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Published Version:
Assumma V., Bottero M., De Angelis E., Lourenco J. M., Monaco R., Soares A. J. (2021). A decision support system for territorial resilience assessment and planning: An application to the Douro Valley (Portugal). SCIENCE OF THE TOTAL ENVIRONMENT, 756, 1-10 [10.1016/j.scitotenv.2020.143806].

Availability:
This version is available at: https://hdl.handle.net/11585/912950 since: 2024-05-11

Published:
DOI: http://doi.org/10.1016/j.scitotenv.2020.143806

Accepted Manuscript

Journal of Science of the Total Environment:

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To appear in: Science of the Total Environment

Received 31 July 2020

Received in revised form 12 October 2020

Accepted 25 October 2020

Available online 26 November 2020

Doi: https://doi.org/10.1016/j.scitotenv.2020.143806

Please cite this article as:

Assumma, V., Bottero, M., De Angelis, E., Lourenço J.M., Monaco, R., Soares, A.J: (2021). A decision support system for territorial resilience assessment and planning: An application to the Douro Valley (Portugal). Journal of Science of the Total Environment, vol 756, 143806, pp. 1-10. DOI: 10.1016/j.scitotenv.2020.143806

A Decision Support System for Territorial Resilience Assessment and Planning: an Application to the Douro Valley (Portugal)

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Abstract

This paper aims to assess the territorial resilience of a socio-ecological system through an innovative integrated evaluation framework to aid the decision-making process in the planning of transformation scenarios. This framework employs a set of resilience indicators through a Multicriteria Decision Analysis (MCDA) coupled with a Lotka-Volterra mathematical model of cooperative type. The set of indicators aims to calculate a composite index of Territorial Resilience (TRI), whereas the mathematical model is an extension of an existing model, aimed to predict possible long-time scenarios. The proposed operational framework for rural and vineyard landscapes aims to bridge the existing gap between territorial resilience theory and practice, with an innovative Decision Support System able to assist decision makers and territory planners in the planning and management of resilient territorial systems. This integrated evaluation framework is applied to a famous wine region in Portugal, the Douro Valley, where Port-wine grows. Such framework, especially in a context of adaptive governance, proves to be a suitable support in the field of landscape and urban planning to evaluate the dynamics of socio-ecological systems and to envision long-term policies and actions.

Keywords: Territorial resilience; Multicriteria Decision Analysis; Mathematical modelling; Spatial mapping.

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1. Introduction

The planet's health continues deteriorating due to the combined impacts of anthropogenic activities and the ongoing situation of climate-change, thus causing a loss of ecosystem services (Carreiro and Zipperer, 2011; MEA, 2005; TEEB, 2010). The International Panel on Climate Change reported alarming data that could cause irreversible changes if a worldwide strategy is not adopted (IPCC, 2019).

Research on resilience (Berkes and Folke, 1998; Holling, 1996, 1973) has been going on for more than fifty years, and the new millennium has assisted to a great interest from academics, organizations, governments and freelancers. The Latin word *resilire* translates literally resilience as the ability "to leap back" and it is used as a polysemic concept (Gunderson, 2010). Resilience is employed in various disciplines along time, such as by engineering, ecology, psychology, economy, urban planning, disaster risk management, climate planning, among other.

In Engineering, resilience means the "stability at a presumed steady-state, and stresses resistance to a disturbance and the speed of return to the equilibrium point" (Berkes and Folke, 1998). It reveals suitable for actions, e.g. testing materials stability or evaluating the risk of cultural heritage (Appiotti et al., 2018; Ceravolo et al., 2016). Psychology conceives resilience to study the individual and since the 80s was intended as the community's capacity to respond after disasters and dramatic events (Adger, 2000; Prati and Pietrantoni, 2009; Tobin and Whiteford, 2002).

Studies on ecological resilience began during the 60´s with attempts to model the ecosystems and investigate the alternative ecological states (Allen and Holling, 2010; Gunderson, 2000). Holling defined ecological resilience the "measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables", so differentiating it from the engineering resilience (Holling, 1996, 1973). Resilience is not necessarily characterized by hierarchical interactions. The system can skip directly to a reorganization phase, without intermediate phases, and even can interact across scales (Gunderson and Holling, 2002). This definition lends itself to the unpredictable nature of resilience (Holling, 1996; Pendall et al., 2010). Holling's studies became the main reference to conceptualize a formal analytical framework (Cote and Nightingale, 2012; Walker et al., 2007), which incorporated also studies in ecological economics (Anderies et al., 2004; Ludwig et al., 1997; Norgaard, 1994; Perrings, 2006). Subsequently, a co-evolutionary approach was defined through that the coupled socio-ecological systems (SES) were introduced: ecosystems, urban and territorial systems, landscapes (Berkes and Folke, 1998) which “grow, adapt, transform and collapse, at different scales” (Lambin, 2005), thus identifying complex adaptive systems (Folke et al., 2010; Gunderson, 2010).The mentioned studies generated an important step towards a transdisciplinary approach to practice the resilience thinking (Kallis and Norgaard, 2010): the conceptualization of urban resilience according to a holistic approach and considering the dynamic behavior of systems (Meerow et al., 2016), the combination of resilience, sustainability and transformability to trigger important planning challenges (Elmqvist et al., 2019), among other.

International organizations incorporated resilience within their frameworks. The Global Agenda has introduced 17 Sustainability Goals which are today the main reference for all member countries (United Nations, 2015). The Urban Agenda Habitat III (Agenda, 2016) supports the SDGs achievements through guidelines. The Hyogo framework and the Sendai Framework (UNISDR, 2015, 2005) intend resilience as a process within the disaster risk management. Despite the development of various frameworks, mismatches have been detected between government actions and environmental outcomes (Pillay and Buschke, 2020). The growing attention and the overuse of resilience generated confusion in the academic, political and professional fields (Cutter, 2016), leading to have divergent concepts (Huck and Monstadt, 2019). The common trend is to take position definitions with respect to a single dimension, the scale and investigated object or to combine definitions by merging common features and minimizing differences (Chambers et al., 2019).

In recent years, territorial resilience was defined as “an emerging concept capable of aiding the decision-making process of identifying vulnerabilities and improving the socio ecological and technological systems (SETSs)”(Brunetta et al., 2019). Even if the idea of territorial resilience is ever more important for the assessment and planning, its application to the real world is almost absent.

This paper (re)defines territorial resilience as “the ability of a territorial system to absorb the impacts generated by endogenous and exogenous drivers, itself toward a new dynamic equilibrium”, where territorial system intends regions, sub-regions or provinces. This definition takes into account that robust evaluations are required to aid the decision makers in planning resilient policy decisions (Dumitru et al., 2020).

Few studies focus effectively on the resilience practice to deliver best-practices (Bennett et al., 2016), to prepare communities to risk events, to define long-term strategies, to increase governance and adaptive management (Ayre and Nettle, 2017; Mitchell, 2013; Pelling, 2003; Schultz et al., 2015).

The paper aims to bridge the gap between territorial resilience theory and practice with an original Decision Support System, to support the planning and management of territorial systems.

The proposed framework combines indicators developed through a multicriteria approach with a dynamical model of Lotka-Volterra cooperative type (Assumma et al., 2019b; Gobattoni et al., 2011; Monaco and Soares, 2017), finalized by spatial mapping through GIS methods (Malczewski, 2006). It is applied to the wine region of the Douro Valley in Portugal, a UNESCO site inscribed in the World Heritage List (2001). The application to a real territory with its specific characteristics and local/regional agents demonstrates that ecologically-based technical knowledge on territorial resilience can integrate different sets of components, values, criteria and focus in implementation, not necessarily top-down. This novel framework fosters participatory adaptive management based on dissemination of conceptual knowledge and discussion of base-line scenarios. In so doing, it addresses criticisms about resilience involving a top-down approach that does not address decision contexts or about it lacking focus on implementation, especially of transformative adaptation (Colloff et al., 2017).

2. Materials and methods

This study combines Multicriteria Decision Analysis (MCDA), dynamical modelling to support Decision Makers in the planning and management of resilient territorial systems.

The MCDA is employed for the calculation of a composite index of territorial resilience, organizing a set of indicators according to the value tree approach (Keeney and Raiffa, 1979). The SMARTER method (Barron and Barrett, 1996; Edwards and Barron, 1994) has been used as weighting phase of the MCDA to deliver a set of weights for investigating the importance of the indicators and calculating a synthetic index of Territorial Resilience (TRI). As far as the ecological evaluation is considered, several references exist on dynamical models of cooperative type applied to various contexts, known as PANDORA models (Bonacini et al., 2017; Gobattoni et al., 2011; Monaco and Soares, 2017). A revisited version of the dynamical model by Monaco and Soares (2017) is here developed. Figure 1 illustrates the proposed evaluation framework.

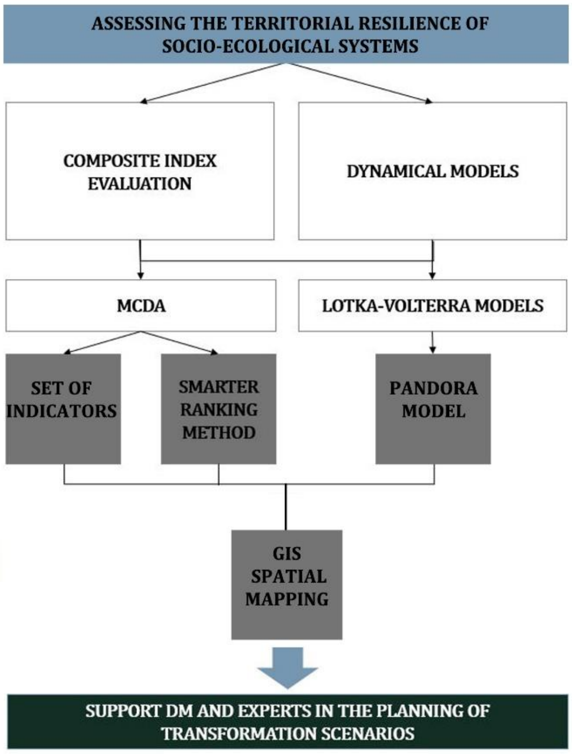

Figure 1. Structure of the evaluation framework.

2.1. Composite index evaluation

Since resilience is a multidimensional concept, the research proposes a composite index evaluation that considers different variables and indicators. The construction of composite indexes has been extensively investigated in the scientific literature and different methods have been suggested (Barron and Barrett, 1996; Edwards and Barron, 1994; Keeney and Raiffa, 1979). Multicriteria Decision Analysis (MCDA) is a wide family of techniques that includes multiple features of a decision problem, both qualitative and quantitative and it takes into account the interests of the actors and stakeholders. Differently from the nonparametric estimation techniques (e.g. discounting cash-flow, Cost Benefit Analysis), MCDA is retained as suitable to deal with complex problems which require multidimensional solutions (Bottero and Mondini, 2009); Kitsiou et al., 2002).

In particular, a three-step procedure has been followed for the calculation of the TRI:

(i) Indicators selection and data collection;

(ii) Weighting and aggregation;

(iii) Spatial analysis and visualization.

2.1.1 Indicators selection and data collection

This set of indicators has been hierarchically organized (Figure 2), where:

- Goal is the territorial resilience assessment of the Douro Valley which performs the Territorial Resilience Index (TRI).
- Components are seven features retained relevant for the territorial resilience of the case study: Cultivations component refers to the relations between the rural landscape, economic aspects and climate change features (Gottero and Cassatella, 2017; Schaller et al., 2018). Tourism considers the tourism offer and the impacts generated on a rural landscape by tourism flows (Terkenli, 2014). Real Estate considers cultural landscapes as positive externalities able to generate benefits on real estate prices (Panduro and Veie, 2013; Tyrväinen, 1997; Waltert and Schläpfer, 2010). Forests are a fundamental resource because deliver benefits to local communities and needs the management to prevent risk events (Jacinto et al., 2015; MEA, 2005; Santos et al., 2018; Steenberg et al., 2012; TEEB, 2010; Todman et al., 2016; Valente et al., 2013; Zêzere et al., 2014). Ecology refers to the ecological features of a SES, e.g. the biological energy, green areas of high quality, or the presence of urban areas that may obstacle the connectivity of the system. Some of them have been used as parameters of the dynamical model as it will be explained in Section 2.3. (Babí Almenar et al., 2018; Bonacini et al., 2017; Dalerum, 2014; Gobattoni et al., 2011). Landscape considers the presence of protected areas and cultural heritage and also those features that may enhance or compromise landscape (Cassatella and Peano, 2011; De Vries et al., 2013, 2007). Regional Development considers socio-economic features, as well as programs and initiatives to increase territorial resilience (Dente, 2014; Scrivens and Smith, 2013).

The indicators are organized into components and they are reported in Tables A.1-A.7 (Supplementary Material).

- Criteria are the system aspects acting on the resilience capability. In particular, Value is represented by the elements that generate benefits to the system under investigation; Vulnerability refers to those factors that solicit perturbations within the system and thus influencing negatively its state; Adaptability represents the ability of the system to respond to one or more perturbations, evolving towards a new equilibrium.
- Indicators measure the performances of the municipalities in terms of territorial resilience and are classified into general and site-specific. The firsts are applicable to whatever wine region, whereas the latter measure the specific characteristics of the Douro Valley. This set of indicators can be considered innovative for assessing territorial resilience of wine regions.
- The alternatives are the municipalities of the NUTS III, Douro, which have been organized into 19 landscape units. More information are reported in section 2.2.

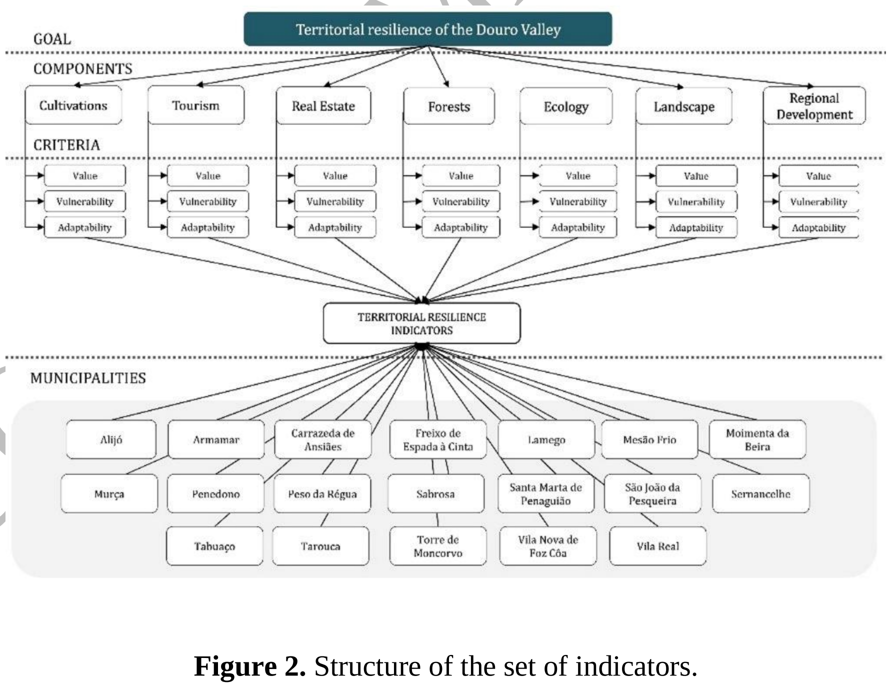

Figure 2. Structure of the set of indicators.

Various data sources were considered (Tables A.1-A.7): statistical data sources (e.g. Instituto Nacional de Estatistica - INE, PORDATA, ICNF, among other), the knowledge of selected experts of the Douro Valley, geographical databases (e.g. IPMA - Portal do Clima, iGEO - Informação Geográfica, INSPIRE Geoportal, or OpenStreetMap) and other data (e.g. urban plans, programs, or SEA and EIA procedures).

2.1.2 Weights assessment and aggregation

An important part of the evaluation procedure is related to the weighting phase. In fact, weights measure the importance of the indicators, criteria and components in the decision problem under examination. Among the different protocols for weights elicitation, the present study makes use of the SMARTER method. This method allows to rank groups of elements from the most important to the less important (Barron and Barrett, 1996; Edwards and Barron, 1994) and to calculate normalized weights. It was chosen due to different motivations: firstly, the SMARTER procedure facilitates an evaluation of numerous elements into the process, and in this sense the ranking reduces the number of comparisons; secondly, it allows the experts to give qualitative judgments and not numerical values, thus increasing the confidence of the experts in the evaluation.

Another crucial aspect for the calculation of the composite index is related to the normalization procedure which allows to compare non-commensurable items. Among the several normalization procedures, this study is based on the min-max transformation that allows to rescale the original values in a 0-1 range (OECD, 2008). The problem under analysis involves both aspects that positively affects the decision (whose corresponding indicators have thus to be maximized) and aspects that negatively affects the decision (whose corresponding indicators have thus to be minimized). Consequently, intermediate values between the minimum and the maximum have been converted through the following formulas (OECD, 2008), depending on the need to maximize or minimize the indicator, respectively:

$$I_i = \frac{x - x_{min}}{x_{max} - x_{min}}, \qquad I_i = \frac{x_{max} - x}{x_{max} - x_{min}} \tag{1}$$

in which I_i is the normalized value for each indicator and x indicates the raw value of the indicator.

After having defined the weights and completed the normalization procedure, the indicators are then aggregated through the hierarchy using an additive function:

$$TRI_j = \sum_i w_i \, I_{ij}$$

(2)

where TRI_j is the composite Territorial Resilience Index for the municipality j, w_i is the weight of the indicator i and I_{ij} is the normalized value of the indicator i for the municipality j.

2.1.3 Spatial analysis and visualization

Spatial analyses can be considered suitable techniques to provide opportunities for resilience thinking and planning (Borie et al., 2019).The final results of the TRI can be then visualized through specific spatial maps developed in GIS environment. The overall objective of this part of the evaluation is to identify those Municipalities with common resilience features, thus defining specific areas of intervention.

2.2. The mathematical model for ecological assessment

In the field of Landscape Ecology (Turner and Gardner, 2015), mathematical models provide dynamical evolutions of possible scenarios of complex environmental systems. Models of cooperative type, already quoted in this paper, are frequently employed in integrating strategic evaluations as support in the assessing process for aiding the decision makers to identify suitable policy decisions. Many applications of such models are described in the literature (Bonacini et al., 2017; Gobattoni et al., 2011; Monaco and Soares, 2017; Murray, 2002), presenting promising results in the study of the ecological-economic evaluation of rural and vineyard landscapes (Assumma et al., 2019b, 2019a). The proposed dynamical model maintains the structure of the one presented (Pelorosso et al., 2012). The novelty is the application to the case study under investigation to obtain evolutionary scenarios of ecological type, thanks to the identification of the meaning and numerical value of the parameters from real data. Moreover, this dynamical model, with respect to the one studied in Monaco and Soares (2017), links the ecological scenarios with the results obtained through an innovative MCDA approach. Thanks to the combination with the SMARTER method it has been possible to modify the role of the parameters, taking into account the particularities of the Douro Valley, a region that is characterized by a significant level of naturalness and contains specific cultivations as the vineyards, so that the ecological component is one of the most important to be considered in this analysis.

The main aim of the model is to describe the ecological state of an environmental system. An environment is intended as an isolated system divided in n landscape units (LU) which are specified by their borders, constituted by natural or anthropological barriers, e.g. roads, motorways, railways, buildings, industrial infrastructures, rivers, or hill ridges. Each i-th LU, $i = 1, \dots, n$, is formed by m_i-biotopes which are patches characterized by a uniform land cover. In our model, the ecological state of the i-th LU is described by two normalized variables varying in [0; 1], namely V_i and b_i, for $i = 1, \dots, n$. Variable V_i represents the percentage of all green areas with high ecological quality in the i-th LU. More in details, V_i is obtained by dividing the sum of all green areas with Biological and Territorial Capacity (BTC), greater than $2.4\, Mcal/m^2\ per\ year$ (Gobattoni et al., 2011) by the total area of the LU itself. Moreover, variable b_i is the percentage of biological energy produced by the LU's biotopes and it is defined as follows

$$b_i(t) = \frac{1}{B_{max} S_i} \sum_{j=1}^{m_i} B_{ji} s_{ji} \tag{3}$$

where B_{ji} is the BTC value of the biotope *j* belonging to the i-th LU of area S_i and s_{ji} is the area of the biotope *j*. Moreover, $B_{max} = 6.5\, Mcal/m^2\ per\ year$ is the maximum value of BTC for the vegetation at the European latitudes and corresponds to oak woods. Variables $V_i(t)$ and $b_i(t)$ change in time and their evolution is given by the following system of ordinary differential equations (ODEs),

$$\begin{cases} b_i'(t) = a_i b_i(t)[1 - b_i(t)] - [1 - V_i(t)] b_i(t) \\ V_i'(t) = \varphi_i d_i V_i(t)[1 - V_i(t)] - U_i V_i(t) \end{cases}, \qquad i = 1, \dots, n \tag{4}$$

coupled with the initial data at $t = 0$,

$$V_i(0) = V_{i0}, \quad b_i(0) = V_{i0}, \quad i = 1, \dots, n \tag{5}$$

System (4) includes the parameters a_i, d_i, U_i and φ_i which can be considered as ecological indicators. It has to be noticed that the same parameters are also included in the MCDA procedure in the form of indicators belonging to the component Ecology. Indeed, the main novelty of the proposed model is that the ecological parameters are included both in the dynamical model as input data to predict future possible scenarios, both in the MCDA to evaluate the current ecological performance of the Douro Valley. In detail:

Indicator a_i of solar exposure of biotopes

The indicator a_i measures the solar exposure of the i-th LU by considering the following formula

$$a_i = \frac{w_1 S_i^{SE} + w_2 S_i^{W} + w_3 S_i^{NE}}{S_i} \leq 1 \tag{6}$$

where S_i^{SE}, S_i^{W}, S_i^{NE} indicate the area of the LU exposed at South-East, West and North-East, respectively, and the weights w_1, w_2, w_3 are respectively given by 0.50, 0.25 and 0.25.

Indicator d_i of solar exposure, humidity and ecotone length

The indicator d_i is the average value of the indicators of solar exposure a_i, relative humidity k_i^{hu} and ecotone length k_i^{ec}, that is

$$d_i = \frac{1}{3}(a_i + k_i^{hu} + k_i^{ec}) \tag{7}$$

where the parameters k_i^{hu} and k_i^{ec} are given by

$$k_i^{hu} = \frac{1}{S_i}\left(w_1 S_i^{h} + w_2 S_i^{s}\right), \quad k_i^{ec} = 1 - P_i\left(\sum_{j=1}^{m_i} P_{ij}\right)^{-1} \tag{8}$$

where S_i^h and S_i^s are respectively the humid and the semi-humid areas of the LU, w_1 = 0.75 and w_2 = 0.25. Moreover, P_i is the perimeter of the i-th LU and P_{ij} the perimeter of the j-th biotope.

Indicator U_i of building density

The indicator U_i is defined by the ratio of the total building area of the i-th LU and S_i.

Indicator φ_i of connectivity

The indicator φ_i refers to the global connectivity among the LUs that exchange bioenergy with their neighbors, according to the formula, see Monaco and Soares (2017),

$$\varphi_i = \sum_{k \in I_i} \frac{H_{ki}}{L_{ki}} \tag{9}$$

where I_i is the number of the LUs bordering the i-th LU and

$$H_{ki} = \sum_{r=1}^{s} L_{ki}^r p_r, \qquad L_{ki} = \sum_{r=1}^{s} L_{ki}^r \tag{10}$$

with L_{ki}^r being the length of the portion $r, r = 1, \ldots, s$ of the border between the LU *i* and *k*, with a permeability index $p_r \in [0, 1]$.

An important step for the qualitative analysis of our model consists in determining its equilibrium solutions and analyzing their stability behavior. The equilibrium solutions represent some possible ecological scenarios for the LUs and their stability analysis establish if they represent an attainable future scenario for each LU.

2.2.1 Equilibrium solutions

The equilibrium solutions of system (4) (Murray, 2002) are obtained by solving

$$\begin{cases} a_i b_i(t)[1 - b_i(t)] - [1 - V_i(t)]b_i(t) = 0 \\ \varphi_i d_i V_i(t)[1 - V_i(t)] - U_i V_i(t) = 0 \end{cases}, \quad i = 1, \dots, n$$

We obtain:

$$\left(V_i^{(1)}(t), b_i^{(1)}(t)\right) = (0, 0), \tag{11}$$

which represents a scenario of strong fragmentation characterized by a strong loss of bio-energy and green area of high ecological quality;

$$\left(V_i^{(2)}(t), b_i^{(2)}(t)\right) = \left(1 - \frac{U_i}{\varphi_i d_i}, 0\right), \tag{12}$$

which corresponds to a scenario with a poor value of bio-energy and some sparse green islands and it occurs if $U_i < \varphi_i d_i$. Finally, the third equilibrium is given by

$$\left(V_i^{(3)}(t), b_i^{(3)}(t)\right) = \left(1 - \frac{U_i}{\varphi_i d_i}, 1 - \frac{U_i}{\varphi_i a_i d_i}\right), \tag{13}$$

which represents a scenario with appreciable ecological quality, characterized by significant or even large values of both green areas and bio-energy. This equilibrium point occurs if $U_i < \varphi_i a_i d_i < \varphi_i d_i$.

2.2.2 Stability conditions

In order to complete the analysis of the model, it is necessary to determine the stability conditions for the equilibrium solutions. Such an analysis consists in determining the sign of the eigenvalues of the Jacobian matrix of system (4), (Murray, 2002). Thus, for the equilibrium solutions of system (4) we obtain three couples of eigenvalues, given by

First equilibrium

$$\lambda_{1i}^{(1)} = a_i - 1, \quad \lambda_{2i}^{(1)} = \varphi_i d_i - U_i \tag{14}$$

Second equilibrium

$$\lambda_{1i}^{(2)} = U_i - \varphi_i d_i, \quad \lambda_{2i}^{(2)} = a_i - \frac{U_i}{\varphi_i d_i} \tag{15}$$

Third equilibrium

$$\lambda_{1i}^{(3)} = U_i - \varphi_i d_i, \quad \lambda_{2i}^{(3)} = \frac{U_i}{\varphi_i d_i} - a_i \tag{16}$$

The stability conditions ask that both eigenvalues are negative, so that we get

- the first equilibrium is asymptotically stable if $\varphi_i d_i < U_i$, otherwise it is unstable;
- the second equilibrium is respectively asymptotically stable or unstable if $\varphi_i a_i d_i < U_i < \varphi_i d_i$;
- the third equilibrium, if it exists, that is if $U_i < \varphi_i a_i d_i$, it is asymptotically stable.

3. Results

3.1. Case study: the Douro Valley

The Douro Valley is a wine region in the North-Eastern side of Portugal and it extends for about 40.000 ha. The Douro Valley is partially included in the UNESCO site "Alto Douro Wine Region" as “an evolving and living cultural landscape” (World Heritage Committee, 2001): the boundaries of its core zone are the result of landscape studies and assessments, whereas the boundaries of its buffer zone overlay most of the Demarcated Douro wine region (DDR).

A non-uniform urban morphology can be recognized between the internal area and the coast as testimony of a common trend in Portugal since the 18th century (Lourenço et al., 2009). The Douro region was involved in several territorial development plans and programs, EU investments to raise the local economy for triggering a socioeconomic improvement, job creation and life quality (Lourenço et al., 2009). This research work has selected the 19 Municipalities of the NUTS III, Douro. From an ecological point of view, each Municipality has been intended as a Landscape Unit:

LU1 - Alijó
LU2 - Armamar
LU3 - Carrazeda de Ansiães
LU4 - Freixo de Espada à Cinta
LU5 - Lamego
LU6 - Mesão Frio
LU7 - Moimenta da Beira
LU8 - Murça
LU9 - Penedono
LU10 - Peso da Régua
LU11 - Sabrosa
LU12 - Santa Marta de Penaguião
LU13 - São João da Pesqueira
LU14 - Sernancelhe
LU15 - Tabuaço
LU16 - Tarouca
LU17 - Torre de Moncorvo
LU18 - Vila Nova de Foz Côa
LU19 - Vila Real

3.2 Results of the Territorial Resilience Index

A crucial part of the evaluation was related to the organization of different panels and focus group with local experts and stakeholders for collecting their preferences about the weights to be used in the calculation model.

A pre-test was performed in April 2019 involving a panel of experts, one expert for each component. The objective was the investigation of the importance of the set of indicators to deliver an initial set of weights of territorial resilience.

The complete survey (September - November 2019) was addressed to a larger group of actors and stakeholders involved in the Douro Valley activities. Work meetings were organized to ask to the experts to rank the indicators and to define potential actions of territorial resilience for the Douro Valley. The survey was also proposed online to the members of the Association of Port Wine Companies (AEVP).

The average set of weights obtained through this survey was applied to calculate the TRI for each municipality (Figure A.1, Supplementary Material). The results were represented in thematic maps (Figure A.2) and then aggregated into a final map (Figure 3).

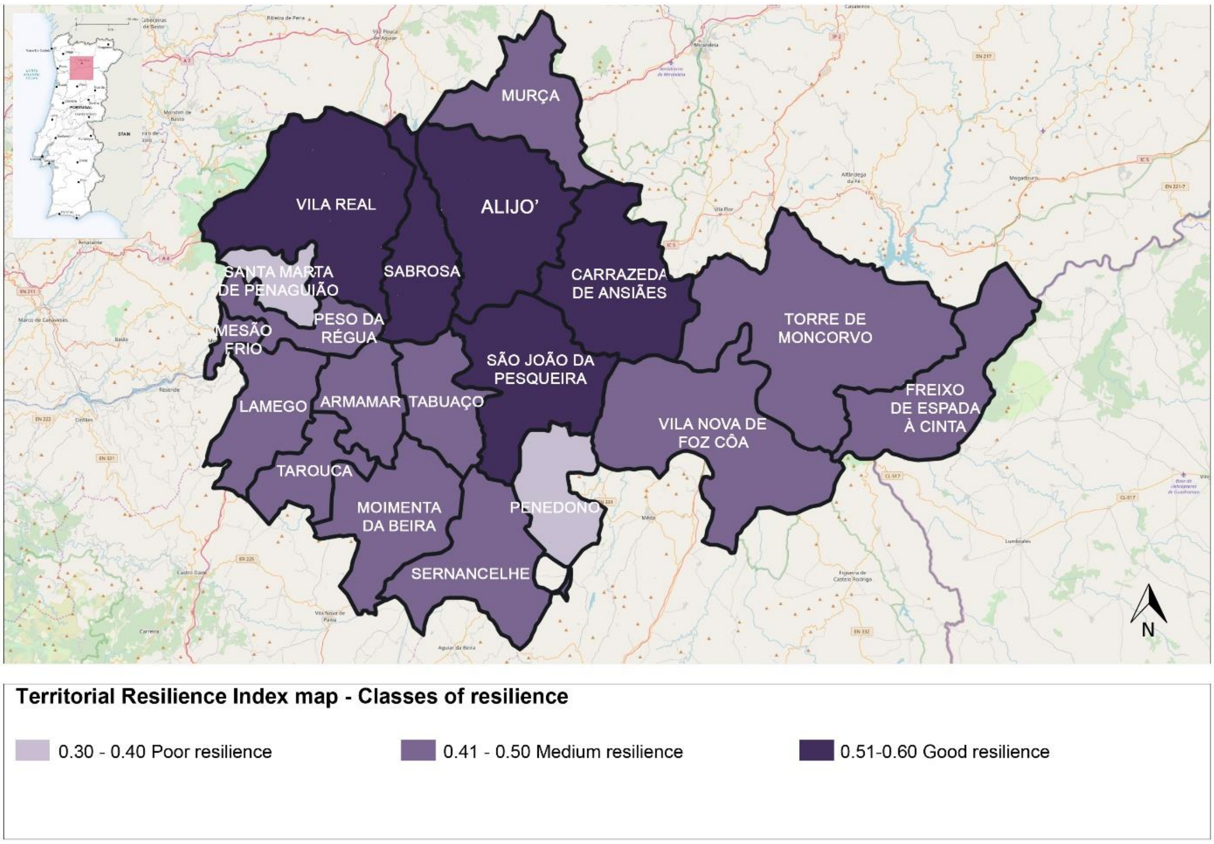

Figure 3. Spatial visualization of the TRI indices using resilience classes.

Most of the municipalities record a medium resilience. São João da Pesqueira and Vila Real are the most resilient (0.59 and 0.58) thanks to the high performance recorded in each component. Some municipalities recorded a medium-low resilience, e.g. Penedono (0.41) due to low performances on cultivations and landscape. Santa Marta de Penaguião confirms its low performances with the lowest resilience (0.38).

3.1.2 Results of the dynamical model

Most of the LUs reach the third scenario with appreciable ecological quality (Table A.8, Supplementary Material). Nevertheless, there are several LUs (LU4, LU5, LU8, LU9, LU16 and LU17) that reach scenarios presenting poor bio-energy and isolated green areas. Finally, there are two LUs (LU6 and LU19) that reach the scenario of strong fragmentation. In order to show some examples of the evolution behavior of the state variables, Figure 4 shows the time behavior of $V_i(t), b_i(t)$, for three LUs: LU3 (Carrazeda de Ansiães, Good), LU8 (Murça, Medium) and LU19 (Vila Real, Poor). The results of the other LUs are shown in Supplementary Material (Figures A.3 and A.4).

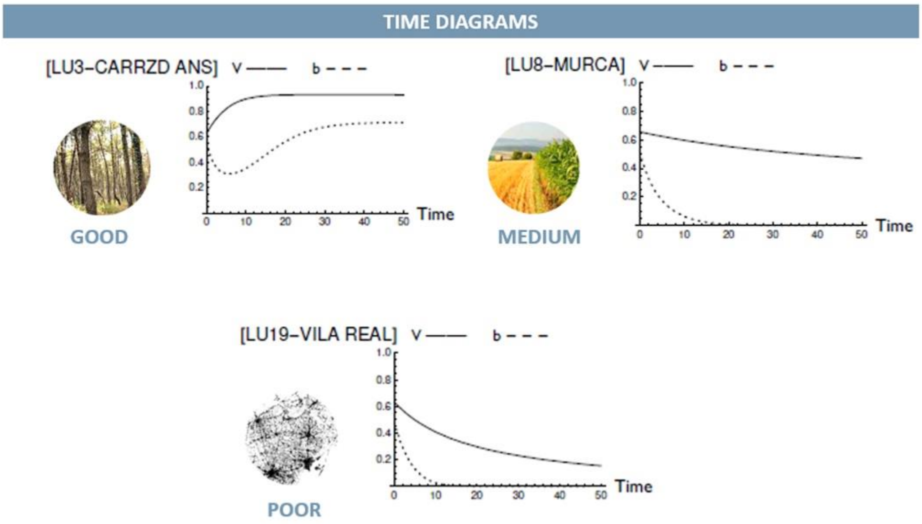

Figure 4. Some ecological scenarios as output of the model.

4. Discussion and conclusions

The compared analysis of the models' results allows to interpret the connection between the territorial resilience status and the possible ecological evolution scenarios. As described in the previous sections, the TRI has been calculated by aggregating specific indicators across different territorial dimensions, i.e. cultivations, tourism, real estate, forests, ecology, landscape and regional development. As far as the ecological dimension is considered, the indicators are those employed also in the dynamical model which enabled to predict future evolution scenarios. The integration of the two evaluations allowed to have a complete picture of the territory under investigation that is the one provided by the TRI values, as well as a prediction of future possible evolution scenarios, which are those delivered by the dynamical model. Table 1 shows the results of the two models. It is interesting to observe that while 5 LUs are portrayed with Good Resilience by the TRI index, the category of Good Ecological Scenario reaches the double of the LUs.

Therefore, there is a match at the highest level, between the highest TRI classified with Good Resilience and the dynamical modelling of the Ecological Scenario. But this is not necessarily the case at lower classifications of TRI.

Municipalities	Cultivation	Tourism	Real Estate	Forests	Ecology	Landscape	Regional Develop.	TRI	Classes of resilience	Ecological Scenario
LU1-Alijó	0.58	0.44	0.68	0.53	0.58	0.44	0.52	0.52	Good	E3-Good
LU2-Armamar	0.33	0.50	0.44	0.37	0.47	0.49	0.54	0.45	Medium	E3-Good
LU3-Carrazeda de Ansiães	0.38	0.63	0.41	0.59	0.63	0.48	0.54	0.52	Good	E3-Good
LU4-Freixo de Espada à Cinta	0.26	0.48	0.44	0.39	0.42	0.45	0.55	0.42	Medium	E2-Medium
LU5-Lamego	0.52	0.68	0.45	0.48	0.29	0.42	0.55	0.47	Medium	E2-Medium
LU6-Mesão Frio	0.12	0.44	0.51	0.43	0.49	0.48	0.56	0.42	Medium	E1-Poor
LU7-Moimenta da Beira	0.28	0.45	0.64	0.58	0.57	0.46	0.60	0.48	Medium	E3-Good
LU8-Murça	0.20	0.47	0.62	0.40	0.48	0.56	0.58	0.46	Medium	E2-Medium
LU9-Penedono	0.14	0.54	0.39	0.49	0.63	0.35	0.45	0.41	Poor	E2-Medium
LU10-Peso da Régua	0.31	0.47	0.68	0.36	0.48	0.47	0.57	0.46	Medium	E3-Good
LU11-Sabrosa	0.29	0.51	0.40	0.60	0.62	0.60	0.58	0.53	Good	E3-Good
LU12-Santa Marta de Penaguião	0.25	0.54	0.57	0.47	0.37	0.31	0.45	0.38	Poor	E1 - Poor
LU13-São João da Pesqueira	0.61	0.51	0.49	0.64	0.62	0.58	0.59	0.59	Good	E3 - Good
LU14-Sernancelhe	0.18	0.58	0.44	0.55	0.61	0.39	0.59	0.46	Medium	E3 - Good
LU15-Tabuaço	0.28	0.39	0.51	0.50	0.53	0.50	0.53	0.46	Medium	E3 - Good
LU16-Tarouca	0.14	0.52	0.45	0.51	0.49	0.50	0.53	0.44	Medium	E2 - Medium
LU17-Torre de Moncorvo	0.41	0.60	0.28	0.76	0.39	0.51	0.55	0.50	Medium	E2 - Medium
LU18-Vila Nova de Foz Côa	0.49	0.41	0.61	0.60	0.40	0.43	0.60	0.48	Medium	E3 - Good
LU19-Vila Real	0.46	0.84	0.59	0.74	0.40	0.57	0.68	0.58	Good	E1 - Poor

Table 1. MCDA and dynamical model results.

Some representative LUs revealed interesting results (see Figure 5): from the left side, São João da Pesqueira is characterized by a good territorial resilience and a good ecological performance at the initial time t_0 and asymptotically evolves towards a scenario with appreciable ecological quality at time t_1. The second case is Santa Marta de Penaguião, which shows a poor territorial resilience and a poor ecological performance at initial t_0 and it maintains the same conditions when asymptotically evolves to the limiting scenario at t_1. The third case is Vila Real, which records a good territorial resilience and a poor ecological quality at the state of the art, and its potential ecological scenario tends to asymptotically degenerate toward a strong fragmentation at t_1.

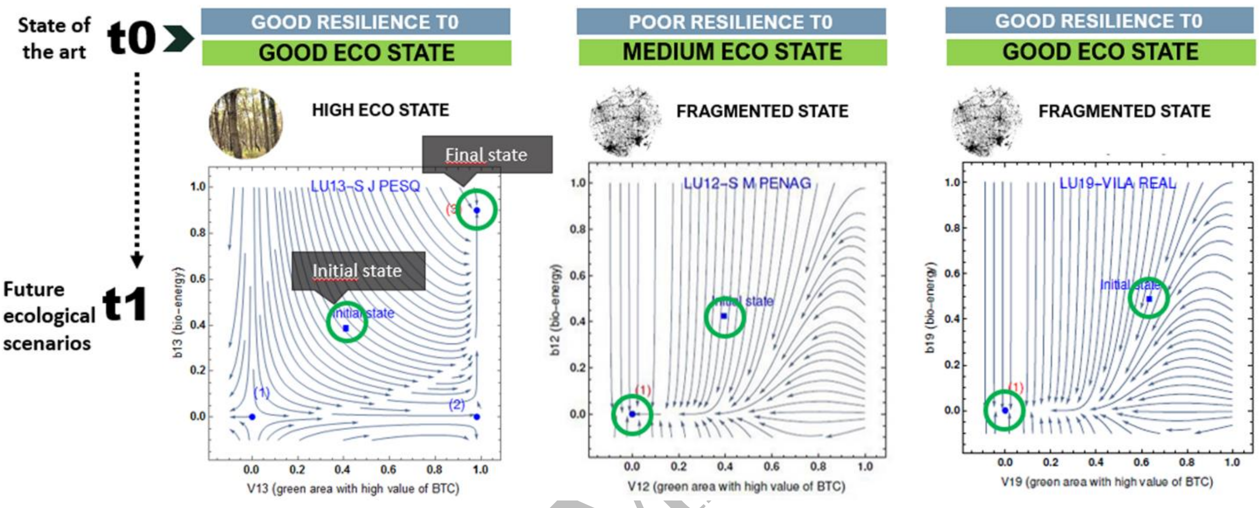

Figure 5. Dynamic interpretation of the territorial resilience in some LUs.

The presented framework has bridged the gap between territorial resilience theory and practice with an innovative and original Decision Support System to assist Decision Makers in the planning and management of resilient territorial systems. This paper focused on the territorial resilience assessment of a SES represented by a famous wine region. The use of specific decision support systems is extremely important when public administrations need to incorporate the resilience thinking within plans and programs.

This framework has combined a set of indicators developed through a multicriteria approach and a Lotka-Volterra model of cooperative type, obtaining a dynamic territory interpretation.

The TRI index was useful to represent the actual conditions of the wine region that is vast and heterogeneous. The mathematical model has predicted possible ecological scenarios by maintaining the actual conditions of the region. The strong participation of local actors and stakeholders in the discussions of the organized meetings confirms that the GIS visualization allows for more democratic participation of involved stakeholders as they relate in visual and user-friendly ways to their local territories.

In this study, the asymptotic behavior of the ecological variables underlined the need to include the other components investigated with the MCDA model. An average TRI index will be calculated as new parameter of the dynamical model. Although these remarks retain very promising future steps for this research, the proposed framework needs further application into other vineyard territories to confirm its reliability.

A further step into adaptive governance can be fostered if, for example, Geodesign methods (Steinitz, 2014) and integrated GIS tools (Yousefi et al. 2020) are introduced for aiding the local actors and stakeholders to design shared policies and actions in the planning of resilient futures.

Acknowledgements

Part of this research work has been developed within the Ph.D. thesis by V. Assumma "Assessing the Resilience of Socio-Ecological Systems to Shape Scenarios of Territorial Transformation". The authors are indebted to many CCDR-N staff members such as the ex-Vice President Eng. R. Magalhães, Dr. V. Devesa, Arch. F. Girão, the Head of Division Eng. H. Teles and several collaborators of Missão Douro/CCDR-N. Many thanks are also due to Dr. S. Machado (AEVP), Prof. D. Souto Rodrigues (C-TAC, UMINHO), Prof. R. Bento, Prof. I. Bentes, Prof. D. Lopez and Prof J. Rebelo (UTAD) and experts from Douro organizations and wine companies Dr. P. Russell-Pinto (IVDP) and Dr. O. Martinez (Lavradores de Feitoria).

Funding

The research by A.J.S. has been partially supported by the Portuguese Funds FCT Projects UIDB/00013/2020 and UIDP/00013/2020.

Disclosure statement

The authors declare no conflict of interest.

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CULTIVATIONS						
Code	***Indicators***	***Description***	***um***	***Preference***	***Type***	***Source***
Value	Agriculture farms	The indicator considers the number of enterprises by head office municipality and according to CAE-Rev.3 classification (2016)	No.	max	General	CCDR-N
	Agriculture labour force	It measures the number of workers qualified in agriculture, hunt and forests	No.		General	CCDR-N
	Utilized Agriculture Surface	It represents the incidence of Utilized Agricultural Surface	ha.		General	CCDR-N
	Permanent cultivations	It summarizes the Mediterranean cultivations, such as almonds and olive trees. This indicator may represent the elements that characterize, together vineyards, the agriculture tradition and landscape composition.	No.		General	CCDR-N
	Vineyard surface	It measures the hectares of vineyards surface in the territory.	ha		General	CCDR-N
	PDO/PGI Wine production declared	It records the annual wine production with PDO/PGI certification	hl/year		Site-specific	CCDR-N
Vulnerability	Precipitation variation	It measures the annual precipitation variation between 1988-2012	mm/year	min	General	CCDR-N
	Temperature variation	It measures the annual temperature variation by considering the time period 1988-2012	C°/year		General	CCDR-N
	Wind speed	It measures the wind speed by modelling the historical series 1971-2000 as number of days average 10m > 5,5 m/s	No. days		Site-specific	IPMA - Portal do Clima
	Soil slope higher than 30%	It considers the soil with slope >30% where the grape harvest is more difficult, and it causes an economic loss	ha		Site-specific	COPERNICUS DEM
Adaptability	LEADER programme investments	It considers the economic resources provided by LEADER (2006-2013) to support farmers and rural development	€	max	Site-specific	LEADER 2006-2013
	Participation of Municipalities in projects of rural development	It considers the Municipalities participation in projects of rural development within the PDR-UTAD 2014-2020	No.		Site-specific	PDR-UTAD 2014-2020
	Young farmers	It considers the young farmers (21-36 yo) as generational renovation and at the same time the generation who preserves local knowledge.	No.		General	CCDR-N

Table A.1. Set of resilience indicators: Cultivations component.

TOURISM

Criteria	*Indicators*	*Description*	*um*	*Preference*	*Type*	*Source*
Value	Tourism operators	The indicator measures the incidence of tourism operators in the territory	No.	max	General	RNT
	Tourism presences	It refers to the tourists that sleep at least one night in tourism establishments	No.		General	INE
	Accommodation capacity	It refers to the number of rooms provided by the tourism establishments	No.		General	INE
	Cultural events and recreative activities	It considers the number of events (e.g. seminars, workshops, exhibitions) that promote the territory	No.		General	Municipalities cultural agendas
	Average cost of tourism destinations	It is the weighted average between the prices on travel, transportation, food - drink and sport activities in the tourism heavy season and the base period. If the value is near to 1, it shows a criticality, whereas if the value is near to 0 it shows a lack of vulnerability	0; 1		General	Airbnb - Tripadvisor-GuidaMichelin
Vulnerability	Tourism pressure	It provides the incidence of tourists (in a year) with respect to the residents that live in the territory	%	min	General	INE
	Days of cold waves	It refers to the days of cold waves that may influence tourism flows, especially in out-season	days		General	IPMA - Portal do Clima
	Days of heavy rains >= 10 mm/h	It refers to the days of heavy rains >= 10 mm that may influence tourism flows.	days		Site-specific	IPMA - Portal do Clima
	Days of heat waves	It refers to the days of heat that may influence the tourism flows and in the long- term also the type of tourism in the territory.	days		General	IPMA - Portal do Clima
Adaptability	Programmes and Projects of tourism development	It considers programmes and projects finalized to the tourism development.	No.	max	General	UTAD, PIOT-ADV, Municipalities websites
	Initiatives of tourism innovation	It considers the initiatives of tourism promotion through the support of innovation technologies (e.g. *Loja interativas*, DOUROTOUR)	No.		Site-specific	Porto e Norte (TEM)

Table A.2. Set of resilience indicators: Tourism component.

REAL ESTATE						
Criteria	***Indicators***	***Description***	***um***	***Preference***	***Type***	***Source***
Value	Average real estate value	The indicator measures the average real estate value of buildings	€/m^2	max	General	INE
Vulnerability	Age of buildings	The indicator considers the amount of buildings realized before 1919 and between 1919 and 1945	Age	min	General	PORDATA 2017
Adaptability	Restructured buildings	The indicator measures the number of restructured buildings as indirect measure of urban life quality	No	max	General	PORDATA 2017

Table A.3. Set of resilience indicators: Real Estate component.

FORESTS						
Criteria	***Indicators***	***Description***	***um***	***Preference***	***Type***	***Source***
Value	Forest surface	The indicator measures the total forests surface	ha	max	General	COS 2015
	Forest road network	It refers to the presence of road for the safeguard of forests against fire events	kml		General	OSM data
	Fire-fighters workers	It considers the fire workers with respect to the Norte fire workers as forestry management.	No.		General	CCDR-N
Vulnerability	Forest surface burnt by fires	It measures hectares of forests that have been destroyed by fires in the last year.	ha	min	General	CCDR-N
	Land take	It is given by the land take in terms of urban areas and infrastructures with respect to the total surface of the Municipality	%		General	CLC 2000, COS 2015
	Extreme precipitations > 50 mm/h	It refers to the occurrence of extreme precipitation higher than 50 mm/h. The forests cannot contain a large amount of water in the short time, thus causing floods and landslides events	%		General	IPMA - Portal do Clima
Adaptability	Municipal Forest Fire Protection Plans (PDMFCI)	It considers the presence of local plans for the prevention of fire risk in the forests	%	max	Site-specific	ICNF
	Areas of Forests Intervention (ZIF)	The ZIF is a tool that has been integrated in Portuguese legal framework for forest management and protection against fires (DFCI) after the wildfires in 2003. The ZIF law was amended in 2009.	ha		Site-specific	CCDR-N
	Investments for forest management (PDR, PRODER)	It considers the amounts of investments in national and international programs for managing and preserving forestry heritage.	€		Site-specific	ICNF

Table A.4. Set of resilience indicators: Forests component.

ECOLOGY						
Criteria	***Indicators***	***Description***	***um***	***Preference***	***Type***	***Source***
Value	Biological and territorial energy capacity	The indicator measures the flux of bio-energy produced by a Municipality (or Landscape Unit)	%	max	General	COS 2015
	Green areas of high ecological quality	It considers the green areas that produces bio-energy higher than 6,5 Mcal/m^2 * year	%		General	COS 2015
Vulnerability	Density of urban areas	It is obtained by dividing the total built-up areas with the total surface of Municipality	%	min	General	COS 2015
	Dispersion of urban areas	It is calculated by dividing the overall perimeter of the Municipality by the sum of all perimeters of the urban fabric	%		General	COS 2015
	Density of impermeable barriers	It is obtained by considering the total surface of the environmental system and the surface of impermeable barriers. The indicator should me minor or equal to 1.	%		General	COS 2015
Adaptability	Global connectivity	It measures the connectivity between municipal bounders that are able to exchange fluxes of bioenergy with neighbouring landscape units.	%	max	General	COS 2015
	Solar exposure of biotopes	It measures the solar exposure of biotopes, by considering the weighted aggregation of biotopes surfaces exposed at South-East-South (SE), at South-West (W) and at North-East (NE)	%		General	COPERNICUS DEM
	Humidity relative of biotopes	It calculates the average value between the indicators of solar exposure, relative humidity and ecotones length barriers	%		General	COPERNICUS DEM, COS 2015, PT CLIMATE DATA

Table A.5. Set of resilience indicators: Ecology component.

LANDSCAPE						
Criteria	***Indicators***	***Description***	***um***	***Preference***	***Type***	***Source***
Value	Density of terrestrial protected areas	The indicator calculates the extension of protected areas related to the territorial surface.	%	max	General	CCDR-N
	Density of Natura 2000 sites	It considers the extension of Natura 2000 sites in the considered territory, related to the total number of the region/nation.	%		General	CCDR-N
	Density of protected cultural assets	It considers the number of protected cultural assets with respect to the total cultural assets in the territory.	%		General	CCDR-N
	Landscape viewpoints	It considers the number of high scenic value viewpoints from that is possible to appreciate the aesthetic value of the considered landscape	No.		General	CIM DOURO
	Accessibility from PORTO	It estimates the time distance from Porto to reach Douro Municipalities. The indicator is closely related to the degree of infrastructure accessibility and regional integration.	minutes	min	Site-specific	Guida Michelin
Vulnerability	Skyline disturbances	It records the presence of visive disturbances that may compromise the perception of landscape (e.g. pylons, wind turbines, highway)	No.	min	General	EDP distribuçao
	Non-protected cultural heritage	It considers the incidence of non-protected cultural assets with respect to the overall cultural heritage in the considered territory	%		General	IGEO
	Landscape fragmentation	It considers the degree of heterogeneity of the territory by calculating the Shannon index. When the value is near to 1, it means the landscape composition is homogeneous and this favours the continuity and conservation, whereas when the value is near to 0 this means there is a high landscape diversity	%		General	COS 2015
Adaptability	Environmental associations	It measures the incidence of environmental associations with respect to the overall associations in the considered territory.	No.	max	General	PORDATA
	Municipal investments for protected areas and biodiversity	It refers to the amount of municipal investments for preserving and enhancing protected areas and biodiversity	€/y		General	CCDR-N
	Group of Local Actions (GAL)	It records the number of Groups of Local Actions (GAL) as public-private partnerships for the local development of rural areas.	No		General	ENRD

Table A.6. Set of resilience indicators: Landscape component.

REGIONAL DEVELOPMENT						
Criteria	***Indicators***	***Description***	***um***	***Preference***	***Type***	***Source***
Value	Cohesion between actors and stakeholders	It calculates the density of relations between the local actors and the stakeholders with respect to the resilience of the territory	%	max	General	Computed after Dente 2014
	Population with high education degree	It considers the residents with high education degree with respect to the total population in the territory	%		General	CCDR-N
	Accessibility to services	It considers the time distance to reach primary services (e.g. hospitals, schools) as indirect measure of the urban life quality	minutes		General	Google Maps, OSM, KITCASP
	Gross value added by economic activities	It measures the gross value added that is generated by economic activities and non-financial firms	%		General	CCDR-N
	Renewable energy production	It considers the incidence of renewable energy with respect to the annual energy production in the territory	%		General	CCDR-N
	Incidence of recycled waste	It considers the production of recycled waste with respect to the overall waste production in the territory.	%		General	CCDR-N
	ICT enterprises	It considers the number of ICT enterprises as new frontier for the regional and local economy.	No.		General	CCDR-N
Vulnerability	Inactive population (<15 yo and >65 yo)	It summarizes the residents with age under 15 yo and over 65 yo as the part of population that is most exposed to risks	No.	min	General	CCDR-N
	Incidence of Population flows	It measures the population flows in terms of in-migration and outmigration.	%		General	CCDR-N
	Greenhouse gas emissions	It measures the green-house emissions released in the atmosphere in the considered territory	kt		General	APA ambiente
	Flood risk area	It considers the area affected by flood risk with respect to the total municipal surface.	%		General	SNIamb
	Non-occupation rate	It measures the percentage of people that is searching for a job with respect to the labour force of the territory	%		General	CCDR-N
Adaptability	Projects presented in the program Norte 2020	It considers the number of projects approved in the Norte2020 program to sustain the regional development	No.	max	Site-specific	Norte2020
	Adoption of Climate planning	It considers the number of climate plans at local scale adopted in the territory	No.		General	Municipalities websites
	Projects of sustainable mobility	It refers to the Municipalities participation to the project "Accessibility for all" for increasing the sustainable mobility	0; 1		Site-specific	MPT Dept. Portugal
	Projects presented by citizens	It considers the projects presented by citizens to empower the territorial local development.	No		Site-specific	OPP 2017
	EIA and SEA procedures approved	It refers to the EIA and ESA evaluation procedures approved in the territory.	No.		General	APA ambiente
	Municipal plans updated (last 10 years)	It considers the number of municipal plans updated in the last 10 years.	0; 1		General	Municipalities websites

Table A.7. Set of resilience indicators: Regional development component.

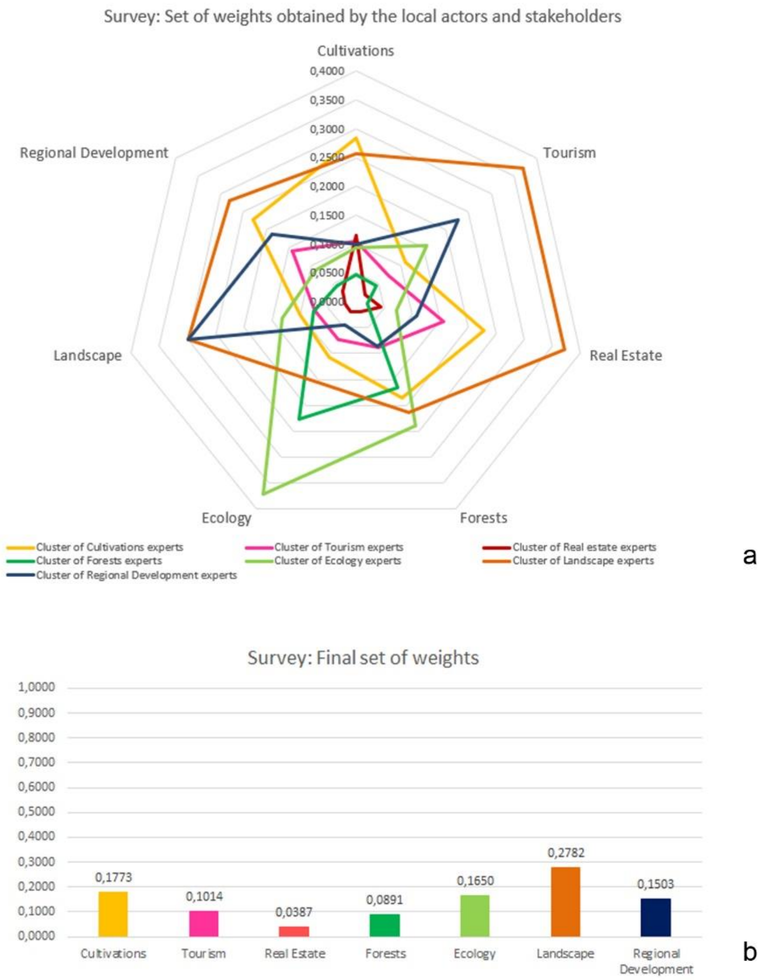

Figure A.1 Illustration of the evaluations of the single experts (a) and final set of weights (b).

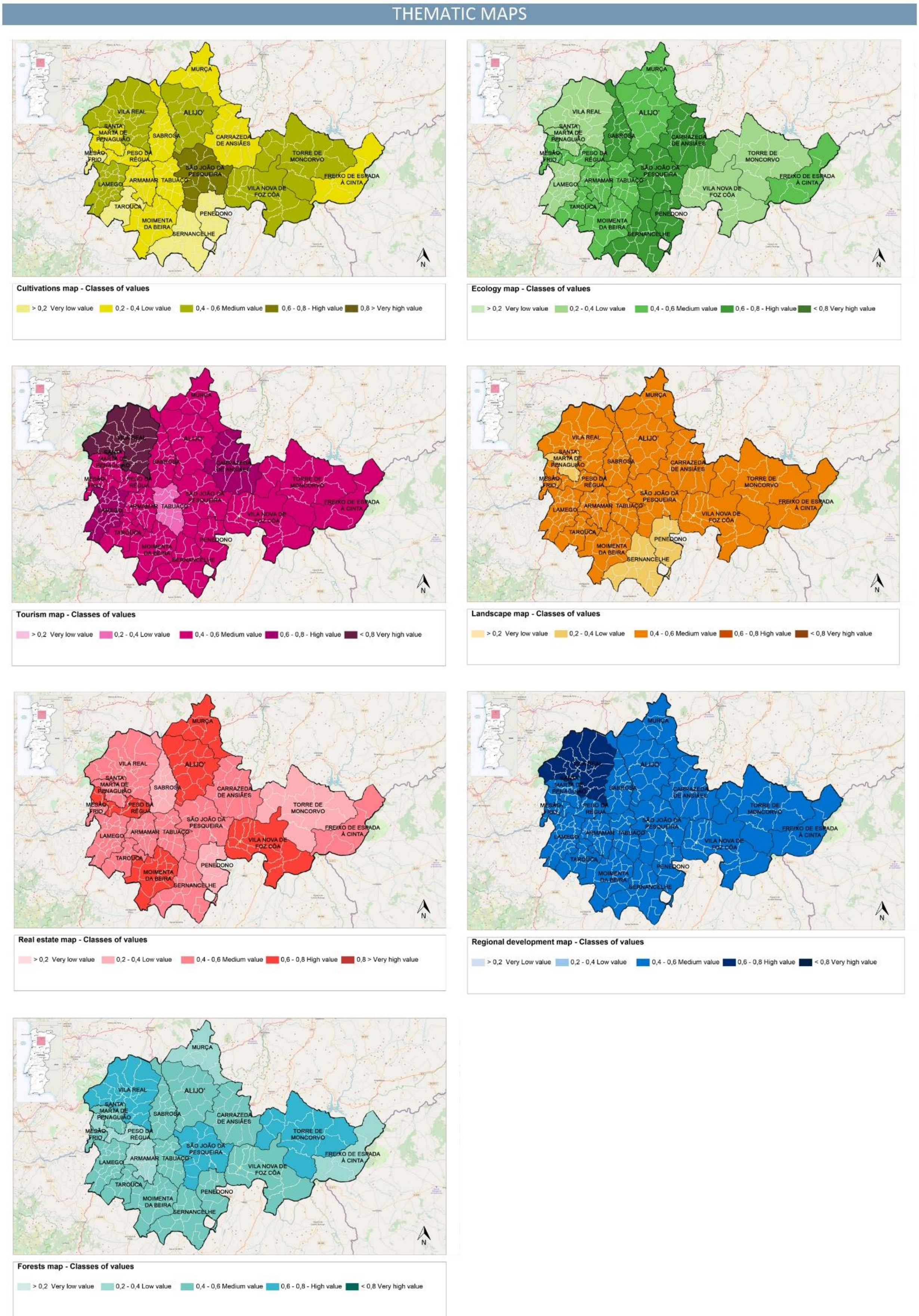

Figure A.2. Thematic maps of the seven components.

LU	Municipalities	V_{i0}	b_{i0}	Ui	a_i	d_i	φ_i	S_i	P_i	*Equilibria*
1	*Alijó*	0.5780	0.4699	0.0289	0,2415	0.6781	0.3059	29760	310.34	**3** (1), (2)
2	*Armamar*	0.4544	0.4096	0.0272	0,1694	0.6343	0.6688	11720	222.91	**3** (1), (2)
3	*Carrazeda de Ansiães*	0.6344	0.5594	0.0178	0,2333	0.6792	0.3944	27920	306.43	**3** (1), (2)
4	*Freixo de Espada à Cinta*	0.6335	0.4205	0.0085	0,2407	0.5707	0.0400	24410	169.97	**(2)** (1)
5	*Lamego*	0.4816	0.3745	0.0551	0,1256	0.6353	0.2356	16540	312.14	**(2)** (1)
6	*Mesão Frio*	0.3212	0.3476	0.0366	0,3030	0.6865	0.0338	2660	68.28	**(1)**
7	*Moimenta da Beira*	0.6304	0.4827	0.0316	0,2087	0.6986	0.2907	22000	277.74	**3** (1), (2)
8	*Murça*	0.6552	0.5161	0.0221	0,2109	0.6348	0.0533	18940	179.27	**(2)** (1)
9	*Penedono*	0.7128	0.5663	0.0209	0,1965	0.7133	0.1049	13370	153.34	**(2)** (1)
10	*Peso da Régua*	0.3243	0.3150	0.0570	0,2753	0.6078	0.6571	9490	180.64	**3** (1), (2)
11	*Sabrosa*	0.5522	0.4870	0.0334	0,2314	0.6671	0.6472	15690	224.67	**3** (1), (2)
12	*Santa Marta de Penaguião*	0.3946	0.4196	0.0512	0,2189	0.5760	0.0373	6930	278.92	**(1)**
13	*São João da Pesqueira*	0.4128	0.3763	0.0133	0,1844	0.6550	1.0982	26610	154.36	**3** (1), (2)
14	*Sernancelhe*	0.7113	0.5080	0.0217	0,2054	0.6754	0.2853	22860	264.77	**3** (1), (2)
15	*Tabuaço*	0.5996	0.4928	0.0195	0,1946	0.6100	0.3744	13390	211.52	**3** (1), (2)
16	*Tarouca*	0.6432	0.4925	0.0317	0,1884	0.6809	0.1118	10010	135.75	**2** (1)
17	*Torre de Moncorvo*	0.6641	0.4071	0.0129	0,2138	0.5834	0.0804	53160	414.91	**2** (1)
18	*Vila Nova de Foz Côa*	0.5295	0.3511	0.0158	0,1953	0.5809	0.4366	39820	379.36	**3** (1), (2)
19	*Vila Real*	0.6330	0.4808	0.0810	0,2464	0.6676	0.1124	37880	450.00	**(1)**

Table A.8. Model parameters and equilibria.

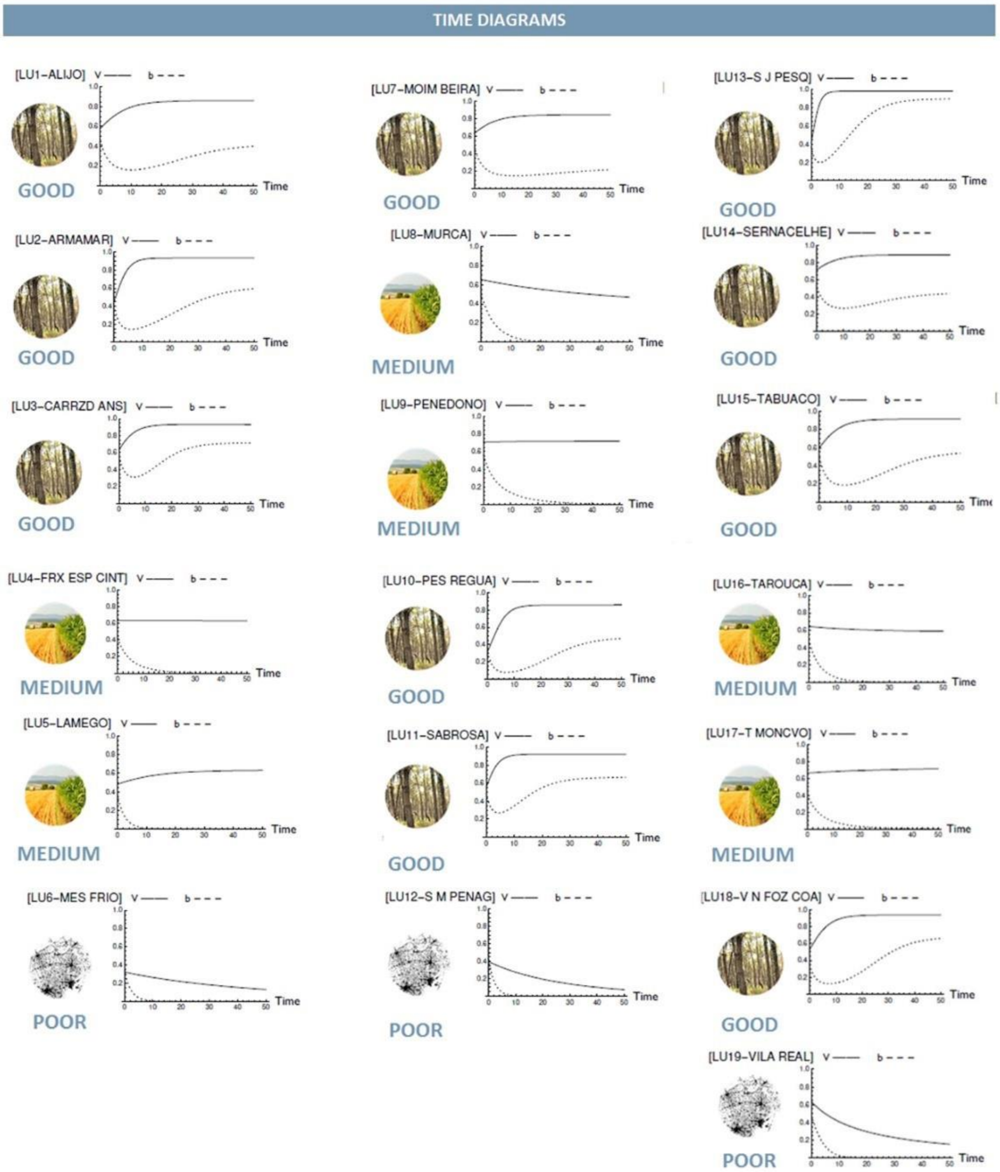

Figure A.3 Time diagrams of the 19 LUs. Elaborations made with Mathematica Software, 2019

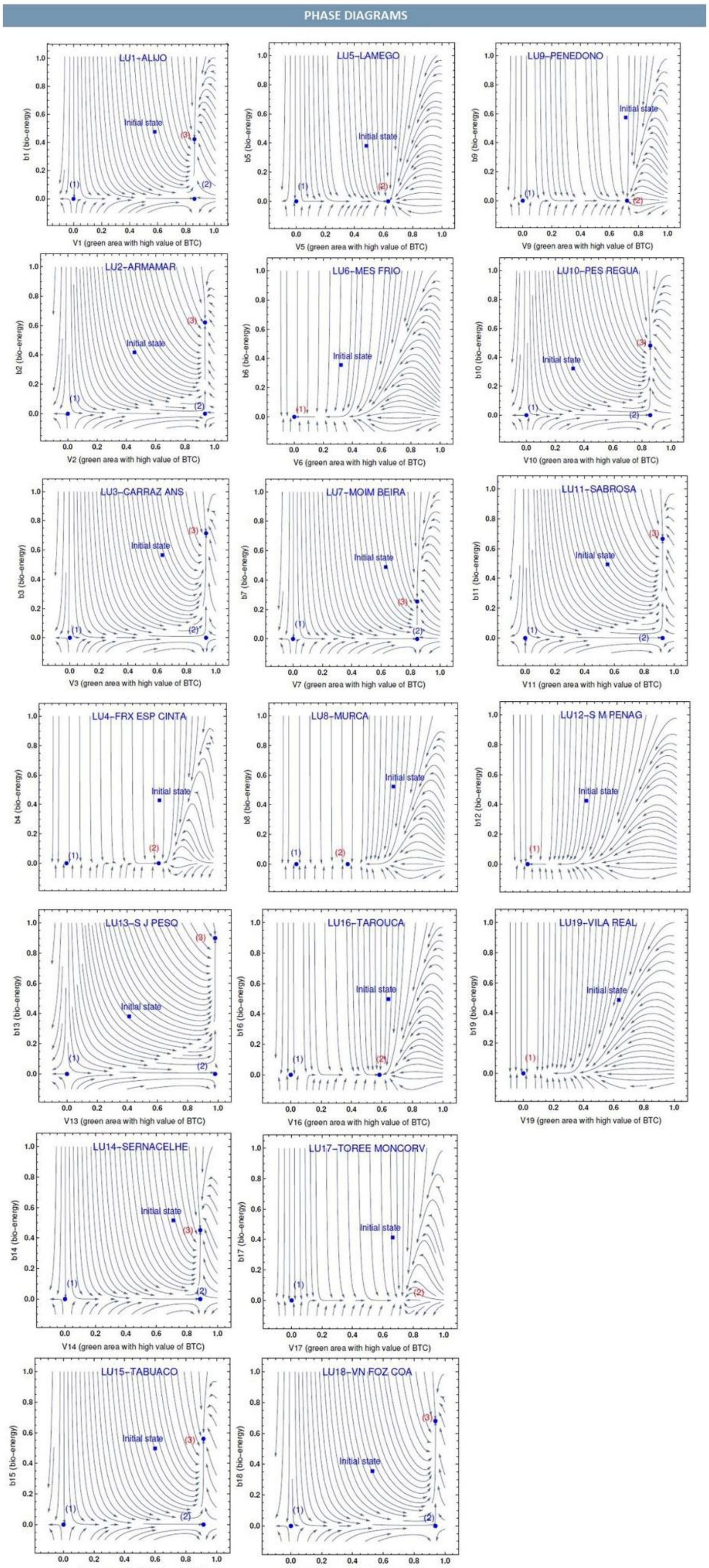

Figure A.4. Phase diagrams of the 19 LUs. Elaborations made with Mathematica Software, 2019