Examining the sustainability and development challenge in agricultural-forest frontiers of the Amazon Basin through the eyes of locals

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Abstract

The Amazon basin is the world's largest rainforest and the most biologically diverse place on Earth. Despite the critical importance of this region, Amazon forests continue inexorably to be degraded and deforested for various reasons, mainly a consequence of agricultural expansion. The development of novel policy strategies that provide balanced solutions, associating economic growth and environmental protection, is still challenging, largely because the perspective of those most affected- local stakeholders- is often ignored. Participatory Fuzzy Cognitive Mapping (FCM) was implemented to examine stakeholder perceptions towards the sustainable development of two agricultural-forest frontier areas in the Bolivian and Brazilian Amazon. A series of development scenarios were explored and applied to stakeholder derived FCM, with climate change also analysed. Stakeholders in both regions perceived landscapes of socio-economic impoverishment and environmental degradation driven by governmental and institutional deficiencies. Under such abject conditions, governance and well-integrated social and technological strategies offered socio-economic development, environmental conservation, and resilience to climatic changes. The results suggest the benefits of a new type of thinking for development strategies in the Amazon basin, and that continued application of traditional development policies reduce the resilience of the Amazon to climate change, whilst limiting socio-economic development and environmental conservation.

Key words: agriculture expansion, deforestation, stakeholder perception, fuzzy cognitive mapping, sustainable development strategies, Amazon basin.

1 Introduction

The Amazon basin is the world's richest biological reservoir and a globally significant carbon sink. Since the 1960's, deforestation and forest degradation has weakened the basin's natural function, causing a substantial loss of biodiversity, provision of ecosystem services, and changes in local and global weather patterns (Harris et al., 2012; Haddad et al., 2015; Zemp et al., 2017). Weak governments and political instability in Amazonian countries have reduced capacity to halt deforestation and related expansion of illegal activities. Recent increases in deforestation and megafire clearances reinforce the continued threatened state of the basin (Global Forest Watch, 2019). In addition, climate change will most likely lead to increased drought in the Amazonia, which will pose a further threat to the sustainability of the region (Malhi et al., 2008; Guimberteau et al., 2017). Future scenarios suggest a continuation of the current basin's precarious state (e.g. Folhes et al., 2015; Tejada et al., 2016), with Lenton (2011) proposing that ecological tipping points could be reached.

Agricultural and extraction activities are cited as major drivers of deforestation and forest degradation in the Amazon basin (Hosonuma et al., 2012; García et al., 2019). These activities have, in many cases, been supported by policies to encourage rural development whose lasting benefits are unclear (Rodrigues et al. 2009; Celentano et al, 2012; Oliviera et al., 2013; Weinhold et al., 2015). Policies concentrating upon agricultural intensification and resource extraction may provide economic gains (Le Tourneau et al., 2013; Ioris, 2016), but may also have negative long-term social and environmental impacts (Weinhold et al., 2015). Conversely, conservation policies aimed at preserving and restoring forest ecosystems have been implicated as drivers of negative socio-economic changes (Chomitz, 2007; Carr, 2009; Guedes et al., 2014). These findings point toward the trade-offs in rural development objectives (McNeil et al., 2012), which increasingly focus upon socio-economic development through extracionist activities, or environmental conservation that excludes them. This dichotomy has dominated the political and developmental discourse of the Amazon for decades, with Nobre et al. (2016) suggesting they represent the basin's established development model.

The state and outlook of the Amazon basin, along with the limitations of the entrenched development policies, beg the question as to whether other options exist to transition the basin towards a sustainable, less conflict-ridden state. Nobre et al. (2016) promote a "third-way", driven by investment in technical and social capital, catalysing a localised industrial revolution. Guedes et al. (2014) offer that increased access to technical assistance may permit communities to develop more sustainable livelihoods, converting natural capital to social. Lapola et al. (2014) infer that technological improvements along with sustainable land management could drive sustainable land use shifts. A further possibility may lie in the results of recent analyses, which suggest that socio-economic development in forest frontier regions of Brazil has uncoupled from environmental exploitation and degradation, due to policy development and implementation (e.g. Weinhold et al., 2015; Caviglia-Harris et al., 2016). Tritsch and Arvor (2016) propose that recent improved governance structures have begun to address competing rural development goals. Godfray et al. (2011) and Newton et al. (2013) advocate that governance and institutional improvements could provide a balance between conservation, development, and climate change mitigation. The implementation of such reforms, or similar strategies could offer an interesting discussion point to reassess the emphasis of

rural development policies. However, consideration of novel strategies would be reliant upon modelling and testing, offering scope for scenario development and application. The development of such scenarios could aid in quantifying the impacts of potential strategies in improving factors within the three main rural development dimensions, social, economic, and environmental, whilst simultaneously mitigating climate change.

5   However, in analysing the Amazon basin, development strategies and scenario development, it is easy to ignore the perspective of those most likely to be affected- local stakeholders. Stakeholder involvement can provide new interpretations to previously studied problems, improve the understanding of complex situations, reduce unforeseen consequences of policy implementation, and empower local communities (Folhes et al., 2015; Olazabal and Pascual, 2016). A number of methods are available to incorporate stakeholder perspectives into such analyses (e.g. Verburg et al., 2014), including Fuzzy

10   Cognitive Mapping (FCM). FCM involves the development of a visual representation (map) of perceptions of a given system (Kok, 2009) and permits the application of scenarios to these maps (Vasslides and Jensen, 2016).

Using stakeholder derived information collected from workshops performed in forest frontier communities of the Bolivian and Brazilian Amazon (the province of Guarayos in Bolivia and the Tapajós National Forest in Brazil), this paper aims to identify how such communities perceive the present state of their region using FCM. In general, deforestation and the

15   expansion of the agricultural frontier in Bolivia have been less well studied than in Brazil, probably due to its relatively recent development (Pacheco, 2006; Killeen et al., 2008). However, increasing efforts are being made to study both parts of the Amazon basin. Further, this analysis will apply development scenarios (including climate change) to these FCM, analysing how each region reacts to the sustainability and development challenge, changing socio-economic, political, and climatic conditions.

2 Description of the study area

Given the size of the Amazon basin, two study sites with similar problems were selected within the framework of the ROBIN[1] project. Firstly, the Province of Guarayos (20,029 km^2), in the northwest corner of the Department of Santa Cruz in lowland Bolivia; the second, the Tapajós National Forest (5,449 km^2) in the western part of the State of Pará (municipalities

25   of Belterra, Placas, Rurópolis and Aveiro), in northern Brazil (Fig. 1).

Figure 1 here

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[1] The research project ROBIN (The Role of Biodiversity in Climate change Mitigation) (2011-2015), funded by the European Union Seventh Framework Programme under grant agreement No 283093, aims at quantifying interactions between terrestrial biodiversity, land use and climate change potential in tropical Latin America. More information can be found at https://cordis.europa.eu/project/rcn/100815/reporting/.

The Province of Guarayos (henceforth Guarayos) is located in the transition zone between the humid Amazon forest and the dry Chiquitano forest. It has a tropical climate and hosts important protected forest areas, such as the 'Reserva Nacional de Vida Silvestre Ríos Blanco y Negro' (dating from 1990). In the vicinity of theses protected areas lives the Guarayos indigenous community (a branch of the Guaraní), whose livelihoods depend on fishing, hunting, and gathering fruit, as well

5 as the cultivation of rice, pineapples, bananas, manioc, and other crops. The extraction of wood is limited, with only informal timber networks in place (Albornoz et al., 2008). Since 1996, land is collectively owned and managed by the Guarayos through a 'community land of origin', which has contributed to the sustainable conservation and utilisation of forests. However, legal uncertainty surrounding the system of land tenure in Bolivia, coupled with increasingly frequent arrivals of large-scale farm operators in the area, have resulted in highly conflicted situations, with illegal appropriation of common

10 lands and environmental degradation (Killeen et al., 2008; Stavenhagen, 2009). Agricultural is main employer for the Guarayos, being the major source of income for households, in this region of elevated poverty. Soya dominates both winter and summer cultivation, followed by sunflower, maize, rice, and sorghum (INE, 2015).

The Tapajós National Forest (henceforth Tapajós) is located at the heart of the Amazonian rain forest in Brazil. The climate is humid tropical and the natural vegetation is dense terra firme (upland) tropical moist forest (Dubois, 1976). Tapajós has

15 been protected since 1974 (Decree nº 73.684, February 19 of 1974), and is classed as an IUCN category VI protected area (IBAMA, 2004). Most of the population live along the Tapajós River, in well organised communities of 'ribeirinhos' (or Caboclos, which derived from theintermingling between the first European colonialists and the Amerindian populations). These communities have historically been very active in governance processes. During the 30-year period (1980-2010), they held an important resistance movement to avoid eviction and gain land tenure and resource rights. This movement was

20 pioneering in Brazil and led to a commercial community forest management system that has attracted both national and international attention (Bicalho and Hoefle, 2015). Despite this, the 'ribeirinhos' face difficult living conditions, with poor access to social services. Logging is the main economic source for the population, who subsist on very low incomes subsidised by small-scale farming activities (manioc, beans, and corn), fishing, hunting, and non-logging activities (eco-tourism and the sale of wood-latex-leather handicrafts). Most residents are dependent on government transfer payments

25 (Hoefle, 2016). The environment and the protected areas inhabited by the 'ribeirinhos' are increasingly threatened the expansion of intensive agriculture and cattle grazing areas coming mainly from the neighbouring Cerrado and the development of infrastructure (highways and dams) for the acceleration of growth (Fearnside, 2007; Verburg, 2014; Fearnside, 2015; Gibbs et al., 2015).

3 Methodology

3.1 Participatory development of FCMs

The FCM concept is attributed to Kosko (1986) who provided the fuzziness to earlier cognitive mapping techniques (Tolman, 1948; Axelrod, 1976). Maps developed from FCM visualise components and their causal relationships within a
5   system (Kok, 2009) as perceived by an individual, or group. This mapping can be developed through participatory interviews or workshops, where components (called nodes, concepts or vertices) representing features of the system are identified, and causal relationships (links, connections or arcs) between them are defined through weighted and meaningful directed linkages (Gray et al., 2015). The weight of these relationships range from -1 to +1 (Özesmi and Özesmi, 2004) and define the scale of influence (positive or negative) that one component has upon another.

10   The causal networks developed from FCM have considerable flexibility for analysis in a range of fields (e.g. Papageorgiou et al., 2013) and support scenario development (e.g. Kok, 2009). The methodology can incorporate multiple stakeholders' perspectives and knowledge (Gray et al., 2015) through combination of multiple maps into one 'community' map (Fairweather, 2010) or development of a single map by a group of stakeholders (Varela-Ortega et al., 2014), aggregating and incorporating distinct perspectives of different groups into a single vision. Participatory development of FCMs can improve
15   communication through the development of an open, neutral, and informal forum for participants to give their opinions. The FCM methodology can incorporate both measurable (e.g. deforestation) and qualitative concepts (e.g. awareness of environmental problems). FCM can provide useful output for data scarce problems or in areas where data it is difficult to obtain and can be complementary to quantitative models (Olazabal and Pascual, 2016). The results of FCM are semi-quantitative and can only be interpreted relative to other values within the system (Kok, 2009).

20   In this study, we use FCMs to visualise the perceptions of local stakeholders concerning the direct or indirect interactions of variables that influence the state of the local environments in both Guarayos and Tapajós. The steps implemented as part of the methodology are illustrated in Fig. 2.

Figure 2 here

In each of the case studies, two stakeholder workshops were held within the framework of the ROBIN project. In the first, and following the author's previous experience from a large EU project (SCENES) (Kok and van Vliet, 2011), we facilitated two focus groups of 12 to 15 persons each to ease the process of producing FCM. As much as possible, the two focus groups were equally balanced in terms of gender, age, and stakeholder group representation. Each stakeholder group included
30   representatives from the policy and private sectors, non-governmental organisations and scientists, thus covering a broad range of expertise on agro-forestry issues (Table 1).

Table 1 here

Each focus group developed its own FCM. Thus, the FCM developed represented stakeholder group knowledge (Ösezmi and Ösezmi, 2004). Participants were invited to offer their perspectives on the present state of the environment in the region and what they considered to be the key features and processes inherent to it. First, every participant was asked to write up to three factors in cards that they considered to contribute most to the present situation and explained their choices with the rest of the group. Following discussion, similar factors were clustered and new factors were identified and added to the original selection. After a final selection of factors was chosen, participants established links (arrows) among them and identified the sign of the links: positive (+) when an increase in one factor causes an increase in the other; and negative (-) when an increase in one factor causes a decrease in the other. Finally, they assigned values to these links indicating how strong they were using a scale within the range 0 (very weak) to ± 1 (very strong).

After the first stakeholder workshop and following Ösezmi and Ösezmi (2004), the two group maps from each case study were combined into one 'Case Study FCM'. As part of the combination process, components identified as representing similar features were merged, where possible. However, in combining components, conflicting connections were identified, normally involving the wording "Lack of…" In these cases, and following Vasslides and Jensen (2016), wording of the more prevalent component was kept, and connection weights were inverted appropriately.

The combined FCM was presented in the second workshop for enrichment, validation, and interpretation. Once the 'Case Study FCM' was agreed, a discussion on possible futures and sustainable strategies was held, serving as input for scenario development and simulation. To ensure continuity, care was taken that similar stakeholders (or stakeholder groups) were present in the second workshop.

3.2 FCM analysis

The two 'Case Study FCMs' were analysed following Reckien (2014) and Olazabal and Pascual (2016) considering their structure, dynamics, and the impacts of scenarios on their dynamics.

3.2.1 Structural metrics

As FCM are considered complex networks, the structural metrics here used to analyse them are complex network parameters commonly applied in the literature (see Table 2). Further, we also include two novel metrics for the measurement of centrality in FCM analysis: page rank (PR) and betweeness (Bw). Centrality is used to determine the importance or influence of a given node in the network. This concept was first introduced in sociology to quantify the influence of an individual in the whole social network (Freeman, 1978). In the two networks analysed (FCM of Guarayos and Tapajós) the ties among nodes have weights assigned to them, therefore the FCM are considered weighted networks and the centrality measures are weighted as well.

Table 2 here

Bw was first introduced by Freeman (1977) to quantify the control that an individual can achieve on the communication between other humans in a social network. PR was named after Larry Page (Page, 1999), and is used by Google Search to rank websites in their search results. While Bw measures the influence of a node within a network by calculating the number of times a node acts as an intermediary along the shortest path between two other nodes, PR calculates the probability of visiting each node if we were randomly 'surfing' the net.

3.2.2 Dynamic analysis

Besides the structural metrics of Table 2, the dynamic behaviour of the maps was also analysed to gain an insight into how components interact with each other, over multiple iterations (Gray et al., 2015). This analysis permitted comparison between the steady state values (Kosko, 1994) for each component, as well as the simulation of scenarios.

To calculate the steady state values and perform the dynamic analysis, each Case Study FCM was converted into an adjacency matrix (Tables S1 and S2), which was then multiplied by a state vector A (Eq. 1) over various iterations (k). According to Kok (2009), this calculation results in four potential dynamic outcomes: components return to zero, components continuously increase/ decrease, components continuously cycle, and components stabilise at a fixed value.

$$A_i^{(k+1)} = f\left(A_i^{(k)} + \sum_{\substack{j \neq i \\ j=1}}^{N} A_j^{(k)} w_{ji}\right) \tag{1}$$

Where $A_i^{(k+1)}$ is the value of the component C_i at iteration k +1; $A_i^{(k)}$ is the value of component C_i at iteration k; $A_j^{(k)}$ is the value of the component C_j at iteration k; and w_{ij} is the weight of the connection between components C_i and C_j.

The state vector A initially sets values for all components to 1 (Olazabal and Pascual, 2016), assuming all components are equally important and is multiplied against the adjacency matrix. The resultant vector is transformed to a logistic expression f, binding values between 0 and 1 (Kosko, 1986). This output vector is once again multiplied against the adjacency matrix, producing bound results between 0 and 1. This process is repeated until the dynamic outcome becomes evident, usually after 20-30 iterations (Kok, 2009).

Output (steady state) values close to 0 are representative of a strong decrease in the component, whereas values closer to 1 represent a strong increase (Reckien, 2014). The steady state values were interpreted as the current state of each component within the system (map) and were used as a baseline for interpreting the impacts of the scenarios.

3.3 Scenario development

Development of scenarios can provide a useful mechanism to evaluate the localised impacts of potential policy implementation. In the present study, scenarios that mimic traditional rural development policies are compared with novel

policy strategies, to analyse the system impacts on Guarayos and Tapajós. We designed and implemented four scenarios (Table 3). Two to replicate the binary development strategies traditionally applied in the region: agricultural development (Scenario 3); and environmental conservation (Scenario 4). A further two scenarios were developed: techno-social reforms (Scenario 1) to replicate Nobre et al. (2016) 'third- way' for rural development; and governance reforms (Scenario 2) cited by stakeholders to be fundamental for sustainable futures in the region (Varela-Ortega et al., 2015). We also analysed the cumulative effects of climate change on each of the scenarios.

Following Reckien (2014) and based on discussions with stakeholders, we translated each scenario into the analysis through the manipulation of individual component state vector values (A of Eq. 1: Sect. 2.3.2) (Table 3). For each scenario, different components were identified as being directly affected by the scenario implementation. For these selected components, their values were fixed between 0-1, depending upon the scale of the scenario's impact. A strong increase in the selected component was translated by a state vector value of 1, whilst a strong decrease was set to 0. Intermediate values represent less intense increases or decreases. All other components had their values set to 0.

Table 3 here

The output values for components under each scenario were then compared to their baseline values, with differences suggesting the relative impacts of each scenario. Further, the effects of the four development scenarios were also tested under the conditions of climate change, where the climate change component was fixed to 1.

To determine the wider impacts of the scenarios on the system, cumulative impacts for each scenario were analysed. To do so, components were categorised as positive, negative, or neutral (Reckien, 2014; Olazabal and Pascual, 2016) (Supplementary Table S1). Categorisation of components was based upon the perception of the role that each component would have in developing more sustainable regions. Components were categorised to recognise the equal importance of a reduction in a negative component, as an increase in a positive one, when considering the cumulative impacts of the scenarios. As with Reckien (2014), an aggregated impact value was calculated as the sum of: increases in positive components and decreases in negative components (from baseline to scenario).

It should be noted that the output results of FCMs are semi-quantitative. As such, outcomes can only be used to determine impacts on components, relative to other components, rather than absolute changes (Özesmi and Özesmi, 2004; Kok, 2009). Impact comparisons can only be made within the system and cannot be compared with absolute indicator values (Reckien, 2014; Devisscher et al.,2016).

4 Results

4.1 Structure analysis of FCM

Analysis of the two Case-Study FCMs demonstrated structurally similar systems (Table 4), with divergent contents (Fig. 3, 4 and 5).

Table 4 here

The two maps have comparable component numbers and similar densities of 0.052 (Guarayos) and 0.048 (Tapajós). The density difference may suggest that stakeholders in Tapajós perceive greater causal relationships between components. According to Özesmi and Özesmi (2004) this may offer greater possibilities to elicit change within Tapajós, compared to Guarayos. The complexity of the Guarayos map (0.57) was almost double that of Tapajós (0.33), suggesting that Tapajós is a more hierarchical system (Özesmi and Özesmi, 2004), with more transmitting components. This hierarchical lean is reflected in the components of the Tapajós map (Fig. 5), dominated by political and institutional concepts, whilst the Guarayos map (Fig. 4) appears more heterogeneous.

A first look at the results obtained in Bw and PR (Table 4) shows that the maximum Bw value in Guarayos is double than in Tapajós, 0.21 and 0.09 respectively, as we observed with Complexity. In both cases the highest Bw corresponds to Deforestation. Meanwhile PR maximum values are more similar in both case studies being higher in Tapajós than in Guarayos. Studying the values distribution for both metrics (Bw and PR) in percentage of components, it is possible to compare both cases. With respect to Bw (Fig. 3a), the highest six values are quite differentiated from the rest, in Guarayos showing a range from 0.05 till 0.21. These correspond with ordinary components: Agricultural Expansion, Climate change, Illegal logging, Lower crop yields and Deforestation. In the case of Tapajós, there is only one differentiated value corresponding to Deforestation. With respect to PR (Fig. 3b), both cases present several differentiated values that are visualized in the network (Fig. 3 and 4) for a deeper analysis.

Figure 3 here
Figure 4 here
Figure 5 here

Stakeholder perceived both systems as dominated by environmental problems, with deforestation and biodiversity loss having the highest page rank value in Guarayos and Tapajós. It is also important to note, the importance of poverty and low crop yields in Guarayos and forest products value and population purchasing power in Tapajós. For stakeholder in Guarayos, deforestation is the most influential component (highest outdegree, see Table S2) driving climate change, soil erosion, and biodiversity loss (Figure 4), whereas in Tapajós deforestation was perceived as the most influenced component (highest indegree, see Table S3) affected by amongst others: infrastructure projects, lack of public policy, and agricultural expansion (Fig. 5). In Tapajós, stakeholder depicted a lack of efficiency in policies for subsistence farmers as the factor with the greatest influence (highest outdegree, see Table S3), causing incomplete production chains, lack of technical capacity, and

access to viable economic activities (Fig. 5). Components including contamination and biodiversity loss were found in both maps to have high indegrees (see Tables S2 and S3), suggesting their sensitivity to other components.

In Guarayos and Tapajós the aggregated page rank of the component groups was dominated by the environmental and economic groups, followed by political, social, and technical. In both maps, the environmental grouping is the most heavily influenced and sensitive group with the highest group indegree values. The components identified as transmitters (square components) were largely political and economic, mostly defined as ineffective or with negative connotations, with the use of words such as "Lack of..."or "Poor..." The influence of these components in driving the situation in both regions (Fig. 4 and 5) is supported by their outdegree values (Tables S2 and S3). The sensitivity of environmental components was once again demonstrated by the majority of receiver components (diamonds) being environmental.

Despite the differences in components within each map there was still overlap between them, with 15 of the 61 total components representing similar concepts (environmental degradation, worsening socio-economic situations, and poor governance). This suggests that despite the maps being developed in distinct regions and with unique stakeholders, there is some continuity in the problems that afflict both regions and potentially the basin as a whole.

4.2 Dynamic analysis of FCM

4.2.1 Baseline situation

Dynamic analysis of the aggregated maps (Fig. 6 and 7) demonstrate significant overlap, despite the ~2000km that separate the case studies. Both regions (Guarayos and Tapajós) are characterised by worsening environmental degradation and apparently bleak socio-economic opportunities for local communities, coupled with low institutional safeguards.

Figure 6 here

Figure 6 characterises Guarayos as a region where environmental degradation is high, facilitated by low (and declining) application of the forest law and poor (and worsening) compliance with land zoning, coupled with low socio-economic opportunities. The system is dominated by increasing contamination, deforestation, loss of biodiversity, soil erosion, fires, poverty and agricultural expansion.

Figure 7 here

The situation in Tapajós (Fig. 7) depicts a similarly degraded system, where environmental conditions are deteriorating, facilitated by limited economic opportunities, and poor environmental monitoring. Tapajós is dominated by loss of environmental services and biodiversity; and increasing contamination, deforestation, infrastructure projects, and agricultural

expansion. Contrarily, socio-economic opportunities for locals are apparently diminishing with reducing value of forest products and limited access to viable economic activities. Further, monitoring of environmental degradation is inhibited by limited environmental monitoring.

4.2.2 Scenario outcomes

5   Figure 8 establishes the aggregate effects of the four development strategies on the mapped system. The values for the components fixed within each scenario have not been included, to highlight the subsequent systemic impacts of changes to components fixed within each strategy.

Figure 8 here

The governance strategy was responsible for the greatest 'desired' change in both Guarayos and Tapajós, with the agricultural development strategy causing the biggest 'undesired' change. The techno-social and conservation strategies also resulted in desirable changes.

A more detailed description of the individual impacts of the scenarios on components in both systems is given below, with

15   the extent of component changes shown in Supplementary Fig. 1 and 2. In general, implementation of these strategies results in greater changes to individual components in Guarayos than in Tapajós, which may be attributable to the higher density of the Guarayos map.

The *governance strategy* results in the greatest systemic relative changes and some of the greatest changes to individual components. This may demonstrate the integrated nature of governance components and their connectivity within both

20   systems. The strategy encourages reductions in environmental degradation across the two systems including deforestation, logging, and forest fires. It also drives socio-economic improvements reducing poverty, increasing access to financial aid and viable economic alternatives, improving population purchasing power in Tapajós and reducing the inequality of benefits in Guarayos. In Tapajós, it also elicits considerable improvements in the technical capacity of the region.

The *techno-social strategy* encourages a suite of positive changes to both systems, reducing environmentally degrading

25   activities, whilst providing simultaneous economic development. In Guarayos poverty is reduced, along with reductions in contamination, deforestation, illegal hunting, and logging. The strategy provides similar reductions in environmental degradation in Tapajós, with large reductions in deforestation and fires, whilst increasing population purchasing power and improving the value of forest products. Further, it also encourages greater social organisation and political participation, demonstrating a potentially beneficial unforeseen knock-on effect of such reforms.

30   The *conservation strategy* has limited impacts across the two systems, fomenting change only on environmental components. In Guarayos it reduces deforestation, whilst in Tapajós it reduces deforestation as well as other environmental degrading activities including; forest fires, logging, deforestation, and biodiversity loss.

The *agricultural development strategy* encourages substantial differences in the responses of the two systems. In Guarayos, crop yields improve with the expansion in both agriculture and grazing expansion, and results in reductions in poverty. Further, it also encourages positive environmental change with reduced illegal logging, hunting and fishing. However, in general environmental conditions worsen greatly with for example deforestation increasing, along with contamination, soil erosion, loss of biodiversity and destruction of pampas. In Tapajós, the rural development strategy results in no socio-economic benefits, but encourages considerable environmental degradation with deforestation, forest fires, loss of environmental services and biodiversity and contamination all increasing.

Figure 9 demonstrates the sensitivity of the systems under each scenario, whilst experiencing continued climate change, with some scenarios demonstrating greater resilience than others.

Figure 9 here

Figure 9 reveals that the governance reforms (and to a lesser extent techno-social reforms) may provide the most effective and resilient means of instigating regional improvements, even under climate change. Guarayos is more heavily influenced by climate change than Tapajós, which considering the page rank of climate change in both systems (Fig. 4 and 5) may have been expected. In Guarayos, the effect of climate change was so great that despite the conservation strategy the overall state worsened, compared with the baseline. In Tapajós, the impacts of climate change were still notable, but not to such an extreme extent as to further worsen the situation of the region. In both Guarayos and Tapajós, the agricultural development strategy offered the least resilient development strategy.

5 Discussion

5.1 The Amazon as mapped by Stakeholders

The utility and flexibility of Fuzzy Cognitive Mapping to elicit a stakeholder-derived interpretation of the present state of two forest frontier regions of the Amazon basin has been demonstrated in this analysis. FCM afforded the combination of knowledge from regional experts and local community members, offering the opportunity to improve and enrich the understanding of these regions, whilst providing a low-resolution demonstration of their present state. We also outline the potential to include novel network analysis metrics into parsing out the current situation of the Amazon. The highest values in PageRank and Betweeness are useful to detect the key components in the network. The use of FCM also facilitated the use of scenarios to analyse how these regions may react to development strategies, and climate change.

Despite the two maps reflecting systems on opposite sides of the Amazon basin, they yielded strikingly similar results. Stakeholders in both Bolivia and Brazil mapped systems plagued by environmental degradation, with weak social and governance support structures, inhibiting local community benefits. The perceived lack of effective governance is apparently

incongruent to the contemporary literature, which suggests recent improvements in the governance model (World Bank, 2016). The presence of inequality, poverty, and deforestation is consistent with the paradox of poverty in resource rich systems (Ioris, 2016), with stakeholders appearing to characterise the same "...landscapes of impoverishment..." as Ioris (2016, p. 187). Stakeholders in both Bolivia and Brazil identified similar barriers to development, with poor governance and conflicting policy measures inhibiting widespread socio-economic development, and hindering environmental conservation, supporting previous findings (Simmons et al., 2007). Further, the inconsequential nature of climate change for stakeholders in both cases was unexpected, considering its already noted impacts (and potential future impacts (e.g. Malhi et al., 2008; Spracklen and Garcia-Carreras, 2015). This unanticipated outcome may support the findings of Brondizio and Moran (2008), who suggest that the memory of climatic changes is short-lived. This finding may also reflect the distinct cultural and linguistic meaning or representations of climate changes (e.g drought, flooding) across the two sites. However, Varela-Ortega (2014) found that stakeholders considered climate change a fundamental component in the future of both regions and in Tapajós in the present.

5.2 Encouraging positive change in the Amazon

Implementation of the suite of scenarios affected substantial and variable changes. Governance and institutional reforms appear to offer the most effective means of transitioning Amazonian regions towards more sustainable 'desirable' states, even under the conditions of climate change. The positive effects of governance and institutional reforms are unsurprising considering the constraining effect (McNeil et al., 2012) that poor governance can have in inhibiting sustainable development, with its effects well documented in the Amazon (e.g. Rodrigues-Filho et al., 2015). The results evidence the liberating effect that improving institutional capacity can have in instigating desirable social, economic, and environmental change. These multi-dimensional benefits apparently confirm the transversal nature of institutions and governance in the context of sustainable development (McNeil et al., 2012). The positive impacts of governance have precedence in the Amazon, where institutional and governance improvements have encouraged environmental conservation (Nepstad et al., 2014; Tritsch and Arvor, 2016) and socio-economic development (Caviglia-Harris et al., 2016). Further, the literature widely supports the need for strong governance and institutions with Müller (2014), Verburg et al. (2014b), and Høiby and Zenteno-Hopp (2014) contending that the likelihood for long-term environmental conservation is slim under poor governance conditions. Lapola et al. (2014) promotes the need for policy enforcement and institutional support to encourage sustainable development, whilst Guedes et al. (2014) propose that pathways towards future environmental conservation can be founded upon investments in local institutions.

Techno-social reforms also represent an alternative strategy, driving environmental protection, economic development, and social improvements. In Brazil, the difference in desired change between this strategy and governance reforms was minimal, suggesting its considerable potential. These results support the vision of Nobre et al. (2016), where rural development is encouraged through social and technological reforms, with both environmental and social components improving. The

implementation of this scenario suggests that investments in technical capacity building and social reforms may reverse the poverty traps (Reardon and Vosti, 1995) in which stakeholders mapped both regions appear to be locked. Investments in social and technical reforms may have wider unforeseen benefits, improving societal attitudes towards natural capital conservation (Salahodjaev, 2016), aiding in flattening environmental Kuznet´s curves (Tritsch and Arvor, 2016), and driving

5   positive changes in agricultural methods (Assunção et al., 2013). Many of these points are suggested in the results of this analysis. However, this strategy was admittedly found to be susceptible to climate change, more so than the institutional reforms.

Traditional developmental strategies relying upon conservation or extractionist policy implementation have driven trade-offs across the Amazon (Le Tourneau et al., 2013). The impacts of these binary choices can be stark, with decision makers

10   having to make substantial compromises between environmental conservation and agricultural development (e.g. Manners and Varela-Ortega, 2018). The application of the conservation strategy had limited system wide impacts, resulting in environmental improvements, but offering little opportunity for socio-economic development, potentially confining local communities to conditions of poverty and limited development. Further, implementation of such a narrow strategy was found to be particularly susceptible to climate change. The application of this strategy, or one similar, may have little chance of

15   providing sustainable rural development without concomitant offering of economic alternatives for locals, or the need for systems like Payments for Ecosystem Services to potentially alleviate poverty and encourage conservation (Pinho et al. 2014). Tejada et al. (2016) found that limiting future environmental degradation, specifically deforestation, in the Bolivian lowlands without offering new economic alternatives is unlikely.

The results also outline the negative effects of a strategy solely focussing upon agricultural development, with the long-term

20   benefits limited, especially under climate change. This strategy improved social factors like poverty and inequality (in Bolivia), but at a cost to local ecosystems in both Bolivia and Brazil. The outcomes of this scenario appear consistent with the literature, suggesting that purely agriculturally orientated strategies, without supporting policies may result in limited economic benefits for locals (Rodrigues et al. 2009; Ioris 2016) and some environmental costs (Weinhold et al., 2015). Further, these results appear not to demonstrate the uncoupling of agricultural development from environmental degradation

25   as identified in Brazil (Caviglia-Harris et al., 2016). However, focussing solely upon the local-scale economic and social benefits of such extractive strategies, as touched upon by Celentano et al. (2012), may ignore their wider national developmental benefits.

In summary, application of the two traditional scenarios for rural development (agricultural development and environmental conservation) demonstrate the trade-offs in their application and their ability to improve regional economic, social, and

30   environmental conditions. Development of new strategies concentrating upon governance and techno-social reforms could instigate positive shifts in the trajectory of these regions, even under the effects of climate change. However, moving from the modelled world to the real, where implementation of such strategies requires: consideration of social acceptability; likelihood of implementation; willingness of politicians and institutions to reform; coherence with current policy landscapes; and funding availability may result in complications. Despite improvements in governance across many Amazonian

countries in recent decades (World Bank, 2016), implementation of the governance reform may be challenging, especially under increasingly turbulent political landscapes, exemplified by Brazil. Further, potentially intangible (in the short-term) and time-consuming governance and institutional reforms may be unpalatable for voter conscious and electioneering administrations. Governments wanting to appear proactive in terms of rural development may consider other, more palpable options. The benefits of institutional reforms may only be reaped in the long-term, by which time governments may have changed and the benefits of change lost for the implementing administration. This may highlight the space for market-based interventions to encourage more sustainable development (e.g Nepstad et al., 2014; Gibbs et al., 2015). Beyond this, strategies aimed at techno-social reforms may garner less systemic positive changes but offer more tangible actions for voters and governments alike, whilst fomenting positive change, even under worsening climatic conditions. However, the financial implications of such reforms must be considered, with them likely requiring significant and long-term public or private investments. However, such funding is invariably scarce (Ferraro and Pattanayak, 2006).

6 Conclusions

The use of FCM to visualise the perceptions of stakeholders across the Amazon basin has shown that on both sides of the basin, landscapes of socio-economic impoverishment and environmental degradation are present, driven to varying degrees by governmental and institutional deficiencies. Even under such abject conditions, these processes have been modelled to be theoretically reversible through application of governance and well-integrated technical and social reform strategies. These strategies were found to encourage positive regional changes even under the pressure of climatic change. However, what is apparent in both regions is that a continuation of the current rural development programmes cannot continue, with these results showing that concentration on only conservation or agricultural development policies would reduce the resilience of both regions to climate change, whilst also providing limited socio-economic development and continued environmental degradation.

Author contribution

The conceptualisation and methodology design were done by CVO (PI of Spain's research team in the ROBIN project) and IB. The development and implementation of the stakeholder workshops were done by IB, CVO, LGM and MT. AT carried out the mathematical analysis of FCM. RM performed the simulations and supported the scenario development and processing of results. IB and RM prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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Table 1: Stakeholder workshops held in Guarayos (Bolivia) and Tapajós (Brazil).

Case Study	Workshops	Nº Stakeholders	Stakeholder Group	Name of stakeholder
Guarayos (Bolivia)	First: 30th January 2013	30	Policy/Administration	Autonomous Government of Santa Cruz (GDASC) Authority and Social Control of Forest and Land (ABT) Forestry Services Department of Natural Resources (DIRENA) Department of Agriculture (SEDACRUZ)
			Private sector	Indigenous Guarayos Forestry Association (IRARAI) Farmers Federation Guarayos Timber Association (AMAGUA) Guarayos Cattle Association (AGUAGUA)
	Second: 18th June 2014	27	Non-governmental organisation	Organisation Centre of Guarayo Native People (COPNAG) Guarayos Indigenous Women Centre (CEMIG) Ascensión Inter-Ethnicity Centre (CIEA) Rio Blanco and Rio Negro Wildlife Reserve
			Research	Tropical and Agricultural Research Centre (CIAT) Instituto Boliviano de Investigación Forestal
Tapajós (Brazil)	First: 27th November 2013	23	Policy/Administration	Ministry of Agriculture (MAPA) Federal Government Agency- Chico Mendes Institute for Biodiversity Conservation (ICMBIO) Institute of Technical Assistance and Rural Extension (EMATER)
			Private sector	Soybean production company
	Second:28th November 2013	26	Non-governmental organisation	Indigenous Communities (Flona Tapajós-Communidade do Maguari) Hope Foundation (IESPES) The Nature Conservancy (TNC)
			Research	The Federal University of Western Pará (UFOPA) EMBRAPA Eastern Amazon Luiz de Quieroz College of Agriculture (ESALQ-USP)

Table 2: Structural metrics of Fuzzy Cognitive Maps analysed.

Structural Metric	Definition	Source
Outdegree $(od(vi))$	Cumulative total of transmitted connection weights from each component (horizontal cumulative sum within adjacency matrix).	Wasserman and Faust 1994
Indegree $(id(vi))$	Cumulative total of received connection weights to each component (vertical sum within adjacency matrix).	Wasserman and Faust 1994
Receiver variables (R)	Components that receive connections from other components but does not influence others through outward connections (components with zero $od(vi)$)	Özesmi and Özesmi 2003
Transmitter variables or drivers (T)	Components that solely influences other components through outward connections but does not receive connections (components with zero $id(vi)$)	Özesmi and Özesmi 2003
Ordinary variables (O)	Components that both influence and are influenced upon within the system	Özesmi and Özesmi 2003
Density (D)	Number of connections (C) divided by the maximum number of possible connections between a number N of components $$D = \frac{C}{N(N-1)}$$	Devisscher et al. 2016; Hage and Harary, 1983
Complexity (CM)	Number of receiver components (R) divided by the number of transmitters (T). A receiver being a $$CM = \frac{R}{T}$$	Devisscher et al. 2016; Özesmi and Özesmi 2004
Betweeness (Bw)	Betweenness is a centrality measure of influence of a node within a network. This measure quantifies the number of times a node acts as an intermediary along the shortest path between two other nodes.	Freeman, 1977; Brandes, 2001
Page Rank (PR)	Used to determine a node's relevance or importance. PageRank value for a node u is dependent on the PageRank values for each node v contained in the set Bu (the set containing all nodes linking to node u), divided by the number L(v) of links from page v. $$PR\,(u) = \sum_{v \in B_u} \frac{PR(v)}{L\,(v)}$$	Page et al., 1999; Berkhim, 2005; this study

5 **Table 3: Overview of the simulated scenarios.**

Scenario	Description	Case Study					
		Guarayos			Tapajós		
		Component	Value change (with respect to steady state baseline)	Scenario fixed value	Component	Value change (with respect to steady state baseline)	Scenario fixed value
1. Governance Reform	Introduces institutional and governance improvements to the system, with policies widely implemented and governmental communication and efficiency improved	Lack of understanding, application and coordination of laws	Decrease	0.4	Lack of governmental co-ordination	Decrease	0.4
		Poor administration by community leaders	Decrease	0.3	Lack of efficiency in policies for subsistence Farming	Decrease	0.4
					Lack of public policy	Decrease	0.4
2. Techno-Social Reform	Considers a system in which investments are made in technical and social capital through capacity building, improvements in education and protection of traditional communities.	Lack of awareness of environmental problems	Decrease	0.2	Lack of environmental awareness	Decrease	0.2
		Land encroachment	Decrease	0.3	Lack of technical training and assistance	Decrease	0.3
		Loss of subsistence agriculture by Guarayos Communities	Decrease	0.3	Technical and productive capacity	Increase	0.8
					Lack of protection of traditional communities	Decrease	0.3
3. Agricultural Development	Encourages extractionist activities, such as agricultural expansion, encouraged to improve the socio-economic conditions of each region.	Agricultural expansion	Increase	0.9	Agricultural expansion	Increase	0.9
		Application of agricultural Law	Increase	0.8	Use of agrochemicals	Increase	0.9

		Agricultural intensification	Increase	0.8			
		Compliance with land zoning	Increase	0.8	Environmental monitoring	Increase	0.8
4. Conservation	Focusses solely upon conserving the environment, with no consideration of socio-economic development.	Application of forest law	Increase	0.8			

Table 4: Guarayos and Tapajós fuzzy cognitive maps indices. Standard deviations shown in brackets and maximum values of the centrality indices.

Indices	Guarayos	Tapajós
Components	29	32
Transmitters	7	9
Receivers	4	3
Ordinary	18	20
Connections	44	50
Average Connection Weight (SD)	0.57 (0.26)	0.61 (0.22)
Connections per Component	1.52	1.56
Density	0.052	0.048
Complexity	0.57	0.33
Betweeness	0.21	0.09
PageRank	0.13	0.17

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5   **Figure 1: Location of the case study sites (the Province of Guarayos in Bolivia and the Tapajós National Forest in Brazil). Case studies shaded in brown. The Department of Santa Cruz (Bolivia) shaded in dark blue and the State of Pará (Brazil) in dark green. The extent of the Amazon Basin is outlined in red.**
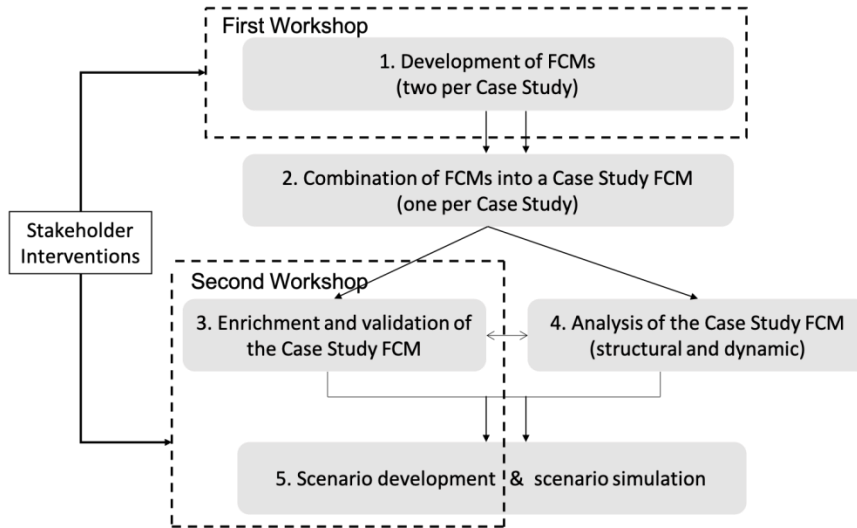
Figure 2: Methodological steps in the research.
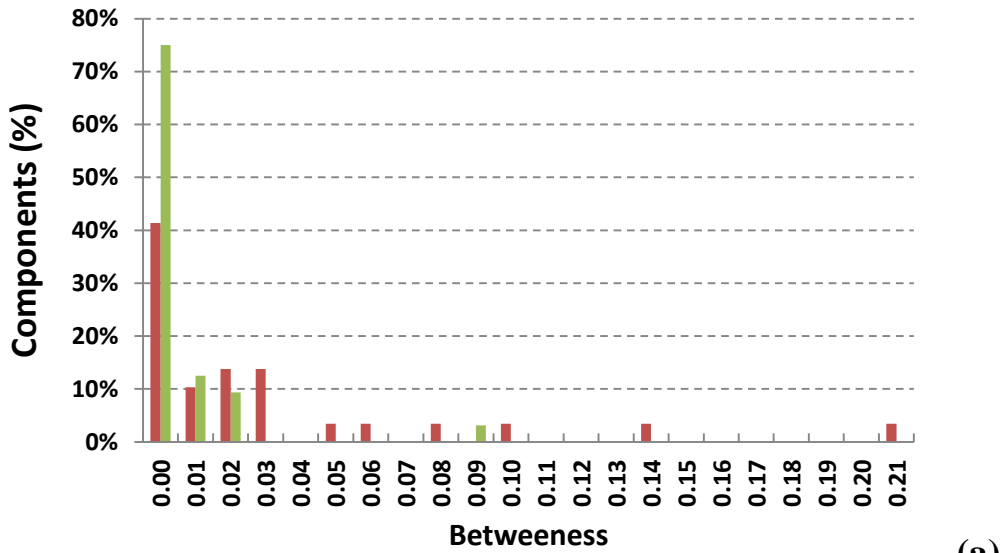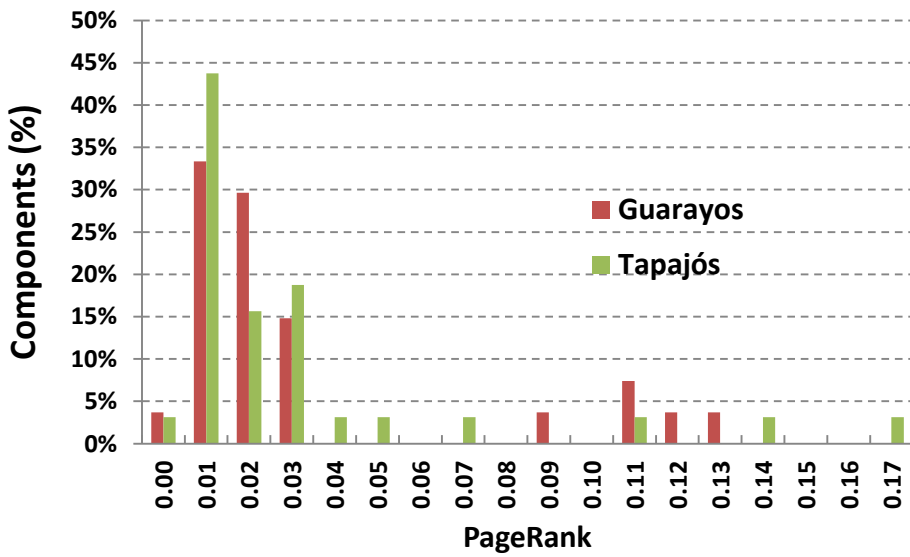
Figure 3: Frequencies of Betweeness (A) and PageRank values (B) in both case studies: Guarayos (red) and Tapajós (green)
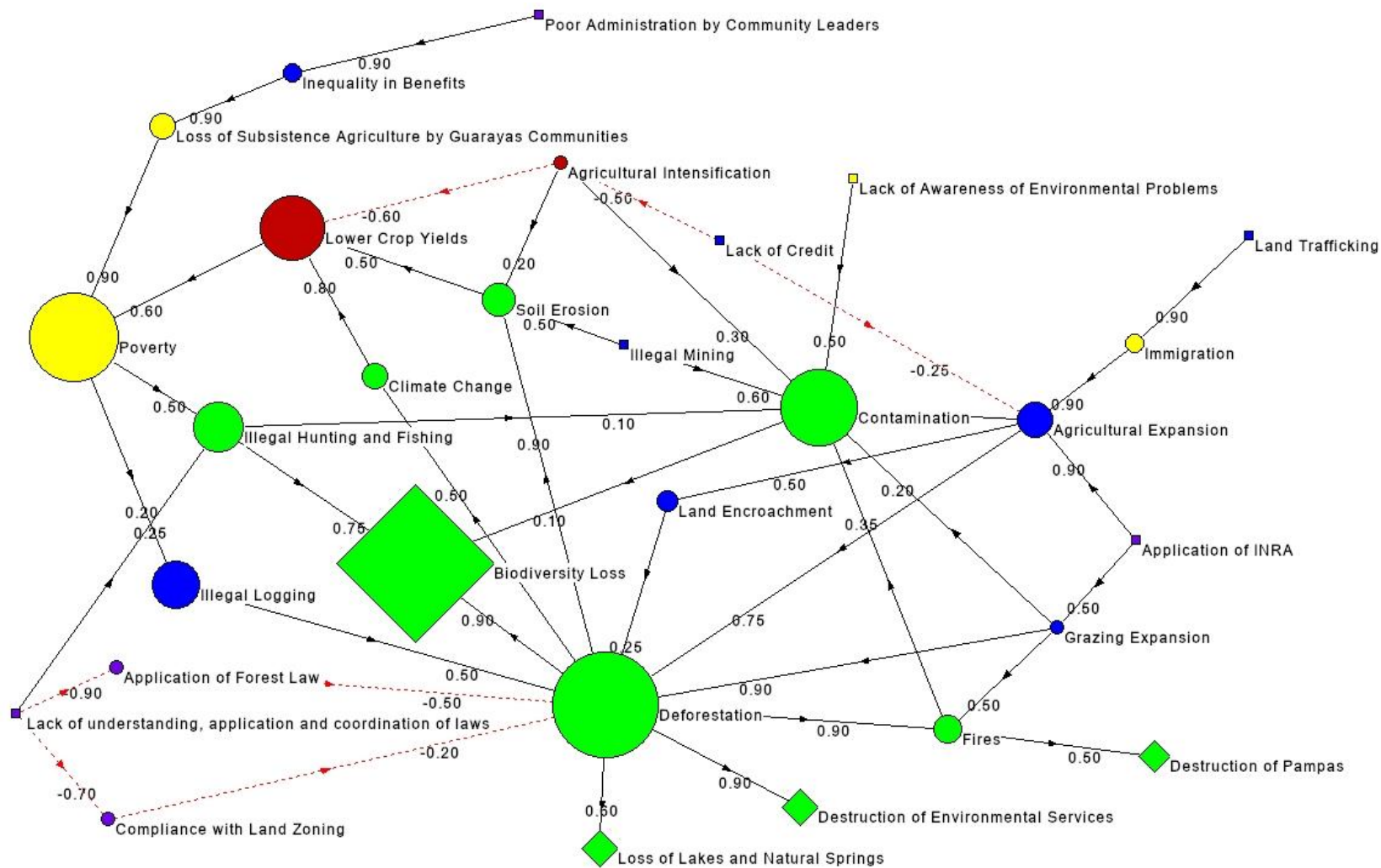
Figure 4: Network visualization of the Case Study FCM developed by stakeholders in Guarayos. Size of each component represents their page rank.
Solid black lines represent positive connection weights and red dotted lines negative. Shape of each component represents its type (square=transmitter,
circle=ordinary and diamond=receiver) and colours their grouping (green=environmental, blue=economic, yellow=social, purple=political/ institutional
and red=technical).
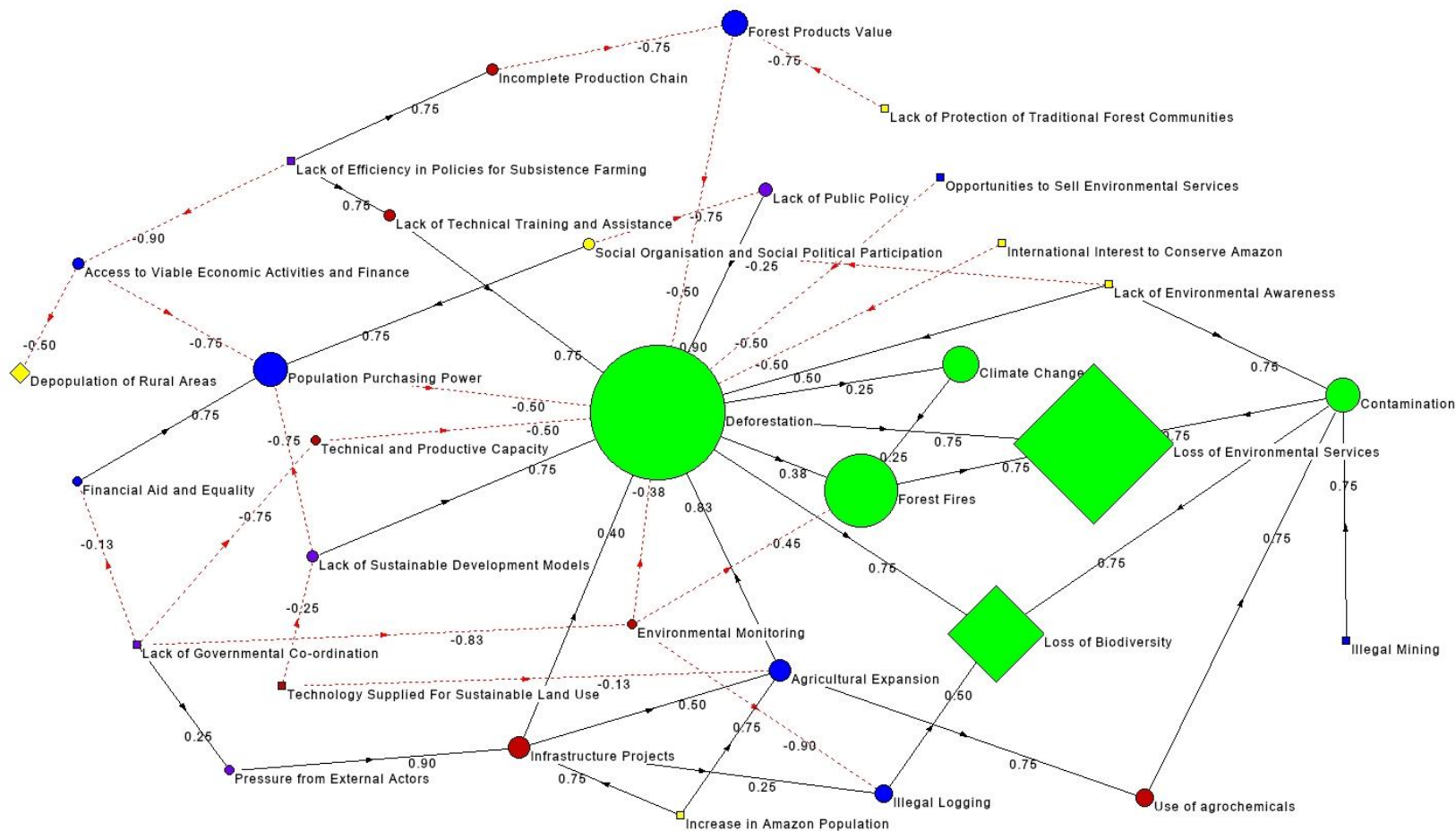
Figure 5: **Network visualization of the Case Study FCM developed by stakeholders in Tapajós. Size of each component represents their page rank. Solid black lines represent positive connection weights and red dotted lines negative. Shape of each component represents its type (square=transmitter, circle=ordinary and diamond=receiver) and colours their grouping (green=environmental, blue=economic, yellow=social, purple=political/ institutional and red=technical).**
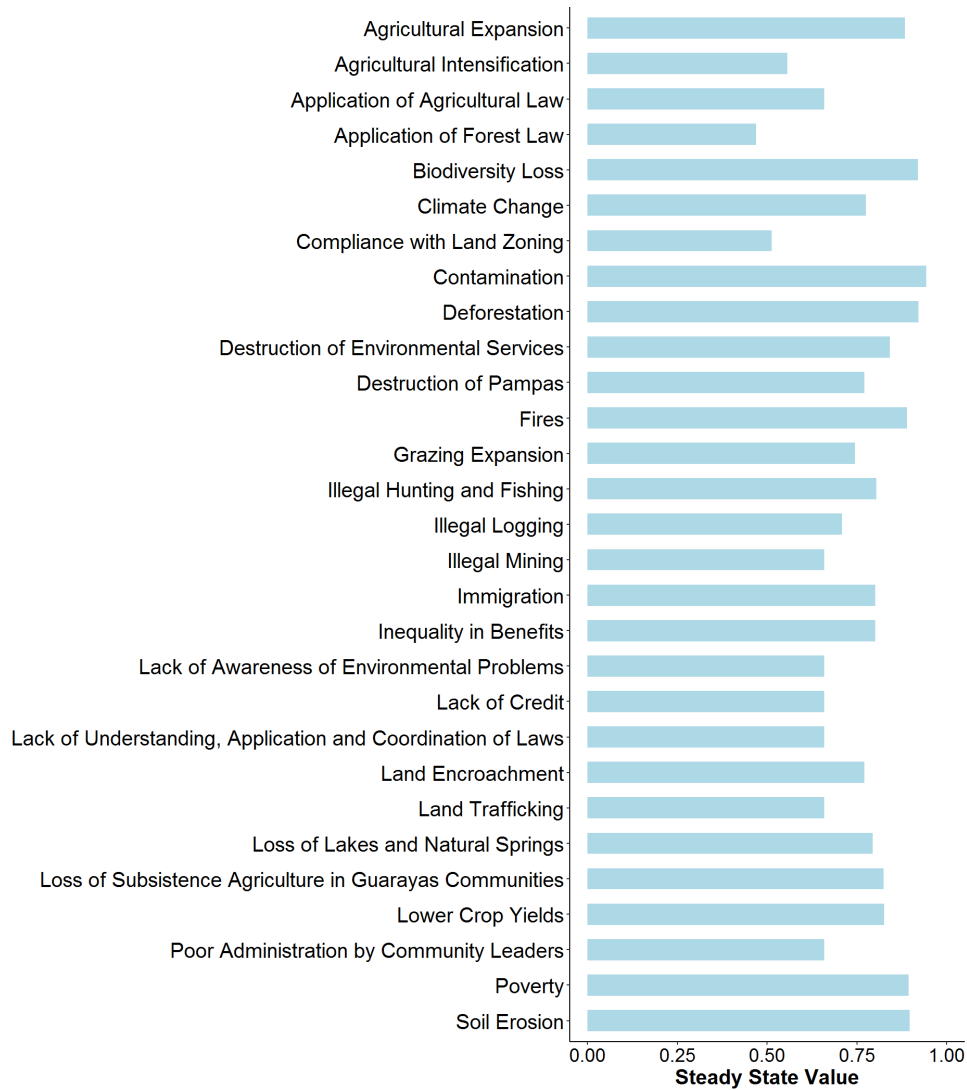
Figure 6: Component values for Guarayos Case Study FCM under steady state 'baseline' conditions. Values close to 0 represent a strong decrease in the component, whilst values closer to 1 represent a strong increase.
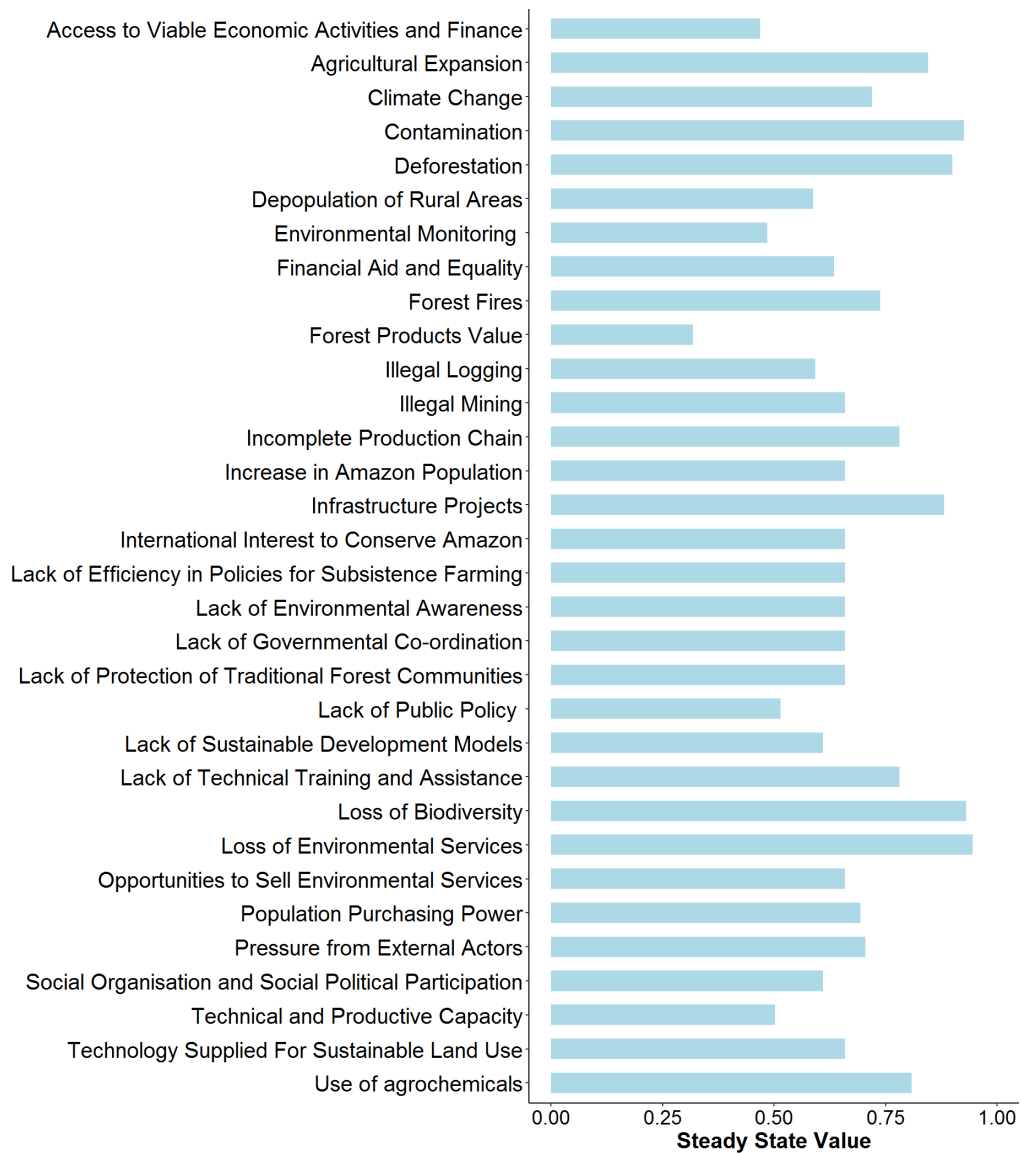
Figure 7: Component values for Tapajós Case Study FCM under steady state 'baseline' conditions. Values close to 0 represent a strong decrease in the component, whilst values closer to 1 represent a strong increase.
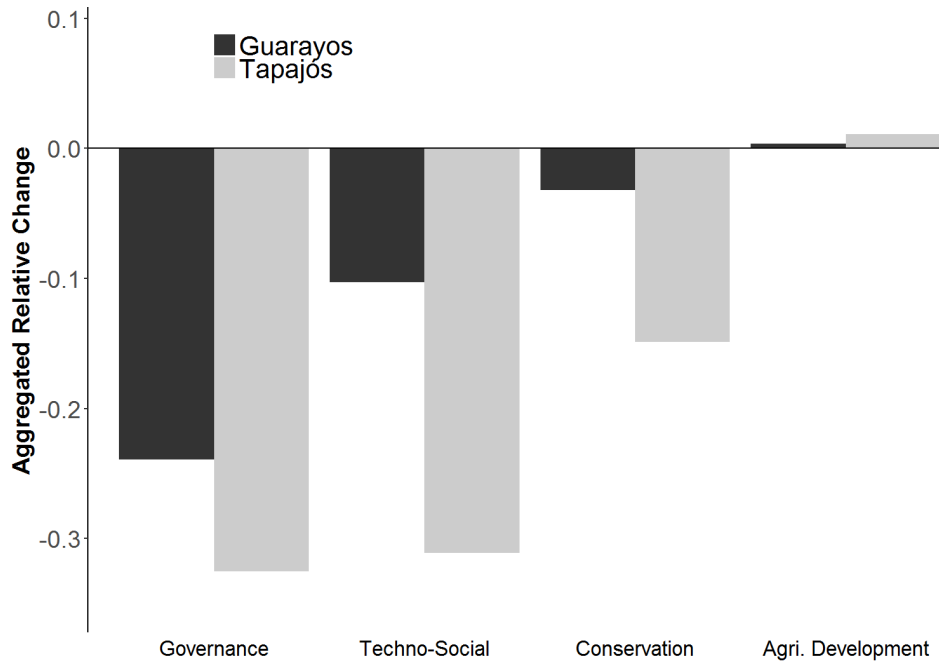
Figure 8: Aggregated relative change and response of scenarios, compared with baseline. Negative values represent a 'desirable' change in the system. Positive values represent an 'undesirable' change in the system.
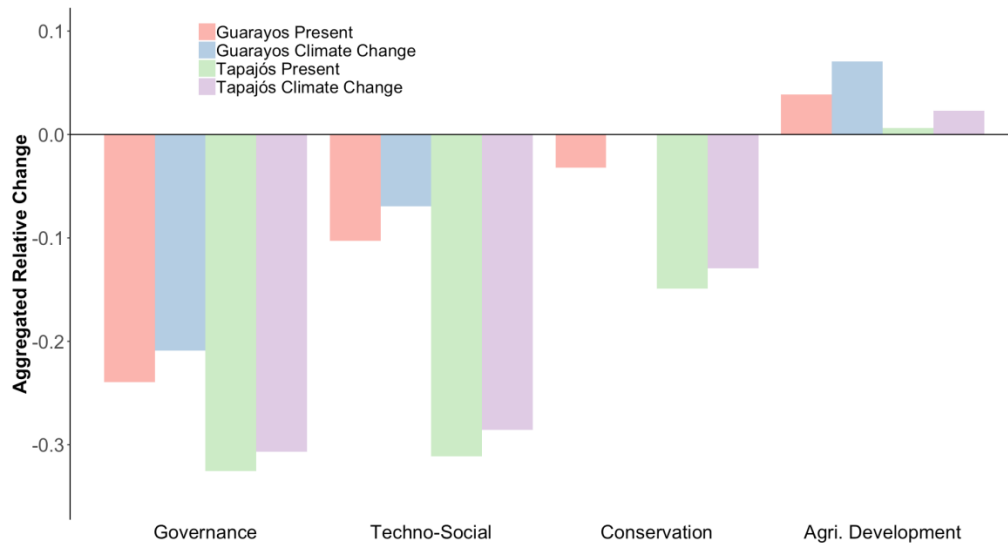
Figure 9: Aggregated relative change and response of scenarios under present climatic conditions, and climate change. Negative values represent a 'desirable' change in the system. Positive values represent an 'undesirable' change in the system.