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Landscape sustainability analysis: Methodological approach from dynamical systems

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Abstract. Sustainable development is a concept that has been maturing since its promulgation in Brundtland in 1987. Following a complex systems-based reflection that involves system dynamics, dynamical systems and viability theory, is proposed that sustainability is an emerging expression of the landscape, whose emergence results from the socio-ecological interactions of the landscape, so its analysis must be of a type systemic, incorporating the temporal transformation of all landscapes aspects, and not only portions of them, in addition, in this paper is explained that sustainability does not exist as a single state, but that there are sustainabilities and that, although its analysis is specific space, it should allow comparison with higher and lower spatial scales. In this way, a methodological approach is made from dynamical systems theory for sustainability landscape analysis. This perspective not only allows to recognize the trend behavior of a socio-ecological system in the landscape establishing its sustainability, but it is also oriented to decision-making, so, the management of sustainability indicators should not be done as if in the landscape were disconnected, causing possible deterioration of other indicators during the management, but through sustainability principles defined as indicators set satisfying constraints. In this way, the perspective from the dynamical systems theory allows the recognition of sustainability and guides on the decision making in the landscape.

1. Introduction

Sustainable development is a concept that has been maturing since its promulgation in Brundtland in 1987 [1]. The emphasize in the Brundtland definition is about “the dynamic balance between human development and environmental protection, as well as intra- and intergenerational equity” [2]. Other definitions and perspectives of sustainable development and sustainability have been published since the definition of Brundtland, being recognized the triple bottom line perspective [2] and weak, strong, and absurdly strong sustainability [3, 4]. In the implementation it is usual to find actions and indicators that emphasize sustainability dimensions, referring an unconscious way to remain in time one of the sustainability dimensions as a priority, which is wrong when framed as sustainable development.

In this paper the sustainability will be considered like an emerging expression of the landscape, which comes from the socio-ecological interactions of the landscape, that is, a sustainability landscape is the result of all relationships that exist between all intrinsic attributes of the landscape, in interaction with other landscapes, producing different relational arrangements over time, with the sole purpose of preserving life in all its dimensions. In this way, it is proposed that a sustainability analysis should be systemic.

About sustainability assessment modeling, sustainability studies have employed the autoregressive distributive Lag model over time series data [5, 6]. For the study of landscapes, land use models based on cellular automata have been used, which have been calibrated with artificial neural networks (ANN) applied on big data of land uses [7]. Holistically assessment has been used for identifying the efficacy and sustainability of different intensification options through grassland-based ruminant livestock models (GRLM) [8]. The complexity of land-use-change patterns has been modeled using support-vector machines (SVMs) [9]. In [10] are discussed and illustrated modelling scenarios by the following specific studies: explanation of land-cover changes with empirical models, projection of future land-cover changes with descriptive models, projection of future spatial patterns of changes with spatial statistical models, test of scenarios on future changes in land-cover with dynamic ecosystem models, and design of policy interventions with economic models. Other sustainability assessment models for the industry have been developed based on the general life cycle assessment (LCA) framework [11].

Other sustainability approaches have been development around viability theory, like [12], and Smooth and Filippov models, like [13]. The latter, performed the analysis of bifurcations of a two-dimensional model proposed D'Alessandro [14]. The methodology proposed in this article for carrying out landscapes sustainability analysis is presented in the section 3.

2. Methodology

For doing landscape sustainability analysis oriented to making decisions a methodology was proposed, taking as framework the knowledge management framework explained in [15]. In this way, was well defined the landscape sustainability problem and its scope for making decisions, and was realized a mathematical and statistics methods assessment for solving the problem, concluding that system dynamics is the most appropriate for the representation of the intricate web of relations of a socio-ecological system and that the mathematical model obtained from its implementation (an ordinary differential equations system of first order), is sensitive to be studied as Filippov's system or, failing that due to lack of technical competence, as a viability problem. The remaining methodology results for landscape sustainability analysis were obtained in the complex systems-based reflection for adreessing the making decisions over landscapes.

3. Results and discussion: Sustainability perspective from dynamical systems

The following subsections correspond to the results and discussion of results from the perspective to address sustainability from the dynamical systems theory.

3.1. Selection of the landscape spatial unit, and define types for carrying out the sustainability analysis

The space scale where the model will be implemented so-called landscape. A landscape (L) is understood like a partition of the space (S) under different criteria c_i, *i.e.*, L=S/$\{c_1, \ldots, c_p\}$. For example, in landscape sustainability analysis for a country, space is the national territory, and we have proposed that criteria must be climate, physiography, land cover, type of agricultural producer and technology.

Landscapes that belong to the same class in the partition constitute a type of landscape, which is useful for defining sustainability management guidelines. From the selection of the spatial unit of the landscape, supra and sub landscape scales are defined that allow the multiscale validation of the elaborated model, which is possible due to the versatility of the systems dynamics. So, although sustainability analysis is a specific space, it should allow comparison with higher and lower spatial scales.

3.2. Modeling of the landscape web and their uses with system dynamics

System dynamics is a systemic and deterministic methodology, see for example [16–18], that allows obtaining a system of differential equations, which is susceptible to be studied with dynamical systems or viability theory. See dynamical systems details in [19–22] and viability theory details in [23].

However, what guided his choice as a methodology for the sustainability analysis in a landscape was his ability to capture the web of the landscape and its versatility for the representation of different agricultural uses of the landscape.

The expression “web” was taken from the book “the web of life” [24], to take into consideration that each element of the landscape has a behavior that is determined by its relation with the other elements of the landscape, so, the system dynamics results in an ideal tool that allows expressing that “web”. In this order of ideas, the modeling of the landscape web involves the recognition of the attributes and relationships of each landscape, and how they are affected by different uses, through sustainability indicators.

The sustainability indicators, which will not be mentioned in this article, have been organized through three sustainability principles: productivity, well-being, and multifunctionality, calling attention to 1) sustainability is an emerging expression of the interactions between all aspects of the landscape, 2) the principles of sustainability are met in each one of the aspects of sustainability and 3) each principle is a set of indicators on which a viability constraint, also called threshold, has been defined.

3.3. Collection data to feed the mathematical model

Again, in the knowledge management framework proposed by [15], the data collecting follows the conceptual modeling, which was proposed for sustainability analysis in this paper through system dynamics.

Data capture has two possibilities. The first considers the evaluation of a single landscape, while the second considers the evaluation of multiple landscapes of a certain territory. For the case in which the evaluation of a single landscape is carried out, it is sufficient to find the landscape data required by the model. For the case in which different landscapes are evaluated, it must be guaranteed that the source of the data of all the landscapes complies with the same validity characteristics and that the data are found for all the landscapes evaluated.

In this way, the modeling exercise is also useful for the identification of the databases that should be monitored by the competent authority on issues of sustainability on the landscape/territory and thus deploy a monitoring program towards landscape sustainability.

3.4. Mathematical model evaluation

The evaluation of the mathematical model involves two activities: calibration and validation of the model. The calibration is related to the inclusion of the collected data and the definition of adequate conversion factors between the different magnitudes that are handled in the model. The validation includes activities aimed at generating confidence in the results that would be obtained from the model, rather than a duality between accepting or rejecting the model [25].

In this way, at the time of the calibration, it is important to carry out a verification of the coherence between the units used in the modeling and to use appropriate conversion factors.

On the other hand, in the evaluation of the model developed with system dynamics, it must be verified that the model generates the “right output behavior for the right reasons” [25]. In this sense, a validation of the structure of the model must be made and, later, a validation of the accuracy of its behavior.

In [25] it is proposed that the validation of the structure of the model involves direct analysis of the structure and behavior-oriented analysis of the structure. In the direct analysis of the structure, an empirical and theoretical evaluation of the relationships that constitute the systemic structure of the model is made. In the analysis of behavior-oriented to the structure are carried out: extreme-condition test, behavior sensitivity test, modified-behavior prediction, and boundary adequacy test, among others.

After the validation of the structure has generated sufficient confidence, it is possible to start applying different evaluations oriented to measure the precision that the model has to reproduce the behavior of the real system, involving measurements of the period, frequency, trends, phase lags, amplitudes, etc. [25]. It is recommended to check more details about formal aspects of model validity and validation in system dynamics in [25].

3.5. Dynamical systems analysis

A demo was developed with two simple sustainability indicators for economic and environmental dimensions, obtaining a filippov system whose phase portrait is presented in Figure 1 following the ideas for the partition of the space of states proposed by [13]. The boundaries defined (black lines partitioning the phase portrait in regions), obey to decision rules in the socio-ecological system represented, which increase the dynamical richness of the model. Figure 1 shows four attraction basins for four equilibria points whose behavior remain in time, we mean, the system has four kinds of sustainabilities in the system setup, because an equilibria point is a sustainable behavior. It is interesting becauseit means that sustainability is not necessarily a unique state of the system.

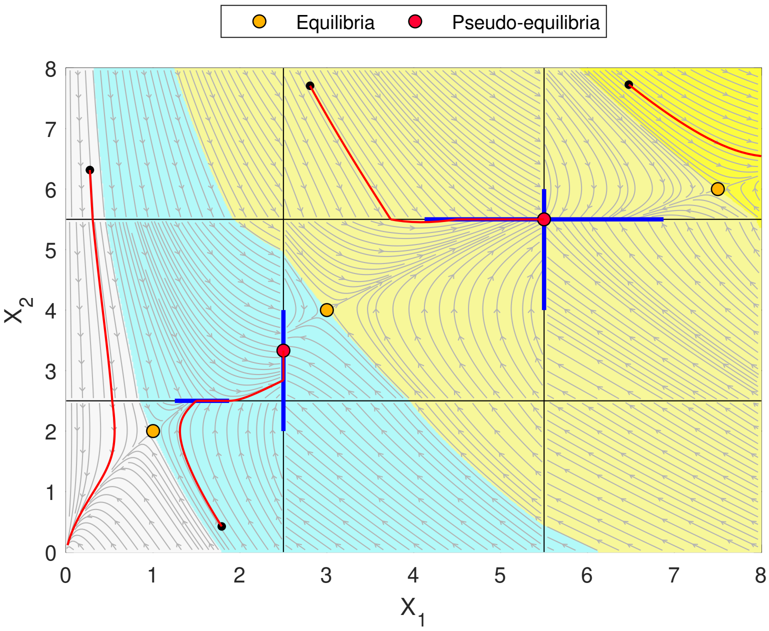

Figure 1. Each color in the phase portrait represents a sustainability. The black dots are the initial conditions of their red orbits. A state is sustainable if their orbit converges to an equilibria point with componenets non zero.

Now, complex systems are not related to the number of elements, but the number of relationships, because the number of elements is a heap, but the number of relationships is a structure and the structure defines the behavior [18]. In this sense, note that four initial conditions were defined in Figure 1, each of them in a different basin of attraction. In terms of quantity, the initial condition of the gray basin has a state that is higher than the condition in the blue region for the variable x_2 that represents the economic dimension. An analysis based on the number of elements will conclude that the condition in the gray region is more sustainable than the initial condition in the blue region, but an analysis based on the number of relationships immediately concludes that the evolution over time of the first condition is not sustainable because its equilibrium point has values in its coordinates that are zero, while the second initial condition converges to a point of equilibrium in which it is guaranteed that the values of the state variables are not annulled.

In this way, we can see that the mathematical methodology proposed in this article not only allows us to identify the existence of sustainabilities but also allows the inclusion of the notion of temporality that is implicit in the definition of sustainable development of [1]. Then, in this article it has been proposed that a state x_0 of a landscape is sustainable, if it is in a sustainable orbit $\mathcal{O}$, where: $\mathcal{O}(\mathrm{x_0}) = \{\mathrm{x} \in \mathbb{R}^\mathrm{n} : \phi_\mathrm{t}(\mathrm{x_0}) \rightarrow \bar{\mathrm{x}} \text{ when } \mathrm{t} \rightarrow \infty \text{ and no coordinate component of } \bar{\mathrm{x}} \text{ is zero}\}$. This means that a state is sustainable if it converges in time to a point of equilibrium or any other invariant set, in which none of its state variables (*i.e.* sustainability indicators) are annulled. The bifurcations analysis implications are shown in the next section.

3.6. Analysis of the trend behavior scenarios

For the analysis of the trend behavior of different scenarios, among which is the business as usual (BAU) and a business as landscape transition (BALT), it has been worked with time series projections in which it is assumed that what has happened will happen. This type of trend analysis of the behavior of a system considers the history above the rules of the system and is incapable of estimating unexpected behaviors that satisfy the rules and that history does not register.

In this sense, it is proposed in the first instance to perform an analysis of trend behaviors from the bifurcation diagrams, see bifurcation analysis in [20, 21], for looking the all possible prospective scenarios of the system, like is explained in [26], so that it is possible to establish which are those parameters that leverage the system to totally different behaviors, in mathematical terms, which are the bifurcation parameters that lead to non-topological equivalence of system phases portrait.

However, bifurcation analyzes are not necessarily trivial to perform, so, in the case of technical incapacity, it is recommended to appeal, as a second instance, to viability analyzes, thus transforming the analysis approach from stationary behaviors to transitory behaviors.

The main idea of the viability analysis proposed in this article to establish the sustainability of different scenarios in a landscape is to consider each scenario as an opportunity for the system, which must meet satisfaction thresholds within a well-defined evaluation time. That is, each new scenario is a new vector field that must satisfy a set of constraints within a given period. The purpose of this viability analysis is not different from the viability theory: identifying the viability kernel [23], with which the recommendations for use will be made, which could be conducive to a sustainable transition of the landscape if the BAU does not meet the principles of sustainability.

However the identification of a set of sustainable scenarios, through a robust methodology such as the one proposed in this article, is not enough to achieve the sustainable transition of a landscape. It must also be considered that each landscape has defined a governance model that conditions the implementation of viable scenarios. This occurs because the notion of the well-being of each landscape, from an objective perspective, is different, and comes from the knowledge systems that the landscape inhabitant community has, see Figure 2. That is, this methodology is necessary but not sufficient to achieve the transitions towards sustainability.

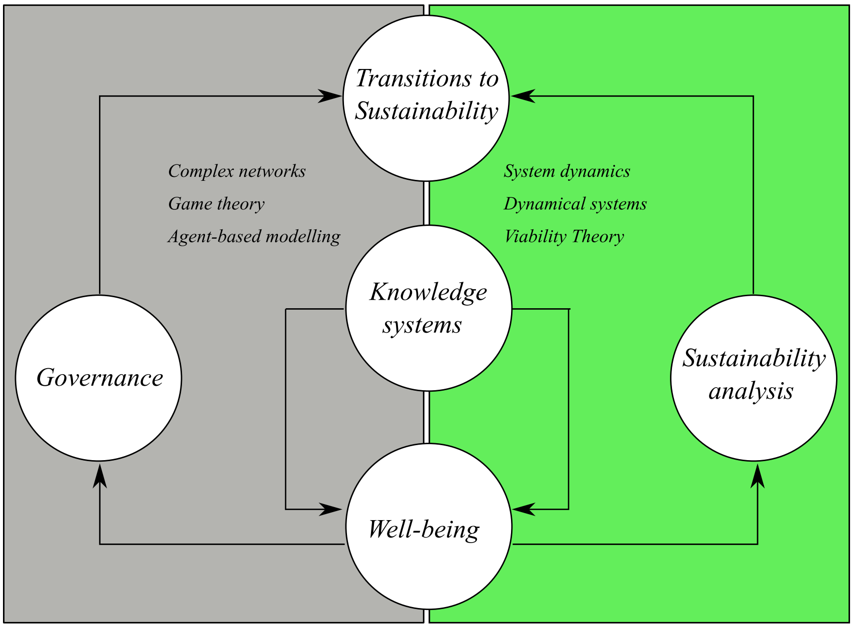

Figure 2. Necessary conditions for transitions to sustainability. The definition of viable sustainability scenarios is insufficient to make a sustainable transition of the landscape. It also requires at least analysis of governance, well-being and knowledge systems.

3.7. Guidelines definition for landscape sustainability management

Generically, management is carried out based on the verification of the goals of some indicators defined to know the state of the system. Management consists of defining strategies to meet the goals of the indicators, involving planning, execution and control activities.

Very often happens that the implementation of the strategies leads to the obtaining of the results on the managed indicators, in spite of the deterioration of other indicators. This occurs because it is considered that the management must be punctual and not systemic, understanding the system as isolated points to which must intervene with specific actions and not as a set of interwoven elements.

The systemic perspective is the one that leads to the recognition of the global effects of specific actions on the system, so that, the definition of strategies for management is carried out under controlled simulation environments in which each strategy is reviewed by the evaluation of its global effects on the system.

The approach from the dynamical systems with systems dynamics proposed in this article for the landscape sustainability analysis, proposes an additional step to the proposed for the evaluation of strategies in controlled simulation environments, when it is possible to obtain the bifurcation diagram, given that the bifurcation diagram is a map of all the prospective scenarios of the system due to the variation of parameters [26], which implies being able to know a priori the types of strategies that are viable for the landscape management due to the variation of the system parameters (understanding strategy as an arrangement of parameters with which the system is intervened).

In this way, sustainability management guidelines can be defined from the dynamical systems analysis, allowing carried out a viable, assertive and pertinent landscape intervention, which biodiversity conservancy, social inclusion, and economic competitiveness would be met in a more general framework of productivity, well-being, and multifunctionality.

4. Conclusions

The methodology for landscape sustainability analysis proposed in this document integrated different math modeling challenges with novelty sustainability framework obtained because of the integration. Furthermore, take in to account different issues for implementing successfully the landscape sustainability analysis. The methodology of the systems dynamics is suitable for modeling oriented to the landscapes sustainability analysis because it captures the relationships of its different aspects, defining a structure with which one can speak about the landscape and the reasons for its behavior.

The perspective from the dynamical systems presented in this article allows us to conclude that in a landscape there may be sustainabilities, that is, that sustainability is not a unique state of a landscape, and that a state of the landscape is not sustainable only because of what is, but also for what it will be. Bifurcation Theory and Viability Theory are two key instruments for the sustainable management of landscapes that allow identifying the sustainability of the complex human being - nature relationship, allowing the rules-based evaluation of different scenarios such as the business as usual BAU and a business as landscape transition BALT.

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