Climate Change Policy: IPCC Consensus Is Not Enough

Intergovernmental Panel on Climate Change (IPCC) consensual scientific knowledge on climate change and its effects is to some extent the known truth, but not necessarily the entire truth. Consensual scientific knowledge is only a minimum common denominator for thousands of scientists of different disciplines and thousands of studies that, due to their multiplicity, heterogeneity, and complexity, may sometimes mismatch. If we, scientists and science managers just prosecute credibility and consensus, we may end up misleading society. For the sake of humanity, we must also take into account the possibility of events and scenarios that have not yet gained consensus. It is, of course, impossible to adapt to the worst possibilities in any aspect of the global change. However, society must keep an eye on non-linear, steep, catastrophic possibilities and should prudently create a reaction system that would mobilize people and resources to face unexpected, rapid, and severe events. We call here for the implementation of such reaction policy by the United Nations (UN).

The IPCC has accomplished an incredible task in assembling scientific evidences that a climate change is occurring as a consequence of CO₂ emissions and land-use changes, and showing that present trends can produce catastrophic effects if they continue in a near future. The IPCC AR4 SYR Summary for Policymakers (1) states that “confidence has increased that a 1.5–2.5°C increase in global mean temperature above pre-industrial levels poses significant risks to many unique and threatened systems including many biodiversity hotspots” and that “key vulnerabilities may be associated with many climate sensitive systems, including food supply, infrastructure, health, water resources, coastal systems, ecosystems, global biogeochemical cycles, ice sheets, and modes of oceanic and atmospheric circulation.” This is quite clear.

However, the IPCC documents are far from clear for the reference values that could serve to guide mitigation and adaptation strategies that human society should implement in order to avoid negative impacts. From the IPCC statements, policymakers could deduce that we might try to limit warming to 2°C above present average temperature by stabilizing the atmospheric CO₂-equivalent around 550 ppm. This way, we could avoid excessively negative impacts on Earth systems. IPCC models suggest that a rise of global carbon prices could serve to stabilize greenhouse gases at around 550 ppm CO₂-eq by 2100. This seems overly optimistic because we already have 450 ppm CO₂-eq right now, with higher rates of increase each year. Recent data (2) indicate that the 2°C and 550 ppm CO₂-eq thresholds could be exceeded much before the end of the century.

The consensus may be also too optimistic regarding impacts. Let us focus, for example, on one of the effects of the climate change considered to be most likely, sea-level rise. It seems that in this consensual scenario, the sea-level rise might be kept lower than 50 cm at the end of the century. The IPCC AR4 SYR Summary for Policymakers indicates that its moderate model predictions “exclude future rapid dynamical changes in ice flow.” It recognizes that there are “ice dynamical processes seen in recent observations but not fully included in the assessed ice sheet models,” and that “the risk of additional contributions to sea level rise from both the Greenland and possibly Antarctic ice sheets may be larger than projected by ice sheet models and could occur on century time scales.” This does not seem very worrying. However, scientific assessments that have not yet found scientific consensus indicate that i) glaciers can run faster than expected (3), ii) when ice shelves split from the continent, glaciers in that continent find no obstacle, and there is an increase in the rate of ice discharge into the sea, and iii) under the Antarctic ice, there is a system of liquid-water lakes, more or less interconnected, and there is a risk that a part of that water would also flow to the sea, if obstacles are removed. These phenomena could produce much steeper rises of sea level than those predicted by IPCC. They are less probable, but they can occur. Furthermore, in the other pole, the decrease of ice surface in the Arctic Ocean is proceeding at an unpredicted rate because positive feedbacks are at work (4). In addition, of course, there are many other examples of positive feedbacks that can act in other Earth system processes. For instance, even with a mere 2°C increase and a decrease in rainfall, fire and droughts can become the driving factors in desertification of the Mediterranean and other semiarid regions.

Meanwhile, although some companies and some nations are implementing programs driving to a more sustainable model, most activities around the world continue to be run “business as usual,” ignoring even the consensual IPCC assessments. A minimum of caution calls for human society to consider also scenarios resulting from scientific knowledge but that have not gained consensus. It is impossible to adapt to any one of the worst possibilities or even to many of them, but we must strongly recommend that, apart from using consensual scientific knowledge for most initiatives, we take into account nonlinear, steep, catastrophic possibilities, and, while doing that, we develop a reaction system to face unexpected, fast changes, mobilizing people and resources to fight these kind of events.

The United Nations has already created the Hyogo Framework, a plan of action to advise policymakers of the different countries on reducing our collective vulnerability to natural hazards, and the Global Platform for Disaster Risk Reduction, in order to increase the commitment of nations by advising them on ways to strengthen public infrastructures, coastal facilities, and homes to withstand more extreme weather, flooding, and rising waters, and to develop better drought management, better early warning systems and evacuation plans, stronger building codes, improved land and water management policies, expanded disaster education programs for local communities, etc. All of this should be backed by stronger institutions and proper funding, even from the economic point of view. A recent expert study in the United States shows that one dollar invested today in disaster risk reduction saves four dollars in the future cost of relief and rehabilitation—a bargain by any standard (J. Holmes, 2007, First Session of the Global Platform for Disaster Risk Reduction). However, national commitments will be slow, and many countries do not have the means to follow these recommendations. Meanwhile, we need a UN environmental emergency force, including resources (people, equipment, money) for medical assistance and for fighting fire, floods, severe droughts, and other hazards.

A continuous multiscale, multifactorial monitoring of the Earth system is vital to keep an eye on these not-yet-consensual possible environmental changes, and a renovated United Nations economic and political effort is necessary to develop such a reaction system. These are two important challenges for science and society in this emerging twenty-first century. We call here for their consideration. After all, this is what is done in many other smaller-scale
anthropic processes; just consider the security levels and reaction systems with which we build our bridges or our houses in earthquake prone areas. Earth is now a climate-quake prone area for us, and many people are unable to defend themselves singlehandedly.

References and Notes


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Synopsis

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Grassland Classification in Naqu Prefecture of Tibet

Naqu Prefecture is a part of Tibet and covers a vast territory with an average altitude of 4500 m (Fig. 1). It is one of the most important centers for animal production in Tibet and carries about 6.92 million head of various livestock on about 286 900 km$^2$ of native grasslands. Yak and sheep are well adapted to the local environment and account for 40% and 31% of livestock population in Tibet, respectively (1). However, animal husbandry in Naqu prefecture has faced severe development problems due to the combined effects of grassland degradation, long cold seasons, and economic constraints including distance from market centers, inadequate infrastructure, and uncertain grassland tenure arrangements (2). To resolve some of these problems facing herdsmen and regional planners, a joint research effort by Naqu Animal Husbandry Bureau and Gansu Grassland Ecological Research Institute (GGERI) was initiated in 1990 to improve production of grassland and livestock (3). This paper focuses on the results of a grassland classification survey that included an evaluation of grazing capacity and comments on relevant policy implications. The research approach adopted was a combination of remote sensing technologies and traditional field survey methods.

Remote sensing technology was combined with field survey as the research approach used to overcome the problems of the vast area and terrain diversity in Naqu. The grassland classification was made using the results of interpretations of Landsat images and field survey. It followed the procedures used in the China Grassland Classification System that were developed from a grassland classification system used in the former Soviet Union and modified for Chinese conditions (4, 5). According to this system that is promulgated by the Ministry of Agriculture (6), the grassland is classified in terms of zonal climatic features, degree of use by livestock, and characteristics of plant community. There are three levels of classification units in this system. The first level (called “class”) incorporates grasslands with similar macrotopographical condition and landscape into one type that mainly reflects the feature of a climatic zone, e.g., temperature and moisture. Classes are subdivided at a secondary level into “groups” according to the foraging attributes of plants for livestock use and variation of mesotopography and

Figure 1. Naqu location map.
Grassland Classification

The native grasslands of Naqu Prefecture were subdivided into 4 classes, 10 groups, and 32 types. The distribution of grassland classes was identical to the geographic-climatic zones and included bush meadow, alpine meadow, alpine steppe, and desert steppe, which form a horizontal-zonal pattern.

Bush Meadow

The bush meadow class is distributed mainly over the hilly areas in the eastern counties of Naqu (e.g., Jiali, Suoxian, Biru, and Baqing), where the climate is wet and comparatively temperate. The annual precipitation ranges from 579 mm to 650 mm, with 80% occurring in the growing season (200–224 d). Average annual temperature ranges from 1.5°C to 3.5°C. Owing to the diversified ecological conditions caused by topographic variation the farming systems are mixed, with large areas of native pasture in the lowland and river valleys already converted to grain and cash crops. Wheat, peas, rape, potato, millet, corn, and buckwheat are major crops in these counties, as well as traditional highland barley. Yak and Tibetan sheep are the major grazing livestock with yaks accounting for 40% of the prefecture livestock because they are so well adapted to the wet climate and highland conditions. Cattle and horses are also important, although cattle are mainly kept for use as draft animals for crop cultivation. The emergence of the mixed farming systems has led to peasants becoming settled in villages, which in turn has resulted in the development of animal husbandry methods that differ significantly from the traditional ones in pure pastoral areas. The use of lowlands and river valleys for crop production has shifted livestock grazing to the hilly areas. Although the grasslands are abundant, precipitous terrain and forestry lands restrict grazing activities to certain altitudes (between 4200 and 4600 m) and places with relatively gentle slopes (<2°). Grasslands with these features account for 8% of total usable grassland area in the prefecture. Within this restricted usable grassland area, one typical group, gramineae, is identified. On the north-facing slopes between 4300 and 4600 m, Rhododendron nivale Hook. f. are dominant, in association with Sibiraea angustata Hand-Mazz., Spiraea alpina Pall., and Potentilla fruticosa L., which are often used by yak and cattle. Above 4700 m, herbs graduually replace the dominant bushes. On the south-facing slopes between 4200 and 4500 m, Elymus nutans Griseb., Festuca ovina L., and Poa annua L. are dominant, in association with Kobresia pygmaea, Kobresia humilis, and Sabina tibetica Kom. Because of the high foraging value of these herbs and the relatively warm conditions, yaks, sheep, cattle, and horses are intensively grazed on the south-facing slopes in the summer periods, causing severe overgrazing. In winter, livestock are grazed near the villages on the scattered grassland in the valleys and lowlands and supplemented with crop residues and hays.

Alpine Meadow

Alpine meadow is distributed over the river terraces, valleys, and alluvial fans in the west parts of the four eastern counties, large areas of Naqu and Nierong, and part of Anduo County. It is the major grassland class for livestock production in the prefecture, accounting for 43% of the total usable grassland area. Cyperaceae form the most abundant and forageable group, which accounts for 73% of the grassland area in this class. Four grassland groups were identified in this class based on the foraging values of plants and the mesotopography. This vegetation is widely distributed over flatter highlands, valleys, and sunny sides of hills over an altitude range between 4000 and 5200 m in the east and central parts (e.g., Biru, Suoxian, Jiali, Baqing, Naqu, Nierong, and Ando). The climate is suitable for this grassland group that prefers cold and wet climatic conditions with a protracted cold season as long as 8 mo and average rainfall of 400 mm. The K. pygmaea grassland is the major type and provides the best summer and autumn grazing for sheep and yaks in the prefecture as a result of its high foraging value and flatter terrain. Although the composition of the grassland is relatively complex, K. pygmaea generally dominates the community with Sarracenia purpurea, Polygonum macropyllum D. Don, and E. nutans present as subdominants. Some higher producing Kobresia grasslands are cut for hay production. Overgrazing, drought, and rodents are thought to be responsible for the severe degradation of this grassland type.

The gramineae form the next important grassland group in the class of alpine meadow. Kobresia pygmaea has a strong ecological adaptation that enables it to dominate plant communities above 5300 m with cushion plants as a subdominant. This vegetation is mainly distributed in the transition zones between alpine meadow and steppe classes and located in the valley, lake basin, and saline meadows between 4500 and 5200 m. Three types of grassland within this group were identified based on the dominant species which included E. nutans, Achnatherum hookeri Keng, and Puccinella himalaica Tzvel.

Evergreen shrubs are the third group in the alpine meadow that is located on the north-facing sides of hills with altitude between 4200 and 4600 m in the eastern counties. These types of grassland usually provide winter and spring grazing for livestock.

Deciduous shrubs are the last group of alpine meadow. Rhododendron nivale dominate this group, and the areas with less canopy density are usually used for grazing yak and cattle in the warm season. This group is mainly distributed on north-facing hills with altitude between 4600 and 4900 m in Naqu, Suoxian, Biru, Jiali, and Baqing. It is also distributed on the south-facing sides of hills at 4000 and 4500 m, with P. fruticosa and Elsholtzia fruticosa Kehl, as the dominant species. Cutting by farmers for household fuel for a long period of time has reduced canopy density over large areas that are now used as grazing lands for sheep, yak, and cattle. The areas with altitude of 4600 to 4900 m are usually used as grazing in the warm season, and the grasslands below these altitudes are used in the cold season.

Desert Steppe

Desert steppe is widely distributed in the sandy land of lake basins, alluvial fans, and slopes of hills, between Keketil and Kunlun Mountains, where the average altitude exceeds 5000 m and the climate is extremely cold and dry. Annual rainfall averages only 100 mm. Grassland composition is very simple and only includes three to five species, of which Carex compacta, with C. moorcroftii and S. purpurea occur frequently. Desert steppe areas are “unpopulated areas” where wildlife such as wild yak, Tibetan wild donkey, Tibetan antelope, wolf, fox, etc. may be found.
INTRODUCTION

Due to the contribution of a hitherto neglected ecosystem, one of the richest mineral provinces in the world, at the heart of a center of floristic diversity, may prove much more diverse and vulnerable than the current figures show.

The Iron Quadrangle (local name Quadrilátero Ferrífero), located in southeast Brazil, covers an area of approximately 7200 km² and represents one of the most important and well-studied geological sites on the planet. It is contained entirely within the wealthy state of Minas Gerais, the area of which is approximately 587 000 km², larger than France. The Portuguese name, “general mines,” attests to the historical ties of this state with the mining industry since colonial times. Constituted by very old—Archean and Paleoproterozoic—terrains, the Iron Quadrangle landscape is presently a mosaic at the ecotone of two Brazilian hotspots, Cerrado and Atlantic Forest, which have been profoundly transformed by human activities, namely urbanization and mining.

The region is one of the leading producers of metallic minerals in the world, especially superficial iron ore. The intense mining activity entails a complete alteration of the landscape, with enormous impacts on the local and regional biodiversity. The superficial iron crusts, locally known as canga, are the result of weathering of minerals derived from banded-iron formations (BIFs), compact hematite, and limonite (1), and they are distributed on the tops and sides of some mountains formed by the huge deposits of iron ore that set the limits of the Iron Quadrangle. These outcrops form islands on top of hills at altitudes ranging from ~1000 to 2000 m.

Currently, there are about 50 iron-ore opencast mines, the extents of which may reach 2000 ha. Opencast mining is highly aggressive to the environment because the ironstone outcrops, and their associated biota, are discarded so that the iron-ore deposits can be reached, and the excavations can reach 300 m depth and expose the water table. Furthermore, the waste derived from these activities contaminates nearby watersheds with heavy metals and toxic elements (2).

These outcrops harbor characteristic rupestral vegetation, which is shrub-dominated, together with a large number of sedges, grasses, and orchids, most of which are epilithic. Due to their very restricted area, difficult access, and because they are associated with high-quality iron-ore deposits, the plant communities over canga are among the most threatened and least studied in the otherwise thoroughly surveyed ecosystems of southeast Brazil. Until recently, rupestral plant communities in the region had been given no differentiation with respect to the type of substrate that harbored them. Hence, plants growing over iron ore were frequently recorded together with those growing over ironstone outcrops. This synopsis was not peer reviewed.

The Contribution of Ironstone Outcrops to Plant Diversity in the Iron Quadrangle, a Threatened Brazilian Landscape

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References and Notes

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Ironstone outcrop plant community.

growing over sandstone or granite. The historical lack of differentiation among lithologies has prevented us from fully comprehending the role of the flora and fauna biodiversity associated with these ironstone outcrops. Recent studies, however, have begun to reveal that the plant communities over ironstone outcrops, which are almost exclusively found in the Iron Quadrangle, with exception of Carajás in north Brazil (equally threatened by iron-ore mining), have a floristic identity and an extremely high local and regional floristic diversity that equals or surpasses those of the other two lithologies.

Preliminary comparative surveys among the two major outcrop types in the Iron Quadrangle, sandstone and ironstone, suggest that the plant communities established over the latter contribute more heavily to the biodiversity of the region than had been previously imagined. In only six ironstone outcrops recently surveyed, which together barely reach 100 ha, 430 angiosperm species distributed among 78 families were catalogued. This number represents 36% of all the families in Brazil, the country with the highest plant diversity. Notably, some of these species are endemic to very few outcrops in the Iron Quadrangle, such as the milkweed Ditassa monocoronata and the cactus Arthrocrucus glaziovii. These surveys illustrate the need to accelerate studies of this particular environment, which, in contrast to the well-documented and world-known sandstone outcrops (the predominant rock type in the area), is undergoing increasing economic pressure.

WHY RESEARCH IRONSTONE OUTCROPS?

The Iron Quadrangle makes up the southern end of an orographic group known as Espinhaço Range, which is recognized as one of the regions with highest floristic diversity in South America, having more than 30% endemic species, most of which are associated with rock outcrop environments (3). These, among other peculiarities, recently granted the Espinhaço Range the status of Biosphere Reserve by the United Nations Educational, Scientific and Cultural Organization.

Following this lead, and with the aim of establishing their identity, an ongoing project at the Federal University of Minas Gerais is devoted to determining the contribution of the flora on ironstone outcrops to the regional plant diversity and to ascertaining the conservation status of these ecosystems throughout the Iron Quadrangle. The initiative, which combines botanists and ecologists, has already revealed a very high local diversity showing astonishing numbers, such as 16 species of vascular plants in a single square meter. This variety is due to the small size of plants, the rich matrix in which they are embedded, and the mineral and topographical heterogeneity of these outcrops, which create distinct microhabitats side by side and result in a unique association of plants (4). Aside from the more typical communities that are also common to other lithologies, virtually nothing is known about two plant communities typical of ironstone outcrops: temporal ponds, and penumbral rock communities associated with cliffs and cave entrances.

The high diversity contrasts with the severe edapho-climatic conditions typical of outcrops in general, such as high ultraviolet (UV) intensities, daily thermal substrate variations that can reach 45°C, rapid water loss, and poorly developed soil cover, which, in the case of ironstones are further aggravated by a high content of heavy metals. One of the most relevant plant communities for conservation in regions with intense mining activities are metallophyte plants, which encompass those species that have mechanisms of resistance, tolerance, or bioaccumulation regarding metals, usually taxa that are endemic to metalliferous areas. These communities are being investigated for ecological services such as phytoexcretion, phytostabilization, and phytoremediation. At present, several research groups are focusing on the conservation and sustainable use of these communities, following the recommendations of the Convention on Biological Diversity to identify and conserve metallophytes. These recommendations have even been proposed for inclusion in the Environmental Management System ISO 14 000 (5). This proposal is fundamental to the short-term conservation of plant communities on ironstone outcrops, because to date, there is no specific environmental legislation that protects this ecosystem. In Brazil, there are important regions with rock outcrops rich in metals, like the Iron Quadrangle itself. However, metallophyte communities, in spite of their evident environmental importance, have yet to become the focus of attention.

From the applications for sustainable use or for recovery of areas degraded by mining, the isolation among outcrops and plant and physiological adaptations make these environments a model system for fundamental ecological and evolutionary questions such as patterns of species richness and distribution of species.

BIODIVERSITY LOSS AND CONSERVATION STATUS

Habitat loss and alteration have long been recognized as leading threats to world biodiversity. In Brazilian ironstone outcrops, this process occurs basically in association with mining activities. Recently, this historical regional vocation has been heavily accelerated as a consequence of the economic emergence of China, which has generated unprecedented demand for raw materials worldwide, in particular high-quality iron ore, a phenomenon that has been termed “the China effect” in the commodities jargon. Mining activities contribute heavily to the Brazilian gross domestic product (GDP). In 2000, the iron ore produced in the region accounted for ~12% of the total value of Brazilian mineral production, excluding the fossil fuels petroleum and gas (6).

Most floristic surveys of ironstone outcrops in the Iron Quadrangle are very recent. Of the handful outcrops surveyed, only one is located within a conservation unit. The others are located in areas owned by mining companies, which unfortunately reflects the vulnerable status of this ecosystem. The mineral rights granted to industry until 2002 cover an area of ~207 000 ha of the Iron Quadrangle. This represents roughly 28% of the total Iron Quadrangle area, and probably 90% of all ironstone outcrops in the region, and illustrates that iron-ore exploitation overlaps heavily with these environments.

Currently, there are nine national parks in southeast Brazil that contain rock outcrops, and these are distributed throughout extensive mountain ranges such as the Mantiqueira and Serra do Mar (granite outcrops), and Canastra and Espinhaço (sandstone outcrops), which together cover ~679 000 ha. In the state of Minas Gerais alone, there are 14 state parks that together cover around 212 000

Table 1. Public conservation units in southeast Brazil containing rock outcrops.

<table>
<thead>
<tr>
<th>Rock type</th>
<th>National parks</th>
<th>Minas Gerais state parks</th>
<th>Total park area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ironstone</td>
<td>–</td>
<td>1</td>
<td>3900</td>
</tr>
<tr>
<td>Granite</td>
<td>5</td>
<td>2</td>
<td>210 361</td>
</tr>
<tr>
<td>Sandstone</td>
<td>4</td>
<td>11</td>
<td>676 976</td>
</tr>
</tbody>
</table>

ha. Only one of these, however, encloses a few mountaintops with ironstone outcrops (Table 1). In order to boost regulatory measures to protect these ecosystems, while maintaining sustainable mining activities in the region, a sound proof of the biological value and floristic identity of these outcrops is mandatory and urgent.

References and Notes


Synopsis

This synopsis was not peer reviewed.

Applying a Reverse Auction to Reduce Stormwater Runoff

The effects of stormwater runoff on stream ecosystems are exacerbated by urbanization and the concurrent increase in impervious surface area in a watershed. Proliferation of impervious surfaces creates higher peak flows and higher flow volume during storm events, and it increases the frequency of flows that result in stream-habitat degradation, pollutant loading, and biotic impairment. Current trends suggest that stormwater management should focus on restoring natural drainage processes and through small-scale decentralized efforts at the community level (1). Recent efforts by the US Environmental Protection Agency (US EPA) are focusing attention on the potential use of what is being called green infrastructure to control stormwater flows (2). The US EPA’s green infrastructure website highlights a number of municipalities, ranging from large cities, such as New York and Atlanta, to smaller communities nationwide, that have adopted green infrastructure practices as part of their solution to stormwater and wastewater management. Green infrastructure projects have resulted from two regulatory avenues: i) the implementation of the National Pollutant Discharge Elimination System Phase I and Phase II stormwater regulations for municipal dischargers, and ii) enforcement actions for combined and sanitary sewer overflows (CSO and SSO), where the alleged violators agree to undertake Supplemental Environmental Projects (SEP) in exchange for mitigation of monetary penalties. These SEP are based on the premise, detailed in the National Resource Defense Council’s 2006 report rooftops to Rivers (3), that they will control stormwater volume at the source, thereby reducing overall volume in the system during storm events.

Incentives for commercial properties to adopt stormwater runoff control are usually employed through command-and-control tactics such as stormwater fees and rebates for implementation of certain best management practices (BMP). In recently built housing developments around the country, in part due to increased awareness of the inimical effects of stormwater runoff, municipalities often have sufficient public support to be able to require stormwater runoff BMP. However, property rights issues and lack of impervious surface restrictions during past building periods conspire to cause built residential property to be one of the hardest-to-control sources of stormwater runoff. Parikh et al. (4) suggested a reverse auction as the preferred economic mechanism to create incentives for construction of retrofit, low-technology stormwater runoff retention practices in established residential neighborhoods. Currently, the popular alternative is to offer a fixed payment to residents to install certain BMP on their property (5). We show the auction to be more cost effective.

The Shepherd Creek Project, initiated in 2003 by the US EPA’s Office of Research and Development, used a reverse auction mechanism as an incentive to convince homeowners in an urban residential neighborhood in Cincinnati, OH, to accept rain gardens and rain barrels on their properties as a means to reduce stormwater runoff. In the spring of 2007, we conducted a reverse auction in the Shepherd Creek neighborhood. The auction was designed to compensate residents for their costs of adopting BMP (rain barrels and rain gardens) on their property. Each of approximately 350 homeowners residing in the neighborhood received one educational mailing and one door hanging that summarized information regarding the practical benefits of rain gardens and rain barrels, their appearance, their hydrological effectiveness, and their purported effect on stream ecology. Using a bid form that was mailed to each home approximately two weeks after the informational material, participants submitted bids for the minimum compensation that they would require to accept a rain garden and/or up to four rain barrels. A discriminative price auction was employed because of its theoretical “truth-revelation” properties, including optimal bidding strategy, and it would reflect the actual opportunity cost of BMP adoption.

The goal was to pay those landowners who adopted the most effective BMP at the lowest price. Individual bids were
assessed for their relative acceptability based on the bid price, the cost of installation, and the environmental benefit index (EBI), which is a measure of the infiltration impact of a given property. Bids for rain gardens and rain barrels were evaluated and ranked separately. EBI for the rain gardens was determined using: i) percent total impervious area (TIA) on the parcel; ii) soil drainage characteristics; and iii) proximity to a stream. The environmental value for BMP installation is maximized where there is high TIA on the parcel, soils have comparatively low capacity for drainage, and the property is in close proximity to stream channels. Rain barrels were scored based on percent of TIA currently attached to the storm sewer. The scoring process was designed to be a simple, informative, and repeatable technique for objectively quantifying the potential environmental value of placing BMP on the property.

There were 57 bids for rain gardens, which were ranked according to EBI-weighted bid amount; of those, 56 bids were accepted, and 50 rain gardens were installed. Opportunity cost was taken to be the bid amounts, which ranged from USD 0 to USD 300, for a total of USD 2465 across the 50 parcels. Based on an average cost of installation (USD 1500), we calculated cost per cubic meter of detention as follows: (50 × USD 1500) + USD 2465)/(50 × 4.28). This assumes a 4.28 m³ detention capacity per rain garden. Total storm water detained with this assumption is 214 m³, and the average cost was USD 1549 per homeowner, and we calculated an average cost of USD 362 per cubic meter of stormwater runoff detained via BMP over all properties in the study area. Assuming those who bid USD 0 were those who would have participated following an education campaign, but without the economic incentives, we calculated 30 × USD 1500/30 × 4.28. In this case, storm water detained is 128 m³, and the average cost of stormwater runoff detained via BMP over all properties in the study area is USD 350 per cubic meter. Had we not used an auction to determine the different willingness-to-accept amounts of different homeowners, and just offered the flat amount needed (USD 250) to cause the acceptance of the same number of rain gardens, costs would be USD 409 per cubic meter. The flat price was by far the least cost-effective way to incentivize a decentralized approach to control the stormwater runoff from this area. Based on these data, an educational campaign is expected to be the cheapest method for encouraging homeowners to accept free rain gardens; however, to encourage additional acceptance and runoff reduction capacity, beyond the initial 60% of homeowners (those who bid USD 0), the auction proves to be cost effective.

For rain barrels, there were 60 bids for 118 units, and bids ranged from USD 0 to USD 250 per barrel. One hundred barrels were installed for a total bid payout of USD 2482. Each barrel cost approximately USD 250, including installation, and held either 0.21 m³ (23 units) or 0.28 m³ (77 units). Total detention volume was 26.4 m³, and we calculated the cost per volume of detention as USD 1043 per cubic meter. If we, as in the rain garden example, assume those homeowners who gave a zero bid (37 bids for 63 barrels) could have participated had there been just an educational campaign, the cost of detention is approximately USD 929 per cubic meter. Had we paid a flat rate per barrel of USD 125 (the amount of the highest accepted per-barrel bid), cost for detention would have been USD 1421 per cubic meter.

Disconnection of impervious surfaces and infiltration or retention of runoff has been proposed as necessary to improve the health of freshwater ecosystems in urbanized areas; however, the practical solutions for encouraging enough mitigation within catchments to observe downstream improvements are unknown. The Shepherd Creek Project is structured using a before-after control-impact design and three years of pre-implementation monitoring at the watershed and neighborhood scales. We have now begun three years of postimplementation monitoring to determine if the reverse auction resulted in the installation of sufficient stormwater controls to effect an ultimate improvement in stream hydrology, water chemistry, and biotic integrity.

Not only does this project highlight the cost-effective properties of the reverse auction as an allocation mechanism, it stresses the need for long-term monitoring of green infrastructure projects. By coupling the economic mechanism with the physical monitoring, we can better understand the role of green infrastructure in the advancement of environmental protection in urbanized areas, and we can quantify its economic benefits and costs.

**References and Notes**

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