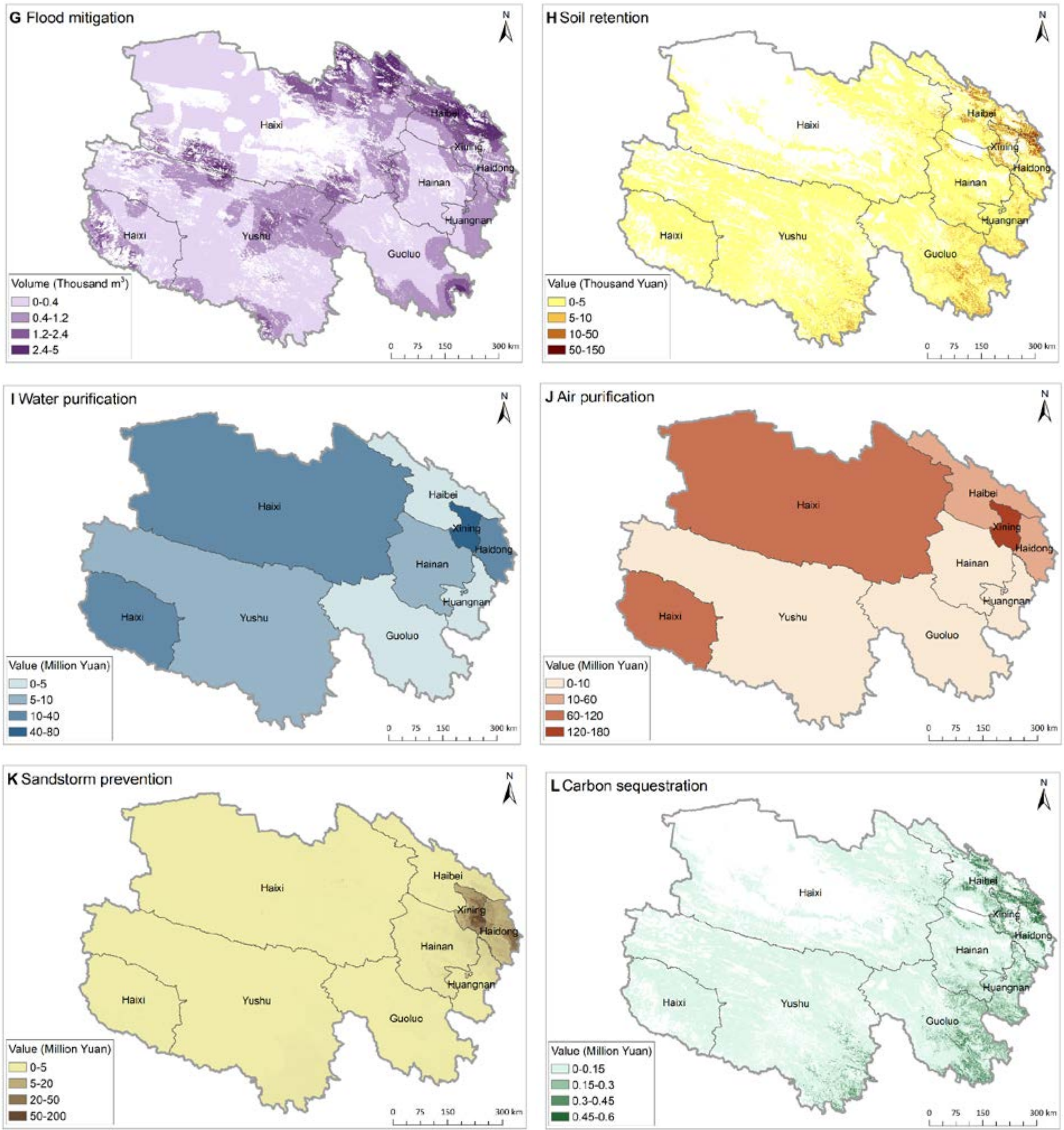
The precipitation gradient in Qinghai increases from west to east. Ecosystem services related to water (e.g. water supply, flood mitigation) generally show higher values in eastern Qinghai compared to western Qinghai (Fig. 2). Population density is also higher in eastern Qinghai, generating higher value 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 attribute the value of all other services based on where the majority of benefits accrue. Accordingly, we attribute 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 attribute 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 attribute the value of air purification and ecotourism to local benefits. We attribute 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).



A Agricultural crop production
N
Haixi
Haibei
Xining
Haidong
Hainan
Huangnan
Haixi
Yushu
Guoluo
Value (Billion Yuan)
0-0.3
0.3-0.6
0.6-1.2
1.2-3
0 75 150 300 km
B Animal husbandry production
N
Haixi
Haibei
Xining
Haidong
Hainan
Huangnan
Haixi
Yushu
Guoluo
Value (Billion Yuan)
0-0.5
0.5-0.7
0.7-0.9
0.9-1.1
0 75 150 300 km
C Fishery production
N
Haixi
Haibei
Xining
Haidong
Hainan
Huangnan
Haixi
Yushu
Guoluo
Value (Billion Yuan)
0-0.01
0.01-0.02
0.02-0.04
0.04-0.2
0 75 150 300 km
D Forestry production
N
Haixi
Haibei
Xining
Haidong
Hainan
Huangnan
Haixi
Yushu
Guoluo
Value (Billion Yuan)
0-0.05
0.05-0.1
0.1-0.15
0.15-0.2
0 75 150 300 km
E Plant nursery production
N
Haixi
Haibei
Xining
Haidong
Hainan
Huangnan
Haixi
Yushu
Guoluo
Value (Billion Yuan)
0-0.05
0.05-0.1
0.1-0.15
0.15-0.2
0 75 150 300 km
F Water supply
N
Haixi
Haibei
Xining
Haidong
Hainan
Huangnan
Haixi
Yushu
Guoluo
Volume (Thousand m^3)
0-5
5-15
15-30
30-45
0 75 150 300 km


G Flood mitigation
Haixi
Haibei
Xining
Haidong
Hainan
Huangnan
Haixi
Yushu
Guoluo
Volume (Thousand m³)
0-0.4
0.4-1.2
1.2-2.4
2.4-5
0 75 150 300 km
H Soil retention
Haixi
Haibei
Xining
Haidong
Hainan
Huangnan
Haixi
Yushu
Guoluo
Value (Thousand Yuan)
0-5
5-10
10-50
50-150
0 75 150 300 km
I Water purification
Haixi
Haibei
Xining
Haidong
Hainan
Huangnan
Haixi
Yushu
Guoluo
Value (Million Yuan)
0-5
5-10
10-40
40-80
0 75 150 300 km
J Air purification
Haixi
Haibei
Xining
Haidong
Hainan
Huangnan
Haixi
Yushu
Guoluo
Value (Million Yuan)
0-10
10-60
60-120
120-180
0 75 150 300 km
K Sandstorm prevention
Haixi
Haibei
Xining
Haidong
Hainan
Huangnan
Haixi
Yushu
Guoluo
Value (Million Yuan)
0-5
5-20
20-50
50-200
0 75 150 300 km
L Carbon sequestration
Haixi
Haibei
Xining
Haidong
Hainan
Huangnan
Haixi
Yushu
Guoluo
Value (Million Yuan)
0-0.15
0.15-0.3
0.3-0.45
0.45-0.6
0 75 150 300 km

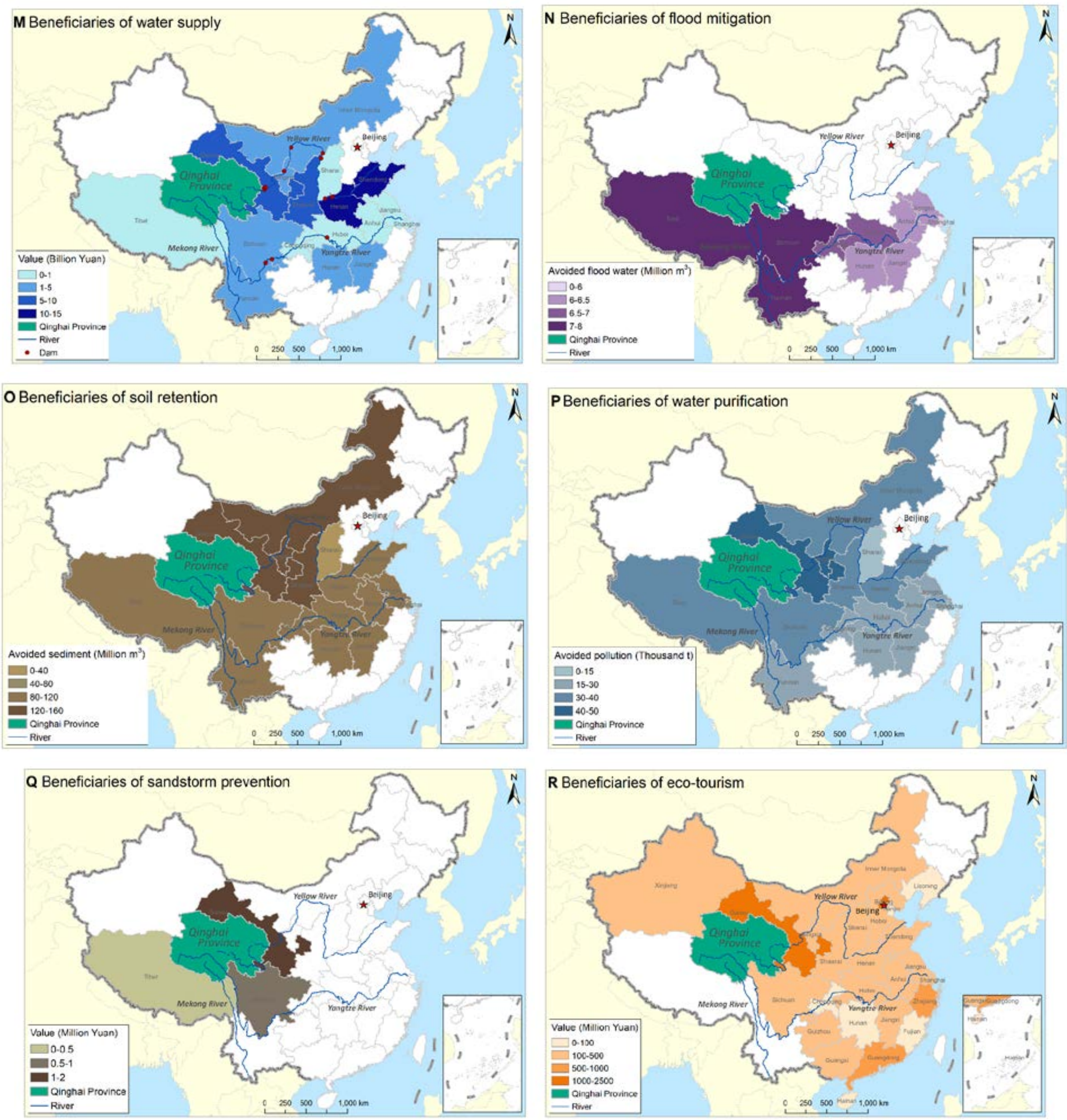


Figure 2. Spatial distribution showing where ecosystem services are produced within Qinghai (A-L), and the location of beneficiaries in recipient provinces (M-R). (A-E) Value of material production services reported at the district level. (F) Origin of water supply in biophysical terms in Qinghai modeled 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 in the SI.

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, i.e., 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 towards sustainable development (73). A tractable measure 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 (74). 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.

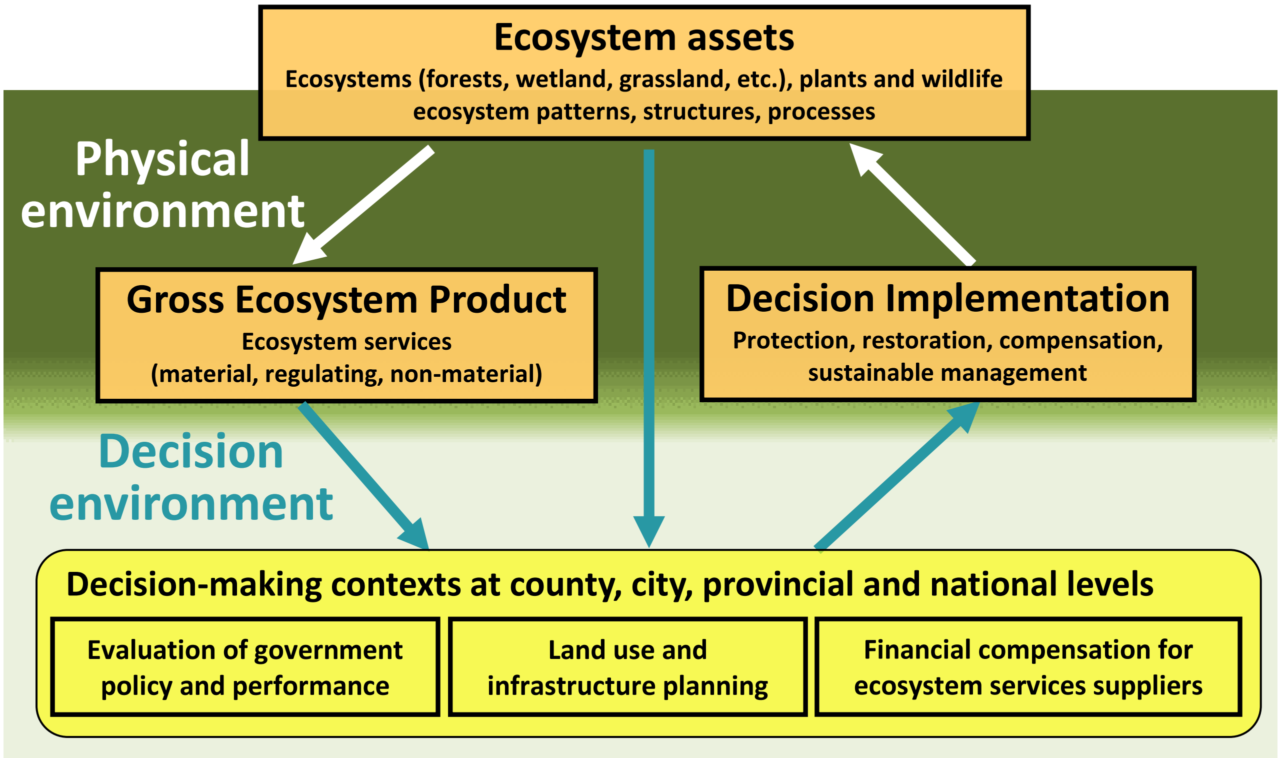


Figure 3 Relationships among ecosystem assets, GEP, and decision-making. The condition of ecosystem assets determines the output of ecosystem services and GEP. Then, GEP can be used in evaluation of government policy and performance, in planning, and in the determination of eco-compensation. Policy,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

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 versus 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 3/4 as large as GDP in 2015 (185.4 billion Yuan for GEP versus 242 billion Yuan for GDP). Part of the reason that GEP is large relative to GDP is that GEP measures the value of non-marketed 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 (75-76). 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 (75, 77), it is possible to conserve ecosystem assets, and in the 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 valuing CO_2 sequestration (78-81) or used benefit transfer methods based on an ecosystem classification to assign a value per hectare that aggregated to a large total estimate (82-83).

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 (84) 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 towards 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 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, etc.) 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, etc.). At present, however, data does 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 (85-86).

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 non-material 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 (87). On-going work led by the UN is working towards adoption of an international agreement on a system of environmental-economic accounts (88). 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 (73), 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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Supplementary Information

S1 GEP Accounting Methods

In this study, we calculate GEP based on the IPBES ecosystem service classification that includes material services, regulating services, and non-material services (Díaz et al., 2018). In material ecosystem services, we include agricultural crops, animal husbandry, fishery, forestry, and nursery production in Qinghai, along with material services from water supply originating in Qinghai. In regulating services, we include soil retention, sandstorm prevention, flood mitigation, air purification, water purification, and carbon sequestration. In non-material services, we include ecotourism. We chose to include these ecosystem services both because they are important and we had available data and methods to estimate their value.

S1.1 Material Services

A. Biophysical quantities

Material ecosystem services include the various products produced in Qinghai Province for which ecosystems contribute in a significant way to their output. Information on annual production of material services is obtained from a variety of economic accounting systems including the Qinghai Provincial Bureau of Statistics (2001, 2016).

Water supply

Qinghai Province is the headwaters of three major rivers: the Yellow River, the Yangtze River, and the Mekong River. Water originating in Qinghai is used in Qinghai and in many downstream provinces in the Yellow, Yangtze, and Mekong river basins, along with provinces in several other river basins in Southwestern China. Water resources from Qinghai are used for agricultural, hydropower, and industrial production, and for domestic use.

Water resources use includes: 1) the water supply for industrial use and domestic use in Qinghai Province (m^3), labeled Q_{QI} and Q_{QD}, which comes from the *Qinghai Water Resources Bulletin* (Water Resources Department of Qinghai Province, 2001, 2016); and 2) the water supply for use downstream in the Yangtze River (W_{QYA}, m^3) and the Yellow River (W_{QYE}, m^3), which comes from the *Qinghai Water Resources Bulletin* (Water Resources Department of Qinghai Province, 2001, 2016). The amount of hydropower production includes: 1) hydropower production in Qinghai Province, Q_{QHP} which comes from Q*inghai Statistical Yearbook* (Qinghai Provincial Bureau of Statistics, 2001, 2016); and 2) the hydropower production in all downstream dams, Q_{DHP}.

When we calculate the water resource from Qinghai used in downstream provinces, we first calculate the fraction of surface water in each downstream province that originates in Qinghai. Denote downstream provinces by i, $i = 1, 2, \dots N$. The amount of water that originates in Qinghai flowing into province i is denoted W_{iQ} (m^3). We adjust the amount of water flowing out of Qinghai in the Yangtze River, W_{QYA}, or the Yellow River, W_{QYE} (m^3; Water Resources Department of Qinghai Province, 2001, 2016), by losses as water flows downstream (Chen et al., 2015; Ding, 2012):

$$\text{Yangtze River: } W_{iQ} = W_{QYA} \times (1 - 0.005\%)^{l_i}$$

$$\text{Yellow River: } W_{iQ} = W_{QYE} \times (1 - 0.01\%)^{l_i}$$

where l_i (km) is the length of the river between where the river leaves Qinghai Province and where the river enters into province *i*.

The fraction of surface water in province *i* that originates in Qinghai is defined as $F_{iQ} = \frac{W_{iQ}}{W_{iT}}$. W_{iT} is the total amount of surface water in province *i* is reported by provincial water resource agencies (m^3; Chongqing Water Resources Bureau, Hubei Provincial Department of Water Resources, Ningxia Water Conservancy, Shaanxi Provincial Department of Water Resources, Shanghai Water Authority, Sichuan Provincial Water Resources Department, Water Resources Department of Anhui Province, Water Resources Department of Gansu Province, Water Resources Department of Henan Province, Water Resources Department of Hunan Province, Water Resources Department of Inner Mongolia, Water Resources Department of Jiangsu Province, Water Resources Department of Jiangxi Province, Water Resources Department of Shandong Province, Water Resources Department of Shanxi Province, Water Resources Department of Tibet, Water Resources Department of Yunnan Province, 2001, 2016).

The water resources from Qinghai used by industry in downstream province *i* are $Q_{iI} = F_{iQ}W_{iI}$, where W_{iI} is the amount of water used by industry in province *i* (m^3; Chongqing Water Resources Bureau, Hubei Provincial Department of Water Resources, Ningxia Water Conservancy, Shaanxi Provincial Department of Water Resources, Shanghai Water Authority, Sichuan Provincial Water Resources Department, Water Resources Department of Anhui Province, Water Resources Department of Gansu Province, Water Resources Department of Henan Province, Water Resources Department of Hunan Province, Water Resources Department of Inner Mongolia, Water Resources Department of Jiangsu Province, Water Resources Department of Jiangxi Province, Water Resources Department of Shandong Province, Water Resources Department of Shanxi Province, Water Resources Department of Tibet, Water Resources Department of Yunnan Province, 2001, 2016).

The amount of water from Qinghai in domestic use is defined similarly. The water resources from Qinghai in domestic use in downstream province *i* is $Q_{iD} = F_{iQ}W_{iD}$, where W_{iD} is the amount of water in domestic use in province *i* (m^3; Chongqing Water Resources Bureau, Hubei Provincial Department of Water Resources, Ningxia Water Conservancy, Shaanxi Provincial Department of Water Resources, Shanghai Water Authority, Sichuan Provincial Water Resources Department, Water Resources Department of Anhui Province, Water Resources Department of Gansu Province, Water Resources Department of Henan Province, Water Resources Department of Hunan Province, Water Resources Department of Inner Mongolia, Water Resources Department of Jiangsu Province, Water Resources Department of Jiangxi Province, Water Resources Department of Shandong Province, Water Resources Department of Shanxi Province, Water Resources Department of Tibet, Water Resources Department of Yunnan Province, 2001, 2016).

We include the value of water used for irrigation downstream in the Yellow River Basin, but not for the Yangtze River Basin or other river basins. Crops in the Yangtze Basin and other river basins downstream from Qinghai are mostly grown without irrigation as there is adequate rainfall. Irrigation, however, is common the Yellow River Basin. The amount of agricultural crops grown with irrigation using water resources from Qinghai in province *i*, Q_{iA} (t), is calculated as

$$Q_{iA} = F_{iQ} W_{iA} E_{iI} E_{CU}$$

where W_{iA} is the amount of water used in irrigation in province *i* in the Yellow River Basin (m^3; Ningxia Water Conservancy, Shaanxi Provincial Department of Water Resources, Water Resources Department of Gansu Province, Water Resources Department of Henan Province, Water Resources Department of Inner Mongolia, Water Resources Department of Shandong Province, Water Resources Department of Shanxi Province, 2001, 2016), E_{iI} is the irrigation efficiency of province *i* in the Yellow River Basin (%; Ningxia Water Conservancy, Shaanxi Provincial Department of Water Resources, Water Resources Department of Gansu Province, Water Resources Department of Henan Province, Water Resources Department of Inner Mongolia, Water Resources Department of Shandong Province, Water Resources Department of Shanxi Province, 2001, 2016), and E_{CU} is the crop water use efficiency (t/m^3; Duan et al. 2000).

For downstream hydropower production, we calculate the fraction of hydropower electricity generated at each dam downstream from Qinghai attributable to water resources from Qinghai. Let F_{jQ} be the fraction of water at downstream dam *j*, *j* = 1, 2, …, *J*, that originates in Qinghai: $F_{jQ} = \frac{W_{jQ}}{W_{jT}}$, where W_{jQ} is the amount of water from Qinghai flowing through dam *j* (m^3) and W_{jT} is the total amount of water flowing through dam *j* (m^3; Changjiang Water Resources Commission of the Ministry of Water Resources, Yellow River of Conservancy Commission of the Ministry of Water Resources, 2001, 2016). W_{jQ} for dams along the Yangtze or Yellow Rivers is calculated by taking the amount of water flowing out of Qinghai in the Yangtze River, W_{QYA}, or the Yellow River, W_{QYE} (m^3; Water Resources Department of Qinghai Province, 2000, 2016), adjusted by losses as water flows downstream (Chen et al., 2015, Ding 2012):

$$\text{Yangtze River: } W_{jQ} = W_{QYA} \times (1 - 0.005\%)^{l_j}$$

$$\text{Yellow River: } W_{jQ} = W_{QYE} \times (1 - 0.01\%)^{l_j}$$

where l_j (km) is the length of river between dam *j* and Qinghai Province.

Downstream hydropower production at dam *j* attributable to water resources from Qinghai, measured in kwh, is $Q_{jHP} = F_{jQ} E_j$, where E_j is the amount of hydropower electricity produced at dam *j* (kwh; Changjiang Water Resources Commission of the Ministry of Water Resources, Yellow River of Conservancy Commission of the Ministry of Water Resources, 2001, 2016). We then aggregated hydropower production across all downstream dams: $Q_{DHP} = \sum_{j=1}^{J} Q_{jHP}$.

B. Accounting value

The annual value of material services (Yuan) for agricultural products, animal husbandry products, fishery products, forest products, and nursery products are reported in the *Qinghai*

Statistical Yearbook (2001, 2016). We adjust the value of agricultural products and animal husbandry products to include only the portion of value due to inputs from nature, netting out the portion of value due to labor and other human made inputs. For agricultural crops we used a value of 38.55% for the proportion of value attributable to nature (Tang and Huang 2009). For animal husbandry we used 36.5% for the proportion of value attributable to nature (Liu and Dong 2014).

We calculate the accounting value of water resources from Qinghai used in industry, domestic use, irrigation for agricultural crops, and hydropower production, as follows. We calculate the accounting value of water supply for industrial use by multiplying the amount of industrial water by the market price of industrial water:

$$V_I = Q_{QI}P_{QI} + \sum_{i=1}^{N} Q_{iI}\, P_{iI}$$

where P_{QI} is the market price of industrial water in Qinghai (Yuan/m^3), and P_{iI} is the market price of industrial water of province i (Yuan/m^3). Market prices of industrial water come from the E20 Environment Platform (http://www.h2o-china.com/price/).

We calculate the accounting value of water supply for domestic use by multiplying the amount of domestic water by the market price of domestic water:

$$V_D = Q_{QD}P_{QD} + \sum_{i=1}^{N} Q_{iD}\, P_{iD}$$

where P_{QD} is the market price of domestic water in Qinghai (Yuan/m^3), and P_{iD} is the market price of domestic water of province i (Yuan/m^3). Market prices of domestic water come from the E20 Environment Platform (http://www.h2o-china.com/price/).

For the accounting value of hydropower, we multiply the amount of electric power generation attributable to water resources from Qinghai by the market price of electricity:

$$\mathrm{V_H} = (Q_{QHP} + Q_{DHP}) \times P_E$$

where P_E is the residential electricity price (Yuan/kWh, Zhang et al. 2012). This method will tend to overestimate the value of this ecosystem service because we do not deduct the value of the other human produced inputs including the dams and machinery necessary to convert hydropower into electricity.

For agriculture, we calculate the accounting value of crop production downstream from irrigation made possible by using water resources from Qinghai as follows. We calculate the revenue from crop production net

$$V_\mathrm{A} = \sum_{i=1}^{N} Q_{iA}P_A\, F_A$$

where P_A is the crop price (Yuan/ton), and F_A is the fraction of crop value attributable to nature. For F_A, we use the same proportions here as we did for Qinghai agricultural crops (38.55%). For crop price we use the price of wheat, which is the most common crop in the Yellow River Basin.

The price of wheat comes from National Development and Reform Commission (http://jgs.ndrc.gov.cn/zcfg/201410/t20141016_629600.html). For F_A, we use the same proportions here as we did for Qinghai agricultural crops.

Table S1. **Material services in Qinghai province.** Quantity units: (t) tons, (m^3) cubic meters, (np) number of plants, (kwh) kilowatt hours.

Functional category	Group indicator	Individual product quantity indicators
Agricultural products	Grains	wheat (t), highland barley (t), etc.
	Beans	broad beans (t), peas (t), etc.
	Potato	potato (t)
	Oil	rapeseed (t), flax seed (t), etc.
	Hemp	hemp (t)
	Sugar	beets (t)
	Tobacco	tobacco (t)
	Herbs	traditional Chinese medicine herbs (t)
	Vegetable	Broccoli (t), cabbage (t), etc.
	Melon	melon (t)
	Fruit	apple (t), pears (t), grapes (t), etc.
Animal husbandry products	Meat	beef (t), lamb (t), pork (t), etc.
	Dairy	milk (t)
	Animal fur	wool (t), cashmere (t), plush (t), camel hair (t), horse mane (t), etc.
	Other animal husbandry products	eggs (t), honey (t), etc.
Fishery products	Breed aquatic	breed aquatic (t)
Forest products	Timber	timber (m^3)
	Other forest products	Chinese prickly ash (t), walnuts (t), etc.
Nursery products	Nursery products	flowering plants and seedlings (np)
Water supply	Water resources	Water supply for domestic, industrial and agricultural use in Qinghai and downstream provinces (m^3)
	Hydropower production	hydropower production (kwh)

C. Additional issues, extensions, and omissions

We include the entire value of material output in ecosystem services from fishery, forestry, and nursery production even though the application of human labor, machinery and other human produced inputs contributes to their production. For these services, we overestimate the value of the ecosystem services. We lacked systematic data on costs for human labor, machinery, and other human created inputs for these sectors. The production in these sectors is relatively small. We adjusted the value of agricultural crop production and animal husbandry to include only the proportion of value attributable to nature. Our estimates of value of material services understate the contribution of nature to the extent that we have not included all material services. For example, we did not include the value of water supply downstream in the Mekong River Basin, much of which occurs in Southeast Asian countries outside of China.

S1.2 Soil retention

A. Biophysical quantity

Soil erosion removes topsoil and nutrients, leading to reductions in the fertility of lands. Sediment that reaches streams and rivers contributes to reductions in downstream water quality. Sediment fills in hydropower reservoirs and leads to the decreased hydropower output.

The ecosystem service of soil retention refers to the soil retained by ecosystems, which prevents sediments from entering water bodies and causing damages. We measure soil retention as the difference between soil erosion without vegetation cover and soil erosion under the current land cover pattern and soil erosion control practices (e.g. terraced fields). Soil retention was calculated using the Universal Soil Loss Equation (USLE; Wischmeier et al., 1978) and InVEST model (Sharp et al., 2015), and the model can be expressed as:

$$Q_{sr/h} = R \times K \times LS \times (1 - C \times P)$$

where $Q_{sr/h}$ represents the soil retention capacity (t·ha^{-1}·y^{-1}), R is the rainfall erosivity factor (MJ·mm·ha^{-1}·h^{-1}·a^{-1}) determined using kinetic energy of raindrops and intensity of rainfall (in hectare-millimeters per hour) over one year, K is erodibility of the soil or the amount of soil lost through erosion per unit area following rainfall of a given intensity (t·ha·h·ha^{-1}·MJ^{-1}·mm^{-1}), LS is the topographic factor representing the effect of the length of slope, C is the vegetation cover factor, and P is the practice factors of soil erosion control (e.g., terraced fields).

Rainfall erosivity (R) reflects the potential for rainfall and runoff to cause soil erosion (Wang et al., 1996). In this study, we adopted the Daily Rainfall Erosivity Model (Yin et al., 2013), for which only conventional rainfall data (daily precipitation) is needed. We use rainfall data from 603 weather stations.

$$\bar{R} = \sum_{k=1}^{24} \bar{R}_k$$

$$\bar{R}_k = \frac{1}{n}\sum_{i=1}^{n}\sum_{j=0}^{m}(\alpha \times P_{i,j,k}^{1.7265})$$

where $\bar{R}$ is the average annual rainfall erosivity, $\bar{R}_k$ is the average rainfall erosivity for the kth half month, k is 24 half months in a year (k=1, 2, …, 24), i is the number of years in accordance with rainfall data (i=1, 2, …, n), j is the number of erosive rainfall days in the *k*th half month of the *i*th year (j=0, 1, …, m), $P_{i,j,k}$ is the daily precipitation (mm) on the *j*th erosive rainfall day in the *k*th half month of the *i*th year, and α is a parameter that is assigned a value of 0.3937 for the warm season (May-September) and 0.3101 for the cold seasons (October-April).

Soil erodibility (K) reflects the sensitivity of soil particles to erosive forces and it is an internal factor affecting soil erosion that is closely related to soil attributes (Wang et al., 1996). The Erosion/Productivity Impact Calculator (EPIC) was employed to calculate *K* for soil clay, silt, sand, and organic carbon content (Williams, 1983; Zhang et al., 2008). This study conducted by Zhang et al. (2008) was used for subsequent revisions.

The topographic factor (LS) reflects the effects of terrain (slope length and gradient) on soil erosion (Van Remortel et al., 2001). We integrated the relevant research on gentle and steep slopes, and performed calculations using different slope segments (McCool, 1993; Liu et al., 1994; Rao et al., 2014), making a correction for slopes of >28.81°. The slope length was computed with reference to the ArcInfo AML code (Van Remortel et al., 2001), which was implemented in the ArcInfo Workstation (ArcGIS 9.3; ESRI 2008).

The vegetation cover factor (C) describes the effect of vegetation on soil erosion, and is related to vegetation structure and cover. Parameter values were assigned to the vegetation cover factor according to previous studies (Carter et al., 2004; Liu et al., 1999; Wei et al., 2002), where different ecosystem types and vegetation coverage were considered for forests, shrubs and grasslands (Rao et al., 2014). For farmlands (except paddy lands), the model established by Liu et al. (1999) was applied. For wetlands (including paddy lands, a type of farmland), cities, and bare lands (e.g., deserts, lichens), we used the following values 0, 0.01, and 0.7, which were derived from parameters using in Nonpoint Source Pollution and Erosion Comparison Tool (Carter and Eslinger, 2004). The input data of ecosystem classification images and vegetation cover in 2000 and 2015 were used to calculate the C factor.

The practice factors of soil erosion control (p) describes the effect of artificial erosion control practices on soil erosion, refers to the ratio of soil erosion amount when specific erosion control practices are adopted and corresponding erosion amount when no measures are taken for slope tillage (Wischmeier et al., 1978). If there no artificial practices, P=1 (Xiao et al., 1999).

We sum the per hectare amount of sediment, $Q_{sr/h}$, over the number of hectares in a watershed to generate a measure of soil retention by watershed, Q_{sr} (t).

B. Accounting value

The accounting value of soil retention includes the reduced dredging cost in hydropower reservoirs and reduced non-point source pollution treatment costs:

$$V_{sr} = V_{sd} + V_{dpd}$$

where V_{sr} is the accounting value of soil retention provided by the ecosystem (Yuan/year), V_{sd} is the reduced cost of dredging (Yuan/year), V_{dpd} is the reduced cost of non-point source pollution treatment (Yuan/year).

We measure the value of reduced reservoir dredging cost as

$$V_{sd} = \lambda \times (Q_{sr}/\rho) \times c$$

where λ is the sediment deposition coefficient (Ouyang et al., 1999), ρ is the soil bulk density (t/m^3), *c* is the cost of reservoir dredging per unit (Yuan/m^3).

If pollutants from soil erosion exceed the water environmental carrying capacity, we take the water environmental carrying capacity as the actual water purification capacity. Then the accounting value can be calculated as follows:

$$V_{dpd} = \sum_{i=1}^{2} Q_{sr} \times c_i \times t_i \times d_i \times p_i$$

where c_i is the content of N and P in sediment, t_i is the transfer rate of erosive sediment transfer to river (Wang et al., 2007), d_i is the diffusion rate and refers contribution rate of soil retention to nitrogen and phosphorus in water (Zhu, 2009), and p_i is the cost to treat waste water of nitrogen and phosphorus (Yuan/t) (National Development and Reform Commission, 2003, 2014).

If the pollutants from soil erosion don't exceed the water environmental carrying capacity, we consider that the emitted pollutants from industry and domestic are all purified by ecosystems. The amount of purified N and P by ecosystems is the amount of emitted pollutants.

C. Additional issues, extensions, and omissions

We did not include the loss of topsoil and nutrients leading to reduced soil fertility in the accounting value of the ecosystem service of soil retention for two reasons. First, we currently lack the evidence base on which to build the relationship between soil erosion, soil fertility, and crop productivity for Qinghai. Second, we already include the value of current agricultural crop production, which depends on current fertility. Reductions in soil fertility will affect future crop production (and future GEP) so that reductions in soil fertility should be reflected in ecosystem assets accounting once information is available.

We did not include losses from local landslides. Though local landslides are observable in the remote sensing data (30m x 30m), we do not have information about their impacts or the value of the impacts.

S1.3 Sandstorm prevention

A. Biophysical quantity

Sandstorm prevention (wind erosion control service) refers to the sand retained in an ecosystem for one year. We measure sandstorm prevention as the difference between wind erosion without vegetation cover and wind erosion under the current land cover pattern. We used the Revised Wind Erosion Equation (RWEQ) model (Fryrear et al., 1998) to estimate the sandstorm prevention service. The RWEQ combines empirical and process modeling and has been extensively tested under broad field conditions. To simulate sand/soil loss at a regional scale over varying vegetation cover and patterns, we rewrote the RWEQ into the dynamic modeling language of PC Raster (Karssenberg et al., 2005). PC Raster is an environmental modeling language embedded in a Geographical Information System, providing spatial and temporal functions that can be used to construct regional models.

The RWEQ model estimates sand/soil loss (S_L; kg·m^{-2}) as a function of several factors: weather (*WF*), soil erodibility (*EF*), soil crust (*SCF*), surface roughness (*K'*), and vegetation cover (*C*), which permit estimation of the potential maximum transport capacity without vegetation cover by wind (Q_{pmax}) as follows:

$$Q_{pmax} = 109.8[WF \times EF \times SCF \times K']$$

$$S_p = 150.71 \cdot (\mathrm{WF} \times \mathrm{EF} \times \mathrm{SCF} \times \mathrm{K}')^{-0.3711}$$

$$S_{pL} = \frac{2 \cdot z}{{S_p}^2} Q_{pmax} e^{-(z/S_p)^2}$$

We estimate the wind erosion amount under the current land pattern as follows：

$$Q_{max} = 109.8[WF \times EF \times SCF \times K' \times C]$$

$$\mathrm{S} = 150.71 \cdot (\mathrm{WF} \times \mathrm{EF} \times \mathrm{SCF} \times \mathrm{K}' \times \mathrm{C})^{-0.3711}$$

$$S_{La} = \frac{2 \cdot z}{S^2} Q_{max} e^{-(z/S)^2}$$

To calculate the sand storm prevention (wind erosion control) service for a given location, Q_{sp} (kg·m^{-2}), we calculate the difference in RWEQ model with no vegetation (S_{Lp}) versus with vegetation (S_{La}).

$$Q_{sp} = S_{Lp} - S_{La}$$

where S_{Lp} (kg·m^{-2}) is the potential soil loss caused by wind erosion, S_{La} (kg·m^{-2}) is the soil loss caused by wind erosion, Q_{pmax} (kg·m^{-1}) is the potential maximum transport capacity, Q_{max} (kg·m^{-1}) is the maximum transport capacity, S_p(m) is the potential field length, *S* (m) is the critical field length, *z* (m) is the distance from the upwind edge of the field.

Weather Factor (WF) represents the influence of climate conditions on wind erosion. *WF* is partitioned according to the preponderance and positive parallel ratio values from the weather file (Skidmore et al., 1990, 1996). *WF* is determined by dividing the total wind value for each period by 500 and multiplying by the number of days in the period (Bagnold, 1943; Zingg, 1953).

$$WF = Wf \times \frac{\rho}{g} \times SW \times SD$$

$$Wf = u_2(u_2 - u_1)^2 \times N_d$$

where *Wf* [(m/s)^3] is the wind factor, ρ (kg/m^3) is air density, g (m/s^2) is gravitational acceleration, *SW* is soil factor, *SD* is snow cover factor, u_1 is wind velocity of sand movement, we used 5 m/s, u_2 (m/s) is monthly average wind velocity from meteorological station, N_d is number of days with wind velocity greater than 5m/s.

Soil Erodible Factor (EF). The erodible fraction is that fraction of the surface 25mm of sand/soil that is smaller than 0.84mm in diameter as determined by a standard compact rotary sieve (Chepil, 1962). From a soil sieving data base (Scientific data center of cold region and arid region, http://westdc.westgis.ac.cn/), the highest value for *EF* during a year for each site was correlated with basic soil physical and chemical properties (Fryear et al., 1994).

$$\text{EF} = \frac{29.09 + 0.31sa + 0.17si + 0.33(sa/cl) - 2.59OM - 0.95CaCO_3}{100}$$

where *sa* (%) is coarse sand content of soil, *si* (%) is silty sand content of soil, *cl* (%) is clay particles content of soil, *OM* (%) is organic matter content of soil, C_aCO_3 (%) is $CaCO_3$ content, we used 0 in this research.

Soil Crusting Factor (SCF). When raindrops impact the soil surface, there is a redistribution of soil particles and a formation of surface crust. The resulting soil surface can be extremely hard or very fragile and may decrease or increase wind erosion potential (Zobeck, 1991). The *SCF* equation was developed using laboratory wind tunnel tests on resistance of soil aggregates and crusts to windblown sand (Hagen et al., 1992).

$$\text{SCF} = \frac{1}{1 + 0.0066(cl)^2 + 0.021(OM)^2}$$

where *cl* (%) is clay particles content of soil, *OM* (%) is organic matter content of soil.

Surface Roughness Factor (K'). The original RWEQ was designed to calculate wind erosion loss at a field scale. Tillage operations modify the soil surface roughness and flatten and bury crop residues (Nelson et al., 1993). When scaled up to a region, we replaced soil ridge roughness with roughness caused by topography, and was calculated by the Smith-Carson equation.

$$\text{K}' = e^{(1.86K_r - 2.41K_r^{0.934} - 0.127C_{rr})}$$

$$K_r = 0.2\frac{(\Delta H)^2}{L}$$

where C_{rr} (cm) is random roughness factor, we didn’t consider it in this research; K_r (cm) is topographic roughness factor; L is relief parameter; ΔH is elevation difference within distance of L.

Vegetation Factor (C). The vegetation quantity on the ground surface has a significant impact on sand/soil erosion by wind. To quantify the effect of vegetation, the fraction of the ground surface covered with non-erodible plant material (flat residues), the plant silhouette from standing plant residues (standing residues), and growing crop canopies (crop canopy) are used in RWEQ (Bilbro et al., 1994).

$$\text{C} = e^{-0.0483(SC)}$$

where *SC* (%) is vegetation fraction.

B. Accounting value

The sandstorm prevention service provides benefits through reduction in the health costs of populations living in downwind areas. The accounting value of sandstorm prevention service is equal to the reduction in health costs from reduced exposure to wind borne sand and dust (V_{SP}, Yuan/year), which is found by comparing the difference between the potential exposure to wind borne sand and dust assuming there is no vegetation (V_p), and the actual exposure to wind borne sand and dust (V_a):

$$V_{SP} = V_p - V_a = M \times C \times \left(P_p n_p - P_a n_a\right)$$

where P_p is the potential affected population, P_a is the actual affected population, M is the percentage of the affected population that will become ill due to exposure to dust and sand, C is the health cost per person who becomes ill (Yuan/per capita), n_p is the potential days of exposure to wind borne sand and dust per year with no vegetation cover, and n_a is the actual days of exposure to wind borne sand and dust per year (Li, et al., 2018).

The exposed population is based on the prevailing wind direction and the exposure distance to sand and dust. We include population up to 70 km downwind from a sand and dust source as being affected by sand and dust, which is calculated based on results from Li et al., 2018. Prevailing winds are from the west. We used population distribution based on a 1km x 1km resolution population raster from the Resource and Environment Data Cloud Platform (http://www.resdc.cn/Default.aspx). Vegetation covers the eastern part of Qinghai so that sand and dust originating in Qinghai does not affect downwind provinces. However, the potential affected population (P_p) extends beyond Qinghai because if vegetation cover is removed throughout Qinghai there will be exposed populations in downwind provinces. The percentage of the affected population that will become sick due to exposure to sand and dust (M) comes from Peng et al.(2005). The health cost per person who becomes ill comes from Wang et al. (2011). The actual days of exposure to wind borne sand and dust per year comes from Li et al. 2018. We calculate the potential days of exposure to sand and dust per year (n_p) based on the days of exposure to sand and dust per year within the desert area of Qinghai Province (Li et al. 2018).

C. Additional issues, extensions, and omissions

We did not account for variable wind direction or differences due to interception by landscape features introduced by variable topography.

S1.4 Flood mitigation

A. Biophysical quantity

Heavy rainfall events resulting in flooding causes major economic losses. Natural vegetation, wetlands, lakes, and reservoirs, can store water and affect the timing and magnitude of water runoff and water flows, acting as sponges, intercepting storm rainfall and absorbing water through root systems and storage capacity (Xiao et al., 2016). Flood mitigation can be defined as the storage capacity of natural vegetation, wetlands, natural lakes and reservoirs, which can be used to absorb or spread out the excess water flows during flooding.

The flood mitigated service provided by ecosystems includes: (*i*) runoff retention by vegetation and (*ii*) runoff retention by wetlands, (*iii*) runoff retention by lakes, and (*iv*) runoff retention by reservoirs:

$$C_{fm} = C_{vc} + C_{wc} + C_{lc} + C_{rc}$$

where C_{fm} is the total storage of flood water (m^3), C_{vc} is the storage of flood water from natural vegetation (m^3), C_{wc} is the storage of flood water by wetlands (m^3), C_{lc} is the storage of flood water by lakes (m^3), C_{rc} is the storage of flood water by reservoirs (m^3).

For natural vegetation (forest, shrub and grassland): Flood mitigation from vegetation was calculated based on the difference between runoff with no vegetation and runoff with vegetation in the wet season (m^3). We use the monthly water yield model of InVEST (Sharp et al., 2016) to identify the monthly water yield with current land covers and with no vegetation.

For wetlands: Flood storage provided by wetlands was calculated as follows:

$$C_{wc} = A \times D$$

where A is the wetland area (m^2), and D is the average depth of the wetland (m).

For lakes: Flood storage for lakes was constructed based on the relationship between available storage capacity and lake area (Wang, 1998; Rao et al., 2014a), since the latter is closely related to storage capacity and is much easier to acquire. For lakes in Qinghai, we used the following relationship:

$$Ln(C_{lc})=0.680\ Ln(A)+5.653$$

where A is the lake area (Rao et al., 2014a).

For reservoirs: Flood storage for reservoirs was constructed based on the relationship between flood control storage capacity and total storage capacity (Rao et al., 2014b), which is available for most reservoirs in China:

$$C_{rc} = 0.35 \times C_t$$

where C_t is the total storage capacity of the reservoir (m^3).

B. Accounting value

We calculated the accounting value of flood mitigation by using the average cost of downstream flooding in the wet season along the Yangtze River where flooding is a serious problem. We did not calculate flood mitigation benefits for either the Mekong or Yellow River Basins as flooding is less of a concern in these Basins. The accounting value of the flood mitigation service (V_{fm}; Yuan/year) is

$$V_{fm} = C_{fm} \times C_{fd}$$

where C_{fm} is flood control storage capacity of ecosystems (m^3), C_{fd} is the average cost of downstream flooding disaster in wet season (Yuan/ m^3) based on the relationships between runoff in the main stream of the Yangtze River in wet season and cost of flooding disaster during 2006-2015. We built a statistical model relating the amount of damage caused by flooding per year and the amount of flood water using 10 years of data in Yangtze River Basin. We found that the flood damage increased by 469.2 million Yuan for each billion m^3 of increased flood water, Damage (Yuan) = - 959.6 + 0.4692*Flood water (m^3), R^2=0.44.

C. Additional issues, extensions, and omissions

Hydrological processes (e.g., water retention in ecosystems) are difficult to accurately measure. Other than for reduced flooding, we did not attempt to measure the value of changing the timing of flows of water downstream. We assumed that increased water storage in Qinghai is associated with flood water at downstream locations. There are complicated issues of timing of flows from different places within the Yangtze River Basin so that increased flows from some portions of the basin are more damaging than others, which we did not attempt to model. In addition, we did not assess non-linear effects of flood water on damage. We also did not calculate flood mitigation benefits for the Yellow or Mekong Rivers.

S1.5 Air purification

A. Biophysical quantity

Vegetation contributes to air purification by absorbing or filtering air pollutants and thereby reducing exposure to harmful air pollution. Sulphur dioxide, nitrogen oxides, and industrial sources of particulate matter are the three main air pollutants in China. Each vegetation type i ($i = 1, 2,\ldots, I$) has a capacity to absorb or filter each air pollutant type j (j = SO_2, NO_x, PM) given by QA_{ij} ($kg \cdot ha^{-1} \cdot y^{-1}$), see Table S3. The annual amount of air purification for pollutant j at location l ($l = 1, 2,\ldots, L$) is given by

$$QA_{jl} = Min\left[X_{jl}, \sum_{i=1}^{I} A_{il}\, QA_{ij}\right]$$

where X_{jl} is the total emission amount of air pollutant j at location l ($kg \cdot ha^{-1} \cdot y^{-1}$), and A_{il} is the area of vegetation type i at location l (ha). The total amount of air purification for pollutant j from vegetation in a region is given by

$$QA_j = \sum_{l=1}^{L} QA_{jl}.$$

Table S3. Air filtration capacity of different vegetation types

Ecosystem	Air pollutants	Filtration capacity ($t \cdot km^{-2} \cdot a^{-1}$)	References
Forest	SO_2	24.6	The compilation and writing group of China's national biodiversity research report, 1998, Wang et al. 2012, Jin et al. 2007, Li et al. 2008, Ma et al. 2002.
	NO_x	0.57	Wang et al. 2012, Li et al. 2008
	PM	3831.7	The compilation and writing group of China's national biodiversity research report 1998, Feng et al., 1992, Han et al. 2015, Ma et al. 2002
Shrub	SO_2	8.4	Yuan et al. 2005, Xiao et al. 2011
	NO_x	0.19	Wang et al. 2012
	PM	162.4	Wang et al. 2012
Grassland	SO_2	0.09	Li et al. 2008

NO_x	0.06	Li et al. 2008
PM	12	Liu et al. 2015

B. Accounting value

In China, the National Development Reform Commission (NDRC) assesses a charge for emissions of various air pollutants. These charges are set on a provincial level. We use the charges for Qinghai Province as the accounting price for air pollutants. The value of reducing SO_2, NO_x, and PM, given by C_{SO_2}, C_{NO_x}, C_{PM}, respectively (Yuan/t), comes from National Development and Reform Commission (2003, 2014). The value of air filtration (Yuan/year) is given by

$$V_{AP} = QA_{SO_2} \times C_{SO_2} + QA_{NO_x} \times C_{NO_x} + QA_{PM} \times C_{PM}$$

Table S4. Treatment cost of different air pollution

Types of air pollution	Treatment cost in 2000 （Yuan/t）	Treatment cost in 2015 （Yuan/t）
SO_2	630	1260
NO_x	630	1260
PM	150	150

C. Additional issues, extensions, and omissions

Ideally we would use avoided health damages from air pollution rather than cost of reducing pollution but we lack detailed epidemiological models linking health outcomes with exposure to air pollution. As the value of air purification in Qinghai is low using cost instead of reduced health damages does not affect GEP very much. In other places such as parts of eastern and central China with much higher pollution loads, it is more important to try to assemble the necessary data to use reduced health damages.

S1.6 Water purification

A. Biophysical quantity

Wetlands, lakes, and rivers can provide a valuable water purification service by absorbing and filtering water pollution. We selected three indicators to account for the amount of pollutants purified by wetlands, including the amount of chemical oxygen demand (COD), ammonia nitrogen (NH-N), total phosphorus (TP). Each ecosystem type i ($i = 1, 2, \ldots, I$) has a capacity to absorb or filter each water pollutant type j (j = COD, NH-N, TP) given by QW_{ij} measured in kg per hectare per year. The annual amount of water purification for pollutant j at location l ($l = 1, 2, \ldots, L$) is given by

$$QW_{jl} = Min\left[W_{jl}, \sum_{i=1}^{I} A_{il}\, QW_{ij}\right]$$

where W_{jl} is the total emission amount of water pollutant *j* at location *l* measured in kg per hectare per year, and A_{il} is the area in hectares of ecosystem type *i* at location *l*. The total amount of water purification for pollutant *j* from ecosystems in a region is given by

$$QW_j = \sum_{l=1}^{L} QW_{jl}.$$

B. Accounting value

We use water treatment costs for removing COD, ammonia nitrogen and total phosphorus to assess the *accounting value* of the water purification service. The treatment cost of reducing COD, NH-N, and TP is given by C_{COD}, $C_{\mathrm{NH-N}}$, C_{TP}, respectively (Yuan/t). The treatment costs of reducing COD, ammonia nitrogen and TP come from National Development and Reform Commission (2003, 2014). The value of water filtration (Yuan/year) is given by:

$$V_{WP} = QW_{COD} \times C_{COD} + QW_{NH-N} \times C_{NH-N} + QW_{TP} \times C_{TP}.$$

Table S5. Treatment cost of different water pollution

Types of air pollution	Treatment cost in 2000 （Yuan/t）	Treatment cost in 2015 （Yuan/t）
COD	700	1400
NH-N	875	1750
TP	2800	2800

C. Additional issues, extensions, and omissions

There exists a large gap between where ecological modeling stops (e.g., amount of nutrients in water supply) and where valuation would typically begin (e.g., human health impacts measured in disability adjusted life years). Here we used treatment costs rather than health or other impact costs. In the future, if additional integrated modeling is available we could use relationships between nutrient concentrations in water, exposure to people, and health and other losses associated with exposure to low quality water.

S1.7 Carbon sequestration

A. Biophysical quantity

Carbon sequestration in ecosystems is the process of capture and long-term storage of atmospheric carbon dioxide (CO_2). Carbon sequestration refers to the increase in carbon in terrestrial ecosystems, which slows the current rate of increase of atmospheric CO_2 (Piao et al., 2009), while storage refers to the carbon remaining in terrestrial ecosystems, possibly over the long term (Lewis et al., 2009; Keith et al., 2009). Carbon storage represents not only the result of carbon sequestration (Keith et al., 2009), but also indicates the importance of restoration or avoidance of deforestation (Mandle et al., 2015). We examined the dynamics of biomass carbon storage in Qinghai's forest, grassland, and wetland ecosystems, and estimated the average annual carbon sequestration of Qinghai's terrestrial ecosystems. Since the grassland vegetation will wither every year, its fixed carbon will be returned to the atmosphere or into the soil. Therefore, regardless of the carbon sequestration of the grassland vegetation, only the soil carbon sequestration of the grassland is considered. The biomass carbon storage of different types of ecosystem (Q_{tCO_2}) was obtained with the following formula:

$$Q_{tCO_2} = M_{CO_2}/M_c \times (F_{cs} + G_{cs} + W_{cs})$$

$$F_{CS} = R_{FCS} \times S_F$$

$$G_{CS} = R_{GSCS} \times S_G$$

$$W_{CS} = \sum_{i=1}^{n} R_{iWCS} \times S_{iw}$$

where Q_{tCO_2} is the amount of carbon sequestration in terrestrial ecosystems (tCO_2/y), F_{cs} is annual carbon sequestration of forests and shrubs (tC/y), G_{cs} is annual carbon sequestration of grasslands (tC/y), W_{cs} is annual carbon sequestration of wetlands (tC/y), M_{CO_2}/M_c (44/12) is transformation coefficient of molecular weight from CO_2 to C, R_{FCS} is the carbon sequestration rate of forests and shrubs ($tC \cdot ha^{-1} \cdot a^{-1}$), S_F is area of forests and shrubs (ha), R_{GSCS} is the carbon sequestration rate of grasslands soil ($tC \cdot ha^{-1} \cdot a^{-1}$), S_G is the area of grasslands (ha), R_{iWCS} is the carbon sequestration rate of wetland i ($gC \cdot m^{-2} \cdot a^{-1}$), S_{iw} is the area of wetland i; i is the type of wetland, i=1, 2, …, *n*, *n* is the types number of wetlands.

Table S6. Annual carbon sequestration rate of different ecosystems

Ecosystem types	Carbon sequestration rate of ecosystems ($tC \cdot ha^{-1} \cdot a^{-1}$)		References
	2000	2015	
Forests and shrubs	0.2	0.92	National Forestry and Grassland Administration, 2005, 2014.
Grasslands	0.03	0.03	Yang et al., 2010.
Wetlands-lake	12.57	12.57	Duan et al., 2008
Wetlands-swamp	67.11	67.11	Duan et al., 2008

B. Accounting value

The accounting value of carbon sequestration can be assessed by multiplying the amount of carbon sequestered (tCO_2/y) by a carbon price, P_c ($Yuan/tCO_2$). There are several different approaches for establishing a carbon price: (i) setting price equal to the cost of sequestering carbon via afforestation or reductions in industrial emissions; (ii) using a market price for trade of carbon permits on carbon exchanges; and (iii) setting price equal to the social cost of carbon that measures the present value of damage measured in dollar terms associated with the emission of a unit of CO_2 to the atmosphere (Bernes, 1994). We choose to use the cost of afforestation

(Hou et al., 1995) because Chinese carbon trade market are in a preliminary stage of development, while artificial afforestation is a main measure for ecosystem restoration and protection, and China is the country with the most afforestation in the world. Afforestation should be done in places that do not negatively impinge on other ecosystem services, such as in dry regions where tree planting may reduce water availability (Cao and Zhang 2015, Zastrow 2019). The accounting value of carbon sequestration, V_{cs} (Yuan/year) is given by

$$V_{cs} = Q_{CO2} \times C_c$$

where Q_{CO2} is amount of sequestrated carbon by ecosystems (tCO_2/y), C_c is afforestation cost (Yuan/tCO_2).

C. Additional issues, extensions, and omissions

We did not include greenhouse gas emissions from fires due to low frequency of fire in Qinghai. We also did not include greenhouse gas emissions other than carbon.

S1.8 Non-material services

Non-material ecosystem services refer to a wide range of benefits provided by natural landscapes including tourism and recreation values, mental and physical health values of being in nature, and aesthetic, spiritual and cultural values. While these benefits can be large and of great importance to people they are often quite difficult to accurately measure in monetary terms. Currently, we lack the evidence base to support inclusion of values for many non-material services. Here we include only the value of ecotourism in Qinghai using information on the number of tourist visits and on-site surveys of visitors to top ecotourism sites. There are rich ecotourism resources and many famous scenic locations in Qinghai Province. We choose three famous scenic locations (Beishan Forest Park, Kanbula National Forest Park, and Qinghai Lake) and conducted questionnaire surveys at these locations.

A. Biophysical quantity

We collect the number of tourists in 2000 and 2015 in Qinghai Province according to the statistics data of Qinghai Province.

B. Accounting value

We used surveys to gather information on the expenditure per trip to scenic locations in Qinghai. We conducted onsite questionnaire surveys at Beishan Forest Park, Cambra Forest Park and Qinghai Lake. The useable survey sample size was 462 respondents. The questionnaire was divided into two sections, including (*i*) personal information (gender, age, education, occupation, income, residence address, etc.), and (*ii*) travel information (visiting places, travel time, transportation fee, admission fee, accommodation, etc.). We used the travel information to calculate the travel expenditure. For travel expenditure we took the following cost elements into account: 1) entrance fees, tour costs and other expenses at the recreation site, 2) travel expenses such as tickets, fuel, tolls, etc., 3) accommodation costs, 4) the cost of time spent by the visitor to travel to the site. We use the salary of the visitor to calculate the time cost of the visitor. Recent travel cost analyses relying on real payments data (Fezzi et al, 2014) suggest that such an assumption may be more defensible than the low proportions of wage rate suggested by early studies (e.g. Cesario, 1976).

We used a zonal consumer cost model, which is the simplest implementation of the expenditure method (EM). We collected information on the number of visits to each site from different distances (zones) and the cost of round trips from each of these zones to the sites. Then, we calculated the travel cost and time cost for travel from different zones.

The implementation of a zonal consumer cost model comprises the following main steps:

(i) Definition of geographical zones where visitors to the site come from. Each of these zones should be defined in a way that the travel cost to the recreation area in question will be more or less the same.

(ii) Data collection concerning the number of visitors to the site in question from each defined zone and estimation of the visitation rates from each zone.

(iii) Calculation of the average consumer cost of the round trip from each zone to the recreation site, which includes direct travel cost and time cost, which comes from the questionnaire.

The total ecotourism expenditure is then calculated based on the average expenditure per tourist and tourist number in each zone. We used the proportion of tourists from each zone from the survey and scaled this up to the total number of tourists in each zone using information about the total number of tourists in Qinghai.

Table S7. Ecotourism monetary value in Qinghai (2015)

Travel cost (Billion Yuan)	Time cost (Billion Yuan)	Total visitor cost (Billion Yuan)
18.1	3.5	21.6

The expenditure approach used conforms with recent natural capital accounting exercises such as those carried out for the UK (Office of National Statistics 2019). However, we fully acknowledge that expenditures may not correlate well with the welfare benefits provided by outdoor recreational assets. For example, individuals who value such assets highly may move house to be near them, thereby reducing their travel expenditures in a manner that does not reflect the values they hold for recreational experiences. Economic benefit-cost analyses seek to assess these underlying values, however, such analyses lack the ready tractability and comparability with GDP that our GEP measure provides.

C. Additional issues, extensions, and omissions

We included the entire value of ecotourism in non-material services even though human labor and infrastructure investments also contributes to its production. We do not differentiate the natural contributions of tourism from other investments (e.g., human labor, infrastructure) due to lack of data.

S2 GEP application in China

Table S8. Purposes of using GEP by central government agencies (and their corresponding agencies at the provincial, city, and county levels)

Government agencies	Purposes
National Development and Reform Committee	Composite (integrated, overall) Effectiveness of eco-compensation programs (evaluate all national eco-compensation and conservation programs together)
Ministry of Ecology and Environment	Performance of EFCA counties Overall performance of conservation (all national and local efforts together). Evaluation of local government performance (counties that do not consider GDP ~1000 counties in EFCA counties; effectiveness of conservation for all counties, cities and provinces)
Ministry of Finance	Evaluating effectiveness of ecological financial transfer payment
State Forestry and Grassland Administration	Assessing the ecological benefits of forests, wetlands, wildlife
Ministry of Agriculture	GEP of agricultural systems (croplands, pasture, lakes with focus on fisheries)
Standardization Administration	Guidance for GEP accounting
Ministry of Housing, Urban and Rural Construction	Assessing ecosystem services of urban greenspace
Ministry of Natural Resources of the PRC	Ecological space (natural ecosystems)
Ministry of water resources	Assessing water ecosystems (rivers, lakes, wetlands; focus on water resources)

Table S9. GEP Projects supported by the government agencies

Project name	Project goals	Supporting Agencies	Duration (years)
Accounting methods and pilot study of ecological asset and eco-compensation	Establish technical guidelines and pilot study for EA and GEP accounting to evaluate effectiveness, efficiency and equity of eco-compensation programs at provincial, city, and county levels	Ministry of Science and Technology	2016-2020
PRC GEP Accounting for Eco-Compensation	Establish technical guidelines and implementation for GEP accounting to evaluate overall effectiveness of eco-compensation programs at provincial, city, and county levels	National Development and Reform Committee/ Asian Development Bank	2016-2017
Comprehensive evaluation methods of and policies for counties in key ecological function zones	Develop GEP-based indices for evaluating government performance of counties in key ecological function zones; suggest policies for implementation	National Development and Reform Committee	2015-2016
GEP accounting guidelines and pilot studies	Construct GEP accounting guidelines; Implement pilot studies in different eco-geographical regions	Ministry of Ecology and Environment	2014-2015
GEP accounting and training programs	Carry out national GEP accounting, and train technical experts at provincial, city, and county levels	Ministry of Ecology and Environment	2016
GEP accounting methods and case studies	Develop GEP accounting frameworks and methods Test the frameworks and methods in different regions	Chinese Academy of Sciences	2013-2015
GEP accounting of Hinggan League in Inner Mongolia	Implement GEP and ecosystem assets accounting in six counties of Hinggan League and apply the GEP in performance of counties	Inner Mongolia – Hinggan League	2014-2016
GEP accounting of Erdos and applications	Conduct GEP accounting and ecosystem assets and apply the GEP in effectiveness of conservation and restoration	Inner Mongolia – Erdos City	2014-2015
GEP accounting in Tonghua City, Jilin Province	Carry out ecological asset and GEP accounting and use the GEP in evaluating conservation effectiveness	Jilin – Tonghua City	2015-2016
GEP accounting in Yantian District, Shenzheng	Implement GEP and ecosystem assets accounting and evaluate the ecological benefits in urban areas of Yantian District	Shenzheng – Yantian District	2014-2015
GEP accounting in Xishui County,	Carry out GEP and ecosystem assets accounting and use the GEP in evaluating conservation	Guizhou – Xishui County	2016

Guizhou Province	effectiveness		
GEP accounting in Shunde District, Guangdong Province	Implement GEP and ecological asset accounting and evaluate conservation performance of township governments in Shunde city	Guangdong – Shunde District	2016-2017
GEP accounting in Shenzhen City, Guangdong Province	Conduct GEP and ecosystem asset accounting and apply them in urban management and city sustainability	Guangdong-Shenzhen	2019-2020
GEP accounting in Lishui City, Zhejiang Province	Conduct GEP and ecosystem asset accounting and apply them in effectiveness of conservation and green development	Zhejiang-Lishui city	2018-2019
GEP accounting in Fuzhou City, Jiangxi Province	Conduct GEP and ecosystem asset accounting and apply them in effectiveness of conservation and green development	JIangxi-Fuzhou city	2019-2020

S3 Eco-compensation in Qinghai Province

Table S-10 Eco-compensation programs in Qinghai 2010-2015[a]

Eco-compensation program	Compensation payments (billion Yuan)
Sloping Land Conversion Program (SLCP)	4.234
Compensation for Ecological Benefits of Public Welfare Forest (EBPWF)	3.649
Natural Forest Conservation Program (NFCP)	1.798
Three-North Shelter Forest Program (TNSFP)	0.557
Wetland Ecological Compensation Program (WECP)	0.218
Grassland Ecological Protection Subsidy Policy (GEPSP)	9.736
Return Grazing Land to Grassland (RGLG)	2.871
Ecological Financial Transfer for Key Ecological Function Areas (EFTKEFA)	9.721
Ecosystem Restoration of Qinghai Lake Basin Program (ERQBP)[1]	0.450
Sanjiangyuan Ecosystem Protection and Restoration Project (SEPRP)[2]	12.584
Qilianshan Ecosystem Protection and Ecological Construction (QEPRP)[3]	0.300
Total (billion Yuan)	45.819

Note: [a] All schemes and budgets run from 2010-2015 except: [1] 2010-2012, [2] 2011-2015, [3] 2014-2015.

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