Dynamic Mapping Based on Multi-functional Land Values, Measuring Land Use Resilience for Climate Adaptive Spatial Planning

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Abstract: Land is a complex, dynamic and adaptive system, where its socio-ecological interactions create continuous land processes that provide multifunctional values to society. Overlooking this dynamic condition and these multiple values – and their trade-offs – within decision making processes, as is the case in territorial planning, compromises these values and they are irreversibly lost, decreasing the resilience of our territories. The following body of work discusses the potentials of current digital tools by proposing a framework capable of understanding these complex interactions in a dynamic way. A computational pipeline and feedback-loop methodology is proposed and tested in the case study of Vitoria-Gasteiz municipality. The resulting Decision Support System enables a new spatial planning methodology capable of measuring land resilience for climate adaptive planning.

Keywords: Land value, dynamic mapping, data-driven design, climate adaptive planning, land use resilience

1 Introduction

Within current territorial and urban planning processes, we can observe that decision-making is often constrained through land use categorization. Within this context, land use and land use change only allow recognizing the socio-economic functional dimension of the land, bounding land into spatial categories. This bounded representation of land use categorization does not allow the recognition or planning of land as a system of systems and, consequently further fragments the territory, meaning the breaking up and consequent disintegration of larger areas of natural land cover considered as continuous ecosystems (MITCHELL et al. 2015). In addition to this, land use change and land-cover change represent an abrupt disturbance, causing the loss of several ecosystem functions or services. This disruption in structural ecological connections presents serious threats to the environment's capacity to provide vital ecosystem services, resulting in a decrease in habitat resilience in the general context of climate change.

A consequence of the fact that current spatial planning tools are based on land use categorization, is that more often than not these lead to oversimplified decisions, overlooking policy coordination − especially among sectoral policies − that do not respond to the interlinkages that characterise land as a complex, dynamic and adaptive system. These mechanisms enable solutions that tend to focus only on one of land's values, neglecting land's dynamic multifunctional condition and ignoring the multiple values that land provides, among which multiple Ecosystem Services (ES) and habitat resilience (DEFRIES & NAGENDRA 2017). Ignoring the diverse synergies and trade-offs (for example, soil fertility and biodiversity loss), aside from the expected result of a specific solution (food production increase due to pesticide use), creates the ideal scenario for the continuous loss of multiple land values, and consequent impacts on the greater ecosystems. In a future characterised by uncertainty, the territory needs

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to be enabled to respond to different needs simultaneously in order to guarantee the multiplicity of functions and ensure its resilience (AA.VV. 2022). At the same time, the tools that we develop for territorial planning need to tackle the dynamicity of the processes occurring in land systems in order to provide the dynamic strategies needed for adaptation (EUROPEAN ENVIRONMENTAL AGENCY 2018).

2 A Dynamic Approach to Land Use Resilience

Several land classification systems have addressed either the multifunctional condition of land by exploring different service dimensions (NEIKER 2018), multiple abrupt variations of land-cover change in time (WINKLER et al. 2021) or the pressure based-impacts induced by human activity (THEOBALD 2020). Nonetheless, these classifications fail to understand these variations as transitions characterised by continuous land processes. Moreover, neglecting the transitional dynamics of land becomes an obstacle for spatial development to adapt, necessary in order for it to be able to respond to uncertainty. With this in mind, and the potentials of digital tools to manage complex and dynamic territorial conditions, the body of work that follows discusses a framework and computational pipeline to re-understand land as a system from a multifunctional perspective, where dynamics of functional interactions and the resulting transitions are measured through geospatial data, and algorithmic analysis becomes essential in order to tackle aspects of climate change adaptation. The dynamic understanding of land represents an opportunity to create a feedback-loop methodology capable of measuring land resilience, not only acknowledging land's multiple values, but also by adding the trade-offs, in the form of an impact assessment, of spatial decisions, allowing to make territorial decisions responsive to adaptation.

The pipeline relies on the development of a new assessment framework that plugs into a territorial Decision Support System (DSS) for spatial development based on land's multifunctional value. ES, in this matter, have been recognized as the missing link between social and environmental subsystems, consequently recognizes the multiple values that land provides in terms of Natural Capital through its multiplicity of socio-ecological functions (HAINES-YOUNG et al. 2018). Current tools such as the VivaGrass tool (AA.VV. 2020) have resulted promising in terms of applications of ES as a concept to improve land management through integrated planning by acknowledging land's multifunctionality. This tool also provides the basis for clustering methods to group land based on ES and recognize ES associations. These associations are a "set of associated ecosystem services that are linked to a given ecosystem and that usually appear together repeatedly in time and/or space" (RAUDSEPP-HEARNE et al. 2010). These associations become crucial in order to classify the land based on the values provided. Yet, the tool fails in the constraints of land use, this being the primary parameter to determine the provided ES and their associations. Moreover, the dynamic aspect of land through the continuous measurement of decision-driven impacts is not embedded in the tool. The limitations related to this approach, therefore, disable the possibility of the aforementioned policy coordination, as well as continuous re-assessment, needed for adaptive and resilient territorial and/or urban strategies.

The proposed DSS allows us to simulate and evaluate land resilience through a data-driven approach by creating a cyclical methodology with which to understand land as a dynamic system. Within the practice of urban planning and design, the DSS pipeline is thought as a knowledge-based communication platform, ideally facilitating the connection and collaboration between researchers, policy-makers, and spatial planners. Once implemented, the platform allows primary users to evaluate new strategies based on socio-ecological indicators, and after their implementation, these interventions can be monitored continuously. By challenging current spatial development methodologies based on land use categorization, the DSS pipeline makes the hidden patterns that characterise land as a complex, dynamic and adaptive socio-ecological system accessible in order to propose a dynamic evidence-based spatial planning tool.

For the implementation of the pipeline, a spatial analysis based on several ES must be performed so as to consider the socio-ecological and functional dimensions. This analysis is performed in a 1ha grid rather than basing it on land use boundaries, to understand land as a continuous system. In order to establish the connections between different ES, and identify the required associations between them, a data-driven taxonomy is developed through an algorithmic grouping system (clustering). The result of this process enables the creation of taxons, or groups of land that have similar ES associations, that do not only recognize the diversity of functions in each land unit but also the diversity of interactions between these functions. The method for the proposed taxonomy considers the dynamics of land and function based on a dynamic data-input, allowing it to take into account the ever-changing data flow that feeds the taxonomy itself.

Finally, a multicriteria assessment based on the multiple land values is integrated into the process. Considering multiple values together can enable the proposal of hybrid solutions. Hybrid strategies are necessary in order to measure the synergies and co-benefits land can provide simultaneously, as well as the trade-offs of strategies. Thanks to the consideration of synergies and trade-offs, a comparative analysis of the strategies can be developed through an impact assessment. The comparison allows for better-informed decisions ensuring the recovery of a diversity of land functions, and the land's option value can increase in each decision. As the option value of the land increases, the ability of the territory to respond to uncertainty also increases. By re-understanding land from a socio-ecological perspective, land resilience can be measured, and recognize the trade-offs and synergies of our decisions to plan the urban processes that constantly adapt the land.

3 Feedback-loop Methodology for Resilient Spatial Planning

The methodology developed comprises three strategic stages that allow the translation of land's multifunctional dynamic condition into coherent strategies for policy-makers and spatial planners with the input of research knowledge. The methodology of this framework is circular and proposes a continuous feedback-loop in order to ensure the continuous adaptation of territorial strategies. The experimentation process was conducted in Vitoria-Gasteiz municipality, in the north of Spain.

3.1 A Data-driven Spatial Analysis Based on Land Functions

To measure land's multifunctional value, four ES are selected with methods that allow their spatialization (Fig. 1): Soil Fertility (SF), Habitat Maintenance (HM), Carbon Sequestration (CS) and Food Production (FP). The primary purpose of this stage is to measure the territory's performance for each spatial indicator through a grid, avoiding the constraints of land use boundaries. Global, European, regional and local geospatial and statistical data are combined for the purpose through GIS tools. These datasets are characterized by being or performed yearly or are based in remote sensing methodologies, which enable the possibility of ensuring the monitoring process.

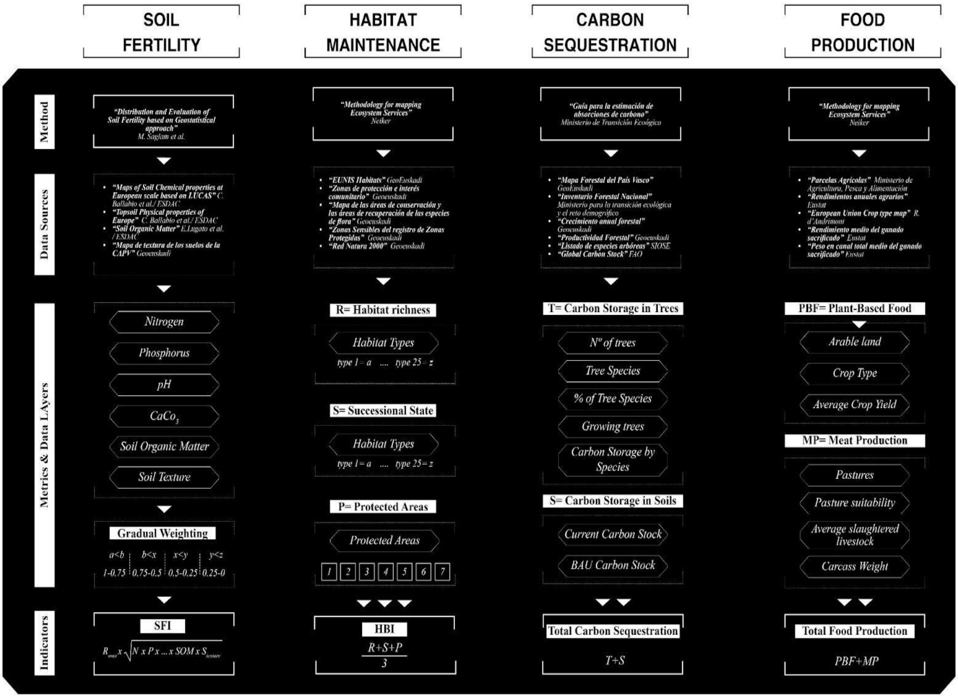

Fig. 1: Methods for Socio-Ecological modelling based on ES: Soil Fertility, Habitat Maintenance, Carbon Sequestration and Food Production

- To analyse the capacity – and potential capacity – of the territory regarding SF, the Soil Fertility Index model (SFI) (SAGLAM & DENGIZ 2014) is calculated. SFI allows scoring soil fertility's spatial variability based on macronutrient and micronutrient availability (BALLABIO et al. 2019), as well as soil properties (KLIMATEK 2019).
- Different ecosystems create the needed habitats characterised by an adequate environment for different kinds of autochthonous flora, fauna, or microorganisms to thrive, and it can be measured through the Habitat Maintenance Index (HMI) (NEIKER 2018). The HMI scores the land based on the protected areas, the richness of autochthonous vegetation species, and the successional state or ecosystem maturity (GOBIERNO VASCO 2019).
- To measure and spatialize the Food Production (FP), Plant-Based Food, and Meat Production are analysed through Neikers' approach (2018). Both indicators are measured with statistical (INSTITUTO VASCO DE ESTADÍSTICA 2021) data and GIS tools, the Plant-Based Food is spatialized only in the arable land, and the meat is spatialized only in the pastures (GOBIERNO VASCO 2022).

- In order to measure the Carbon Sequestration (CS) yearly capacity, both CS in Trees and CS in Soils is measured and developed in the following section to provide one example regarding the spatialization of one of the indicators.

3.1.1 Carbon Sequestration Method

Trees sequester carbon by capturing carbon dioxide through photosynthesis to transform it into biomass. (UNECE n. d.) For the research, regarding CS in trees, only carbon sequestered in the form of biomass is taken into account, and the carbon stock in deadwood and litter is not measured since dead biomass does not actively absorb carbon. The method applied was extracted from the Spanish Government allowing to measure CS depending on tree species (Ministerio para la Transición Ecológica 2019), which is usually used for evaluating Land Use, Land Use Change & Forestry practices. One main factor that compromises the CS in trees is that aged trees almost do not grow and do not increase their biomass volume. Hence, the carbon sequestered in their mass is negligible. Four geospatial datasets are used to filter out the old trees from the calculation. The first two are the tree heights from 2008 and 2012 (DEPARTAMENTO DE DESARROLLO ECONÓMICO, SOSTENIBILIDAD Y MEDIOAMBIENTE 2017). Two parameters are used to select the growing trees: height increase and height decrease from 2008 to 2012 (assuming that would mean that the trees have been replanted). Another two data layers are used to select more accurately growing trees: the apparent age of trees (DEPARTAMENTO DE DESARROLLO ECONÓMICO, SOSTENIBILIDAD Y MEDIOAMBIENTE 2017). Trees over 80 years old are taken out of the analysis. With the resulting geospatial information, a fifth data layer is used to estimate the number of trees per hectare (HAZI 2020). This procedure allows for establishing the number of trees per hectare sequestering carbon. Since not all tree species absorb carbon the same, once growing trees and their amount by hectare are filtered, the type of tree species is embedded in the analysis. The regional database establishes the percentages of the three main species for different forest areas (GOBIERNO VASCO 2021). As a result, the table from the method (MINISTERIO PARA LA TRANSICIÓN ECOLÓGICA 2019) is used to multiply the number of trees of each species by the amount of carbon sequestered by tree per year. The resulting information is geospatialized in tonnes/ha/year.

Carbon Sequestration in Soils (CSS) results from different interactions (photosynthesis, respiration, and decomposition) of soil processes resulting in Soil Organic Carbon (SOC) content. CSS is usually estimated through soil sampling. Nonetheless, there is no such database for Vitoria-Gasteiz and a different approach is used. The FAO has estimated the current SOC stock (FAO 2020) and a Business As Usual (BAU) estimation for SOC sequestration in 20 years (FAO 2020). BAU scenarios are future estimations based on the absence of new action. The CSS is estimated by subtracting the current SOC stock from the BAU SOC stock and dividing this by the number of years. Since the FAO dataset is a global spatial index, the raster pixels' scale is 1 km. In order to increase the resolution of the data, since the grid cell size used is smaller than the data gathered, Smart-Map experimental QGIS plugin is used to reduce the scale of the rasterized data. The Ordinary Kriging interpolation allowed by this plugin has been recognized as an accurate method to extrapolate from in-situ soil data samples to geospatialized information (PEREIRA et al. 2022). Extracting the centroids of the raster layers for the different data allows them to be used as samples for the interpolation. As a result, 100x100m pixel raster layers are created and the CSS is spatialized in tonnes per hectare per year.

3.1.2 Data-driven Spatial Analysis Results

The results allow us to understand the diversity of performances of land depending on the measured function. The distribution of each land function varies in each pixel for each indicator. Hence, from this multicriteria analysis, it is possible to conclude that all indicators show different territorial readings and that land indeed provides a multiplicity of functions simultaneously. Acknowledging the spatial distribution of the land functions' performances enables us to discuss the resilience capacity of the land. The limitations of the methodologies applied for the indicators are related to available data regarding natural stock. In the CS method, on one side, some of the datasets used are in a smaller resolution than the needed one. On the other hand, assumptions related to the filtering of non-growing trees and the BAU scenario have been made. However, these are the most accurate procedures enabled by the available data to understand the CS in Vitoria-Gasteiz.

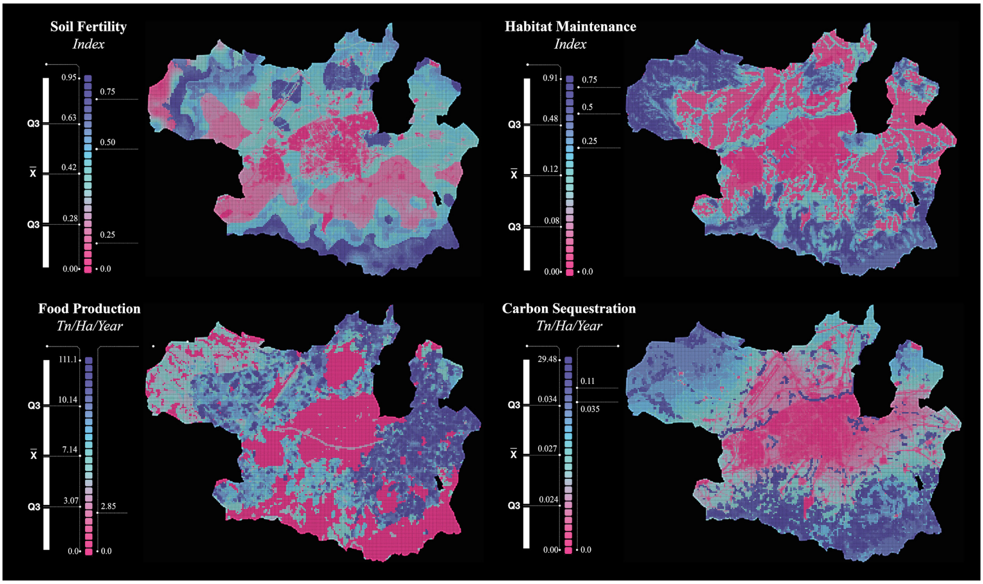

Fig. 2: Multifunctional land Mapping in Vitoria-Gasteiz

3.2 Dynamic Taxonomy and Systemic Relationship Evaluation

The main point of this step is to group the land based on the systemic relationship, or interactions, between the previously analysed land functions. K-means clustering is selected due to the possibility of grouping the land into significantly associated ES, as well as minimising within-group variability (AA.VV. (2020). Currently the Grasshopper3D tool has facilitated the possibility of implementing K-means in a parametric way, by enabling fast and easy clusterization through the Owl component. The use of Grasshopper also enables the parametrization of the data input, as well as the results of the K-means clustering algorithm. The implementation of this logic enables a dynamic taxonomy since the group classification is based strictly on the land values. Each time this classification is done, through the cyclical methodology, an evaluation of the cluster results is needed to understand which hidden patterns emerge from the application of the algorithm. This feedback-loop process enables the reinterpretation of the land groups (clusters), enabling a data-based taxonomy that changes depending on the new values provided by the monitoring process of the last step of the methodology.

The K-means clustering method is applied through the Owls plug-in, taking into consideration the previous spatial analysis, in order to group the land based on shared properties. The results showed that the municipality is grouped into 9 different clusters that correspond to similar ES associations. The taxons are based on the correlation between the values, and most importantly, they are not associated with land use. Figure 3 shows how the arable land of Vitoria-Gasteiz is composed of the 9 clusters, meaning that certain land units of arable land have correlations with forest land use, among others. These results enable the interpretation of different land groups based on different land value relations, enabling in the next step the proposal and evaluation of spatial planning strategies.

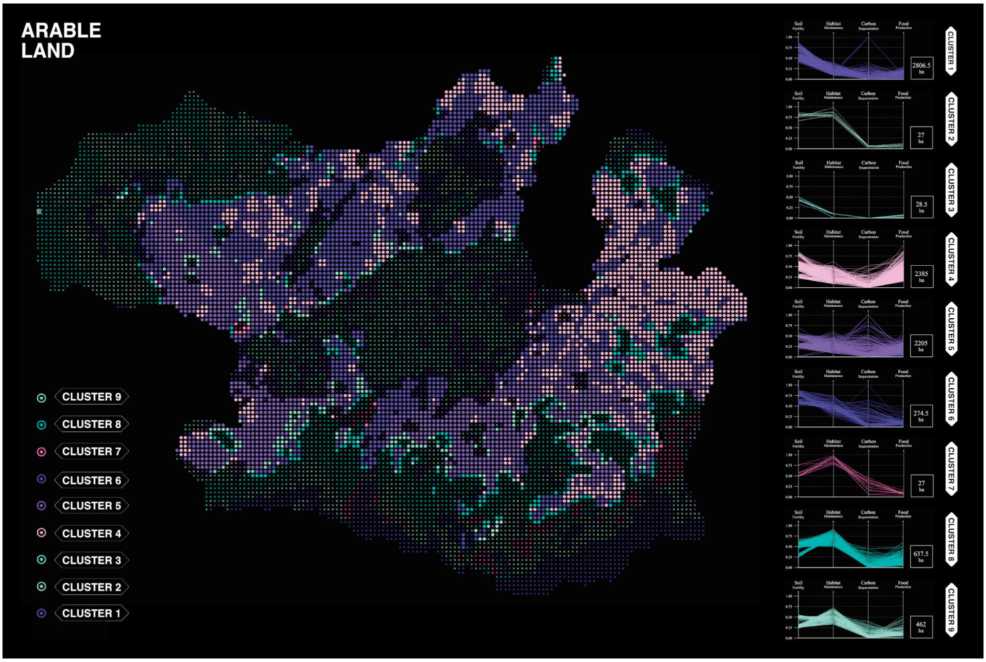

Fig. 3: Results of the dynamic taxonomy of land functions based on K-means clustering

3.3 Strategies Proposal & Evaluation

Once the analysis of the clusters is done, the strategies proposed should be based on the type of land values that want to be enhanced in the territory, by also considering the trade-off values of these strategies. Thus, how specific or multiple strategies affect each land function should be considered. Research on how those strategies affect land should be analysed to be able to evaluate their impact correctly. First, 3 clusters were selected inside the 9 clusters, due to their similar trends of functionality (specifically cluster 1, 3 and 4). These clusters show how FP has a significant trade-off in HM and CS. Through literature review, certain strategies have been analysed and correlated to the increase or decrease of certain values to establish the values for the impact analysis based on synergies and trade-offs. The objective of the hybrid strategies should focus on rebalancing the territory by changing these relationships. While in cluster 1, FP could increase by intensifying agriculture while increasing SF, the other clusters (2 and 3) could reduce FP in exchange for increased CS and HM.

After the most suitable hybrid strategies are selected, the synergies and trade-offs of the strategies are measured through a parametric simulation through Grasshopper3D. This procedure enables a better understanding of the strategies' added value to natural capital. At the same time, the ES loss is simulated through the accountability of the trade-offs. With these results, policy-makers and spatial planners, together with researchers, can make data-driven informed decisions through evidence and implement the strategies. Finally, the new data values are used to recluster the territory and understand the responsiveness of the closed feedback-loop methodology.

The feedback-loop enables the monitoring of implemented strategies to re-measure land value (the first step of the methodology) and can quantify the strategy success rate. The strategies can continuously improve, shifting the actions taken in order to add optional values, and therefore resilience, to the land. At the same time, new data values and input mean a new taxonomy, enabling the dynamic condition of the land to be considered through responsiveness. In the experimentation process, 10 clusters emerged from the application of the complete cycle, instead of the previous 9 clusters. This methodology enables the creation of new knowledge that can provide feedback in improving research about the land itself.

4 Discussion and Conclusions

A new way of visualising the values of a territory has already proven of interest to Vitoria-Gasteiz municipality, which has already implemented the map of CS developed in this research as part of its territorial planning tools, hence these methodologies can also be of interest for different territorial planning agencies. On top of the already implemented visualization, the methodological taxonomy derived from the framework discussed supplies a new way of approaching space-based territorial transitions. Monitoring the strategies can create constant new datasets based on land value evidence. This means that new data inputs are constantly feeding the taxonomy. Once the monitoring data enters the workflow, the clustering process restarts, and new taxons emerge. The new taxonomy that reflects the new land value is accomplished, and the land evolution is reflected thanks to the territorial transition that emerges from the strategies. The feedback-loop process, therefore, creates a responsive taxonomy based on the dynamic condition of the land. With the new values, new interactions between the land functions emerge, and hybrid strategies can be redirected. The territory is understood as a constant cycle of changing in an ever-evolving ever-mutating state. The hinterland-city relations are not understood as static problem-solving scenarios but as a steady decision process.

The value of dynamicity is not only related to recognizing land's dynamic conditions regarding interactions and transition. It is also a valuable mechanism that enables decisions based on shifting baselines. Proposing a taxonomy based on constant new values when the re-assessment is done stimulates the understanding of constantly changing scenarios where uncertainty can be embraced. The strategies implemented due to the feedback-loop methodology can start to be ever-changing instead of finalised solutions. Moreover, understanding the trade-offs generated continuously can be understood not as forever losses but as a regular manageable part of the strategies. The pipeline represents the opportunity to create a framework based on territorial dynamics, where the constant feedback-loop creates a continuous strategic process, no longer working with finished silver bullet solutions, but rather designing for and within climate change adaptation.

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