ANP MODELING OF COMPLEX SOCIO-ENVIRONMENTAL SYSTEMS: ADAPTIVE CAPACITY OF SMALLHOLDER COFFEE SYSTEM IN MESOAMERICA

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ABSTRACT

Coffee has been and still remains one of the most important commodities of the Mesoamerican region. Guatemala, Mexico, Costa Rica and El Salvador are among the top ten largest coffee exports in the world. Nevertheless, the social and economic upheaval that characterized the coffee sector has prompted the need for coordinated regional assessments of rapidly changing social and environmental conditions. Such evaluations of the drivers and outcomes of regional change can help broaden the scope and integration of policy, not only in the context of a particular national setting, but also regionally. In this paper, we applied the ANP to synthesize the collective knowledge of a group of experts in different aspects of the coffee sector in five countries in the region. Through the ANP, these experts identified and linked the drivers, adaptations and capacities that characterize the vulnerability of individual farm households across the Mesoamerican region. Results show that the strength of the ANP is that it can accommodate the intricate interconnections among components of the smallholder coffee system of Mesoamerica. This capability of the ANP enables the development of a sound structured conceptual model of what otherwise would be an unmanageably complex social-environmental system.

Keywords: drivers, adaptations, capacities, household vulnerability, shade grown coffee

1. Introduction

Coffee is not simply an industrial commodity, but rather a complex coupled social-ecological system. In Mesoamerica — a region that includes Costa Rica, El Salvador, Guatemala, Honduras, Mexico, and Nicaragua — coffee not only accounts for as much as 25% of total export values, but also is fundamental for the livelihoods of hundreds of thousands of smallholder households (International Coffee Organization 2001; IDB/USAID/WB 2002; Council 2003; Lewin, Giovannucci et al. 2004). Likewise, shade grown coffee is fundamental for biodiversity conservation and the provision of ecosystem services in this region (e.g., Davidson 2006, Gallina, Mandujano and Gonzalez-Romero 1996, Galvan 2009). Furthermore, the dynamics of globalization and increasingly integrated markets influence policies in coffee markets that often have significant socio-environmental effects at the local level.

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The rapidly changing economic, social and environmental conditions of the coffee sector demand a systemic view of the sector capable of linking the issues regarding smallholder vulnerability with the decision context at the national level (Eakin, Winkels, and Sendizimer, 2008). Nevertheless, viewing coffee through a systemic lens presents significant methodological challenges. Such a system should connect seemingly unrelated concepts including, for example, tropical biodiversity, ecosystem services, indigenous cultural survival, migrant bird habitats, small farmer empowerment, and rural poverty.

In this paper we show how Saaty's (2001) Analytic Network Process (ANP) can be used to address the methodological challenge of representing the coffee sector of Mesoamerica as a coupled socio-ecological system. The ANP provided the appropriate framework for synthesizing the collective knowledge of experts into a conceptual model representing the Socio-Ecological System of Small Coffee Farmers in Mesoamerica (hereafter, SES-SCFM).

This model constituted a coherent representation of three key lines of inquiry, necessary for understanding the coffee as a socio-environmental system: (1) the primary drivers of change — that is, the exogenous stressors (that is biophysical and socioeconomic/political factors) over which individual farm households have had relatively little direct influence; (2) the observed adaptations of small-scale farmers to stressors might be most promising for meeting development objectives — that is, "the decision-making process and set of actions undertaken to maintain the capacity to deal with future change or perturbations to a social-ecological system without undergoing significant changes in function, structural identity, or feedbacks of that system while maintaining the option to develop" (Nelson, Adger and Brown 2007: 397); and (3) the capacities in farm households to take advantage of available opportunities for effective responses — that is, the assets or "capitals" which the household either owned or directly controlled (e.g., land, family labor), or to which the household had access (e.g., transport, credit).

In what follows, we first provide a brief overview of the global circumstances that have introduced new uncertainties into the future of coffee farming in the Mesoamerican region. Next, we describe the implementation of the ANP to develop a representation of the coffee socio-ecological system in Mesoamerica. Then, we discuss the results focusing on the usefulness of the ANP for developing representations of complex coupled socio-ecological systems. While the overall results show how imperfect knowledge and experience of experts can provide valuable information, they also illustrate the usefulness of the ANP for (1) developing systematic and structured models that simplify what otherwise would be an unmanageably complex representation; and (2) enabling an iterative process of analysis which resulted in a effective increment of understanding by the experts about the coffee sector of Mesoamerica.

2. Overview of the coffee sector in Mesoamerica

Coffee is a tree crop that in Mesoamerica is often grown in the under-storey of managed tropical cloud forest, in areas of volcanic soils, at 900-2000 m, and with mean annual precipitation exceeding 1000 mm. Although produced in small-scale coffee farms on steep slopes since the 19^{th} century, shade grown coffee presents several advantages when compared with other agricultural land uses because it protects soils from erosion and helps to maintain proper habitat conditions for important wildlife (Richter, 2000; Manson, 2004; Pérez-Nieto, Valdés-Velarde, et al., 2005).

Yet smallholder coffee production is now threatened by complex web of interrelated processes of socioeconomic and environmental change. Regarding the socioeconomic changes, the major issues include (1) changes in the structure of international coffee markets (in the last half of the 1990s) has caused an increase in supply as well as a decrease in price of coffee around the world (Ponte, 2002); (2)

uncertainty whether global markets can absorb any new growth in supply; and (3) contractions in state support for agricultural services (such as credit and inputs) and commercialization (such as control of prices and marketing) have resulted in increasing vulnerability of small producers to economic marginalization and other social problems associated with rural poverty (Eakin, Tucker and Castellanos, 2006).

With regards to the environmental changes, the major issues include (1) an unusual sequence of El Niño-Southern Oscillation events resulting in prolonged drought conditions, combined with the devastating impacts of hurricanes (Mitch in 1998, and Stan, in 2005), have severely stressed smallholder production; (2) conversion of coffee land to pasture, maize and bean production, sugar cane or even residences raises concerns over the potential for increased rates of soil degradation, further fragmentation of forest cover and increased susceptibility to losses from landslides and torrential rainfall events; and (3) climate change may threaten the long-term viability of coffee in Mesoamerica (Gay Garcia, Estrada, et al., 2006; Baker and Haggar, 2007).

3. Building the ANP model

3.1 Expert consultation

The complexity of SES-SCFM compelled for the implementation of an iterative expert consultation that resulted in the corresponding ANP structure (shown in Figure 1 and explained below in detail). First, we convened a group of experts (from academia and of non-governmental organizations) with experience in working in the coffee sector of Mesoamerica to a two-day workshop in March on 2008. The experts' domains of expertise included rural sociology, agronomy, economics, agroecology, biology, geography, and anthropology. Prior to the workshop, the participants elicited the drivers of change and possible adaptations to these drivers by farm households.

During the workshop, an initial ANP structure was developed by organizing the drivers as elements within clusters. Using Superdecisions v.1.6.0 (downloadable from http://www.superdecisions.com/), the experts carried out the proper pairwise comparisons among linked elements. While the workshop resulted in a preliminary network and prioritization of drivers, another important outcome was the familiarization by the experts on the basics of the ANP, which in the subsequent steps enabled not only the inclusion of adaptations and capacities, but also the refinement of the initial SES-SCFM.

Following the workshop, consultations with experts continued through emailed questionnaires and responses. As a result of these consultations, new information was introduced and some elements and relationships in the initial model were modified, using the literature on smallholder adaptation to global change as the main theoretical reference. Any modification to the model was submitted for approval to the experts in successive consultations. This also produced the list of adaptations and capacities to be included into the SES-SCFM. The adaptations were categorized according to common classes of adaptive responses referred to in the theoretical and empirical literature (e.g., Siegel and Alwang 1999; Agrawal 2007), and took into account empirical work of the experts in Mesoamerica.

The determination of the specific domain of each capacity was based upon a livelihood framework (Scoones 1998). As such, the experts characterized capacities in terms of categories of assets or "capitals" which the household either owned or directly controlled (e.g., land, family labor), or to which the household had access (e.g., transport, credit).

Third, an email survey to the expert group using the AHP/ANP verbal scale was used to formalize and prioritize the relationships between the identified drivers and adaptations, and between adaptations and a list of household capacities.

Finally, the pairwise comparisons of each individual expert were integrated into the final model. In the case of high inconsistencies in the pairwise comparisons, extra consultations were performed to ask the experts to refine and re-evaluate their assessments until the required level of consistency was achieved.

3.2 Description of the SES-SCFM

The SES-SCFM was organized in two subsystems: one for drivers and adaptations, and another one for capacities (Figure 1). The two subsystems simplified the construction of the model and enabled a cogent and comprehensive examination of the elements and linkages of the whole system.

The subsystem for drivers and adaptations consisted of a control hierarchy and two of sub-networks. The control hierarchy related elements in the clusters *Socioeconomic* and *Ecological* to the goal of the model, namely "to describe the primary drivers of change, adaptations and capacities of the Mesoamerican coffee system."

From this control structure, two separate hierarchies were constructed, apparent in the third hierarchical level, to desegregate the drivers of change. Elements in cluster *Socioeconomic* were decomposed into clusters *Cultural Patterns* and *Public Policy* (each with 4 elements), and *Market* and *Social Conflict* (each with 3 elements); and elements in cluster *Ecological* were decomposed as well into clusters *Biological* and *Climate* (each including 2 elements).

Within the hierarchy *Socioeconomic*, outer dependencies connected two elements of cluster *Cultural Patterns* to elements of other clusters: *Religious Diversity* to *Access to Production Processes* (in cluster *Social Conflict*), and *Participatory Governance* to element *New Markets* (in cluster *Market*). These linkages reflected the indirect influences of social organizations on the importance of the adaptations.

Hierarchical structures *Socioeconomic* and *Ecological* were connected through the linkage between elements *Labor Scarcity* (in cluster *Markets*) and *Rising Incidence of Pests/Disease* and *Declining Soil Fertility* (the latter in cluster *Biological*) reflected the observation that pest problems, particularly the incidence of *Hypothenemus hampei*, and soil erosion increases with changes in management associated with poor coffee prices.

In the fourth hierarchical level, only *Agricultural*, *Markets*, *Temperature* and *Precipitation* were decomposed into the corresponding clusters. The linkage between elements *Commodity Promotion* and *New Markets* create a feedback from cluster *Agricultural* to cluster *Markets*.

In the fifth hierarchical level, cluster *Adaptations* included 10 elements – each representing an observed response of farmers to distinct stressors. These were evaluated in relation to specific drivers (the 32 elements) included in the clusters of hierarchies above.

The subsystem for capacities consisted of five clusters (shown within the red squared in Figure 1) that included the assets or capitals that were thought to be necessary for farmers to engage in specific adaptations:. *Human* (with four elements), *Financial, Natural*, *Social* (with three elements), and *Physical* (with two elements).

The two subsystems were integrated into a unified structure through linkages between elements in cluster *Adaptations* and elements in the five clusters of capitals. In this way, the capitals were evaluated with respect to the corresponding adaptation, as shown in Table 1.

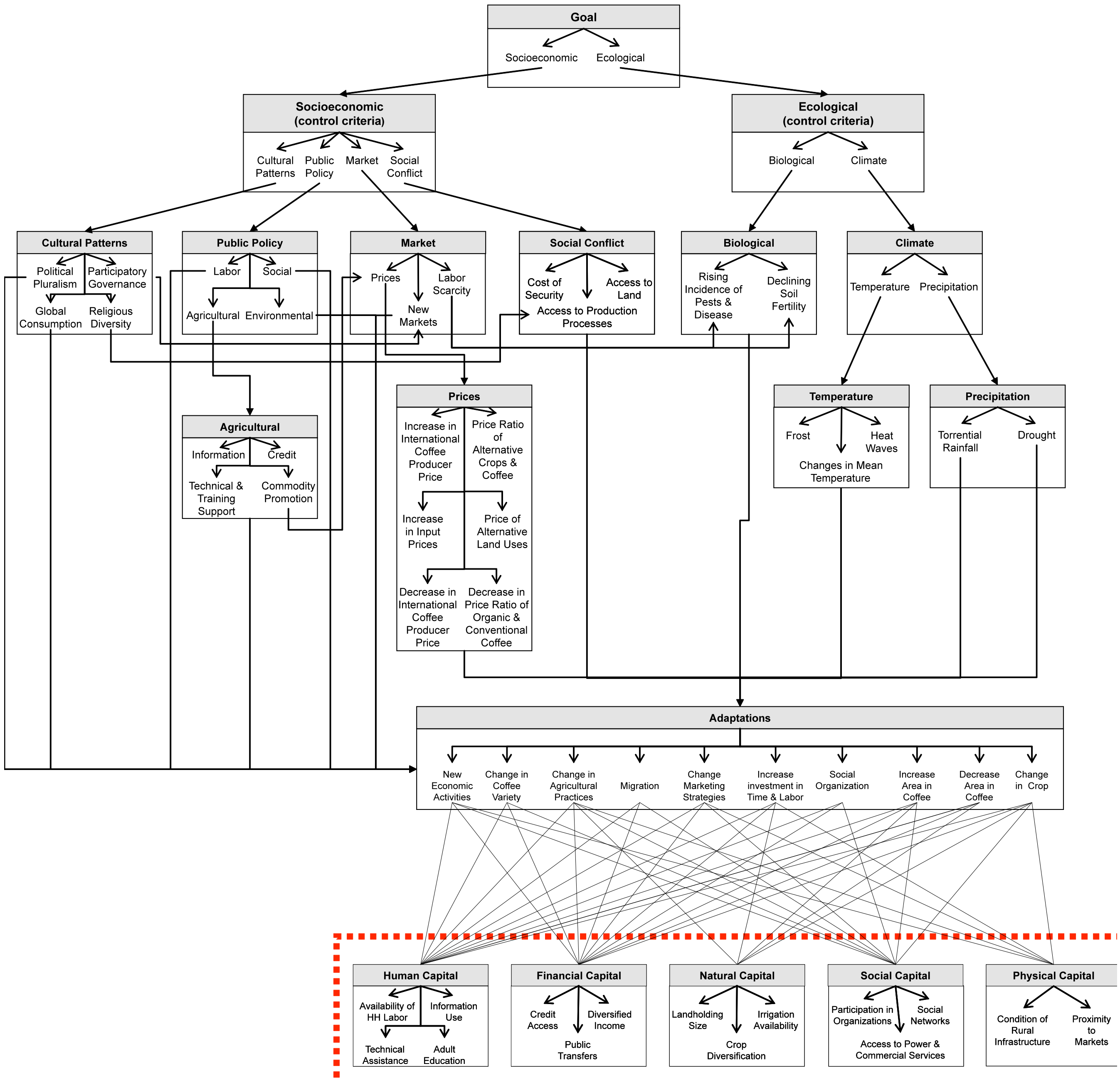

Figure 1. Network of the Socio-Ecological System of Small Coffee Farmers in Mesoamerica. Top: subsystem for drivers and adaptations shown as two hierarchical structures (Socioeconomic and Ecological); bottom (red rectangle): subsystem for capacities shown as clusters representing the five sets of capitals (Human, Financial, Natural, Social, and Physical)

Table 1. Linkages between elements in clusters *Adaptations* and *Capacities* or *Capitals*.

Capital	Element	Adaptation									
		A	B	C	D	E	F	G	H	I	J
Financial	Credit access	●	●	●	●		●	●	●	●	
	Diversified income	●	●	●		●	●	●	●	●	
	Public transfer	●	●	●	●	●	●	●		●	●
Human	Adult education	●		●	●					●	●
	Availability of HH labor					●	●	●	●	●	
	Information use	●	●	●	●			●	●	●	●
	Technical assistance	●	●	●	●		●	●		●	●
Natural	Crop diversification	●		●		●					
	Irrigation availability					●	●	●			
	Landholding size						●				
Physical	Condition of rural infrastructure	●		●	●			●		●	
	Proximity to markets				●			●		●	
Social	Access to power & commercial services	●	●	●	●		●			●	
	Participation in organizations	●		●	●		●			●	●
	Social networks		●						●	●	●

Adaptations:
A = Change in Agricultural Practices; B = Change in Coffee Variety; C = Change in Crop; D = Change in Marketing Strategies; E = Decrease Area in Coffee; F = Increase Area in Coffee; G = Increase Investment in Time & Labor; H = Migration; I =New Economic Activities; J =Social Organization

4. Results

4.1 Drivers

The pairwise among elements of subsystem drivers and adaptations resulted in the normalized weights shown in Table 1.Regarding the control criteria at the second hierarchical level, element *Socioeconomic* was judged twice as important as *Ecological*. This difference in importance was reflected in the prioritization of the elements at the third hierarchical level. Considering the global weights at this level, the priority values of these elements were categorized according to their relevance for describing the SES-SCFM, resulting in the following classification: “Most Important,” *Market and Public Policy*; “Important,” *Climate*; and “Least Important,” *Cultural Patterns* and *Social Conflict* (this categorization was based on the Weber-Fechner law , using a $(1 + r) = 2$; see Saaty, 2001).

A similar classification of elements at the fourth and fifths hierarchical level showed that category:

- “Most Important” included three elements, one of sub-network *Socioeconomic —New Markets* — and one of sub-network *Ecological —Torrential Rainfall*;
- “Important,” three elements of sub-network *Socioeconomic — Decrease in International Coffee Producer Price*, *Credit*, *Social Policy* — and three elements of sub-network *Ecological — Declining Soil Fertility*, *Drought* , and *Rising Incidence of Pests & Disease*; and
- “Least Important,” the remaining 21 elements of the two sub-networks.

The categorization of *New Markets* indicated that the experts considered the relevance of a "shift in state" of the coffee sector. This driver was defined as the set of institutional arrangements and benefits associated with selling coffee in niche markets (e.g., gourmet, organic, fair trade, bird friendly). Thus it implied not only an effect in the structure of the sector as a whole, but also the opening up of new technological, institutional, and socio-cultural relationships for farmers. Similarly, the categorization of *Decrease in International Coffee Producer Price* and *Credit* reflected the price shock and the contraction of financing at the end of the 1990s, which altered labor availability, input use and livelihood structures throughout the region. Likewise, the categorization of *Torrential Rainfalls* and *Drought* reflected the lasting influence of climate shocks, both in terms of production outcomes and human welfare of the population of coffee producers. *Declining Soil Fertility*, *Temperature*, *Drought*, and *Rising Incidence of Pests & Disease.*

Table 2. Normalized weights resulting of pairwise comparisons among elements of subsystem related to the drivers of change (the first hierarchical level is now shown and corresponds to the overall goal).

Hierarchy Level: Control Criteria 2nd	Element 3rd	Driver 4th	Driver 5th	Local Weight
Socio-economic (0.67)	Social Conflict (0.06)	Access to Land		0.72
		Access to Production Processes		0.11
		Cost of Security		0.17
	Market (0.42)	New Markets		0.47
		Labor Scarcity		0.06
		Prices (0.47)	Decrease in Price Ratio of Organic & Conventional Coffee	0.21
			Increase in Input Prices	0.17
			Price Ratio of Alternative Crops & Coffee	0.08
			Price of Alternative Land Uses	0.04
			Increase in International Coffee Producer Price	0.11
			Decrease in International Coffee Producer Price	0.37
	Cultural Patterns (0.10)	Religious Diversity		0.08
		Participatory Governance		0.20
		Global Consumption		0.28
		Political Pluralism		0.44
	Public Policy (0.42)	Environmental Policy		0.13
		Agricultural Policy (0.59)	Information	0.06
			Technical & Training Support	0.17
			Credit	0.64
			Commodity Promotion	0.13
		Labor Policy		0.09
		Social Policy		0.19
Ecological (0.33)	Biological (0.33)	Rising Incidence of Pest & Disease		0.33
		Declining Soil Fertility		0.67
	Climate (0.67)	Precipitation (0.75)	Torrential Rainfall	0.67
			Drought	0.33
		Temperature (0.25)	Heat Waves	0.31
			Changes in Mean Temperature	0.11
			Frost	0.58

4.2 Adaptations

Based upon their global weights, the classification of the elements within cluster *Adaptations* showed that category:

- "Most Important" included two elements — *Change in Agricultural Practices* and *Social Organization*;
- "Important," one element — *Change in Marketing Strategies*; and
- "Least Important," seven elements — *New Economic Activities*, *Change in Crop*, *Decrease Area in Coffee*, *Increase Area in Coffee*, *Increase Investment in Time a& Labor*, *Migration* and *Change in Coffee Variety*.

The two elements in category "Most Important" reflected the relevance for the sector of adjusting inputs and technologies, and the emergence of social groups, cooperatives and small-business associations. Likewise, the element in category "Important" reflected the impact of selling the harvest to different agents, which might require changes in preparation and packaging.

4.3 Capacities

The classification of the elements within the five clusters describing the capitals showed that category:

- "Most Important" included four elements — *Public Transfers*, *Participation in Organizations*, *Credit Access*, *Technical Assistance*, and *Diversified Income*;
- "Important," two element s— *Access to Power & Commercial Services* and *Information Use*; and
- "Least Important," eight elements — *Adult education*, *Availability of Household Labor*, *Social Networks*, *Crop Diversification*, *Condition of Rural Infrastructure*, *Proximity to Markets*, *Irrigation Availability*, and *Landholding Size*.

The elements in category "Most Important" corresponded to those identified as particularly influential in the ability of households to engage in the primary adaptation strategies. These included the three elements of cluster *Financial Capital*, one of cluster *Social Capital* and cluster *Human Capital*. Likewise, the elements in category "Important" corresponded to clusters *Social Capital* and *Human Capital*

4. Discussion and Conclusions

There have been relatively few attempts to systematically document drivers of change in specific social-ecological systems for policy audiences. Thus, the modeling exercise described here is relatively unique in that it uses the ANP to elucidate not only hypothesized cause-effect relationships, but also to emphasize the systemic nature of social-ecological change. Despite that the modeling exercise reflects the limitations of knowledge and experience of the experts involved in the process, our results illustrate one of the main strengths of the ANP: Providing a systematic and rigorous framework for integrating divergent viewpoints and perspectives regarding complex socio-environmental systems.

The ANP enabled a cogent synthesis of the drivers, adaptations and capacities that affect individual coffee farm households across the Mesoamerican. Although we acknowledge that the results are not comprehensive in scope, results of the SEC-SCFM highlights highlight the main drivers, adaptations and capacities that can influence local-level decisions and outcomes.

Based upon the results of the SEC-SCFM, a synthesis of the coffee sector in Mesoamerica can be depicted as follows. There most important have contrasting impacts in the sector. The positive impact of driver *New Markets* on households across Mesoamerica is relatively well-documented in reports of development agencies, whereas the negative impact of driver *Torrential Rainfall* of coffee production has been evident in the aftermath of the numerous tropical storms and hurricanes that affect the region. These drivers of change lead to two main adaptations at the household level, namely *Change in Agricultural Practices* and *Social Organization*. In turn, implementing these adaptations presuppose certain capacities or capitals related to *Public Transfers*, *Participation in Organizations*, *Credit Access*, *Technical Assistance*, and *Diversified Income*.

As illustrated through the development of the SEC-SCFCM, the flexibility of the ANP is fundamental for achieving appropriate models of complex socio-environmental systems. First, the ANP facilitated the decomposition of the coffee sector in terms of interconnected sub-networks and subsystems. Second, the pairwise comparisons among elements required by the ANP simplified the continuation of the expert consultation process after the workshop. In this way, the experts were able to exchange the precise information regarding their judgments on the relative priority order of drivers, adaptations and capacities. In this way, the experts were able to collectively achieve a gradual refinement of the SEC-SCFM at distance through the e-mail.

Based upon the results of the SEC-SCFM, we generalize that the ANP is an effective tool for effectively addressing the challenges of achieving a collective representation of complex socio-environmental systems. As shown in our results, the strength of the ANP resides in its flexibility for handling complex network structures. We find this capability essential for to achieving proper representations of socio-ecological system that involve intricate linkages among socioeconomic, biological and physical attributes.

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