Engineering 19 (2022) 14–21

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

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The Nature-Based Ecological Engineering Paradigm: Symbiosis, Coupling, and Coordination

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1. Introduction

We are currently facing three major ecological threats on a global scale: biodiversity loss, climate change, and environmental pollution exacerbation. The degradation of terrestrial and marine ecosystems poses a major risk to human survival and development, brings serious impacts to the wellbeing of 3.2 billion people, and causes the loss of about 10% of the annual global gross domestic product (GDP) [1,2]. Meanwhile, the coronavirus disease 2019 (COVID-19) epidemic is still spreading rapidly throughout the world, showing that the present relationship between humans and nature is unsustainable. It is necessary to protect nature so as to maintain the self-resilience of ecosystems. For this purpose, the United Nations has successively launched actions such as the Decade of Action for the Sustainable Development Goals, the Decade on Ecosystem Restoration, and the Decade of Ocean Science for Sustainable Development. Moreover, a new post-2020 global biodiversity framework is being negotiated. Against this background, we will step into a new era of the reconstruction of the relationship between humans and nature. The next decade will be a critical period to improve human wellbeing and mitigate the climate and biodiversity crises, and is closely related to the realization of the United Nations 2030 Sustainable Development Goals.

Ecological engineering is a key means to promote ecological restoration (ER), the definition of which was proposed more than 60 years ago. Many scholars around the world have discussed the theory and practices of ER. Research on ecological protection and restoration has been carried out through a large number of practices in Europe, the United States, and other developed countries, resulting in successful cases such as the construction of Yellowstone National Park in the United States, the Rhine River Ecological Restoration Project in Europe, and mine rehabilitation projects in Australia. In the 21st century, ecological engineering has become a major political issue and is a priority in most countries in order to effectively respond to the global ecological crises [3]. Ecological engineering usually focuses on the ecosystem scale and landscape scale, rather than the smaller species scale or community scale, emphasizes the threshold concept of the self-resilience of ecosystems [4], and considers the management and control of human factors in ER [5]. Ecological engineering has also carried out the integration of multi-domain and interdisciplinary theories and methods; examined scientific issues such as ecosystem patterns, processes, services, and sustainable management; and promoted the coordinated realization of the objectives of restoring degraded ecosystems and building sustainable ecosystems [6]. Considerable development has been achieved in ecological engineering through progress in these research fields. In 2016, the Society for Ecological Restoration (SER) released the first edition of International Principles and Standards for Ecological Restoration Practice and then released the second edition in 2019 [7]. In 2020, the International Union for Conservation of Nature (IUCN) released the Global Standard for Nature-based Solutions (NbS) [8].

The concept of ecological engineering in China originated and developed from spontaneous ecological practices in ancient China, such as the mulberry fish pond (an ecological agricultural model combining mulberry planting and sericulture with pond fish culture) and the multi-pond system (a wetland system formed by many small ponds connected by some ditches). In 2013, the idea that *the mountains, rivers, forests, farmlands, and lakes are part of a community of life* was put forward for the first time in China. This idea emphasized following the laws of nature, paid attention to the overall protection and systemic restoration of natural ecosystems, and gave full play to the self-healing ability of nature, while scientifically promoting ecosystem restoration. Under the guidance of this idea, for example, the Chinese government has successively implemented 25 pilot engineering projects for the ecological protection and restoration of mountains, rivers, forests, farmlands, lakes, and grasslands in key national ecological function zones. The main measures of these pilot projects are ecological protection and restoration, innovation in management mechanisms, the establishment of diversified investments, and so on. These pilot projects have achieved multiple ecological, social, and economic

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https://doi.org/10.1016/j.eng.2022.07.004

benefits, improved the ecosystem quality of key ecological areas and ecological nodes in an overall way [9], and benefited 65 poverty-stricken counties. For another example, China's Conversion of Cropland to Forest Program has not only achieved ecological goals such as increasing forest coverage and reducing soil erosion but also achieved social goals such as poverty reduction in the project areas, through measures such as compensation for farmers engaged in the program [10]. At the same time, Chinese scholars have carried out research on the implied aspects, theoretical perspectives, and practical paths of the pilot engineering projects [11], and have determined that the pilot engineering projects are focused on comprehensive, systematic, and source governance—unlike previous engineering projects, which have been dominated by single-factor governance. In spite of the current achievements, scientists have reported that research is still needed to further reveal the ecological coupling mechanisms between the elements of mountains, rivers, forests, farmlands, lakes and grasslands, and the temporal and spatial variation characteristics of regional ecosystem services.

During this period, profound changes have been taking place in terms of the research objects, scales, objectives, and composition of ecological engineering in the academic community. Research objects have expanded from single natural elements to multiple natural–social elements, research scales have shifted from ecosystem services on the meso–micro scale to the reconstruction of ecological security patterns on multiple scales, and research objectives have been upgraded from the optimization of ecosystem structures and functions to the improvement of human and ecological wellbeing [11,12]. Moreover, the application fields of ecological engineering in this period cover both natural ecosystems (e.g., forests, grasslands, rivers, and lakes) and artificial ecosystems (e.g., mines, farmlands, and cities). These trends indicate that ecological engineering is entering a new stage: With the objective of harmonious coexistence between humans and nature, a new ecological engineering paradigm—nature-based ecological engineering (NbEE)—is emerging.

Therefore, we propose the concept and characteristics of NbEE in this paper. According to the research framework of monitoring and evaluation, coupling mechanisms, model simulations, and prediction and optimization, ecosystems' cascading relationships of *pattern*, *process*, *services*, *and wellbeing* are used to build a conceptual model of NbEE and to develop an ecological engineering paradigm. The basic framework of this paradigm is target coordination, diagnostic analysis, pattern optimization, process regulation, and evaluation feedback. Its aim is to scientifically carry out ecological protection and restoration and provide a new path to cope with the global ecological crisis.

2. Concept and characteristics of NbEE

2.1. Concept

In recent years, global ecologists gathered in the International Ecological Engineering Society (IEES) have gradually unified the concept of ecological engineering, which can be defined as follows: "an engineering science to improve human wellbeing with the basic principles and the way of overall thinking of ecology as a problem-solving method" [13]. ER is an important component of ecological engineering and has become one of the most high-profile disciplines in the world, since it is closely related to climate change response, biodiversity protection, and sustainable development [7]. The SER defines ER as a process to restore degraded, damaged, or completely destroyed ecosystems, which has been widely recognized internationally [14]. The IUCN defines NbS as actions to protect, sustainably manage, and restore natural and modified ecosystems in ways that address societal challenges effectively and adaptively, to provide both human wellbeing and biodiversity benefits [8]. Numerous studies on ER have been carried out in China. In particular, ideas on ecological civilization have been put forward in recent years, such as *harmonious coexistence between humans and nature* and *mountains, waters, forests, farmlands, lakes, and grasslands are part of a community of life*. The ER for territorial space has gradually become a research hotspot that focuses on the integrity and systematicness of ecosystem.

As the research objects of ecology have gradually shifted from micro-life phenomena to meso–macro ecological regulations, a new era of ecology is arriving that is based on multiple scales, big data, and interdisciplinary studies. Classical ecological research has mostly focused on a small scale, a single phenomenon, or a process with certain limitations; thus, our knowledge is fragmentated, scattered, and isolated, with a lack of systematicness [15]. It is expected that ecological engineering can provide a systematic and sustainable solution; as the Chinese proverb says, "Our solutions are in nature." For example, the IUCN's proposed NbS is a solution based on which forest landscape restoration (FLR), ecosystem-based adaptation (EbA), the ecosystem approach (EA), and other methods are integrated; it has been applied in biodiversity conservation, climate change adaptation and mitigation, the sustainable use of natural resources, and other fields in many countries [16].

The promotion of new technologies, such as big data and artificial intelligence, provides an opportunity to innovate the ecological engineering paradigm based on new thinking about the relationship between humans and nature, as well as the latest theoretical and practical progress in the field of ecological protection and restoration. Moreover, these developments make process coupling and spatial integration possible based on multiple elements, multiple scales, multiple objectives, and multiple levels. Therefore, NbEE can be defined as a kind of ecological protection and restoration practice that conserves and enhances ecosystem services (e.g., rivers, forests, farmlands, lakes, and grasslands) through the coupling of different spatial scales (e.g., watershed or region, landscape, ecosystem, and field scales) and the comprehensive application of multiple elements, scales, levels, objectives, and means. Its aim is to build a harmonious and symbiotic relationship between humans and nature, with a prerequisite of the law of natural succession and the way of systematic thinking. This will be helpful in promoting the eventual synergistic gain of ecosystem services and human wellbeing.

2.2. Features

NbEE is a new ecosystem governance paradigm developed with the aim of building a new relationship of harmonious symbiosis and coordinative benefits between humans and nature. It is mainly featured as following:

First, NbEE focuses on the symbiotic relationship and coordinative benefit between humans and nature. As a link between natural and social processes, ecosystem services have a tradeoff or synergy with each other [17]. By carrying out ecological engineering, the original one-way relationship resulting in a natural or human beneficiary can be transformed into a two-way relationship that simultaneously benefits both humans and nature. Here, the engineering objective is expanded from pure restoration of the ecological environment to achieving mutual gain between humans and nature, harmonious symbiosis between human and nature, and coordinated development between the economy and the environment. The research elements involved in ecological engineering have shifted from natural elements to multiple social and natural elements and their coupling, and from biological components and function optimization to the common promotion of human and ecological wellbeing. Moreover, NbEE focuses on the coupling of natural restoration with social, human, and management decisions, so as to promote the realization of ecological product values.

Second, NbEE emphasizes that ecosystem process coupling and self-succession of ecosystem should be realized based on natural laws. The essence of basing one's approaches on nature is to follow the law of natural succession and the Chinese basic principles of ecological engineering—namely, integrity, coordination, regeneration, and circulation [18]. This gives full play to the capacity of ecosystems to provide services, such as buffering, purification, regulation, and conservation, and improves the quality and stability of ecosystems. In NbEE, more emphasis is placed on system coupling, the accurate regulation of ecological processes, and the adaptive management of ecosystem restoration [19], while considering the spatiotemporal dynamic characteristics of the natural ecosystem and the uncertainty of restoration processes. NbEE aims to improve the overall functions of regional ecological services through the optimal regulation of social and natural factors within the engineering field. Most of the technologies employed for NbEE are either nature-based or imitate nature to minimize human disturbances during the positive evolution of the ecosystem and to cultivate the ecosystem's self-succession.

Third, NbEE emphasizes systematic regulation, spatial correlation, and spatial coordination. Within an overall system view, NbEE can sort out multiple relations between element and element, structure and function, and humans and nature, and can carry out the optimal regulation of ecosystem based on the whole factors, whole processes, and whole chains. Objective paths can be proposed accordingly for ecological protection and restoration, considering the ecological problems and stress factors at various scales. For example, it is necessary to consider species restoration and community succession at the population scale; structural and functional changes at the ecosystem scale; the ecological security pattern, source–sink relationship, and ecological corridors at the landscape scale; and the state changes of large-scale regional ecosystems at the macro scale. Then, it is necessary to lay the foundation for ecological monitoring, assessment, prediction, early warning, and sustainable management. Building the cascading relationship of *pattern*, *process*, *services*, and *wellbeing* can effectively couple ecological protection, restoration, and reconstruction with human utilization processes at different spatiotemporal scales and produce the coordinative effect of overall improvement among ecosystem services and human wellbeing.

2.3. Comparison of paradigms

Two international mainstreaming paradigms in the field of ecological engineering were compared with NbEE, as shown in Table 1, in order to deeply understand NbEE paradigm. These two paradigms are the SER's International Principles and Standards for the Practice of Ecological Restoration (second edition) and the IUCN Global Standard for NbS (first edition).

(1) In terms of their core ideas, ER, NbS, and NbEE have the same origin, coming from ecological ideas about respecting, complying with, and protecting nature. ER emphasizes following the laws of nature, while focusing on a combination of self design and human-made design to give full play to the self-resilience of ecosystems [7]. NbS advocates the idea of nature-based approaches and relies on natural forces to deal with various social challenges [16,20]. NbEE integrates Chinese ecological and cultural elements, emphasizing philosophies such as a harmonious coexistence between humans and nature, and the perception that mountains, rivers, forests, farmlands, lakes, and grasslands are part of a community of life.

(2) In terms of the research background, the three paradigms have been formed against a background of global ecological crises,

Table 1
Comparison of the ER, NbS, and NbEE paradigms.

Aspects	Paradigm		
	ER	NbS	NbEE
Core ideas	Following the laws of nature and giving full play to the self-resilience of ecosystems	Advocating the idea of "nature-based" and relying on natural forces to deal with various social challenges	Emphasizing the idea of "harmonious coexistence between man and nature" and "mountains, rivers, forests, farmlands, lakes, and grasslands are part of a community of life"
Research background	Due to disorderly human activities, the degradation of ecosystems in large areas has occurred and the capacity of ecosystem service has been damaged	In response to crises such as global change and biodiversity loss, people have gradually realized the important role played by nature conservation actions	The systematic and holistic thinking of ecological protection and restoration has become the mainstream of the times, relying on coordination to break through the bottleneck of ecosystem service improvement
Research objects	Degraded ecosystems	Social–ecological systems	Social–ecological systems
Research scales	Based on the ecosystem scale	Based on the landscape scale	Emphasizing the landscape scale and paying attention to multiscale nested research
Research objectives	Achieving ecosystem restoration	Addressing one or more social challenges while providing benefits for human wellbeing and biodiversity	Achieving economic and ecological goals together and improving human ecological wellbeing
Implementation processes	Planning and design, implementation, monitoring and evaluation, and successive maintenance	Identifying problems, screening measures, designing a scheme, implementing the scheme, communicating with relevant parties, correcting the scheme, and quantifying benefits	Target coordination, cause diagnosis, pattern optimization, process regulation, and evaluation feedback

such as global climate change and biodiversity loss. ER focuses on the restoration of degraded ecosystems. NbS emphasizes the net growth of biodiversity and ecosystem integrity, while paying attention to economic feasibility, social equity, and institutional rationality [16]. NbEE is a model that integrates Chinese ecological philosophies and major ecological engineering experiences based on existing paradigms.

(3) In terms of the research objects, ER takes degraded ecosystems as the main research objects, strengthens research on

socioeconomic and cultural factors, and has introduced the concept of the "social welfare wheel" in order to quantify the degree of realization of social goals by ER projects in recent years [7]. NbS and NbEE are consistent in their research objects, which are social–ecological systems. Both emphasize addressing various social challenges, building a symbiotic relationship between humans and nature, and achieving coordinative benefits.

(4) In terms of the research scales, ER involves the multi-scale restoration of species, population, ecosystem, or landscape [21]. According to the definition of SER, ER is mainly based on the ecosystem scale. Since ecosystems cannot be isolated and are affected by larger-scale terrestrial and marine ecosystems, NbS focuses on larger-scale research, mainly at the landscape scale [22]. In addition to emphasizing protection and restoration at the landscape scale, NbEE focuses on multi-scale system regulation and spatial scale coupling [12].

(5) In terms of the research objectives, ER does not emphasize restoring the ecosystem to its original status; rather, it advocates restoring a certain degree of ecosystem function in order to provide ecosystem services that are similar to those of the original ecosystem [7]. Both NbS and NbEE have the primary goal of ensuring sustainable social development while providing for human wellbeing and biodiversity benefits [16].

(6) In terms of the implementation processes, ER puts forward four processes: planning and design, implementation, monitoring and evaluation, and successive maintenance [7]. NbS puts forward seven processes: identifying problems, screening measures, designing a scheme, implementing the scheme, communicating with relevant parties, correcting the scheme, and quantifying the benefits [23]. NbEE integrates the processes of the above two paradigms, and includes: target coordination, cause diagnosis, pattern optimization, process regulation, and evaluation feedback.

To sum up, paradigms are formed from specific research backgrounds, objects, and objectives, which develop from existing theories and practices. The three paradigms described above are based on the same scientific norms of ecological conservation. Each paradigm focuses on the knowledge from different sources within the understanding of the relationship between humans and nature. Just as SER presumes that ER is a supplement to other conservation activities and NbS [7], while IUCN presumes that global standards for NbS are a supplement to the use of other standards, rather than a replacement for them [16]. Similarly, NbEE is also presumed as a supplement to ER and NbS. The NbEE paradigm is a new achievement based on important concepts and major practices of Chinese ecological engineering, which helps to enrich the theories, paths, and models of ecological protection and restoration in the new era.

3. Construction of the NbEE paradigm

3.1. Conceptual model

The NbEE paradigm is constructed in terms of mutual feedback and a symbiotic relationship between humans and nature. First, it is necessary to effectively identify the cascading relationships among *patterns*, *processes*, *services*, and *wellbeing* according to the concept of symbiosis between humans and nature and the law of ecosystem succession. Second, a conceptual, multi-element, multi-scale, multilevel, and multi-objective model of ecological engineering must be constructed (Fig. 1). Here, "multi-element" refers to natural elements such as forests, grasslands, and wetlands and to social elements such as urban and rural areas, the population, and industry. "Multiscale" refers to population, ecosystem, landscape, and watershed or region scales. "Multilevel" refers to the levels of the elements, structures, and functions of ecosystems. For example, in a study on territorial ER, Fu [12] proposed that key restoration areas should be identified at multiple levels of biogeography and ecological function. "Multi-objective" refers to the multiple objectives of ecological engineering under multiscale and multi-element scenarios. For example, Hallett et al. [24] analyzed more than 200 global restoration network engineering

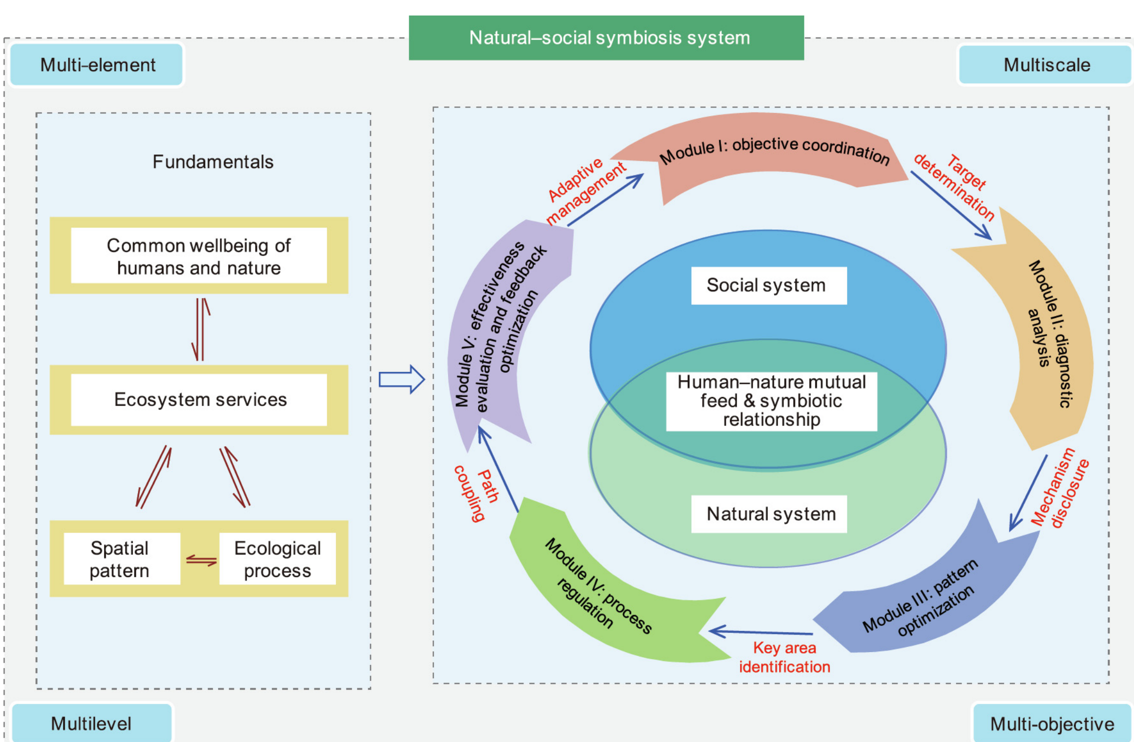

Fig. 1. Conceptual model of the NbEE paradigm.

projects and found that most projects set ecological goals, while social goals were very important for the long-term ecological benefits of the projects. The conceptual model is composed of five modules: objective coordination, diagnostic analysis, pattern optimization, process regulation, and evaluation feedback. Each module interacts with every other module, and progress occurs in a step-by-step manner. Based on the ecosystem service coordination theory and the mutual feed mechanism between landscape patterns and ecological processes, this model can identify the key areas, driving factors, and mutual feeding relationships of degraded ecosystems; explain and quantify the impacts of human activities on ecosystem services; and evaluate the comprehensive effects of ecological engineering in improving the quality and stability of ecosystems and the sustainable development of human society. In this way, it can regulate and optimize objective paths through adaptive management, and promote both the restoration of damaged ecosystems and the sustainable development of human society.

3.2. Module I: Objective coordination—determining engineering objectives based on spatiotemporal variation

Scale effects exist in the spatial distribution and temporal variation of the symbiotic natural–social system. Due to the influence of spatiotemporal imbalances, ecosystem services fluctuate and interact with each other; thus, it is necessary to avoid segmentation and strengthen coordination (Fig. 2). On the spatial scale, the landscape scale is often related to the engineering area, which focuses on pattern optimization and the improvement of ecosystem–landscape connectivity, with the purpose of improving the quality of ecosystems and human wellbeing. The ecosystem scale corresponds to the engineering project, which is composed of various factors, including mountains, rivers, forests, farmlands, lakes, and grasslands. Engineering on the ecosystem scale mainly involves structural adjustment and the process coupling of ecosystems, with the aim of improving the health and function of ecosystems. The field scale corresponds to the engineering unit, with a focus on ecological designs and the application of green materials. Engineering on the field scale is aimed at ER in degraded areas and the improvement and restoration of ecosystem structures. For example, Wu [25] proposed that landscape restoration required an in-depth understanding of the compositions, structures, and functions of the landscape, as well as of the relationship between ecological integrity and meeting human needs. These landscape attributes differ from those that are considered for ER on the ecosystem, community, and species scales. On the time scale, as the coordination of the relationship between humans and nature is enhanced, engineering objectives pass through three successive stages: coordinated layout, systematic governance, and harmony between humans and the land [12]. At the same time, the objective synergy of ecological engineering gradually improves and the quality and stability of ecosystems gradually increase.

3.3. Module II: Diagnostic analysis—revealing the driving mechanisms of multilevel ecosystem degradation

The symbiotic natural–social system is an integration of natural attributes (e.g., elements, structures, and functions) and social attributes (e.g., urban and rural areas, population, and industry). Therefore, it can be classified into many levels. Clarifying the mechanisms of multiscale and multilevel ecological degradation is vital in order to increase the scientific basis for ecological engineering. Based on the pressure–state–response (PSR) analysis framework, a degradation mechanism can be revealed through an ecological security evaluation [26], which can evaluate ecosystems' state of health, analyze ecological issues and their driving forces, and reveal the impacts of various driving factors on ecosystem structures, processes, and functions, so as to put forward engineering objectives and management measures (Fig. 3). While considering the differences among various scales, the driving forces of ecological degradation must be analyzed, and a list of key driving factors on the landscape, ecosystem, and field scales must be established. For example, when Peng et al. [27] analyzed the ecological factors of grassland degradation on different scales, their results showed that the main ecological factors were altitude, slope direction, and average annual precipitation on the small scale (300 m $\times$ 300 m); annual average temperature, slope, and land use types on the mesoscale (1 km $\times$ 1 km); and annual average temperature on the large scale (5 km $\times$ 5 km). Gann et al. [7] reported that landscape restoration involved the biological levels of the ecosystem on multiple scales, and that it was necessary to consider the types and proportions of the ecosystem in the landscape, as well as the spatial structures and functions of landscape units.

3.4. Module III: Pattern optimization—identifying key areas for multiscale ecological protection and restoration

Accurately identifying key ecological areas to be restored is an important measure to enhance engineering effectiveness. An ecological security pattern is composed of key elements in a region,

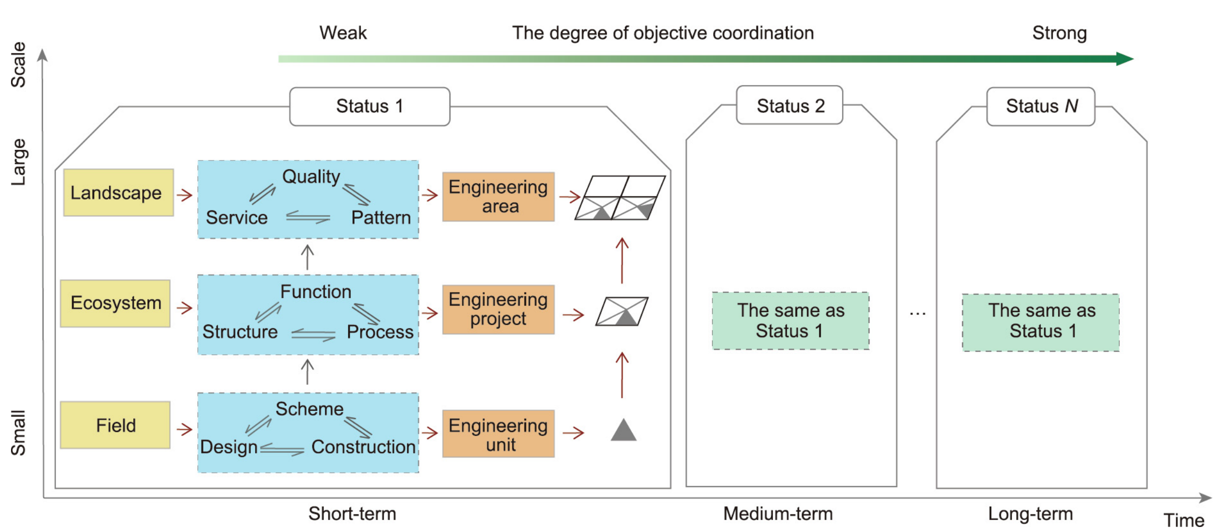

Fig. 2. Module for determining engineering objectives based on spatiotemporal evolution.

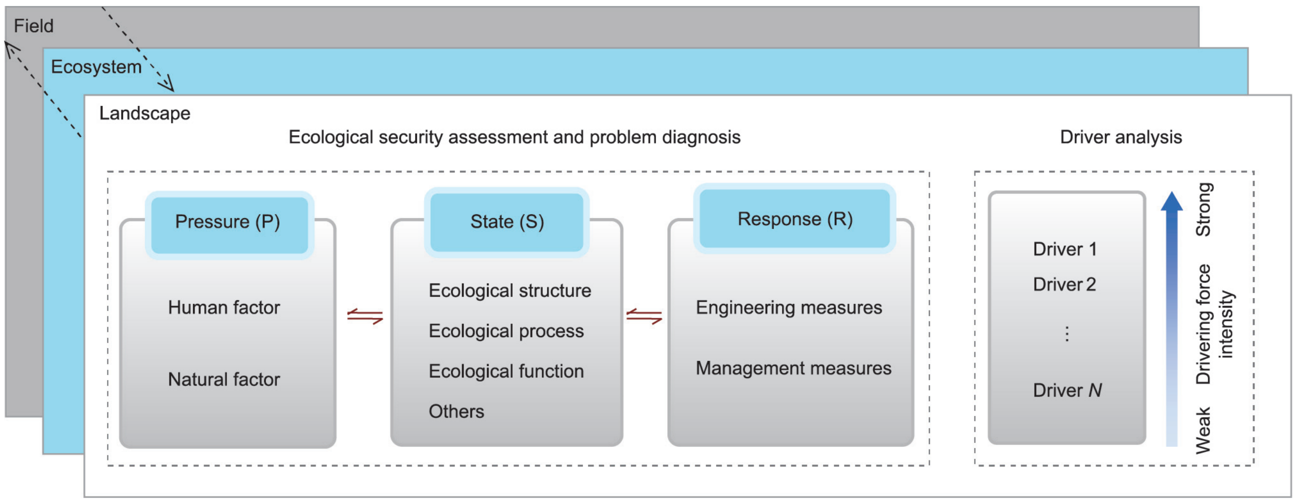

Fig. 3. PSR-based diagnosis module for ecosystem degradation mechanisms and driving forces.

such as ecological sources, ecological nodes, ecological corridors, and ecological networks [28]. As the *source*, *corridor*, and *node* must be identified to construct an ecological security pattern, this mode can provide a methodology for determining key ER areas [29]. However, it is still necessary to strengthen research on zonation theory and methods from the perspective of the coupling of natural and social factors [12]. Next, it is necessary to put forward a zonation scheme for ecological protection and restoration and to further clarify the spatial location and scope of the engineering, ecological problems and risks, main directions, and measures (Fig. 4). Moreover, pattern optimization of ecological security has spatial heterogeneity and scale dependency; that is, for problems existing on a certain scale, it is necessary to explain the genetic mechanisms on a smaller scale and to seek a comprehensive solution on a larger scale [30]. For example, Zhang et al. [31] showed that the increase of rainfall reduced the diversity of soil microorganisms in Alpine native grassland ecosystems. The main reason was that climate change and human activities on the large scale had changed the nutrients and water of the soils on the grassland ecosystem scale, which had then affected soil microbial diversity on the population scale. Therefore, ecological security patterns should be built based on coordination among multiple scales.

3.5. Module IV: Process regulation—path coupling for multiple types of ecological protection and restoration

To address human disturbances ranging from weak to strong, ecological protection and restoration paths can be classified into three types: conservation and restoration, auxiliary regeneration, and ecological reconstruction [7] (Fig. 5). For the purpose of process regulation, it is essential to systematically recognize the spatial nesting among the landscape, ecosystem, and field scales and the hierarchies among structures, functions, and service attributes. On the spatial scale, it is necessary to focus on key areas and main control factors, and to scientifically allocate measures such as conservation and restoration, auxiliary regeneration, and ecological reconstruction. In terms of the time scale, the short term features a prominent and uncoordinated relationship between humans and nature; therefore, measures of auxiliary regeneration or ecological reconstruction should be preferentially employed during ecological engineering, and conservation and restoration can be implemented in important ecological areas. In the medium term, the relationship between humans and nature will be relatively eased. Therefore, measures such as auxiliary regeneration and ecological reconstruction can be gradually reduced, and

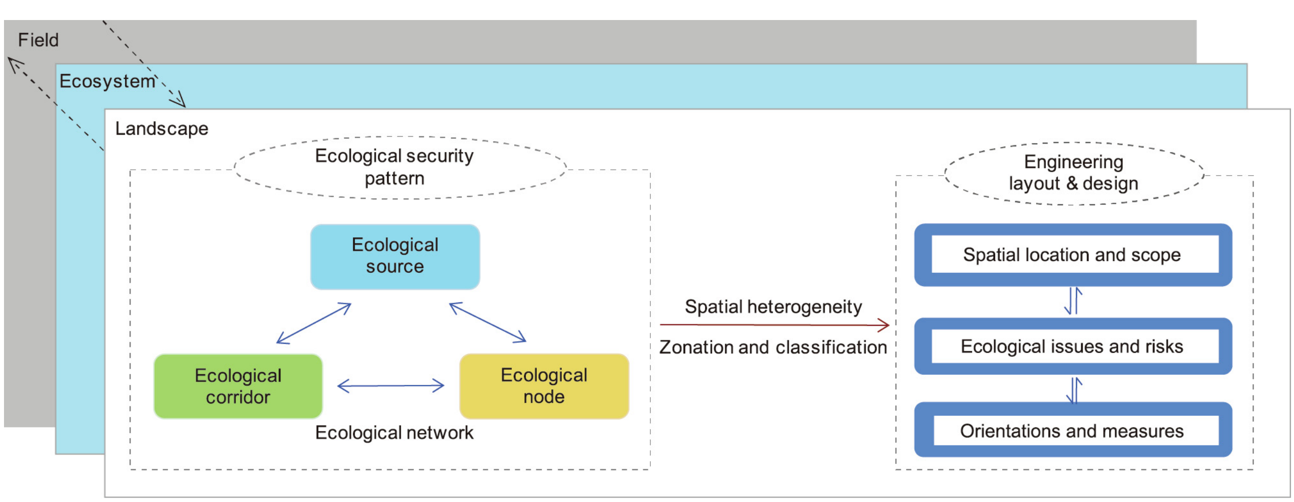

Fig. 4. Ecological engineering layout and design module based on ecological security patterns.

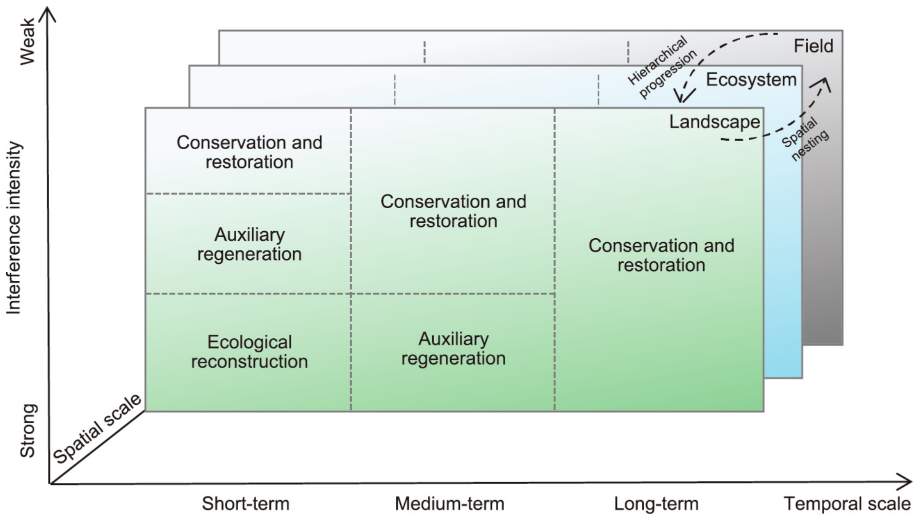

Fig. 5. Process regulation module for multiple types of ecological protection and restoration paths.

conservation and restoration will play a greater role. In the long term, the relationship between humans and nature will become harmonized, and only conservation and restoration measures will be needed.

3.6. Module V: Evaluation feedback—dynamic monitoring and measure optimization of ecological engineering effect

As ecological engineering is characterized by being long term, complex, and uncertain, it is necessary to adopt adaptive management and to regulate and control nonconforming engineering objectives and items in a timely manner through relevant measures, such as monitoring, evaluation, simulation, and optimization (Fig. 6). The effect of adaptive management also depends on the constant regulation and optimization of engineering objectives, layouts, projects, and policies. Therefore, it is necessary to carry out dynamic monitoring and optimization of engineering according to the concepts of *whole process monitoring*, *effect evaluation*, *scene simulation, and dynamic feedback*. Moreover, human society and natural ecosystems (i.e., mountains, rivers, forests, farmlands, lakes, and grasslands) together form a living community; thus, it is necessary to control human factors during the adaptive management of ecological engineering. The specific aim here is to establish a long-term sustainable system for management and protection, to eliminate the adverse impacts of human disturbances on ecosystems, and to ensure the long-term effects of the engineering. For example, Lengefeld et al. [32] suggested that the question of whether or not socioeconomic factors are considered is crucial to the success or failure of recovery practices, and that it is dangerous to ignore key social factors [33].

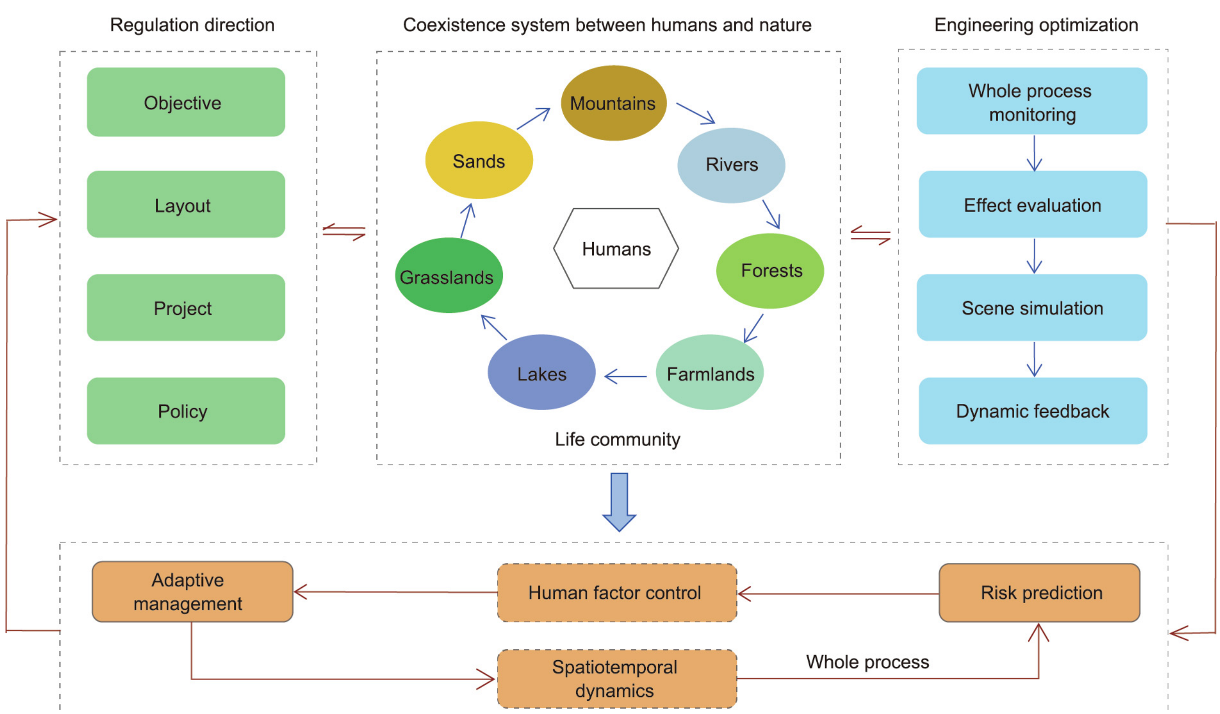

Fig. 6. The NbEE dynamic monitoring and optimal regulation module.

4. Conclusions

At present, ecological engineering is undergoing a new stage of development. The interactions and mutual influences between the natural ecosystem and human society are increasingly deepening in the context of global climate change and the ecological crisis. Moreover, the driving forces of ecological degradation are complex and originate from multiple sources. We must urgently seek a new path for ecological conservation and restoration based on the science of ecological engineering, which can reshape the symbiotic relationship between humans and nature; process the coupling of multiple elements, scales, levels, objectives; and ensure the coordinative benefits of ecosystem services. Based on the concept that *mountains, rivers, forests, farmlands, lakes, and grasslands are part of a community of life*, theoretical and practical achievements have been made in major ecological engineering projects in China, which has accelerated the formation of the NbEE paradigm. NbEE is designed and implemented based on the principles of targeted coordination, diagnostic analysis, pattern optimization, process regulation, and evaluation feedback, according to the cascading relationships of *patterns*, *processes*, *services*, and *wellbeing*. Therefore, NbEE can provide new ideas, new methods, and new paths to lift the restrictions of traditional ecological engineering. At the same time, the impacts of climate change on ecosystem services and human wellbeing are comprehensive, and the pressure from the growth of social demands on complex, multidimensional, and adaptive ecosystems is systematic. Thus, it is essential to further integrate natural and social multidisciplinary theories. It is also necessary to deeply explore the principle of the spatiotemporal variation of ecosystems and the regulation mechanisms of ecological engineering, so as to further deepen and improve the NbEE paradigm. This will push the theories and practices of ecological engineering to new heights.

Acknowledgments

We thank the two anonymous reviewers for their constructive comments on the manuscript, which were very helpful in improving the quality of the manuscript. This work was financially supported by the major consulting research project of the Chinese Academy of Engineering "Research on the ecological protection and high-quality development strategy of the Yellow River Basin" (2020-zd-18) and the Natural Resources Defense Council (NRDC) "Project to promote the mainstreaming of Nature-based Solutions into national climate policy."

References

[1] United Nations. United Nations decade on ecosystem restoration (2021–2030). In Resolution adopted by the General Assembly [Internet]. New York City: United Nations; 2019 Mar 1 [cited 2022 May 20]. Available from: https://undocs.org/A/RES/73/284.
[2] Xinhua News Agency. Guterres launches UN decade on ecosystem restoration [Internet]. Beijing: XINHUANET; 2019 Jun 5 [cited 20 May 2022]. Available from: http://www.xinhuanet.com/english/2021-06/05/c_139989761.htm.
[3] Aronson J, Alexander S. Ecosystem restoration is now a global priority: time to roll up our sleeves. Restor Ecol 2013;21(3):293–6.
[4] Bestelmeyer BT. Threshold concepts and their use in rangeland management and restoration: the good, the bad, and the insidious. Restor Ecol 2006;14(3):325–9.
[5] Shackelford N, Hobbs RJ, Burgar JM, Erickson TE, Fontaine JB, Laliberté E, et al. Primed for change: developing ecological restoration for the 21st century. Restor Ecol 2013;21(3):297–304.
[6] Mitsch WJ. When will ecologists learn engineering and engineers learn ecology? Ecol Eng 2014;65:9–14.
[7] Gann GD, Mcdonald T, Walder B, Aronson J, Nelson CR, Jonson J, et al. International principles and standards for the practice of ecological restoration. 2nd ed. Restor Ecol 2019;27(S1):1–46.
[8] IUCN Global standard for Nature-based Solutions: a user-friendly framework for the verification, design and scaling up of NbS. Global standard. Gland: International Union for Conservation of Nature and Natural Resources (IUCN); 2020.
[9] Luo M, Yu EY, Zhou Y, Ying LX, Wang J, Wu G. Distribution and technical strategies of ecological protection and restoration projects for mountains–rivers–forests–farmlands–lakes–grasslands. Acta Ecol Sin 2019;39(23):8692–701. Chinese.
[10] Gao Y, Liu Z, Li R, Shi Z. Long-term impact of China's returning farmland to forest program on rural economic development. Sustainability 2020;12(4):1492.
[11] Peng J, Li B, Dong JQ, Liu YX, Lv DN, Du RR, et al. Basic logic of territorial ecological restoration. China Land Sci 2020;34(5):18–26. Chinese.
[12] Fu BJ. Several key points in territorial ecological restoration. Bull Chin Acad Sci 2021;36(1):64–9. Chinese.
[13] Mitsch WJ. What is ecological engineering? Ecol Eng 2012;45:5–12.
[14] Martin DM. Ecological restoration should be redefined for the twenty-first century. Restor Ecol 2017;25(5):668–73.
[15] Yu GR, Zhagn L, He HL, Yang M. A process-based model and simulation system of dynamic change and spatial variation in large-scale terrestrial ecosystems. Chin J Appl Ecol 2021;32(8):2653–65. Chinese.
[16] IUCN. Guidance for using the IUCN global standard for nature-based solutions. A user-friendly framework for the verification, design and scaling up of Nature-based Solutions. Gland: International Union for Conservation of Nature and Natural Resources (IUCN); 2020.
[17] Xu S, Liu Y, Wang X, Zhang G. Scale effect on spatial patterns of ecosystem services and associations among them in semi-arid area: a case study in Ningxia Hui Autonomous Region. China Sci Total Environ 2017;598:297–306.
[18] Ge F, Ouyang ZY. Integrity, coordination, circulation, self-generation—Ma Shijun's academic thoughts and contributions. Acta Ecol Sin 2015;35(24):7926–30. Chinese.
[19] Liu J, Mooney H, Hull V, Davis SJ, Gaskell J, Hertel T, et al. Systems integration for global sustainability. Science 2015;347(6225):1258832.
[20] Cohen-Shacham E, Andrade A, Dalton J, Dudley N, Jones M, Kumar C, et al. Core principles for successfully implementing and upscaling Nature-based Solutions. Environ Sci Policy 2019;98:20–9.
[21] Mace GM. Whose conservation? Science 2014;345(6204):1558–60.
[22] Sowińska-Świerkosza B, Garcíab J. What are nature-based solutions (NBS)? Setting core ideas for concept clarification. Nature-Based Solutions 2022;2:100009.
[23] Li YJ, Wang P, Xiao RB. International experience in territorial ecological restoration and its implementation path in Guangdong Province. Acta Ecol Sin 2021;41(19):7637–47. Chinese.
[24] Hallett LM, Diver S, Eitzel MV, Olson JJ, Ramage BS, Sardinas H, et al. Do we practice what we preach? Goal setting for ecological restoration. Restor Ecol 2013;21(3):312–9.
[25] Wu J. Landscape sustainability science: ecosystem services and human well-being in changing landscapes. Landsc Ecol 2013;28(6):999–1023.
[26] Ying LX, Kong LQ, Xiao Y, Ouyang ZY. The research progress and prospect of ecological security and its assessing approaches. Acta Ecol Sin 2020;42(5):1–14. Chinese.
[27] Peng Y, Mi L, Qing FT, Feng JZ, Xue DY. Spatial scale effects of ecological factors on vegetation degradation—Helin case study. J Basic Sci Eng 2015;23(S1):11–9. Chinese.
[28] Peng J, Zhao HJ, Liu YX, Wu JS. Research progress and prospect on regional ecological security pattern construction. Geogr Res 2017;36(3):407–19. Chinese.
[29] Su C, Dong JQ, Ma ZG, Qiao N, Peng J. Identifying priority areas for ecological protection and restoration of mountains–rivers–forests–farmlands–lakes–grasslands based on ecological security patterns: a case study in Huaying Mountain, Sichuan Province. Acta Ecol Sin 2019;39(23):8948–56. Chinese.
[30] Zeng H, Chen LD, Ding SY. Landscape ecology. Beijing: Higher Education Press; 2017.
[31] Zhang Y, Dong S, Gao Q, Liu S, Zhou H, Ganjurjav H, et al. Climate change and human activities altered the diversity and composition of soil microbial community in alpine grasslands of the Qinghai–Tibetan Plateau. Sci Total Environ 2016;562:353–63.
[32] Lengefeld E, Metternicht G, Nedungadi P. Behavior change and sustainability of ecological restoration projects. Restor Ecol 2020;28(4):724–9.
[33] Cao SX, Ma H, Yuan WP, Wang X. Interaction of ecological and social factors affects vegetation recovery in China. Biol Conserv 2014;180:270–7.