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China's response to a national land-system sustainability emergency

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China has responded to a national land-system sustainability emergency via an integrated portfolio of large-scale programmes. Here we review 16 sustainability programmes, which invested US$378.5 billion (in 2015 US$), covered 623.9 million hectares of land and involved over 500 million people, mostly since 1998. We find overwhelmingly that the interventions improved the sustainability of China's rural land systems, but the impacts are nuanced and adverse outcomes have occurred. We identify some key characteristics of programme success, potential risks to their durability, and future research needs. We suggest directions for China and other nations as they progress towards the Sustainable Development Goals of the United Nations' Agenda 2030.

Exploitation of land, forest, water and nature over thousands of years of human occupation and development had seriously degraded China's environment, impoverished its rural people, and accentuated calamities such as floods, droughts and famine[1]. Since the 1950s, political and socio-economic reforms, rapid population rise, industrialization and development, and environmental change accelerated this long-term decline, culminating in a sustainability emergency on a massive scale[1]. Multiple natural disasters in the late 1990s spurred the implementation of a portfolio of large-scale policy programmes aimed at mitigating land and water degradation, conserving forests and biodiversity, increasing production from agriculture and forestry, and alleviating rural poverty[2].

A synthesis of China's recent drive to arrest this long-term decline and ensure sustainability of its land systems is particularly timely given the recent global commitments to the Sustainable Development Goals (SDGs) under the UN's Agenda 2030[3]. China provides an example of how immense challenges for national-scale SDG implementation[4] might be addressed. Some studies have provided deep evaluations of China's more well known programmes, particularly the Grain for Green Program and the Natural Forest Conservation Program[2,5–9]. However, other complementary programmes targeting desertification, grasslands, agriculture and forestry have had comparatively little attention[10,11]. As a result, the full scale and implications of China's integrated, land-system-wide sustainability response remains under-recognized.

Here, we review 16 major programmes as an integrated sustainability response, with a focus on rural land systems for the period since the establishment of the People's Republic of China in 1949. We quantify the investment and area of actions under these programmes and relate this to the 17 SDGs (Supplementary Methods). We review programme impacts across multiple sustainability indicators. We propose some keys to success from China's experience, discuss future risks to large-scale sustainability interventions, and suggest future research priorities. China still faces grave environmental concerns resulting from rapid industrialization, urbanization and development, particularly the pollution of its air, water, and soils[12–15]. However, its recent experience with transformative investment in land-system sustainability can inform how China tackles future challenges and provide invaluable guidance for the rest of the world embarking on a similar journey.

A land-system sustainability emergency

China has been farmed for over 8,000 years[1]. Neolithic farmers occupied the North China Plain and the Loess Plateau (dryland millet) and the Yangtze River valley (wet rice). Over time, forests were progressively cleared for agriculture and exploited for energy, food, medicines and materials; cropping intruded into northern grasslands; and rivers were redirected for irrigation[1]. Over the first 1,400 years AD, nomadic pastoralism expanded in the north and increasingly productive wet-rice farming spread further south, supporting a fairly stable population of 40–60 million[16]. From 1400 to 1750 China's population increased 3–4-fold to 177 million (0.24% per year)[16] supported by agricultural expansion, commerce, markets and trade, with forest cover at around 24.2%[17]. By 1800[1], humans occupied most of China, and population growth accelerated (0.59% per year), reaching around 580 million by 1949[16], alongside an emerging environmental crisis. Increasing demand for natural resources, particularly agricultural and forest products, met by inefficient and unsustainable farming, grazing and logging practices led to widespread land degradation including erosion, sedimentation, flooding, water logging, salinization and desertification[1]. Bears, tigers, leopards, elephants and many other species neared extinction[18]. Soil-nutrient depletion constrained agricultural productivity. Forest cover

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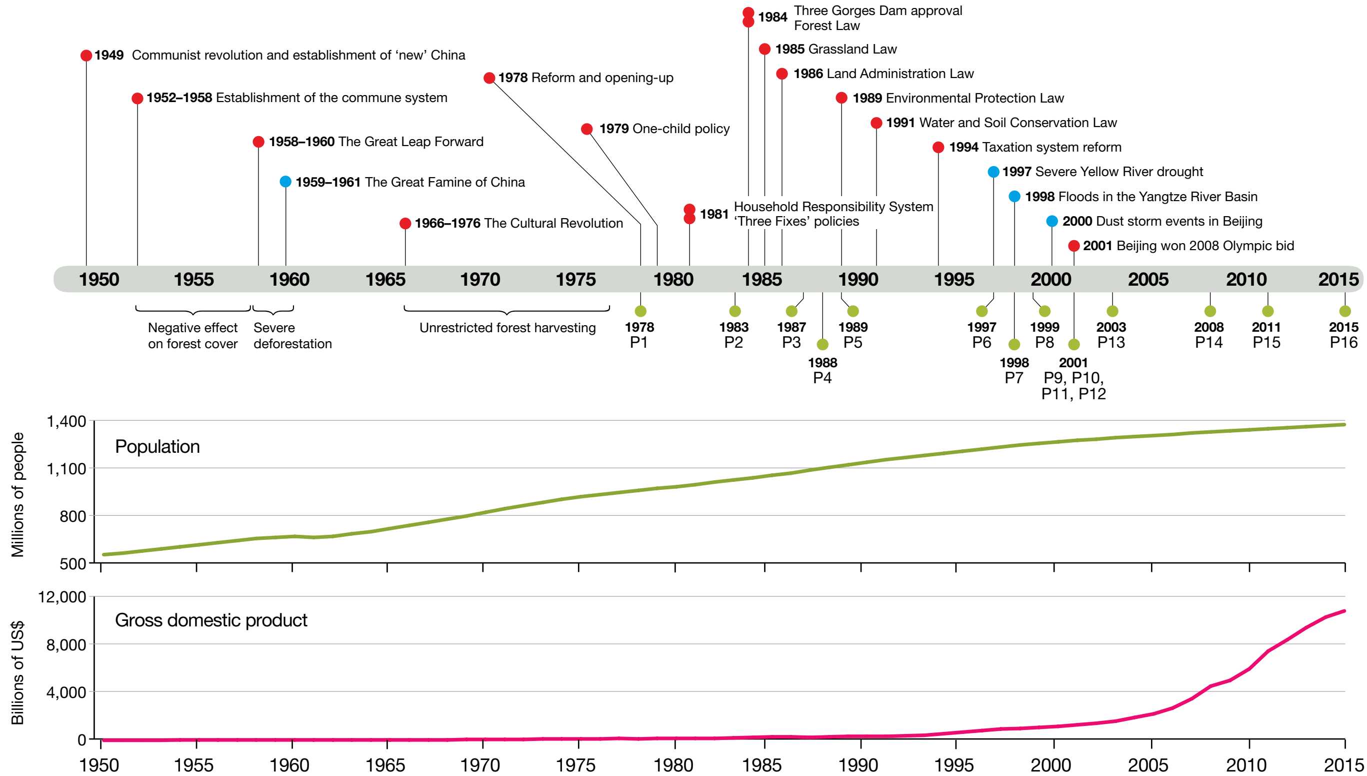

Fig. 1 | Timeline of events. Chronology of key political/socio-economic/policy events (red markers), human-environmental disasters (blue markers), and the 16 major sustainability programme responses (green markers) in China from 1949 to 2015. Also included are the trajectories of population and economic development (gross domestic product or GDP).

was around 11.4%[17] or less[1] and timber was scarce. Rural poverty, social unrest and famine were commonplace[1].

In 1949, the new People's Republic of China inherited a seriously degraded natural environment[18] and in the Mao era through to 1978, China's land, rivers and forests were seen as forces to be controlled and resources to be exploited to support food security, economic development and industrialization[1,5]. Population growth rates increased to 1.36% per year under the new government[16]. In the early 1950s, anticipation of collective ownership policies led to a rush to clear land[2] (Fig. 1). Deforestation intensified under the Great Leap Forward as state forestry bureaus and commune enterprises decimated the meagre forest resources for timber and fuel, in particular for steel-making[5]. Droughts and floods compounded multiple governance failures during the 1950s, which included poor planning, redirection of agricultural labour to industry, and the depletion and inadequate distribution of scarce resources including food. Catastrophic outcomes ensued, most notably the Great Famine of China from 1959–1961 which claimed the lives of 20–45 million people[1,19]. Rivers, particularly the Huai and Yellow, were dammed and dyked for irrigation and flood management[1]. Pursuit of self-sufficiency in grain led to an increase in agricultural production, mostly via farmland expansion (from 80 million hectares (Mha) to around 120–130 Mha in the first 30 years of the People's Republic)[1,20,21]. Forest cover dropped to 8.7% in the 1960s[17]. Clearance of the northeastern and southwestern forests, exploitation of the northern and northwestern grasslands, combined with inappropriate farming practices in marginal environments (such as steep slopes, flood plains and erodible soils) accelerated land, water and ecosystem degradation[1]. During the period of the Cultural Revolution from 1966–1976, environmental degradation was exacerbated by diminished government capacity to manage natural resources[5].

The 1978 Reform and Opening Policy introduced a range of free-market and privatization measures to promote development. The Household Responsibility System, and the re-privatization of land from communes to households led to greatly increased agricultural productivity and expansion, but often via unsustainable practices on marginal land, particularly the overgrazing of grasslands[22]. The One-Child Policy (1979) was introduced to control population growth and reduce demand on natural resources. Improving domestic capacity for chemical fertilizer production[23] gradually led to agricultural surpluses[1]. Rapid economic and social development followed, along with industrialization and urbanization, and an expanding, increasingly wealthy, and technologically advancing population. While this reduced people's direct dependence on land for livelihoods, it also fuelled consumption, in particular demand for forest and agricultural products[12]. The opening of commercial timber markets in the early 1980s accelerated forest harvesting by the rural poor at rates far outpacing natural regeneration and reforestation. Reforms in the 1980s included the reinstatement of the Ministry of Forestry and the enactment of key laws (Fig. 1), but deforestation continued into the 1990s[5,20,24] and beyond[25].

Extreme land degradation ensued throughout the 1970s, 1980s and 1990s. While plantation efforts reversed the decline in total forest cover during this period[1,17,20] (with the definition of 'forest' broadly including a range of vegetation types such as natural forest, orchards, rubber, timber and shelter plantations[26,27]), natural forest decline continued from 102.0 Mha in 1949 to 98.2 Mha in 1975 and 66.7 Mha in 1993, with much of the remaining forests degraded and unproductive[2]. Soil erosion of about 5 billion tonnes annually affected 360 Mha[28], including 75 Mha of the Yangtze and Yellow river basins, and caused major water quality, sedimentation, and flooding problems[2]. In the worst-affected areas of the Loess Plateau, erosion rates reached 100 t ha^{-1} yr^{-1} and the sediment load[29] of the Yellow River—the world's muddiest—reached 1.8 billion t yr^{-1}. Growth in agricultural production was also down, jeopardizing food security[30]. Over 54 Mha (40%) of existing arable land was degraded, and 70% of it was of lower productivity[31]. In northern China, rangelands were degraded and desertification intensified[32], reaching 267.4 Mha in 1999[33]. Causes were both human, particularly through the expansion and intensification of livestock production[34], and environmental, with the naturally sandy soils and the dry, mid-latitude, continental climate becoming drier and windier[35,36]. As poor households with low education and few prospects for off-farm employment overexploited farmlands, pastures, and forests to provide food and

Box 1

Programme aims

This is a summary of the planned timeframe, aims, and objectives of the 16 major Chinese sustainability programmes assessed here. Detailed descriptions and sources are provided in Supplementary Tables 1–16.

P1 Shelterbelt Development Program—Three North. 1978–2050. Control the expansion of sandy/desertified land, and mitigate wind erosion of sand/soil and dust storms in northern China via forest plantation, mountain closure, and sandy area regeneration.

P2 Soil and Water Conservation Program—National. 1983–2017. Control soil erosion; improve farmers' livelihoods; and improve agricultural production, ecology, and the environment by combining prevention, protection, control, repair and ecological regeneration, and utilizing appropriate scientific, engineering, plantation and cultivation measures.

P3 Shelterbelt Development Program—Five Regions. 1987–2020. Arrest environmental deterioration in the Yangtze River, Pearl River, their coastal areas, the Plain, and the Taihang Mountains via artificial plantation, mountain closure, aerial seeding, improving low-yielding forest and establishing shelterbelts.

P4 Comprehensive Agricultural Development Program. 1988–2020. Raise rural quality of life, incomes and food security through land reform, land management, ecological construction, agricultural infrastructure and industry development, and production/efficiency gains using science and technology.

P5 Soil and Water Conservation Program—Yangtze. 1989–indefinite. Reduce sedimentation and improve the health of the Yangtze River, ensure the safe operation of the Three Gorges Reservoir, and enhance regional economic and social development by controlling soil erosion in the upper reaches.

P6 National Land Consolidation Program. 1997–2020. Increase the area of cultivated land and revenues via consolidation (reorganizing and merging fragmented and underused land), reclamation, constructing high-quality cropland, and improving land use and management.

P7 Natural Forest Conservation Program. 1998–2020. Halt logging/deforestation and protect natural forests for ecological/carbon benefits via mountain closure, aerial seeding and artificial planting. Create new business opportunities for traditional forest enterprises; create forest management jobs and relocate redundant forestry workers.

P8 Grain for Green Program. 1999–2020. Prevent soil erosion, mitigate flooding, store carbon, and improve livelihoods by increasing forest and grassland cover on cropped hillslopes and converting cropland, barren hills and wasteland to forest.

P9 Fast-growing and High-yielding Timber Program. 2001–2015. Remedy the decline in timber supply and meet domestic demand for forest resources without affecting natural forests via the establishment of fast-growing and high-yielding timber plantations.

P10 Forest Ecosystem Compensation Fund. 2001–2016. Conserve natural forests and protect species and ecosystems via restoration, protection, and management of forests that have important ecological, biodiversity conservation, and sustainable economic and social value.

P11 Sandification Control Program—Beijing/Tianjin. 2001–2022. Reduce desertification and dust storms, and improve the environment in the Beijing/Tianjin area via reforestation, grassland management, and water conservation, relocating affected people and establishing basic governance of desertified lands.

P12 Wildlife Conservation and Nature Protection Program. 2001–2050. Conserve key wild animal and plant species and natural ecosystems by expanding the number and area of nature reserves, and promoting sustainable development.

P13 Partnership to Combat Land Degradation. 2003–2023. Improve management of land and water resources, reduce poverty, protect biodiversity, and combat climate change in western China by bringing agencies together in partnership to work synergistically.

P14 Rocky Desertification Treatment Program. 2008–2020. Curb rocky/karst desertification, improve the environment, and increase incomes by protecting and establishing vegetation, promoting sustainable land-use, farmland construction, water conservation and relocating poor people.

P15 Grassland Ecological Protection Program. 2011–2020. Mitigate grassland degradation by grazing prohibition and enhancing grassland vegetation coverage/biomass. Increase herder incomes by promoting the sustainable development of pastoral areas.

P16 Cultivated Land Quality Program. 2015–2030. Enhance food security and the quality, safety and ecological sustainability of agricultural production by addressing soil acidification, salinization, nutrient imbalances, pollution, biota, fertility and shallow topsoil.

income, the productivity of these increasingly degraded environments was further diminished, creating a poverty–environmental degradation trap[37]. The economic impacts of land degradation and desertification (0.7%–1.4% of GDP in 1999) impeded rural development[38].

From 1978–1997, the Chinese government launched six programmes to address the parlous state of its rural land systems (P1–P6; Fig. 1, Box 1, Supplementary Tables 1–6). However, modest initial efforts failed to arrest the deteriorating trend and, in the late 1990s, China suffered a series of natural disasters widely believed to be caused by unsustainable land management[5]. In 1997, drought along the Yellow River, greatly amplified by water over-extraction, desiccated 700 km of the waterway for 8 months[39]. The 1998 Yangtze River floods—among China's most devastating, killing 3,600 people, inundating 5 Mha of cropland, and costing US$36 billion—were driven by El Niño but exacerbated by upland deforestation[40]. In the spring of 2000, a sequence of 12 severe dust storms afflicted northern China (Fig. 1), with seven blanketing Beijing within just one month[6]. The storms were attributed to overgrazing and desertification[41] and cost US$2.2 billion[42].

The response

In response to this sustainability emergency, China dramatically ramped up investment in its six existing programmes and launched seven major new programmes from 1998–2003 (P7–P13), complemented in later years by three additional programmes (P14–P16; Fig. 1). Major foci were to reduce erosion, sedimentation and flooding in the Yangtze and Yellow rivers; conserve forest in the northeast; mitigate desertification and dust storms in the dry north and rocky south; and increase agricultural productivity in central and eastern China. Environmental objectives were typically complemented by strong socio-economic objectives such as poverty reduction, rural economic development, and national food security (Box 1, Supplementary Tables 1–16).

Investment in the 16 major sustainability programmes from 1978–2015 totalled US$378.5 billion (in 2015 US dollars). US$351.6 billion was invested from 1998–2015, with total annual investment increasing steadily as China's economy grew, from US$3.52 billion in 1998 (about 0.34% of GDP) to US$40.6 billion in 2015 (about 0.37% of GDP) (Figs. 1 and 2a and b). Programmes addressed a combined area of 623.9 Mha, or 65% of China's land area. Total area increases from 1998–2015 averaged 32 Mha yr^{-1} (not including the 252.1 Mha added in 2011 by the P15 Grassland Ecological Protection Program) (Fig. 2d and e). For reference, China's investment far exceeds other globally important national sustainability programmes such as the US Conservation Reserve Program, where rental payments totalled $46.2 billion from

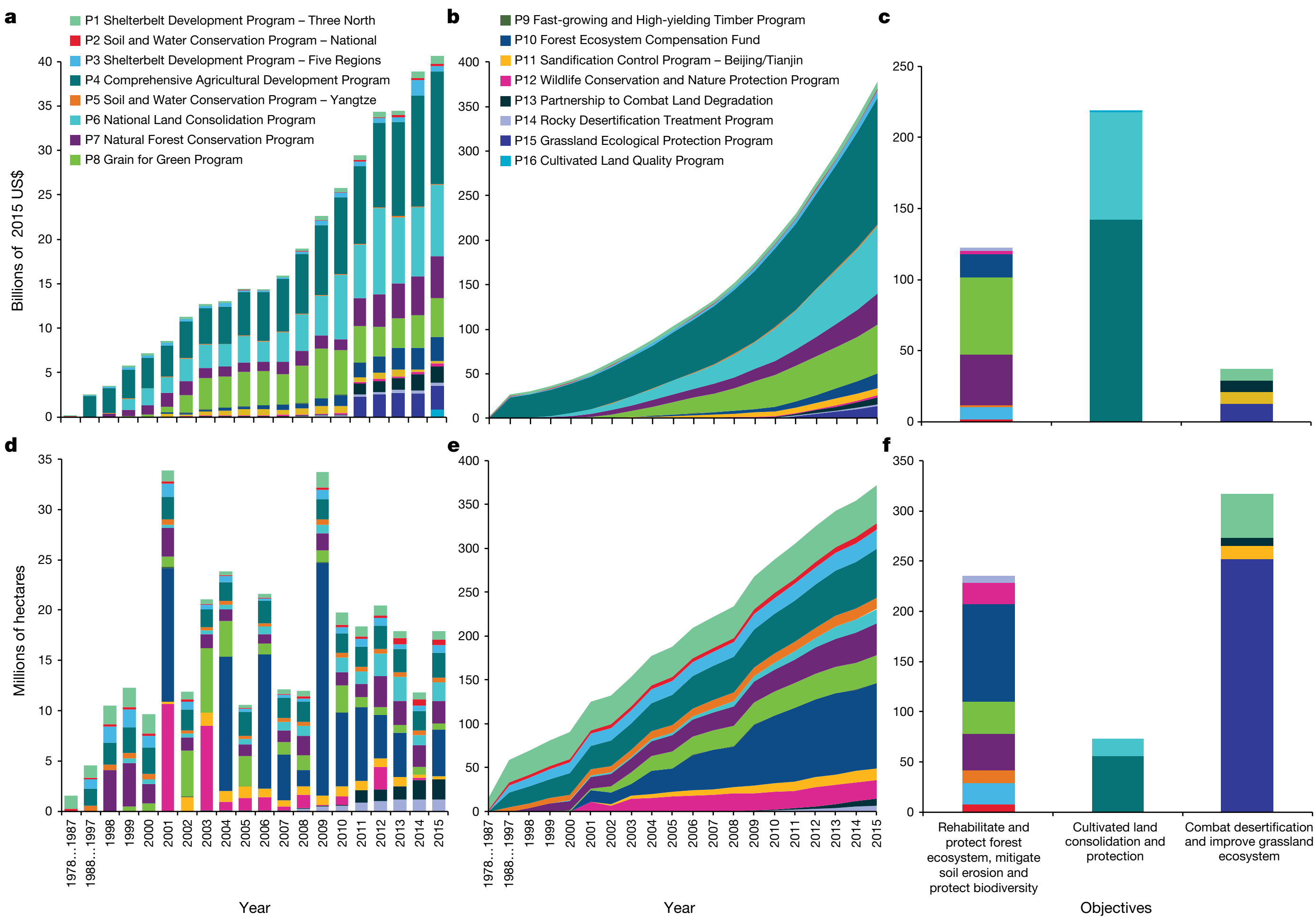

Fig. 2 | Investment and area of interventions. Value of investment (**a**, annual; **b**, cumulative; **c**, by objective) and area (**d**, annual; **e**, cumulative; **f**, by objective) addressed over time for the 16 major sustainability programmes reviewed. Values for the decades 1978–1987 and 1988–1997 are annual averages in **a** and **d**, and summed in **b** and **e**. For readability, area graphs **d** and **e** do not include the P15 Grassland Ecological Protection Program. Data includes area and investment values for nature reserves established from 2001, when the Wildlife Conservation and Nature Reserve Program became a priority programme. 2015 values are interpolated values for some programmes where official data have not yet been published. Data sources and methods are detailed in Supplementary Methods, and the full dataset is provided in Supplementary Data 1 and 2.

1987–2016 (around 0.0094% of the USA's GDP in 2014), and averaged 12.6 Mha annually[43].

Multiple programmes operated within each province (Supplementary Tables 19 and 20). Agricultural production and cultivated land protection dominated investment but covered the least area (Fig. 2c and f) owing to the higher cost of intensifying and expanding agriculture and increasing productivity. Forest ecosystem protection, reforestation, alleviating soil erosion, and protecting biodiversity drew the second-highest investment and area of actions. Combatting desertification and improving dryland ecosystems involved the least investment but covered the greatest area owing to the lower cost of extensive measures such as grazing prohibition and grassland restoration. Across the portfolio, an array of interventions (Supplementary Fig. 1) were implemented to address the multiple socio-economic and environmental objectives (Box 1), with each programme typically including multiple interventions (Supplementary Data 3). Implementation area varied markedly between actions and over time (Supplementary Fig. 1, Supplementary Table 21).

Programme governance was led primarily by the central government (Supplementary Tables 1–16; Fig. 3), which also provided most of the funding, supported by partnering and co-investment from provincial/local governments, enterprises and individuals. With the help of research agencies, the central government designed the sustainability programmes, set high-level objectives, and delegated responsibility to relevant ministries, commissions and administrations (such as the State Forestry Administration). These agencies planned programme scope and priorities, and coordinated implementation, allocating tasks to provincial (including autonomous regions and independent municipalities) government departments. Overseen by their respective governments, provincial/local government departments refined and adapted programme plans based on regional/local conditions and priorities; and developed and implemented projects, managed funding, and supervised and inspected sustainability interventions. Coordination and communication between governments/departments was directed by governance, guidance/supervision and reporting processes. All levels of provincial/local government and their departments raised the awareness and enthusiasm of farmers, herders and enterprises, and mobilized and organized them to implement large-scale sustainability interventions. Public opinion agencies were used to promote sustainability programmes, report progress to the people, and report local society's attitudes and responses to the programmes, which also fed back to government. Research agencies identified potential issues, assessed programme effectiveness, verified implementation, and provided scientific and technological support to implementation agents (such as farmers and enterprises). Monitoring and quality assurance of sustainability interventions usually involved self-appraisal; inspection at the local, provincial and national levels; and verification against accepted standards. Under-performance incurred penalties including withheld payments (Supplementary Tables 1–16; Fig. 3).

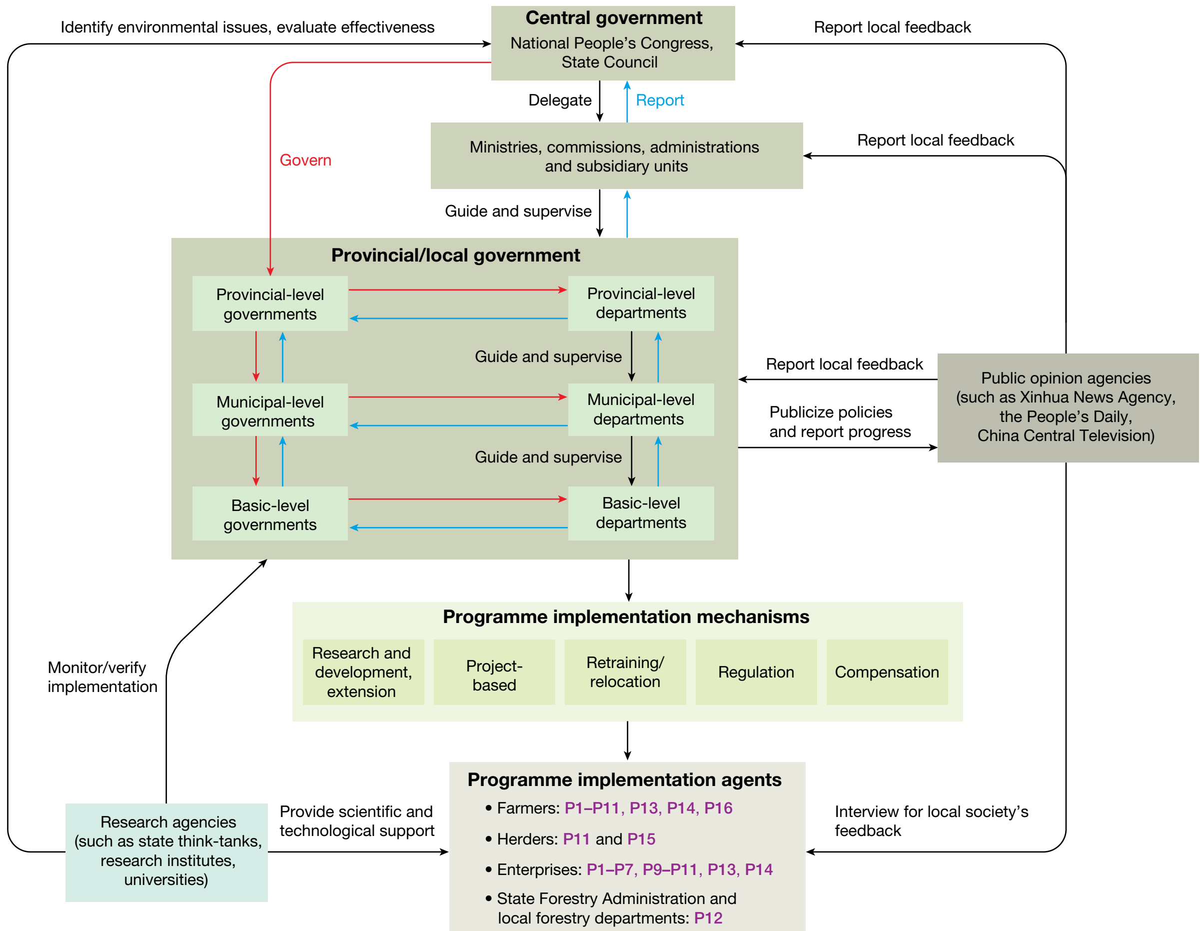

Fig. 3 | Governance, administration and implementation of China's sustainability programmes. Entities are shown in shaded boxes and arrows indicate specific roles, processes and information flows (red arrows, 'Govern'; blue arrows, 'Report'). Examples (purple font) are included to illustrate the programmes engaging each type of implementation agent.

Most programmes employed a variety of implementation mechanisms (such as regulation and compensation) to engage implementation agents (Supplementary Tables 1–16; Fig. 3). Motivating voluntary participation was a common objective, as farmers, landholders and local communities often provided most of the labour for on-ground works. Compensation via direct payments to people for the provision of ecosystem services was widely used to simultaneously reduce poverty and incentivize landholders to change land use and management[44]. While property rights reforms and decollectivization policies provided an essential foundation for sustainable land management, additional regulatory support was necessary to stop over-exploitation[37]. Regulatory controls such as livestock prohibition and timber quotas were used to end unsustainable practices in high-priority areas[7]. Where livelihoods were affected by resource-use regulation, compensation was typically provided as well as retraining and re-employment opportunities such as the conversion of loggers into forest managers[2,8,24]. In the areas worst affected by environmental degradation and poverty, sustainability interventions were preceded by the relocation of local people to relieve environmental pressure[45]. Despite notable exceptions[46], this process of 'ecological migration' was largely voluntary, with households offered education/training, modern housing and land, employment, and financial assistance to move to less-sensitive areas[45,47]. Programmes also engaged enterprises in large-scale project-based interventions and infrastructure including timber plantations; restoration supply chains (such as plant nurseries, seed collection); water supply and drainage management; and transport, energy and telecommunication networks[6,19]. Research, development, application, and extension of technologies such as trait-based plant species selection for erosion control[48], straw-checkerboard desertification control[49], and the biological control of forest pests (such as the fall webworm or mulberry moth, *Hyphantria cunea*)[50] were also important components of many programmes.

Hundreds of millions of people have participated in and been affected by the programmes in various ways (Supplementary Tables 1–16). A vast labour force implemented on-ground sustainability interventions. For example, over 124 million farmers (>32 million rural households) across 2,279 counties and 25 provinces have directly benefited from the Grain for Green Program[5,8]. About 170 million people have been involved in the Shelterbelt Development Program—Three North across 13 provinces and 600 counties[51]. The Soil and Water Conservation Program—Yangtze has mobilized more than 2.1 billion working days of labour towards sustainability interventions[52]. Over 7.7 million people have been relocated from ecologically degraded regions to reduce poverty and environmental pressure[53]. One of the largest examples is the relocation of around one million Hui ethnic minority farmers and herders from the highly degraded central drylands and southern mountains of Ningxia to northern Yellow River irrigation areas[54]. The Natural Forest Conservation Program affected 1.2 million logging and processing workers, most of whom have been transferred (to plantation and forest management activities or to other sectors), retired, or laid off[2,6,8]. Under the Comprehensive Agricultural Development Program, 1.236 million people underwent technical training[55].

Programme impacts

China has undertaken unprecedented investment in sustainability since 1998, addressing vast areas of land. Below, we synthesize current understanding of national-scale impacts on key sustainability indicators and illustrate impacts via regional/local case studies.

Forests and grasslands

China's forest cover transitioned in recent decades, turning from net loss to gain[17,20], and reaching 22.2% national coverage in 2015[56]. Programmes such as Grain for Green and the Shelterbelt Development Program—Three North have greatly increased forest cover through reforestation and afforestation (planting forests where forests had never before grown) of 60.15 Mha from 1998–2014 (Supplementary Fig. 1, Supplementary Data 3). Vegetation cover nearly doubled on the Loess Plateau from 1999–2013, increasing from 31.6% to 59.6% largely due to Grain-for-Green conversion of agricultural land on slopes exceeding 15°[57]. Similarly, multi-programme afforestation of grasslands in Xinjiang in China's arid north-west increased forest cover by 68% from 2000–2009[58].

The vast majority of new forests were 'protection forests' (47.156 Mha from 1998–2014) for stabilizing degraded land, 'economic forests' (6.295 Mha) such as fruit orchards and rubber plantations, and timber forests (6.061 Mha) (Supplementary Fig. 1, Supplementary Data 3). However, natural forest ecosystems have also benefited from the 133.477 Mha of forest protection and management interventions such as mountain closures and logging bans, and 21.695 Mha of nature reserves established from 2001–2014 (adding to the 113.629 Mha established from 1956–2000), which have slowed deforestation, promoted regeneration and enhanced ecological condition[25,59]. The Natural Forest Conservation Program for example, has been associated with large gains in forest cover from 2000–2010[60], and in target provinces has reduced annual deforestation rates to 0.62% (3.3 times lower than in other provinces)[25].

Grassland ecosystems in northern and western China have responded to large-scale restoration[61] and grazing exclusion[62] across 260.276 Mha (Supplementary Fig. 1, Supplementary Data 3). Even before the Grassland Ecological Protection Program boosted grassland conservation in 2011, Inner Mongolia's grassland increased by 7.799 Mha via conversion from desertified land and cropland, at an average net primary productivity (NPP) gain of 29,433 gigagrams of carbon per year (GgC yr^{-1}) from 2001–2009. Roughly 80% of these gains were attributed to programme restoration and de-stocking and 20% to climate change[63]. From 2005–2012, in the Tibetan Plateau Yellow River headwaters, nomadic herder resettlement, protection from livestock, and restoration interventions under multiple programmes have slowed and reversed alpine meadow degradation[64].

Desertification and dust storms

The desertification trend, dominant since the 1950s in China's arid northwest and semi-arid north and northeast regions, has also reversed over the past two decades[35,65,66]. National monitoring reported a decrease in desertified land in China, declining from a peak of 267.4 Mha in 1999 to 261.1 Mha in 2014[33,38]. Although primarily controlled by climate[65,66], in particular reductions in wind speed and increased spring rainfall[35], the greening trend has been enhanced by sustainability interventions in target areas[66].

In China's north, greenness and NPP have recently increased overall, indicating a reversal of the desertifying trend, but this varied over space and time[67]. Some areas, particularly in the northeast (Inner Mongolia, Heilongjiang) and northwest (Xingjiang), continued to degrade; while other areas (such as Qinghai, Gansu, Shaanxi and Shanxi) greened[59,66,67]. Three North greening at 0.86%–1.12% yr^{-1} from 2000–2013 was faster than the national average and faster than the period 1982–2000 (0.28%–0.38% yr^{-1})[68]. While climate had the strongest influence (74%) on NPP changes along with other natural and anthropogenic factors (23%), sustainability programmes had a discernible impact (3%)[67]. Barren and sparsely vegetated land in the Three North region decreased by 7 Mha to 178.65 Mha from 2001 to 2010[67]. In the Beijing/Tianjin Sand Source Region, degradation increased over 6.9%–10.8% of land and decreased over 3.8%–7.0% of land from 2000–2010, with these changes spatially heterogeneous and climate-driven[69]. Dust storms in northern China have also declined since the 1950s[33,66] and while restoration and afforestation may have contributed to this, lessening wind speed and reduced frequency of windy days are the more likely reasons[66].

Soil and water

An overall decrease in soil erosion of 12.9% has been identified nationally from 2000 to 2010[9]. In 11 of China's major river systems, soil erosion decreased by 45.4% on average from 2003–2007 compared to the period 1998–2002, including 58.8% and 27% declines in the Yangtze and Yellow river basins, respectively, associated with large-scale Grain-for-Green restoration[70]. In the Loess Plateau, large-scale restoration and afforestation of cropland and barren land has reduced soil erosion to historically low levels[57]. Illustratively, in the Zuli basin, modelled estimates of a net 25.7% ± 8.5% reduction in soil erosion from 1999 to 2006 included a 38.8% restoration-induced decrease, counteracted by a 13.1% ± 4.3% rainfall-induced increase[71]. Integrated analysis of satellite imagery, restoration statistics and sediment yield monitoring confirmed that large-scale conversion of cropland to forest had a positive impact on greening and mitigation of soil erosion across southern China[72]. Complementary consolidation of farmland in valley bottoms has relieved agricultural development pressure on sloping land and reduced soil erosion by a further 10%[73].

China's sustainability programmes have achieved a range of water management objectives such as improving water quality and reducing river sedimentation, soil water retention and flood mitigation, and water conservation and supply (Supplementary Tables 1–16). Nationwide, improvements in flood mitigation and water retention of 12.7% and 3.6%, respectively, occurred from 2000–2010[9]. Substantial improvements in surface water quality and sedimentation have also resulted from a combination of source-control interventions (such as restoration and land consolidation) and in-stream measures (such as silt check dams and reservoirs)[27]. Since 1950, the sediment load of the Yellow River has fallen by nearly 90%[74]. From 1980 to 1999, cropland terracing and dams/reservoirs reduced sediment load by 33% and 21%, respectively, and large-scale afforestation further reduced sediment loads by 26% from 2000 to 2010[74]. Similarly, Yangtze River sediment load is down 71% since the mid-1900s. Soil and water conservation measures explain 6%–10% of this change, with the Three Gorges Dam accounting for 31%–65% and other dams accounting for 10%–57%[75].

A major consequence of large-scale afforestation has been the impact on water resources via increased evapotranspiration and decreased run-off, stream flow and groundwater, especially in drylands[76,77]. For example, field studies have found soil water depletion (0–1 m depth) of 14.5%–42.0% under Grain-for-Green restoration[76], and afforestation has lowered local groundwater tables between 0.5 and 3.0 m in China's drylands[78]. Soil and groundwater depletion has reduced the survival rates of afforestation to 7%–34% in some areas[78,79], limiting its effectiveness in desertification control[35,77]. Scaled up, the water impacts resulting from the large-scale mismatch of species' water requirements with water availability may be important given northern China's water scarcity[23,77,80]. Afforestation in the Loess Plateau, for example, is approaching the sustainable water resource-use limits, affecting human use, and threatening local/regional food security[81]. However, over the entire Three North region, with afforestation covering just 7.8% from 1998–2014 (Supplementary Data 3), climatic variability/change is likely to have had a far greater water impact[36]. Nonetheless, dryland sustainability programmes need to ensure that the water requirements of species used in large-scale restoration are compatible with local/regional environmental water availability.

Biodiversity

A slight nationwide decline (−3.1%) in ecological habitat from 2000 to 2010 has been reported[9]. However, programmes such as the Natural Forest Conservation Program, which implemented 22.645 Mha of mountain closure and forest tending from 1998 to 2014 (Supplementary Fig. 1, Supplementary Table 21), have substantially slowed the decline in China's natural biodiversity[8,60]. China's nature reserve system also expanded rapidly after 1992 and was consolidated under the Wildlife

Conservation and Nature Reserve Program in 2001. By 2014, it comprised 2,729 reserves and covered around 15.1% of China's territory[82] (Supplementary Fig. 1, Supplementary Data 3). The Forest Ecosystem Compensation Fund has also been implemented over a large area (97.334 Mha) but its effectiveness has not been evaluated. Ex situ conservation measures such as breeding/relocation programmes, botanical/zoological gardens, and gene/germplasm banks have complemented the in situ measures above[7]. Local success stories include the Qinling Mountains biodiversity hotspot with its simultaneous forest protection and recovery, economic development and giant panda population increases[83].

However, there is plenty of room for improvement in biodiversity outcomes across China's sustainability portfolio. Whereas it covers 17.9% of the habitat area of threatened mammals, China's reserve system represents only 8.5% of reptile habitat and poorly represents ecosystem services[82]. China's adoption of the broad definition of 'forest' ignores differences in habitat function and biodiversity values of different forest types[84]. Reports of great forest area increases belie the predominance of non-native, single-species plantations, and the afforestation of vast areas that had never supported forest before, with their attendant biodiversity impacts[26]. In some areas, unintended consequences for biodiversity have resulted from policy incentives motivating landholders to first fell natural forest for sale, then establish programme-funded plantations on the newly-cleared land[26,84]. In addition, fast-growing pioneer tree and forage crop species such as pines (*Pinus* spp.), poplars (*Populus* spp.), and willows (*Salix* spp.) widely used to remediate infertile and eroding soils, have also invaded natural ecosystems[85]. Impacts on animal populations were also evident, as demonstrated in Sichuan where, compared to natural forest, compositionally simple reforestation was 17%–61% and 49%–91% lower in bird and bee diversity, respectively[86]. Prioritizing the restoration of natural ecosystems over monoculture plantations in key areas could substantially improve biodiversity outcomes at low cost[86].

Agriculture and food

From 1985 to 2007, China's agricultural outputs grew 5.1% per year on average following the 1978 reforms[87]. County-level crop production data revealed a near-doubling of cereal production from 1980 to 2010, but improvements varied by farming system and were limited by environmental constraints and climatic variability[30]. Rice yields increased over 12.3 Mha (41.8% of China's rice-growing area), but stagnated over 14.7 Mha (50%); wheat yields increased over 13.8 Mha (58.2%), but stagnated over 3.8 Mha (15.8%); and maize yields increased over 5.3 Mha (17.7%), but stagnated over 16.3 Mha (54%)[30]. From 2005 to 2010, meat production increased by 14%, egg production by 28%, and milk by 38%[88]. In a national survey from 2005–2009, increases in intermediate inputs (seed, fertilizer, irrigation and machinery) accounted for 44.46% of grain production growth, cropped area 18.16%, and Total Factor Productivity growth 17.30%[89]. Hunger has largely disappeared in China following the substantial increase in per-capita food production[90]. However, intensification and decreased nutrient-use efficiency in both crop[91] and livestock[92] systems have led to widespread decline in lake, river and coastal water quality[93].

The Comprehensive Agricultural Development Program reported 28.096 Mha of low-and medium-yield cropland improvement and 4.114 Mha of high-yield cropland demonstration from 1998 to 2014. The National Land Consolidation Program reported 14.978 Mha of agricultural land consolidation, development and reclamation, and 1.968 Mha of small watershed improvement was reported under multiple programmes (Supplementary Fig. 1, Supplementary Table 21, Supplementary Data 3). 29.5% of land parcels that underwent consolidation/reclamation showed improved productivity, and this increased over time[94]. While substantial areas of farmland have been lost to urbanization and ecological restoration, agricultural development and land consolidation programmes have more than offset these area losses[95]. However, productivity suffered because new farmland was often of lower quality than displaced areas[96].

Sustainability programmes have contributed to the growth in China's agricultural production in many ways. For example, productivity growth in Wuqi County of 15.8% from 1998 to 2004 was attributed to technical improvements resulting from Grain-for-Green extension services and diffusion of technical knowledge[97]. Technological advances such as semi-dwarf rice and wheat cultivars, heterosis in rice and maize, and mitigation of soil salinization have also boosted productivity[90]. The impact of large-scale environmental restoration on agricultural production, food prices and imports has been minimized via the targeting of steep, lower-productivity land[98]. Payments have relaxed farm household liquidity constraints, enabling intensification of agricultural production[99] and increased cropped areas[100]. Other policies such as agricultural and land tenure reforms, land-use regulation, and agricultural subsidies have also strongly affected agricultural production in China[87] but further research is needed to tease out their relative influence.

Society and economy

China's sustainability programmes have generally increased incomes and reduced poverty, but the effects have varied[5,101,102]. From 1995 to 2004, of six priority forestry programmes analysed, one was found to have strongly positive short-term impacts on rural household incomes (P6), three had positive impacts (P1, P3, P7), one was negligible (P11), and one was weakly negative (P12)[103]. Income effects became more positive over time however, as households adjusted and as market and environmental conditions improved[101].

Best understood are the socio-economic impacts of the Grain for Green Program and the Natural Forest Conservation Program. While Grain-for-Green payments have had a small direct effect on household incomes, the greater effect has typically been indirect, where relaxed liquidity constraints have freed up farm household labour for higher-paying off-farm employment[104]. The more land enrolled, the greater the effect[105]. In a large-sample longitudinal study in Shaanxi and Sichuan from 1999 to 2008, a 250% increase in household incomes was found, mainly driven by off-farm employment[99]. The socio-economic effects of the Natural Forest Conservation Program have been more mixed. In northern Shaanxi for example, 34.9%, 47.0% and 59.8% of farmers, pastoralists and forest workers, respectively, reported adverse impacts on their livelihoods due to logging and grazing bans, inadequate compensation and cost-sharing expectations. 23.5% of former forest workers remained unemployed after 6 years and livestock incomes were affected by the higher costs of barn-raising animals[106]. In the Wolong Nature Reserve, the Natural Forest Conservation Program had both positive (for example, less labour required to collect fuelwood) and negative (for example, crop raiding by wildlife) effects on households, and while household incomes quadrupled from 1998 to 2007, increases were largely due to engagement in agriculture, off-farm employment and the tourism industry[44].

Ecological migration has lifted many out of abject poverty and dire environmental conditions, particularly in China's north and west[53,107–109]. Benefits include improvements in source-area environments; incomes and living standards; access to housing, utilities, healthcare, transport, and education; safety from floods and landslides; and social engagement and cohesion[47,108]. While initiatives such as the Massive Southern Shaanxi Migration Program and the Ningxia Hui migration have reported overall success[47,108], in many cases, ecological migration has also placed pressure on the receiving environment and caused a range of socio-economic problems[45,109]. New houses and land endowments have been too small to meet needs[54,108]; and migrants, often poorly educated, can be unsuited to off-farm employment[110]. Households also suffered from increased cost of living, loss of social networks[47], and cultural disruption such as the relocation of nomadic tribes and conversion to modern, sedentary urban life[46,107,109].

Addressing the SDGs

Despite the adoption of the SDGs only at the end of our study period (2015), it is instructive to visualize China's sustainability investment in

	SDG 1 – No poverty	SDG 2 – Zero hunger	SDG 3 – Good health and well-being	SDG 4 – Quality education	SDG 5 – Gender equality	SDG 6 – Clean water and sanitation	SDG 7 – Affordable and clean energy	SDG 8 – Decent work and economic growth	SDG 9 – Industry, innovation and infrastructure	SDG 10 – Reduced inequalities	SDG 11 – Sustainable cities and communities	SDG 12 – Responsible consumption and production	SDG 13 – Climate action	SDG 14 – Life below water	SDG 15 – Life on land	SDG 16 – Peace, justice and strong institutions	SDG 17 – Partnerships for the goals
P1	2.09	1.67	1.67			1.50	0.08	1.25			2.09	0.83	6.67		8.34		
P2	0.61	0.35	0.35			0.87			0.35	1.39	1.04		0.35		1.73		
P3	1.95	1.70				1.70	0.08	1.27			6.79		6.79		8.48		
P4	56.82	71.03				7.10		42.62	21.31	28.41	42.62	28.41	14.21		71.03		
P5	0.24	0.32	0.32			1.43				0.80	0.96		0.32		1.43		
P6	45.70	76.17				7.62		15.23	11.43	22.85	15.23	15.23	11.43		57.13		
P7	1.75	3.50				15.77	0.35	5.26		7.01	28.03		35.04		35.04		
P8	21.83	10.91	5.46			27.29	0.55	8.19		10.91	43.66		43.66		49.11		
P9		−0.05				0.02		0.06	0.06			0.06			0.30		
P10	16.12					7.25				12.90			9.67		16.12		
P11	0.08	1.59	1.59			1.19	0.40	1.19			6.36		7.95		7.15		
P12	−0.05					0.72					0.48				2.40		
P13	6.52	4.08				2.45		1.22		4.08	6.52		6.52		8.15		7.74
P14	0.79	0.40				0.99	0.30			0.99			0.40		1.49		
P15	12.76	3.83						1.91		10.21		10.21	12.76		12.76		
P16		0.42	0.34			0.25		0.13	0.08	0.17	0.13	0.34			0.42		
Total	167.22	175.91	9.72			76.14	1.76	78.33	33.23	99.71	153.89	55.09	155.75		281.09		7.74

Fig. 4 | Mapping investment against the SDGs. Illustrative mapping of China's sustainability investment against the 17 UN SDGs. The depth of coloured shading reflects the level of investment for individual programmes (blue) and total (green). Numbers are in billions of US$ (2015 US$). As investment may be aligned with multiple SDGs, row totals are not presented. See Supplementary Methods for a detailed rationale behind programme investment allocation. SDG icon images courtesy of the United Nations.

the context of these global goals. Investment and actions under many programmes simultaneously aligned with multiple SDGs, contributing to 13 of the 17 goals (Fig. 4). Most investment contributed to SDG 15 (Life on land), SDG 2 (Zero hunger), and SDG 1 (No poverty). Owing to its integrated nature, China's sustainability portfolio was characterized by synergies and co-benefits across multiple SDGs, with trade-offs present but forming only a minor component (Supplementary Table 18). For example, Comprehensive Agricultural Development Program investment directly addressed SDGs 15, 2, and 1, but also had co-benefits for several other SDGs including SDG 8 (Decent work and economic growth). Illustrating trade-offs, while Grain-for-Green impacts on water quality made a strong positive contribution to SDG 6 (Clean water and sanitation), water use by inappropriate afforestation in drylands made a minor negative contribution.

Some keys to success

The impacts of China's sustainability programmes have been heterogeneous and nuanced but overwhelmingly positive across multiple aspects of land-system sustainability. While the challenges in programme implementation have been well documented[8,10] (Supplementary Discussion), we propose some key characteristics of success and discuss the implications for other nations pursuing sustainability[3].

Long-term investment at scale

Steadfast government commitment to large financial investment, sustained over decades, was a prerequisite for implementing the scale of interventions required to improve land-system sustainability. Massive public participation and labour was mobilized by this investment, reinforced by the establishment of conservation as a social norm[111]. China's sustainability emergency demanded large-scale and long-term budgetary prioritization of addressing poverty and environmental degradation. China's experience demonstrates that achieving sustainability goals will require a step-change increase in spending for most governments[112], bringing it more in line with expenditure on other public services like health, defence and education. The need for long-term planning will challenge democratic governments, which typically plan over much shorter electoral cycles. For many countries, public engagement and the availability and cost of labour will also be an obstacle to improving land-system sustainability, although technology (for example, autonomous heavy machinery) may provide a partial substitute.

Systemic causes addressed

A key feature of China's programmes was that in jointly addressing systemic socio-economic and environmental causes[113], the programmes aimed to break the vicious cycle of poverty and environmental degradation[37]. Establishment of new land uses that provided both environmental and economic benefits to households underpinned the success of many programmes[21,114]. The widespread use of financial incentives and off-farm income diversification decoupled household income from land use and reduced the need to further exploit land[115]. Parallel processes of population control, industrialization and urbanization also reduced the direct demand on China's rural land systems to provide livelihoods. In designing effective sustainability programmes, other nations must understand the complex dynamics influencing sustainability[37,116,117] and directly target key system components, relationships and leverage points, in particular, the maintenance and diversification of landholder incomes.

A diverse, integrated portfolio

China's sustainability programmes addressed multiple sustainability challenges via a diverse range of policy instruments. Unintended consequences associated with large-scale restoration and bans on deforestation and grazing included reduced food production and timber supply just when demand was booming (Fig. 1). However, these tensions were anticipated and skilfully managed via complementary programmes aimed at increasing agricultural and timber production (although the impacts of China's timber demand are now largely outsourced to other countries via trade[12]). Programmes combined multiple policy instruments (incentives, regulation and education) and were complemented by other institutional arrangements such as population control, environmental laws, and property rights reform (Fig. 1). Despite this integrated approach, trade-offs for water[80] and biodiversity[86] were still prevalent. Sustainability portfolios must be diverse and integrated, completely addressing all aspects of sustainability to anticipate and manage trade-offs and avoid unintended consequences[113,116–118], including indirect impacts on other nations[15].

Evidence-based, coordinated, adaptive

The response to China's sustainability emergency was required before sustainability science and landscape-scale adaptive management were well developed[119]. Nonetheless, interventions were evidence-based, informed by extensive concurrent experimentation, research and technological development[48–50]. New information and technology were disseminated to landholders via large-scale extension and education/training[97]. Programme governance has been adaptive[120], although maladaptation has occurred (for example, afforestation with inappropriate species). Pilots/trials and staged rollouts were employed to enhance programme success and, supported by local, provincial and central government coordination, ongoing project monitoring and evaluation informed regular planning and revision (Supplementary Tables 1–16, Fig. 3). Priorities were changed as capacity, knowledge and technology developed, mistakes were learned from, and sustainability objectives were achieved. Adaptive governance—where programme objectives, policy instruments and on-ground methods are highly responsive to change[113]—supported by multiscale coordination, is essential for the success of sustainability programmes in land-systems where complexity and uncertainty are the norm[120,121].

Decisive action

Deep poverty and poor living standards often co-existed with dire environmental degradation and/or risk from natural hazards. Regulatory controls in combination with ecological migration were effectively used as an emergency response to swiftly break this vicious cycle, yet the latter often caused socio-economic and cultural upheaval[45,107,109]. Relocation continues to be part of the sustainability solution in the poorest and most environmentally degraded areas[46], although its use as a sustainability intervention seems to be declining in China[122]. Environmental regulation is already widely used to promote land-system sustainability in most nations and will remain an important tool for improving land-system sustainability. However, if ecological migration is to be considered as a sustainability emergency response, adequate socio-economic and cultural support is essential. Approaches such as local governance and co-management, where local people are genuine partners in sustainability, may provide less culturally disruptive alternatives[123].

Future risks and their management

Material risks are posed to the durability of China's sustainability interventions. When payments cease, sustainability interventions are at risk of reconversion, and degradation may resume as households return to farming to supplement incomes[79,114,124]. Forest loss from land reconversion has already been detected by remote sensing[125]. Desertification interventions are at risk too[126], as evidenced by payment reductions driving herders to graze restricted grasslands and restock herds[127]. In addition, urban and agricultural land uses, fuelled by increasing population and consumption[13], are competing for land with restored forests and grasslands, and accelerating environmental change will also affect these large-scale sustainability interventions[128]. Without doubt, new risks unforeseen here will also emerge. From on past experience in China's sustainability programmes, we suggest some strategies for managing these risks in uncertain situations.

Income maintenance and diversification

Maintenance and diversification of household incomes are key to minimizing the risk of reconversion of sustainability interventions[129]. Many sustainability interventions were intended to generate income over time, thereby decreasing the likelihood of reconversion once initial payments end[130]. Policies supporting the transition of rural labour to off-farm work can also lower reconversion rates via lessening household reliance on farm profitability and reducing labour surpluses[124]. Households affected by sustainability interventions which reduce economic returns from land (such as grazing bans and forest management) that have not successfully transitioned to off-farm work[106] may require long-term income support or greater assistance in finding new employment. Indefinite government payments are one option, potentially justifiable by the substantial market (for example, carbon value[131]) and/or non-market value[132] of the ecosystem services provided by sustainability interventions. The private sector is another potential source of long-term funding for landholder payments as Chinese citizens increasingly demand greater corporate social responsibility[14].

Better planning and targeting

Long-term durability of sustainability interventions can be enhanced by better planning and targeting to capture win-win socio-economic and environmental opportunities or at least minimize trade-offs[118]. For example, the targeting of steep land, which is also less productive and less profitable, by the Grain for Green Program, minimized the opportunity cost for farmers[133] and reduces the likelihood of reconversion[129]. Planning and targeting should also consider environmental conditions and land-use demand both current and future, identifying appropriate restoration sites, species, and ecosystems that are robust to future environmental change[48]. China's thirteenth 5-year plan[122] introduced a spatial zoning approach where specific areas are designated for agricultural production, forest conservation and development, urban development, and key ecological functions[134]. This can help manage pressure from land-use competition at a large scale, especially when complemented by local-level planning.

Institutional reform and local engagement

Institutional reform and local engagement are also important for ensuring that China's sustainability interventions endure. Better consideration of local heterogeneity and dynamics in social, economic, and environmental systems in policy formulation and implementation is fundamental to widespread success and durability[121,135]. Households with greater autonomy have reported lower reconversion intentions after programme payments cease[129]. Better local engagement requires measures such as locally adapted science and technology transfer to households[136], the tailoring of programmes to specific needs[46,108] and effective and visible local monitoring[124]. Local institutions are needed that implement national and regional sustainability priorities at the local level, and provide feedback to local, regional and national governments, in an ongoing process of multi-scale adaptive improvement[137]. Stronger regulation of land subjected to state-funded sustainability interventions, and enhanced land tenure security, empowered by legal certification and stronger contractual rights, are also important for ensuring long-lasting sustainability outcomes[138].

Outlook for China and the world

China's pursuit of land-system sustainability represents a remarkable achievement of governance, policy and human endeavour. Current evidence suggests that, despite some adverse outcomes, China's integrated portfolio of sustainability programmes has achieved considerable overall success, with measurable benefits for sustainable wellbeing. However, the specific impacts of sustainability programmes are often clouded by the confounding effects of multiple socio-economic, policy and environmental factors operating concurrently[9,59]. For example, in addition to China's sustainability programmes, economic development, industrialization and urbanization have also played important parts in improving farm-household income and reducing the pressure on land to provide livelihoods. Now, 20 years on from China's great acceleration in sustainability investment, a comprehensive and robust quantitative evaluation of the impacts of its programmes is needed. Evaluations of the specific sustainability outcomes of individual programmes are required at multiple scales using causal methods to develop reliable counterfactuals, control for confounding factors, quantify additionality, and attribute causality[66]. Systematic reviews and meta-analyses are then required to quantify the nationwide impacts of individual programmes on specific indicators (for example, ref. [139]), which then need to be synthesized in a comprehensive evaluation of each programme (for example, see refs [5,102]). Disentangling and understanding the contribution of China's programmes to land-system sustainability is critical for informing effective adaptation of priorities and approaches. China still faces enormous social and environmental sustainability challenges associated with rapid development, industrialization and urbanization. Lessons from its land-system portfolio can also guide its approach to these broader sustainability issues such as urban pollution[14] and coastal reclamation[140].

Similarly, China's experience in rural land systems can help other nations to contribute to humanity's shared global sustainability aspirations as embodied in the UN SDGs. Insights from China's programmes suggest that, to have a meaningful impact, other nations must start to think about sustainability as a long-term, large-scale public investment comparable to other services, such as education and infrastructure. Interventions must embrace the complex nature of sustainability challenges and target key systemic causes and leverage points, in particular, addressing socio-economic and environmental feedbacks. An integrated portfolio is required that addresses all components of land-system sustainability, anticipates and manages the trade-offs prevalent in land-systems, and avoids unintended consequences. Programmes must be evidence-based, prioritizing cost-effective interventions, with priorities and approaches adapting over time. Not only do nations need to be prepared to take urgent, strong and decisive action where required to ensure the sustainability of the environment and the people that depend on it, but also to provide appropriate socio-economic and cultural support for those affected. Given that each sustainability programme will probably contribute towards several SDGs and each SDG will be addressed by several programmes, portfolio-wide planning is essential to efficiently and effectively achieve multiple SDGs.

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Additional information

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