REVIEW ARTICLE

Ecosystem service flow networks: A new perspective for analyzing urban-rural coupling mechanisms

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Received: June 20, 2026. **Accepted:** October 1, 2026. **Published:** November 16, 2026.

Urbanization and rural revitalization are reshaping the traditional urban-rural system into an integrated territorial system. This transition has made urban-rural development more complex and less predictable. This research investigated whether ecosystem services constituted a core element of urban-rural coupling. The results showed that an ecosystem service flow network used providing, connecting, and benefiting areas as its basic spatial units, described service flows through volume, velocity, direction, and carrier, and represented these relationships through nodes, edges, and weights. This framework could explain the spatial relation between ecosystem service supply and demand, identify multiscale trade-offs in service flows, and reveal mechanisms of coordinated urban-rural development through the movement of ecosystem services along urban-rural gradients. This perspective extended process-based ecological explanations of urban-rural coupling and provided a theoretical framework for optimizing ecosystem service functions, balancing supply and demand, and building new urban-rural relationships.

Keywords: ecosystem service flow network; urban-rural coupling; ecosystem services; supply-demand matching; complex networks.

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Introduction

During urbanization, the traditional dual urban-rural system has developed into a more integrated urban-rural territorial system [1]. Urban-rural development now faces greater complexity and uncertainty. Reshaping urban-rural relationships requires countries and regions to draw on the distinct resource advantages of cities and villages, establish functional complementarity [2], and develop coupling relationships across multiple dimensions and systems [3]. Urban-rural coupling integrates urban development with rural revitalization. It is also an important pathway for human-nature coexistence and for coordinated regional socioeconomic and ecological development [4]. Ecosystem services connect urban-rural natural ecosystems with socioeconomic systems [5], and they have become a central concern in studies of urban-rural coupling and coordinated development. Traditional views of urban-rural relationships have often overlooked the importance of rural ecosystem services for cities, which has contributed to degradation of rural ecological environments and changes in ecosystem service conditions. Meanwhile, the gap between growing urban demand for ecological services and declining rural ecological service supply has become increasingly evident

[6]. It is therefore necessary to examine how urbanization and rural revitalization affect ecosystem services by studying ecosystem services across urban-rural space to improve the matching of ecosystem service supply and demand [7]. This problem is closely related to maintaining the ecological development potential of urban and rural areas, promoting the two-way flow and optimized allocation of ecological resources, and achieving coordinated urban-rural development [8]. Research on ecosystem service flow networks facilitates the construction of a theoretical framework for balancing supply and demand in urban-rural spaces, the diagnosis of impaired ecosystem service structures and functions, the identification of spatiotemporal supply-demand characteristics, and the provision of support for timely adjustments in regional development management. It can also clarify management pathways for ecosystem services in the urban-rural coupling process and explains mechanisms for high-quality integrated development.

From ecosystem service capacity to ecosystem service flow networks

Static limits in ecosystem service supply-demand research

Existing ecosystem service studies usually examine service supply and service demand separately. Methods for assessing supply are relatively mature, whereas demand assessment remains difficult because it depends on high-resolution data, complete indicator systems, and context-specific methods. Current studies still focus mainly on semi-quantitative or quantitative assessments of regulating, provisioning, cultural, and supporting services. Many case studies also evaluate supply-demand relationships within a single region or for a single service type. These studies reveal the quantity of ecosystem services, but they do not fully explain how services are transmitted, transformed, lost, and realized in urban-rural space. From a capacity perspective, ecosystem services are often described as service supply, demand, and mismatches at a specific time. In line with the theoretical shift from capacity to flow, ecosystem services should not be understood merely as static stocks or potential capacities, rather, they should be viewed as processes of delivery, utilization, and consumption within specific social-ecological systems [9]. It will be difficult to assess actual ecosystem service consumption or to explain spatial mismatches between supply and demand and their effects on urban-rural development if transfer, conversion, transmission, and maintenance processes are ignored.

Ecosystem service flow as an intermediate link in supply-demand coupling

Ecosystem service flow emphasizes the dynamic spatial transfer of ecosystem services from providing areas to benefiting areas. It is the intermediate link between supply and demand. Service supply forms the source, service demand forms the endpoint, and the two are usually spatially separated [10]. Through the three basic links of supply, flow, and demand, providing areas and benefiting areas form spatiotemporal connections. These connections appear as spatial displacement between the place where a service is supplied and the place where it is used. The formation, classification, transmission attributes, and source-to-sink characteristics of ecosystem service flows have been widely discussed. Based on the spatial locations of providing and benefiting areas, researchers can determine whether service supply and demand overlap, and can distinguish *in situ* service flows, directional service flows, and omnidirectional service flows [11, 12]. In quantitative terms, service flows usually include volume, velocity, direction, and carrier [13]. Volume refers to the amount of service transmitted from a providing area to a benefiting area. Velocity reflects the relationship between distance and time during transmission from providing area to user area. Direction indicates the spatial movement of a service along its carrier and pathway. The carrier is the material or nonmaterial medium through which the service is transmitted.

From service flow to service flow network

Service flows do not exist in isolation. The supply, connecting, and demand spaces of different ecosystem services interweave along urban-rural gradients, forming spatial relationships with multiple nodes, pathways, and levels. By linking nodes, service flows form spatial networks of carriers. These networks express the complexity and synergy of ecosystem service supply and demand. Complex network theory abstracts dynamic, irregular, and spatio-temporally evolving systems into nodes, edges, and weighted relationships, which provides a structured expression for ecosystem service flow research [14, 15]. An ecosystem service flow network reorganizes and coordinates flow between service supply and demand, producing new structural and functional characteristics. Its purpose is not simply to describe the flow path of a single service. Rather, it integrates supply, connection, demand, carriers, volume, velocity, direction, and urban-rural socio-economic responses within a single network framework, which makes it possible to analyze spatial associations, hierarchical structures, trade-offs and synergies, and evolutionary mechanisms of ecosystem services.

Conceptual connotation and structural expression of ecosystem service flow networks

Basic spatial units: providing areas, connecting areas, and benefiting areas

An ecosystem service flow network is based on spatial units of ecosystem service supply and demand. Terrain, vegetation, soil, land use, and other factors shape the heterogeneity of ecosystem service supply and demand. Based on mismatches among supply space, demand space, and consumption space and their spatial relationships, basic units can be divided into providing areas, connecting areas, and benefiting areas. Providing areas generate products or services. Connecting areas transmit ecosystem service flows. Benefiting areas use or consume ecosystem services [16]. In urban-rural space, providing areas are often associated with rural areas, ecological conservation zones, lakes and wetlands, forests, and farmland. Benefiting areas are closely associated with urban cores, urban expansion areas, and spaces where population and industries are concentrated. Connecting areas mediate service transmission, attenuation, obstruction, or enhancement. Dividing the space into supply, connecting, and beneficiary areas provides a clear spatial framework and process boundaries for the supply-demand relationship of urban-rural ecosystem services.

Service flow attributes: volume, velocity, direction, and carrier

The attributes of ecosystem service flows can be summarized as volume, velocity, direction, and carrier. Volume represents the amount of service transmitted from a providing area to a benefiting area. It can be used to identify damaged, impaired, or interrupted service flows. When supply equals or exceeds demand, service flow can be calculated according to demand. When supply is lower than demand, service flow is quantified according to the available supply. Velocity can be represented by the ratio of transmission distance and transmission time between the providing and user areas [21, 22]. It helps identify changes in flow volume with spatial distance during service transmission. Direction is related to the carrier. Water provision services can be simulated using downhill and downstream runoff paths based on digital elevation model (DEM) and river-network data. Soil conservation service flow paths can be determined mainly from DEM and river networks. Carbon sequestration service flow paths can be inferred from wind fields and atmospheric movement. Carriers include water flow, air, species migration, soil, and information flows. They may serve only as transmission media, or they may also be part of the service itself.

Network expression: nodes, edges, weights, and hierarchy

In an ecosystem service flow network, spatial supply-demand units can be abstracted as nodes, transmission paths of service flows as edges, and attributes such as volume, velocity, and direction as edge weights [14, 23]. Nodes include not only

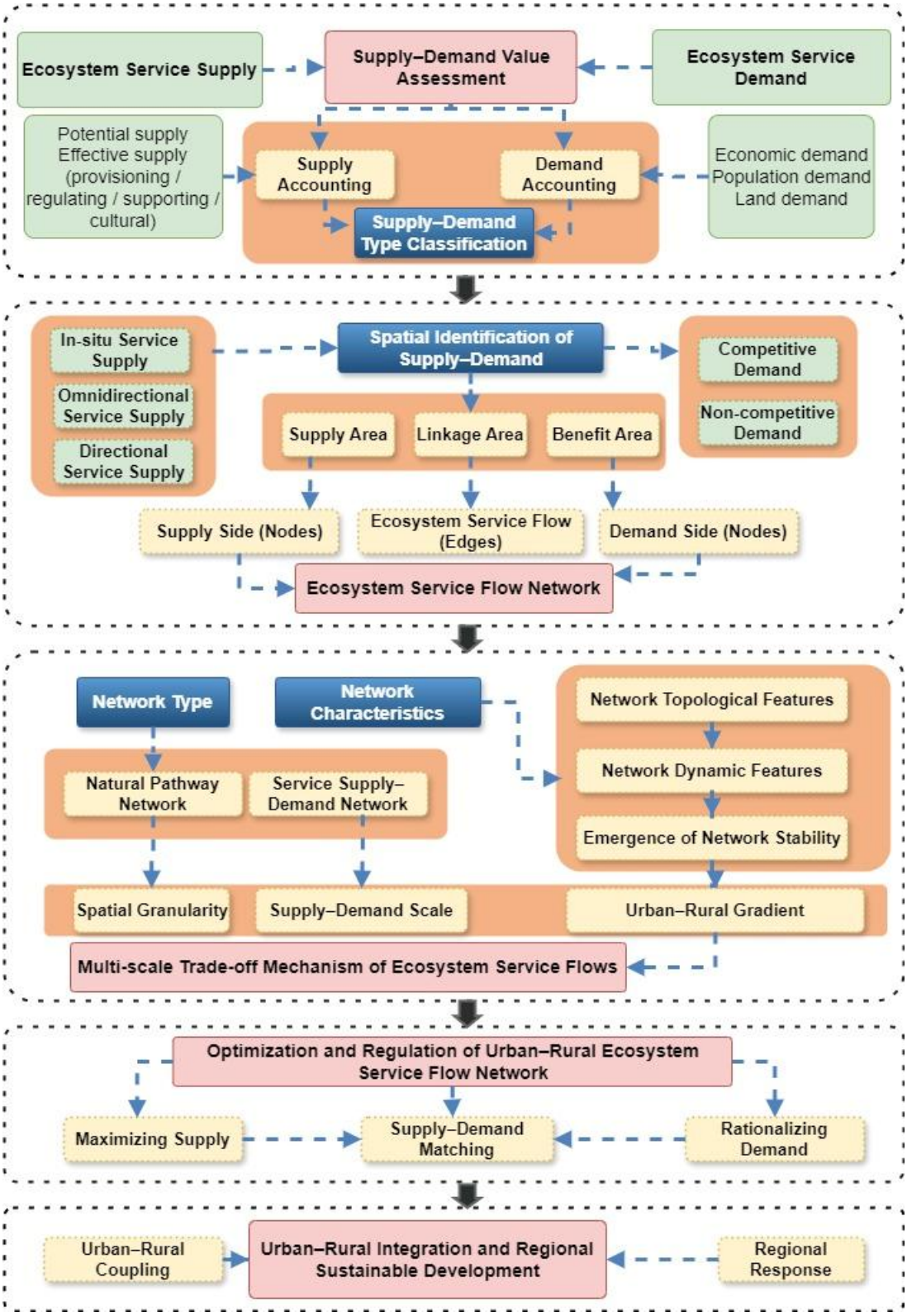


Figure 1. Analytical framework of urban–rural coupling mechanisms from an ecosystem service flow network perspective.

service-providing and service-demand areas but also connecting areas that mediate service transmission. Edges represent actual or potential connections through which ecosystem services move from sources to sinks in urban-rural space. The relationships among supply, flow, and demand can therefore be represented as a weighted network with spatial units as nodes, ecosystem service flows as edges, and service flow attributes as edge weights. From macro to micro levels, ecosystem service flow networks can be organized hierarchically into networks, modules, and units. A module can represent the local network of basic spatial units, or it can serve as a node in a higher-scale analysis. Complex network indicators including average path length, betweenness, connection probability, clustering coefficient, degree, and degree distribution can be used to identify network type, connection capacity, coupling mode, modularity, and other topological features [15, 23]. Based on the above conceptualization, ecosystem service flow networks can be understood as a sequential analytical framework that links supply–demand assessment, spatial identification, network construction, multiscale trade-off analysis, and network regulation. This framework further explains how ecosystem service flows mediate urban–rural coupling and support regional sustainable development (Figure 1).

Urban-rural coupling mechanisms from the perspective of ecosystem service flow networks

Supply-demand matching mechanism: from spatial mismatch to network connection

Cities and villages together form the primary spaces of human activity. The spatial evolution and expansion of flows and networks in ecosystem service supply and demand directly affect urban-rural spatial development. Meanwhile, urban-rural coupling patterns also affect the relationship between ecosystem services and human well-being [17]. Cities usually have limited natural resources but high demand. As urbanization expands human settlement space over natural ecological space, it can intensify spatial mismatch and supply-demand imbalance in ecosystem services. Rural ecological space has natural attributes and can continuously provide ecosystem services, but production processes during rural revitalization may also create ecological pressure. An ecosystem service flow network reframes urban-rural supply-demand matching as a problem of network connectivity. By identifying supply, connecting, and beneficiary areas, researchers can pinpoint the locations where ecosystem services are generated, the carriers and pathways of their transmission, and the entities that ultimately utilize these services. Supply-demand matching is no longer only a numerical balance within a single administrative unit. It becomes a network balance across urban-rural space, service types, and scales.

Multi-scale trade-off mechanism: from node trade-offs to edge trade-offs

Ecosystem service flows are strongly scale dependent. The forms and drivers of urban-rural integration vary across scales. Relationships among ecosystem services may also shift from trade-off to synergy or from synergy to trade-off as scale changes [24]. Based on ecosystem service flow networks, multiscale trade-offs can be examined at three levels including nodes, edges, and network stability. Network nodes contain complex supply or demand information and can indicate supply-side and demand-side trade-offs among service types. Further, network edges represent trade-offs in service flows, which include flow attributes along transmission carriers and pathways, as well as flow effects reflected in supply-demand matching [24]. Furthermore, network stability and dynamics reflect multiscale trade-offs along urban-rural gradients. Landscape patterns, urbanization level, human disturbance, and ecological resilience can be incorporated to assess multiscale trade-off mechanisms of ecosystem services along urban-rural gradients.

Network structure maintenance mechanism: complex associations, hierarchical organization,

and evolutionary feedback

The structural maintenance mechanism of an ecosystem service flow network is mainly reflected in complex associations, hierarchical organization, and evolutionary feedback [15, 23]. The ecosystem service flows connect nodes and their relationships and together represent the spatial movement of ecosystem services. Specific association patterns among nodes form complex interactions, so service supply-demand networks tend to be large, highly complex, and strongly affected by external factors. The ecosystem service flow networks are hierarchical. Local relations among providing areas, connecting areas, and benefiting areas can form modules, and these modules can form higher-level regional networks. This hierarchical structure means that urban-rural ecosystem services are not merely attributes of single units. They are spatial networks maintained by multiple levels, actors, and carriers [26]. The networks exhibit evolutionary feedback. Node attributes, edge strength, service flow direction, clustering coefficient, community structure, and spatial connectivity all change with land-use change, urbanization, population migration, and ecological governance.

Regulation and optimization mechanism: from flow restoration to urban-rural coordination

An ecosystem service flow network is both an explanatory and a regulatory framework [25]. By identifying key drivers of dynamic ecosystem service flows and trade-offs, it is possible to locate fragile links and interrupted points in service flows and then restore or reconstruct damaged ecosystem service flows. Regulation should focus on identifying how natural, socioeconomic, and population-structure factors affect service flows along urban-rural gradients, addressing the dominant drivers of service flow degradation, and optimizing the network structure among providing areas, connecting areas, and benefiting areas. In practice, network coupling patterns and dynamic characteristics can be used to examine the complex responses of ecosystem service supply-demand relationships to different drivers [25]. The results can guide balanced allocation of ecosystem service supply and demand within a region, improve urban-rural ecosystem service levels, and support coordinated urban-rural development. In this sense, ecosystem service flow networks provide a theoretical pathway from ecological processes to spatial governance for building new urban-rural relationships.

Ecosystem service flow networks as a new paradigm for analyzing urban-rural coupling mechanisms

Urban-rural coupling is not limited to coordination among population, industry, land, and infrastructure. It also includes coordination among the supply, transmission, consumption, and feedback of ecosystem services. Ecosystem service flow networks can reveal the movement and combination of ecosystem service elements in urban-rural systems, explain differences in ecosystem service supply and demand, clarify the mechanisms of element flow and allocation, and examine supply-demand matching patterns at different scales. This supports the development of a theory of ecosystem service supply-demand matching and balance. Research on ecosystem service flow networks combines the process logic of supply, flow, and demand with the network logic of nodes, edges, and weights to establish a spatial, process-based, and network-based framework for analyzing urban-rural coupling mechanisms. It therefore provides a new analytical perspective for this field. Human society is the ultimate node in ecosystem service flow networks [18]. Cities and villages together form the primary spaces of human activity. The spatial evolution and expansion of ecosystem service flows and networks directly affect urban-rural spatial development, while urban-rural coupling space also affects the relationship between ecosystem services and human well-being [17]. Cities and villages share symbiotic units, modes, environments, and interfaces. Urban-rural integration is an important driver of interactions among urban-rural ecosystem services, and it is central to coordinating

ecosystem service conservation with improvements in human well-being [19]. On the one hand, cities have scarce natural resources and high demand. Urbanization expands human settlement space over natural ecological space and is significantly negatively correlated with multiple ecosystem services. Ecosystem services generated by supply units may not meet the needs of users in the same region, which intensifies spatial mismatch and supply-demand imbalance in urban ecosystem services and affects ecosystem health. On the other hand, rural ecological space has natural attributes and can continuously provide ecosystem services. However, production processes associated with rural revitalization may also cause environmental pollution and resource waste, disturb the human-nature relationship, and affect ecosystem services in key ecological function zones [20]. The integration of ecosystem services across urban-rural space supports the coordination of new urbanization and rural revitalization. It also helps form and maintain a unified urban-rural ecosystem, provides the conditions for the ecological effects of urbanization to emerge, and can serve as a basic pathway for evaluating regional security and urban-rural development. Compared with traditional ecosystem service assessment, the theoretical value of the ecosystem service flow network can be described in terms of three shifts. The first is a shift from capacity to process that ecosystem services are understood not only as potential supply, but as actual transmission, consumption, and feedback processes. The second is a shift from spatial distribution to spatial relationships that the analysis asks not only where providing and demand areas are located, but also how they are connected through pathways, carriers, and intensities. The third is a shift from a single scale to multiscale networks that the framework can explain trade-offs and synergies at the landscape scale, urban-rural gradient scale, and supply-demand scale. This paradigm also faces theoretical and methodological challenges. Spatial extraction of ecosystem service flows still depends on multisource data, model parameters, and differences among service types. The abstracting and dynamically describing service flows in network simulations require more stable interfaces among ecological process models, complex network models, and socioeconomic response models. The link between network structure and ecosystem service function requires further clarification, especially the explanatory boundaries of nodes, edges, weights, modules, and network stability in relation to urban-rural coupling effects. Despite these challenges, research on ecosystem service flow networks offers a useful analytical direction for urban-rural coupling mechanisms. It integrates ecosystem service cascades, complex networks, urban-rural gradients, and social-ecological system coupling within a single research framework, which can move urban-rural integration research from socioeconomic coordination toward ecological-process coordination, from static assessment toward dynamic regulation, and from spatial-pattern description toward network-mechanism explanation.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 42271229).

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