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A Bioregional Framework for Structuring Rural Self-Sufficiency in Dispersed Settlement Systems: The Case of Arbo, Galicia (Spain)

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Abstract

Rural territories characterised by dispersed settlement systems face mounting challenges related to demographic decline, economic fragility, ecological degradation, and the erosion of local knowledge systems. In this context, rural self-sufficiency has re-emerged as a strategic objective; yet it remains inadequately operationalised within spatial planning and territorial assessment practices. This paper proposes a bioregional framework for operationalising rural self-sufficiency in dispersed territories, integrating ecological, morphological, socio-productive, cultural, and governance dimensions across multiple spatial scales. The framework is structured around a tiered system of 108 indicators, hierarchised into priority, secondary, and aspirational levels, combined with a multi-scalar territorial reading articulated through five nested frames—ranging from municipal systems to local productive units. Rather than constituting a mere checklist for immediate quantitative evaluation, the indicator system functions as a structured diagnostic universe, enabling progressive operationalisation based on data availability and governance capacity. To bridge the gap between diagnosis and action, the framework introduces 34 strategic drivers and 28 spatial artefacts, conceived as reversible and context-sensitive interventions. The framework is demonstrated through the case of Arbo (Galicia, Spain), illustrating its capacity to structure territorial diagnosis and articulate coherent pathways from analytical interpretation to strategic spatial intervention. The proposed approach contributes a replicable methodological tool for bioregional and rural planning in dispersed settlement systems. The study contributes to advancing bioregional planning by demonstrating how extensive indicator universes can be rendered operational through selective tiering and multi-scalar deployment.

Keywords: bioregional planning; rural self-sufficiency; dispersed settlement systems; indicator framework; multi-scalar analysis; territorial diagnosis; rural regeneration; sustainability transitions

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1. Introduction

Rural territories characterised by dispersed settlement systems face mounting challenges related to demographic decline, economic fragility, ecological degradation, and the

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erosion of local knowledge systems [1–3], particularly in relation to rural depopulation processes [1], landscape abandonment [2], and the loss of traditional ecological knowledge [3]. In many European contexts, depopulation has produced fragmented settlement patterns, underutilised productive landscapes, and weakened governance capacities, limiting the effectiveness of conventional spatial planning instruments [4,5]. Within this scenario, rural self-sufficiency has re-emerged as a strategic objective—particularly in relation to food systems, energy autonomy, ecosystem services, and local socio-productive networks [6–8]. Yet, despite its growing relevance in policy and academic discourse, it remains insufficiently operationalised within territorial planning and assessment frameworks [9].

Existing approaches to rural sustainability frequently rely on sectoral assessments [10] and aggregated indicator approaches [11,12], typically based on extensive and non-hierarchised indicator sets, or on administrative boundaries that fail to capture the relational and multi-scalar dynamics of dispersed territories. While numerous indicator-based frameworks assess sustainability and resilience [13], they often present two key limitations in rural contexts: excessive reliance on exhaustive indicator sets that exceed institutional capacity [11,13], and weak links between diagnostic assessment and spatial action [14,15].

Bioregional planning, rooted in territorialist and ecological planning traditions [16–18], has gained renewed attention as a means of reconnecting ecological structures, productive systems, settlement patterns, and governance within territorially coherent frameworks. By emphasising place-based resources and socio-ecological relationships, it offers a promising alternative to sectoral approaches [19]. However, translating bioregional principles into operational planning tools remains a significant methodological challenge, particularly in dispersed systems where conventional zoning proves insufficient [20,21].

Considering these limitations, this study addresses the following research question: How can bioregional planning principles be operationalised in dispersed rural settlement systems without exceeding institutional capacity?

This study contributes to existing research in three main ways. First, it operationalises bioregional planning principles through a tiered indicator system that reconciles conceptual completeness with institutional feasibility. Second, it introduces a multi-scalar territorial framework that enables the integration of ecological, socio-productive, and governance dynamics across nested spatial levels. Third, it bridges the gap between diagnosis and action by linking indicator-based assessment to strategic drivers and spatial artefacts, providing a structured pathway from analytical interpretation to situated spatial intervention in dispersed rural systems.

To respond, this paper proposes a bioregional framework for operationalising rural self-sufficiency in dispersed territories. Conceived as a methodological structure rather than a performance assessment tool, the framework integrates ecological, morphological, socio-productive, cultural, and governance dimensions across multiple scales [22]. Its core components include a tiered system of 108 indicators—organised into priority, secondary, and aspirational levels to balance conceptual depth with feasibility [23]—and a multi-scalar territorial reading structured through five nested frames, from municipal systems to local productive units [24].

To bridge the gap between analysis and action, the framework introduces strategic drivers and spatial artefacts as reversible, context-sensitive operational levers linking diagnosis to intervention pathways, drawing on approaches to tactical and adaptive urban interventions [25,26] as well as temporary and incremental spatial strategies [27,28]. The approach is demonstrated through the case of Arbo (Galicia, Spain), a rural municipality marked by ecological continuity, dispersed settlement patterns, and long-term demographic decline [29,30]. Arbo functions as a 'rural laboratory' to illustrate how the framework structures territorial diagnosis and articulates coherent pathways from analytical interpretation

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to spatial intervention, without claiming a comprehensive empirical evaluation of self-sufficiency outcomes.

2. Materials and Methods

The methodological framework is structured as a progressive sequence of interconnected components, linking conceptual foundations, indicator system design, and multi-scalar operationalisation.

2.1. Methodological Approach and Scope

This study adopts a methodological, framework-based approach, rather than an empirical performance evaluation, to address the operationalisation of rural self-sufficiency in dispersed settlement systems. The proposed methodology is conceived as a proof-of-concept framework, designed to structure territorial diagnosis and support strategic decision-making in rural contexts characterised by limited data availability, fragmented governance structures, and complex socio-ecological dynamics. This approach builds on sustainability assessment frameworks [10,13], which emphasise structured evaluation models; indicator-based approaches [11], focused on measurable territorial variables; and broader sustainability science perspectives [14,15], which highlight systemic integration and cross-scale dynamics.

The research does not aim to quantify self-sufficiency outcomes or to measure all proposed indicators empirically. Instead, it focuses on the development, structuring, and internal coherence of a bioregional planning framework capable of linking analytical interpretation with strategic spatial action. This methodological positioning directly responds to limitations identified in contemporary sustainability assessment practices, where extensive indicator systems [11,13] often exceed institutional capacities and remain poorly integrated with planning implementation [14].

2.2. Conceptual Basis: Bioregionalism and Rural Self-Sufficiency

The framework is grounded in bioregional planning theory, which conceptualises territory as an integrated socio-ecological system structured by ecological processes, productive landscapes, settlement patterns, and governance relations [16–18]. Within this perspective, territory is not understood as a passive spatial container, but as an active and relational structure capable of organising metabolic, social, and economic processes across multiple scales. This systemic understanding, rooted in the territorialist tradition developed by Magnaghi and complemented by urban ecological approaches such as those of Rueda, provides the theoretical basis for integrating environmental, spatial, and socio-productive dimensions within a unified analytical framework [16,17,22].

The incorporation of socio-ecological systems thinking further reinforces this perspective by emphasising the interdependence between ecological processes and social organisation, as well as the importance of adaptive, place-based governance structures [19]. However, despite its conceptual robustness, bioregionalism continues to face significant challenges in terms of operationalisation within spatial planning practice, particularly in complex and dispersed territorial contexts, as reflected in debates on collaborative planning and flexible territorial governance [20,21]. In many instances, it remains positioned at a normative or strategic level, with limited translation into methodological tools capable of supporting decision-making and implementation processes.

In parallel, the notion of rural self-sufficiency has gained renewed relevance in both academic and policy debates, particularly in relation to food systems [6,8], energy autonomy [6], and local economic resilience [7]. Nevertheless, existing approaches frequently address self-sufficiency through sectoral or mono-dimensional lenses, often focusing on individual subsystems without fully accounting for the interdependencies that characterise rural socio-ecological systems. This fragmentation limits its capacity to inform integrated territorial strategies, especially in contexts defined by dispersed settlement patterns and uneven institutional capacity.

In response to these limitations, this study proposes a reinterpretation of rural self-sufficiency not as territorial autarky, but as a relational and emergent capacity of socio-ecological systems to sustain key functions—such as food provision, energy cycles, ecosystem services, cultural reproduction, and local governance—through locally embedded resources and networks [6–8]. This perspective aligns with sustainability assessment and planning approaches that emphasise systemic integration in evaluation frameworks [10,13], understood as the need to articulate multiple territorial dimensions into coherent analytical structures; cross-scale interactions in sustainability processes [14,15], highlighting the interdependence between local and supra-local dynamics; and the importance of localised resource cycles in strengthening territorial resilience [11,12], particularly in contexts characterised by limited external inputs.

From this standpoint, bioregionalism provides the structural logic through which territorial systems are understood, while rural self-sufficiency represents a functional expression of that structure. The articulation of both concepts enables a shift from abstract theoretical principles towards an operational framework capable of linking territorial diagnosis with spatial intervention. In this sense, the proposed approach does not merely apply bioregional principles but reconfigures them into a methodological structure that integrates ecological, morphological, socio-productive, cultural, and governance dimensions within a coherent and multi-scalar system [16,18], thereby enabling a direct linkage between territorial analysis and spatial intervention.

2.3. Development of the Tiered Indicator System

The framework employs a set of 108 indicators derived from the bioregional planning theories of Magnaghi and Rueda, who conceptualise territory as an integrated socio-ecological system articulated through ecological, morphological, productive, cultural, and governance dimensions. Rather than merely redefining this indicator universe, this study reconfigures and operationalises the Magnaghi–Rueda framework through a tiered, multi-scalar structure specifically calibrated for the constraints of dispersed rural territories.

The adoption of a hierarchical structure aligns with established methodological practices in spatial planning and sustainability assessment, which advocate for compact core indicator sets—typically between 15 and 25 metrics—complemented by extended conceptual layers to balance operational feasibility with analytical depth. International frameworks, such as KITCASP, UN-Habitat SDG monitoring systems, and various sustainability assessment toolkits, consistently emphasise the necessity of limiting indicator sets for immediate decision-making, while retaining broader universes for contextual interpretation and longitudinal analysis. Within this methodological context, the framework is organised into seven analytical domains: Cultures and Knowledges; Environmental Structure; Polycentric Settlements; Bioregional Heritage; Local Energy Resources; Agroforestry Structures; Self-Governance Structures. This taxonomy ensures that ecological, morphological, socio-productive, cultural, and institutional dimensions are addressed concurrently, eschewing the sectoral or mono-dimensional interpretations that often plague rural self-sufficiency assessments.

To reconcile conceptual breadth with operational viability, the indicators are hierarchised into three implementation tiers: Tier 1 (Priority): A streamlined set of core indicators for immediate application using readily available datasets; Tier 2 (Secondary): Context-specific metrics requiring bespoke local surveys, field measurements, or simulation-based assessments, facilitating analytical depth over medium-term monitoring cycles; Tier 3 (Aspirational): Indicators that preserve the conceptual integrity of the bioregional framework, supporting qualitative diagnosis, scenario-building, and long-term comparability without imposing an immediate data-collection burden.

Rather than constituting an arbitrary aggregation, the 108-indicator universe derives from a systematic reinterpretation of the Magnaghi–Rueda bioregional framework, preserving its conceptual completeness while reorganising it according to operational criteria. Indicator selection and structuring were guided by three interrelated conditions: (i) theoretical relevance within bioregional socio-ecological systems, ensuring alignment with the integrated territorial perspective underpinning the framework; (ii) feasibility in contexts characterised by limited data availability and uneven institutional capacity, particularly in dispersed rural territories; and (iii) scalability across multiple territorial frames, enabling the articulation of cross-scale dynamics and context-sensitive implementation.

In this sense, the total number of indicators does not correspond to an operational requirement, but to a comprehensive conceptual universe intended to preserve the multidimensional integrity of bioregional systems.

Indicators are conceived as interpretative and diagnostic tools rather than fixed quantitative metrics. Their role is not to provide standardised scoring, but to structure territorial analysis and support the identification of strategic drivers and spatial interventions within context-specific conditions.

The tiered structure is designed to reconcile analytical depth with operational feasibility, taking into account data availability, institutional limitations, and territorial complexity. In this context, each indicator is associated with a qualitative interpretation protocol defining its analytical function, data requirements, and role within the diagnostic and decision-making process.

To visualise the hierarchical organisation of the indicator system, Figure 1 presents a radial synthesis of the seven analytical domains and their distribution across the three implementation tiers (1–3). The formal definition of the tier structure—specifying the number of indicators, implementation timeframes, and the scientific functions associated with each level—is detailed in Table 1. Based on this architecture, the set of Tier 1 (priority) indicators selected for immediate application is specified in Table 2. For full transparency and reproducibility, the complete tier assignment for all 108 indicators, organised by analytical domain, is provided in Supplementary Table S1, while the technical specifications for Tier 2 indicators are documented in Supplementary Table S2.

Table 1. Tier structure of the bioregional indicator framework.

Tier	Nº Indicators	Implementation	Scientific Function
Tier 1 Priority	18 core	Year 1 annual monitoring	Immediate operationalisation using readily available datasets (e.g., statistical records, cadastral and environmental databases); supports initial territorial diagnosis and decision-making
Tier 2 Secondary	15 extended	Years 2–3 biennial monitoring	Analytical deepening through context-specific indicators requiring local surveys, targeted measurements or institutional data integration
Tier 3 Aspirational	75 framework	Years 4–10 quinquennial or qualitative monitoring	Preserves the conceptual integrity of the bioregional framework (Magnaghi–Rueda); supports qualitative diagnosis, scenario-building and long-term comparability without operational overload

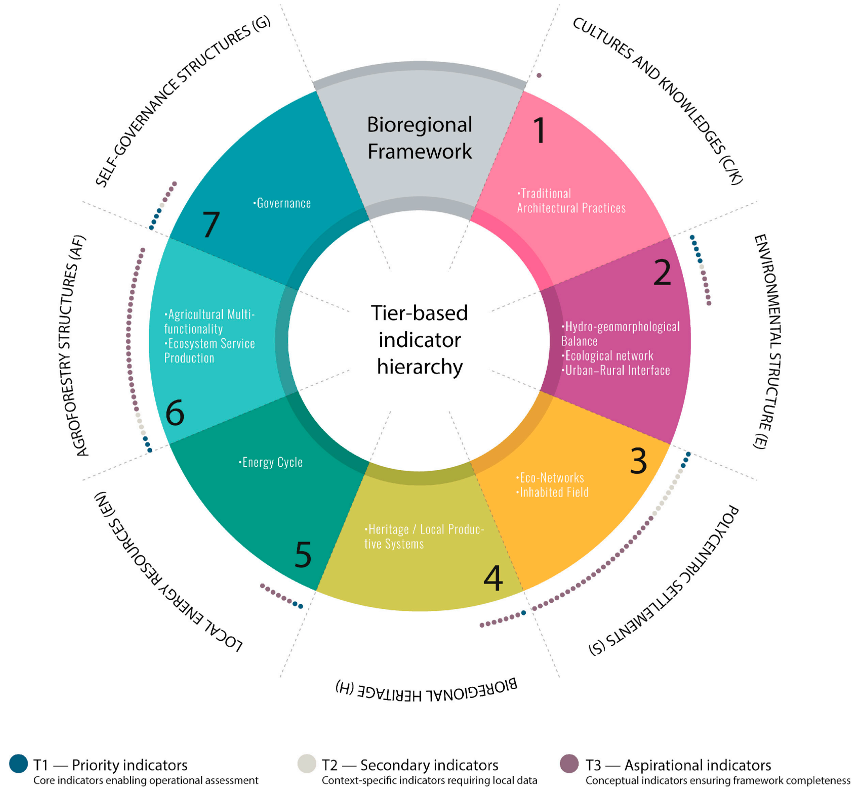

Figure 1. Radial representation of the 108 indicators. Magnaghi–Rueda bioregional framework, hierarchised into three implementation tiers (Tier 1–3) and organised by analytical domain.

Table 2. Tier 1 Priority Indicators (18 core indicators) were applied in this study. The table presents the set of Tier 1 indicators selected for immediate operationalisation, organised by analytical domain and subcategory, and specifying indicator codes, data sources and associated analytical frames. Data sources are expressed in standardised terms. Geospatial analyses can be conducted using standard GIS platforms such as QGIS (QGIS Development Team, Switzerland) or ArcGIS Pro 3.2 (Esri, Redlands, CA, USA). Environmental, statistical, and sectoral data refer to national or international institutional databases (e.g., European Environment Agency, national statistical institutes), depending on data availability in each territorial context.

Category	Subcategory	Indicator	Tier Code	Framework ID	Data Source	Frame
Environmental Structure	Hydro-geomorphological Balance	Level of protection of alluvial zones	T1-E1	1	Planning Instrument; GIS	Ecological
		Functional fluvial systems	T1-E2	4	Hydrological maps	Ecological
	Ecological Network	Biodiversity level	T1-E3	5	Environmental databases	Ecological
		Continuity of ecological corridors	T1-E4	7	GIS-based ecological planning	Ecological
	Urban–Rural Interface	Containment of settlement dispersion	T1-E5	10	Land-use data	Morphological
Polycentric Settlements	Eco-Networks	Accessibility to services	T1-S1	17	Network analysis (GIS)	Infrastructural
		Level of pedestrian connectivity	T1-S2	20	Mobility networks	Infrastructural
	Inhabited Field	Balance between open and built spaces	T1-S3	23	Land cover data (GIS)	Morphological

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Table 2. *Cont.*

Category	Subcategory	Indicator	Tier Code	Framework ID	Data Source	Frame
Bioregional Heritage	Heritage/Local Productive Systems	Locally produced goods	T1-H1	50	Economic statistics	Cultural
Local Energy Resources	Energy Cycle	Building energy quality	T1-EN1	59	Energy certification	Infrastructural
		Local renewable energy production	T1-EN2	62	Energy agencies	Infrastructural
Agroforestry Structures & Multifunctional Values	Agricultural Multifunctionality	Urban–rural perimeter	T1-AF1	66	Planning maps	Morphological
	Ecosystem Service Production	Maintenance of natural habitats	T1-AF2	84	Environmental agencies	Ecological
		Local agro-food chains	T1-AF3	85	Food-system data	Cultural
Self-Governance Structures	Governance	Provision of basic facilities	T1-G1	103	Municipal data	Social
		Proximity to basic facilities	T1-G2	104	GIS	Social
		Public space	T1-G3	105	Urban cartography	Social
		Community relationship entities	T1-G4	108	Institutional data	Social

2.4. Scientific Justification of the Tiered Structure

Extensive literature demonstrates that large, non-hierarchised indicator sets frequently exceed the operational capacity of local administrations—particularly within rural and dispersed territories—resulting in stalled implementation and diminished policy impact, as discussed in indicator-based assessment frameworks [11,12] and broader sustainability evaluation approaches [14].

International planning and monitoring frameworks consistently advocate for compact core sets to ensure effective operationalisation. Within spatial planning contexts, methodological toolkits rarely exceed 15–25 core indicators [21], even when addressing multifaceted sustainability objectives [15].

Within sustainability science, the literature emphasises the need to decouple conceptual breadth from operational feasibility through hierarchical or phased systems [10,13,24]. Compact subsets are consistently identified as a prerequisite for effective decision support [11,12], whereas broader indicator universes retain value primarily for conceptual framing, qualitative interpretation, and long-term scenario development.

2.5. Multi-Scalar Territorial Frames

To overcome the limitations of analysis based strictly on administrative boundaries, the methodology introduces a multi-scalar territorial reading articulated through five nested analytical frames (XL to XS). These frames correspond to functionally distinct territorial scales, ranging from municipal or supra-municipal systems to local productive units and settlement clusters, drawing on debates on flexible and non-administrative planning spaces [21] and on scalar reconfigurations of territorial governance [24].

These frames are not conceived as rigid spatial delimitations, but rather as analytical lenses that enable the interpretation of complex relationships between ecological structures, settlement patterns, productive landscapes, and governance mechanisms across scales. This

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approach facilitates the identification of scale-dependent dynamics, synergies, and conflicts that are frequently obscured in single-scale analyses—a critical factor in the study of dispersed settlement systems, where functional relationships often transcend jurisdictional lines [20,21].

2.6. Strategic Drivers and Spatial Artefacts

To bridge the recurrent gap between diagnosis and action, the framework incorporates a set of 34 strategic drivers and 28 spatial artefacts. These elements are conceived as operational levers that link indicator-based diagnosis to strategic intervention pathways.

Strategic drivers are defined as catalytic mechanisms capable of activating territorial processes by addressing key leverage points identified through the diagnostic framework. Spatial artefacts represent tangible or programmatic interventions—such as infrastructural adaptations, governance mechanisms, or productive systems—that operationalise these drivers in spatial terms. Both components are designed to be reversible, scalable, and context-sensitive, allowing for adaptive implementation and iterative refinement.

Rather than prescribing fixed solutions, the strategic drivers–artefacts logic functions as a decision-support structure. It enables planners and local stakeholders to explore alternative pathways that remain consistent with bioregional principles while responding to specific territorial conditions.

2.7. Case Demonstration: Arbo as a Rural Laboratory

The municipality of Arbo (Galicia, Spain) serves as a demonstrative case to illustrate the application of the proposed framework. Arbo was selected due to its pronounced dispersed settlement pattern, significant ecological assets, agroforestry traditions, and protracted demographic decline—features that, in combination, exemplify the structural challenges faced by many rural territories across Southern Europe [29,30].

The case study demonstrates how the tiered indicator system, multi-scalar frames, and strategic drivers can be integrated to structure territorial diagnosis and articulate strategic intervention pathways. Its purpose is not to provide an exhaustive empirical assessment of rural self-sufficiency outcomes, but rather to evaluate the internal coherence, interpretive capacity, and operational logic of the proposed methodology.

2.8. Data Considerations and Replicability

The framework is designed for compatibility with publicly available datasets—including statistical records, cadastral information, and environmental databases—alongside qualitative sources such as planning instruments and institutional reports. While no primary data collection was conducted for this proof-of-concept, secondary data sources informed the architectural structuring of the indicators and analytical domains.

All methodological stages—indicator selection and tiering, the definition of multi-scalar frames, and the strategic drivers–artefacts linkage—are explicitly documented to ensure replicability and facilitate contextual adaptation. Future applications may incorporate participatory processes, field measurements, and longitudinal monitoring to further operationalise and validate the framework in diverse territorial settings. Geospatial analyses referenced in the framework can be conducted using standard GIS platforms such as QGIS (QGIS Development Team, Switzerland) or ArcGIS Pro 3.2 (Esri, Redlands, CA, USA), ensuring methodological reproducibility while maintaining flexibility across different institutional contexts.

3. Territorial Diagnosis: The Case of Arbo (Galicia, Spain)

The following subsections do not present isolated thematic descriptions, but correspond to an integrated diagnostic reading structured according to the dimensions defined in the methodological framework. Each subsection corresponds to a specific analytical domain and set of indicators defined in Section 2, ensuring methodological consistency between framework design and territorial diagnosis.

In this sense, the case study is not approached as a descriptive account of territorial conditions, but as a structured and operational application of the methodological framework. The analysis focuses on the activation of Tier 1 indicators through the identification of strategic drivers and their materialisation into spatial artefacts across multiple territorial frames. This approach enables the translation of indicator-based diagnosis into situated and scale-specific interventions, demonstrating the operational capacity of the proposed framework in a dispersed rural context.

3.1. Contextualisation of the Case Study

Arbo is a rural municipality situated in southern Galicia (north-western Spain), within the Lower Miño River basin and bordering northern Portugal. The territory is defined by a pronounced dispersed settlement system, robust ecological continuity—underpinned by fluvial and forested structures—and a resilient agroforestry tradition. Consistent with many rural regions in Southern Europe, Arbo has undergone sustained demographic decline, population ageing, and economic restructuring in recent decades. These processes have exerted increasing pressure on local productive systems and governance capacities [31–33]. Figure 2 situates the municipality within its broader territorial and bioregional context, illustrating its multi-scalar positioning from the continental to the local level.

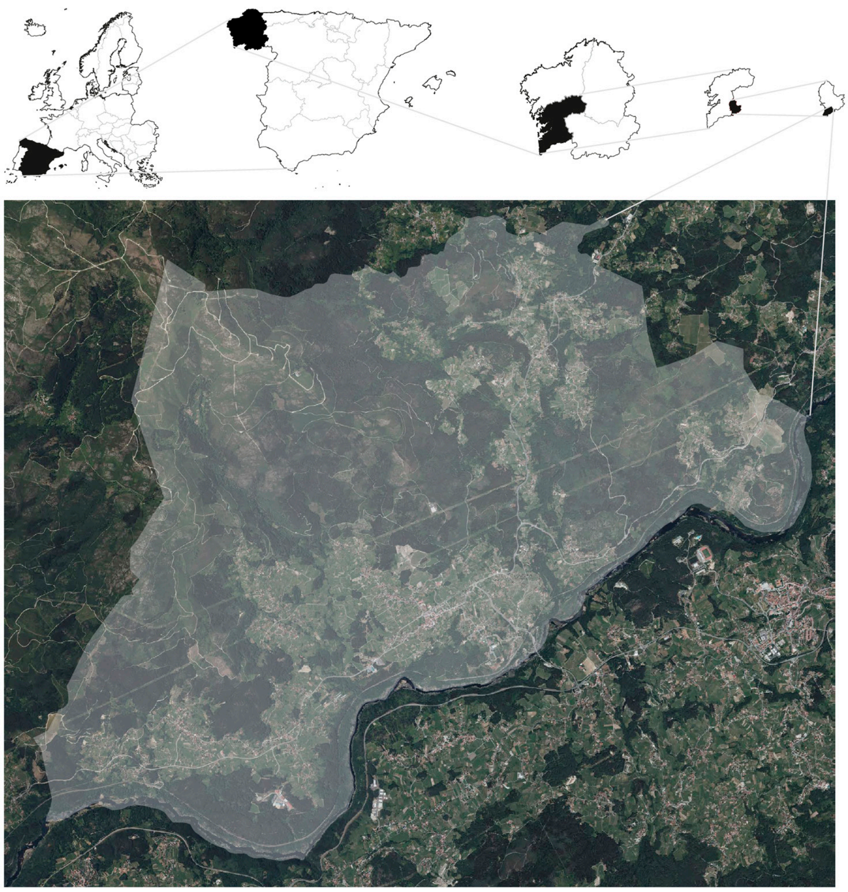

Figure 2. Territorial location and municipal boundary of Arbo (Galicia, Spain). The diagram illustrates the location of Arbo across European, Iberian, regional and provincial territorial frames, together with the delineation of its municipal boundary over aerial imagery. The representation highlights the extent and morphology of the municipality, the dispersed settlement pattern, and its structural relationship with the Miño river corridor within the bioregional context of north-western Iberia.

The selection of Arbo as a case study responds to its suitability as a 'rural laboratory' for evaluating the interpretative and structuring capacity of the proposed bioregional framework. The municipality encapsulates a high environmental value, vernacular settlement dispersion, and underutilised productive landscapes. This combination makes it representative of the systemic challenges faced by rural territories characterised by low-density, fragmented settlement patterns [34].

3.2. Settlement Structure and Dispersed Territorial Patterns

Arbo exhibits a settlement structure dominated by small-scale nuclei, isolated dwellings, and linear aggregations, historically aligned with ancient pathways, agricultural plots, and watercourses. This dispersed morphology reflects protracted interactions between productive practices, topography, and land-tenure patterns. However, it also presents contemporary challenges concerning service provision, mobility efficiency, and infrastructural maintenance [35,36].

From a bioregional perspective, dispersed settlement patterns are not interpreted merely as spatial inefficiencies, but as a structural territorial condition that shapes landscape management, territorial metabolism, and social relations [37]. The diagnostic framework facilitates the identification of both inherent vulnerabilities—such as infrastructural fragmentation and governance gaps—and latent potentials, including deep landscape embeddedness, proximity to productive land, and opportunities for closed-loop, localised resource cycles. This reading is consistent with research on rural settlement patterns and land-use dynamics, which emphasises the interdependence between spatial configurations, environmental conditions, and socio-economic processes in rural systems [38].

These patterns are interpreted through indicators related to settlement dispersion, accessibility, and spatial connectivity, allowing the identification of structural imbalances and potential leverage points (Figure 3).

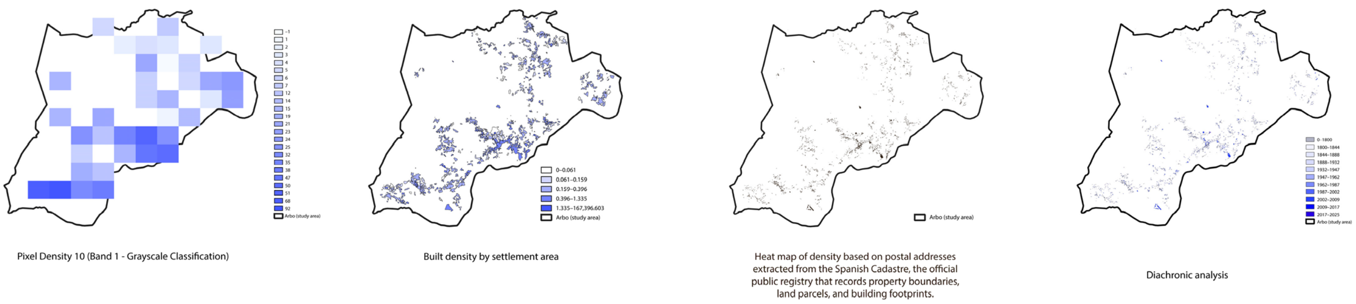

Figure 3. Multi-scalar density analysis and temporal evolution of settlement patterns in Arbo (Galicia, Spain). From left to right: (1) Pixel-based density grid showing coarse concentrations of built structures. (2) Built density by settlement area, revealing internal variation within Arbo's dispersed system. (3) Heat map based on geolocated cadastral postal addresses, identifying fine-grained occupation clusters. (4) Diachronic analysis of construction periods from cadastral data, evidencing historical expansion, contraction and recent demographic decline.

3.3. Environmental Structure and Landscape Systems

The environmental structure of Arbo is fundamentally shaped by the Miño River and its tributaries, which constitute a continuous fluvial corridor of high ecological significance. Riparian systems, forested slopes, and agricultural terraces form a heterogeneous landscape mosaic that sustains biodiversity, provides critical ecosystem services, and ensures landscape connectivity [39,40]. This environmental framework serves as a primary bioregional asset, underpinning food production, water regulation, climate moderation, and cultural identity. However, contemporary processes—notably land abandonment, forest homogenisation, and the fragmentation of ecological corridors—threaten the long-term resilience of these systems [41]. The proposed framework facilitates a multi-scalar interpretation of these dynamics, highlighting the vital interdependence between ecological continuity and settlement patterns [42] (Figure 4). These dynamics are analysed through indicators associated with ecological continuity, biodiversity, and hydro-geomorphological balance, enabling a multi-scalar diagnosis of environmental resilience.

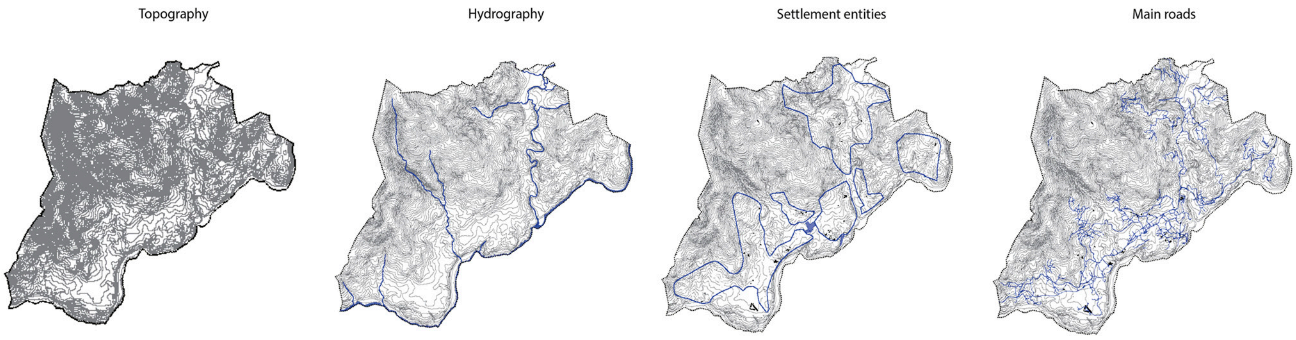

Figure 4. Spatial layers of Arbo: topography, hydrography, settlement patterns, and road network, providing the territorial base for the multi-scalar analysis. Blue lines represent hydrographic features (rivers and streams), while grey lines correspond to topographic contour lines derived from elevation data.

3.4. Productive Systems and Agroforestry Dynamics

Historically, Arbo's economy has been anchored in agroforestry practices, small-scale agriculture, and river-based activities. While many of these systems have experienced decline or structural transformation, their spatial and cultural imprints remain deeply embedded in the landscape, continuing to dictate contemporary land-use patterns [43].

The territorial diagnosis reveals a systemic decoupling between historical productive infrastructures and current socio-economic dynamics. Nevertheless, it identifies significant opportunities for reactivation through short food supply chains, multifunctional land use, and the reintegration of agroforestry systems into broader bioregional cycles [44,45]. Within this framework, productive systems are addressed not as isolated economic sectors, but as integral pillars of rural self-sufficiency and territorial resilience [46].

Within the framework, these processes are examined through indicators related to local agro-food chains, multifunctional land use, and resource cycles, supporting the identification of opportunities for system reactivation.

3.5. Governance, Services and Socio-Spatial Relations

Governance in dispersed rural territories, such as Arbo, is chronically hindered by limited institutional capacity, demographic decline, and the spatial fragmentation of population and services. Access to essential facilities, public spaces, and collective infrastructures remains uneven, exacerbating socio-spatial inequalities and deepening the dependence on external systems [47].

The diagnostic framework underscores the critical role of multi-level governance arrangements, local social networks, and community-based organisations in sustaining territorial functions [48]. In many instances, informal practices and locally embedded knowledge systems compensate for institutional voids, highlighting the indispensable nature of governance indicators and cultural dimensions within a bioregional approach [49].

These conditions are assessed through governance-related indicators addressing service provision, accessibility, and community structures, highlighting systemic gaps and institutional constraints.

3.6. Synthesis: Diagnostic Implications for Framework Demonstration

Rather than producing a quantified performance assessment, the territorial diagnosis of Arbo serves to demonstrate the interpretative capacity of the proposed framework. By structuring ecological, morphological, productive, and governance dimensions within a coherent analytical system, the framework facilitates the identification of key tensions, synergies, and leverage points that inform subsequent strategic reasoning [31].

This diagnostic synthesis provides the logical foundation for the operational framework developed in the following section, where indicator hierarchisation, multi-scalar analysis, and strategic drivers are explicitly linked to strategic intervention pathways. In this sense, the diagnosis functions as a critical methodological bridge—linking territorial interpretation to strategic spatial action—rather than as a static analytical output [50].

This integrated diagnostic reading ensures consistency between the analytical dimensions and the operational framework developed in Section 2, enabling the identification of cross-dimensional relationships and strategic leverage points.

4. Operational Framework: Tier 1 Implementation Pathways Across Nested Frames (XL–XS)

The operational framework translates the Tier 1 (Priority) indicator set into situated implementation pathways by coupling—Strategic Drivers: problem-oriented leverage mechanisms derived from the diagnostic phase; Spatial Artefacts: site-specific spatial, programmatic, or governance interventions that materialise those drivers within the territory. In Arbo, this coupling is structured through five nested territorial frames (XL, L, M, S, XS), ensuring that Tier 1 indicators are operationalised coherently—from large-scale municipal structures down to domestic and productive micro-units. This multi-scalar (Table 3) integration ensures that strategic objectives are not lost in translation when moving from policymaking to physical or social intervention.

Table 3. Multi-scalar territorial frames and their operational focus within the bioregional framework applied to Arbo. The table defines five territorial frames (XL–XS), outlining their spatial scales and operational focus. Together, they structure the deployment of Tier 1 strategic pathways across municipal, corridor, parish, hamlet-cluster and household levels, enabling coherent multi-scalar implementation in a dispersed rural context.

Frame	Scale	Operational Focus
XL	Municipal	Territorial metabolism, structuring ecological and infrastructural corridors
L	River corridor (Miño River)	Riparian dynamics, cross-border interface, linear public-space systems
M	Parish	Settlement systems, local services and socio-productive structures
S	Hamlet cluster	Community life, shared facilities and collective infrastructures
XS	Household	Micro-ecological production, domestic metabolism and social interactions

To clarify the relationship between territorial scales and the allocation of indicators, Table 4 summarises the functional role of each scale and the types of indicators associated with it.

Table 4. Indicator–scale matching and functional roles within the multi-scalar framework.

Scale	Territorial Level	Functional Role	Indicator Types
XL	Supra-municipal/ Bioregional	Ecological regulation and territorial connectivity	Ecological continuity, biodiversity, landscape systems

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Table 4. *Cont.*

Scale	Territorial Level	Functional Role	Indicator Types
L	Municipal	Structural territorial organisation	Land use, infrastructure, mobility, resource management
M	Parish/Intermediate	Socio-productive organisation	Agro-food systems, local economies, productive networks
S	Settlement/Cluster	Local accessibility and service provision	Services, accessibility, social infrastructure
XS	Household/Unit	Micro-scale self-sufficiency and resource cycles	Domestic production, energy, water, circular systems

4.1. From Tier 1 Diagnosis to Action: Strategic Drivers vs. Spatial Artefacts

Strategic Drivers are defined as transferable operational logics—such as "energy autonomy", "local agro-food chains", or "walkable connectivity"—that catalyse territorial change by targeting specific leverage points revealed during the Tier 1 diagnosis. In contrast, Spatial Artefacts are the tangible territorial devices through which these logics are implemented: infrastructures, productive nodes, spatial prototypes, or governance-enabled public spaces. This distinction is fundamental: the driver constitutes the why/how (the strategic mechanism), whereas the artefact represents the where/what (the situated materialisation).

To bridge the gap between diagnostic outputs and spatial action, the framework introduces an intermediate operational layer where drivers and artefacts intersect. Strategic drivers function as decision-levers that respond to Tier 1 indicator imbalances, while spatial artefacts provide the context-sensitive response across different territorial frames. While Figure 5 introduces the conceptual mechanism linking indicators and strategic drivers, Figure 6 illustrates their operational translation into spatial artefacts across territorial scales.

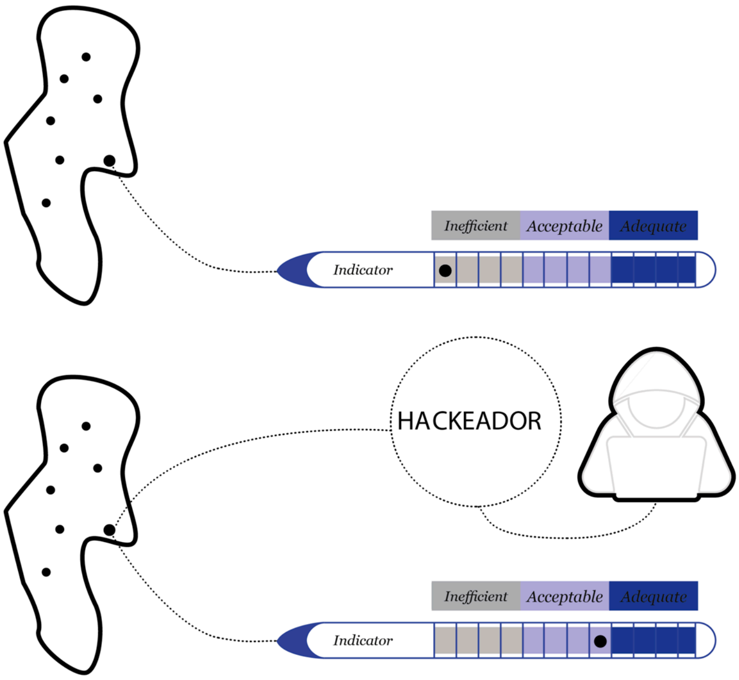

Figure 5. Conceptual operational logic linking Tier 1 indicators, strategic drivers and spatial intervention. The diagram illustrates the abstract mechanism through which indicator-based diagnosis informs the activation of strategic drivers as leverage points for system transformation. It represents a generalised performance gradient, highlighting how targeted interventions can shift territorial systems from inefficient to optimal conditions without prescribing specific spatial solutions.

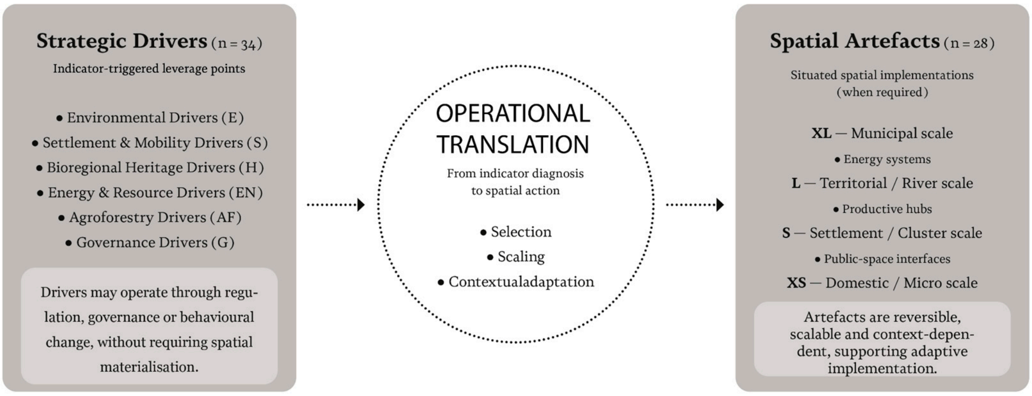

Figure 6. Operational translation of strategic drivers into spatial artefacts across territorial scales. The diagram represents the applied dimension of the framework, showing how strategic drivers are selectively materialised as spatial artefacts depending on context and scale. It highlights the one-to-many relationship between drivers and artefacts, and their deployment across different territorial frames, bridging diagnostic assessment and situated spatial implementation.

This diagram establishes the analytical bridge between indicator-based diagnosis and situated spatial intervention, clarifying how strategic drivers are translated into concrete artefacts across scales.

As conceptually illustrated in Figure 6, spatial artefacts operate as mechanisms through which strategic drivers are materialised in specific territorial contexts. In the case of Arbo, the river promenade exemplifies how a spatial artefact can activate the strategic drivers of ecological connectivity and active mobility, simultaneously addressing Tier 1 indicators related to ecological continuity and pedestrian accessibility along the Miño corridor.

At the XS scale, vertical gardens exemplify how a single artefact can simultaneously address food production, energy efficiency and microclimatic regulation, translating abstract self-sufficiency objectives into feasible, household-scale interventions embedded in everyday spatial practices.

4.2. Frame-Based Deployment of Tier 1 Pathways in Arbo (XL–XS)

XL—Municipal Frame (Structural Enabling Conditions). At the XL scale, Tier 1 pathways prioritise systemic capacity by fostering local production, institutional coordination, and baseline service provision. Artefacts such as 'Local timber as a construction material' and 'Biodiversity and landscape' reinforce municipal-scale conditions for bioregional value chains and ecological resilience. Concurrently, 'Sustainable mobility' initiatives support ecological continuity and mitigate the fragmentation inherent in the dispersed settlement fabric.

L—River/Linear Corridor Frame (Connectivity and Public-Space Systems). The L frame operationalises Tier 1 through walkability, connectivity, and the democratisation of public-space accessibility along the Miño corridor. Artefacts such as the 'Promenade' and 'Carreiro' (traditional pathways) function as linear devices that enhance pedestrian continuity, structure access to shared facilities, and integrate isolated hamlets into a coherent territorial armature.

M—Parish Frame (Socio-Productive Clustering and Service Logic). At the M scale, implementation focuses on the minimum thresholds of self-sufficiency: local goods, agro-food chains, and essential facilities. Artefacts such as the 'Agro-food cluster' and 'Community facilities' act as centripetal forces that counterbalance dispersion by clustering production and exchange, thereby reinforcing proximity-based accessibility and local economic circuits.

S—Hamlet-Cluster Frame (Collective Facilities and Public Space). Within hamlet clusters, Tier 1 is expressed through artefacts that institutionalise collective life, including the 'Stadium', 'Eco Park', and 'Public recreation facilities'. In dispersed systems, these elements operate as structuring nodes that concentrate social interaction and community organisation, directly addressing Tier 1 governance and service-level indicators.

XS—Hamlet/Household Frame (Micro-units for Food, Energy, and Social Life). At the XS scale, Tier 1 pathways are implemented through domestic and micro-productive artefacts such as 'Vertical gardens', 'Water harvesting and treatment', and the 'Household Regen system'. These devices translate self-sufficiency from an abstract planning goal into feasible, incremental practices embedded in everyday spatial routines, supporting local resource autonomy at the smallest operative scale. Table 5 synthesises the mapping between Tier 1 strategic drivers and their spatial artefacts across frames (Figure 7).

Table 5. Spatial artefacts as situated implementations of Tier 1 strategic drivers across nested territorial frames (XL–XS) in Arbo (Galicia, Spain). The table links Tier 1 strategic drivers to their concrete spatial artefacts and identifies the territorial frame(s) in which they operate. Artefacts represent site-specific infrastructural, productive, spatial or governance interventions that materialise priority indicators within the dispersed settlement system of Arbo.

Frame	Strategic Driver ID	Spatial Artefact	Tier 1–Priority
XL	01	Local timber as a construction material	Local goods/value chains (T1–H1) enabling bioregional production logic
XL	20	Biodiversity and landscape	Ecological structure & continuity (T1–E3/T1–E4) dispersion containment support (T1–E5)
XL	22	Sustainable mobility	Pedestrian connectivity/access logic (T1–S2; T1–S1)
L	02	Promenade	Pedestrian connectivity + access structuring (T1–S2; T1–S1)
L	12	Vertical gardens	Local agro-food chain support (T1–AF3) domestic-scale productive device
L	23	Viewpoints	Public space system/social use nodes (T1–G3)
L	02	Promenade	Connective structuring across parish (T1–S2; T1–S1)
M	25	Community service facilities	Basic facilities provision (T1–G1; T1–G2)
M	27	Social spaces	Public space + community anchoring (T1–G3; T1–G4)
M	28	Landscape integration	Supports ecological structure logic (T1–E3/T1–E4)
M	30	Energy adaptation of traditional systems	Local renewables/building-energy pathway (T1–EN2; T1–EN1)
M	34	Interior–exterior spatial continuity	Public-space habitability/social interface (T1–G3)
S	17	Stiva da morts	Public space/community node (T1–G3; T1–G4)
S	21	Green spaces	Public space system (T1–G3)
S	24	Public recreation facilities	Basic facilities + public space (T1–G1; T1–G3)
S	26	Viewpoints	Public space + territorial legibility (T1–G3)
XS	04	La Pinada Lab	Community relationship entities + facilities logic (T1–G4; T1–G1)
XS	09	Regen system	Local agro-food chain support (T1–AF3) + local goods logic (T1–H1)
XS	11	Flexible design	Supports housing/service usability → basic facilities proximity logic (T1–G2)

Table 5. *Cont.*

Frame	Strategic Driver ID	Spatial Artefact	Tier 1–Priority
XS	13	Rainwater collection and greywater treatment	Supports ecological and settlement operability by reinforcing hydrological continuity (linked to Tier 1 indicators T1–E1 and T1–E2).
XS	15	Waste	Supports service provision operability (T1–G1) (indirect)
XS	16	Ethical purchasing and social clauses	Local goods/value chain enabling (T1–H1)
XS	18	Topographic adaptation	Dispersion containment/settlement performance (T1–E5) (indirect)
XS	31	Formal reinterpretation of the construction system	Building energy quality pathway (T1–EN1)
XS	32	Reinterpretation of openings	Building energy quality pathway (T1–EN1)
XS	33	Reinterpretation of traditional structure	Building energy quality + local production logic (T1–EN1; T1–H1)

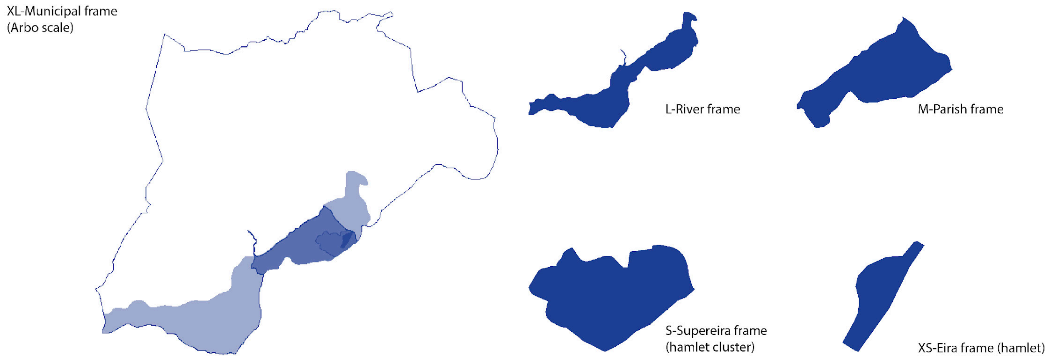

Figure 7. Multi-scalar territorial frame system applied to Arbo (Galicia, Spain). The figure shows five nested territorial frames (XL, L, M, S, XS) representing the ecological and socio-spatial organization of Arbo. Together, these frames provide a concise multi-level structure for coordinating diagnostic insights and operational pathways in rural regeneration processes.

The Promenade–Vertical Garden system (Figure 8) constitutes a paradigmatic example of how Tier 1 strategic drivers are translated into situated spatial artefacts in Arbo. At the river-corridor scale (L), pedestrian connectivity and service accessibility operate as primary strategic drivers; here, the promenade functions as the main connective artefact, structuring movement, visibility, and social interaction. The integration of vertical gardens at key access points and threshold spaces introduces a complementary domestic-scale productive artefact. This intervention directly activates Tier 1 indicators related to local agro-food chains, microclimatic regulation, and biodiversity enhancement. This assemblage demonstrates how a single spatial intervention can simultaneously operationalise multiple Tier 1 indicators across scales, effectively linking infrastructural connectivity with productive and ecological functions.

At the smallest operative scale (XS), complementary artefacts such as rainwater harvesting and greywater reuse systems reinforce this logic by supporting food production and microclimatic performance at the household or hamlet level. Although modest in spatial extent, these XS artefacts play a critical role in closing resource cycles, ensuring that Tier 1 drivers related to environmental structure and basic service provision are effectively operationalised at the point of everyday use. Together, these examples illustrate the capacity of the framework to articulate coherent intervention pathways—transforming strategic diagnosis into concrete, multiscale spatial implementation.

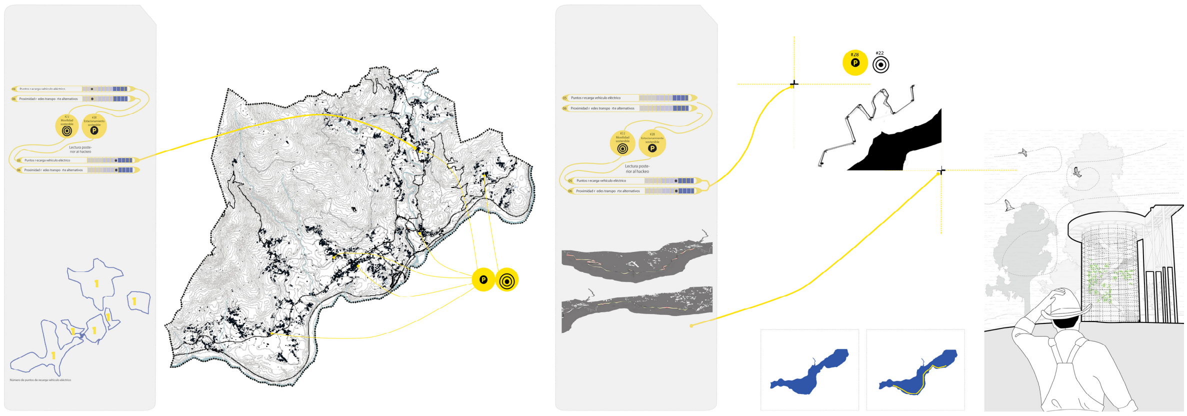

Figure 8. Representation of the Promenade (Strategic Driver ID 02) and the system of river viewpoints within the River Frame (L). The figure illustrates the spatial configuration of the elevated walkway aligned with the ecological continuity of the Miño River corridor, as well as the placement of strategic visual nodes that structure the perceptual relationship with the valley landscape. Vertical Gardens are integrated at the access points to both the walkway and the viewpoints, operating as domestic-scale productive artefacts that enhance food autonomy, microclimatic regulation, and biodiversity within the broader bioregional system.

4.3. Operational Logic and Monitoring Implications

Although Tier 1 indicators define the minimum operational dataset, their implementation in Arbo is not conceived as a single, isolated intervention. Instead, it constitutes a portfolio of frame-specific artefacts that collectively target ecological structures, settlement connectivity, socio-productive circuits, and governance frameworks. This multi-frame deployment ensures high transferability: while the strategic driver logic remains universal, the artefacts themselves are adaptable to local morphology, institutional capacity, and regional data availability.

Tier 2 indicators are designed as a layer of methodological deepening. They are intended to be activated progressively, as governance capacity, data resolution, and institutional coordination evolve. This tiered architecture allows for a more granular territorial analysis over time, ensuring that the long-term sophistication of the monitoring system does not compromise the immediate operability of the core framework.

5. Discussion

This study contributes to contemporary debates on bioregional planning by demonstrating how an extensive indicator framework can be rendered operational without sacrificing conceptual integrity. Rather than treating the Magnaghi–Rueda bioregional indicator set as a static evaluative tool, the proposed tiered structure enables a selective and staged deployment aligned with data availability, institutional capacity and territorial complexity.

5.1. Advancing Bioregional Planning Through Operational Tiering

This positions the framework within ongoing debates on the implementation, where the translation from conceptual models to planning practice remains limited. In this context, the main contribution of the study lies in the methodological reconfiguration of an extensive indicator system into a hierarchical and multi-scalar framework capable of linking territorial diagnosis with spatial intervention.

The empirical application in Arbo illustrates that the added value of the framework does not lie in the exhaustive measurement of all indicators, but in the capacity to translate a limited subset of priority indicators (Tier 1) into actionable strategic drivers and spatial artefacts. This finding is consistent with previous work identifying the persistent gap between sustainability assessment frameworks and their integration into spatial planning practice [51,52], as well as with studies highlighting the limited implementation of evaluation tools in decision-making processes [53,54].

This approach aligns with recent perspectives in sustainability science that emphasise the role of leverage points and system-oriented interventions in enabling transformative change [55–57], rather than relying on exhaustive indicator monitoring [53,54]. At the same time, it contributes to this body of work by embedding these interventions within a territorially structured planning framework, linking systemic leverage points with spatially explicit strategies.

5.2. Addressing Dispersed Settlement Systems Through a Multi-Scalar Operational Logic

Dispersed rural settlement systems pose persistent challenges to conventional planning approaches, particularly regarding accessibility, service provision and socio-ecological continuity. These challenges have been widely documented in the literature on rural planning and territorial governance, particularly in relation to low-density settlement patterns and fragmented institutional capacity.

The Arbo case demonstrates how a multi-scalar operational logic, structured through nested territorial frames (XL–XS), can respond to these challenges without resorting to centralisation or densification strategies.

By deploying Tier 1 indicators through frame-specific strategic drivers and spatial artefacts, the framework enables differentiated yet coordinated interventions: landscape-scale ecological regulation at the municipal level, connective infrastructures along river corridors, socio-productive clustering at parish scale, and micro-scale productive and social devices embedded in domestic environments. This extends existing approaches by showing how cross-scale coordination can be operationalised through spatially explicit interventions adapted to the functional role of each territorial scale. This confirms that self-sufficiency in dispersed contexts is not achieved through uniform solutions, but through the strategic articulation of interventions adapted to the functional role of each scale.

These findings resonate with multi-level governance and cross-scale interaction frameworks, which emphasise the need to align decision-making processes and interventions across spatial and institutional levels to address complex territorial challenges, as discussed in multi-level governance literature [55,58] and cross-scale interaction frameworks [56,57,59,60]. However, while such frameworks are often conceptual, the present study contributes a concrete methodological structure that translates these principles into actionable planning strategies.

5.3. From Indicator Proliferation to Strategic Selectivity

A recurring critique of sustainability assessment frameworks concerns the proliferation of indicators and the resulting implementation burden placed on local administrations. This issue has been widely discussed in the literature, particularly in relation to the limited usability of extensive and non-hierarchised indicator systems in planning contexts. The tiered approach adopted in this study directly addresses this issue by decoupling conceptual completeness from operational feasibility.

The Arbo case provides empirical support for the argument that an extensive indicator universe does not imply an equivalent number of actions. On the contrary, Tier 1 indicators are materialised through a limited and strategically selected set of spatial artefacts, each capable of addressing multiple indicators simultaneously. This demonstrates how prioritisation can be operationalised without reducing analytical scope, but rather by structuring it hierarchically. This selective operationalisation confirms that prioritisation, rather than simplification, is the key to maintaining analytical robustness while enabling real-world application.

This perspective is consistent with critical literature on sustainability indicators, which highlights the limitations of large, non-hierarchised indicator sets [61] and advocates for more focused, decision-oriented frameworks capable of effectively supporting policy and planning processes [62,63]. However, while such approaches often emphasise reduction or simplification, the present study contributes a methodological alternative based on structured selectivity, preserving conceptual completeness while enabling practical implementation.

5.4. Transferability, Limits and Future Extensions

While the spatial artefacts implemented in Arbo are necessarily context-specific, the driver–artefact–frame logic underpinning the framework is transferable to other dispersed rural systems with analogous socio-ecological conditions. This distinction between context-specific outputs and transferable methodological structures is consistent with place-based planning approaches that emphasise adaptability across different territorial contexts [64]. The framework does not prescribe fixed solutions, but rather provides a structured method for identifying leverage points and designing scale-appropriate interventions.

Nevertheless, the study also highlights limitations. Tier 2 indicators are conceived as a methodological deepening layer, activated when governance capacity, data availability and institutional coordination allow for more detailed analysis without compromising the operability of the core framework. Tier 3 indicators retain a primarily conceptual role, supporting qualitative diagnosis and long-term scenario-building. These limitations reflect well-documented constraints related to uneven institutional capacity and data availability in complex territorial systems.

These considerations align with debates on adaptive governance and multi-level coordination [65–68], and with literature addressing the implementation challenges of sustainability frameworks in contexts of limited institutional capacity and territorial complexity [69,70]. In this sense, the framework should be understood as an adaptive and scalable structure rather than a fully deployable model under all conditions.

However, the applicability of the framework may be constrained in rural contexts characterised by limited governance capacity and strong market pressures. In such scenarios, the implementation of multi-scalar coordination and indicator-based planning may face institutional fragmentation, reduced administrative capability, and competing short-term economic interests. This may limit the effective activation of Tier 2 indicators and the consolidation of integrated territorial strategies.

In these conditions, it should be understood as a guiding structure rather than a fully deployable system, requiring adaptive implementation, simplified operational layers, and strong reliance on local actors and bottom-up processes. This highlights the importance of aligning the framework with context-specific governance capacities and socio-economic dynamics.

Future research should explore how these layers can be progressively integrated through participatory processes and longitudinal monitoring.

6. Conclusions

This study contributes to the operationalisation of bioregional planning by proposing a framework for structuring rural self-sufficiency in dispersed settlement systems, addressing the persistent gap between conceptual sustainability models and their application in spatial planning. The framework integrates a tiered indicator system with a multi-scalar territorial structure, enabling the linkage between territorial diagnosis and strategic spatial intervention.

The application to the case of Arbo suggests that the framework can support the identification of key territorial dynamics and the translation of selected priority indicators into strategic drivers and spatial artefacts. Rather than relying on exhaustive indicator measurement, the results indicate that selective operationalisation, structured through hierarchical and scale-sensitive logic, can enhance feasibility while preserving conceptual robustness.

At the same time, the findings indicate that the effectiveness of the framework is closely dependent on context-specific conditions, particularly governance capacity, data availability, and institutional coordination. In this sense, the framework should be understood as an adaptive and scalable methodological structure rather than a universally deployable model.

While the results obtained in Arbo provide a relevant proof of concept, the broader transferability of the framework remains to be further validated. Future research should therefore explore its application across diverse rural contexts, assessing its robustness, adaptability, and capacity to inform spatial planning under varying socio-economic and institutional conditions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land15040689/s1, Table S1: Complete tiered indicator system of the Magnaghi–Rueda bioregional framework applied in this study; Table S2: Tier 2 indicators: extended operational indicators and monitoring requirements.

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