REVIEW ARTICLE

From flow to network: A perspective for analyzing the complexity of forest ecosystem services

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Ecosystem services demonstrate spatially linked flow characteristics, wherein the transfer mechanisms and patterns of ecosystem services can be observed across time and space. The network of flows of ecosystem services within a forest ecosystem acts as an abstract representation of the intricate relationships within these services, playing a crucial role in understanding the complexity and multi-scale nature of forest ecosystem services. By examining the flow and network perspective, this study explored the fundamental essence, system architecture, and mechanistic framework of forest ecosystem services. The complexity of forest ecosystem service components was delved by building upon existing research on ecosystem services to explain how the constituent elements and attributes of ecosystems form the foundation of the intricacy found in forest ecosystem service components. The spatial heterogeneity of forest ecosystem services serves as a visible manifestation of this complex composition. The interconnectedness of forest ecosystem services across different scales and their link to human well-being at multiple levels were elucidated, thus revealing the intricacies of the functional structure and evolutionary complexity of ecosystem services. In addition, the composition and attribute characteristics of ecosystem service flows by conceptually characterizing the real-world transmission and flow processes of these services were summarized. The mechanisms behind the formation of ecosystem service flows were analyzed and the theoretical exploration of the transition from capacity to flow in forest ecosystem services was discussed. The network modeling techniques were utilized to construct the forest ecosystem service flow network and the network analysis tools were employed to identify its structure. This study investigated the complexity of the forest ecosystem service flow network from hierarchical, process-oriented, and multidimensional perspectives. To better understand the intricate relationships within the network, the creation of a comprehensive multidisciplinary research framework that aimed to facilitate intuitive representation and quantitative analysis of complex networks was proposed, which provided a fresh paradigm for ecosystem service research.

Keywords: forest ecosystem services; ecosystem services flow; network of services flow; complex network; capacity.

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Introduction

Forest ecosystems are highly complex systems that provide essential ecological services for human survival and development. These forest ecosystem services act as a bridge that connects various natural systems with human well-being, rooted in the structural functions and ecological processes of forests [1]. The antifeedback mechanisms operating within these functions

and processes exhibit a notable level of complexity [2], highlighting the pressing need for a novel approach in complex science research. In recent years, complex network theory has emerged as a fresh perspective for exploring complex issues. Complex networks generally refer to networks with dynamic and irregular structures that evolve over time [3]. This concept has gradually extended to different fields including biology, ecology, and geography. Complex network studies focus on unraveling intricate network mechanisms, exemplified by metabolic networks, protein interaction networks, food web networks [4], urban networks, and landscape networks. The forest ecosystem service network depicts the spatiotemporal evolutionary trajectory of forest ecosystem services, revealing new features through the integration and coordination across various scales. This network serves as an expression of the complexity inherent in ecosystem service mechanisms. While scholars have begun exploring aspects such as the valuation of forest ecosystem services, trade-offs, scale effects, and contributions to human well-being, understanding the multi-scale interactions, spatiotemporal matching of supply and demand, and the complexity of social-ecological cascades in forest ecosystem services remains a central task in comprehensive research. Complex network methodologies can assist in unraveling the intrinsic complexities of forest ecosystem service mechanisms. However, the current exploration of complex networks in the study of ecosystem services is still in its early stages, primarily focusing on descriptive attributes of network structures with limited in-depth analysis of the implications and features expressed by these networked complex systems. Hence, integrating spatiotemporal complexity in forest ecosystem service research is becoming a pivotal direction for advancing forest management and ecological development. By employing the methods and tools of complex science and networks, we can uncover the intricate mechanisms underlying forest ecosystem services, providing valuable insights for both theoretical research and practical applications in this field.

The complexity of forest ecosystem services

Complexity research has increasingly emphasized the dynamic nature of processes and the integrated study of complex interactions across multiple scales. Scale complexity is a prevalent pattern in complexity studies [4]. Forest ecosystem services, as an open system with nested hierarchies, exhibit both structural formation and dynamic development driven by key processes. Each scale and subsystem type possesses its own complex characteristics. Simultaneously, the interconnections between scales determine macroscopic behavior through a hierarchical structure [5], reflecting scale complexity. Forest ecosystem services demonstrate multi-scale trade-offs and synergies. The non-stability of trade-off relationships among forest ecosystem services primarily arises from regional heterogeneity and spatial scale [6]. Ecosystem elements on the supply side of ecosystem services are intricately related and exhibit a hierarchical structure. From a holistic perspective, lower-level components display hierarchy and dynamics through nonlinear interactions. Multi-scale trade-offs and synergies emerge as macroscopic behaviors. Nonlinear trade-offs in forest ecosystem services exhibit multiple couplings between structure and process [7], characterized by specific scales and multi-scale associations [8]. As scale increases, the strength of synergistic or trade-off interactions between ecosystem services may change with synergistic relationships dominating at larger spatial scales [9], and trade-off relationships becoming more prominent at medium to small scales [10]. Forest ecosystem services are linked to multi-tier human well-being. Human well-being is characterized by multiple complex indicators including life satisfaction, health, achievements, interpersonal relationships, and security [11]. The extent of human well-being largely depends on the distribution and satisfaction level of consumption

provided by the supply side, leading to intricate relationships between ecosystem services and human well-being. Macroscopic scales emphasize the diversity of regional social development and natural endowments [12]. Simultaneously, forest ecosystem services are influenced by the preferences of different stakeholders, demonstrating scale complexity. Rapid socio-economic development results in multi-tiered demands for human well-being, reflecting the complexity of forest ecosystem services [13]. The evolutionary complexity of forest ecosystem services is driven by inherent complex mechanisms, resulting in spatial forms of structural and functional succession within corresponding periods or global processes [14]. Forest ecosystem services undergo continuous processes of evolution, characterized by complexity. From the perspective of natural mechanisms on the supply side of forest ecosystem services, ecosystems are nonlinear dynamical systems. Forest ecosystems, composed of various factors, are dissipative dynamic systems, and their sustainability involves nonlinear changes that contribute to the complexity of the evolution of ecosystem services [15]. Evolutionary outcomes possess a certain degree of uncertainty while also carrying causal relationships, showcasing complex features in evolutionary behavior. This is manifested through a trade-off and synergistic relationship of ebb and flow [16], capturing the complexity of the natural mechanisms of forest ecosystem services. Examining the cascading relationships of forest ecosystem services, the social system and the ecological system are intricately coupled in evolutionary processes. The socio-ecological system represents a complex system tightly interlinked between humans and nature [17], comprising various subsystems such as economics, society, and ecology [18]. Ecosystem services reflect the interactive relationship between economic and social development [19], simultaneously representing the natural mechanisms of service supply and the social mechanisms of demand. In the progressive cascade process where ecosystem services act as connecting nodes, natural geographic elements and socio-economic factors serve as the driving forces of evolution [20]. The socio-ecological system is an adaptive integrative entity, where forest ecosystem services exhibit intricate feedback relationships among society, economy, and the natural system. These reflect the real causal pathways and mechanisms from the ecosystem to human well-being realization. Through adaptive learning and interactive feedback with the external environment, the system reshapes its organizational structure, achieving self-organizing evolution and emergent wholes [21].

Forest ecosystem service flow: Complexity description of the evolution from capacity to flux

1. Bottleneck issues and breakthroughs from the capacity perspective

Extensive research on ecosystem services has been conducted by numerous scholars, employing various methods including monetary valuation based on value quantity and non-monetary assessment based on material quantity [22-24]. Currently, assessment methods for ecosystem service material quantity can be categorized into two types including energy-based methods and model-based methods. Value quantity methods, on the other hand, include the equivalent factor method and functional value method. Existing research primarily focuses on the state of specific ecosystem services at a particular point in time, describing service supply, demand, and the supply-demand mismatch from a capacity perspective [25]. However, due to the complexity of ecosystem structure, function, and evolution, ecosystem services exhibit spatial and temporal variations [26]. They are interconnected with both natural ecology and human society, involving complex processes of transmission and spatial matching from supply to beneficiaries. Analyzing forest ecosystem service characteristics solely from a static capacity perspective without considering the processes of transfer, transformation, transmission, or the

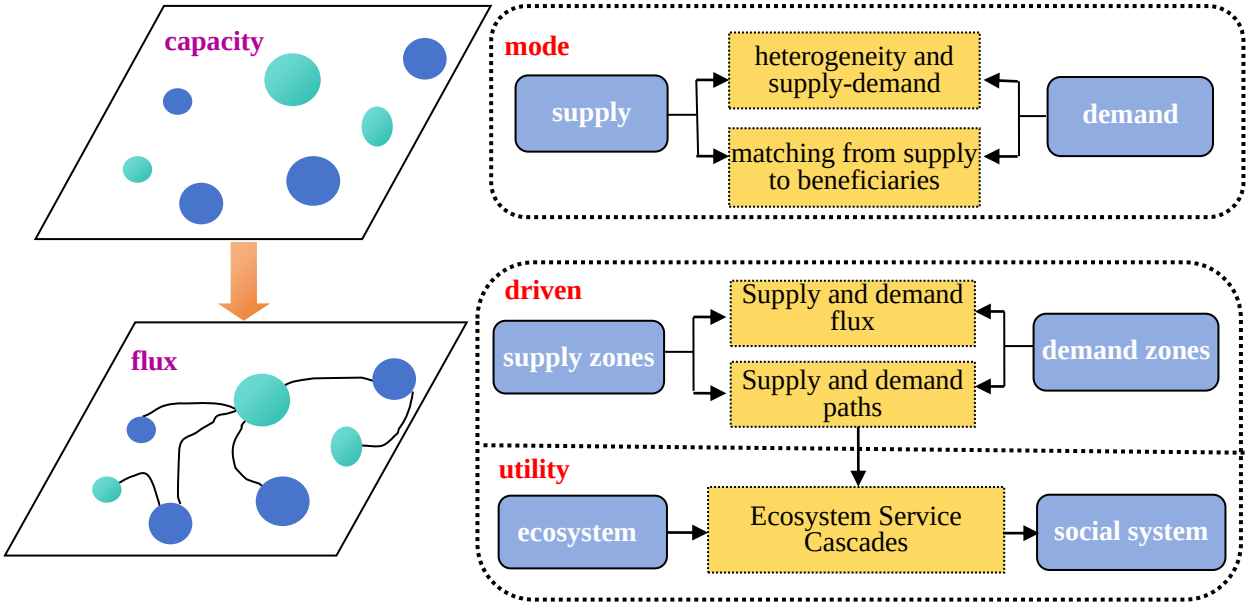

Figure 1. Diagrammatic representation of the framework of forest ecosystem services from capacity to flow.

factors across multiple temporal and spatial scales lacks the classification and recognition of dynamic features and transmission processes of ecosystem services. This approach fails to adequately describe the crucial impacts on forest ecosystem service usage, determine the actual consumption of forest ecosystem services, or address the spatial mismatch between ecosystem service supply and demand [27]. Therefore, integrating ecosystem structure with ecological processes to explain ecosystem services by incorporating the dynamics of ecological processes becomes essential. This approach encompasses the dynamic source and flow of ecological processes, transitioning from a capacity perspective to a flux perspective in the study of forest ecosystem services. It analyzes the coupling between society and the ecosystem, revealing attribute variations and spatial patterns of different types of ecosystem service transmission. This progression enhances the "process-oriented" and "holistic" aspects of ecosystem services, moving beyond the "state-flow-utility" framework of ecosystem service flux (Figure 1).

2. Complex Description of Forest Ecosystem Service Flux

(1) Complex representation of forest ecosystem service flux

In open complex systems, the interaction between the system and the environment is characterized by the flow of material and non-material entities across different regions [28]. The concept of "flow" captures the understanding of processes, combining space and time to express spatial interactions [29]. This approach enables the study of spatiotemporal processes and often reveals mechanisms through the characteristics of "flow." The forest ecosystem service flux exhibits distinct temporal and spatial attributes that reflect changes in the quality of forest ecosystem services. Describing the forest ecosystem service flux involves capturing the nonlinear interactions between ecosystem services and the environment, highlighting the complexity of the mechanisms and spatial associations underlying the generation of ecosystem services [30]. Due to the spatial separation between supply and demand regions for ecosystem services, there is a quantity imbalance and spatial mismatch [31], resulting in the flow of ecosystem services within

space. The forest ecosystem service flux follows defined pathways, exhibiting changes in the direction, scale, and intensity of the flow [32]. It encompasses the transfer characteristics from the source to the destination, emphasizing the transmission of services [33, 34]. This reflects mechanisms such as aggregation and diffusion, correlation, and differentiation, providing a comprehensive description of the entire process of ecosystem service generation, maintenance, transmission, and utilization [35]. The formation of the ecosystem service flux exhibits clear heterogeneity in terms of content, types, carriers, features, patterns, preferences, and influencing factors, making it increasingly complex across different spatial scales. The forest ecosystem service flux is interconnected with the social-ecological system, highlighting the coordination between natural and social mechanisms, and revealing the complexity of ecosystem service evolution. Through the three fundamental stages of service supply, flow, and demand, the forest ecosystem service flux establishes spatiotemporal connections and effectively couples the supply and demand of ecosystem services with spatial heterogeneity characteristics [36]. It serves as an intuitive spatial medium for the interaction between ecosystem services and human well-being, forming a coupling chain from the natural environmental system to the human social system. It depicts the complete process from the generation and transmission of ecosystem services to their utilization. Driven by the ecosystem service flux, the spatiotemporal transfer from the ecosystem to the social system is achieved, ultimately supporting the consumption and enjoyment within the social system. Decisions based on flux value contribute to human well-being [37], and the concept of "flow" enables the reintegration and coordination of dynamics, resulting in the emergence of new features in structure and functionality [38].

(2) Attributes and characteristics of the forest ecosystem service flux

The ecosystem service flow is a spatial process that involves the dynamic transfer of services from supply regions to beneficiary regions. Its attribute features can be classified into four aspects including flow direction, flow velocity, flow volume, and carrier [39]. Ecosystem service flows are typically categorized based on factors such as the spatial locations of service supply and beneficiaries, mobility of supply-demand entities, and driving forces. Various classification methods exist including those based on spatial flow mechanisms [40], supply-demand locations, and reachable range of spatial service flow. Ecosystem service flow volume refers to the actual quantity of services transferred during the supply-demand exchange process [41]. It is primarily determined by the spatial positions of human activities, disturbance range, and intensity. This measure reflects the temporal-spatial transiency and dynamics of service flows, helping to discern situations where the flows are disrupted, damaged, or blocked. Ecosystem service flow velocity represents the speed at which services are transferred between supply and demand regions, reflecting the efficiency of human access to services. By considering temporal and spatial scales, a comprehensive understanding of the temporal-spatial dynamics of ecosystem service flows can be gained. Factors such as geographical elements and landscape types affect flow velocity. Ecosystem services require certain carriers to enable their spatial transmission. Carriers are the material foundation for the spatial movement of ecosystem service flows and can include physical carriers such as natural environmental elements and biological components, as well as non-material carriers in the form of virtual carriers. Some carriers solely serve as tools for transmitting ecosystem service flows, while others function as both transmission tools and services themselves.

Forest ecosystem service flow network: The complexity implications from flow to network mapping

1. Analyzing the complexity of forest ecosystem service flow networks

The complexity observed in real-world systems can be effectively described using complex networks. Ecological system service flows, which constitute the fundamental elements of flowing spaces and networks, form intricate and hierarchical complex systems across various temporal and spatial scales. Complex network models serve as abstract representations and structural forms to capture the mechanisms and evolutions within flowing spaces. The application of complex network theory has great potential in unraveling the intricacies and non-linear aspects of ecological system service flows, emerging as a novel trend in studying complex relationships within ecological systems. Ecological system service flow networks embody characteristics of cross-scale interactions that heavily rely on temporal and spatial variations. These flows exhibit distinct hierarchical differences and multi-scale features. The spatial heterogeneity creates gradient potentials for ecological system service flows, while non-linear driving forces facilitate their formation. Through multi-scale interactions and successive connections, intricate and complex network structures emerge, spatially portraying the multi-dimensional, multi-structural, multi-layered, and multi-elemental interconnections within forest ecosystem services. Ecological system service flow networks express emergent macroscopic behaviors of ecosystem service flows, determining the structure, functionality, and evolutionary patterns of these services. By representing the structure of forest ecosystem systems through spatially heterogeneous nodes, with humans positioned at the ultimate nodes of the network, the spatial flow and interrelations of forest ecosystem services are intricately woven together. This approach unveils the intricate coupling between forest ecosystem services and human beings, showcasing the dynamics of structural changes and emergent functionalities in forest ecosystem services, while explicating the concepts of holistic understanding and collective effects. The service flow network represents an abstract framework of the structure and functionality of forest ecosystem services. It quantitatively expresses and visually presents complex relationships, serving as a mapping of the flow processes of ecosystem services. This approach offers a novel means of describing ecosystem services. The service flow network presents the complexity of structure and functionality, unveiling various macroscopic phenomena and self-organizing mechanisms of forest ecosystem services. It integrates both structure and process, revealing the interdependence among ecosystem service components. It reflects the origin and destination of certain processes or "flows", highlighting the nonlinear coupling effects between forest ecosystem services. From a functional perspective, the service flow network incorporates both biophysical and socio-economic indicators from the supply and demand sides of ecosystem services. Through ecosystem service supply, demand, and flow, it vividly depicts the dynamic delivery of functional and ecological flows from supply zones to demand zones, enhancing the deep functional connection between the internal and external environment within the network representation. In terms of a comprehensive dimension of structure and function, the service flow network combines structural and functional networks, forming a hierarchical structure and functional network morphology of the ecosystem. This overcomes the limitations of structural measurements and conveys the complexity of spatiotemporal flow behaviors. The service flow network encompasses the interaction relationships of forest ecosystem services, and the abstraction of these interactions is key to the complexity of network structure. Complexity is intrinsic to networks, often characterized by strong interactive relationships. From the perspective of ecosystem service supply, each component forms an organic whole, and interactions exhibit significant nonlinear features, manifesting as nodes or links within the network. Ecosystem service flows, connecting nodes and their associations within the network, jointly characterize the spatial flow processes of ecosystem services. Within the framework of

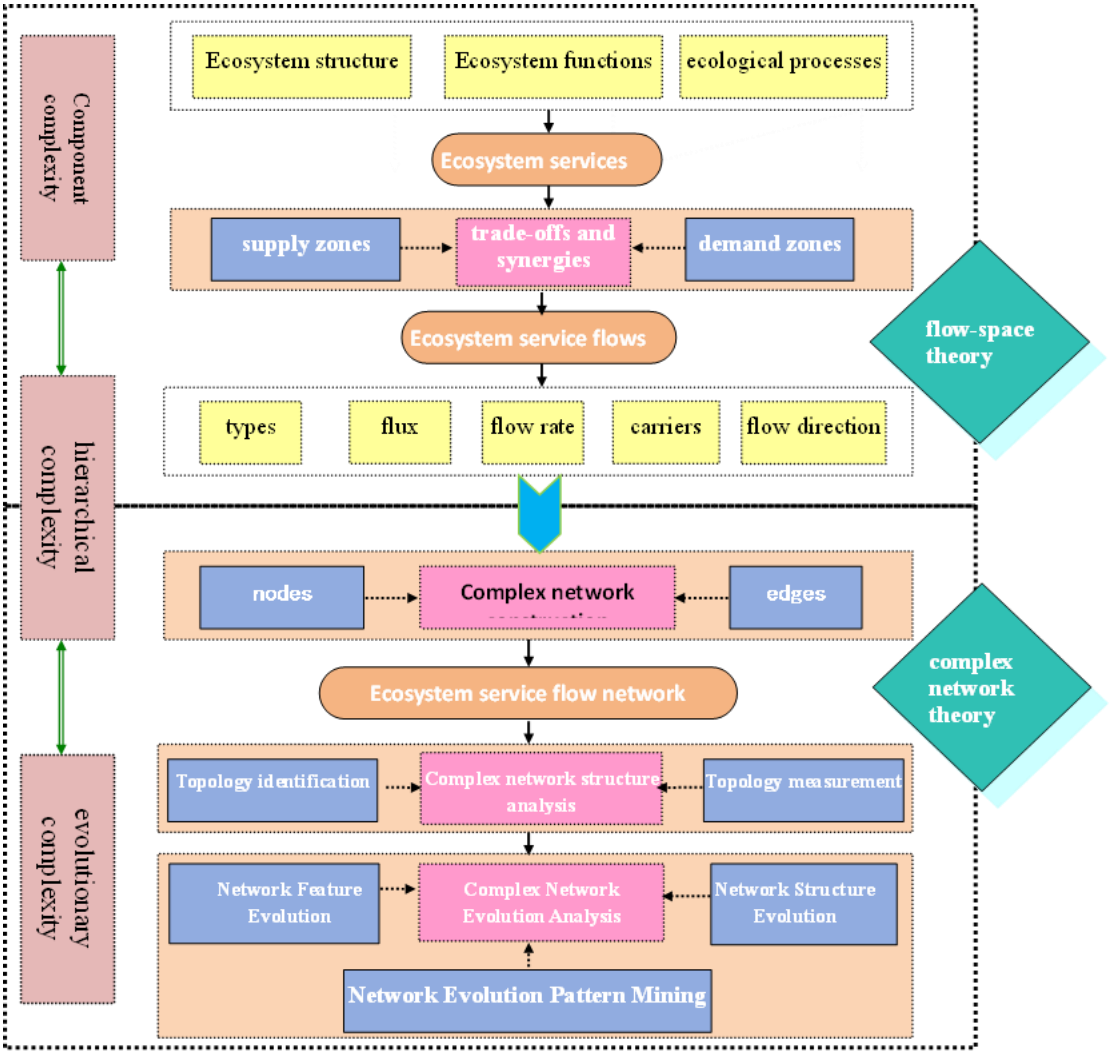

Figure 2. A framework for complexity analysis of forest ecosystem service flow networks.

network relationships, specific node-to-node and inter-node association patterns form complex interaction relationships. These interactions give rise to dynamic and complex networks of large scale and high complexity, heavily influenced by external factors. They provide a visual and effective structural model for depicting and studying the interactions between individuals within a population.

2. Analytical framework for understanding the complexity of complex networks in forest ecosystem service flow

To understand the complexity of forest ecosystem service flow networks, an analytical framework can be established, focusing on three dimensions of component complexity, hierarchical complexity, and evolutionary complexity. This framework utilizes network modeling techniques to construct and identify the structure of the ecosystem service flow network and employs complex network analysis as a tool for investigating network evolution. By delving into these dimensions, the framework aims to elucidate the inherent complexity in forest ecosystem service flow networks (Figure 2). Forest ecosystem service flows establish connections through the movement of matter and energy, leading to the reintegration and emergence of new characteristics in ecosystem

services. This approach examines the attributes and processes of forest ecosystem service flows, considering spatial heterogeneity and supply-demand mismatch, starting from the structure, function, and ecological processes of forest ecosystems. By elucidating the underlying mechanisms embedded in forest ecosystem service flows, it forms the basis for data-driven quantitative analysis and network construction, facilitating further exploration and explanation of the complex mechanisms involved. The construction of the forest ecosystem service flow network involves extracting the supply and demand regions of the forest ecosystem services as nodes and the service flows within the supply-demand associations as edges. This process aims to establish connections between spatial nodes, quantitatively describing the inherent relationships among supply and demand areas. The complex topological features of the forest ecosystem service flow network are calculated and examined through the analysis of characteristics such as scale-free properties, small-world properties, centrality, vulnerability, and spatial centrality. This analysis helps identify and extract network structures that consider spatial effects, such as communities, motifs, and subgraphs. Additionally, principles from the theory of complex network analysis are utilized to analyze the basic static characteristics, correlation indices, and connectivity indices of the network. Based on the structure of the forest ecosystem service flow network, a deep exploration of the network's dynamic processes can be achieved through the analysis of its topological properties. Examining the network from the perspectives of network features, network structure, and network patterns reveals the dynamic evolution patterns of the network's structure. This approach enables the effective prediction and control of the emergence and maintenance mechanisms of collective behaviors on complex networks. The evolution of network features encompasses node features, edge features, and overall network characteristics. Node feature evolution investigates how the attributes and characteristics of nodes change over time, while edge feature evolution focuses on how the strength and direction of service flows change over time. The evolution of overall network features examines whether the degree distribution, clustering coefficient, and other network-wide properties change. Network structure evolution encompasses changes in community structure, motif structure, and spatial structure. Evolution in community structure studies how groups within the network reconfigure and reassemble, motif structure evolution observes changes in specific subgraphs, and spatial structure evolution examines whether the connectivity between different spatial regions changes. Network pattern evolution involves abnormal evolution patterns, process evolution patterns, and interaction evolution patterns. Abnormal evolution patterns investigate how abnormal events in the network trigger changes in structure and behavior. Process evolution patterns focus on how dynamic processes within the network evolve over time, while interaction evolution patterns reveal how interactions between different nodes change over time. Through the analysis of these aspects, a more comprehensive understanding of the dynamic evolution characteristics of the forest ecosystem service flow network can be attained, providing essential theoretical and practical guidance for predicting and controlling network behavior in the future (Figure 2).

Exploring the path of complexity thinking paradigm in forest ecosystem service flow networks

1. Hierarchical thinking: Expanding the dimensions and scales of service flow research to enhance the applicability and acceptance of networks

The study of service flows often faces challenges in capturing both the internal differences within ecological systems and their holistic features. Macroscopic approaches tend to overlook internal variations, while mesoscopic approaches struggle to capture the complete picture. Existing

research often neglects the bottom-up holistic nature of ecological systems and the top-down interrelationships, which leads to an incomplete understanding of the intricate relationships among different types of ecological system service structures and functions. Investigating the scale-dependency of ecosystem services helps in comprehending the complexity of ecological issues. The forest ecosystem service flow network represents multi-scale correlations, aligning with the connectivity of the entire forest ecosystem service. By evaluating the multi-scale coupling criteria of forest ecosystem services, this approach provides a detailed depiction and analysis of the intricate mechanisms intrinsic to forest ecosystem services. However, research on ecosystem service flow networks often remains conceptual, and there is a need to enhance the applicability and acceptance of the network structure framework to elucidate the scales, mechanisms, and system embedded within the service flow network.

2. Process-oriented thinking: Identifying network co-evolution patterns to scientifically uncover the dynamic mechanisms of ecosystem service flows

Understanding the dynamic processes within the forest ecosystem service flow network is crucial for studying ecosystem services. It is essential to focus not only on characterizing the interactions between nodes but also on capturing the dynamic processes of these interactions. This approach allows for the reintegration and synergy of spatial flow processes, leading to the emergence of novel features. The service flow, facilitated by the connections between nodes, shapes a network of spatial carriers, reconstructing the dynamic progression of ecosystem service complexity. To achieve this, research into the forest ecosystem service flow network should involve depicting static network structures across various temporal and spatial contexts. Additionally, mathematically or physically sound network dynamic models should be established to unveil the temporal and spatial dynamic processes and their potential causes. This enables the revelation of dynamic feedback mechanisms inherent in forest ecosystem service provisioning. Utilizing the forest ecosystem service flow network for quantitative analysis and simulation of ecosystem service flows will contribute to a more accurate understanding of the evolution of ecosystem service processes. This approach represents a cutting-edge and focal direction for future research in this field.

3. Multidimensional thinking: Integrating ecosystem service cascades, systematically constructing a cross-disciplinary framework for future research

The interaction between ecosystem services and human well-being is becoming increasingly intertwined, with human societies relying more on ecosystem services. Forest ecosystem service flows establish a link between ecological and social systems, serving human societies sustainably by connecting natural ecosystems and socio-economic systems. To make scientifically informed decisions about ecosystem services, there is a need to expand the theoretical foundation of coupled natural and socio-economic systems and adopt a more interdisciplinary approach. Building upon the framework of ecosystem service cascades, interdisciplinary integration and collaboration among relevant fields are crucial. Exploring the cascading impacts of ecosystem services on multi-level human well-being and constructing an interdisciplinary research framework for forest ecosystem services can enhance the accuracy of forest ecosystem process models and reveal the mechanisms of ecological-social coupling. In practical application, challenges lie in spatially extracting ecosystem services when constructing forest ecosystem service flow networks, abstracting and dynamically characterizing these flows in network simulations, and further integrating the nonlinear interactions of various factors within the forest ecosystem service flow. Determining how network structure affects ecosystem service functionality requires linking network structure with forest ecosystem functionality. The framework of network research offers a new avenue for studying the complexity of ecosystem

components and quantifying the dynamic nature of ecosystem processes. While complex network research is still in its exploratory phase, its application prospects are promising in unraveling the significance of forest ecosystem service flow network models in forestry and ecology.

Conclusion

The forest ecosystem service flow network serves as a testament to the complexity of ecological interactions, intricately mapping the interplay between fluidity and network structure. Complex network theory holds tremendous potential in uncovering the associative mechanisms between components and dynamics within the forest ecosystem service flow. Forest ecosystem services emerge from diverse components and multilayered processes, showcasing the complexity of component diversity and scale. These services are intricately intertwined with the socio-ecological system, embodying the interplay of both natural and societal mechanisms. The evolving relationship between ecosystem structure and function contributes to the complexity of the ecosystem service evolution process. Unraveling the intricate mechanisms behind forest ecosystem services is a pivotal task within the field of ecosystem service research. The forest ecosystem service flow adeptly intertwines ecosystem structure and ecological processes, elucidating the essence of ecosystem services. This amalgamation results in a description that harmoniously merges structural and procedural aspects. Simultaneously, the forest ecosystem service flow interconnects humanity, nature, and relevant interest groups, encapsulating the dynamic shifts in sources and directions of ecological processes. In quantifying attributes of ecosystem service flow, flow rate and direction take center stage. From a perspective of spatial movement, the concept of ecosystem service flow centrally revolves around the dynamic spatial movement of ecosystem services, encompassing a cross-scale, cross-regional nature. The extent of this scale may vary according to different types of ecosystem services. The forest ecosystem service flow network embodies interaction characteristics and cross-scale expressions, forming an abstract framework for understanding the structure, function, and interaction of forest ecosystem services. This mapping of relationships within the forest ecosystem service flow into a complex network transcends the confines of structural measurement, offering a lucid depiction of the topological structure and evolutionary mechanisms of forest ecosystem services. This transformation is poised to become a new paradigm for analyzing the mechanisms of forest ecosystem service through a network approach.

The forest ecosystem service flow network transcends geographical continuity, comprehensively considering the intricate characteristics of forest ecosystem service complexity. It establishes a multidimensional, holistic, and multi-agent mindset, fostering further exploration of the complex mechanisms underlying forest ecosystem services. This aligns with the call for novel concepts, perspectives, and strategies within the realm of ecosystem service flows.

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