correlations with SMI are positive between 47° and 49°N and become negative above 50°N. As for precipitation, the majority of the significant correlations are negative above 51° to 52°N (Fig. 3B). To summarize, all three climate variables point toward a low-temperature constraint in black spruce forests north of approximately 49°N. The average MAT of forests sampled at this latitude is 1.1 ± 0.7°C (SD) and may be a threshold of MAT below which the growth of black spruce trees is constrained by low temperatures (Fig. 3C). In contrast to typical climate envelope models, which use species distribution data to estimate their climatic niche, our approach uses the climate sensitivity of thousands of black spruce trees.

According to median temperature projections for a low- and a high-emission scenario (4.5 and $8.5\ \mathrm{W\ m^{-2}}$) for 2041–2070, 63 to 80% of the territory from 49° to 52°N should still be subject to MAT associated with positive temperature responses (Fig. 3C). Considering that (i) increasing growth rates are being reported at the species treeline [55° to 58°N (*18*)] and (ii) the species is already dominant at these latitudes although at lower density, we see no major constraint against a shift of the refugium into the open-crown forests located north of the study area, despite the presence of less fertile soils. We acknowledge that there is a potential warming threshold when the region would lose its capacity to favor black spruce growth.

The essentially monotypic black spruce boreal forest dominating at latitudes from 49°to 52°N has a largely positive growth response to the combined increase in temperature and decrease in precipitation, thus supporting the hypothesis that low temperatures are the dominant climatic growth constraint. Conversely, growth reductions associated with increases in temperature and decreases in precipitation and SMI are mostly found south of 49°N. This conclusion agrees well with (i) satellite-derived observations of recent increases in photosynthetic activity in high-latitude forests of NENA (*12*, *13*, *33*), (ii) ground-based reports of a recent increase in black spruce growth in the northern forest-tundra of NENA (*18*), and (iii) predictive growth models for boreal tree species of NENA (*17*). The poor adaptation of black spruce to warm temperatures (*6*) that is responsible for its lower relative abundance south of 49°N (fig. S1), coupled with the higher water requirements of the denser, taller, and more productive forest stands found at these latitudes, may contribute to the observed response gradient. Being mainly driven by temperature, this gradient is likely to also affect other boreal species of NENA, although species-specific adaptations at the scale of this study are unknown.

In contrast to the moisture-sensitive boreal forests of central and western North America, results from this heavily replicated network indicate that eastern black spruce populations north of 49°N show no sign of a negative response to climate warming and instead respond positively to increased temperature and reduced precipitation. Although these conclusions do not take into account the predicted changes in biotic and abiotic disturbances (*2*), they do suggest that the higher NENA water availability could allow boreal tree species such as black spruce to better withstand a warmer climate in NENA than in the central and western portions of North America. Outside of the potential for extreme disturbance events, NENA may act as a refugium for the boreal forest.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Figs. S1 and S2
References (*36*–*53*)

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ECOSYSTEM SERVICES

Improvements in ecosystem services from investments in natural capital

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In response to ecosystem degradation from rapid economic development, China began investing heavily in protecting and restoring natural capital starting in 2000. We report on China's first national ecosystem assessment (2000–2010), designed to quantify and help manage change in ecosystem services, including food production, carbon sequestration, soil retention, sandstorm prevention, water retention, flood mitigation, and provision of habitat for biodiversity. Overall, ecosystem services improved from 2000 to 2010, apart from habitat provision. China's national conservation policies contributed significantly to the increases in those ecosystem services.

Through pursuit of rapid economic development, China has become the second largest economy in the world and has lifted hundreds of millions of people out of poverty since the "reform and opening up," begun in the 1970s. Yet the costs of this success are reflected in high levels of environmental degradation. In 1998, massive deforestation and erosion contributed to severe flooding along the Yangtze River, killing thousands of people, rendering 13.2 million homeless, and causing about U.S. $36 billion in property damage (*1*). This crisis prompted creation of the world's largest government-financed payment for ecosystem services programs: the Natural Forest Conservation Program (NFCP) and the Sloping Land Conversion Program (SLCP) (*2*, *3*). By 2009, the cumulative total investment through the NFCP and SLCP exceeded U.S. $50 billion and directly involved more than 120 million farmers in 32 million households in the SLCP alone (*4*). These programs aim to reduce natural disaster risk by restoring forest and grassland, while improving livelihood options and alleviating poverty.

Although there are scattered case studies [e.g., (*5*)], systematic, comprehensive, and rigorous assessments of the ecosystem services and people affected by these conservation policies at the national level have been lacking. To address this knowledge gap, in 2012, China's Ministry of Environmental Protection and Chinese Academy of Sciences launched a national ecosystem assessment to quantify ecosystem status and trends, and ecosystem service provision between 2000 and 2010. The China ecosystem assessment (CEA) was designed to address central questions of how ecosystem services are changing, where important services originate, and what should be protected and restored to increase ecosystem services.

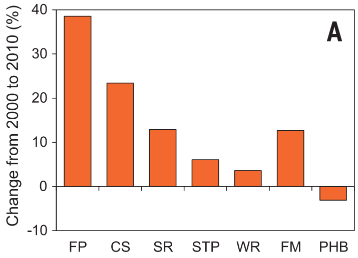
Here, we report on results of the first CEA, which covered all of mainland China from 2000 to 2010. The assessment used data from a variety of sources, including >20,000 multisource satellite images, recorded biophysical data [such as soil, digital elevation models (DEMs), hydrology, and meteorology], >100,000 field surveys; historical records of biodiversity; and special assessments from several government ministries (e.g., surveys of desertification, soil erosion). All lands were classified using a newly established ecosystem classification system for China (*6*). The CEA collected data on food production by crop converted to kilocalories (kcal) and modeled the level of provision for six other important ecosystem services [carbon sequestration (metric tons), soil retention (metric tons), sandstorm prevention (metric tons), water retention (metric tons), flood mitigation (m^3), and habitat provision for biodiversity (total habitat area of endemic, endangered, and nationally protected species per county)] using InVEST (a suite of free, open-source software models designed for Integrated Valuation of Ecosystem Services and Tradeoffs) (*7*, *8*) and other biophysical models (*6*).

We translated biophysical supply of ecosystem services into importance of service provision by weighting supply by the number of people affected. For example, sandstorm prevention is weighted by the population downwind. The importance of food supply and carbon sequestration has the same value in all locations, which reflects the uniform atmospheric mixing of CO$_2$ and integrated markets for crops (*6*).

All ecosystem services evaluated increased between 2000 and 2010, with the exception of habitat provision for biodiversity. Food production had the largest increase (38.5%), followed by carbon sequestration (23.4%), soil retention (12.9%), flood mitigation (12.7%), sandstorm prevention (6.1%), and water retention (3.6%), whereas habitat provision decreased slightly (–3.1%) (Fig. 1A).

Not all regions had a positive trend. Ecosystem services increased, in aggregate, in the Loess Plateau in western China (the most severe soil erosion area in the world); the Sanjiangyuan area in the center of the Tibetan Plateau (the headwater region of the Yellow River, Yangtze River, and Mekong River); and the Taihang Mountains in north China (the water provision area for the North China Plain) (Fig. 1B). Ecosystem services decreased, in aggregate, in the southwestern Tibetan Plateau, the western Hunshandake Sandy Area in northern China, and the northern Tianshan Mountains in western China (Fig. 1C). There are also tradeoffs between services (e.g., food production and soil retention). However, we see many synergistic increases or decreases among services (e.g., carbon sequestration, soil retention, and sandstorm prevention).

Food production in China is concentrated in the eastern plains (including the Northeast Plain, North China Plain, and Middle and Lower Yangtze Plain) and the Sichuan Basin (Fig. 2A and fig. S2). Important areas providing the other ecosystem services (carbon sequestration, soil retention, sandstorm prevention, water retention, flood mitigation, and provision of habitat for biodiversity) occur throughout the country. The government's priority areas for securing these ecosystem services are in the Great Khingan and Changbai Mountains in northeastern China, the Hunshandake Sandy Area in northern China, the Tianshan Mountains, and Loess Plateau in northwestern China, the Sanjiangyuan Area and Hengduan Mountains in southwestern China, the adjacent Mountains of Zhejiang Province and Fujian Province, the Nanling Mountains in southeastern China, and the Qinling-Daba Mountains in central China (Fig. 2, B to G, and fig. S5). These priority areas provide 83.4% of carbon-sequestration services, 77.7% of soil retention services, 59.1% of sandstorm prevention services,



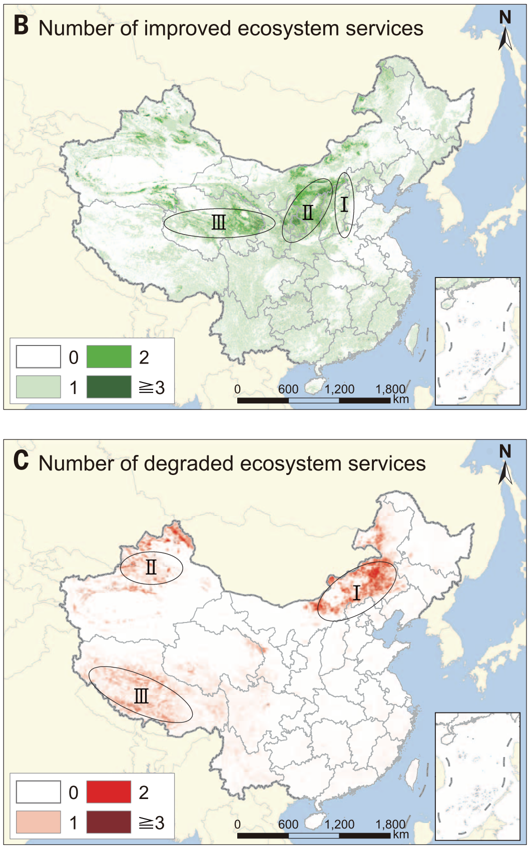


Fig. 1. Improvement in ecosystem service provision and decline in habitat for biodiversity in China from 2000 to 2010. (**A**) Aggregate change in provision of ecosystem services, for the seven focal ecosystem services: FP, food production; CS, carbon sequestration; SR, soil retention; STP, sandstorm prevention; WR, water retention; FM, flood mitigation; and PHB, provision of habitat for biodiversity. Changes of SR, STP, and WR were presented by the reduction rates of soil erosion, wind erosion, and storm runoff, respectively, using models that link ecosystem conditions and processes to services. (**B**) Spatial pattern of ecosystem service increases. (I) Taihang Mountains in north China; (II) Loess Plateau in western China; (III) Sanjiangyuan area in the center of the Tibetan Plateau. (**C**) Spatial pattern of ecosystem service decreases. (I) Western Hunshandake Sandy Area in northern China; (II) Northern Tianshan Mountains in western China; (III) Southwestern Tibetan Plateau.

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80.4% of water retention services, and 56.3% of natural habitats, although they make up only 37.0% of the area of China (Fig. 2H).

The changes in the provision of ecosystem services from 2000 to 2010 are the result of natural capital investment policies, changes in biophysical factors, and socioeconomic development (Table 1) (*6*). Overall, our results suggest that China's national conservation policies contributed significantly to the increases in four key ecosystem services. For carbon sequestration and soil retention, coefficients for the SLCP targeting forest restoration (SLCP_F) and NFCP are positive and statistically significant. For sand fixation, SLCP targeting grassland restoration (SLCP_G) is positive and statistically significant ($P < 0.05$) whereas SLCP_F is not. For water retention, NFCP is positive and statistically significant ($P < 0.001$) but SLCP_F is not.

The results of the CEA show that improving ecosystem services and economic growth can coexist. Analyses using model simulations in the United Kingdom (*9*), the United States (*10*), and Australia (*11*) also show that it is possible to increase the provision of key ecosystem services with economic growth through intelligent policy design, although ecosystem services can decline without proper policies in place. Further developing the CEA can help inform future efforts to sustain and enhance ecosystem services and human well-being, not only in China but worldwide (*12–15*).

The results generated by the CEA have already been applied by policy-makers in China at national, provincial, and local levels, by several parts of government (e.g., Ministry of Environmental Protection and the National Development Reform Commission). For example, 49.4% of China's land area (4.74 million km^2 over 63 locations) has been newly incorporated into Ecosystem Function Conservation Areas (EFCAs), designed to secure the nation's most vital natural capital, on the basis of CEA's characterization of important source areas for ecosystem service provision (Fig. 2H) (*16, 17*). EFCAs include areas that provide 77.7% of carbon-sequestration services, 75.3% of soil-retention services, 60.7% of sandstorm-prevention services, 76.8% of water-retention services, 60.2% of flood-mitigation services, and 67.6% of natural habitats. The CEA also informed the national-level policy of ecological protection red-lining (EPR) that designates lands for strict protection to ensure sustainable provision of ecosystem services (*18*). The national EPR, as well as EPR planning, in provinces and localities was based on priority sources of ecosystem services and covers 34.4% of the area of China (Fig. 2H) (*18, 19*). The results of the CEA have also been applied in national transportation network planning to identify sensitive areas for protection when designing road projects (*20*).

Although the CEA and some other studies [e.g., (*21*)] have documented improvement in ecosystem services, there remain serious environmental challenges, including deteriorating air and water quality, increasing greenhouse gas emissions, and an

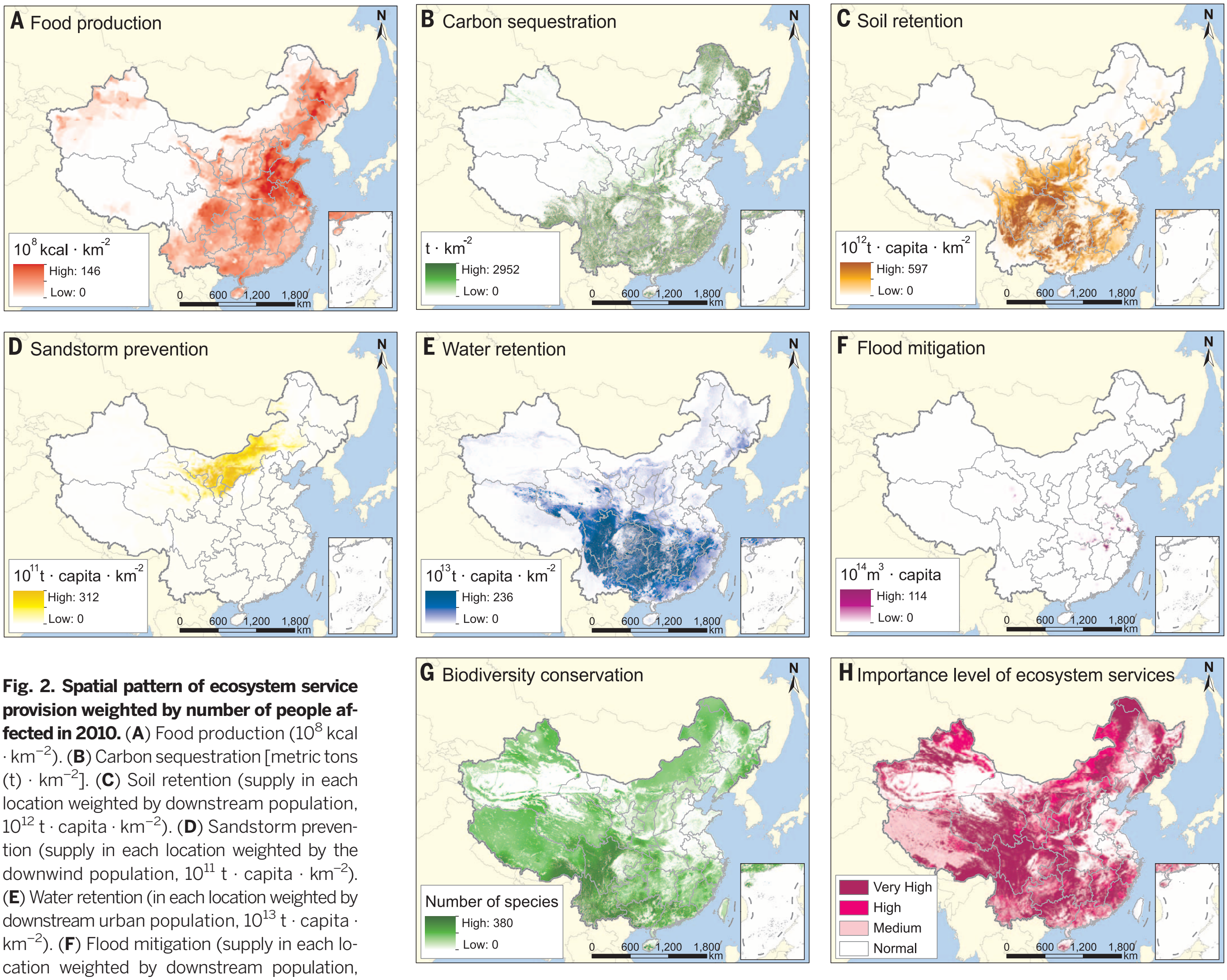

Fig. 2. Spatial pattern of ecosystem service provision weighted by number of people affected in 2010. (**A**) Food production (10^8 kcal · km^{-2}). (**B**) Carbon sequestration [metric tons (t) · km^{-2}]. (**C**) Soil retention (supply in each location weighted by downstream population, 10^{12} t · capita · km^{-2}). (**D**) Sandstorm prevention (supply in each location weighted by the downwind population, 10^{11} t · capita · km^{-2}). (**E**) Water retention (in each location weighted by downstream urban population, 10^{13} t · capita · km^{-2}). (**F**) Flood mitigation (supply in each location weighted by downstream population, 10^{14} m^3 · capita). (**G**) Provision of habitat for biodiversity (total species richness of endemic, endangered, and nationally protected species per county). (**H**) Index of relative importance of ecosystem services (*6*).

Table 1. Factors associated with increases in four key ecosystem services. Unit of analysis is the county. Dependent variables are increases in per-unit-area carbon sequestration, soil retention, sandstorm prevention, and water retention, respectively. Standardized coefficients and robust standard errors are reported outside and inside parentheses, respectively. Model results passed standard regression diagnostics. Variance inflation factors (VIFs) were tested to be <5.

Category	Independent variable	Carbon sequestration	Soil retention	Sandstorm prevention	Water retention
Policy	SLCP targeting forest restoration (1: yes; 0: no)	0.029** (0.006)	0.069* (0.067)	0.060 (0.152)	0.005 (0.107)
	SLCP targeting grassland restoration (1: yes; 0: no)	-	-	0.125* (0.138)	-
	NFCP (1: yes; 0: no)	0.062*** (0.007)	0.227*** (0.051)	-	0.094*** (0.387)
Biophysical variables	Initial service amount in 2000 $(10^3\ \text{ton} \cdot \text{km}^{-2})$	0.873*** (0.004)	0.676*** (0.002)	0.729*** (0.042)	0.454*** (0.002)
	Above-ground forest biomass per unit area in 2000 $(10^3\ \text{t} \cdot \text{km}^{-2})$	-	−0.586*** (0.042)	-	-
	Above-ground grass biomass per unit area in 2000 $(10^3\ \text{t} \cdot \text{km}^{-2})$	-	-	−0.135** (0.612)	-
	Proportion of forest area in 2000	-	-	-	−0.255*** (1.797)
	Change in proportion of forest area 2000 to 2010	-	-	-	0.799*** (54.831)
	Proportion of shrub area in 2000	0.074*** (0.037)	−0.060* (0.235)	-	−0.034 (1.617)
	Change in proportion of shrub area 2000 to 2010	0.021* (0.146)	0.006 (1.448)	-	0.580*** (50.793)
	Proportion of grassland area in 2000	−0.059*** (0.017)	-	-	−0.063* (1.245)
	Change in proportion of grassland area 2000 to 2010	0.036** (0.259)	-	-	0.192*** (18.980)
	Proportion of cropland area in 2000	-	0.045 (0.136)	−0.083 (0.401)	-
	Change in proportion of cropland area 2000 to 2010	-	−0.285** (2.780)	−0.1112* (1.632)	-
Socioeconomic variables	Human population density in 2000 $(10^3\ \text{individual} \cdot \text{km}^{-2})$	−0.024† (0.012)	−0.172** (0.168)	-	0.059† (0.992)
	Change in human population density 2000 to 2010 $(10^3\ \text{individual} \cdot \text{km}^{-2})$	0.025* (0.060)	0.074** (0.616)	-	−0.085** (5.942)
	Proportion of urban population in 2000	−0.008 (0.022)	−0.007 (0.136)	-	−0.021 (1.237)
	Change in proportion of urban population 2000 to 2010	−0.008 (0.016)	0.045 (0.171)	-	−0.093*** (1.274)
	Livestock inventory in 2000 $(10^3\ \text{sheep unit} \cdot \text{km}^{-2})$	−0.013 (0.009)	−0.116*** (1.12E-04)	-	−0.125** (0.001)
	Change in livestock inventory 2000 to 2010 $(10^3\ \text{sheep unit} \cdot \text{km}^{-2})$	−0.039*** (0.014)	0.007 (1.23E-04)	-	−0.064* (0.001)
R^2	-	0.859	0.285	0.596	0.545
N	-	1296	1136	186	871

†$P < 0.1$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

expanding global ecological footprint from importing raw materials (*22*, *23*). Solutions will require interventions beyond the ecosystem restoration that is the focus of the CEA.

Although the CEA has already had notable success, providing improved policy guidance in the future depends on making progress in several aspects. First, rapid technological advances can enable more frequent data collection at finer resolution. Second, direct measurement of variables that are more directly linked to service provision can improve accuracy of results (e.g., wide spatial coverage of measures of soil loss). Third, an expanded set of ecosystem services could be quantified, including ecosystem contributions to securing water and air quality, both of which have deteriorated in China in recent decades, and mental health benefits of exposure to nature (*24*). Fourth, improved measures can be used that more directly link ecosystem services to human well-being, such as economic measures of value and direct measures of impact on health, livelihoods, happiness, or other aspects of well-being (*25*, *26*). Finally, better understanding of human behavioral responses to changes in policy or market conditions could improve policy effectiveness. Regularly repeating the CEA can provide insight into future national development pathways (*27*).

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/352/6292/1455/suppl/DC1
Materials and Methods
Figs. S1 to S5
Tables S1 to S5
References (*28*–*98*)

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HUMAN BEHAVIOR

New online ecology of adversarial aggregates: ISIS and beyond

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Support for an extremist entity such as Islamic State (ISIS) somehow manages to survive globally online despite considerable external pressure and may ultimately inspire acts by individuals having no history of extremism, membership in a terrorist faction, or direct links to leadership. Examining longitudinal records of online activity, we uncovered an ecology evolving on a daily time scale that drives online support, and we provide a mathematical theory that describes it. The ecology features self-organized aggregates (ad hoc groups formed via linkage to a Facebook page or analog) that proliferate preceding the onset of recent real-world campaigns and adopt novel adaptive mechanisms to enhance their survival. One of the predictions is that development of large, potentially potent pro-ISIS aggregates can be thwarted by targeting smaller ones.

Extremist entities such as ISIS (known as Islamic State) stand to benefit from the global reach and speed of the Internet for propaganda and recruiting purposes in ways that were unthinkable for their predecessors (*1*–*10*). This increased connectivity not only may facilitate the formation of real-world organized groups that subsequently carry out violent attacks (e.g., the ISIS-directed attacks in Paris in November 2015) but also may inspire self-radicalized actors with no known history of extremism or links to extremist leadership to operate without actually belonging to a group (e.g., the ISIS-inspired attack in San Bernardino in December 2015) (*11*). Recent research has used records of attacks to help elucidate group structure in past organizations for which the Internet was not a key component (*3*, *6*, *12*), the nature of attacks by lone-wolf actors (*13*), and the relationship between general online buzz and real-world events (*14*–*16*). Online buzz created by individuals that casually mention ISIS or protests is insufficient to identify any long-term buildup ahead of sudden real-world events (see, for example, fig. S1). This leaves open the question of how support for an entity like ISIS develops online—possibly before any real-world group has been formed or any real-world attack has been perpetrated—whether by "recruits" or by those simply "inspired."

Our data sets consist of detailed second-by-second longitudinal records of online support activity for ISIS from its 2014 development onward and, for comparison, online civil protestors across multiple countries within the past 3 years, following the U.S. Open Source Indicator (OSI) project (*14*–*16*). The supplementary materials (SM) provide a roadmap for the paper, data descriptions, and downloads. The data show that operational pro-ISIS and protest narratives develop through self-organized online aggregates, each of which is an ad hoc group of followers of an online page created through Facebook or its global equivalents, such as ВКонтакте (VKontakte) at http://vk.com/ (Fig. 1). These generic web-based interfaces allow such aggregates to form in a language-agnostic way and with freely chosen names that help attract followers without publicizing their members' identities. Because the focus in this paper is on the ecosystem rather than the behavior of any individual aggregate, the names are not being

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Improvements in ecosystem services from investments in natural capital

Zhiyun Ouyang, Hua Zheng, Yi Xiao, Stephen Polasky, Jianguo Liu, Weihua Xu, Qiao Wang, Lu Zhang, Yang Xiao, Enming Rao, Ling Jiang, Fei Lu, Xiaoke Wang, Guangbin Yang, Shihan Gong, Bingfang Wu, Yuan Zeng, Wu Yang and Gretchen C. Daily (June 16, 2016)

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Editor's Summary

China's national ecosystem assessment

China recently completed its first National Ecosystem Assessment covering the period 2000–2010. Ouyang *et al.* present the main findings of the assessment. Investment in the restoration and preservation of natural capital has resulted in improvements at the national level in most of the major ecosystem services measured. In particular, food production, carbon sequestration, and soil retention showed strong gains; on the other hand, habitat provision for biodiversity showed a gradual decline. Regional differences remain nonetheless, and there are serious environmental challenges still to be met in areas such as air quality and the wider global footprint of raw material imports.

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