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Sustainable livelihoods approach through the lens of the State-and-Transition Model in semi-arid pastoral systems

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Abstract. Dealing with complex challenges worldwide regarding sustainable development and environmental management requires applied frameworks to understand and manage change in complex social-ecological systems. In this regard, frameworks that have originated from different research arenas such as the State-and-Transition Model and the sustainable livelihoods approach provide a conceptual basis for theory and operative integration. The aim of this paper was to provide a conceptual model for social-ecological research and sustainable management in semi-arid pastoral systems. We suggest integrating the state-and-transition model by including structural and functional features of social-ecological systems into the sustainable livelihoods approach. Both attributes are analysed at a household level in five types of capital that typically comprise social-ecological systems: natural, human, manufactured, social and financial. We propose to perform the structural-functional analysis for each capital as separate sub-systems in order to assess the impact of different disturbance factors. Some implications of this framework are explained by providing an example of the impact of drought in smallholder pastoral systems from semi-arid rangelands of North-West Patagonia, Argentina. This approach is encouraging as a step towards two main challenges: (i) the provision of applied frameworks for social-ecological assessment and management, and (ii) an attempt to bring closer science and decision making.

Additional keywords: disturbance, rangeland, resilience, social-ecological systems, threshold, vulnerability.

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Introduction

Dealing with complex challenges worldwide, regarding sustainable development and environmental management, needs an integration of social and ecological sciences. Sustainability science is an emerging and growing research program, and involves understanding the dynamics of evolving, coupled social-ecological systems (Clark and Dickson 2003; Ostrom 2007). From a policy perspective, it emphasises the growing role of science in tackling practical problems to better inform decision making, which require integrative and adaptive approaches across spatiotemporal scales (Pintér *et al*. 2012). However, sustainability science faces several challenges. One of them is how to develop diagnostic approaches that integrate in a simple and understandable manner complex, non-linear, cross-scale and changing systems (Ostrom 2007). Another challenge is how to assess and monitor some system properties that synthesise complex social-ecological dynamics, focusing on the relationships between system components, but emphasising the functioning of the systems as a whole (e.g. Folke 2006; Nelson *et al*. 2007). In recent decades, a growing consensus has emerged regarding the study of resilience in social-ecological systems (Walker *et al*. 2004), particularly motivated by climate change and desertification in the case of arid and semi-arid regions (e.g. Reynolds and Stafford Smith 2002; Reynolds *et al*. 2007; Easdale and Domptail 2014). However, sustainability science needs an increasing effort to bring closer together resilience and vulnerability approaches, in order to provide opportunities for theory integration and collaboration among researchers from different disciplines (Turner *et al*. 2003; Miller *et al*. 2010). Thereby, the purpose of this paper is to integrate two approaches rooted in different frameworks and scientific disciplines. The state-and-transition model is used as a development rooted in resilience approach and natural sciences (e.g. Bestelmeyer and Briske 2012), whereas the sustainable livelihoods approach is proposed as a perspective rooted in vulnerability approach and social sciences (e.g. Scoones 2009). In particular, we provide a framework which encompasses the multidimensionality of social-ecological systems as measured in different livelihoods, integrated into the assessment of states and transitions in relation to key thresholds. In the following sections, we first define the conceptual basis and the proposed model. Then, we provide an example of pastoral systems from semi-arid rangelands of North-West Patagonia, Argentina. Finally, we synthesised the main scientific and operative implications, emphasising some challenges and future steps.

State-and-Transition Model

One of the main contributions of the resilience approach is that social-ecological systems can be described as several possible states (Gunderson and Holling 2002; Berkes *et al*. 2003; Nelson *et al*. 2007). The State-and-Transition Model (STM, Westoby *et al*. 1989) is an approach with origins in ecology to understand and manage change in complex natural systems, and a conceptual basis to bring closer science and decision making (Briske *et al*. 2008; Bestelmeyer and Briske 2012). However, although STM have been increasingly used in rangeland ecology and management during the recent decades, it has potential to be applied in other scientific disciplines. The STM is a flexible model that defines different alternative states of a system. It is usually presented as a diagram, in which boxes represent alternative states for a given ecosystem, whereas arrows indicate transitions among states. Ecosystem states have as a reference a pristine environmental condition based on key features that define the ecological site (e.g. soil, climate, vegetation), which is named state of reference. This reference state provides the greatest range of potential environmental services and represents the historical or natural range of variability. It can also be defined as the set of conditions most preferred by society based on current scientific knowledge (Bestelmeyer and Briske 2012). Hence, there are negative transitions consisting of system degradation, and positive transitions of recovery. These models are often developed through a combination of expert knowledge, analysis of ecosystem quantitative data and feedback from stakeholders (for more information see Bestelmeyer *et al*. 2003, 2009, 2011). One of the main contributions of the STM is the possibility to integrate different kinds of knowledge into a simple communicational procedure, which is useful for management decisions.

Recently and from an ecological perspective, theoretical and methodological advances on STM are encouraging in bringing this conceptual model closer to social-ecological research and management. First, the inclusion of structural and functional ecological features enhanced the explanatory capacity of the original STM, providing a useful method to identify different states and thresholds (e.g. Bestelmeyer *et al*. 2009; López *et al*. 2011). In this sense, the Structural-Functional State-and-Transition Model (SFSTM, as it was named) provides opportunities to assess some attributes of resilience such as ecosystem amplitude and elasticity, and relate them to a critical threshold (López *et al*. 2011). A critical threshold is associated with the significant decrease or loss of the original resilience, which is identified when an increased intensity and/or frequency of a disturbance factor causes changes in system structure, and a significant increase in the loss rate of ecosystem functions and services (Groffman *et al*. 2006; López *et al*. 2011; Fig. 1).

The assessment of states and transitions of any system should consider its structural and functional features (Briske *et al*. 2005).

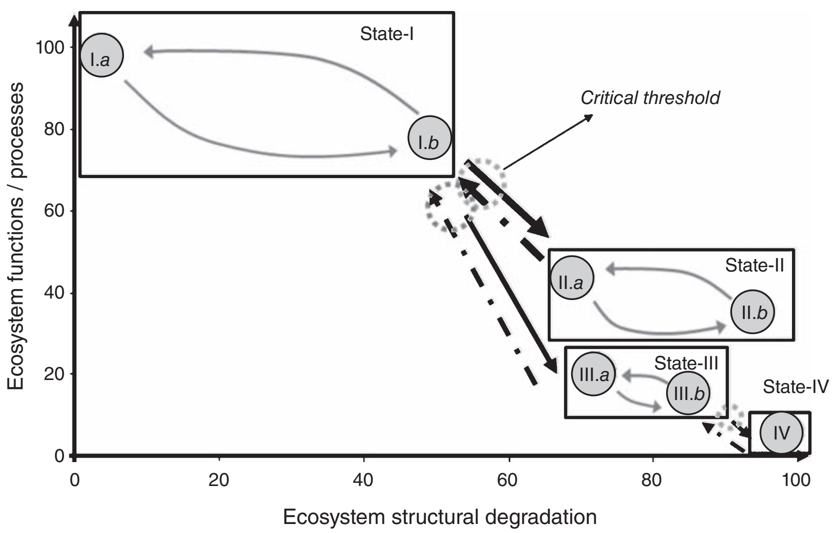

Fig. 1. Conceptual framework of the Structural-Functional State-and-Transition Model for ecosystem assessments (López *et al*. 2011). The *x*-axis represents the ecosystem structural degradation and the *y*-axis represents ecosystem functions and processes. Different states are identified by boxes and Roman numerals (the highest value indicates the more degraded states), whereas grey circles represent different phases within each state (e.g. I.*a* and I.*b* for the state I). The likelihood of a transition (irreversibility degree of a threshold crossing) is reflected by the width and filling of the arrow: negative transitions (more feasible than positive transitions) with thicker and filled arrows; positive transitions (more unlikely to occur) with thin arrows, and positive transitions that are virtually improbable with dotted arrows. Gray dotted circles indicate critical thresholds. There is an implicit increased direction of the intensity, frequency and/or durability of the disturbance factor, from top-left towards bottom-right. Note that the influence on structure and functions is not necessarily linear and continuous.

López *et al*. (2011) proposed for ecosystem assessments two axes over which the STM could be optimised (Fig. 1): (*a*) the structural ecosystem degradation (*x*-axis, e.g. vegetation cover loss, soil loss), and (*b*) the level of ecosystem functions and/or processes (*y*-axis, e.g. key plants-species recruitment, rain-use efficiency). Once the ecosystem faces an increased disturbance such as overgrazing, then ecosystem composition, structure, productivity and functioning are affected (López *et al*. 2013). A critical threshold is identified when a change or degradation at the structural level has a concomitant significant loss of ecosystem functions and processes. In these cases, a negative transition occurs and the ecosystem moves towards another state (e.g. S-II, S-III, Fig. 1) where the ability to return to its original states (e.g. S-I, Fig. 1) is severely diminished or lost. The irreversibility is dependent on the extent and duration of structural and functional ecosystem modifications (Briske *et al*. 2005).

The Structural-Functional State-and-Transition Model (SFSTM, López *et al*. 2011) does not assume that the *x*-axis is the independent variable, neither that the *y*-axis is the dependent variable, but recognises that both features are interdependent. The concept of critical threshold is supported by definitions of ecological thresholds discussed by Groffman *et al*. (2006), Briske *et al*. (2005, 2006) and Suding and Hobbs (2009). They defined a threshold as the point at which an abrupt change occurs in some property or process that is important for an ecosystem, which alters not only the structure but also the ecosystem services and functions. The SFSTM suggests that persistent changes in structure and function as a consequence of a disturbance determine a critical threshold, which is ultimately recorded in a significant loss of key ecosystem functions or processes (López *et al*. 2011). As well, a disturbance factor can first affect the ecosystem structure with a concomitant impact on functions, and vice versa, and these impacts are not necessarily linear and continuous (Scheffer and Carpenter 2003; Andersen *et al*. 2009). We propose that the state-and-transition approach can be applied to other dimensions of social-ecological systems.

Sustainable livelihoods approach

The sustainable livelihoods approach is a framework with origins in social sciences for thinking and communicating about factors that impact on the livelihoods of rural families from a multidimensional perspective, including wellbeing, health, income, social networks, the local environment and governance systems (Scoones 1998, 2009). It is designed to assist in identifying changes or transformations that can be produced in institutions, assets or strategies of rural families in order to promote adaptive capacities and to reduce the vulnerability of local communities (e.g. Meert *et al*. 2005; Davies *et al*. 2008). The approach focuses on the capabilities and strengths of families and households, rather than their needs, desires or their deficits. Ellis (2000) concludes that it is also valuable in building an understanding of how various factors outside the control or influence of rural households affect their access to different types of capital, opportunities and services, and hence their capacity to pursue strategies that will return outcomes to which they aspire. Setting up the sustainable livelihoods approach to assess dynamic changes in social-ecological systems is not a trivial issue and we suggest some modifications. More precisely, we propose to explicitly identify structural and functional features of different livelihoods of rural households.

Social-ecological systems are complex systems comprised by social and ecological domains interacting in space and time. In a broad sense, such a linkage is generally mediated by a production process (e.g. Easdale and Aguiar 2012), interpreted as a process in which environmental goods and services are appropriated by humans for their wellbeing (e.g. agriculture, pastoralism, fishery, forestry, tourism, energy systems). Then, social-ecological systems are constituted by different sub-systems, or also called capitals from the lens of the sustainable livelihoods approach (Scoones 1998). Hereafter, we use the term capital metaphorically as similar to livelihood, as it has a clear heuristic and communicative value (Nahapiet 2011). The essence of the capital concept is that it is a stock, which is characterised by tangible and intangible assets that confer structure and possess the capability to produce a flow of functions. In agro-ecosystems (as social-ecological systems), the functions or processes provide system self-organisation, coordination capabilities and stability over time, whereas some of them are involved in a production process (Ekins *et al*. 2003). The central attribute of a stock is its temporal durability. Stocks are suitable for depicting the influences the systems' history has on its present states and hence for analysing historical developments and for system monitoring (Faber *et al*. 2005). From a social perspective, a capital structure emphasises the importance of the pattern and connections among different components of capitals, in particular their interactions (Nahapiet 2011).

From a social-ecological perspective, there are two general sources of wellbeing: services of natural capital and services of human-made capital (Daly and Farley 2004). In order to better understand the interactions between different livelihoods and drivers, more disaggregated classifications identify four different types of capital: natural, human, manufactured, and social (Ekins 1992; Ekins *et al*. 2003), whereas some authors have also included financial capital (e.g. Scoones 1998; Davies *et al*. 2008; synthesised in Table 1). Natural capital is the biophysical stock (e.g. related to soil, water, and biodiversity), which produces the flux of natural resources (e.g. primary and forage productivity, nutrient cycling, carbon sequestration, oxygen generation) (Daly 1994). Manufactured capital comprises biotic and abiotic material or physical goods involved in a production process (e.g. domestic livestock, crop seeds, machineries, infrastructure), which produces a flux of production functions (e.g. secondary productivity such as meat, fibre, grains). Human capital comprises all household individualities (e.g. rural family composition, health, knowledge, skills) with their respective capabilities (e.g. labour, learning and innovation processes), which are important for the pursuit of any livelihood. Social capital relates to networks and institutions that relate to different social processes (e.g. coordination of individual contributions and actions, flow of information). Financial capitals are economic or monetary assets (or equivalent; e.g. monetary funds, earned income, remittances, bonds, shares), and the current monetary value of different physical assets. These financial assets provide different functions (e.g. profit, revenue, income rates) (Table 1).

Table 1. Description of capital assets, functions/processes, and examples for different types of capital used in the proposed framework
References are provided only as examples for further information, definitions and/or applications

Type of capital	Capital structure, assets	Functions and/or Processes	References (e.g.)
Natural capital	Minerals and nutrients, native living organisms, genes e.g. vegetation cover, soil organic matter, species richness, diversity, wildlife, genetic structure	Provision of resources for production regulation (bio-geochemical cycles, water purification) e.g. primary and forage production, rain use efficiency, species recruitment rate	Ekins *et al*. 2003; de Groot *et al*. 2002; Azqueta and Sotelsek 2007; Chiesura and de Groot 2003
Human capital	People, household members, knowledge, education Skills, expertise, other attributes (innate talent and abilities) Health, gender e.g. workers, family/household members, educational level, health status, known technologies	Working capacity Learning processes Innovation e.g. working efficiency, birth rate, used technologies	Cash *et al*. 2003; Brian 2007; Nahapiet 2011; Cooper *et al*. 1994
Manufactured capital	Infrastructure, machines, tools, livestock, crop seeds, breeding e.g. domestic livestock number, types and number of machines, irrigated area	Secondary production e.g. fibre, meat, grain production	Ekins *et al*. 2003; Scoones 1998; Villagra *et al*. 2015; Weisz *et al*. 2015;
Social capital	Social relations and networks e.g. institutions, social organisations, laws and policies, network topology (ties and nodes)	Social processes, coordination e.g. flow of information, performance of reciprocity, collective action, trust	Coleman 1988; Burt 2000; Westley *et al*. 2002; Cash *et al*. 2003; Janssen *et al*. 2006; Nahapiet 2011; Zheng 2010; Glasbergen 2011; McAllister *et al*. 2011
Financial capital	Monetary funds yearly available, financial assets, remittances, monetary value of assets e.g. monetary funds, bonds, notes, remittances	Income rent, relative prices of products e.g. yearly net income, profitability, earned income, interest rates	Cooper *et al*. 1994; Escobal 2001; Barrett *et al*. 2001; Easdale and Rosso 2010; Villagra *et al*. 2015

Linking Structural-Functional State-and-Transition Model and sustainable livelihoods approach

The household social-ecological pyramid

We argue that different sub-systems (i.e. capitals), which comprise a social-ecological system in agricultural landscapes (hereafter named agro-ecosystems) should be founded on a structural-functional balance among them, which depend on a trade-off among each other. From this perspective, we highlight that agro-ecosystems have already induced a natural capital modification to promote the development of others (e.g. manufactured, financial capitals). In other words, the development of agricultural landscapes implies that natural capital was modified from its pristine environmental situation. For instance, other components such as human, social and manufactured capitals are developed, with the concomitant introduction of other dimensions for system diversity (Niehof 2004). This agro-ecosystem is a social-ecological system and the structural-functional balance among different capitals needs to be identified in a given region to determine the reference state for both management and monitoring (similar to STM methodology, Bestelmeyer *et al*. 2009). We suggest that this reference state should consider that the bases of a social-ecological system are the natural and the human capitals. Therefore, a sustainable management should maintain the ecological integrity of the natural landscape (see more in Müller *et al*. 2000; Reza and Abdullah 2011) and the integrity of the human sub-system (i.e. human wellbeing of rural people). Consequently, the five types of capital were hierarchically organised into what we called the 'household social-ecological pyramid' (Fig. 2*a*), which is a multidimensional and hierarchical representation of the different livelihoods of a rural household. In this conceptualisation, the focus is posed on the kind of interactions among capitals, whereas structural and functional features are implicitly included in different boxes that represent capitals.

The bottom of the pyramid is constituted by the natural and human capitals since they represent the basis for human living. Towards the top of the pyramid, other capitals that complement human wellbeing are organised at different hierarchical levels, by considering the current style of life in a capitalised world. In this scheme, an agro-ecosystem is defined by the interaction of the natural, human and manufactured capitals, among which there are flows of matter, energy and information. In addition, the social-domain of the system is mainly represented by the interactions among the human, social and financial capitals. These interactions involve different levels of social organisation such as farms, families, cooperatives, private and public institutions,

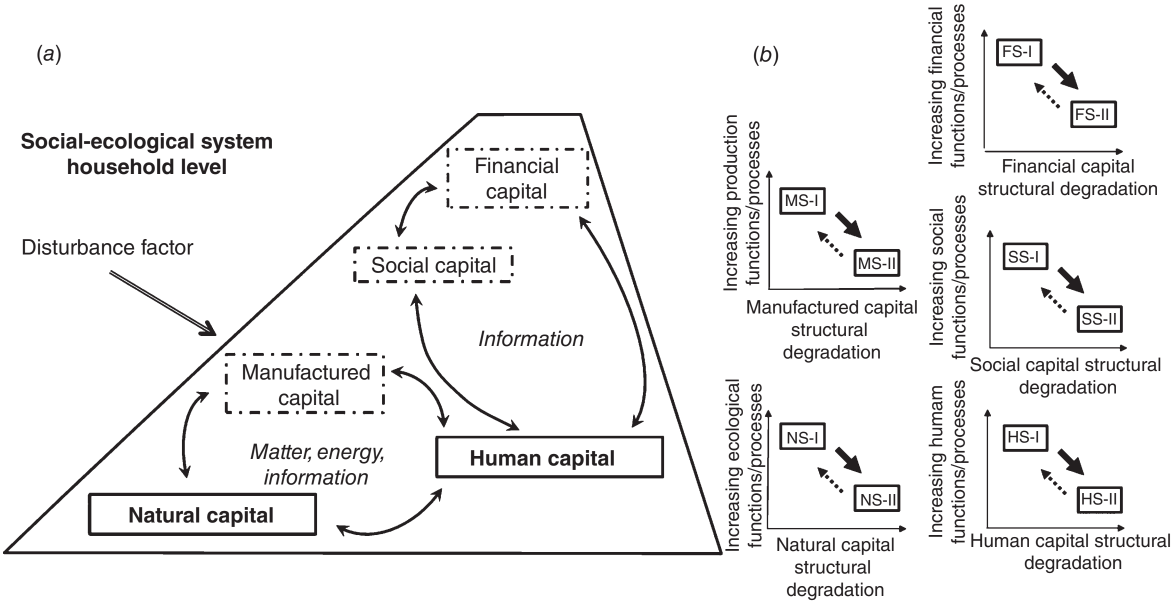

Fig. 2. (*a*) The household social-ecological pyramid. The bottom of the pyramid is constituted by the natural and human capitals, since the natural sub-system represents the basis for human living, and both capitals are the foundations of a SES (boxes with filled lines). Towards the top of the pyramid, capitals that complement human wellbeing are organised at different hierarchical levels (manufactured, social and financial, boxes with cut lines). Arrows connecting boxes indicate the main fluxes among capitals. (*b*) Conceptual framework of the Structural-Functional State and Transition Model for each livelihood. Different states are identified by boxes with the capital letters that refer to the capital (natural NS, human HS, manufactured MS, social SS and financial FS). Roman numerals identify the state, for which the higher value indicates the more degraded state. In order to simplify, only two states are represented and between them there is a critical threshold. The likelihood of a transition is reflected by the width and filling of the arrow: negative transitions (more feasible than positive transitions) with thicker and filled arrows; positive transitions (more unlikely to occur) with thin arrows, and positive transitions that are virtually improbable with dotted arrows.

among which there is a flow of different kinds of information (e.g. knowledge, experience, whereas money is used as a tool that provides information of the values of physical and non-physical assets) (Fig. 2*a*).

The five types of capital were integrated into the SFSTM perspective. We suggest that each capital can be assessed by its structural and functional features in order to identify different states and their respective critical thresholds. In order to make it operative key structural and functional variables associated with each capital should be identified and selected (Table 1). In this regard, structural changes as well as modifications in the provision of functions and processes, derived from each capital, should be assessed explicitly in relation to different disturbance factors (Fig. 2*b*).

The distinction among capitals and flows allows the analysis of the interactions among them, and the relative impacts of different disturbance factors (Fig. 2*a*). For example, in pastoral systems, drought has a direct impact on natural capital by reducing forage productivity (natural function). Then, less forage productivity negatively affects manufactured livestock productivity (e.g. less offspring or animal fibre, which are manufactured functions, e.g. Texeira and Paruelo 2006; Easdale *et al*. 2014), whereas livestock loss occurs when animals die in severe situations such as starvation (manufactured structural loss). This situation has two main subsequent implications: (i) less food for household members and (ii) less income due to less livestock products (see details of this example below). Another different example is a disease affecting animals, causing a direct negative impact on animal productivity (manufactured function) or by increasing livestock mortality (manufactured structure). Then, this effect would spread to reducing household income (financial capital) and therefore to the human capital. But, if the disturbance factor (i.e. disease) produces livestock mortality, this would not necessarily affect the natural capital (or it would be even beneficial for forage species cover and biomass, which may increase due to less grazing pressure). From another perspective, lowering market prices of livestock products has a direct impact on reducing revenues for a given unit of product (financial function) and hence household income, whereas the reduction of the current value of physical assets and products may generate decapitalisation in the long-term (financial structure) (Domptail *et al*. 2013).

Therefore, we propose that in order to analyse how different drivers or disturbance factors impact on different sub-systems of the social-ecological system, structural-functional analysis might be performed for each capital as separate sub-systems (Fig. 2*b*). This procedure provides more detailed information of different sub-systems or components and their dynamics. In addition, partial analysis provides opportunities to include disturbance factors from very different sources, which generally have a direct impact on a particular capital (i.e. state change), with subsequent consequences on other capitals as explained above.

The relationship between each capital and disturbance factors is assessed in relation to critical threshold, implicitly included in the movement from the top-left quadrant towards the bottom-right quadrant (depending on the agro-ecosystem, each capital can have multiple states, with their respective thresholds) (Fig. 2*b*). Then, if the critical threshold is crossed in a given capital (i.e. a transition occurs between alternative states), indirect impacts on other capitals could be triggered afterwards due to their interdependence. However, different capital configurations may provide a range of vulnerability situations with regard to a particular exposition to a disturbance affecting just one of them. Even more, non-affected capitals can offset the impact of a disturbance factor affecting one particular capital. Hence, in social-ecological systems with different capital configurations, the interactions among capitals and different kinds of disturbance factors provide an integrative perspective to explicitly assess different kinds of system and sub-system sensitivities (and in relation to what), and different levels of exposure to disturbances (Turner *et al*. 2003). This kind of assessment can give rise to an empirical tool for social-ecological vulnerability analysis and monitoring in arid agro-ecosystems. In the following section, these concepts are explained by providing an example of structural-functional states and transitions applied for different capitals in pastoral systems from semi-arid rangelands of North-West Patagonia, Argentina.

An example of the impact of drought in smallholder pastoral systems from semi-arid rangelands of North-West Patagonia, Argentina

To illustrate the main operative and conceptual implications of the proposed integration between the STM and the sustainable livelihoods approach, we provide an example of the impact of drought on different capitals of smallholder pastoral systems from North-West Patagonia, Argentina. We reanalysed and reorganised already published data by Easdale and Rosso (2010).

We used this case study to explain in a simple manner the utility of the model, by exemplifying the performance of some capitals in a context of drought. As the application of the SFSTM for natural capital is explained in detail in López *et al*. (2011, 2013), in the example of this paper we decided to focus on other capitals. We provide data of a single variable for the *x*-axis named Structural level Capital Loss and one variable for the *y*-axis named Functional level both for manufactured and financial capitals. Whereas the SFSTM was used to assess critical thresholds, in our example thresholds were defined empirically based on literature and our expert knowledge in the field. The structure of manufactured capital was described by the relative change in total livestock by comparing the year before and after the drought, as measured by the livestock loss per unit of farm area (Sheep Livestock Unit, SLU ha^{-1}) relative to a regional intermediate stocking rate as a reference of a sustainable level (i.e. 0.2 SLU ha^{-1}), based on Oñatibia *et al*. (2015). The structural threshold was defined by the relative level of livestock that can be self-recovered, based on 1-year offspring obtained in an average year from remaining breeding females (i.e. ~30%). The manufactured function was represented by the relative annual marking rate, estimated as the difference between current marking rate and the expected level for an average year for sheep, goat and cattle, respectively, based on Villagra *et al*. (2015). Annual marking rate is the number of offspring that were branded at the end of the reproduction season in relation to breeding females at mating. The functional threshold was defined by the minimum relative level of marking rate needed to assure 1 year of livestock reposition (i.e. marking rate ~50%). The values of these thresholds are associated to time-periods needed for livestock recovery without external inputs, which may not significantly affect household wellbeing (<2 years).

Financial capital was described by the relative difference in the monetary value of livestock as a financial structure, and the structural threshold was defined by a relative level equal to zero in current prices, whereas negative values defined a financial decapitalisation. We notice that financial valuation depends on relative prices that vary over time (i.e. inter-annual variation of relative prices is an important driver of this sub-system). Hence, it is difficult to determine a state or level of reference for monetary values of physical assets. Due to this challenge, we suggest considering the monetary value at the initial moment of a monitoring process or assessment study. Regarding the function of financial capital, we used yearly household gross income as measured by farm and off-farm income. Half an annual rural wage for the year 2008 was used to define the functional threshold (see Easdale and Rosso 2010). In addition, household gross income was used as a response measure of the social implications of different capital configurations, or levels of diversification, based on different livelihood strategies (Easdale and Rosso 2010): (i) household only relying on livestock production, (ii) income diversification (i.e. off-farm income based on human capital diversity), (iii) social networks involving partnership (i.e. better wool prices obtained from associated sales, based on a social capital diversity), and (iv) the integration of strategies (ii) and (iii).

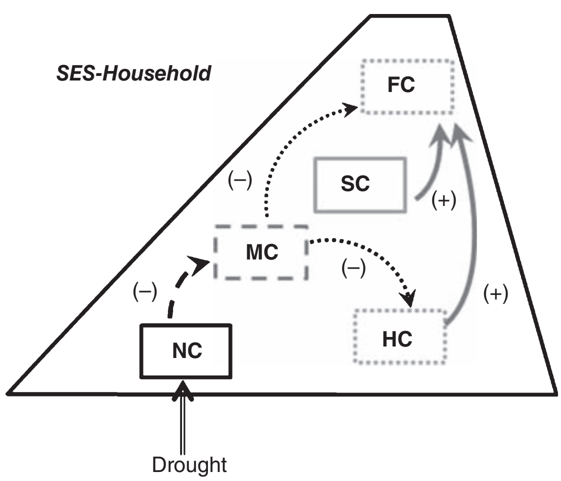

Fig. 3. Conceptual representation of the impact of drought on a smallholder pastoral system of North-West Patagonia (Argentina), from the perspective of the household social-ecological pyramid. Drought had a direct impact on natural capital (black arrow and box), with subsequent consequences on manufactured capital (negative, arrow and box with cut line) and indirect impacts on human and financial capitals (negative, grey arrows and boxes with dotted line). Human and social livelihood strategies offset the negative impact of drought on financial capital (positive, grey arrows).

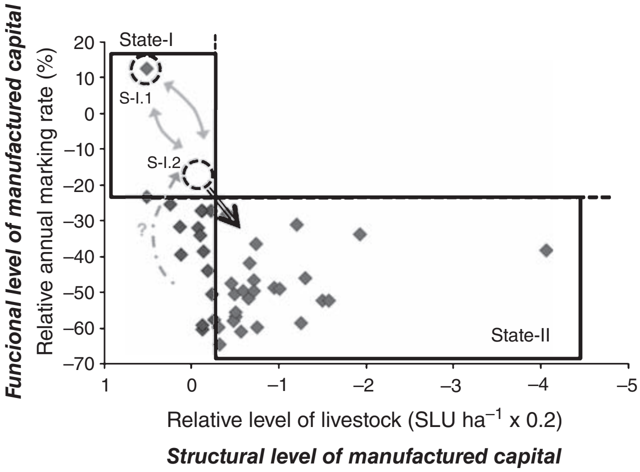

Fig. 4. Structural-Functional State and Transition Model for manufactured capital in smallholder pastoral systems of North-West Patagonia, Argentina, in a context of drought. Structural level loss (*x*-axis) is represented by the livestock loss per unit of farm area (Sheep Livestock Unit, SLU ha^{-1}) relative to a regional intermediate stocking rate as a reference of a sustainable level (i.e. 0.2 SLU ha^{-1}), based on Oñatibia *et al*. (2015). Functional level (*y*-axis) is represented by the relative annual marking rate, estimated as the difference between current marking rate and the expected level for an average year for sheep, goat and cattle, respectively, based on Villagra *et al*. (2015). Each rhomb represents a household. Black cut lines identifies the structural-functional critical threshold. Structural threshold was defined by the relative level of livestock that can be recovered with 1-year reposition of herds without compromising other household needs (~30%), and functional threshold was defined by the minimum relative level of marking rate that assures yearly livestock reposition and household consumption (~0.5). Marking rate refers to the number of offspring that were branded at the end of the reproduction season in relation to breeding females at mating. Boxes represent different states (State I and II). The straight arrow depicts the transition from S-I to S-II. The grey dotted-curved arrow represents hypothetical phase's changes. Different extreme hypothetical phases of State-I are represented by dotted circles and grey arrows (S-I.1, S-I.2). Data source: Easdale and Rosso (2010).

A drought occurred in the year 2008 (see more details in Easdale and Rosso 2010), and had a direct impact on natural capital by causing a reduction in forage production and water availability (Fig. 3), which then affected animal body condition and hence reduced marking rates, and in almost all cases animal mortality also occurred (i.e. manufactured capital structural loss, Fig. 4). The yearly reduction in livestock and animal productivity levels (i.e. mainly meat and animal fibre products, manufactured capital functional reduction), had a subsequent negative impact on farm income and household food supply. However, although most households crossed the functional manufactured capital threshold indicating productivity loss (i.e. less offspring), some households crossed the structural-functional critical threshold. These households which crossed the threshold become poorer after the drought without possibilities to return to the previous state in the short-term (e.g. households in S-II, Fig. 5). The different magnitudes of structural and functional loss may represent different phases of this state, as well as different abilities to recover the initial structural-functional levels (State II, Fig. 4). Nevertheless, different financial and social capital diversification strategies of some households did offset the negative impact by helping to reach a higher household income level (Fig. 3). These diversification strategies prevented these households from crossing a critical threshold in the financial capital (Fig. 5), which may serve as a buffer while livestock recovers the initial structural-functional levels.

Livelihood diversification level can provide complementary information about the household configuration assemblages that constitute different states or phases within states. For instance, whereas there is a highly variable situation, households that only crossed the functional threshold or both structural and functional thresholds were mostly the less diversified cases (Fig. 5). In addition, half of them crossed both thresholds in manufactured and financial capitals suggesting more critical circumstances (see triangles with dark lines, Fig. 5). Households that only crossed a structural or a functional threshold (e.g. points in the upper right quadrant and the lower left quadrant of Figs 4 and 5), may represent: (i) a first stage of a transition towards an alternative state (e.g. S-II.), or (ii) a downward phase or phase risk (*sensu* Bestelmeyer *et al*. 2010) of the original or pre-disturbance state, for which a recovery phase may follow (e.g. grey dotted arrows in Figs 4 and 5). The evolution of households should be monitored in the medium to long-term periods in order to discriminate temporal shocks from persistent changes (Domptail *et al*. 2013). Nevertheless, our example allows us to infer that the likelihood of households experiencing a transition towards another state will depend on the level of diversification and interactions among different capitals.

Livelihood diversification can affect the resilience of the entire social-ecological system. This information can be used to orient policy intervention strategies. Results indicate that for the cases that only crossed the functional threshold of manufactured capital, the main support should only focus on productive issues such as providing fodder for animal nutrition supplementation (e.g. Ares 2007), in order to avoid crossing a structural threshold. However, those that only relied on farm income and crossed both manufactured and financial critical thresholds, suggest a productive and a social emergency situation. For these cases, policies should mostly be oriented to social assistance (State II, Fig. 5). The example emphasises that different livelihood configurations and strategies such as partnership to achieve better prices (i.e. strong social capital based on local networks) and off-farm income (i.e. based on human and financial capital diversities) provided opportunities to decouple the impact of drought on farm productivity from household income (i.e. households in the right upper quadrant of Fig. 5, Easdale and Rosso 2010). Such alternatives may function as adaptive livelihood strategies, which may enhance resilience during post-drought periods. However, the example highlights the differences in social-ecological vulnerabilities due to different sensitivity to drought, and the need for differentiated intervention policies that should consider this heterogeneity. In particular, this approach may help in the early identification of system bottlenecks occurring when a particular sub-system has crossed over a critical threshold (or is near to it) and may drive the whole social-ecological system towards another state. These kinds of early warnings may provide another perspective for policy intervention in critical situations.

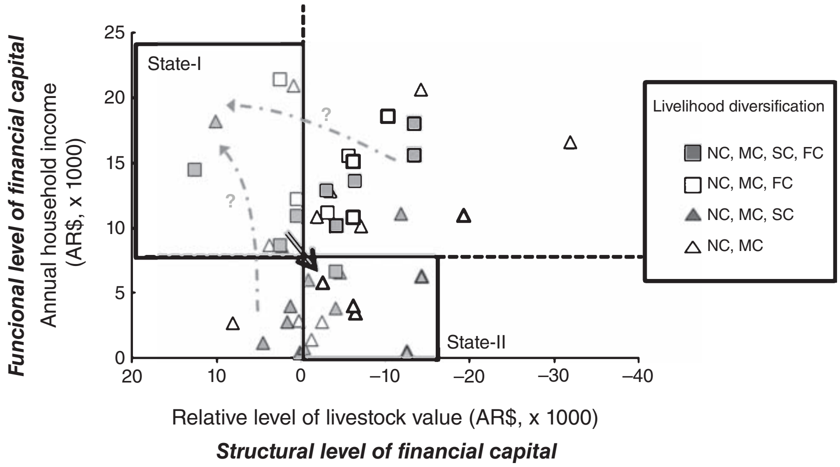

Fig. 5. Structural-Functional State and Transition Model for financial capital in smallholder pastoral systems of North-West Patagonia, Argentina. Structural level loss (*x*-axis) is represented by a relative level of livestock current value and the functional level (*y*-axis) is represented by annual household income. Each data point is a household with a different set of capitals. Black cut lines identifies Structural-Functional critical thresholds. Structural threshold was defined by the monetary value of livestock loss indicating financial decapitalisation, and functional threshold was determined by half an annual rural wage. The straight arrow depicts the transition from S-I to S-II. The grey dotted-curved arrow represents hypothetical phase's changes. Symbols with dark lines represent households that crossed over the manufactured structural-functional threshold (State-II, Fig. 4). Symbols with light lines identify households that did not cross over the critical manufactured threshold. Different symbols and fills identify different livelihood diversification of households. References: Natural Capital (NC), Human Capital (HC), Manufactured Capital (MC), Social Capital (SC) and Financial Capital (FC). Data source: Easdale and Rosso (2010).

Final thoughts: synthesis, challenges and future steps

Social-ecological sustainability analysis should integrate the natural and social sciences for seeking creative solutions to complex challenges such as desertification in arid and semi-arid regions (Easdale 2016). There is a need for novel theoretical and methodological proposals to understand and manage changes in social-ecological systems (Clark and Dickson 2003; Jerneck *et al*. 2011). We acknowledge that one of the main identified limitations to achieving this aim is the asymmetry in the use of resilience theory in ecology compared with social science disciplines. In particular, the unification ambition with respect to methodological developments and incommensurability problems constrain the interdisciplinary dialogue (Olsson *et al.* 2015). For instance, a major challenge of the proposed framework is the definition of states or levels of reference for each of the capitals that comprise the household social-ecological system. However, and with this in mind, we argue that the integration of the sustainable livelihoods approach (with strong roots in rural sociology) and the STM (with strong bases in rangeland management and ecology), may contribute to bring closer interdisciplinary initiatives. The emphasis on critical thresholds and the overall problem-oriented approach gives opportunities to better understand complex challenges (i.e. as promoted by different disturbance factors) and alternative pathways, which may help to inform decision makers for mitigation or adaptation earlier. In addition, the proposed framework may develop as a monitoring tool for adaptive management in pastoral social-ecological systems, by informing structural-functional changes that are related to the proximity to thresholds, as well as management and intervention impacts (Groffman *et al*. 2006; Briske *et al*. 2008).

The utilitarian and quantitative approach of capitals might be a matter of discussion from a 'soft system' perspective (Jansen 2009). Particularly, the argument that human behaviour is not so much determined by cause and effect, as by peoples' construction of reality, which is driven by reasons, human intentions and perceptions (Röling 1999). This issue concurs with the idea that resilience in social systems has the added capacity of humans to anticipate and plan for the future (Carpenter *et al*. 2001), with emergent novel transitions, innovation and adaptability (Gunderson and Holling 2002; Jerneck and Olsson 2008). Many are critical of the value associations of the concept capital, and there are strong reservations about whether or not these newly labelled intangible assets or sub-systems (e.g. social, human, cultural and even some features of natural) should be called capital (Nahapiet 2011). Although debates continue today, we recognise the epistemological basis of these arguments and emphasise the need to advance in philosophical and ontological fields among different sciences (Jansen 2009; Jerneck *et al*. 2011). Many researchers argue that notwithstanding its limitations, using the term capital metaphorically has clear heuristic value, bringing fresh insights and producing important advances in both theory building and policy across several fields (Adler and Kwon 2002; Nahapiet 2011).

Finally, we stress some considerations regarding the proposed framework by emphasising that the model (as any model) is a simplification of reality. We aimed at helping to organise information and interpretation of complex dynamics and patterns. In this regard, we underline three main issues: (i) there are multiple phases within a similar state in dynamic equilibrium (i.e. oscillatory dynamic in a basin of attraction, Bestelmeyer *et al*. 2009), (ii) the axes synthesise multiple dimensions, some of them not explicitly included, and (iii) there is a focus on a household level, which is appropriate as a first step, but future developments should include other scales (e.g. regional, global) to better assess cross-scale interactions. In order to keep the simple methodological structure of STM to help interpretation, temporal scale and interactions among disturbance factors are still implicitly included in the narrative specifications of transitions and triggers (e.g. Briske *et al*. 2008; Bestelmeyer *et al*. 2009, 2010). With the aim of improving the operational capacity of the model, future steps need to focus on geographic and modelling tools (e.g. Kitzberger *et al*. 2012; Van Dyke 2015), with integration of data from different sources and in different spatial and temporal scales. Another challenge relates to the integration of information from sub-system components to social-ecological system level, involving both geographic and network dimensions (e.g. McAllister *et al*. 2008; Adams *et al*. 2012; Easdale *et al*. 2016). In addition, normative and actor-based approaches should be included in STM narrative, which can lead to novel interpretations for improved management (Bestelmeyer *et al*. 2011). Sustainability science needs to move forward with complementary approaches and methods, and a possibility at hand is to build a participatory dialogue in order to include different perspectives.

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