Towards Resilient Land Use Systems. A Multi-Scale Network Analysis for the Water-Energy-Land-Food Nexus

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Abstract

This paper emphasizes the importance of incorporating the land perspective (L) into Water-Energy-Food (WEF) nexus approaches. While the WEF nexus has gained attention to achieve interdependent sustainable development goals, interactions among its nexus elements are context-specific and strongly influenced by land use changes. We present an analytical framework to study the extent to which land use changes impact the composition and resilience of the WELF nexus. By maximizing resilience, policymakers can design more effective and targeted policies for achieving long-term sustainable development goals. This is because greater resilience improves the capacity of land use systems to manage uncertainties and recover from disruptions like climate change or political instability. Our framework is applied to the case of Maria La Baja, a sub-watershed situated in the Colombian Caribbean. The results show that the WELF nexus manifests differently across different scales, wherein agriculture (Food) consistently emerges as a crucial factor in maximizing resilience. The significance of other nexus elements like Energy and Water varies considerably depending on the scale of analysis. Other factors like abandonment of agricultural lands or increased deforestation play a key role in determining resilience at sub-regional scales. Finally, we identify which policies can be most effective in maximizing resilience.

Keywords: Land use and land cover change; Maria la Baja; Network analysis; Systemism; Sustainable development.

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1. Introduction.

A growing body of research (Schmalzbauer and Visbeck, 2016; Munroe and Müller, 2020) together with global agreements like the 2030 Agenda have emphasized that land use system approaches play a fundamental role in achieving long-term sustainable development goals (Ehrensperger et al., 2019). This is especially the case for territories currently undergoing a growth in their economies where shifts from primarily agrarian or rural-based economies to more industrialized ones are often accompanied by significant deforestation, increased demand for water and energy, and expansion of agriculture (Mullan et al. 2018; Simpson and Jewitt, 2019; López-Carr, 2021).

Land use systems are major interfaces between societies and ecosystems (Letourneau et al., 2012). Different interests associated to different land use options, e.g., existing trade-offs between economic growth and conservation of natural capital, have to be balanced carefully to maintain the resilience of land use systems as a whole in response to external shocks like climate change or political instability (Meyfroidt et al., 2022). Otherwise, the achievement of long-term sustainable development goals may be seriously compromised (Bouma, 1998).

Effective land use system approaches require multi-scale assessments since changes in land use are the result of a wide range of interests operating over multiple spatial scales (Letourneau et al., 2012; Nörstrom et al., 2014; Jiménez-Aceituno et al., 2020). If the scale of analysis is too small, it may not be possible to identify all relevant drivers of land use change and understand the complex interactions and interdependencies among them. If the scale is too large, it may become difficult to accommodate the diverse visions and interests of different stakeholders. If well implemented, it can contribute to improving coordination and pursue many concerted interests to promote sustainable development (Brugmann, 1996; Ball, 2002; Reed et al., 2015; Satterthwaite, 2018; Smith et al., 2018; Stephens et al., 2018; Guerini et al., 2022).

This paper aims to provide methodological advances for characterizing and analyzing the complex interactions and interdependencies that emerge in the context of the WELF nexus (Mohtar, 2011; Ringler et al., 2013; Simpson and Jewitt, 2019; Elagib and Al-Saidi, 2020). The WELF nexus is defined as a land use system where key resource sectors like Water (W), Energy (E), and Food (F) interact through land use and land cover (LULC) changes over time. The study of how and to what extent changes in one nexus element influence the resilience of the WELF nexus has become a prominent line of research for the next years (OECD, 2017; Karabulut, 2018; Ibrahim et al., 2019; Psomas et al., 2021; Gaddam and Sampath, 2022; Meyfroidt et al., 2022; Mohtar, 2022). Although maximizing resilience is not an end goal, it can help policymakers to design more effective and targeted policies for achieving sustainable development given that resilient WELF nexus will be more able to cope with uncertainties and recover from disruptions (Kharrazi et al., 2017).

To address these questions, we not only characterize the WELF nexus as a series of pairwise interactions among its nexus elements but as a network. Network analysis has several advantages for studying resilience in the context of the WELF nexus (Kharrazi et al., 2017; Dawes, 2022). First, it allows analyzing spillover effects which are otherwise difficult to predict given the complex interdependencies among nexus elements. Second, it provides valuable information about the existence of implicit element hierarchies within the nexus. Third, it helps to identify which interactions among nexus elements point to the likelihood of greater improvement of resilience.

Our analytical framework is applied to the case of Maria La Baja, a sub-watershed situated in the Colombian Caribbean. We show that the WELF nexus manifests differently across different scales, with agriculture (Food) always playing a central role in improving overall resilience within the WELF nexus. However, the significance of other nexus elements such as Energy and Water varies considerably depending on the scale of analysis. Specifically, the process of abandoning agricultural lands plays an important role in determining resilience at sub-regional scales. We also identify and discuss the most effective policy interventions aimed at improving the resilience of the WELF nexus.

The remainder of the paper is organized as follows. Section 2 presents the rationale of the modelling approach and how data were collected and treated. Section 3 provides a summary and a discussion of the results. In Section 4, policy recommendations are presented based on the results, while Section 5 offers concluding remarks and suggests ideas for future research.

2. Material and Methods.

2.1. The study area.

The region of Montes de Maria is one of the most important food pantries in Colombia. Especially Maria La Baja, a sub-watershed in Montes de Maria, presents continuous water supply and climate conditions that favor food production (Cely-Santos and Hernández-Manrique, 2021). The Maria La Baja sub-watershed (hereinafter MLBsw) comprises two departments, 12 municipalities and 120 veredas[1], and covers an area of 177,948 hectares (see Figure 1). It includes several small rivers and streams that flow into the Magdalena River, a source of cultural identity in Colombia. Favorable conditions in MLBsw are primarily driven by the conjunction of northern and northeastern trade winds, the proximity to the Caribbean continental coast, and the Serrania (highlands) of San Jacinto. The climate is warm, varying from semiarid to semi humid, with an annual average rainfall of 1500mm, an average temperature of 27.8°C, and an average relative humidity of 80% (Aguilera, 2013). Rainy seasons occur from September to November and from May to June. However, during the last decade, the influence of "la Niña" and "el Niño" phenomena influence both rainfall and temperature patterns, resulting in massive floods and prolonged drought periods, affecting food and energy production (Melo Leon et al., 2017; Espitia et al., 2018).

The selected period (2002-2018) has significant features in MLBsw. It coincides with an important transformation of its productive structure (i.e., proliferation of palm oil plantations and abandonment of agricultural lands), deforestation, massive displacements[2] due to a long-lasting armed conflict, intensification of competition for land, as well as the Colombia's peace agreement and subsequent policy and institutional changes of the country (Daniels-Puello, 2016; Moreno-Saboya, 2016; Cely-Santos and Hernández-Manrique, 2021). For additional context about the study area, please refer to Appendix 1.

[1] Veredas are the rural administrative regions comprising a municipality in Colombia.

[2] The region has registered 149,747 forced displacements since year 2002 (own calculation from national surveys).

In summary, climate change and political instability are the two primary factors that pose a threat to the resilience of MLBsw in the near future.

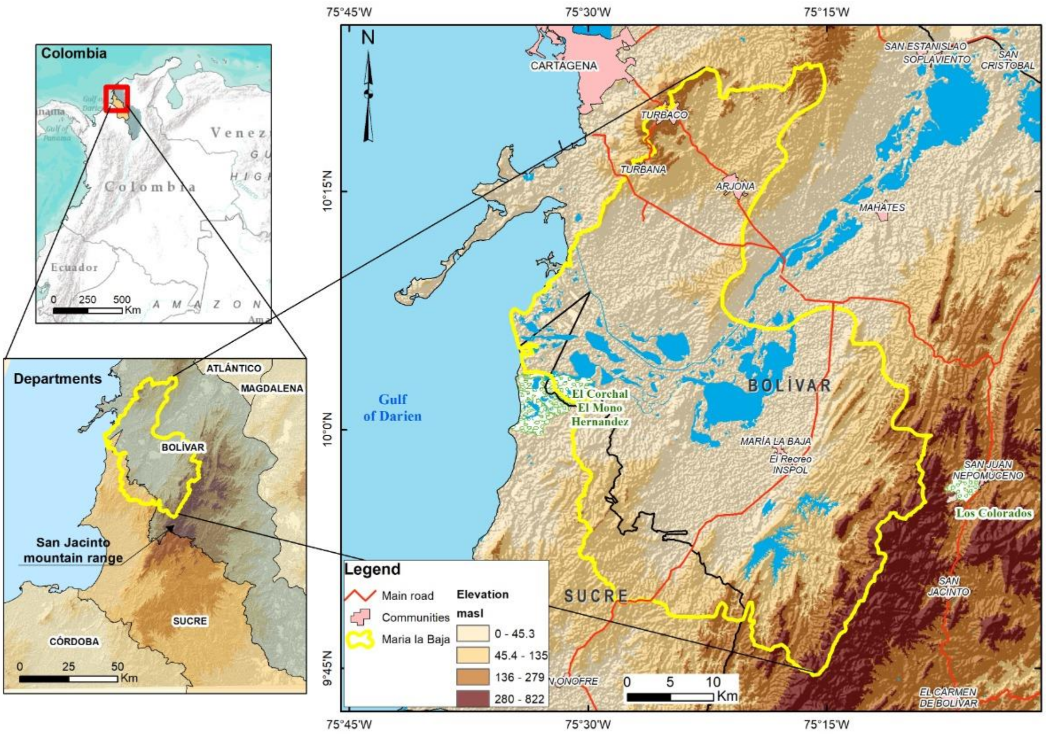

Figure 1. Regional context and location of Maria La Baja sub-watershed.

2.2. LULC changes and the WELF nexus.

This section includes a workflow of data collection (Section 2.2.1), reclassification of nomenclature (Section 2.2.2), and intersectional operation (Section 2.2.3), as illustrated in Figure 2.

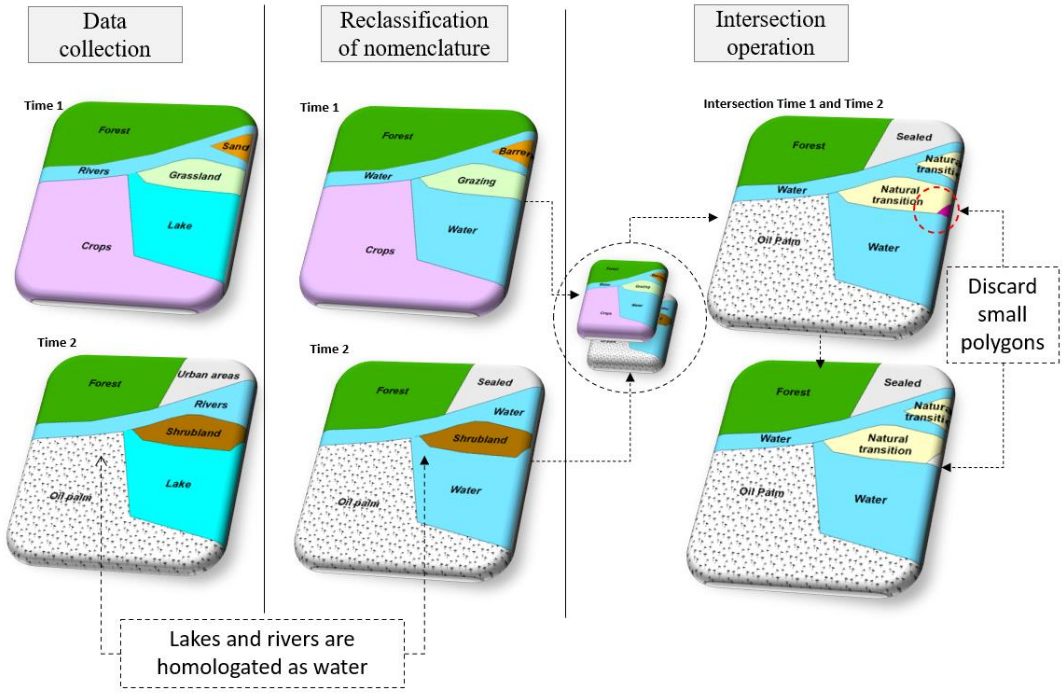

Figure 2. Schematic workflow representing LULC data processing.

2.2.1. Data collection.

Geospatial data were obtained from the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM[3], abbreviation in Spanish). They were used to assess the temporal changes and develop thematic LULC maps of the study area. In IDEAM, the most relevant spatial information consists of four annual LULC maps from 2002, 2009, 2012 and 2018 at a scale 1:100.000. IDEAM created these maps in digital vector format as polygons form. The LULC maps follow the Corine Land Cover Methodology using Landsat satellite images[4] with a spatial resolution of 30 meters. All the maps meet spatial

[3] The data from IDEAM can be downloaded here.
[4] Image sources are Landsat 5 and 7 for years 2002 and 2009, Landsat 7 for year 2012, and Landsat 8 for year 2018.

and thematic accuracy[5] standards defined by the Colombian Institute of Geography and Cartography (IGAC, abbreviation in Spanish).

After data collection, LULC changes among different time periods were detected via reclassification of nomenclature (Section 2.2.2), and intersection operation (Section 2.2.3). This workflow was written and processed using Python (version 3.8.5) code on Jupyter notebooks.

2.2.2. Reclassification of nomenclature.

The comparison between maps with dense nomenclatures such as Corine Land Cover makes the detection of LULC changes challenging. While the legend classes for levels 1 and 2 remain the same as 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 our case, it was important to make a synthesis of the classes provided by IDEAM (2010) with the purpose of making operational and clear the identification of potential changes. This action reviewed all the previous levels and, depending on the complexity of the class, were merged to a level-up (e.g., aquatic vegetation, rivers, and lakes were clustered as water class) or leave it as the original Corine Land Cover class (e.g., palm oil plantation class). This homologation, in our specific case, ended up with 11 thematic LULC classes that were uniformly used in all maps.

It is worth noting that a limitation of this study is basing LULC assignments to WELF nexus elements and their changes only on a desk-based classification. The previous needs further field data collection and interviews with stakeholders for

[5] The overall thematic accuracy is not given for years 2002 and 2009. It is around 85% for years 2012 and 2018.

verification and quality control. To overcome this limitation, LULC assignments to WELF nexus elements were performed 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[6]. Second, ancillary data was used to increase the quality of the assignments. The ancillary data included national statistics, cadastral information, or national agricultural surveys[7] which allowed us to identify the most common socio-economical activities in the study area during the stated period. For example, it helped us to identify that mining was not related to the Energy nexus element. Table A1 in Appendix 2 summarizes the assignment process complemented with qualitative explanations.

The Water nexus element 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). Our interpretation of the Energy nexus element focused solely on palm oil plantation (Cely-Santos and Hernández-Manrique, 2021), as mining serves purposes other than energy production. The Food nexus element was interpreted as all LULC classes oriented to food production such as croplands, grazing lands for livestock, or lands 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 additional nexus elements are: (i) Urban, (ii) Other, (iii) Anthropic Transition (hereinafter A Transition), and (iv) Natural

[6] Sustainable management of forest ecosystems is crucial for the regulation and provision of water resources (Brockerhoff et al., 2017; Sheil, 2018), which is essential for the well-being of both human societies and the environment.
[7] The data from the National Administrative Department of Statistics (DANE, abbreviation in Spanish) can be downloaded here.

Transition (hereinafter N Transition). The Urban nexus element includes continuous and discontinuous urban fabric, industrial and commercial areas, the entire road and rail network and associated land, and airports. The Other nexus element refers to any land-based economic activity other than Energy or Food. In this context, it was interpreted solely as mining areas. The A Transition nexus element includes all LULC classes that have not yet been assigned to the cluster Water, Energy, and Food, but with evident current human intervention leading to transform land use, e.g., bare and degraded lands, and burned areas[8]. Similarly, the N Transition nexus element includes all LULC classes that have not yet been assigned to the cluster Water, Energy, and Food, but with no evident current human intervention leading to transform land use, e.g., secondary or transition vegetation, natural sandy areas and rocky open grasslands. Following deforestation or afforestation activities, N Transition marks the initial phase of plant succession that occurs primarily in abandoned agricultural lands (IDEAM, 2010). N Transition 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 Food or Energy. These seven nexus elements constitute the WELF nexus in the study area.

<u>2.2.3. Intersection operation</u>.

This operation process aims to identify changes in the sequences of LULC maps by overlapping and intersecting the maps to evidenced variations. It should be noted that each intersection must be larger than 0.4 hectares to be considered as a change in our study. We have used this criterion considering that 0.4 hectares is the minimum mapping unit of analysis (according to expert advice, based on spatial analysis). As such, all polygons smaller than this minimum size were discarded for calculations.

[8] Notice that for analytical convenience we are assuming that all burned areas are the result of human intervention which may be not necessarily true as for example the case of wildfires.

The magnitude of change[9], measured in hectares, for each nexus element between two consecutive time points, namely, 2002-2009, 2009-2013, and 2013-2018, was determined as follows

$$\frac{\partial A_i}{\partial t} = A_i^{t+1} - A_i^t . \quad (1)$$

Where i denotes the nexus element, A denotes the total area, in hectares, that i represents in the study area, and $t \in \{2002, 2009, 2021, 2018\}$ the year of analysis. Year 2002 is the baseline for calculations. We next present the economic model underlying our analytical framework and discuss the assumptions made.

2.3. 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 such as 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. The model reads as follows

$$\frac{\partial A_i}{\partial t} = D_i\left(v_i^{t+1}, \mathbf{z}_i^{t+1}\right). \quad (2)$$

Equation 2 provides intuition to the previous equation 1 as it relates the magnitude of change to a demand function, $D_i : \mathbb{R}_{\geq 0}^2 \to \mathbb{R}_{\geq 0}$, that in turn depends on the opportunity cost, or price of conversion, of nexus element i, $v_i^{t+1} \in \mathbb{R}_{\geq 0}$, and a vector $\mathbf{z}_i^{t+1} = 1 \times n \in \mathbb{R}_{\geq 0}^n$ of exogenous factors such as income per capita, population density, quality of

[9] In this paper, the magnitude of change is also expressed in relative terms, $\frac{\partial A_i}{\partial t} = \frac{A_i^{t+1} - A_i^t}{A_i^t} \times 100$.

institutions, agricultural yield, etc. This model assumes $\frac{\partial D_i}{\partial v_i^{t+1}} > 0$ 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 Appendix 1, we discuss the more relevant events that took place during the 1960-2018 period in MLBsw and that, in our opinion, can help to better interpret the socio-economic context and competition for land in the selected region. Based on this discussion, we derive that $v_E^t > v_F^t > v_W^t$, for each t, such that $\frac{\partial A_E}{\partial t} > \frac{\partial A_F}{\partial t} > \frac{\partial A_W}{\partial t}$ always holds. 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 N Transition. 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 2).

Upon completion of the process described in Section 2.2, we will be able to characterise the WELF nexus as a series of interactions within and among its elements in the form of a change detection matrix. Using pivot tables, the strength of each interaction will be characterized by the magnitude of change (equation 1) within and among nexus elements. The change detection matrix helps us to determine the directionality of changes occurred during the stated period. Each interaction represents a transfer in terms of LULC change, in hectares, between pairs of nexus elements. Notice that transfers within the WELF nexus behave as a zero-sum game in which one nexus element's gain is equivalent to other element's loss and therefore net LULC change is zero (see Table 1).

We also identify hotspots as sub-regions where the magnitude of change was most significant. The selection of hotspots was done on the vereda scale. Hotspots allows to identify areas where competition for land is hypothesized to be more intense, e.g., those veredas that present favorable socio-economic conditions ($\mathbf{z}_i$) for promoting energy production.

2.4. The WELF nexus as a network.

In this section, we discuss the transformation of the change detection matrix into a network (Section 2.4.1), along with the metrics used to analyze the resilience of the WELF nexus (Section 2.4.2). Additionally, we present two network centrality metrics that help to identify which nexus elements are most critical for maximizing resilience (Section 2.4.3).

2.4.1. Network representation.

The network of interactions, or 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 $\ell : V \times V \to \{0,1\}$, 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 transfers occur within the same nexus element, i.e., persistence. The network is connected since there always exists a finite sequence of links connecting any pair of nexus elements within the network, that is, no nexus element is isolated. For analytical purposes, non-interacting nexus elements will be removed from the network. The strength of links among nexus elements is captured by ω, where $\omega_{ij} \in \mathbb{R}_{\geq 0}$ denotes the weight of the link between any pair of nexus elements i and j. In our context, ω_{ij} denotes the magnitude of transfers, i.e., number of hectares changing, from element i to element j. The network is directed given that the magnitude of transfers from i to j, and from j to i, may not coincide; that is, $\omega_{ij} \neq \omega_{ji}$. In other words, links among nexus elements are not necessarily symmetrical.

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. Analogously, $u_i^{out} = \sum_{j \in V} \omega_{ij}$ and $u_i^{in} = \sum_{j \in V} \omega_{ji}$ respectively denote the out-strength and in-strength of links that involve the nexus element i.

2.4.2. Network resilience.

Resilience is founded on the adaptive cycle paradigm, which recognizes the ever-changing nature of land use systems and the need for adaptive policies to achieve the sustainable development goals over the long term (Kharrazi, 2019). Concretely, resilience is torn between two antagonistic dimensions: efficiency and redundancy. We interpret these two dimensions of resilience in the context of the WELF nexus.

Efficiency relates to the capacity of the WELF nexus to increase the intensity of transfers between its elements. It is denoted by $\eta \in \mathbb{R}$ and computed similarly to the average mutual information of a network (Kharrazi et al., 2017) as follows

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

Where $\omega_{..} = \sum_{ij} \omega_{ij}$ denotes the total transfers within the WELF nexus. Redundancy relates to the capacity of the WELF nexus to increase maneuverability in the provision, and exchange, of transfers. It is denoted by $\beta \in \mathbb{R}$ and computed similarly to the conditional entropy of a network (Kharrazi et al., 2017) as follows

$$\beta = -\sum_{i,j} \frac{\omega_{ij}}{\omega_{..}} \log \frac{\omega_{ij}^2}{u_i^{out} u_j^{in}} . \tag{4}$$

Efficiency is often favored by increased competition for land which in part can be controlled by the structure of opportunity costs discussed above. However, highly efficient networks 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, or link, is affected by an external shock, e.g., climate change or political instability, the flow of transfers is impaired or stopped entirely. Higher redundancy prevents the network from bottlenecks and contributes to maintaining the flow of transfers active during disruptions. In contrast, highly redundant networks may be stagnant and lack the capacity to promote economic growth since they usually present a lower quantity of total transfers (Kharrazi et al., 2017).

For this reason, resilience requires a balance between efficiency and redundancy (Ulanowicz, 2019). Let the ratio $\alpha = \frac{\eta}{\eta + \beta} \in [0,1]$ measure this balance. Resilience is denoted by $\Re \in \mathbb{R}_{\geq 0}$ and computed (Kharrazi et al., 2017) as follows

$$\Re = -\alpha \log \alpha . \tag{5}$$

Since $\alpha \in [0,1]$, then $\max\{\Re\} = 0.16$ which is reached when $\alpha = 0.37$. Notice that a small bias towards redundancy is often preferable when maximizing resilience

(Kharrazi, 2019). This maximum value is of purely theoretical interest and policymakers should promote it with caution based on the specific sustainable development goals they want to prioritize and the external factors that threaten the WELF nexus under study. Yet, it allows policymaking to identify which dimension of resilience, whether efficiency or redundancy, should be promoted with the most interest.

2.4.3. Network centrality.

We present the two network centrality metrics that, to the best of our knowledge, have the closest relationship with network resilience: the weighted page rank centrality and betweenness centrality. For their computation, we used the *igraph* and *wdnet* packages in the R statistical software (R Core Team, 2020).

2.4.3.1. Weighted page rank centrality.

Weighted page rank centrality, denoted by C, relates to efficiency as it evaluates the centrality, or hierarchy, of a nexus element based on endorsement. The more links a nexus element has pointing to it, and the more important (in total land shares, see below) those linking elements are, the higher the C score is. Nexus elements with higher C scores become more relevant for policy design since they have higher influence in determining the directionality and intensity of transfers, that is, they determine the functionality of the network as a whole. This metric has been proven to perform well in weighted, directed networks (see Zhang et al., 2022 for a deeper discussion) like the WELF nexus. The C_i of each nexus element i is computed as follows

$$C_i = \gamma\left(\sum_{j \in V} \frac{\ell_{ji}\omega_{ji}}{u_j^{out}} C_j\right) + \frac{(1-\gamma)\beta_i}{\sum_{i \in V} \beta_i} \in [0,1]. \tag{6}$$

Notice that $\sum_{i=1}^{n} C_i = 1$. As shown in equation 6, the centrality of nexus element i is influenced by the centrality of all the other elements i is linked to. Parameter $\gamma \in [0,1)$ is generally used to improve the performance of the algorithm, by default $\gamma = 0.85$ as suggested by Zhang et al. (2022). Finally, parameter $\beta_i \in \mathbb{R}_+$ refers to some element-specific quantifiable information attached to i, for instance, the importance of the element in terms of total land shares. Therefore, β_i is independent of ω_{ij}, and $L = \sum_{i=1}^{n} \beta_i = 1$, where L denotes total land, in hectares.

2.4.3.2. 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., transfer facilitator, between other nexus elements. Specifically, it computes the number of shortest paths between pairs of nexus elements that pass through a particular element. Nexus elements with higher BC scores become more relevant for policy design since they have higher potential to control the flow of transfers through the network during disruptions. The BC_i of each nexus element i is computed as follows

$$BC_i = \sum_{i \neq j \neq k} \frac{\sigma_{jk}(i)}{\sigma_{jk}} \in \mathbb{R}_{\geq 0} \quad . \tag{7}$$

Where $\sigma_{jk} \in \mathbb{R}_{\geq 0}$ denotes the number of shortest paths from element j to element k, and $\sigma_{jk}(i) \in \mathbb{R}_{\geq 0}$ denotes the number of those paths that pass through element i, such that $\sigma_{jk}(i) \leq \sigma_{jk}$. To compute shortest paths, we use the inverse of the strength of the link, $\tilde{\omega}_{ij} = 1/\omega_{ij}$, as an indicator of the distance between nexus elements. That is, higher transfers from i to j indicate shorter distance among them.

3. Results and discussion.

3.1. LULC changes and the WELF nexus.

The lower panel of Figure 3 displays the LULC classes assigned to the WELF nexus elements in the study area. Figure 4 illustrates significant changes that occurred in the WELF elements during every two consecutive time points, namely, 2002-2009, 2009-2012, and 2012-2018. We identified several patterns in LULC change across the study area. 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 due to modernization of irrigation systems for agricultural production since the 1960s. 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. This phenomenon became prevalent in the mid-1990s due to a combination of factors including the intensification of a long-lasting armed conflict and drops in agricultural yields. 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 period between 2012 and 2018.

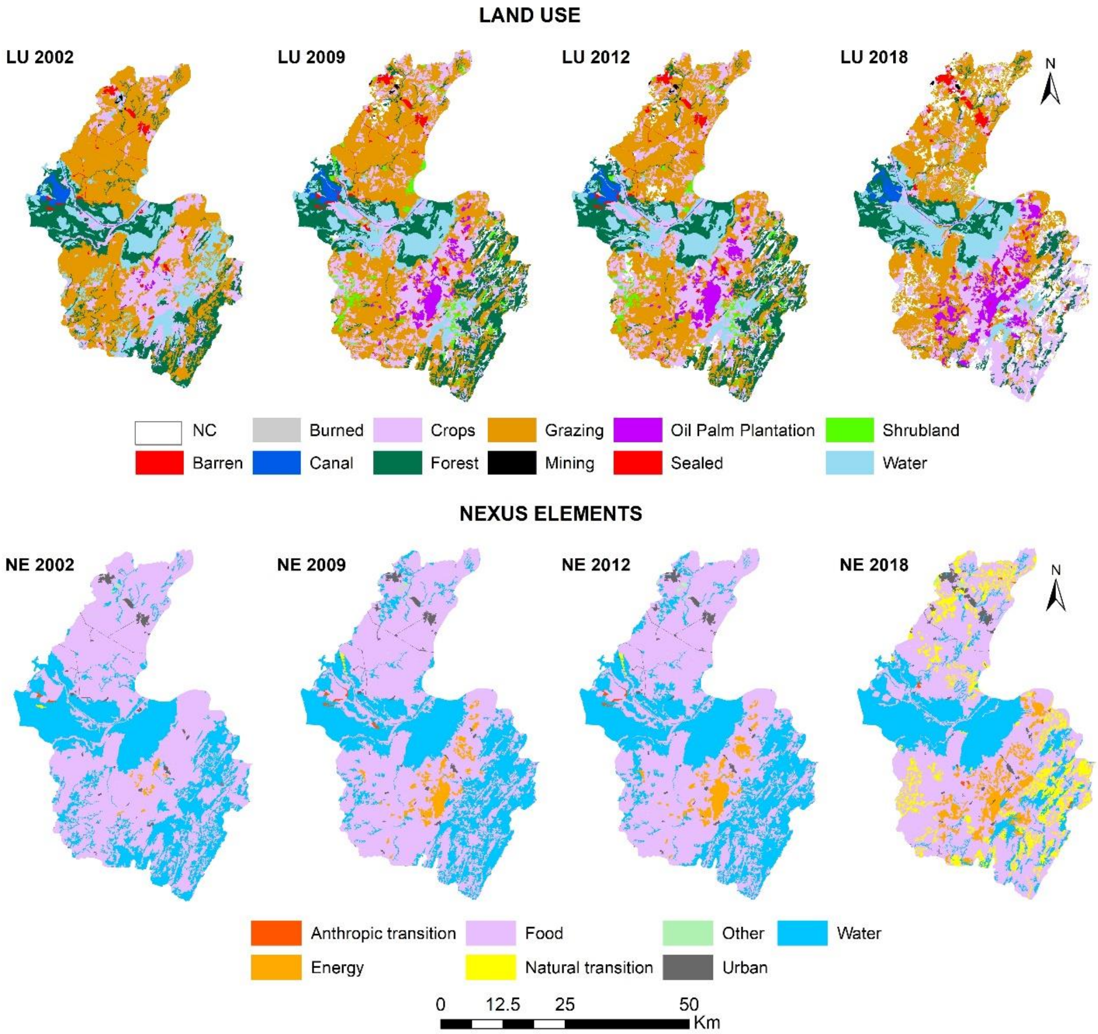

Figure 3. LULC assignments to WELF nexus elements in Maria la Baja sub-watershed. Years 2002, 2009, 2012, and 2018.

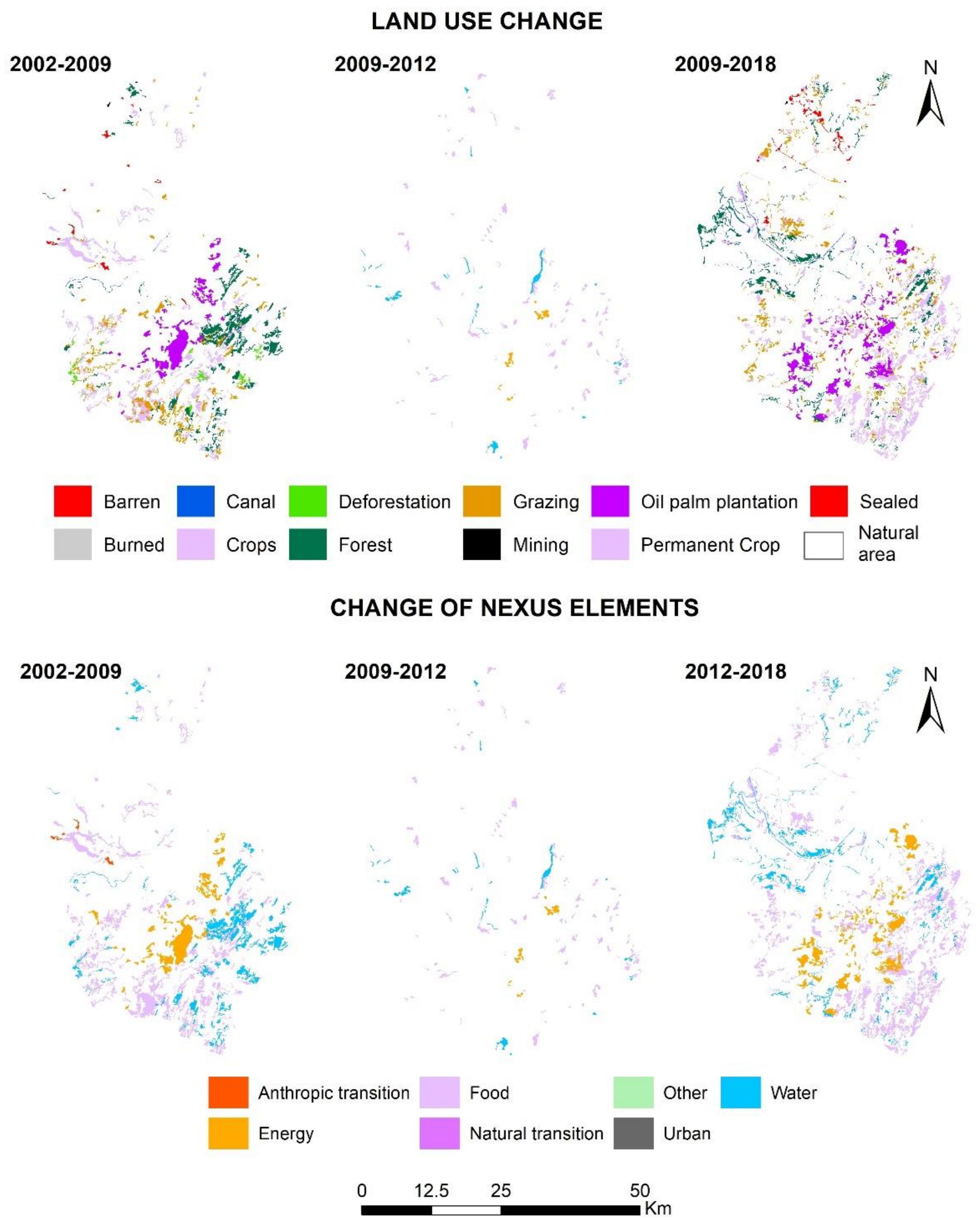

Figure 4. Upper panel: LULC changes in Maria la Baja sub-watershed in 2002-2018 period. Lower panel: Changes referred to WELF elements.

Table 1 reports the WELF nexus dynamics during the stated period. Our results indicate that in year 2002 (baseline), Food and Water were the most significant nexus elements, accounting for 98.13% of the total land. However, over time, the share of these two nexus elements decreased, with Water experiencing the most significant loss (32% of hectares) followed by Food with 8.88%. N Transition and Energy were the nexus elements that experienced the most significant increase, with growth rates of 1681.31% and 1268.67%, respectively. In 2018, N Transition and Energy represented 17.51% of total land while in 2002 they only represented 1.07% of total land. Their rapid increase occurs in 2012 onwards. The cluster comprising Water, Energy, Food and N Transition accounted for 98.91% of total land at the end of the stated period, whereas the cluster comprising Urban, Other and A Transition accounted for only 1.09% of total land. These results confirm the rapid transformation that the WELF nexus has undergone in recent years.

Table 1. Changes in WELF nexus elements, in hectares, in Maria la Baja sub-watershed for the 2002-2018 period.

Baseline (year 2002)			**Year 2009**		**Year 2012**		**Year 2018**		**Total variation in 2002-2018**	
WELF element	**Hectares (Ha)**	**%**	**Ha**	**%**	**Hectares (Ha)**	**%**	**Hectares (Ha)**	**%**	**Hectares (Ha)**	**%**
Energy	695.44	0.39	5194.07	2.92	4911.00	2.76	9518.23	5.35	8822.79	1268.67
Food	112980.65	63.49	109868.84	61.74	110333.87	62.00	102950.13	57.85	-10030.52	-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	1214.70	0.68	7239.51	4.07	8315.91	4.67	21637.56	12.16	20422.86	1681.31
Urban	1104.07	0.62	1180.90	0.66	1190.11	0.67	1418.72	0.80	314.65	28.50
Water	61640.58	34.64	53879.43	30.28	52705.60	29.62	41910.73	23.55	-19729.86	-32.01
Total	177948.50	100	177948.50	100	177948.50	100	177948.50	100	0	

Table 2 illustrates the change detection matrix used to describe how the different elements of the WELF nexus interact over time. The diagonal of the matrix, e.g., Energy-Energy or Food-Food, accounts for both the absence of transfers and transfers that occur within the same nexus element. The remaining cells in the matrix take into account the magnitude and directionality of transfers among nexus elements. These cells indicate an increase of one nexus element (columns) at the expense of another (rows). Transfers are represented in hectares (Ha), and Table 2 displays the mean of the total transfers that occurred between pairs of nexus elements during the stated period.

Higher transfers occur respectively from Water to Food (6272.45 Ha), Food to Energy (2490.66 Ha), N Transition to Food (1323.98 Ha) and Food to N Transition (1176.46 Ha). Most of these transfers behave following the structure of opportunity costs discussed above. Yet, transfers to N Transition appear to be influenced by both opportunity costs and other socio-economic factors. Concretely, N transition experiences more gains from the abandonment of agricultural lands (65% of total gains) due to the presence of the armed conflict or drops in agricultural yields than from increased deforestation (35% of total gains) driven by intensified agriculture or peasants seeking to improve their agricultural yields. Our results also show that the impact of Energy to Water losses, e.g., deforestation, is lower than that of Food. This is because in Energy, 93% of the total gains come from Food, while the remaining 7% come from Water. In contrast, in Food, 79% of the total gains come from Water.

Persistence is presented in the last row of Table 2 and measures the likelihood of no transfer occurring among nexus elements. To obtain the levels of persistence, we estimated a multinomial logistic regression model (see Appendix 3 for details). Our results indicate that Other and Urban exhibit the highest levels of persistence, with 0.83 and 0.82, respectively, whereas N Transition and Water exhibit the lowest levels of persistence, with 0.58. Energy and Food exhibit identical high levels of persistence with 0.77. These results reveal that N Transition and Water are the nexus elements most likely to experience losses in favor of other nexus elements.

Table 2. Change detection matrix, in hectares, and persistence in Maria la Baja sub-watershed for the period 2002-2018.

WELF elements	**Energy**	**Food**	**Other**	**A Transition**	**N Transition**	**Urban**	**Water**	Total

Energy	2222.73	159.10	0	0	0	6.40	0	2388.22
Food	2490.66	72793.33	17.49	94.93	1176.46	152.47	2287.38	79012.71
Other	0	6.34	129.53	0	0	0	0	135.87
A Transition	0	56.51	0	113.37	0	0	8.58	178.47
N Transition	4.92	1323.98	0	16.92	7975.70	9.23	224.91	9555.66
Urban	0	101.76	0	0	0	776.86	6.40	885.03
Water	187.52	6272.45	2.44	23.05	146.08	2.47	34560.72	41194.72
Total	4905.82	80713.46	149.46	248.27	9298.24	947.43	37087.99	**133350.68**
Persistence	0.77	0.77	0.83	0.65	0.58	0.82	0.58	

In addition to Table 2, we found that the mean size of an individual transfer to Energy was 56 Ha, with a standard deviation of 136. The mean size of an individual transfer, along with their standard deviations in parentheses, to the other nexus elements were Food 73 Ha (194), Water 62 Ha (194), and N Transition 62 Ha (95). Urban accounted for the lowest values with 9 Ha (19). These results suggest that most transfers within the WELF nexus are more likely to affect small- and medium-size lands[10].

After characterizing and analyzing the WELF nexus at the regional scale, we applied the same methodology to repeat our analysis at sub-regional scales. At the municipality scale, we find that Maria La Baja municipality accounts for 79.25% of Energy. The rest of Energy is heterogeneously concentrated in other five municipalities as follows: San Onofre (8.8%), Mahates (5.95%), Arjona (4.7%) and El Carmen de Bolivar (1.3%). Food and Water are present in all municipalities, however, we found that three municipalities concentrate 64.59% of Food and 76.15% of Water. These municipalities are Maria La Baja (30.26% of Food and 31.35% of Water), Arjona (20.86% of Food and 36.9% of Water) and San Onofre (13.47% of Food and 7.9% of Water). It indicates that competition for land to produce energy or food is mostly concentrated in three out of the twelve municipalities. In contrast, N Transition expands more uniformly across municipalities. In terms of total land shares, this nexus element

[10] Small- and medium-size lands in Colombia are considered to be between 10 and 200 Ha.

becomes especially significant in municipalities like Maria La Baja (16.65%), San Juan Nepomuceno (16.63%), Arjona (12.54%), San Onofre (12.23%), Turbaco (12.16%), Turbaná (8.01%) and San Jacinto (7.9%). According to our results, we observe that the abandonment of agricultural lands or increased deforestation often occur in municipalities that are not directly affected by Energy.

Finally, we identified hotspots at the vereda scale where transfers among nexus elements were concentrated to a greater extent. For the sake of concreteness, but without loss of insight, we focus our analysis on Maria La Baja municipality, which accounted for 36% of the total transfers in the study area during the stated period. In comparison, Arjona municipality is a distant second, responsible for only 13% of the total transfers. We selected Maria La Baja municipality because competition for land is anticipated to be higher compared to that of an average municipality. Moreover, in Maria La Baja municipality, the mean size of an individual transfer to Energy was 69 Ha, with a standard deviation of 158. The mean size of an individual transfer to other nexus elements, in parenthesis the standard deviation, are Food 88 Ha (206), Water 80 Ha (240), and N Transition 84 Ha (117). Urban accounted for the lowest values with 8 Ha (11). On average, these results are 12.24% higher than the results obtained at the regional scale.

Table 3 reports the distribution of nexus transfers within Maria La Baja municipality and identifies three important hotspots: Nueva Florida, San Jose de Playon, and La Pista. These hotspots are highlighted in grey in Table 3 and defined as those veredas with the highest transfers accumulated over time.

Table 3. Hotspots selection based on the veredas in Maria La Baja municipality, where a higher quantity of transfers, in hectares, occurs during the 2002-2018 period.

Name of the vereda	**Area where transfers (in hectares) 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	1014.77	262.55	1031.57	10	18	11	12.9
Majagua- San Pablo	377.77	306.03	373.92	4	21	4	9.4
Mampujan	1121.69	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	1750.93	149.14	1367.98	18	10	14	14.0
San Jose del Playon	1872.39	65.08	1022.27	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	**9744.21**	**1485.27**	**9809.17**	**100**	**100**	**100**	**100**

We find that Nueva Florida presents the highest percentage of total transfers within Maria La Baja municipality, accounting for 14%, followed by La Pista at 12.9% and San Jose del Playon at 11.3%. The WELF nexus in these three hotspots is characterized as follows (see Figures A1-A3 in Appendix 2 for illustrations): Nueva Florida had a 600% increase in Energy covering 1838.72 Ha, a 32% decrease in Food covering 3006.99 Ha, a 97.98% decrease in Water covering 5.26 Ha, and a 108.85% increase in Urban covering

117.89 Ha. When compared to the regional case, persistence levels in Nueva Florida are 2.9% higher. Concretely, A Transition, Urban, and Energy exhibit the highest levels of persistence, with 1 and 0.69, respectively, whereas Water exhibits the lowest levels of persistence with 0.44. Food and N Transition fall within the middle range, with respective persistence levels of 0.61 and 0.67. On average, the size of transfers among nexus elements in Nueva Florida is 13.93% higher than the results obtained at the municipal scale. The pattern observed in Nueva Florida is contrary to that observed at regional and municipal scales, with almost complete deforestation resulting from the expansion of Energy and Food. On the other hand, La Pista is characterized by 260.2 Ha for Energy (not present in 2002, the baseline year), 3479.43 Ha for Food (2% decrease), 1117.05 Ha for Water (32% decrease) and 353.99 Ha for N Transition (not present in 2002). When compared to the regional case, persistence levels in La Pista are 2.84% lower. In this case, Urban and Energy exhibit the highest levels of persistence with 1 and 0.86, respectively, whereas N Transition and Water exhibit the lowest levels of persistence with 0.33 and 0.56, respectively. Food falls within the middle range, displaying a persistence level of 0.72. On average, the size of transfers among nexus elements in La Pista is 14.05% lower than the results obtained at the municipal scale. Despite being located in a municipality favorable to energy production, La Pista does not show a remarkable expansion in any of the nexus elements. Finally, San Jose del Playon is characterized by a remarkable increase (4489.82%) in Energy covering 1649.89 Ha, a 33.81% decrease in Food covering 2911.42 Ha, a 56.54% decrease in Water covering 490.06 Ha, and 477.31 Ha for N Transition (not present in 2002). When compared to the regional case, persistence levels in San Jose del Playon are 4.72% higher. Concretely, N Transition and Urban exhibit the highest levels of persistence, with 1 and 0.81, respectively, whereas Water exhibits the lowest levels of persistence with 0.4. Energy and Food fall within the middle range, with respective persistence levels of 0.79 and 0.74. On average, the size of transfers among nexus elements in San Jose del Playon is 12.23% lower than the results obtained at the municipal scale. San Jose del Playon exhibits a similar pattern to Nueva Florida, with a significant expansion of Energy, but with lower Water losses.

On the vereda scale, our results suggest that the highest quantity of transfers does not necessarily lead to a significant intensification in land competition, even when a hotspot exhibits lower levels of persistence, such as in the case of La Pista. If this is not the case, the selection of hotspots can help to identify trends that differ from those observed at the regional scale. For example, Energy being a major contributor of Water losses, as observed in Nueva Florida and to a lesser extent in San Juan del Playon (see below for a deeper analysis).

3.2. Network analysis.

This section presents the results of our network analysis and discusses the influence of nexus elements on resilience based on their network centrality scores. The analysis was performed on two scales, the regional scale and the vereda scale, using the case of Nueva Florida as an example. The results for other significant hotspots, such as La Pista and San Jose del Playon, are outlined in Appendix 2.

3.2.1. Network resilience.

Figure 5 illustrates variations in network resilience across regional and vereda scales. The dotted line serves as a benchmark for evaluating the performance of heterogeneous WELF nexus and is calculated through theoretical analysis. Redundancy dominates over efficiency in three out of the four WELF nexus, i.e., the regional case and veredas Nueva Florida and San Jose del Playon. It is indicated by the ratio α skewed towards lower values, which brings them close to maximum resilience with a mean of 0.14 compared to the maximum value of 0.16. Although these three WELF nexus exhibit similar levels of resilience, our results reveal that the regional case presents higher levels of both efficiency (0.189) and redundancy (0.686) compared to Nueva Florida (0.153 and 0.451) and San Jose del Playon (0.111 and 0.462). However, it is important to notice that Nueva Florida shows a better balance between efficiency and redundancy, resulting in higher network resilience performance. In contrast, La Pista exhibits a dominance of efficiency (0.296) over redundancy (0.182), and thus presents the lowest level of resilience among the analyzed nexuses. This can be attributed to the fact that La Pista has very low diversity of transfers among its nexus elements, as illustrated in Figure A5 of Appendix 2.

In a recent study, Kharrazi et al. (2017) demonstrated that in redundant networks that are close to maximum resilience, efficiency has a greater impact on maximizing resilience, whereas redundancy plays a lesser role. Conversely, the reverse is true, and redundancy plays a more significant role. This has important implications for guiding network centrality analyses and policy design, as our results suggest that a focus on improving efficiency is the preferred strategy to maximize resilience (except for La Pista).

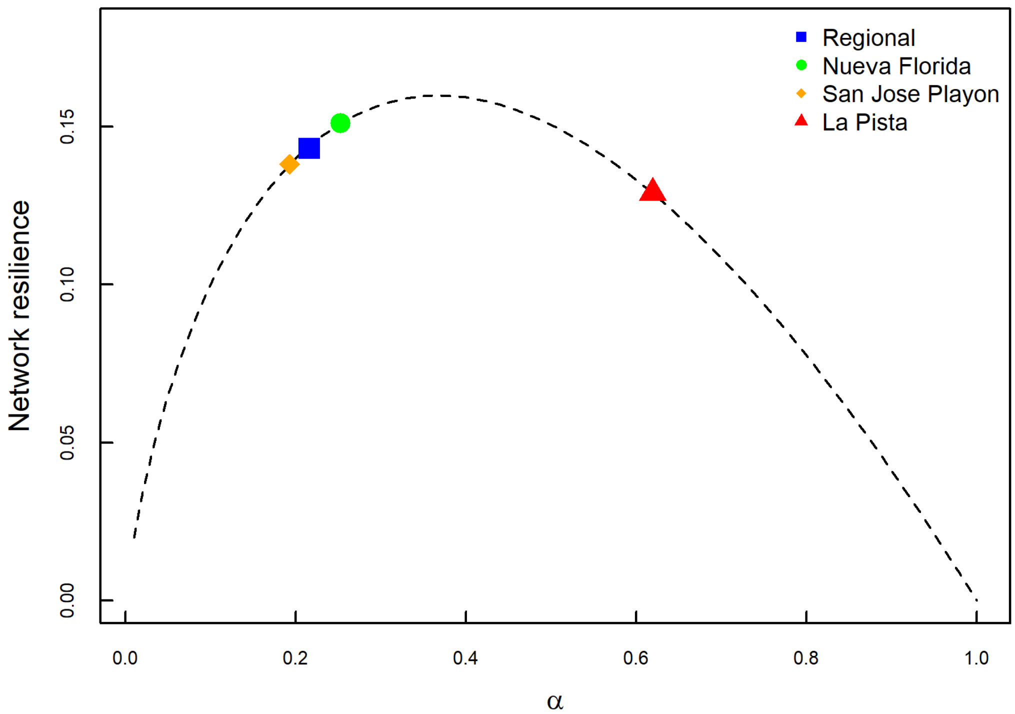

Figure 5. Resilience of the WELF network at different sites.

Given the above, the following analysis focuses on the potential of the nexus elements to control the directionality and intensity of transfers.

3.2.2. Network centrality scores.

To provide a clear illustration of our approach, we limit the focus of this section to comparisons between the regional case and the most significant hotspot, vereda Nueva Florida. The remaining two cases, veredas La Pista and San Jose del Playon, are presented in Appendix 2 (Tables A2 and A3, and Figures A4 and A5).

Figure 6 illustrates the transformation of the change detection matrix (Table 2) into a network at the regional scale. Each nexus element is represented by a node in the network, and 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 higher transfers among nexus elements. The size of a node is re-scaled based on weighted page rank centrality scores (equation 6). The resulting network is depicted in a blue scale, where darker nodes indicate the highest centrality scores, and darker links indicate all transfers starting from those nodes.

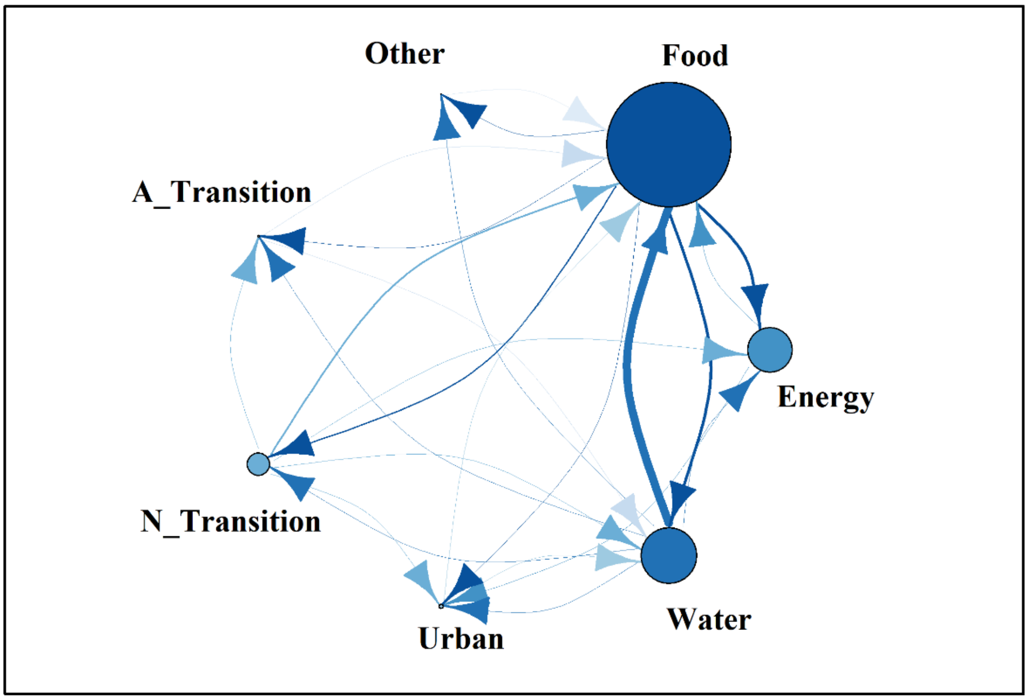

Figure 6. The WELF nexus as a network in Maria La Baja sub-watershed, period 2002-2018.

Table 4 summarizes the significance of nexus elements based on different characteristics analyzed, such as total land shares[11], efficiency, and redundancy. This table reveals important differences among the nexus elements. For instance, 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 highest opportunity costs of nexus elements, making it function as a sink, i.e., attractor of transfers, within the WELF nexus. This factor, along with its very limited interaction with other nexus elements, contributes to its poor performance in betweenness centrality, i.e., redundancy. Water represents a significant share of the total land (29.52%) and it

[11] For calculations, total land shares are averaged over the entire study period (see Table 1).

ranks second in influencing efficiency. Unlike Energy, Water serves as a source, i.e., origin of transfers, in the WELF nexus, as illustrated in Table 1. The low opportunity costs of Water compared to other nexus elements largely account for this result. In all analyses, Food consistently ranked first. It suggests that Food plays a crucial role in maintaining the continuous flow of transfers within the WELF nexus due to its participation in most transfers, either directly or indirectly. Compared to Water, Food has a greater influence on redundancy due to the significantly higher number of transfers involving it. Higher transfers decrease the distance between Food and other nexus elements, leading to improved centrality scores. N Transition ranked third in total land shares and fourth in efficiency. Although N Transition 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.

Table 4. Differences in the significance of nexus elements according to total land shares and network centrality metrics. The case of Maria La Baja sub-watershed during the 2002-2018 period.

	Total land shares		**Weighted page rank centrality**		**Betweenness centrality**	
Nexus element	**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	

Similarly, Figure 7 depicts the WELF nexus in Nueva Florida for the stated period, using the same node and link characterization as before.

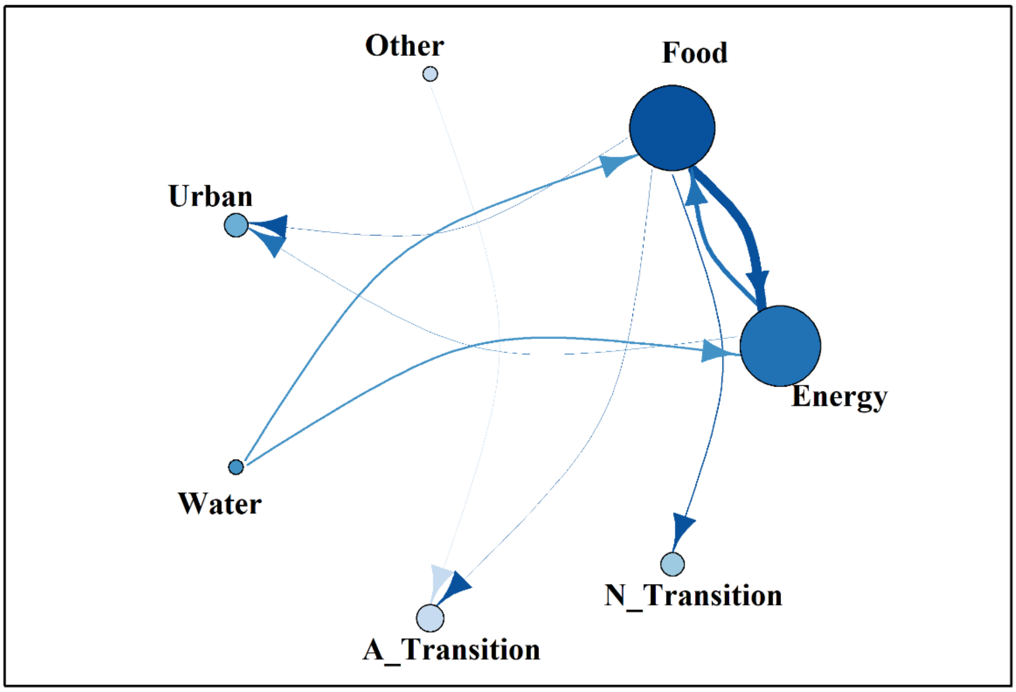

Figure 7. The WELF nexus as a network in vereda Nueva Florida, period 2002-2018.

Table 5 summarizes the differences in the significance of nexus elements for Nueva Florida. Notably, 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%) involve Food, the most important nexus element in terms of total land shares. Water also differs significantly from the regional case. This nexus element plays no significant role in Nueva Florida 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 of which Energy is a major contributor. Specifically, Energy is responsible for 52% of the total losses in Water, followed by Food at 48%. These results confirm that Water has significantly lower 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 N Transition ranks fifth in terms of total land shares, it holds the third position in terms of efficiency. This is because N Transition expands at the expense of Food, as a result of the abandonment of agricultural lands.

Table 5. Differences in the significance of nexus elements according to total land shares and network centrality metrics. The case of vereda Nueva Florida during the 2002-2018 period.

	Total land shares		**Weighted page rank centrality**		**Betweenness centrality**	
Nexus element	**Score**	**Ranking**	**Score**	**Ranking**	**Score**	**Ranking**
Energy	26.52	2	0.29	2	0	
Food	66.60	1	0.31	1	4	1
Other	0.001	6	0.05	7	0	
A Transition	0.001	6	0.08	5	0	
N Transition	0.72	5	0.1	3	0	
Urban	1.45	4	0.09	4	0	
Water	4.70	3	0.06	6	0	
Total	100		1		4	

3.2.3. Influence of transfers on resilience.

This section analyzes which interactions among nexus elements are most indicative of improved resilience. To this end, we focus on the effects of a 30% increase (decrease) in transfers between pairs of nexus elements, both at the regional and vereda scales. Increasing (decreasing) transfers is the preferred strategy for improving efficiency (redundancy) and ultimately improving resilience (Kharrazi et al., 2017). Our recommendations align with this view, as we suggest improving efficiency in the regional context and in veredas Nueva Florida and San Jose del Playon. In contrast, prioritizing redundancy improvements in La Pista plays a greater role in achieving a better balance between redundancy and efficiency, which is key to improving resilience.

We first examine the influence of transfers on resilience at the regional scale. When transfers from Food to Energy increase by 30%, we observe a 2.16% increase in efficiency and a 0.78% increase in resilience. However, increasing the same quantity of transfers from Water to Energy leads to a decrease of 0.85% in resilience and 1.9% in efficiency. Moreover, if transfers increase from Water to N Transition, the results are further worsened, with efficiency and redundancy decreasing by 4.13% and 1.5%, respectively. Compared to other strategies, transferring 30% more resources from N Transition to Food improves both efficiency (by 1.99%) and resilience (by 0.61%). Recovering Water from Food, however, has a less significant effect, increasing efficiency by only 0.8% and resilience by only 0.1%, whereas preventing losses from Water to Food increases resilience by 1.35% and redundancy by 4.27%. Lastly, if N Transition expands at the expense of Food, efficiency would decline by 0.36% and redundancy by 2.13%.

Likewise, when examining the influence of transfers on resilience at the vereda scale, specifically in Nueva Florida and San Jose del Playon, we find that increasing transfers from Food to Energy by 30% results in an average increase of 2.6% in efficiency and 2.05% in resilience. Conversely, the same quantity of transfers from Water to Energy leads to an average decrease of 2.99% in resilience and 6.6% in efficiency. Transfers from Food to N Transition have similar effect, decreasing both efficiency (by 0.15%) and resilience (by 0.35%). For the case of La Pista, reducing transfers from Water to Food by 30% contributes to a 5.5% increase in resilience and a 16.64% increase in redundancy. Similarly, reverting 30% of transfers from Food to N Transition results in an increase of 2.79% in redundancy and 4.78% in resilience.

4. Resilient WELF nexus and policy implications.

In the study area, the composition of the WELF nexus is primarily influenced by the following dominant processes: the promotion of energy production, the abandonment of agricultural lands, and significant deforestation. We have shown that the WELF nexus manifests differently across different scales, with Food assuming a central role in its composition at both regional and vereda scales. Nonetheless, the significance of other nexus elements such as Water, Energy, and N Transition, varies considerably in terms of their total land shares and contributions to resilience. Specifically, the process of abandoning agricultural lands, which is associated with N Transition, impedes the cluster Water, Energy, and Food from emerging as the dominant configuration within the WELF nexus at the vereda scale (hotspots). Given these results, and to ensure effective policymaking, we recommend that any intervention aimed at improving the resilience of the WELF nexus should rely on multi-scale assessments. According to our results, increasing efficiency is the preferred strategy for improving the resilience of the WELF nexus in a more effective manner. It can be achieved by exerting greater control over the directionality and intensity of transfers, specifically by paying more attention to the current structure of opportunity costs, in which Energy and Food play a major role. Yet, other socio-economic factors like the armed conflict and drops in agricultural yields significatively influence the WELF nexus dynamics at sub-regional scales. The overall significance of agriculture (Food) in the study area suggests that prioritizing the resilience of the food system is paramount. Implementing technological innovation through integrated crop-livestock-forestry systems, together with boosting the local economy through greater control over production prices, are ways to achieve this goal. Complementary measures such as improving land distribution and tenure, as well as favoring the conversion of abandoned lands towards more sustainable land-based economic activities and/or conservation of natural capital may also contribute to an increase in the overall resilience of the WELF nexus. Although some increase in energy production is still possible, this measure must be adopted with caution because it can aggravate conflicts over land tenure or the impact on water scarcity and/or pollution. Furthermore, an accurate estimation of the economic value of forests for different ecosystem services, such as water supply and regulation, carbon sequestration, wildlife habitat and recreation, has the potential to shift the structure of opportunity costs in favor of conservation. When combined with the implementation of market-based conservation mechanisms, such as payments for ecosystem services, this can be instrumental in reducing deforestation rates.

5. Conclusions.

Recognition of the importance of land for the study of Water, Energy and Food interactions has grown considerably over the last years (Gaddam and Sampath, 2022). The resulting nexus is often known as the WELF nexus. Achieving long-term sustainable development goals within the context of the WELF nexus often creates harmful trade-offs between economic growth, i.e., energy and food production, and conservation of natural capital, i.e., the water cycle. It is in part explained because the latter usually presents lower opportunity costs, which causes a greater focus on economic growth in competition for land. To design more effective policies, we need to improve our understanding of how the different nexus elements are configured and interact with each other, and how these interactions influence the composition and dynamics of the WELF nexus at different scales. We have shown that varying scales can exhibit distinct nexus configurations and dynamics. This implies that the WELF nexus should be interpreted as a flexible analytical object that arises as a result of context-specific backgrounds and socio-economic and environmental factors. In this vein, we developed a novel analytical framework to study how and to what extent land use changes influence the composition and dynamics of the WELF nexus. We also presented an extension of the nexus approach, termed as the network approach, in where the structure of interaction among nexus elements, i.e., directionality, strength and diversity of links, is analyzed. Specifically, we analyzed spillover effects among nexus elements and determined the significance of nexus elements in terms of total land shares and network resilience. Our analytical framework can be employed to compare very heterogeneous WELF nexus, and it is also suitable for multi-scale assessments because its application allows to observe nexus-oriented land use dynamics both at regional scale and at more detailed scales such as the vereda scale. Furthermore, it allowed us to identify hotspots, defined as sub-regions where interactions among nexus elements were more prominent, so that the government entities concerned may make timely decisions oriented to reduce competition for land. For illustrative purposes, our framework was applied to the case of Maria La Baja, a Colombian sub-watershed situated in the Colombian Caribbean. Using this example, we showed that substituting the representation of change detection matrices to networks allows not only to identify the overlapping elements of the WELF nexus, but also to better characterize the dynamics between and within nexus elements through the land uses that they encompass. Thus, the interactions and interconnectedness among nexus elements can be understood from the lens of land use more easily, giving the land and the WELF nexus a socio-economic dimension that change detection matrices are not able to convey. The presented analytical framework is only a starting point for beginning to unveil socio-ecological transitions not only as ongoing scenarios but to identify socio-economic factors which may exacerbate competition for land. The results of this study show that the expansion of palm oil plantations and the intensification of agriculture have put a strain on conservation of natural capital. Moreover, the study area is a contested region in Colombia and therefore important levels of resilience are lost as a result of abandonment of agricultural lands. With respect to future research, our analytical framework allows incorporating whether positive or negative evaluations of interactions among nexus elements. Taking into account the suitability of a given piece of land to maintain an economic activity or conserve natural capital, we can evaluate if interactions among nexus elements create positive or negative impacts on overall resilience. This would allow a better characterization of synergies (positive impacts) and trade-offs (negative impacts) among nexus elements. By using land suitability maps, we propose the development of a metric similar to the total interaction score (Nilsson et al., 2016) to determine the overall impact of interactions. Consequently, the representation of the WELF nexus as a network may potentially consist of both positive and negative links. In this case, alternative network centrality metrics such as the PN centrality (Everett and Borgatti, 2014) would be more recommendable to analyze the significance of nexus elements according to their influence on resilience. Extensions of this kind may help to improve our ability to identify and prioritize the most pressing local challenges in a given region. Additionally, they may facilitate cross-sectoral coordination and enable the pursuit of locally concerted visions and interests.

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Conflicts of interest.

The authors declare no conflict of interest.

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APPENDIX

Appendix 1. Background of the study area.

In the 1960s to the 1980s, Maria La Baja sub-watershed (MLBsw) was determined by peasant life. The Food nexus element consists of traditional crops such as rice, plantain, corn, and sugarcane crops (unprofitable cultivation since the 1980s). Livestock is unrepresentative, experiencing a moderate boom in the early 1970s. The Water nexus element is characterized by the modernization of irrigation systems and the construction of dams, as well as containing a large part of subtropical forest, one of the most threatened ecosystems in the world (especially in the Latin America region). Water is managed as a common use resource; however, the peasant and ethnic communities have not received the collective titling yet and the forest is without protection figure. Thus, for practical purposes, Water functions as open access.

In the mid-1980s appears a long-lasting armed conflict in the region. The conflict has important consequences for Food by causing massive, forced displacements and the disappearance of the Agricultural Marketing Institute (IDEMA, abbreviation in Spanish), in charge of marketing peasant products and managing fair payments (price regulation). At the same time, in these years (especially in mid-1990s) the economic opening of Colombia to international markets took place. Among other measures, agribusiness (monocultures) was promoted due to the drop in yields of traditional crops such as rice (going down from 8000 cultivated hectares to only 200 hectares). Agribusiness becomes an important strategy for Colombia to reduce foreign debt through exports.

At the end of the 1990s, the Productive Strategic Alliance was created to promote palm oil plantations, projecting 5000 hectares of arable area as a goal. This Alliance involves the Ministry of the Environment, companies, and municipalities like María La Baja. The reconversion of food production towards monocultures (Food and Energy) is promoted through economic stimuli such as subsidies (direct and indirect), income tax exemptions, investment credits and preferential treatment to access land and use of water. It also benefits from international agreements.

For the study period (2002-2018), we identify in MLBsw two well differentiated agricultural models. The first corresponds to intensified agriculture, with representative crops such as corn and pineapple (Food) and palm oil (Energy). The second corresponds to peasant agriculture, where farmers continue to have problems accessing land and obtaining fair payments for their products. Around 53% of peasant families have a salary below the minimum in the region. Both agricultural models end up affecting deforestation. Monocultures due to high demand for productive lands for exports. The peasants because they seek to improve the yields of their crops.

The abandonment of agricultural land is the result of the combination of a long-lasting armed conflict and the drop in yields of traditional crops that have caused many peasants to end up in debt. The N Transition nexus element captures both deforestation and land abandonment processes, assuming a transition (not yet determined) either towards Water or towards land-based economic activities such as Food or Energy.

Appendix 2. Supplementary tables and figures.

Table A1. LULC assignments to WELF nexus elements (column 3), with qualitative explanations (column 4) based on literature review and ancillary data. The first two columns correspond to the Corine Land Cover methodology adapted for Colombia (IDEAM, 2010).

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	Food	Crops for food purposes

	crops		
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.
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
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.

31112	3.1.1.1.2. High flooded dense forest	Water	Forest
31121	3.1.1.2.1. Dense lowland forest	Water	Forest
31122	3.1.1.2.2. Low flooded dense forest	Water	Forest
31221	3.1.2.2.1. Open forest below ground	Water	Forest
32112	3.2.1.1.2. Dense wooded dryland grassland	Water	Natural vegetation including Páramo and Sub-Páramo
32122	3.2.1.2.2. Rocky open grassland	N Transition	Soils that do not hold humidity
321121	3.2.1.1.2.1. Flooded dense grassland not wooded	Water	Permanently oversaturated soils with vegetation
321122	3.2.1.1.2.2. Dense grassland flooded with trees	Water	Soils that are flooded most of the year

Table A2. Differences in the significance of nexus elements according to total land shares and network centrality metrics. The case of vereda San Jose del Playon during the 2002-2018 period.

	Total land shares		Weighted page rank centrality		Betweenness centrality	
Nexus element	**Score**	**Ranking**	**Score**	**Ranking**	**Score**	**Ranking**
Energy	19.94	2	0.31	2	2	2
Food	61	1	0.33	1	4	1
Other	0.001	6	0	6	0	
A Transition	0.001	6	0	6	0	
N Transition	2.33	4	0.16	3	0	
Urban	1.33	5	0.13	4	0	
Water	16.5	3	0.08	5	0	
Total	100		1		6	

Table A3. Differences in the significance of nexus elements according to total land shares and network centrality metrics. The case of vereda La Pista during the 2002-2018 period.

	Total land shares		Weighted page rank centrality		Betweenness centrality	
Nexus element	**Score**	**Ranking**	**Score**	**Ranking**	**Score**	**Ranking**
Energy	5.37	4	0.17	3	0	
Food	60.6	1	0.33	1	5	1
Other	0.001	6	0	6	0	
A Transition	0.001	6	0	6	0	
N Transition	6.79	3	0.29	2	0	
Urban	0.09	5	0.1	4	0	
Water	27.18	2	0.09	5	0	
Total	100		1		5	

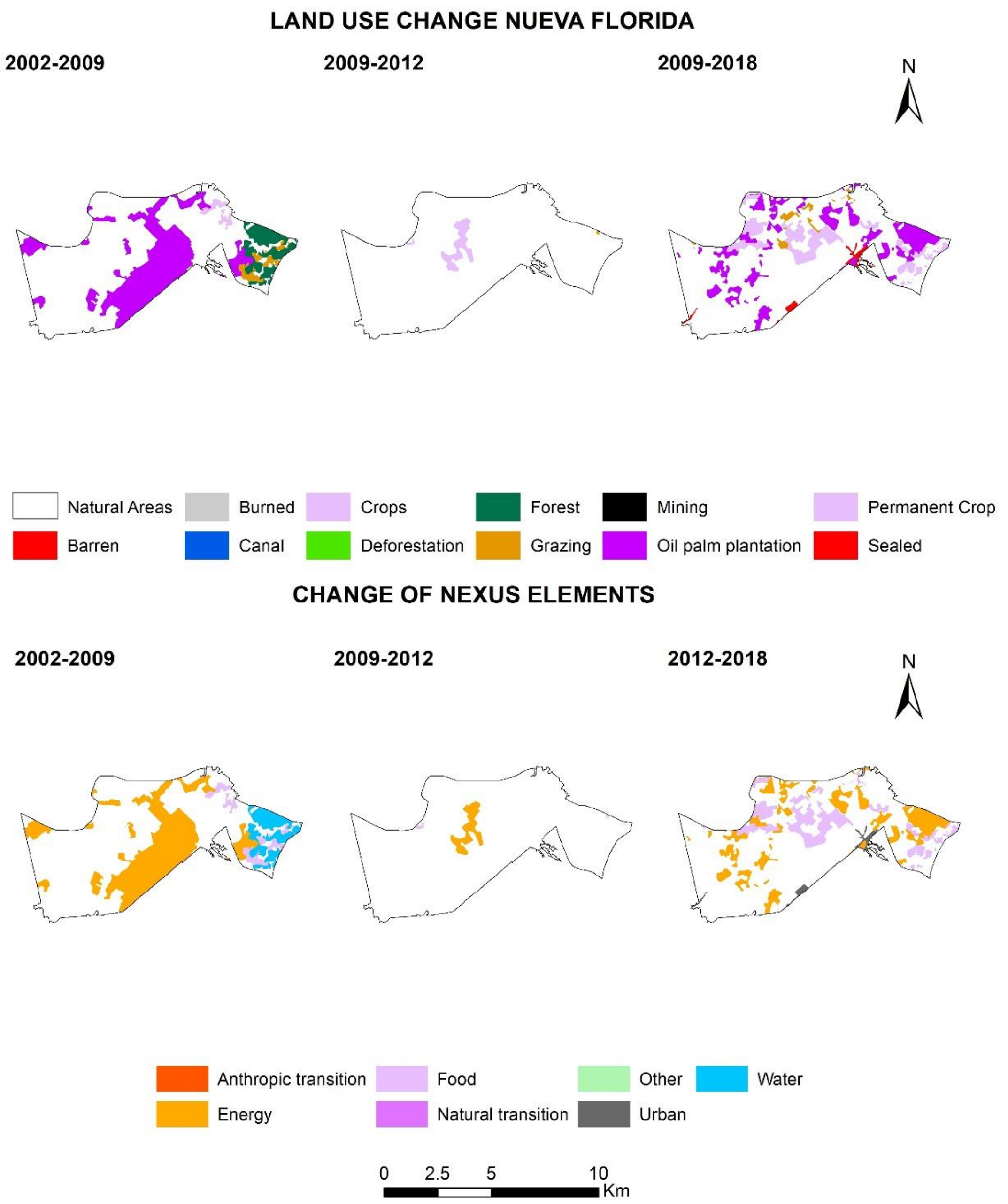

Figure A1. Upper panel: LULC changes in vereda of Nueva Florida, Maria la Baja municipality, in 2002-2018 period. Lower panel: Changes referred to WELF nexus elements.

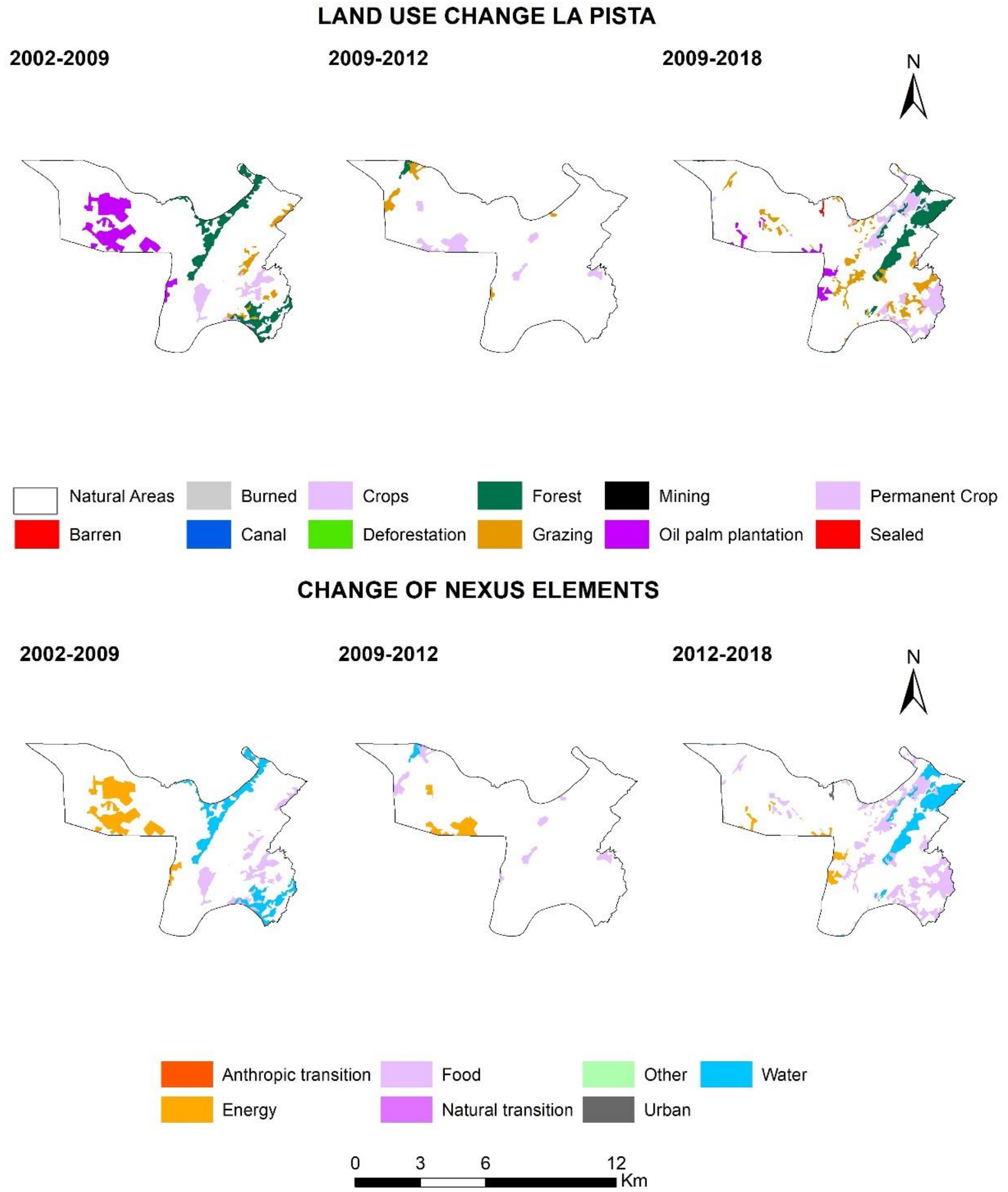

Figure A2. Upper panel: LULC changes in vereda of La Pista, Maria la Baja municipality, in 2002-2018 period. Lower panel: Changes referred to WELF nexus elements.

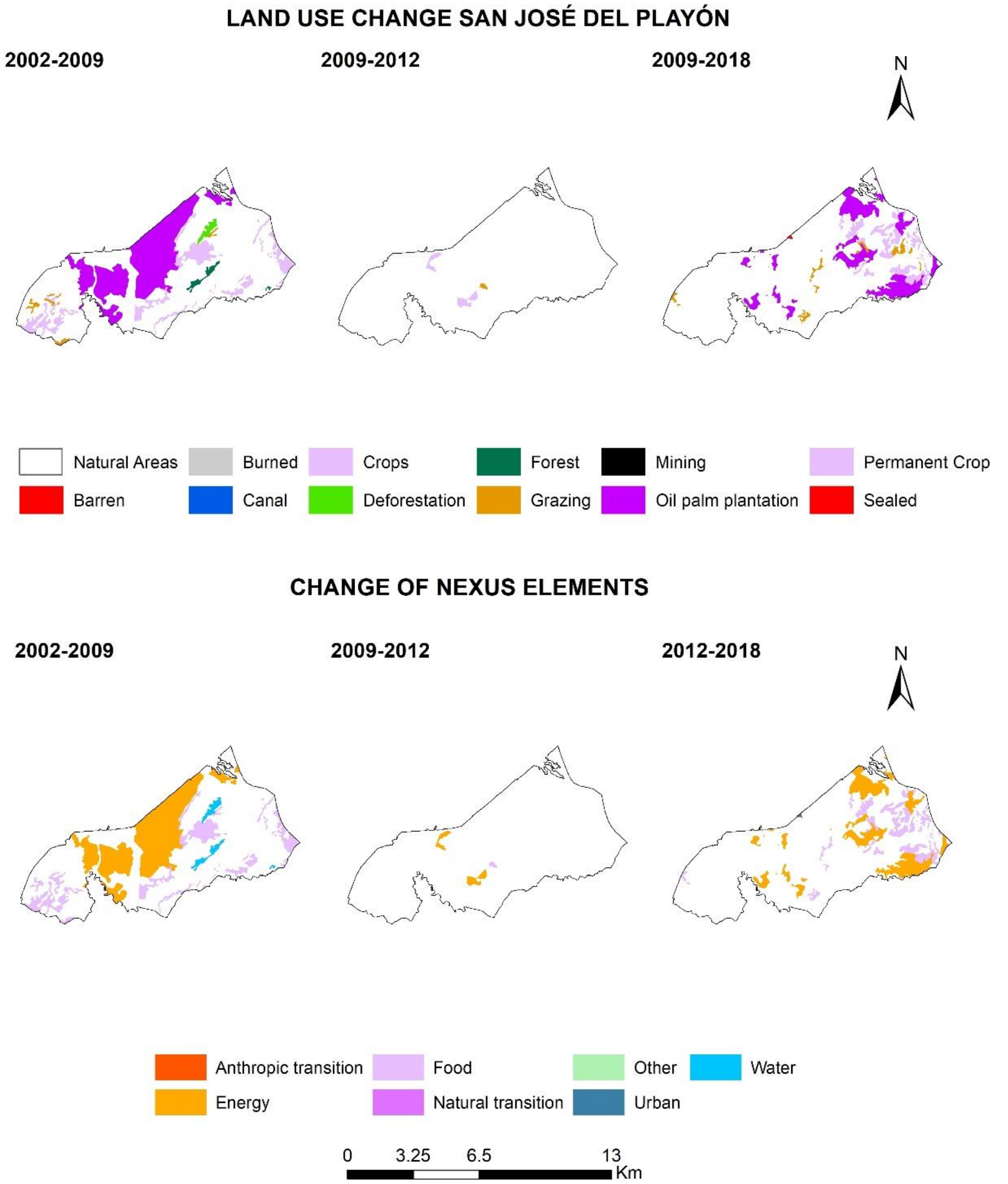

Figure A3. Upper panel: LULC changes in vereda of San Jose del Playon, Maria la Baja municipality, in 2002-2018 period. Lower panel: Changes referred to WELF nexus elements.

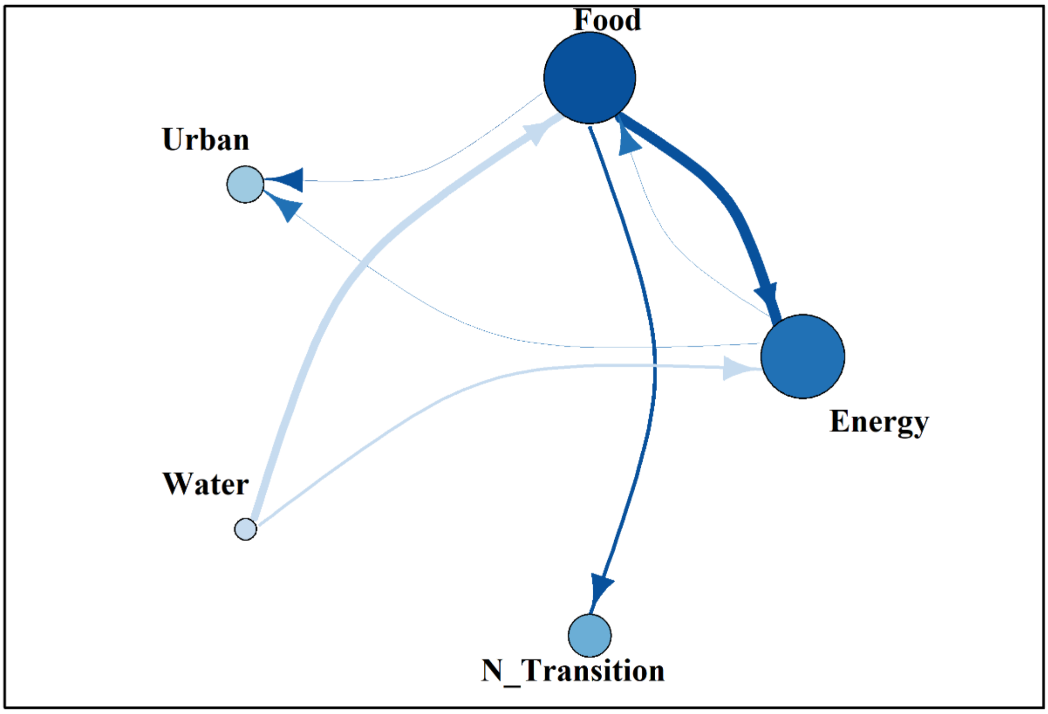

Figure A4. The WELF nexus as a network in vereda San Jose del Playon, period 2002-2018.

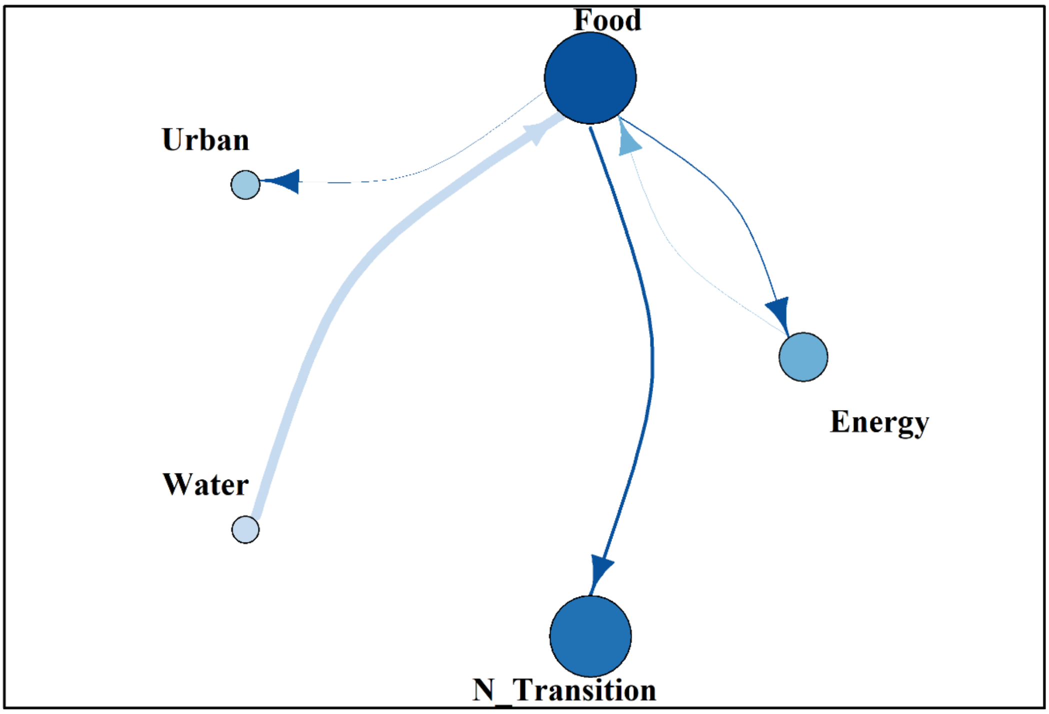

Figure A5. The WELF nexus as a network in vereda La Pista, period 2002-2018.

Appendix 3. 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 as follows

$$P[Y = j \mid x] = \pi_j(x) = \frac{\exp\left(g_j(x)\right)}{\sum_{k=0}^{r-1}\left[g_k(x)\right]} = \frac{\exp\left(\beta_{j0} + \beta_{j1}x_1 + \beta_{j2}x_2 + \ldots + \beta_{jm}x_m\right)}{\sum_{k=0}^{r-1}\exp\left(\beta_{k0} + \beta_{k1}x_1 + \beta_{k2}x_2 + \ldots + \beta_{kp}x_p\right)}. \tag{A1}$$

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

$$l\left(\beta\right) = \prod_{i=1}^{n}\left[\pi_0\left(x_i\right)^{y_{0i}}\ \pi_1\left(x_i\right)^{y_{1i}}\ \pi_2\left(x_i\right)^{y_{2i}} \ldots \pi_{r-1}\left(x_i\right)^{y_{(r-1)i}}\right]. \tag{A2}$$

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

$$L\left(\beta\right) = \ln\left[\prod_{i=1}^{n}\left[\pi_0\left(x_i\right)^{y_{0i}}\ \pi_1\left(x_i\right)^{y_{1i}}\ \pi_2\left(x_i\right)^{y_{2i}} \ldots \pi_{r-1}\left(x_i\right)^{y_{(r-1)i}}\right]\right]. \tag{A3}$$

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.