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Network-based assessment of multi-scale resilience in the water-energy-land-food nexus: a case study in the Colombian Caribbean

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ABSTRACT

Global change threatens socio-ecological systems, particularly in regions with rapid land use changes and competing demands for water, energy, and food. However, the impact of land use changes on the resilience of interconnected systems remains largely unexplored. To address this gap, this study advances the Water-Energy-Food (WEF) nexus approach by integrating land as a central element, forming the Water-Energy-Land-Food (WELF) nexus. It introduces an analytical framework to quantify the effects of land use changes on nexus composition and resilience across spatial scales, from regional to local. The framework characterizes resilience as a macroscale property of the nexus using geospatial land use and land cover data and decomposes it into microscale components through a network approach, identifying how nexus elements and land use transfers among them influence resilience. The framework is applied to the Maria La Baja sub-watershed (2002–2018) in the Colombian Caribbean, during significant structural transformation. Results reveal scale-dependent variations in WELF nexus composition and resilience, with the Food element consistently enhancing resilience, while the contributions of Water and Energy vary by scale. Scenario analysis shows that a reduction in land use transfers consistently decreases resilience across scales. In contrast to literature, this study finds that increasing land use transfers does not always enhance resilience. While resilience theory can support balancing competing land demands and adapting socio-ecological systems to global change, this study emphasizes the need for careful characterization of nexus elements, interactions, and feedback loops, identifying a necessary condition for land use transfers interventions to enhance resilience effectively.

1. Introduction

Global change challenges the functioning of socio-ecological systems, bringing resilience-based management into greater recognition as a pathway to sustainable development (Sellberg et al., 2018; Marchese et al., 2018; Grafton et al., 2019). However, resilience theory still requires a deeper understanding of the complex interactions that emerge within interconnected systems (Schmalzbauer and Visbeck, 2016; Ehrensperger et al., 2019; Munroe and Müller, 2020). This need is particularly pressing in regions undergoing economic transformation, where transitions from agrarian to industrial economies often lead to deforestation and increased demands for water, energy, and food (Mullan et al. 2018; Simpson and Jewitt, 2019; López-Carr, 2021).

The Water-Energy-Food (WEF) nexus approach is an interdisciplinary effort to understand the interactions among strategic elements of socio-ecological systems (Gaddam and Sampath, 2022). Yet, it often fails to account for how land use and land cover (LULC) changes shape these interactions through synergies, trade-offs, and feedback loops (Ringler et al., 2013; Simpson and Jewitt, 2019; Elagib and Al-Saidi, 2020). Land not only serves as an element in the nexus but also as a medium for the production and exchange of Water, Energy, and Food (Mohtar, 2011). This study advances the WEF nexus approach by incorporating land as a

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central nexus element, forming the Water-Energy-Land-Food (WELF) nexus. In the WELF nexus, each element interacts with others through land transfers that vary across spatial scales and time. Resilience supports balancing competing land demands for Water, Energy, and Food within the nexus. An example of a resilient WELF nexus is a farming community adapting to climate change by using drought-resistant crops and preventing deforestation, thereby preserving ecosystem services while maintaining food production.

It is important to note that the current literature defines resilience as a macroscopic property of a system, focusing on generalized interventions targeting one of two goals: efficiency, which favors economic performance, and redundancy, which favors ecosystem conservation and option value (Ulanowicz et al., 2009; Letourneau et al., 2012; Meyfroidt et al., 2022). Consequently, while adaptation to disruptions over time is considered, changing social, economic, and environmental conditions at different spatial scales are often ignored. Furthermore, this definition does not adequately address the synergies, trade-offs, and feedback loops that changes in one nexus element may cause in others, potentially producing unintended effects on resilience outcomes (Kharrazi et al., 2017). Existing research on resilience has yet to fully explore the integrated impact of LULC changes on the resilience of interconnected systems (OECD, 2017; Karabulut et al., 2018; Ibrahim et al., 2019; Psomas et al., 2021; Gaddam and Sampath, 2022; Meyfroidt et al., 2022; Mohtar, 2022). This issue is particularly relevant in regions where rapid LULC changes, such as deforestation, have significantly modified the composition of the WELF nexus. The loss of forests reduces water retention, increases soil erosion, and leads to lower water availability, disrupted food production, and higher energy demands, ultimately reducing resilience.

This study addresses this gap in literature by developing an analytical framework to quantify the impact of LULC changes on the composition and resilience of the WELF nexus. It advances our understanding of the complex interactions within interconnected systems and provides a versatile tool with broad applicability across diverse regions. We address three research questions: (i) how do WELF nexus elements and interactions evolve over time? (ii) how do these dynamics influence the composition of the WELF nexus at different spatial scales? (iii) what role do nexus elements and interactions play in determining the resilience of the WELF nexus? Our framework is applied to the Maria La Baja sub-watershed in the Colombian Caribbean, a region characterized by extensive agricultural expansion, deforestation, and socio-political instability. The analysis covers 2002 to 2018, a period of significant transformation in its productive structure.

To address questions (i) and (ii), we conduct multi-scale assessments to identify the diverse interests and drivers of change across spatial scales, ranging from regional to local (Bouma, 1998; Letourneau et al., 2012; Norström et al., 2014; Jiménez-Aceituno et al., 2020). An assessment that is too narrow might overlook important elements and interactions, while one that is too broad may fail to identify stakeholder interests. By assessing changes over time at different scales our framework aims to improve regional and local management coordination, aligning multiple interests to enhance nexus resilience (Brugmann, 1996; Ball, 2002; Reed et al., 2015; Satterthwaite, 2018; Smith et al., 2018; Stephens et al., 2018). Our framework is specifically applied to departments, municipalities, and veredas—the smallest rural subdivisions in a Colombian municipality. We introduce a network approach to address question (iii). Instead of viewing resilience only as a macroscopic property of the nexus, we decompose it into microscale components. By focusing on microscale components, we uncover different territorial patterns that reveal how and to what extent LULC change impacts the nexus ability to respond to disruptions. This network approach offers several methodological advancements for assessing resilience: it identifies feedback loops within nexus interactions (Wolde et al., 2021) and reveal implicit hierarchies of nexus element roles in enhancing resilience (Dawes, 2022).

The responses to (i), (ii), and (iii) show that generalized interventions focused on efficiency and redundancy goals may result in unintended resilience outcomes. To address this, we have identified a necessary condition for targeted interventions, which focus on key nexus elements and interactions, to effectively enhance resilience.

This study is organized as follows: Section 2 introduces the study area, providing relevant context and background. Section 3 details the methodology for data collection and processing and outlines the rationale behind our framework. Section 4 presents the research findings. Section 5 provides a discussion of the main findings, offers policy recommendations, and suggests ideas for future research. Section 6 concludes.

2. Case study

The Maria La Baja sub-watershed (MLBsw) is situated in the Montes de Maria region of the Colombian Caribbean, covering an area of 177,948 ha (Fig. 1). It plays a crucial role in providing a continuous water supply and favorable climatic conditions for agricultural production (Cely-Santos and Hernández-Manrique, 2021). This sub-watershed includes two departments, 12 municipalities, and 120 veredas. It is also home to several small rivers and streams that feed into the Magdalena River, a significant cultural landmark in Colombia. The combination of a warm climate and high humidity contributes to the region's productive agricultural conditions (Aguilera, 2013). However, over the past decade, MLBsw has experienced significant changes in rainfall and temperature patterns due to trade winds, resulting in extensive flooding and prolonged droughts, which have had a considerable impact on agricultural output (Melo Leon et al., 2017; Espitia et al., 2018). The study period, 2002 to 2018, was chosen to capture significant transformations in MLBsw, specifically the proliferation of palm oil plantations and the abandonment of agricultural lands. MLBsw has also been impacted by armed conflict and displacement, with 149,747 forced displacements recorded since 2002 (own calculation from national surveys). This is in addition to Colombia's peace agreement and subsequent policy and institutional changes in the country (Cely-Santos and Hernández-Manrique, 2021). These socio-political changes, along with climate variability, make MLBsw an ideal case study for exploring how and to which extent LULC changes affect the composition and resilience of the WELF nexus.

3. Methodology

This section introduces the analytical framework and the steps for assessing the impact of land use changes on the composition and resilience of the WELF nexus across spatial scales, as illustrated in the schematic flow chart in Fig. 2. The framework begins by addressing practical challenges in analyzing territorial resilience. It characterizes WELF nexus elements within the study area using geospatial land use data (Section 3.1) and examines how land use changes affect the interactions among these elements (Section 3.2). Resilience is defined as a macroscopic property of the WELF nexus, reflecting its ability to maintain function in response to disruptions. It is quantified as a balance between two opposing dimensions: efficiency, which favors economic performance, and redundancy, which favors ecosystem conservation and the preservation of option value (Section 3.3). The main innovation of this framework is its network-based approach to resilience (Section 3.4), which decomposes resilience into microscale components, helping to understand how individual nexus elements and their interactions contribute to system-wide resilience. Focusing on elements, interactions, and feedback loops, the framework uncovers territorial patterns, showing how micro-level land use dynamics affect the ability of the nexus to respond to disruptions. Finally, the multi-scale approach of the framework, from regional to local, provides actionable insights for decision-makers.

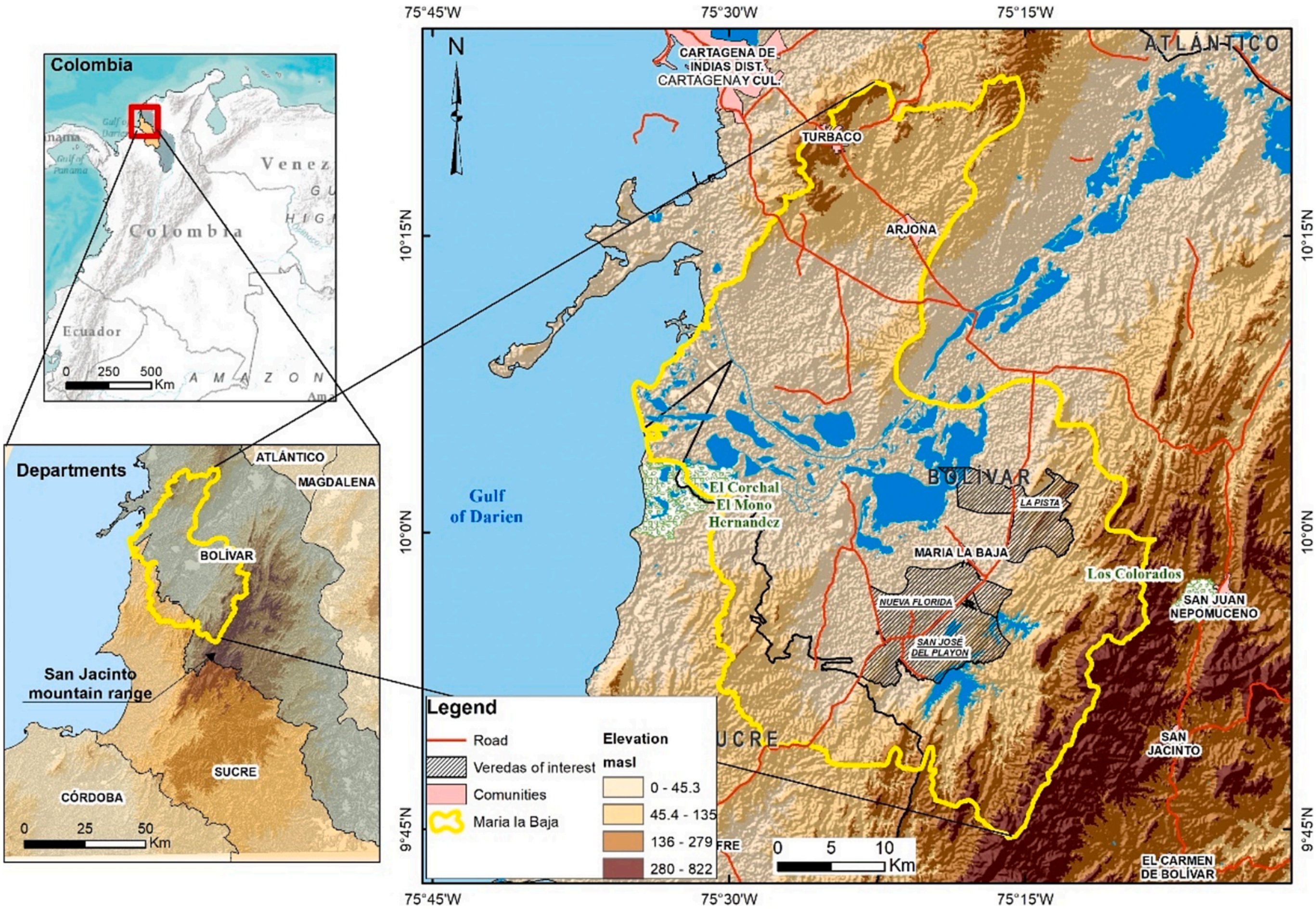

Fig. 1. Regional context and location of Maria La Baja sub-watershed.

3.1. *The WELF nexus*

This section includes a workflow of data collection (Section 3.1.1), nexus element classification (Section 3.1.2), and spatial intersection operations (Section 3.1.3), as illustrated in Fig. 3.

3.1.1. *Data collection*

Geospatial LULC data were obtained from the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM). These data consist of four annual LULC maps from 2002, 2009, 2012 and 2018 at a scale of 1:100.000. IDEAM created these maps in digital vector format in polygon form. The LULC maps follow the Corine Land Cover methodology using Landsat satellite images[1] with a spatial resolution of 30 m. All the maps meet the spatial and thematic accuracy[2] standards defined by the Colombian Institute of Geography and Cartography (IGAC). After data collection, LULC changes among different time periods were detected via reclassification of nomenclature and intersection operations. All processes in this workflow were written using Python (version 3.8.5) code on Jupyter notebooks.

3.1.2. *Nexus element classification*

The comparison between maps with dense nomenclatures such as Corine Land Cover makes it challenging to detect LULC changes. While the legend classes for levels 1 and 2 remain the same as the Europe Corine Land Cover legend, the classes from level 3 to level 6 were adapted by IDEAM for Colombia (IDEAM, 2010), varying in the different groups of coverages. Such variations depend on the type of coverage and detail of the application. In this context, it was important to synthesize the classes provided by IDEAM (2010), with the purpose of clearly identifying potential changes. In this process, we reviewed all the previous levels and, depending on the complexity of the class, either merged the level up (e.g., aquatic vegetation, rivers, and lakes were clustered as the water class) or left it as the original Corine Land Cover class (e.g., palm oil plantation class). This homologation ended up with 11 thematic LULC classes that were uniformly used in all maps. These classes were used to assess spatial–temporal changes and develop thematic LULC maps of the study area.

Once LULC maps were created, each class was assigned to one of the WELF nexus elements. A limitation of this approach is the assignment of LULC to WELF nexus elements based on a desk-based classification only. This assignment needs further field data collection and interviews with stakeholders for verification and quality control. To overcome this limitation, we assigned LULC to WELF nexus elements in two consecutive steps. First, we reviewed the related literature to identify which LULC classes were more closely associated with each element of the WELF nexus, e.g., the forest class was interpreted as Water (Brockerhoff et al., 2017; Sheil, 2018) and oil palm agriculture was assigned to Energy (Marin-Burgos and Clancy, 2017). Second, ancillary data was used to increase the quality of the assignments. The ancillary data included national statistics, cadastral information, and national agricultural surveys, which allowed us to identify the most common socio-economic activities in the study area during the study period. For instance, this

[1] Image sources are Landsat 5 and 7 for years 2002 and 2009, Landsat 7 for year 2012, and Landsat 8 for year 2018.

[2] The overall thematic accuracy is not given for years 2002 and 2009. However, it is around 85% for years 2012 and 2018.

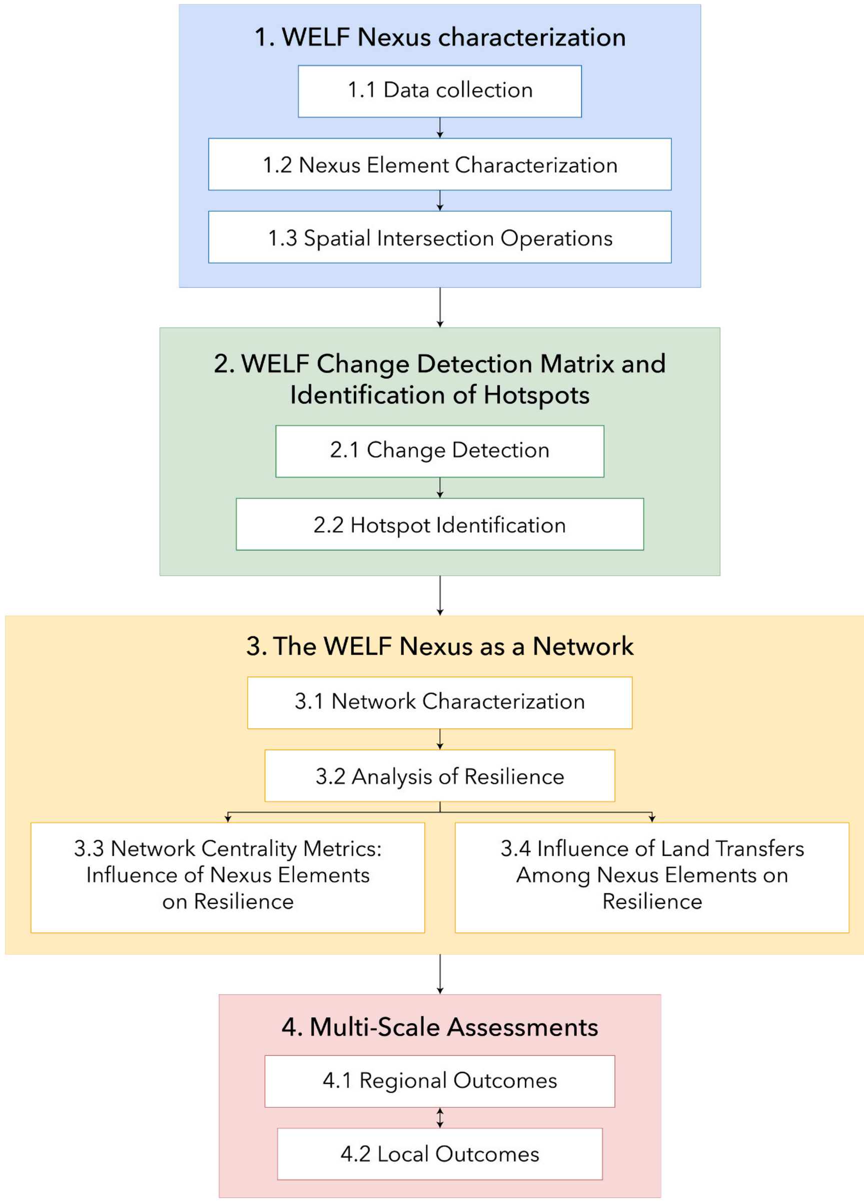

Fig. 2. Schematic flow chart of the analytical framework.

information helped us identify that mining is unrelated to Energy because its primary focus lies in the extraction of construction materials for roads and buildings. Table A1 (Appendix A) summarizes the assignment process, complemented with qualitative explanations.

Another limitation of this approach is the assignment of each LULC class to a single WELF nexus element. In reality, land use can serve multiple purposes simultaneously. For instance, grassland mosaics might provide both grazing (Food) and water regulation (Water) services. While our framework simplifies these functions, future research could explore more complex multi-functional classifications.

The assignment of LULC classes to WELF nexus elements was approached in the following manner. Water was interpreted as all LULC classes related to water supply and regulation, such as forests, wetlands and paramo areas, water bodies, or permanently oversaturated soils with vegetation (Baker and Miller, 2013; Siddik et al., 2022). Energy was associated only with palm oil plantation (Cely-Santos and Hernández-Manrique, 2021). Food was interpreted as all LULC classes oriented to food production, such as croplands, grazing land for livestock, and land oriented to aquaculture production (Wolde et al., 2021).

The cluster comprising Water, Energy, and Food did not encompass all the land in the study area, due to incomplete coverage of LULC classes. Hence, four additional nexus elements were identified and analyzed. These supplementary elements comprise both permanent land use classes and land use transitions: (i) Urban, (ii) Other, (iii) Anthropic Transition (AT), and (iv) Natural Transition (NT). Urban includes continuous and discontinuous urban fabric, industrial and commercial areas, the entire road and rail network and associated land, and airports. Other refers to any land-based economic activity other than Energy or Food. In this context, it was interpreted only as mining areas. AT includes all LULC classes that have not yet been assigned to the nexus, but with evident current human intervention leading to transformed land use, e.g., bare and degraded lands and burned areas. Similarly, NT includes all LULC classes that have not yet been assigned to the nexus, but with no evident current human intervention leading to transformed land use, e.g., secondary or transition vegetation, natural sandy areas, and rocky open grasslands. Following deforestation or afforestation activities, NT marks the initial phase of plant succession that occurs primarily in abandoned agricultural lands (IDEAM, 2010). NT does not exclude past human interventions; rather, it represents an uncertain period that may result in either Water or land-based economic activities such as

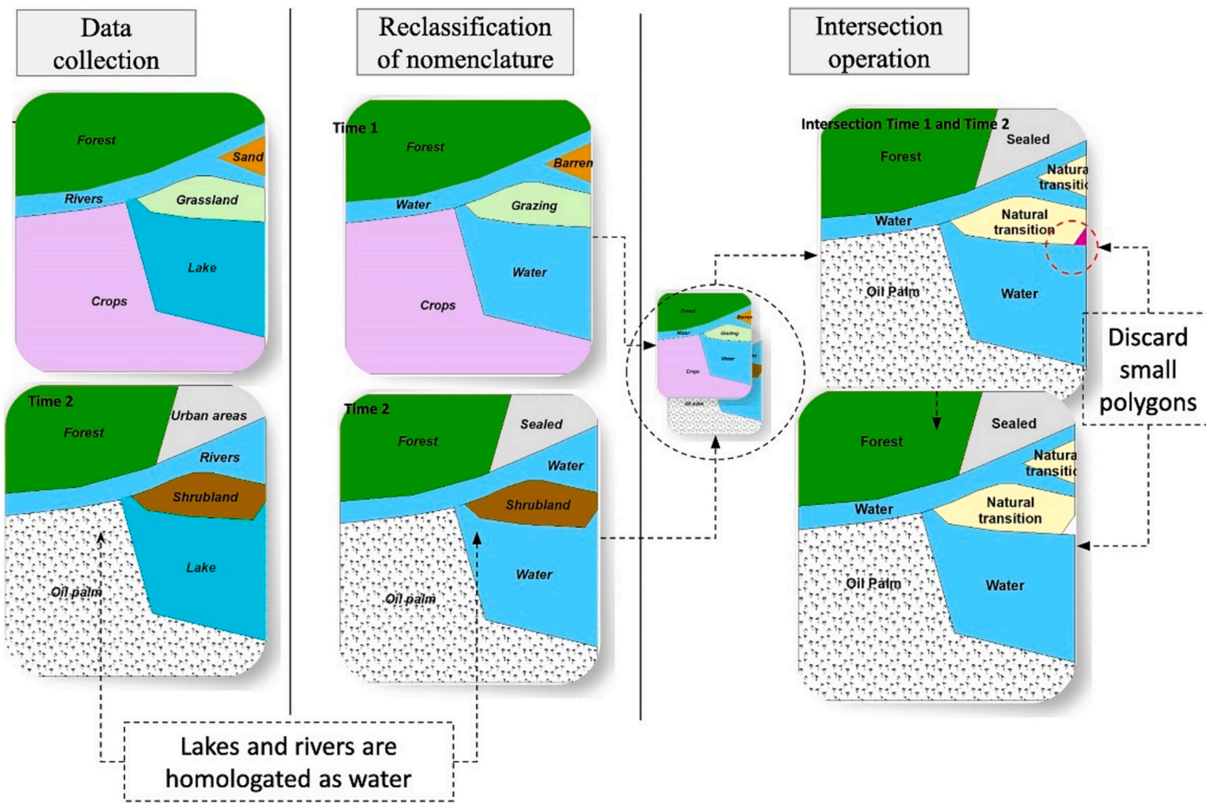

Fig. 3. Schematic workflow representing LULC data processing.

Food or Energy. These seven nexus elements constitute the WELF nexus in the study area.

3.1.3. Intersection operation

The intersection operation process aims to identify changes in the sequences of LULC-WELF (WELF nexus) element maps by overlapping the maps with significant variations. That is, we use LULC maps assigned to the WELF elements. The selection of an appropriate minimum mapping unit of analysis is an important consideration, as it significantly affects the accuracy and relevance of intersection operations for their intended use (Knight and Lunetta, 2003; Congalton and Green, 2008). In this study, a minimum mapping unit was established at 0.4 ha, based on the technical specifications provided by IDEAM (2010), ensuring that the analysis aligns with the study's objectives and LULC characteristics of the study area. Therefore, any polygons smaller than this threshold were excluded from the calculations. The magnitude of change for each nexus element between two consecutive time points, i.e., 2002–2009, 2009–2013, and 2013–2018, was measured in hectares and determined as follows

$$\Delta A_i = A_i^{t+1} - A_i^t \tag{1}$$

where i denotes the nexus element, A_i the total area that i represents in the study area, and t the year of analysis. Year 2002 is the baseline for calculations. In Appendix B, we present the economic model underlying this analytical framework.

3.2. Change detection matrix and hotspots

The WELF nexus was characterized as a series of pairwise interactions within and among its elements in the form of a change detection matrix. The strength of each interaction is defined by the magnitude of change, equation (1), within and among nexus elements. The change detection matrix allows us to determine the directionality of changes that occurred during the stated period. Each interaction represents a transfer in terms of LULC change, in hectares, between pairs of nexus elements. Transfers within the WELF nexus behave as a zero-sum game in which one nexus element's gain is equivalent to another element's loss; therefore, net LULC change is zero. Additionally, we identify hotspots as sub-regions where the magnitude of change was most significant. Hotspots identify areas where LULC change is more intense, e.g., those veredas that present favorable socio-economic conditions for promoting Energy.

3.3. Resilience

Resilience is defined as a macroscale property of socio-ecological systems that requires a balance between two opposing dimensions: efficiency and redundancy (Ulanowicz, 2019). We analyze these dimensions within the context of the WELF nexus, with resilience metrics presented in Section 3.4.1. Efficiency is related to competition for land (Martin et al., 2018) and is favored by concentrated land use, determined by the structure of opportunity costs discussed in Appendix B. These opportunity costs reflect the value lost by forgoing alternative uses of land. However, highly efficient nexuses may become undesirable as they increase the risk of losing option value, i.e., the value of having a more diverse set of options in the future, which implies challenges for intergenerational justice (Meyfroidt et al., 2022). If a nexus element is disrupted, the flow of transfers is impaired or completely interrupted. Redundancy is related to the capacity of the WELF nexus to increase maneuverability in the provision and exchange of land use transfers (Kharrazi, 2019). It prevents bottlenecks and contributes to maintaining the flow of transfers that are active during disruptions. Conversely, highly redundant nexuses often exhibit stagnation, lack the capacity to promote economic growth, and result in fewer total transfers (Kharrazi et al., 2017). For these reasons, resilience requires a balance between efficiency and redundancy.

3.4. Network-based approach to resilience

This section presents how the network approach can be used to decompose resilience into microscale components. The importance of individual WELF elements and their interactions, with respect to their contribution to the efficiency and redundancy of the nexus, is captured through two network centrality metrics.

3.4.1. The WELF nexus as a network and resilience metrics

The transformation of the change detection matrix into a network is as follows. The network of links is represented by $g = (V, S, \omega)$, where $V : \{1, ..., n\}$ is the set of nexus elements and S the set of links among them. The elements in set S consists of the values of the indicatrix link function $\ell : V \times V \rightarrow \{0, 1\}$, where $\ell_{ij} \in \{0, 1\}$ indicates whether any pair of nexus elements $(i, j) \in V$ are linked, $\ell_{ij} = 1$, or not, $\ell_{ij} = 0$. Self-loops, $\ell_{ii} = 1$, indicate that land use transfers occur within the same nexus element, i.e., persistence. The network is weighted and $\omega_{ij} \in \mathbb{R}_+$ denotes the strength of land use transfers (number of hectares changing) from i to j. It is directed since transfers between element pairs may not coincide, $\omega_{ij} \neq \omega_{ji}$. For any $i \in V$, let $k_i^{out} = \sum_{j \in V} \ell_{ij}$ and $k_i^{in} = \sum_{j \in V} \ell_{ji}$ respectively denote the out-degree and in-degree of i, referring to the number of links pointing out and in from i. Similarly, $u_i^{out} = \sum_{j \in V} \omega_{ij}$ and $u_i^{in} = \sum_{j \in V} \omega_{ji}$ respectively denote the outflow and inflow of transfers that involve i.

Once the network is characterized, resilience metrics are introduced. Efficiency is denoted by $\eta \in \mathbb{R}_+$ and computed by

$$\eta = \sum_{i,j} \frac{\omega_{ij}}{\omega_{..}} \log \frac{\omega_{ij} \omega_{..}}{u_i^{out} u_j^{in}} \tag{2}$$

Where $\omega_{..} = \sum_{i=1}^{n} \sum_{j=1 \neq i}^{n} \omega_{ij}$ denotes total transfers. Redundancy is denoted by $\beta \in \mathbb{R}$ and computed by

$$\beta = -\sum_{i,j} \frac{\omega_{ij}}{\omega_{..}} \log \frac{\omega_{ij}^2}{u_i^{out} u_j^{in}} \tag{3}$$

Resilience is denoted by $\Re \in \mathbb{R}_+$ and computed by

$$\Re = -\alpha \log \alpha \tag{4}$$

The ratio $\alpha = \frac{\eta}{\eta + \beta} \in [0, 1]$ measures the balance between efficiency and redundancy. According to equation (4) and given that $\alpha \in [0, 1]$, maximum theoretical resilience is achieved when $\Re_{\max} = 0.16$, occurring under the condition that $\alpha = 0.37$. As a general guideline, a slight bias toward redundancy is typically preferred to enhance resilience (Kharrazi et al., 2016; Kharrazi, 2019). Minimizing deviations from maximum theoretical resilience levels can serve as a preventive adaptive management strategy, protecting the socio-ecological system from reaching an irreversible tipping point (González, 2023).

3.4.2. Network centrality metrics: Influence of nexus elements on resilience

3.4.2.1. Weighted page rank centrality. Weighted page rank centrality (C) relates to efficiency, as it evaluates the centrality of a nexus element based on endorsement. Endorsement means that the more transfers a nexus element has pointing to it, and the more important those linking elements are, the higher the C score is. Higher C scores are indicative of greater significance in determining the directionality and intensity of transfers, as well as improved functionality of the WELF nexus. C has been proven to perform well in weighted, directed networks (Zhang et al., 2022) such as the WELF nexus. The score $C_i \in [0, 1]$ of each nexus element i is computed by

$$C_i = \gamma \left(\sum_{j \in V} \frac{\ell_{ji} \omega_{ji}}{u_j^{out}} C_j \right) + \frac{(1 - \gamma) \beta_i}{\sum_{i \in V} \beta_i} \tag{5}$$

With $\sum_{i=1}^{n} C_i = 1$. C_i is influenced by the centrality of all the other nexus elements i is linked to, C_j. Parameter $\gamma \in [0, 1)$ improves the performance of the algorithm, with a damping factor of $\gamma = 0.85$ by default (Zhang et al., 2022). Parameter $\beta_i \in \mathbb{R}_+$ refers to some element-specific quantifiable information attached to i, e.g., the importance of i in terms of total land shares. β_i is independent of land use transfers ω_{ij} and $L = \sum_{i=1}^{n} \beta_i = 1$, where L denotes total land, in hectares.

3.4.2.2. Betweenness centrality. Betweenness centrality (BC) relates to redundancy, as it evaluates the centrality of a nexus element based on how often it acts as a bridge, i.e., a transfer facilitator, between other nexus elements. It computes the number of shortest paths between pairs of nexus elements that pass through a particular nexus element. Higher BC scores are indicative of greater potential to control the flow of transfers within the WELF nexus during disruptions. The score $BC_i \in \mathbb{R}_+$ of each nexus element i is computed by

$$BC_i = \sum_{i \neq j \neq k} \frac{\sigma_{jk}(i)}{\sigma_{jk}} \tag{6}$$

Where $\sigma_{jk} \in \mathbb{R}_+$ denotes the number of shortest paths from element j to element k, and $\sigma_{jk}(i) \in \mathbb{R}_+$ denotes the number of those paths that pass through element i, such that $\sigma_{jk}(i) \leq \sigma_{jk}$. We use $\widetilde{\omega}_{ij} = 1/\omega_{ij}$ as an indicator of the distance between nexus elements. That is, higher transfers from i to j indicate shorter distance among them.

3.4.3. Network interactions: Influence of land use transfers on resilience

To assess the interactions among nexus elements in terms of land transfers that most effectively enhance resilience, we analyze the impact of a percentage change in land transfers between pairs of nexus elements. In this study, we present a 30 % land transfer scenario as a feasible projection. The 30% increase from i to j is calculated as $\omega_{ii}^{t+1} = \omega_{ii}^t - 0.3\omega_{ii}^t$ and $\omega_{ij}^{t+1} = \omega_{ij}^t + 0.3\omega_{ii}^t$, where ω_{ii}^t denotes both the absence of transfers and transfers that occur within the same nexus element. Similarly, a 30% decrease from i to j is calculated as $\omega_{ii}^{t+1} = \omega_{ii}^t + 0.3\omega_{ii}^t$ and $\omega_{ij}^{t+1} = \omega_{ij}^t - 0.3\omega_{ii}^t$, however, if $0.3\omega_{ii}^t \geq \omega_{ij}^t$ then $\omega_{ii}^{t+1} = \omega_{ii}^t + \omega_{ij}^t$ and $\omega_{ij}^{t+1} = 0$. By analyzing all transfers between nexus element pairs, we evaluate how and to which extent land transfers influence efficiency, redundancy, and resilience at both the regional and local scales, with the effects expressed as percentages of change.

4. Results

4.1. The WELF nexus

Fig. 4 displays the LULC classes and assignments to the WELF nexus elements in the study area. Fig. 5 illustrates changes in the WELF elements over the consecutive periods: 2002–2009, 2009–2012, and 2012–2018. We identified several patterns in LULC change. The central-western part of the region is predominantly characterized by water bodies such as swamps and marshes. This part has been partially unaltered over time. Conversely, the southeastern part has a significant concentration of forested areas that have undergone rapid degradation due to the expansion of the agricultural frontier, especially since 2009. Both the northern and southern parts of the region have significant areas of abandoned agricultural lands. The expansion of palm oil plantations is mainly concentrated in the central-eastern part of the region, which witnessed a significant boom between 2002 and 2009, followed by another expansion between 2012 and 2018.

Table 1 reports the WELF nexus dynamics during the stated period. In year 2002 (baseline), Food and Water were the most significant nexus elements, accounting for 98.13% of the total land. Over time, the share of these two nexus elements decreased, with Water experiencing the most significant loss (32%), followed by Food with 8.88%. NT and Energy were the nexus elements that experienced the most significant

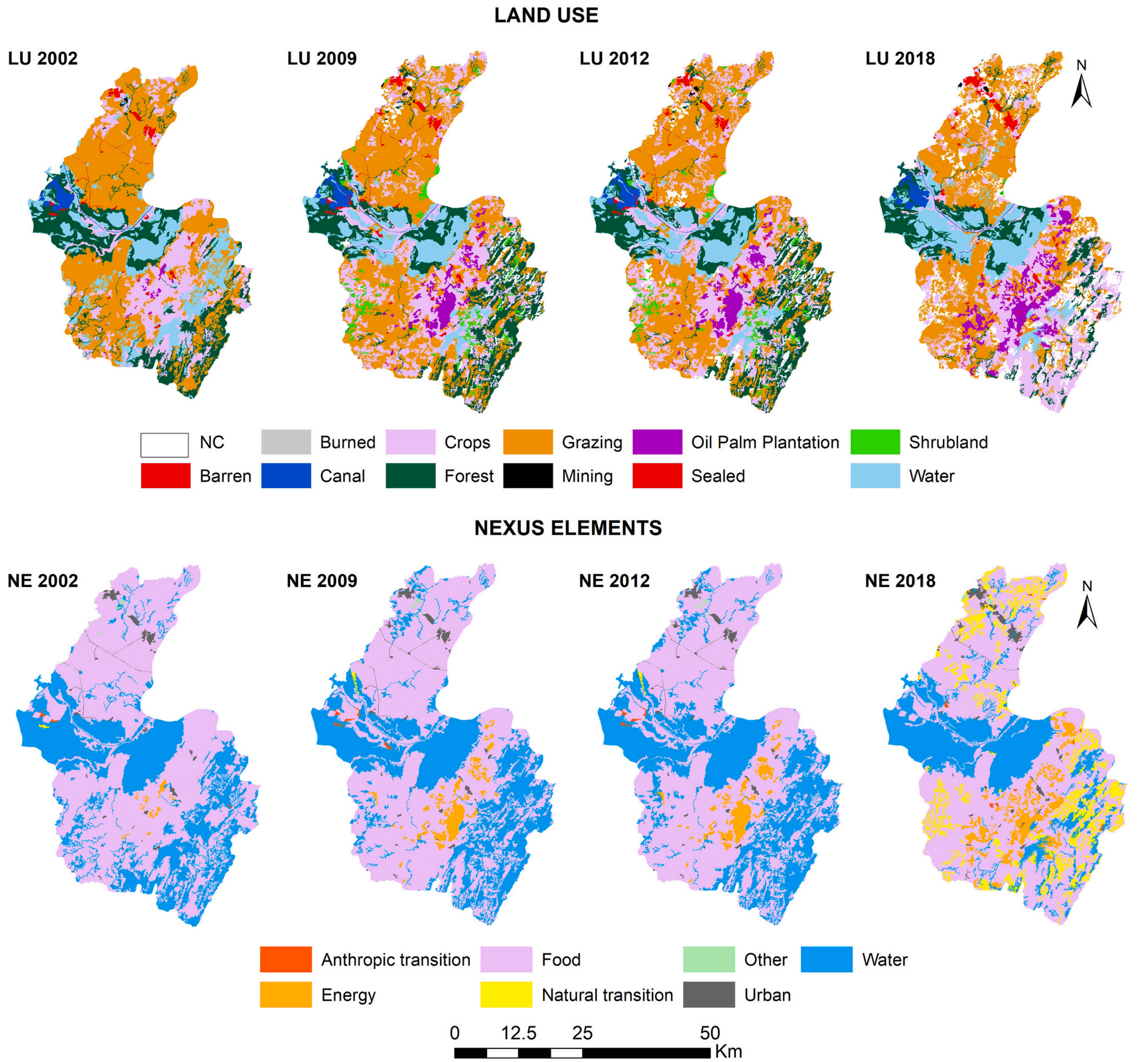

Fig. 4. Upper panel: LULC in Maria la Baja sub-watershed. Lower panel: Assignments of LULC to WELF nexus elements. Years 2002, 2009, 2012, and 2018.

increase, with growth rates of 1,681.31% and 1,268.67%, respectively. In 2018, NT and Energy represented 17.51% of total land, while in 2002 they represented only 1.07% of total land. The rapid increases of NT and Energy began in 2012. The cluster comprising Water, Energy, Food and NT accounted for 98.91% of total land at the end of the stated period, whereas the cluster comprising Urban, Other and AT accounted for only 1.09% of total land. These results confirm the rapid transformation that the WELF nexus has undergone in recent years.

4.2. Change detection matrix and hotspots

Table 2 presents the change detection matrix describing interactions among WELF nexus elements. Each cell represents the average land transfers, in hectares (Ha), between pairs of elements during the stated period. The diagonal accounts for intra-element transfers and non-transfers, while the other cells convey transfer directionality and magnitude, showing how one element may increase at the expense of another. Higher transfers involve Water to Food (6,272.45 Ha), Food to Energy (2,490.66 Ha), NT to Food (1,323.98 Ha), and Food to NT (1,176.46 Ha). Most of these transfers follow the opportunity cost structure presented in Appendix B. However, transfers to NT are influenced by opportunity costs and other socio-economic factors. NT gains more from agricultural land abandonment (65% of total gains), due to armed conflict or decreases in agricultural yield, compared to deforestation (35%), which is driven by the expansion of the agriculture frontier or peasants seeking better yields. Water to Energy losses, such as deforestation, are lower than Food to Energy losses, with Energy gaining 93% from Food and 7% from Water. In contrast, Food gains 79% from Water. In the final row of Table 2, persistence indicates the likelihood of no transfer among nexus elements. Persistence levels are derived from a multinomial logistic regression model, as described in Appendix C. The results highlight NT and Water as the elements most prone to losses in favor of other nexus elements.

The average size of transfers to Energy was 56 Ha (136), to Food 73 Ha (194), to Water 62 Ha (194), to NT 62 Ha (95), and to Urban 9 Ha (19). Standard deviation in parentheses.

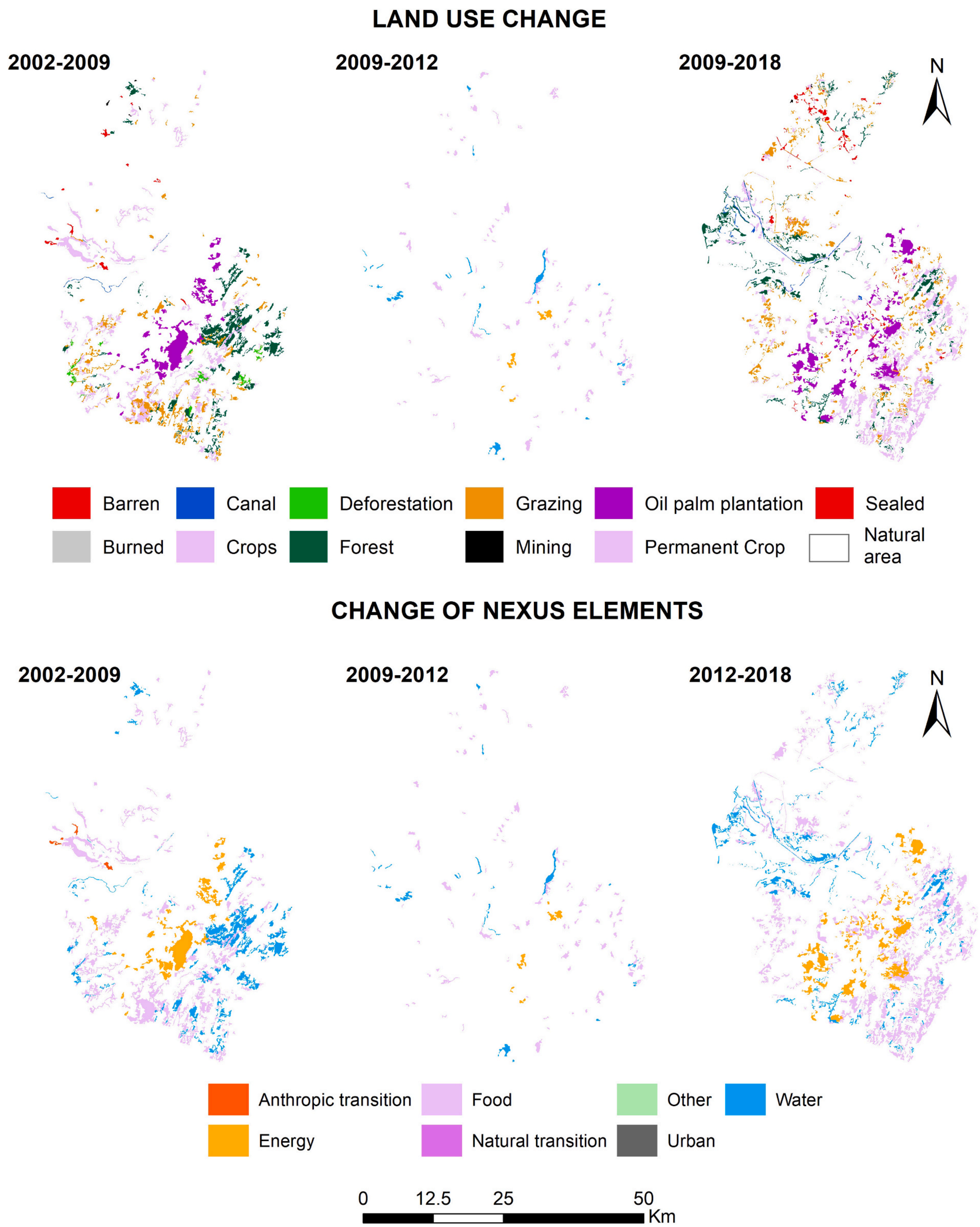

Fig. 5. Upper panel: LULC changes in the Maria la Baja sub-watershed. Lower panel: Changes in WELF elements. Changes are measured over consecutive periods: 2002–2009, 2009–2012, and 2012–2018.

At sub-regional scales, we identify concentration patterns. Maria La Baja municipality dominates Energy (79.25%), while other municipalities contribute to Energy to varying extents: San Onofre (8.8%), Mahates (5.95%), Arjona (4.7%), and El Carmen de Bolivar (1.3%). Food and Water are distributed across all municipalities, yet three municipalities are key, holding 64.59% of Food and 76.15% of Water. These are Maria La Baja (30.26% Food and 31.35% Water), Arjona (20.86% and 36.9%), and San Onofre (13.47% and 7.9%). This indicates concentrated land use for Energy and Food in these three municipalities. In contrast, NT shows a more uniform distribution, with significance in Maria La Baja (16.65%), San Juan Nepomuceno (16.63%), Arjona (12.54%), San Onofre (12.23%), and Turbaco (12.16%). Agricultural land abandonment and deforestation trends are notably pronounced in municipalities with low Energy presence.

Table 1
Changes in WELF nexus elements, in hectares, in MLBsw. Period 2002–2018.

Baseline (Year 2002)			Year 2009		Year 2012		Year 2018		Total variation in 2002–2018	
WELF element	Hectares (Ha)	%	Hectares (Ha)	%	Hectares (Ha)	%	Hectares (Ha)	%	Hectares (Ha)	%
Energy	695.44	0.39	5,194.07	2.92	4,911.00	2.76	9,518.23	5.35	8,822.79	1,268.67
Food	112,980.65	63.49	109,868.84	61.74	110,333.87	62.00	102,950.13	57.85	−10,030.52	−8.88
Other	159.48	0.09	213.15	0.12	218.16	0.12	166.53	0.09	7.05	4.42
A Transition	153.59	0.09	372.60	0.21	273.86	0.15	346.60	0.19	193.01	125.67
N Transition	1,214.70	0.68	7,239.51	4.07	8,315.91	4.67	21,637.56	12.16	20,422.86	1,681.31
Urban	1,104.07	0.62	1,180.90	0.66	1,190.11	0.67	1,418.72	0.80	314.65	28.50
Water	61,640.58	34.64	5,3879.43	30.28	52,705.60	29.62	41,910.73	23.55	−19,729.86	−32.01
Total	177,948.50	100	177,948.50	100	177,948.50	100	177,948.50	100	0	

Table 2
Change detection matrix, in hectares, and persistence in MLBsw. Period 2002–2018. Percentages with respect to total land in parentheses.

WELF elements	Energy	Food	Other	A Transition	N Transition	Urban	Water
Energy	2,222.73 (1.7 %)	159.10 (0.12 %)	0	0	0	6.40 (0 %)	0
Food	2,490.66 (1.9 %)	72,793.33 (54.6 %)	17.49 (0.01 %)	94.93 (0.07 %)	1,176.46 (0.88 %)	152.47 (0.1 %)	2,287.38 (1.7 %)
Other	0	6.34 (0 %)	129.53 (0.1 %)	0	0	0	0
A Transition	0	56.51 (0.04 %)	0	113.37 (0.09 %)	0	0	8.58 (0 %)
N Transition	4.92 (0 %)	1,323.98 (1 %)	0	16.92 (0.01 %)	7,975.70 (5.98 %)	9.23 (0 %)	224.91 (0.17 %)
Urban	0	101.76 (0.08 %)	0	0	0	776.86 (0.58 %)	6.40 (0 %)
Water	187.52 (0.14 %)	6,272.45 (4.7 %)	2.44 (0 %)	23.05 (0.02 %)	146.08 (0.1 %)	2.47 (0 %)	34,560.72 (26 %)
Persistence	0.77	0.77	0.83	0.65	0.58	0.82	0.58

Finally, we identified vereda-scale hotspots. By focusing on Maria La Baja municipality, accounting for 36% of total transfers in the study area, we anticipate more competition for land here than in an average municipality. In contrast, Arjona municipality, a distant second, is responsible for only 13% of total transfers. Individual transfer sizes[3] exceed regional averages by 12.24%. Table 3, shaded in grey, highlights three key hotspots within Maria La Baja: Nueva Florida (NF), San Jose Playon (SJP), and La Pista (LP). These veredas have the highest accumulated transfers over time.

NF leads with 14% of total transfers, followed by LP at 12.9% and SJP at 11.3%. These hotspots in the WELF nexus show distinct patterns (see Figs. D1-D3 in Appendix D). (i) NF exhibits a remarkable 600% increase in Energy, covering 1,838.72 Ha; a 32% decrease in Food, spanning 3,006.99 Ha; and a 97.98% drop in Water, covering 5.26 Ha. Compared to the regional case, persistence levels and transfer sizes are respectively 2.9% and 13.93% higher. (ii) In contrast to regional and municipal scales, LP experiences full-scale deforestation due to Energy and Food expansion: 260.2 Ha for Energy (absent in 2002), 3,479.43 Ha for Food (2% decrease), and 1,117.05 Ha for Water (32% decrease). Compared to the regional case, persistence levels and transfer sizes are 2.84% and 14.05% lower. LP, despite favorable conditions for Energy and Food, shows limited expansion in these nexus elements. (iii) SJP, on the other hand, witnesses a dramatic 4,489.82% increase in Energy (1,649.89 Ha), a 33.81% decrease in Food (2,911.42 Ha), and a 56.54% decrease in Water (490.06 Ha). In comparison to the regional case, persistence levels are 4.72% higher, and transfer sizes are 12.23% lower. SJP follows a similar pattern to NF, with substantial Energy expansion and comparatively lower Water losses.

The vereda-based hotspot selection reveals differing trends from regional and sub-regional scales. For instance, Energy significantly contributes to Water losses, observed in NF and somewhat in SJP. Further analysis follows in the subsequent sections.

4.3. Resilience

Table 4 and Fig. 6 present resilience variations at regional and vereda scales. The dotted line in Fig. 6 serves as a benchmark calculated through theoretical analysis. The vertical line represents the maximum theoretical resilience point, with more redundancy to its left and more efficiency to its right. Redundancy prevails over efficiency in half of the WELF nexus analyzed (veredas NF and LP), with resilience values of 0.14 and 0.16, respectively. NF exhibits the lowest efficiency at 0.14, potentially due to its low quantity of transfers per interaction (16.9 Ha per interaction[4]), as seen in Table D1 (Appendix D) and Fig. 8. This may put the WELF nexus at risk of stagnation. Conversely, the regional case and vereda SJP demonstrate a dominance of efficiency over redundancy, with resilience values closely approaching the theoretical maximum (Fig. 6). This situation carries the potential risk that concentrated land use will lead to increased efficiency but, at the same time, a decrease in resilience.

4.4. Network-based approach to resilience

4.4.1. Network centrality metrics: Influence of nexus elements on resilience

We limit the focus of this section to comparisons between the regional case and NF. The remaining two cases, LP and SJP, are presented in Appendix D. Fig. 7 illustrates the transformation of the change detection matrix (Table 2) into a network at the regional scale. Nexus elements are represented by nodes; transfers between them are indicated by links. The directionality of transfers is shown with arrows, while the width of links represents the intensity of transfers. Wider links indicate greater transfers among nexus elements. The size of a node is adjusted

[3] Average sizes were Energy 69 Ha (158), Food 88 Ha (206), Water 80 Ha (240), NT 84 Ha (117), and Urban 8 Ha (11). Standard deviation in parentheses.

[4] Quantity of transfers (Ha) per interaction in the other three nexuses are 138.76 (regional case), 24.9 (SJP) and 23.19 (LP).

Table 3
Vereda-based hotspot selection in Maria La Baja municipality, where significant quantity of transfers, in hectares (Ha), occurred between 2002–2018.

Vereda name	Area where transfers (in Ha) among nexus elements occurred			% of total transfers			
	2002–2009	2009–2012	2012–2018	2002–2009	2009-2012	2012-2018	Average 2002–2018
Bolito	512.23	0.00	703.86	5	0	7	4.1
Colu	42.41	0.87	202.36	0	0	2	0.9
Correa	55.19	79.58	255.23	1	5	3	2.8
Flamenco	489.96	173.34	543.28	5	12	6	7.4
Guaricimo	344.66	114.21	318.96	4	8	3	4.8
Isla Providencia	339.69	0.00	407.19	3	0	4	2.5
La Pista	1,014.77	262.55	1,031.57	10	18	11	12.9
Majagua- San Pablo	377.77	306.03	373.92	4	21	4	9.4
Mampujan	1,121.69	71.35	319.24	12	5	3	6.5
Manguma	552.15	24.93	884.68	6	2	9	5.5
Matuya	257.36	0.00	992.28	3	0	10	4.3
Montecarlo	307.41	74.25	492.46	3	5	5	4.4
Nispero	607.98	118.63	687.46	6	8	7	7.1
Nueva Florida	1,750.93	149.14	1,367.98	18	10	14	14.0
San Jose Playon	1,872.39	65.08	1,022.27	19	4	10	11.3
Santa Fe de Icotea	36.73	0.97	82.39	0	0	1	0.4
Sena	60.88	44.33	124.05	1	3	1	1.6
TOTAL	**9,744.21**	**1,485.27**	**9,809.17**	**100**	**100**	**100**	**100**

Table 4
Resilience of the WELF nexus, and dimensions of resilience, at different sites.

	Regional	Nueva Florida (NF)	San Jose Playon (SJP)	La Pista (LP)
Efficiency	0.26	0.14	0.29	0.22
Redundancy	0.34	0.46	0.38	0.47
Alpha	0.43	0.23	0.43	0.32
Resilience	0.16	0.14	0.16	0.16

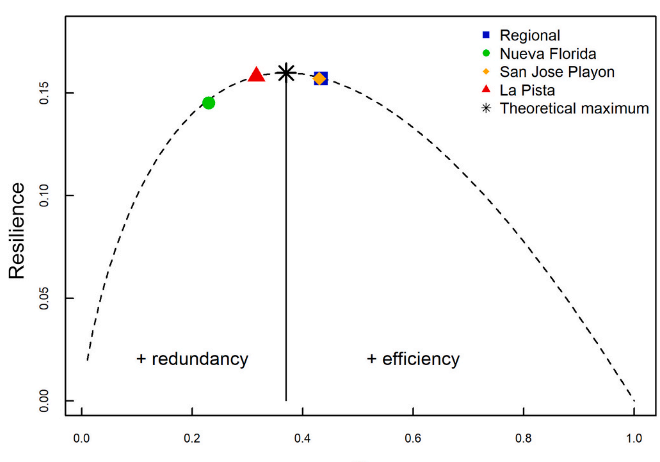

Fig. 6. Resilience of the WELF nexus at different sites.

according to weighted page rank centrality scores, reflecting the node's ability to attract transfers within the WELF nexus. The resulting network is depicted using a blue scale, where darker nodes indicate the highest centrality scores, and darker links indicate all transfers starting from those nodes.

Table 5 summarizes the significance of nexus elements based on different characteristics analyzed: total land shares (Table 1), efficiency, and redundancy. It reveals important differences among nexus elements. Although Energy accounts for only 2.85% of the total land, it ranks third in terms of influencing efficiency, primarily due to its strong interactions with the most important nexus elements in terms of total land shares: Food (87%) and Water (13%). Energy presents the lowest opportunity

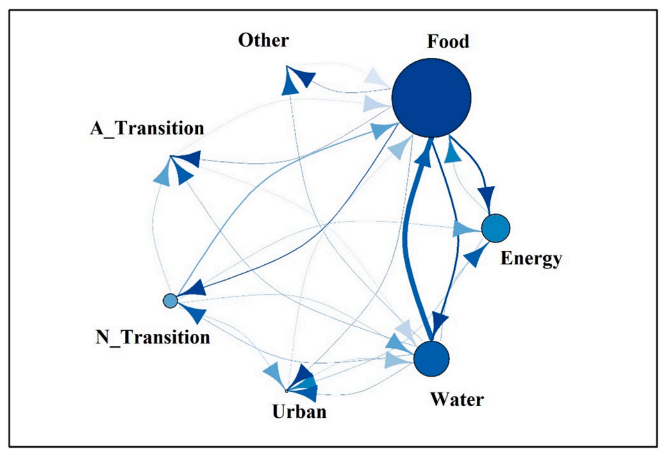

Fig. 7. The WELF nexus as a network in the regional scale, period 2002–2018.

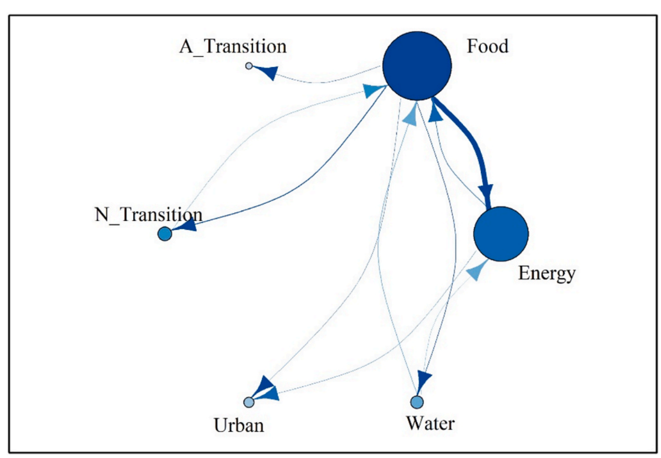

Fig. 8. The WELF nexus as a network in Nueva Florida, period 2002–2018.

costs of nexus elements, making it function as a sink, i.e., an attractor of transfers, within the WELF nexus. This factor, along with its very limited interaction with other nexus elements, contributes to its poor

Table 5
Significance of nexus elements according to total land shares and network centrality metrics. The regional case.

Nexus element	Total land shares		Weighted page rank centrality (Efficiency)		Betweenness centrality (Redundancy)	
	Score	Ranking	Score	Ranking	Score	Ranking
Energy	2.85	4	0.18	3	0	
Food	61.27	1	0.49	1	29	1
Other	0.11	7	0.00	7	0	
A Transition	0.16	6	0.01	6	0	
N Transition	5.40	3	0.09	4	0	
Urban	0.69	5	0.02	5	0	
Water	29.52	2	0.22	2	5	2
Total	100		1		34	

performance in redundancy. Water represents a significant share of the total land (29.52%) and ranks second in influencing efficiency. Unlike Energy, Water serves as a source, i.e., an origin of transfers, in the nexus, as illustrated in Table 1. The high opportunity costs of Water compared to other nexus elements may largely account for this result. In all analyses, Food consistently ranked first. This suggests that Food plays a crucial role in maintaining the continuous flow of transfers within the nexus, due to its direct or indirect participation in most transfers. Compared to Water, Food has a greater influence on redundancy, due to the significantly higher number of transfers involving it. More transfers decrease the distance between Food and other nexus elements, leading to improved centrality scores. NT ranked third in total land shares and fourth in efficiency. Although NT interacts primarily with Water and Food, much like Energy, its influence on efficiency is less significant compared to Energy, due to the lower intensity of transfers involved.

Similarly, Fig. 8 depicts the WELF nexus in NF for the stated period, using the same node and link characterization as before.

Table 6 summarizes the differences in the significance of nexus elements for NF. Importantly, Energy yields different results compared to the regional case, as it now accounts for 26.52% of total land and holds a significantly greater influence in efficiency. Again, this result is explained by the fact that many transfers to Energy (80%) are from Food, the key nexus element in land shares. Water also differs significantly from the regional case. This nexus element plays no significant role in NF, given that it only represents 4.7% of total land and performs poorly in network centrality scores. The poor performance of Water is worsened by increased deforestation rates, to which Energy is a major contributor. Specifically, Energy is responsible for 52% of the total losses in Water, followed by losses from Water to Food, at 48%. These results suggest that Water has significantly higher opportunity costs compared to Energy or Food. This puts Water at high risk of disappearing. Consequently, Water plays a residual role in terms of efficiency and redundancy. Food continues to play a key role in determining resilience. While NT ranks fifth in terms of total land shares, it holds the third position in terms of efficiency. This occurs because NT expands at the expense of Food due to the abandonment of agricultural lands.

Table 6
Significance of nexus elements according to total land shares and network centrality metrics. Vereda Nueva Florida.

Nexus element	Total land shares		Weighted page rank centrality (Efficiency)		Betweenness centrality (Redundancy)	
	Score	Ranking	Score	Ranking	Score	Ranking
Energy	26.52	2	0.33	2	3	2
Food	66.60	1	0.41	1	11	1
A Transition	0.001	6	0.04	6	0	
N Transition	0.72	5	0.08	3	0	
Urban	1.45	4	0.06	5	0	
Water	4.70	3	0.08	4	0	
Total	100		1		14	

4.4.2. Network interactions: Influence of land use transfers on resilience

We assess which nexus element interactions, land transfers, most effectively indicate resilience enhancement by analyzing the effects of a projected 30% increase or decrease in transfers between pairs of nexus elements, using Table 2 as a reference. Table 7 illustrates how and to which extent transfers influence efficiency, redundancy, and resilience at the regional scale, with the effects expressed as percentages of change. The results reveal a consistent trend: a 30% reduction in transfers always leads to a decrease in resilience. The interaction between the pair Water and Food is of particular interest, especially when transitioning from Water to Food, resulting in a 17.41% reduction in resilience. Across all situations, there is a consistent trend of increased efficiency and decreased redundancy. Conversely, a 30% increase in transfers yields mixed effects, particularly within transfers involving Food or Water. Notable improvements in resilience are observed during transitions from Food to Energy (1.5%), Water to Energy (1.5%), NT to Water (1.23%), and NT to Food (1.16%). Increasing transfers from Food to Water substantially undermined resilience, leading to an almost 7% reduction. In this scenario, efficiency consistently shows a decrease, while redundancy consistently exhibits an increase.

As shown in Table 8, distinct results may emerge when analyzing the impact of transfers at the vereda scale. The consistent trend of reduced efficiency and increased redundancy with a 30% increase in transfers between pairs of nexus element contrasts with specific cases revealing shifts in resilience effects. For example, in SJP, increasing transfers from Water to Food improves resilience by 1.43%, in contrast to the 0.25% decrease in resilience at the regional scale. Similarly, in NF and LP, increasing transfers from Energy to Food and Food to Energy significantly reduces resilience, compared to a marginal increase in resilience at the regional scale.

5. Discussion

5.1. Contribution to related literature

This study advances the operationalization of resilience in socio-ecological systems through models, metrics, and management strategies. It provides a framework for resilience-based assessments across multiple scales, addressing different scenarios and interventions related to land use transfers. It focuses on a WELF nexus, an integral component of socio-ecological systems, facing structural transformations driven by land use changes (Walker et al., 2006; Cretney, 2014; Wolde et al., 2021; MathisonSlee et al., 2022). Resilience-based management is increasingly recognized as a pathway to sustainable development, as it helps balance competing land demands and adapt socio-ecological systems to global change (Folke, 2006; Carpenter et al., 2009). To date, resilience-based management has predominantly treated resilience as a macroscopic property of socio-ecological systems (Kharrazi et al., 2016). Consequently, management strategies aimed at enhancing resilience have predominantly focused on generalized interventions targeting one of two macroscale dimensions: efficiency and redundancy. Proposition 1 summarizes a widely accepted result from the resilience literature (Kharrazi et al., 2017).

Table 7
Effect of varying transfers on efficiency, redundancy, and resilience at the regional scale.

Regional		30 % increase			30 % decrease		
Transfer	Baseline (Ha)	Efficiency (%)	Redundancy (%)	Resilience (%)	Efficiency (%)	Redundancy (%)	Resilience (%)
E to F	2,223	−4.87	4.65	0.38	2.74	−1.16	−0.25
E to NT	2,223	−4.87	4.65	0.76	0	0	0
E to W	2,223	−1.07	1.74	0.55	0	0	0
F to E	72,793	−1.07	1.74	1.50	2.74	−12.79	−4.70
F to NT	72,793	−16.29	48.26	−0.25	2.74	−9.88	−4.70
F to W	72,793	−35.31	62.79	−6.61	10.35	−18.60	−5.34
NT to E	7,976	−8.68	1.74	0.82	0	0	0
NT to F	7,976	−8.68	10.47	1.16	6.54	−9.88	−4.70
NT to W	7,976	−8.68	10.47	1.23	2.74	−1.16	−0.89
W to E	34,561	−8.68	27.91	1.50	2.74	−1.16	−0.25
W to F	34,561	−27.70	27.91	−0.25	25.57	−36.05	−17.41
W to NT	34,561	−20.09	36.63	−0.25	2.74	−1.16	−0.25

Table 8
Effect of varying transfers on efficiency, redundancy, and resilience at the vereda scale. (*) and (=) respectively indicate varying and similar resilience impacts relative to the regional scale.

NF		30 % increase			
Transfer	Baseline (Ha)	Efficiency (%)	Redundancy (%)	Resilience (%)	Regional case
E to F	731	−37.06	18.28	−18.81	*
F to E	2,113	−30.07	22.58	−16.78	*
F to W	2,113	−16.08	29.03	−12.04	=
W to E	101	−9.09	3.23	−4.60	*
W to F	101	−16.08	3.23	−4.53	=
SJP		**30 % increase**			
Transfer	**Baseline (Ha)**	**Efficiency (%)**	**Redundancy (%)**	**Resilience (%)**	**Regional case**
E to F	588	−20.69	21.05	1.03	=
F to E	2,101	−13.79	23.68	1.32	=
F to W	2,101	−27.59	52.63	−2.87	=
W to E	636	−17.24	18.42	1.28	=
W to F	636	−13.79	13.16	1.43	*
LP		**30 % increase**			
Transfer	**Baseline (Ha)**	**Efficiency (%)**	**Redundancy (%)**	**Resilience (%)**	**Regional case**
E to F	135	−9.09	4.26	−1.39	*
F to E	2,021	−9.09	23.40	−3.80	*
F to W	2,021	−36.36	38.30	−16.46	=
W to E	840	−27.27	14.89	−6.96	*
W to F	840	−18.18	19.15	−5.70	=

Proposition 1. [Enhancing resilience through macroscale dimensions]. *In a redundant nexus near maximum theoretical resilience, efficiency has a greater impact on enhancing resilience, while redundancy becomes more significant in an efficient nexus approaching maximum theoretical resilience.*

Proof: The proof of this proposition is provided in the Supporting Information (S1 File) in Kharrazi et al. (2017).

While Proposition 1 suggests that changes in the macroscale dimensions of resilience can predictably enhance system-wide resilience, our analysis of the regional case and vereda SJP, both efficient nexuses nearing maximum theoretical resilience, reveals a more complex dynamic. Although increasing land transfers among nexus elements consistently increases redundancy at both scales, this does not necessarily lead to enhanced resilience. For instance, a 30% increase in transfers from Food to Water increases redundancy but reduces resilience. Similarly, increasing transfers from Water to Food produces mixed results: it increases both redundancy and resilience at the vereda scale, yet at the regional scale, it increases redundancy while reducing resilience. These findings emphasize the need to consider the specific structure of interactions among nexus elements and the intensity of land transfers, suggesting that a complementary approach focused on network effects may contribute to a more comprehensive understanding of resilience dynamics. Proposition 2 is derived from our analytical framework, refining Proposition 1 by identifying a necessary condition for the effective enhancement of resilience, considering the interactions and dynamics of land transfers within the nexus.

Proposition 2. [Enhancing resilience through land transfers]. *An increase in land transfers among nexus elements increases redundancy and resilience if and only if* $\omega_{ij} < \left(\sqrt{u_i^{out} u_j^{in}}\right) e^{-1}$. *An increase in land transfers increases efficiency and resilience if and only if* $\omega_{ij} > \left(\frac{u_i^{out} u_j^{in}}{\omega_{..}}\right) e^{-1}$.

Proof: It is obtained by evaluating the partial derivatives of equations (2) and (3) with respect to ω_{ij}.

As shown in Proposition 2, predicting the overall impact of redundancy and efficiency on resilience is a complex task, as it depends on the interactions among nexus elements, the intensity of land transfers, and feedback loops. Therefore, the recommendations in Proposition 1 should be applied with caution, particularly in socio-ecological systems where land use dynamics shape resilience within a zero-sum context. Interestingly, Proposotion 2 shows that changes in land transfers influence redundancy not by changing the total volume transferred but by modifying how land uses are distributed among nexus elements. An increase in redundancy and resilience occurs when multiple nexus elements have similar significance. Even if the total transfer volume remains constant, land use redistribution can either improve or reduce the efficacy of interventions, depending on the intensity of land transfers, resulting in different responses to disruptions. In other words, prioritizing targeted interventions that focus on key nexus interactions and the intensity of land transfers (Proposition 2), rather than broad or generalized interventions (Proposition 1), would enhance resilience while ensuring the efficacy of interventions. The findings of this study may help advance the understanding of socio-ecological transitions driven by land use change to enhance resilience over time and space (Martin et al., 2018).

5.2. Policy implications

The following insights emerge from our study area, shedding light on the complexities and strategies for managing the WELF nexus and enhancing resilience across spatial scales.

First, balancing economic performance with ecosystem conservation is critical in achieving sustainable development. As these objectives conflict, the higher opportunity costs of ecosystem conservation often led to a greater focus on economic performance and increased land competition over time. Resilience theory offers insights into managing this balance, but solutions depend on quantifying the effects of land use changes on nexus composition across spatial scales. This emphasizes the importance of incorporating multiple levels of decision-making (Toman, 1994; Riekhof et al., 2019; Kurniawan et al., 2021).

Next, we find that the composition of the WELF nexus is influenced by factors such as energy production priorities, land abandonment, and deforestation. While Food plays a central role in both regional and sub-regional scales, the significance of Water, Energy, and NT varies depending on land shares and the scale of analysis. Moreover, at the vereda scale, the abandonment of agricultural lands prevented the formation of a dominant nexus cluster involving Water, Energy, and Food. This emphasizes the importance of tailoring land use and management practices to specific nexus elements to enhance resilience (Marin-Burgos and Clancy, 2017; Cely-Santos and Hernández-Manrique, 2021). In line with these findings, resilience-based management must prioritize Food at regional and sub-regional scales. This can be achieved through integrated crop-livestock-forestry systems and increasing local control over production prices, which can improve food security (Speratti et al., 2014; Carrer et al., 2020). Additionally, converting abandoned lands into sustainable economic activities or ecosystem conservation efforts could offer significant resilience benefits (Queiroz et al., 2021). Identifying hotspots at the vereda scale and involving small- and medium-scale farmers in interventions can have a more immediate impact. Addressing land tenure issues for smallholders, particularly those with land holdings between 10 and 200 Ha, along with market-based conservation practices like ecosystem service payments, can help reduce deforestation and enhance resilience (Börner et al., 2017; Queiroz et al., 2021). Energy expansion at the regional scale holds potential for enhancing resilience, but it must be carefully managed to avoid intensifying land tenure conflicts and negative environmental impacts at the sub-regional scales, such as water scarcity and pollution. At the vereda scale, the effects of energy expansion on resilience were mixed, emphasizing the need for context-specific policies that consider local conditions and socio-economic factors (Cely-Santos and Hernández-Manrique, 2021).

Furthermore, increasing land transfers among nexus elements emerges as a promising strategy for improving resilience. Increasing transfers from NT to Water by 30% leads to a 1.65% improvement in resilience, and even more notably, a 1.23% improvement at the regional scale. Such improvements suggest the potential advantages of adjusting land transfers, but they must be done carefully, considering opportunity costs, particularly in Energy and Food. Socio-economic factors, such as armed conflict or reductions in agricultural productivity, also need to be factored into policy design at sub-regional scales (Barbier, 2019). Additionally, our findings reveal the complexity of promoting ecosystem conservation strategies, particularly Water conservation. Expanding water conservation at the expense of Food can significantly reduce resilience. A 30% increase in transfers from Food to Water could result in a reduction of resilience by up to 16.4%. Decision-makers must carefully consider trade-offs to avoid unintended negative consequences for resilience (Tables 7 and 8).

Lastly, adaptive management must account for long-term variations in nexus resilience and the socio-economic factors influencing land use decisions. By monitoring efficiency and redundancy trends over extended periods, decision-makers can gain actionable insights into resilience dynamics and make better-informed decisions.

5.3. Future research

This study does not directly assess land suitability for balancing economic performance and ecosystem conservation, but it provides a foundation for identifying synergies and trade-offs among nexus elements as a step toward achieving this goal. Integrating land suitability maps and developing a metric like the total interaction score (Nilsson et al., 2016) could enhance our understanding of how and to what extent nexus elements and interactions impact resilience. Representing the WELF nexus as a signed network with both positive (P) and negative (N) links enriches the analysis. For example, consider a scenario where the objective is to increase land transfers from Food to Energy, aiming to allocate agricultural land for palm oil production to meet energy demands. However, land suitability maps indicate that this transition may not be optimal, as it could lead to food insecurity, loss of biodiversity, and soil degradation in certain regions. In this case, the land transfer is represented as a negative link in the WELF nexus network, reflecting the potential adverse impacts of this transfer on resilience. Alternative network centrality metrics, such as Positive-Negative (PN) centrality (Everett and Borgatti, 2014), could refine the assessment of the significance of nexus elements and interactions by not only evaluating their impact but also anticipating potential unintended negative consequences on resilience outcomes. These advancements may also promote better cross-sectoral coordination and more effective land use planning. Future research could apply the framework to conduct comparative case studies and assess its potential for guiding resilience enhancements across diverse geographical and socio-economic contexts.

6. Conclusions

This study introduces an analytical framework to assess how and to what extent land use changes influence the composition and resilience of the WELF nexus. Applied to the Maria la Baja sub-watershed in the Colombian Caribbean during the 2002–2018 period, the main conclusions are as follows. The composition and resilience of the WELF nexus are sensitive to spatial scales, emphasizing the context-dependent nature of socio-ecological systems in response to land use changes. A network approach uncovers implicit hierarchies among nexus elements and their interactions, quantified through land use transfers. Food consistently enhances resilience, while the contributions of Energy and Water are more scale dependent. Increases in land use transfers generally improve resilience, though their effects vary depending on spatial scale, particularly when Food or Water are involved. It also offers practical insights into decision-making. Decision-makers should consider scale-specific land use dynamics when designing interventions, prioritize Food due to its central role, and promote land use transfers cautiously, assessing both direct impacts and feedback loops. Targeting interventions in hotspots and focusing on the most significant interactions and their intensity, rather than implementing generalized interventions at the regional scale, would enhance resilience while ensuring the efficacy of interventions.

CRediT authorship contribution statement

Jorge Marco: Conceptualization, Investigation, Methodology, Writing – original draft. **Miguel Ramírez:** Conceptualization, Visualization. **William Martínez:** Conceptualization, Visualization. **Iván Lizarazo:** Conceptualization, Writing – review & editing. **Jorge Montero-Mestre:** Methodology. **Jorge Forero:** Conceptualization, Writing –

review & editing. **Ali Kharrazi:** Conceptualization, Visualization. **Nadia Combariza:** Conceptualization. **Alicia Correa:** Conceptualization, Validation, Visualization, Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Assignment process complemented with qualitative explanations

Table A1
LULC assignments to WELF nexus elements (column 3), with qualitative explanations (column 4) based on literature review and ancillary data*.

Code	Description	Nexus element	Observations
111	1.1.1. Continuous urban fabric	Urban	Buildings and infrastructure
112	1.1.2. Discontinuous urban fabric	Urban	Buildings and infrastructure
121	1.2.1. Industrial or commercial Areas	Urban	Buildings and infrastructure
122	1.2.2. Roads, rails and associated lands	Urban	Buildings and infrastructure
124	1.2.4. Airports	Urban	Buildings and infrastructure
131	1.3.1. Mining zones	Urban	Mining for construction
141	1.4.1. Urban green areas	Water	Areas with vegetation > 5Ha
142	1.4.2. Recreational facilities	Urban	Buildings and infrastructure
211	2.1.1. Other transitory crops	Food	Crops for food purposes
224	2.2.4. Agroforestry crops	Food	Crops for food purposes
231	2.3.1. Clean pastures	Food	Grazing land for livestock
232	2.3.2. Wooded pastures	Food	Grazing land for livestock
233	2.3.3. Weedy pastures	Food	Grazing land for livestock
241	2.4.1. Crop mosaics	Food	Crops for food purposes
242	2.4.2. Mosaics of pastures and crops	Food	Crops for food purposes
243	2.4.3. Mosaics of crops, pastures and natural spaces	Food	Crops for food purposes
244	2.4.4. Grass mosaic with natural spaces	Food	Mixes of crops and grazing land
245	2.4.5. Mosaic of crops with natural spaces	Food	Crops for food purposes
314	3.1.4. Gallery forest and riparian	Water	Forest
315	3.1.5. Forest plantation	Water	Forest
323	3.2.3. Secondary or transition vegetation	Water	Forest
331	3.3.1. Natural sandy areas	N Transition	Natural ecosystem transition
333	3.3.3. Barren lands and degraded	A Transition	
334	3.3.4. Burned areas	A Transition	We assume they have been caused by human activities such as land clearing, agriculture, and accidental ignitions. This assumption may be not necessarily true as for example the case of wildfires.
411	4.1.1. Wetland areas	Water	
413	4.1.3. Aquatic vegetation and water bodies	Water	
421	4.2.1. Coastal wetlands	Water	
512	5.1.2. Lagoons, lakes, and natural marshes	Water	
513	5.1.3. Canals	Water	
521	5.2.1. Coastal lagoons	Water	
522	5.2.2. Sea and Oceans	Water	
523	5.2.3. Marine aquaculture ponds	Food	
1422	1.4.2.2. Sport areas	Urban	Buildings and infrastructure
2121	2.1.2.1. Rice	Food	Crops for food purposes
2211	2.2.1.1. Other crops herbaceous permanents	Food	Crops for food purposes
2221	2.2.2.1. Other crops shrubby permanents	Food	Land in preparation for agriculture
2232	2.2.3.2. Oil Palm Plantation	Energy	Agricultural areas where oil palm trees are grown for the production biofuels

(*continued on next page*)

Table A1 (*continued*)

Code	Description	Nexus element	Observations
2233	2.2.3.3. Citrus	Food	Crops for food purposes
3131	3.1.3.1. Fragmented forest with pastures and crops	Water	Forest
3132	3.1.3.2. Fragmented forest with secondary vegetation	Water	Forest
3221	3.2.2.1. Dense shrubland	Water	Páramo and Sub-Páramo
3222	3.2.2.1. Open shrubland	Water	Ecosystem where its natural structure has not been altered
3231	3.2.3.1. Tall secondary vegetation	N Transition	It corresponds to the intermediate stages of plant succession, after a process of deforestation of forests or afforestation of pastures occurs. It develops mostly in abandoned agricultural areas.
3232	3.2.3.2. Low secondary vegetation	N Transition	It corresponds to the initial stages of plant succession, after a process of deforestation of forests or afforestation of pastures occurs. It develops mostly in abandoned agricultural areas.
31,112	3.1.1.1.2. High flooded dense forest	Water	Forest
31,121	3.1.1.2.1. Dense lowland forest	Water	Forest
31,122	3.1.1.2.2. Low flooded dense forest	Water	Forest
31,221	3.1.2.2.1. Open forest below ground	Water	Forest
32,112	3.2.1.1.2. Dense wooded dryland grassland	Water	Natural vegetation including Páramo and Sub-Páramo
32,122	3.2.1.2.2. Rocky open grassland	N Transition	Soils that do not hold humidity
321,121	3.2.1.1.2.1. Flooded dense grassland not wooded	Water	Permanently oversaturated soils with vegetation
321,122	3.2.1.1.2.2. Dense grassland flooded with trees	Water	Soils that are flooded most of the year

*Source: The first two columns correspond to the Corine Land Cover methodology adapted for Colombia (IDEAM, 2010).

Appendix B. The competing land use model

Much of the economic growth in developing economies depends on rapid LULC change, mostly the conversion of forest, and other natural capitals, to agriculture or other land-based economic activities like energy production. The competing land use model (Barbier, 2019) identifies two main drivers for rapid LULC change: (i) opportunity costs, and (ii) structural agricultural, institutional, and socio-economic factors. It reads

$$\Delta A_i = D_i\left(v_i^{t+1}, \mathbf{z}_i^{t+1}\right). \tag{B.1}$$

Equation (B.1) provides intuition to the equation (1) in the main text as it relates the magnitude of change to a demand function, $D_i : \mathbb{R}_+^2 \rightarrow \mathbb{R}_+$, that in turn depends on the opportunity cost of nexus element i, $v_i^{t+1} \in \mathbb{R}_+$, and a vector $\mathbf{z}_i^{t+1} = 1 \times n \in \mathbb{R}_+^n$ of exogenous factors such as income per capita, population density, quality of institutions, agricultural yield, etc. This model assumes $\frac{\Delta D_i}{\Delta v_i^{t+1}} < 0$ which has been proven to be a good predictor of rapid LULC change in tropical countries (Barbier and Burgess, 1997). However, we depart from the observation that in those countries it is often difficult to obtain good quality spatiotemporal data on both v_i and $\mathbf{z}_i$, especially in contested regions like MLBsw. In their work, Marin-Burgos and Clancy (2017) and Cely-Santos and Hernández-Manrique (2021) delve into the significant events that occurred within the study period in MLBsw. These events serve to provide valuable insights into the socio-economic context and the competition for land in the selected region. Based on this work, we derive that $v_E^t < v_F^t < v_W^t$, for each t, such that $\frac{\Delta A_E}{\Delta t} > \frac{\Delta A_F}{\Delta t} > \frac{\Delta A_W}{\Delta t}$ may hold. In words, demand for Energy is always higher than Food and demand for Food is always higher than Water. However, this approach falls short to explain the emergence of other nexus elements like NT. First, because we cannot determine the opportunity costs of the other nexus elements unambiguously and, second, because we have scarce information about the vector $\mathbf{z}_i^t$. Given the contested situation in MLBsw, the unobserved socio-economic dimensions of vector $\mathbf{z}_i^t$ will be key to correctly characterize the WELF nexus and explain its dynamics. For all these reasons, we prioritize a spatiotemporal analysis of the magnitude of change (equation (1) as an indicator of demand and competition for land (equation (B.1).

Appendix C. Multinomial logistic regression model

To obtain the levels of persistence, we estimated a multinomial logistic regression model. This model employs a maximum likelihood estimation method to examine the probability of change/no change (transfers) at time t according to information at time $t-1$. The multinomial logistic regression employed for calculation is computed by

$$P[Y = j|x] = \pi_j(x) = \frac{\exp\left(g_j(x)\right)}{\sum_{k=0}^{r-1}[g_k(x)]} = \frac{\exp(\beta_{j0} + \beta_{j1}x_1 + \beta_{j2}x_2 + \ldots + \beta_{jm}x_m)}{\sum_{k=0}^{r-1}\exp(\beta_{k0} + \beta_{k1}x_1 + \beta_{k2}x_2 + \ldots + \beta_{kp}x_p)} \tag{C.1}$$

Where $P[Y = j/x]$ denotes the conditional probability of any nexus element j at time t, $\pi_j(x)$ the multinomial logistic regression method, $g_j(x)$ the logit model for nexus element j, $g_k(x)$ the logit model for nexus element k, with $k \neq j$, and β_j the coefficient estimated for nexus element j at time t. The conditional probability function applied for n observations can be written as follows

$$l(\beta) = \prod_{i=1}^{n} \left[\pi_0(x_i)^{y_{0i}} \pi_1(x_i)^{y_{1i}} \pi_2(x_i)^{y_{2i}} \ldots \pi_{r-1}(x_i)^{y_{(r-1)i}}\right] \tag{C.2}$$

For linearity purposes, logarithms are applied to both sides of the function. It leads to

$$L(\beta) = \ln\left[\prod_{i=1}^{n}\left[\pi_0(x_i)^{y_{0i}}\pi_1(x_i)^{y_{1i}}\pi_2(x_i)^{y_{2i}}\ldots\pi_{r-1}(x_i)^{y_{(r-1)i}}\right]\right] \tag{C.3}$$

The value of β lacks interpretability. Therefore, to capture the dynamics of variation based on the estimated relationship of each nexus element at times t and $t-1$, we estimate predicted probabilities from the estimated β values. This approach allows us to effectively capture the variation in the probability of each nexus element being present or absent over time. It is important to remark that the estimates of the multinomial logistic regression model are derived through an iterative process that aims to maximize the $L(\beta)$ function. However, in certain instances, the iterative process fails to achieve concavity, which hinders the identification of the maximum of the function. In this case, the results presented are merely illustrative and lack robustness due to the challenges encountered in optimizing the function.

Appendix D. Supplementary tables and figures

Table D1
Change detection matrix, in hectares, in Nueva Florida for the period 2002–2018.

WELF elements	Energy	Food	A Transition	N Transition	Urban	Water
Energy	730.04	76.18			5.17	
Food	508.27	2113.42	0.06		11.37	74.77
A Transition			0.01			
N Transition		14.76		21.90		
Urban					42.48	
Water	37.26	56.28				100.60

Table D2
Change detection matrix, in hectares, in vereda La Pista for the period 2002–2018.

WELF elements	Energy	Food	N Transition	Urban	Water
Energy	134.65	8.09			
Food	143.70	2020.88	125.36	1.69	99.35
N Transition		49.31	229.46		68.27
Urban				2.65	
Water		195.37			840.44

Table D3
Change detection matrix, in hectares, in San Jose Playon for the period 2002–2018.

WELF elements	Energy	Food	N Transition	Urban	Water
Energy	587.54	4.62		1.23	
Food	435.02	2100.56		0.22	10.87
N Transition			119.33		
Urban		3.72		50.52	
Water	35.04	229.26			635.95

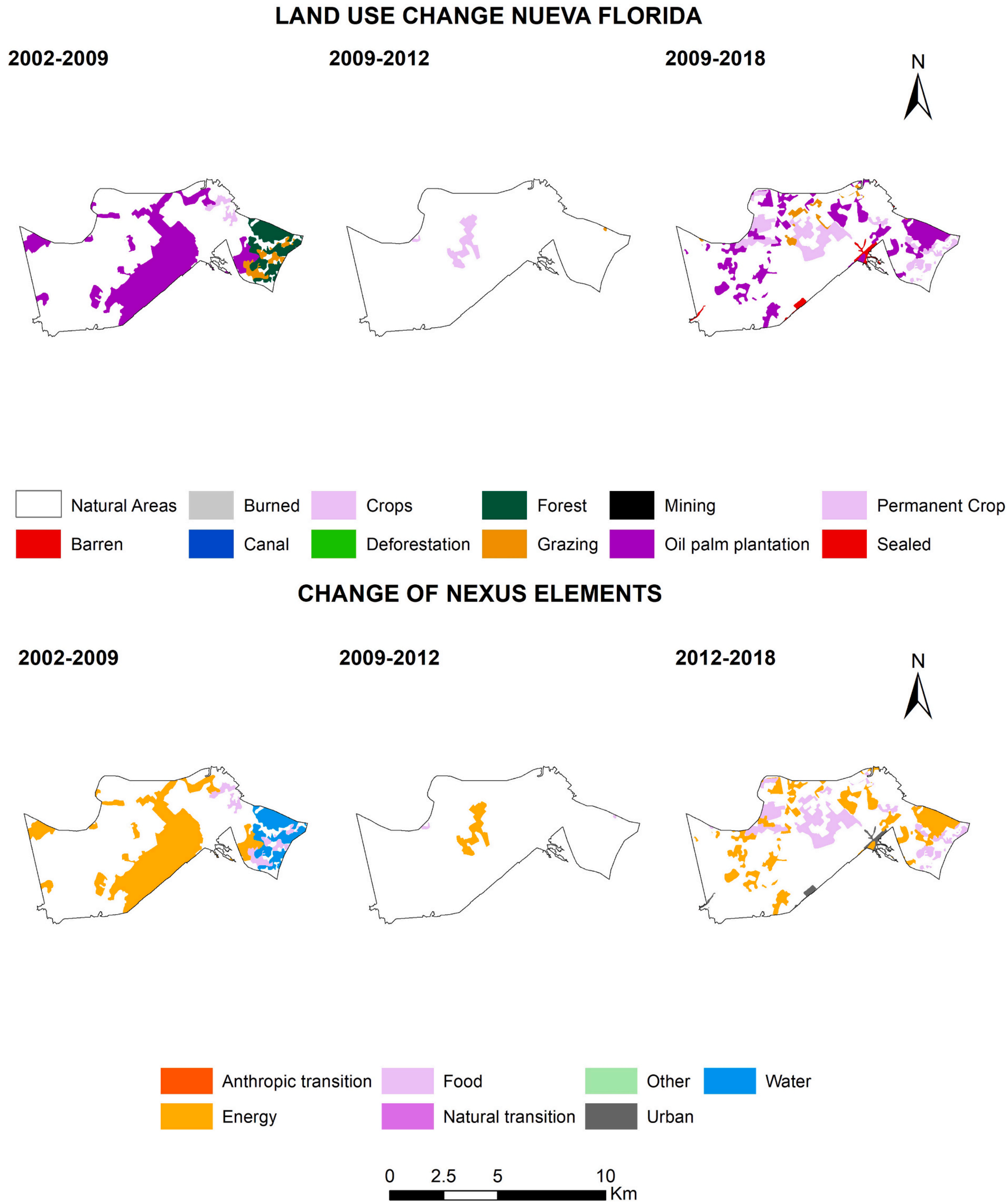

Fig. D1. Upper panel: LULC changes in vereda Nueva Florida, period 20022018. Lower panel: Changes referred to WELF nexus elements.

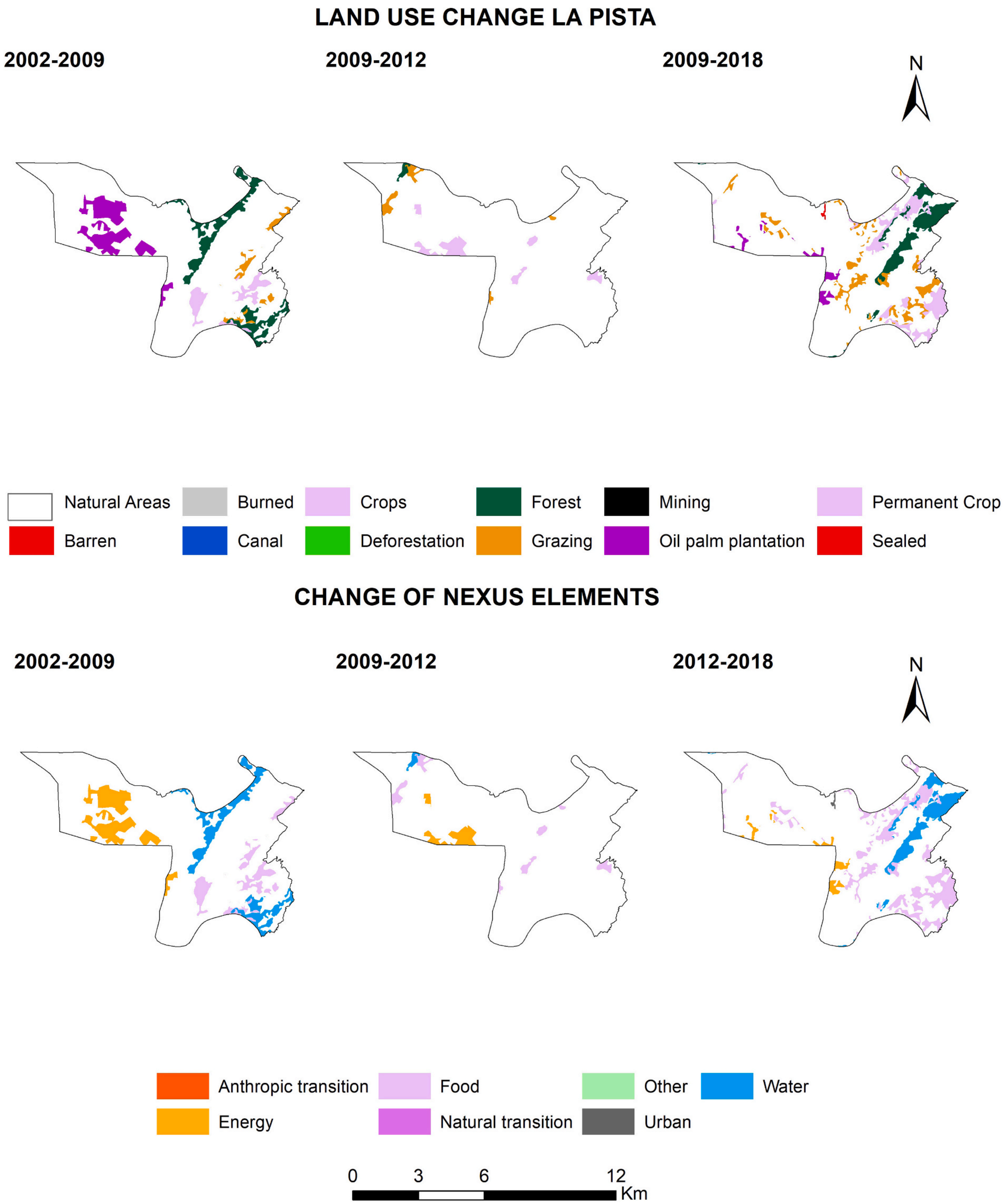

Fig. D2. Upper panel: LULC changes in vereda La Pista, period 20022018. Lower panel: Changes referred to WELF nexus elements.

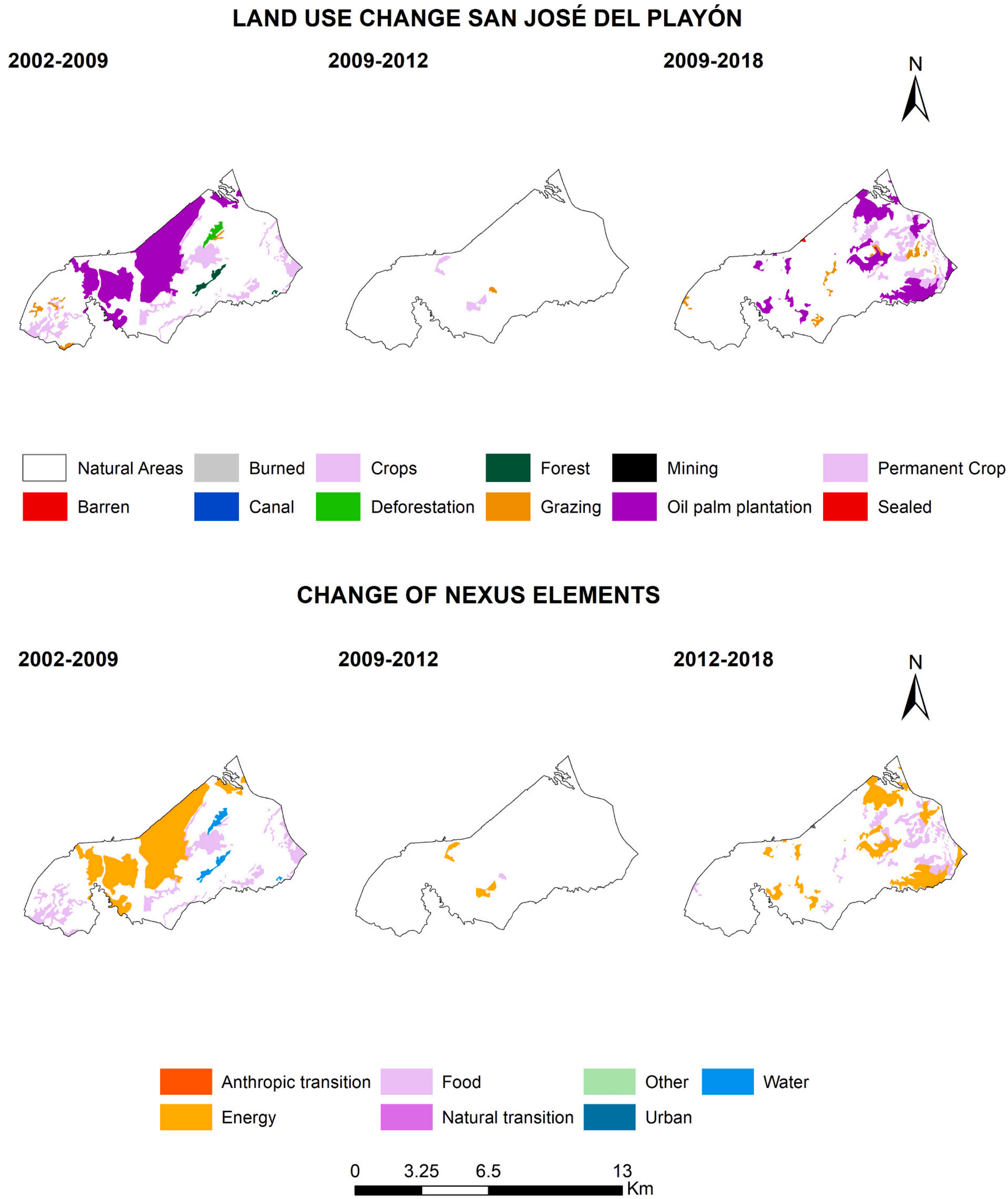

Fig. D3. Upper panel: LULC changes in vereda San Jose Playon, period 20022018. Lower panel: Changes referred to WELF nexus elements.

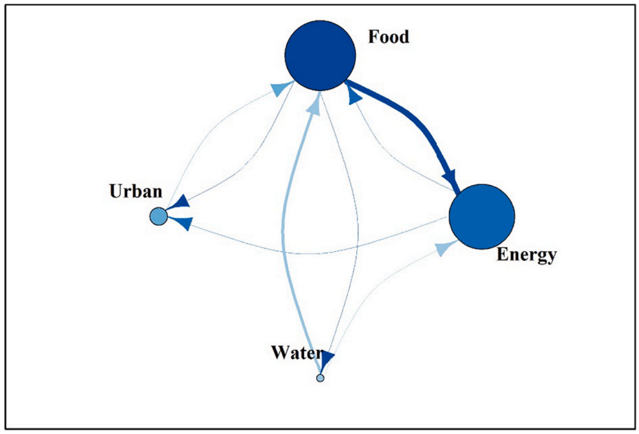

Fig. D4. The WELF nexus as a network in vereda San Jose Playon, period 20022018.

Table D4
Differences in the significance of nexus elements according to total land shares and network centrality metrics. Vereda San Jose Playon.

	Total land shares		Weighted page rank centrality (Efficiency)		Betweenness centrality (Redundancy)	
Nexus element	**Score**	**Ranking**	**Score**	**Ranking**	**Score**	**Ranking**
Energy	19.94	2	0.41	2	2	2
Food	61	1	0.44	1	5	1
Urban	1.33	5	0.11	3	0	
Water	16.5	3	0.05	4	0	
Total	100		1		7	

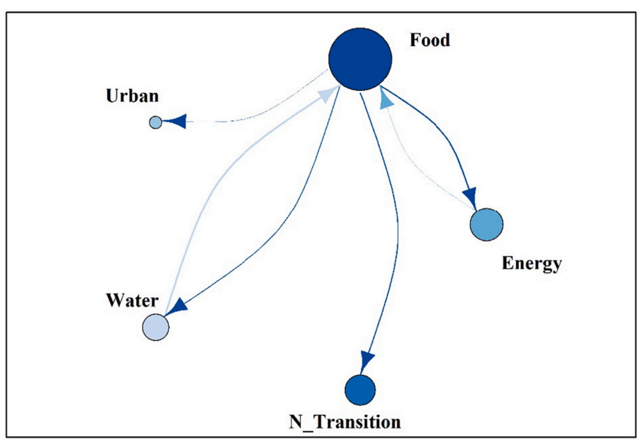

Fig. D5. The WELF nexus as a network in vereda La Pista, period 20022018.

Table D5
Differences in the significance of nexus elements according to total land shares and network centrality metrics. Vereda La Pista.

	Total land shares		Weighted page rank centrality (Efficiency)		Betweenness centrality (Redundancy)	
Nexus element	**Score**	**Ranking**	**Score**	**Ranking**	**Score**	**Ranking**
Energy	5.37	4	0.20	2	0	
Food	60.6	1	0.38	1	6	1
N Transition	6.79	3	0.18	3	0	
Urban	0.09	5	0.08	5	0	
Water	27.18	2	0.16	4	0	
Total	100		1		6	

Data availability

Data will be made available on request.

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