that mouthpiece to preempt anticipated outbreaks of disease, making it a powerful component of its developing proactive response mechanism.

As emerging and reemerging infectious diseases continue to pose a serious threat, it is essential that the public health community adapt by adopting a proactive approach to disease prevention. Current efforts to bolster vaccine development, production and distribution form the core of that approach, but they are not enough. A means of increasing and fortifying public confidence in those measures is absolutely essential if they are to succeed. Otherwise, vaccines, one of mankind's great humanitarian accomplishments and one of our best investments, will be doomed to being compromised, and so are our lives. Therefore, the time to act is now.

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ENVIRONMENT/ECOLOGY

Developing a sustainable strategy to conserve reservoir marginal landscapes

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China has accelerated its pace in building dams to meet growing demands in energy consumption, as well as to alleviate air pollution resulting from fossil fuel emissions and to mitigate global climate change impacts. Large rivers in southwestern China (i.e. the Jinsha, Yalong, Dadu, Wu, Nu, Lancang and upper Yangtze rivers) have primarily been targeted as major basins for hydropower development, where cascade dams have been constructed or are proposed. Among them, the Three Gorges Dam is the world's largest hydropower project and the most important water regulation scheme on the Yangtze River. It has a full water storage capacity of 39.3 billion m^3 and a flood regulation capacity of 22.4 billion m^3, which permits it to supply multiple benefits including hydropower production, flood control, navigation and tourism [1]. Since its impoundment, a distinctive reservoir marginal landscape, which is also referred to as the water level fluctuation zone, has been created by a specific flow regulation mode [2]. The Three Gorges Dam will be discussed herein as a sentinel example of reservoir marginal landscape development, degradation and conservation, but the lessons learned may be applied globally.

Dams represent the most significant anthropogenic disturbance to global rivers [3]. Although a comprehensive environmental impact assessment was performed for the Three Gorges Dam [4], post-dam flooding disturbance to the reservoir marginal landscape is unprecedented and was underestimated. This reflects the complexity and unpredictable nature of a large dam system, as well as a lack of existing knowledge [1]. Multiple processes including ecological degradation in terms of vegetation loss and habitat fragmentation, geomorphological adjustment through bank erosion and sedimentation, and environmental pollution, are all currently exhibited in the reservoir marginal landscape of the Three Gorges Dam [2].

Protecting reservoir marginal landscapes from constant degradation is

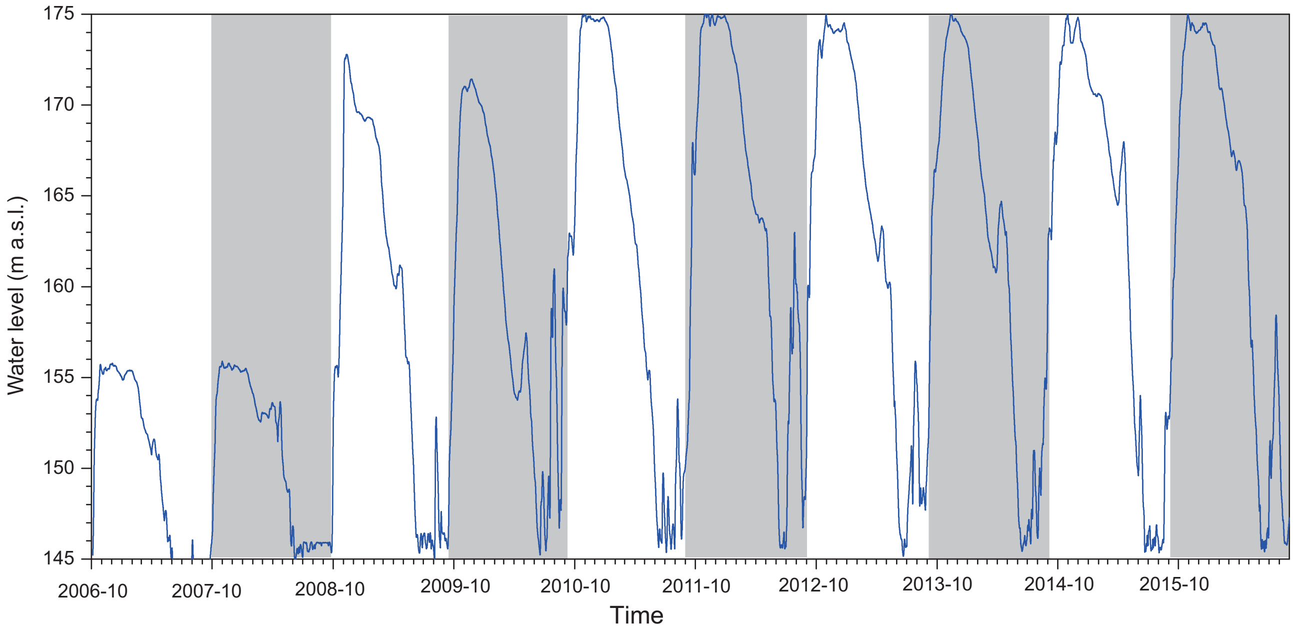

Figure 1. Temporal changes of water level operated by the Three Gorges Dam, featuring steps of water impoundment with increasing magnitudes and seasonal water level fluctuation. Each hydrological cycle is differentiated using different background colours.

critical in view of the multiple ecosystem services that can be provided, including bank stabilization, overland runoff regulation, sediment trapping, diffuse contaminant abatement, plant diversity conservation, and water quality protection, as well as maintenance of aesthetic value for recreational activities. These services are essential for sustainable delivery of the operational goals. Here, we argue that contemporary conservation measures for the marginal landscape of the Three Gorges Reservoir need to be refined and improved by integrating multidisciplinary perspectives and balancing the trade-offs associated with the costs, effectiveness, and environmental, social and economic consequences of different management options. There is a need to expand conservation to improve the management of cascade reservoirs in China, as well as those in countries around the world.

HYDROLOGICAL REGIME SHIFTS FOLLOWING ROUTINE FLOW REGULATION

A specific flow regulation mode has been carried out by the Three Gorges Dam. Four stages of water impoundment were performed, with maximum inundation height being elevated to 135 m in 2003, 156 m in 2006, 172 m in 2008 and 175 m in 2010 (Fig. 1). On an annual basis, incoming water is stored during the dry season for hydropower production, followed by water release for flood control and sediment discharge during the rainy season. Consequently, a strict temporal schedule for water level fluctuation is dictated by this routine operational scheme (Fig. 1). In the context of routine water level fluctuation, the reservoir marginal landscape comprises all geomorphological landforms falling in the elevation ranges between 145 m and 175 m [2].

Flow regulation has resulted in dramatic hydrological regime shifts within the dammed channels (Fig. 2). Natural river flows were altered to a lacustrine regime by reducing flow velocity and increasing water retention time [5]. Flooding regime (timing, magnitude, frequency and duration) varies considerably along elevation gradients within the marginal landscape [6]. Compared to the riparian zones of unregulated rivers, the reservoir marginal landscape experiences relatively longer duration artificial flooding but with lower suspended sediment fluxes. River continuity has been substantially altered by dam placement and physical interception. A substantial proportion (64%–95%) of inflowing suspended sediment has been retained by the dam, and corresponding loads exhibit marked seasonal variability [7].

MULTIPLE PROCESSES CAUSE MARGINAL LANDSCAPE DEGRADATION

The marginal landscape of the Three Gorges Reservoir was once composed of terrestrial uplands with diverse land use, but has been transformed to a transitional area with water level fluctuations that displays sensitive responses to the artificial hydrological regime. Flooding perturbation following routine water impoundment has obviously modified ecosystem type, composition and patterns, and has intensified multiple ecological, geomorphological and environmental processes, thereby resulting in substantial landscape degradation (Fig. 2).

One direct consequence lies in the reorganization of habitat configuration and the remarkable depletion of vegetation cover at the Three Gorges Reservoir. The original terrestrial habitat was impaired by long duration winter flooding and fragmented by the resultant formation of isolated islands. Over

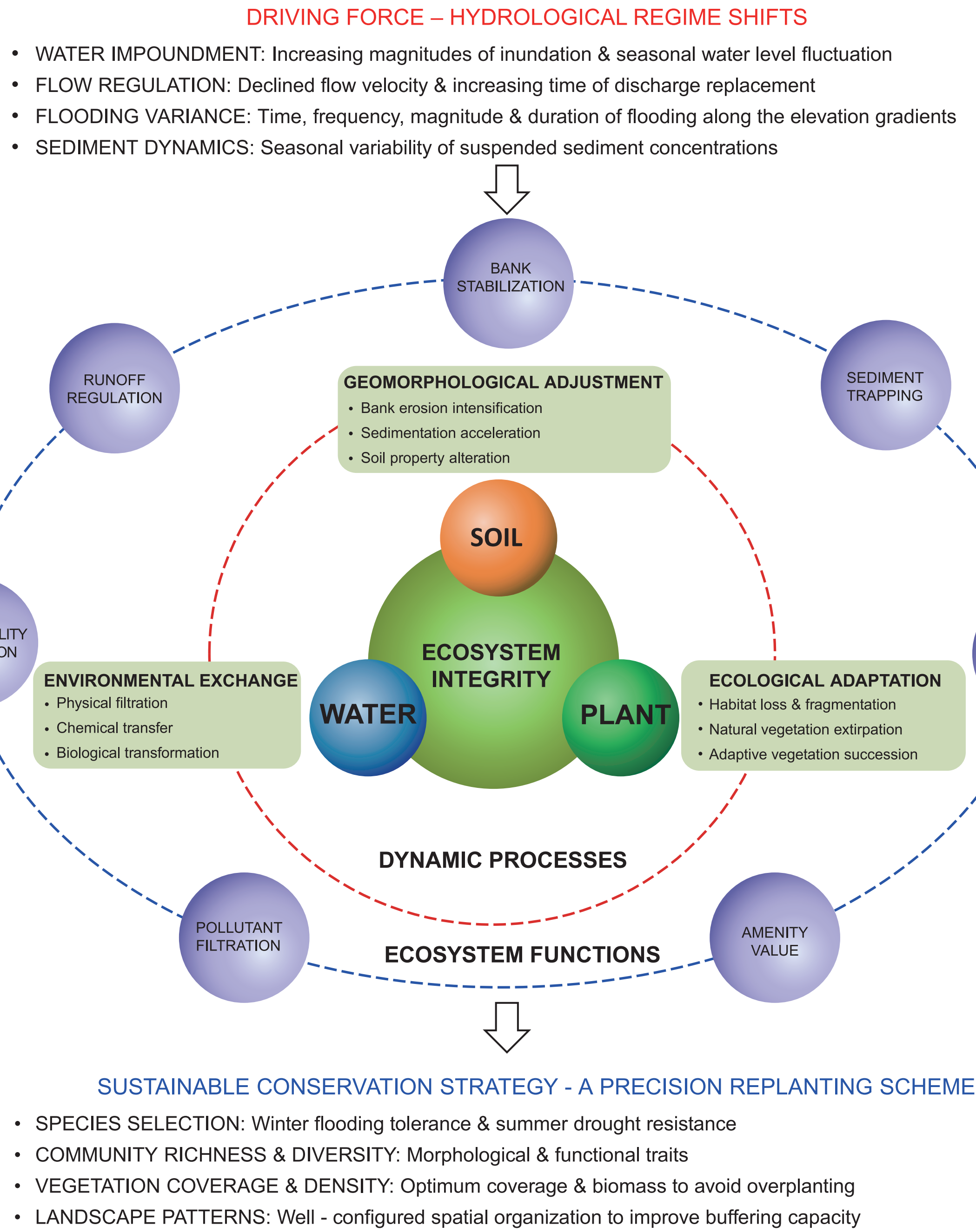

Figure 2. A system schematic illustrating the fundamental components of reservoir marginal landscapes highlighting major hydrological regime shifts (driving force for ecosystem degradation), ecosystem services, dynamic geomorphological, ecological and environmental processes impacting on ecosystem integrity, and the resultant need for a sustainable conservation strategy.

time, the habitat became heterogeneous and discontinuous and its quality was impaired by bank erosion, nutrient leaching and burial by deposited sediment. Most native plant species were extirpated by the long duration winter flooding stress and summer drought severity, leading to a remarkable decline in vegetation cover and community diversity (Fig. 3c). Factors such as bank erosion, sediment burial and periodical extreme drought hamper vegetation growth recovery. However, water level fluctuations create a vertical gradient of hydrological conditions that may favor different plants to be established, and periodical exposure during the summer growth season provides valuable opportunity for plant colonization and succession [8]. Here, adaptive species with different levels of resistance to flooding and drought become dominant [9]. Flooding gradient catalyzes the development of an elevation-dependent pattern of vegetation distribution. Annual herbs prevail in the lower portion, perennials herbs dominate in the middle portion, arid

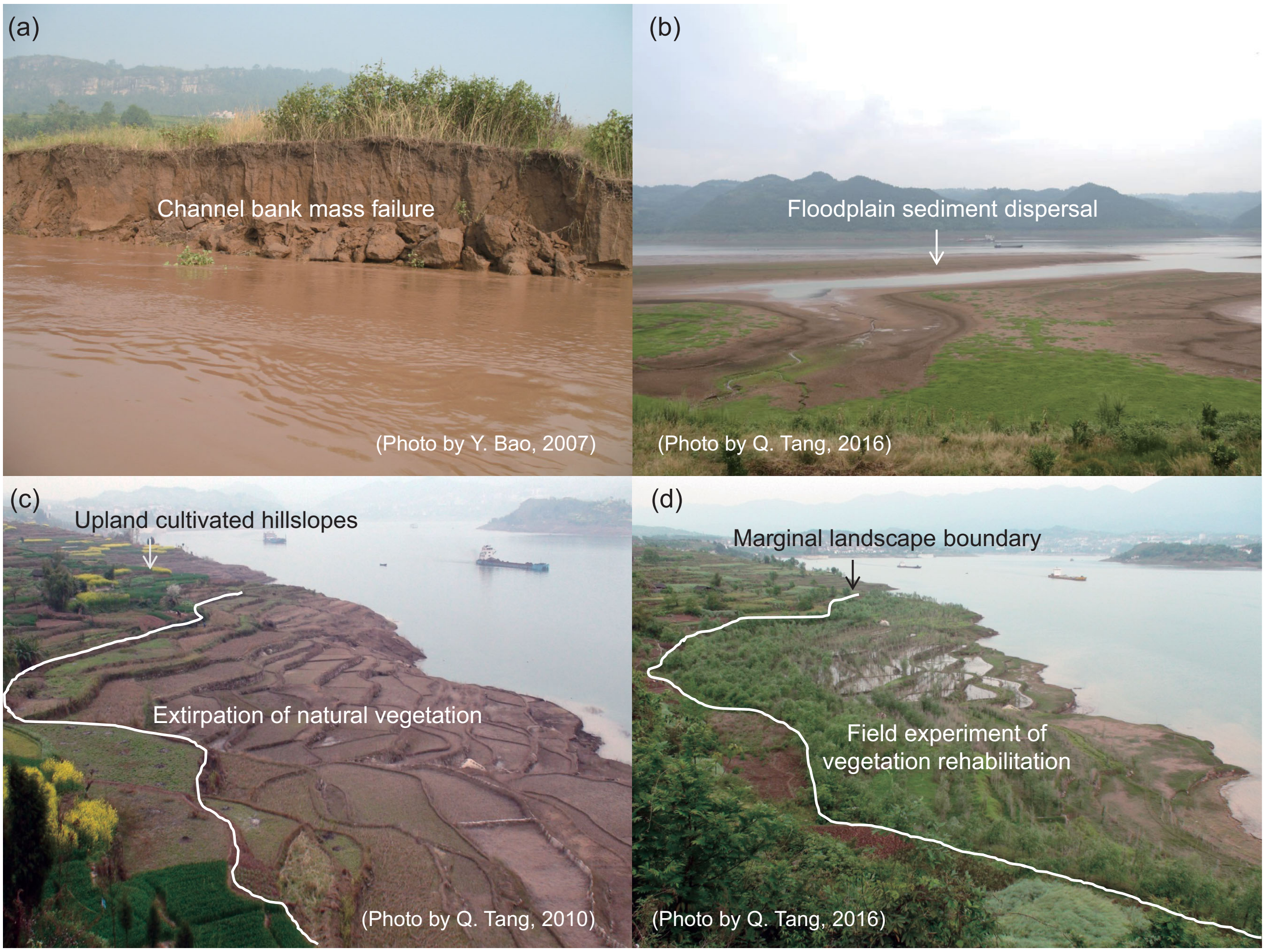

Figure 3. Representative images showing: (a) channel bank mass failure making sediment susceptible to fluvial entrainment during episodic flooding periods, (b) floodplain sediment dispersal, (c) natural vegetation extirpation following winter flooding disturbance, and (d) field experiment for vegetation rehabilitation.

grass and shrubs succeed in the upper portion, and trees prevail in the highest portion (Fig. 3d).

Geomorphological adjustment in terms of bank erosion and sedimentation has been intensified due to changes in external hydraulic forces (i.e. frequent water level fluctuations, wave action from wind and boat traffic, and overland runoff), a reduction in vegetation cover and root density, and a change to soil mechanical properties following flooding disturbance. Bank erosion results from fluvial entrainment during the inundation periods and runoff denudation during the exposed periods, in the forms of mass failure, gullying, rilling and sheet wash (Fig. 3a). Denudation differs both spatially (e.g. main channel vs. tributaries, geomorphic locations with different slope aspects, gradients and elevations) and temporally in its forms and magnitude. Discrete flooding derived from either natural events or artificial flood pulses associated with water impoundment give rise to sediment dispersal, whereas low flow velocities encourage deposition in the reservoir marginal landscape (Fig. 3b). Sedimentary dynamics are principally modulated by variation in the flooding regime, seasonal suspended sediment loads, bank morphology and landform topography. Generally, sedimentation rates decrease with increasing elevations due to spatial changes in the flooding regime (magnitude, frequency and duration) interacting with the availability of suspended sediment [6, 10].

Exchanges of nutrients and contaminants between soil, sediment, water and plants through physical retention, chemical transfers, and biological transformation are closely related to geomorphological, ecological and biochemical processes. Plants uptake available nutrients and contaminants from the soil during the growing season, and these assimilated elements are finally released to the water and soil through biomass decomposition during the flooding period. These processes are further mediated by aerobic and anaerobic conditions associated with alternate flooding and exposure. Interactions between the mineral properties of sediment and water chemistry determine the exchange direction across the sediment–water interface, resulting in sediment becoming either an internal source or sink of contaminants. Sediment accretion can alter biogeochemical and microbial processes through its effect on microorganisms or benthic invertebrates, and thus regulate nutrient and contaminant cycling.

TOWARDS A SUSTAINABLE CONSERVATION STRATEGY

Marginal landscapes on reservoir banks represent an important functional element of dam systems. Soil, sediment, water and plants represent essential ecosystem components, and to maintain ecosystem integrity it is critical to devise sustainable conservation strategies to ensure the realization of multiple benefits (Fig. 2). Ecological restoration through vegetation rehabilitation and reinforcement of its fundamental functions could be the most applicable approach, given the essential role of well-maintained vegetation in sustaining multiple services [11]. Well-maintained vegetation can contribute significantly to bank stabilization due to increased hydraulic roughness, surface land biomass coverage and underground root consolidation of soils, as well as to buffering capacity in terms of filtering and trapping sediment and associated nutrients and contaminants (Fig. 2). Vegetation also provides aesthetic services that maintain the quality of recreation and tourism [12]. Contemporary vegetation restoration campaigns are at the early stages of development, focusing solely on promoting plant survival rate and enhancing land coverage, but ignoring their effectiveness and, critically, any potential unintended detrimental consequences. Recent studies, for example, have revealed that over-planting may release large amounts of nutrients back to the water column during the winter flooding periods in association with litter decomposition, and that this can be a direct contributor to the eutrophication commonly observed in the ensuing spring season [13].

Given such negative unintended consequences of current conservation strategies, we therefore advocate a refined precision replanting scheme comprising multiple dimensions, but with specific emphasis on improving vegetation composition and its spatial organization to obtain optimal conservation efficacy while eliminating or reducing potential unintended negative consequences, especially for water quality (Fig. 2). The proposed scheme defines criteria for screening adaptive plant species, diversifying community morphological and functional traits, maintaining optimum vegetation density and coverage, and promoting the well-configured spatial organization of plant cover to maximize ecological benefits.

Plant species selection should be assessed on the basis of long winter flooding tolerance and summer drought resistance. The adaptive strategy of suitable plants to different levels of waterlogging pressure at morphological, physiological and metabolic levels needs to be incorporated to enable species selection at different elevation ranges along the reservoir marginal landscape (Fig. 3d). Morphological and functional traits at the species level, as well as the economic potential arising from plant harvest, should also be considered, in order to ensure community richness and diversity. Vegetation cover and density should be maintained at an optimum level based on land supporting capacity (e.g. timing and duration of landscape exposure for plant growth, water and nutrient limitation), and maximized potential for channel bank consolidation. Here, it is important to avoid overplanting. Plant spatial organization should also be configured based on landscape ecology theory to support optimal impact with respect to hillslope runoff regulation, sediment retention and pollutant filtration.

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SUPPLEMENTARY DATA

Supplementary data are available at *NSRCP* online.

Conflict of interest statement. None declared.

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