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Policy Outlook

Establishing a nation-wide eco-environment monitoring network for sustainable governance

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Humanity currently faces unprecedented challenges in global environmental governance. Air and water pollution remain acute worldwide, causing millions of premature deaths each year and impeding progress toward the United Nations Sustainable Development Goals (SDGs) related to clean air and water [1]. According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6), global average temperatures have already risen over 1.1 °C above pre-industrial levels. If current emission trajectories continue, the world is likely to exceed the 1.5 °C threshold by 2030, directly endangering the survival and safety of around three billion people [2]. Concurrently, the United Nations Environment Programme has reported an unprecedented rate of biodiversity loss, with approximately one million species at risk of extinction [3]. Effective environmental governance at both domestic and global scales—encompassing climate change action and biodiversity conservation—relies on high-quality data. Accurate, comprehensive, and timely environmental information underpins policy formulation, enabling the assessment of ecological trends and broad-based international collaboration on urgent environmental challenges. In this context, acquiring real-time, wide-ranging, and precise monitoring data has emerged as a pivotal component for addressing the world's environmental crises.

Recognizing the critical importance of comprehensive environmental monitoring for global sustainability, China has elevated ecological protection to an unprecedented strategic level, guided by Xi Jinping's Thought on Ecological Civilization. Key concepts such as “Lucid waters and lush mountains are invaluable assets” and viewing “mountains, rivers, forests, farmlands, lakes, grasslands, deserts, and glaciers as a life community” underscore the holistic, systematic nature of ecosystems while emphasizing the importance of harmony between humanity and nature. These ideas significantly inform China's overall environmental governance strategy, positioning eco-environmental monitoring as a foundational element of ecological civilization. Since 2012, the country has undertaken a series of major actions and reforms in eco-environmental monitoring. In 2015, the General Office of the State Council issued the *Plan for the Construction of an Eco-Environmental Monitoring Network*, which laid out goals for building a unified, integrated monitoring system spanning Space–Air–Ground–Sea, and supporting information sharing [4]. Subsequently, additional policy documents, including the *Outline of the Eco-Environmental Monitoring Plan (2020–2035)*, have been released to strengthen and refine China's monitoring capabilities [5]. These measures aim to enhance China's capacity for eco-environmental monitoring and offer critical data to achieve the “Beautiful China” blueprint and the “Dual Carbon” objectives. Through sustained efforts, China has established a three-dimensional (3D) monitoring system that covers air, water, terrestrial, and marine environments, significantly influencing both domestic environmental management and international decision-making processes. This outlook first reviews the achievements of China's eco-environmental monitoring network and ongoing technological advancements, then discusses the implications of China's experience for global environmental governance, and finally offers conclusions and recommendations for international collaboration.

1. Achievements and experiences of China's eco-environmental monitoring network

Over several decades of focused development, especially since 2012, China has made substantial progress in building a far-reaching eco-environment monitoring network. This system encompasses key elements, including air, surface water, groundwater, soil, noise, marine, and ecosystem parameters. Nationwide, more than 33,000 monitoring stations operated by central authorities are supplemented by approximately 300,000 local or pro vincial sites, collectively providing comprehensive coverage of nearly all prefecture-level cities as well as ecologically critical regions until 2024 [6]. The air monitoring network hosts 1734 stations, delivering near real-time data on major pollutants (e.g., $PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3, and CO) to enable timely air quality forecasts and pollution control efforts. Surface water observations include 3646 monitoring sections, focusing on major rivers, lakes, and reservoirs; these sites employ automated instruments that continually measure pH, dissolved oxygen, ammonia-nitrogen,

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total phosphorus, and other indicators, thus offering immediate water-quality assessments and early warnings. Soil surveillance operates at 22,000 locations, primarily measuring the severity of soil contamination in croplands and construction sites and informing remediation. Meanwhile, groundwater data come from 1912 sites, enabling long-term evaluation of resources and pollution trends. Ecological monitoring is conducted through 171 integrated observatories and 16,400 ecological sampling plots, spanning forests, grasslands, wetlands, and deserts to track ecosystem structure, function, and services. In addition, marine monitoring at 1359 stations captures nearshore water quality and broader oceanic processes. Technological advancements have progressed toward automation and integrated systems, supported by seven environment-focused satellites currently in orbit. These satellites offer short-revisit, wide-swath, and multi-band remote sensing data, meeting large-scale, cross-regional, and multi-factor monitoring demands (Fig. 1).

To ensure that monitoring data are “authentic, accurate, comprehensive, rapid, and up-to-date,” China has instituted a robust management framework. Reforms such as clarifying oversight responsibilities, vertical administrative management, and partnerships with socialized monitoring entities have helped diminish local administrative interference. Simultaneously, the principle of “whoever produces the data bears responsibility” and the employment of automated systems have established extensive quality management and traceability protocols, sustaining the credibility and comparability of monitoring outputs.

Such monitoring efforts have played a foundational role in eco-environmental governance and policy-making. In both pollution control campaigns and key watershed restoration endeavors, consistent and accurate data have furnished powerful decision-support tools. For instance, pinpointing $PM_{2.5}$ emission sources and ensuring ongoing regulatory attention have markedly improved China's air quality. From 2015 to 2022, average annual $PM_{2.5}$ levels nationwide fell by approximately 35.6%, a reduction similar in scale to the improvements the United States achieved across three decades under the Clean Air Act [7,8].

2. Technological advances and digital transformation

Looking ahead, China plans to further advance the technological modernization and digital transformation of its eco-environment monitoring network, aiming to develop a fully integrated Space–Air–Ground–Sea integrated eco-environment monitoring network. This major transition goes beyond conventional single-parameter data collection, evolving toward a full-chain model combining “intelligent sensing, smart analytics, and precise decision support.” Ultimately, these efforts are expected to yield a multi-tiered technological system characterized by “comprehensive coverage, multidimensional coordination, and interconnected intelligence,” providing enhanced capabilities for ecological and resource management in pursuit of the “Beautiful China” vision.

2.1. Establishing a “smart brain” oriented towards value realization

Given the growing complexity of ecological governance, China is building a triple-layered scheme of “data infrastructures, intelligent tools, and scenario-based applications.” This platform integrates monitoring data across water, air, soil, and ecology with meteorological, hydrological, and remote sensing information from multiple domains. By developing a “big-data toolbox” and large-scale models

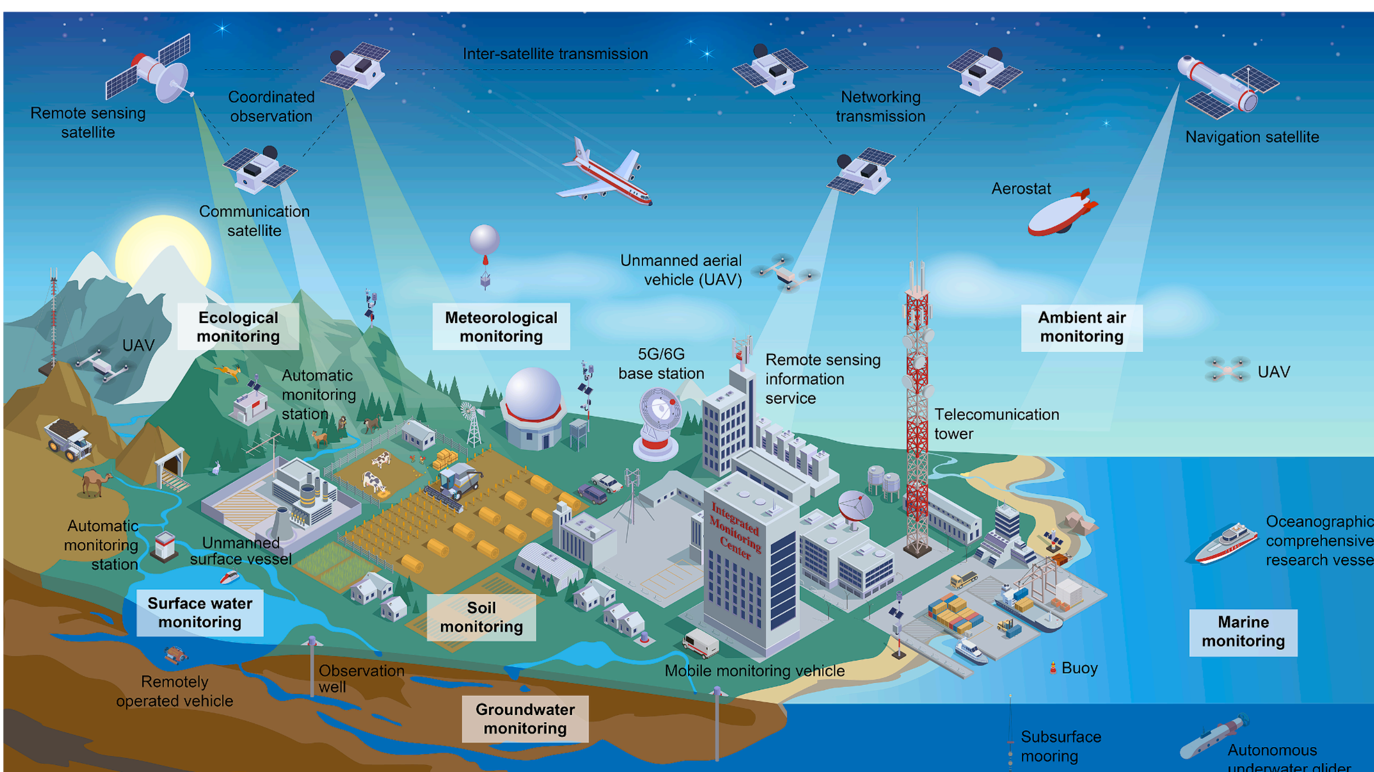

Fig. 1. Schematic diagram of the Space–Air–Ground–Sea integrated eco-environment monitoring network. The integrated network comprises four interconnected domains: (1) Space segment with remote sensing, communication, and navigation satellites providing coordinated observation and inter-satellite transmission; (2) Air segment including unmanned aerial vehicles, aerostats, and telecommunication infrastructure; (3) Ground segment encompassing automatic monitoring stations for air quality, surface water, soil, groundwater, ecological, and meteorological monitoring; and (4) Sea segment consisting of research vessels, autonomous underwater vehicles, and marine monitoring platforms. The architecture enables real-time data acquisition and networking transmission for integrated environmental monitoring and assessment.

specialized for eco-environmental monitoring, raw data can be efficiently standardized, fused, and turned into predictive and actionable insights. Practical applications in pollution trend analysis, proactive problem detection, and ecosystem condition assessment have revealed that converting monitoring data into valuable intelligence dramatically shortens the response time of environmental interventions, improving enforcement accuracy.

2.2. Creating a new generation of intelligent sensing networks through unmanned operations

To enhance monitoring efficiency and oversight, China is intensifying research and deployment of emerging technologies, such as unmanned maintenance, automated sampling, and “smart labs devoid of human intervention.” For example, using unmanned aerial vehicles, mobile monitoring vehicles (both land- and water-based), or drive-by sampling platforms, high-frequency measurements can cut operational time and labor costs by over 70% compared to conventional methods. Coupled with next-generation quantum lidar, microfluidic chip labs, and automated image recognition, these approaches represent a leap forward from “visible measurements” to “precise detection.” In surface water monitoring, integrated intelligent sampling units reduce sampling times and transport expenses by more than half, while simultaneously increasing the objectivity of on-site measurements.

2.3. Building an intelligent operations and control platform for complex networks

Given the massive and stratified nature of China's eco-environmental monitoring system, a comprehensive intelligent operations and control (IOC) platform is under development. By merging data production, quality control, and supervisory functions, the platform enables full lifecycle management of monitoring devices, automated observations, and system-wide security checks. An end-to-end quality module assures traceable data collection, transmission, and storage, while real-time oversight and sub-minute alarm features proactively identify anomalies or potential data manipulations. This transformation from fragmented, manual quality control to systematic, integrated management is expected to substantially improved data consistency and comparability.

2.4. Establishing a national IoT-based data exchange platform

In line with the “edge–cloud” synergy concept, China supports an intelligent edge-computing dispatch network that merges multi-source data from atmospheric, terrestrial, and marine realms. Through standardized and correlated datasets, institutional and technical barriers are minimized, preventing isolated data silos (so-called “data archipelagos”). Responding to user requests at various administrative levels, government authorities have introduced “four lists”—covering product directories, application demands, formatting protocols, and sharing service guidelines—while offering open APIs and advanced retrieval services. These measures optimize data distribution and utilization across departments, research institutions, and the private sector.

2.5. Towards a systems-theory perspective for Space–Air–Ground–Sea integrated monitoring

On this foundation, China aims to develop a conceptual framework following system theory, information theory, and cybernetics, progressing from raw data (Data) through information (Information) and knowledge (Knowledge) to enhanced decision-making (Wisdom) [9]. Through integrated designs spanning central–local, orbital–ground, and source–sink elements, and by reinforcing the monitoring network's self-learning and self-optimizing capacities, this conceptual DIKW-based model aspires to handle complex ecological contexts more effectively. This approach can inform next-generation monitoring architecture worldwide, potentially driving more agile, data-driven governance of ecosystems.

3. Implications for global environmental governance

Amid the intertwined challenges of the SDGs, climate change, and ecological security, China's construction of its large-scale eco-environment monitoring network offers an exemplary model for the international community, particularly for countries and regions with insufficient environmental monitoring capacities. These experiences extend beyond technological and institutional aspects, highlighting innovations in concepts and paradigms.

3.1. Shifting from reactive management to proactive prevention

Traditional environmental governance often relies on post-event responses, acting after pollution has occurred. This reactive approach struggles to address the complexity and suddenness of environmental issues effectively. China's experience demonstrates that establishing a comprehensive, real-time eco-environment monitoring network enables immediate perception of environmental changes, facilitating a shift from reactive management to proactive prevention. This transformation allows for earlier problem identification and risk assessment, enabling the implementation of forward-looking measures that prevent the escalation and intensification of environmental problems.

3.2. From single-element management to systematic collaborative governance

Historically, environmental governance has been limited to managing individual elements such as air, water, or soil, lacking a holistic understanding of ecosystems. Guided by the concept that“-mountains, rivers, forests, farmlands, lakes, grasslands, deserts, and glaciers as a life community,” China has constructed a three-dimensional monitoring system covering Space–Air–Ground–Sea. This system achieves integrated monitoring across multiple elements and scales. Such systematic collaborative governance helps reveal the complex interactions among various ecosystem components, providing a scientific basis for formulating comprehensive environmental policies.

3.3. Data-driven scientific decision-making and management

A significant challenge in global environmental governance is the lack of high-quality, credible data. By implementing a data management system characterized by “authentic, accurate, comprehensive, rapid, and up-to-date,” China ensures the quality and credibility of its monitoring data. This solid foundation supports data-driven scientific decision-making. High-quality data not only enhance domestic environmental management but also provide reliable evidence for international cooperation and exchange, supporting global collaborative actions in pollution control, climate change mitigation, and biodiversity conservation.

3.4. Leading role of technological innovation and intelligent monitoring

China integrates advanced technologies such as artificial intelligence, the Internet of Things, and big data analytics into eco-environmental monitoring, achieving automation and intelligent operations. This integration improves monitoring efficiency and accuracy while reducing costs, offering feasible technological pathways for resource-limited developing countries. Technological innovation enables countries to leapfrog traditional limitations, directly advancing into a new stage of intelligent environmental monitoring. China has successfully established a large-scale automated monitoring network within approximately three years, providing a replicable model for building water quality laboratories in Belt and Road regions [10], where automated laboratory efficiency has increased by 100% and costs have decreased by 20%.

3.5. Necessity of global cooperation and sharing

Environmental issues are transboundary and global in nature, making it challenging for any single country to address them alone. China's practices in promoting international cooperation—such as participating in the Group on Earth Observations (GEO) and building the Belt and Road Big Data Service Platform for Environmental Protection—illustrate the necessity of global collaboration and data sharing. Additionally, the establishment of Lancang-Mekong Water Resources Cooperation Information Sharing Platform under the Lancang-Mekong Cooperation framework with downstream riparian states represents a concrete manifestation of this approach, facilitating hydrological data transparency and collaborative flood management [11]. These initiatives demonstrate how strengthening international cooperation and sharing monitoring data and technological expertise enable countries to collectively enhance their environmental governance capabilities, addressing global environmental challenges effectively.

3.6. Institutional innovation and multi-stakeholder governance

Through institutional innovations like vertical management and the collaboration between socialized monitoring and government regulation, China has mobilized multiple parties to participate in eco-environmental monitoring. This approach demonstrates that environmental governance requires joint participation from governments, enterprises, social organizations, and the public, establishing a framework of multi-stakeholder governance. Such institutional innovations improve the efficiency and equity of environmental management, offering new perspectives for global environmental governance.

China's experience indicates that facing global environmental challenges necessitates systemic transformations in concepts, institutions, and technologies. Establishing a comprehensive, real-time, and precise eco-environment monitoring network is a critical step toward scientific governance and sustainable development. This approach not only aids in resolving domestic environmental issues but also provides a practical paradigm for global environmental governance.

4. Conclusions and call to action

Against the backdrop of interlinked ecological crises and sustainable development goals, China's construction of the world's largest eco-environment monitoring network offers broad insights for the global community. A systematic, digitally advanced, and integrated approach to monitoring can substantially enhance environmental protection, effective climate action, and sustainable development outcomes. Therefore, we propose.

4.1. Strengthening existing international mechanisms

Leverage platforms such as the Group on Earth Observations (GEO), the United Nations Environment Programme (UNEP), and the Global Environment Monitoring System (GEMS) to deepen the global exchange of monitoring data and technologies. Actively engage in the Belt and Road Big Data Service Platform for Environmental Protection, collaboratively improving monitoring capacity with participating countries.

4.2. Global environmental monitoring partnership (GEMP)

We propose establishing a tighter technical and policy cooperation across nations to tackle shared environmental risks as highlighted by China's experience in Section 3.5. Special efforts should be made to enhance technical support and capacity-building for less-developed regions, thus narrowing gaps in monitoring capabilities and data availability.

4.3. Advancing integrated design and standardization

Within frameworks such as the Belt and Road Initiative and international standard-setting organizations, technical norms, data-quality management protocols, and information-sharing standards for eco-environmental monitoring should be developed and refined, building upon China's experience as detailed in Section 3.3. Greater interoperability and comparability across countries will facilitate integrated global datasets and more cohesive partnerships.

4.4. Enhancing systemic perspectives and forward-looking strategies

Encourage robust collaboration among academia, industry, and government to continuously update monitoring infrastructures and methodologies. By establishing cross-disciplinary, multi-stakeholder platforms, cutting-edge theories in systems science, emerging information technologies, and artificial intelligence can be harnessed to accelerate progress toward global sustainability targets.

China welcomes the opportunity to collaborate with the international community and to share lessons learned in building its eco-environmental monitoring network. Through coordinated efforts, all nations can further improve the quality of global environmental governance, thereby contributing to the construction of a shared future for humankind.

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