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A social-ecological spatial framework for policy design towards sustainability: Mexico as a study case

Un esquema socio-ecológico y espacial para el diseño de políticas para la sustentabilidad: México como caso de estudio

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Resumen

No existen marcos espaciales integrados para evaluar los sistemas socio-ecológicos acoplados y para diseñar políticas públicas *ad hoc*. Utilizamos a México como caso de estudio para: i) desarrollar un marco espacial socio-ecológico, las socio-ecoregiones, ii) describir los patrones resultantes, y iii) explorar cómo este marco podría ser usado para el diseño de políticas hacia la sustentabilidad. Usamos las ecoregiones y el Índice de Desarrollo Humano para construir las socio-ecoregioness. Mostramos cómo el marco socio-eco-regiones refleja la heterogeneidad ecológica y social del país. Este marco resulta ser útil para diseñar políticas socio-ecológicas. Discutimos que este marco puede ser fácilmente desarrollado para otras regiones, a nivel mundial o local, y contribuir al desarrollo de políticas más integradas hacia la sustentabilidad.

Palabras clave

Socio-ecológico, ecoregiones, Índice de Desarrollo Humano, políticas públicas, manejo de ecosistemas.

Abstract

Integrated spatial framework to assess coupled social-ecological systems and design *ad hoc* public policies is still lacking. We used the country of Mexico as a case study to: i) develop a social-ecological spatial framework, the socio-ecoregions, ii) describe the resulting patterns, and iii) explore how the framework can be used for designing policies towards sustainabillity. Ecoregions and Human Development Index were used to build socioecoregions. We showed how the socio-ecoregions framework reflects the ecological and social heterogeneity of the country. This framework was shown to be useful to design social-ecological policies. We discuss that this framework may easily be developed for other regions at global to local scales and contribute to the development of more integrated policies towards sustainability.

Keywords

Social-ecologic, ecoregions, Human Development Index, public policies, ecosystem management.

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1. Introduction

The perspective of social-ecological systems has increasingly been adopted as an analytical framework to assess the interlinked dynamics of environmental and societal change. Conceptual frameworks and analytical tools for describing and understanding these social-ecological systems are increasingly being developed (Liu *et al.* 2007a; Carpenter *et al.* 2009). This perspective shows that societies strongly depend on ecosystems, but that at the same time human enterprise has profound impacts on ecosystems. Understanding the complex inter-relationships between the components of these complex systems is needed to identify which policies and technologies that can lead towards or away from their sustainable stewardship (Carpenter *et al.* 2012).

Integrating the social-ecological perspective beyond research and into the policy design arena faces the need to deal with multiple spatial scales. Initiatives such as the Millennium Ecosystem Assessment (MA, 2003), The Economics of Biodiversity (Sukhdev *et al.* 2010), ant the International Platform on Biodiversity and Ecosystem Services (Larigauderie *et al.* 2012) have been mainstreaming the strong interconnectedness between societies and ecosystems into the policy design. The global to supra-national scales associated with these initiatives strongly contrasts with the regional scale (hundreds to thousands of square kilometers) at which most social-ecological research has been occurring (Berkes *et al.* 2003; Alessa *et al.* 2008; Brondizio *et al.* 2009). An approach that can be used at a range of spatial scales is needed.

Integrating a social-ecological perspective into policy design also faced the need to adequately understand the role of context in shaping the characteristics and dynamics of such complex systems. The particular biophysical conditions as well as the history of society within a system strongly determines the particular characteristics of each social-ecological system, as well as the range of management and governance alternatives towards sustainability (Folke *et al.* 2005). Tools are then needed to assess those biophysical and social characteristics of contrasting social-ecological systems.

A set of tools that can be used at multiple spatial scales and that can inform on the biophysical and social characteristics of social-ecological systems are readily available. Conservation action has been relying on the identification of ecoregions (Omernik 1987; Olson and Dinerstein 1998), hotspots (Myers *et al.* 2000) and networks of priority areas for conservation (Ganz and Burckle 2002). Poverty reduction strategies and economic development priorities have relied on spatially explicit indicators of economic development (Auty 2001), GDP (Piazza 2006; Feige and Urban 2008), poverty indicators (Collier and Dollar 2002) and the Humand Development Index (Neumayer 2001; Neumayer 2012) to guide policy design. Other tools have assessed interactions between society and ecosystems, such as the global terrestrial anthromes or anthropogenic biomes (Ellis and Ramankutty 2008) or the global map of human impacts on marine ecosystems (Halpern *et al.* 2008), that can inform on legacies by human enterprise on these systems.

Yet, a truly social-ecological spatial framework should emphasize not only the conditions of ecosystems but also that of societies. Similar emphasis would be given to past and current characteristics of life-supporting systems as well as to historical and present conditions of society. While various approaches have been suggested for integrating ecological and societal information in spatially explicit platforms at the landscape scale (Rollings and Brunckhorst 1999; Alessa and Chapin III 2008; Alessa *et al.* 2008; Zhang *et al.* 2012) much less has been done at regional to national and global scales.

A social-ecological spatial framework that could be used to guide policy design would then rely on the classification of social-ecological systems based on available spatial frameworks to classify ecological and social systems. The delimitation of such contrasting social-ecological systems would rely on the use of spatial boundaries that differentiate regions with contrasting biophysical properties, i.e. those that allow classifying the biophysical world, as well as on the use of political boundaries, i.e. those that separate countries, states or municipalities. The characterization of the corresponding social-ecological system would change across spatial scales in a nested fashion, just like ecoregions or political boundaries among and within countries are. Such hierarchical approach would allow operationalization at nested spatial scales, to account for changes in social and ecological drivers across scales (He *et al.* 2010).

A particularly favorable case study for developing a social-ecological spatial framework is that of Mexico. There, multiple social (*e.g.* political, cultural, economic, social) and ecological (*e.g.* geological, climatic, biological) drivers operating at different spatial scales have contributed to an exceptional biological and cultural diversity (Sarukhán *et al.* 2009). They have also contributed to a current situation with highly heterogeneous welfare conditions. As in many countries, governmental initiatives have fostered the identification of priority areas for the conservation and management of Mexican terrestrial and aquatic ecosystems (Arriaga *et al.* 1997), as well as that of areas for most urgent social and development interventions based on marginalization, poverty and social exclusion (Sedesol 2010). Also, cross-sectorial initiatives (*i.e.* those that involve Ministries of Environment, Economy, Governance, Social Development) that simultaneously integrate ecological and social perspectives (*sensu lato*) into policy design are on the way (Boyd and Ibarrarán 2011). Yet no unified spatial framework for mapping social-ecological systems is available to date to guide such policy design.

In this paper, we aim at developing a social-ecological spatial framework for the case of Mexico. We: i) use widely used spatial ecological and social frameworks to build a socio-ecoregions map, and ii) describe the type of information provided by the map at two different spatial scales and resolutions, iii) provide an example of how the spatial social-ecological framework can be used for designing policies towards sustainabillity.

2. Methods

We developed an approach to build socio-ecoregions maps and show how they can be used to design policies following four steps: a) the identification of adequate ecological and social spatial networks that could be used as building blocks, b) the classification of the national territory into socio-ecoregions, c) the reproduction of the classification into socio-ecoregions at a different spatial scale (the state), and d) the exploration of how the socio-ecoregions map at the two spatial scales and resolutions could be used to design transversal policies.

2.1. Identifying the adequate ecological and social spatial framework

We aimed at obtaining maps that would allow for the characterization of contrasting social-ecological systems for which different policies towards sustainable stewardship would be designed. The first step was then identifying sources of information that could: a) be used as indicators of the ecological (*i.e.* past and current climate, soil and biodiversity conditions) and the social context (*i.e.* past and present socioeconomic conditions, past and present governance), b) be readily available at the spatial scales relevant to the variable and to the associated decision-making processes, and c) had been already used to guide policy design and thus widely recognized in the policy arena.

2.1.1. The ecological spatial framework. We searched for an ecological spatial framework that could account for abiotic conditions, landcover types, and biodiversity. We chose the ecoregions because they include all the above features and have been widely used in development policies directed to conservation (CEC 1997; INEGI-Conabio-INE 2008). The ecoregions spatial framework has a hierarchically nested structure; we chose the categories with the higher hierarchy to emphasize the main contrasts and avoid dissecting the country into a too complex mosaic. The Mexican ecoregions are: Mediterranean California (MC), Great Plains (GP), North American Deserts (NAD), Southern Semi-arid Highlands (SSH), Tropical Humid Forests (THF), Tropical Dry Forests (TDF) and Temperate Sierras (TS).

2.1.2. The social spatial framework. We searched for a social spatial framework that would be inform on the past and present socio-economic and governance context, but also that would most relevant to both ecosystem management decisions and policy design. Such indicator would need to summarize the societal conditions that underpin ecosystem management decisions (*e.g.* access to financial resources, markets, and technologies, income, infrastructure, property rights, local governance arrangements, cultural ties to the land) Carpenter *et al.* (2009), and provides information on different dimensions of the societal conditions and well-being (*i.e.* legacies, current conditions and capabilities for the future).

While no panacea was available to truly account for all the above requirement, we used the Human

Development Index (HDI), in this case the one adapted to Mexico (Sedesol 2010), as a proxy of some of the most critical drivers highlighted above. We considered this framework as acceptable for the following reasons. First, given that most decisions are made at the municipality level in Mexico (Cotler 2004), we used a framework with information available for each individual municipality. Second, the HDI has been widely used to guide the social development and poverty reduction agenda at the global level (UNDP 2010), and in Mexico. Third, it includes many societal indicators that are indirectly related to ecosystem management decisions. The HDI includes an Education Index, which can be linked to social capital, self-determination, and thus the range of choices for ecosystem management and economic enterprise. The HDI also includes per capita Gross Product, which is an indicator of the standard of living; this standard of living can be related to access to financial resources, technologies, inputs, and consumption levels. Fourth, it provides information on different dimensions of societal conditions. HDI includes indicators of health, nutrition and access to sanitation through Child Death Rate as an indicator of health, education as well as income; it thus provides a pulse of society beyond just mere GDP (Stiglitz *et al.* 2010).

Yet, the use of HDI is also limited. While HDI directly accounts for health, education and GDP, the links between poverty, access to technologies or credits, management approach, and needs from ecosystems are quite complex and occur at multiple interacting spatial and temporal scales (Bremner *et al.* 2010). Here, HDI is largely an indicator of context, suggesting that different contexts are associated to very different dynamics of the social-ecological system.

We grouped the HDI values available for each of the 2,454 municipalities of the country (INEGI 2005b) into four contrasting categories comparable to those used globally (http://hdr.undp.org/en/statistics/). The corresponding HDI categories were very high (HDI4), high (HDI3), intermediate (HDI2) and low HDI (HDI1). We chose not to use the world level threshold values for distinguishing among categories of HDI conditions but rather adapted them to Mexico to better emphasize the range of contrasting conditions that actually occur within the country. Also, rather than using the four quartiles (as done globally) we used K-means clustering to ensure that groups were internally consistent and showed the lowest variance between groups.

The resulting threshold values that define the separation between HDI categories are:

HDI1: 0.3-0.67
HDI2: 0.68-0.75
HDI3: 0.76-0.80
HDI4: 0.81-0.95

2.2. Classifying the territory into socio-ecoregions

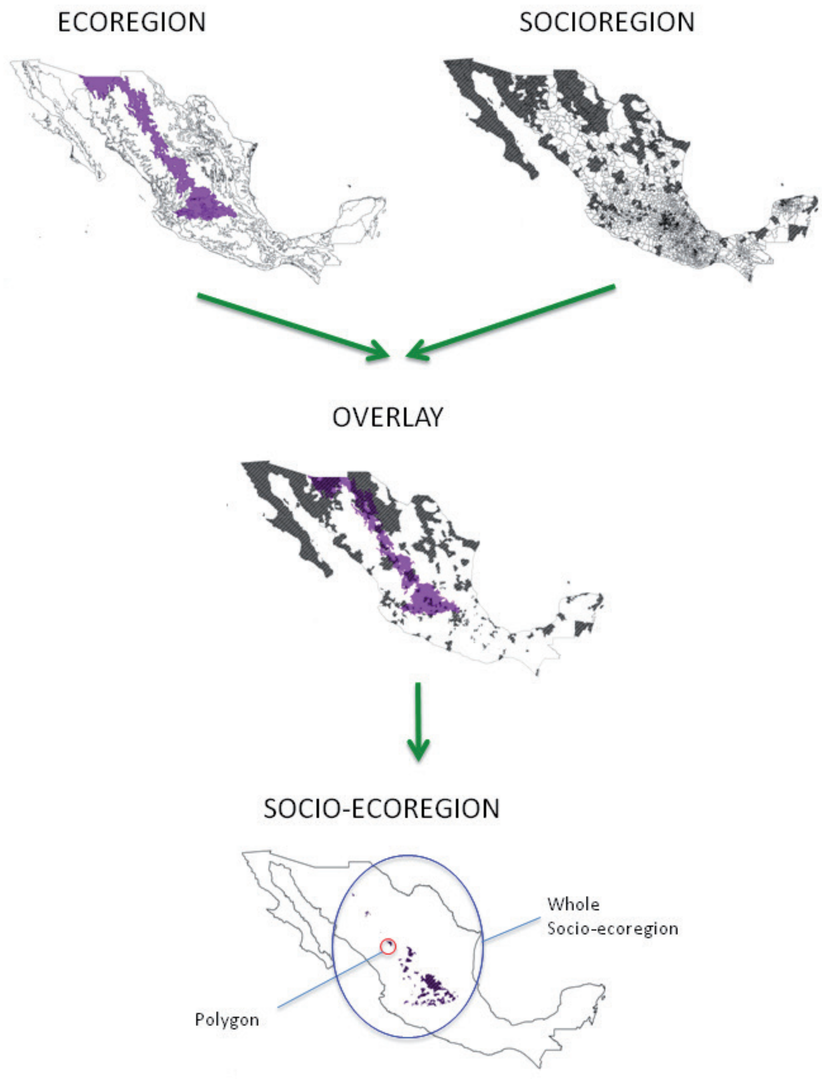
The second step was to classify the territory into contrasting socio-ecoregions. A socio-ecoregion is defined as a spatial unit that results from a unique combination of ecological and social conditions within that region. A socio-ecoregion reflects the fact that a particular social-ecological system can be distinguished from others because it has particular ecological and social conditions. The characteristics and dynamics of the social-ecological system are not necessarily well known, but it is assumed that its particular context makes it different to other systems found elsewhere (Liu *et al.* 2007b). Of course, this is a simplification and abstraction given that strong interconnections are likely to happen among nearby or distant social-ecological systems at a range of spatial scales (Liu *et al.* 2013)

The socio-ecoregion spatial framework resulted from simply overlapping ecoregions with the socio-regions, given by all municipalities within the HDI (Fig.1).

We first divided the country into the eight ecoregions. Within each ecoregion, we overlapped each municipality (or portion of a municipality, given by the ecoregion boundary) with each one of the four HDI levels, or socioregion.

A single socio-ecoregion is made up of multiple polygons. This is given by the fact that a single ecoregion can intersect multiple municipalities, and that many of those municipalities can correspond to the same a particular HDI condition (*e.g.* HDI4). Similarly, a single municipality with a particular HDI conditions can intersect multiple ecoregions, and can intersect various times the same ecoregion. We recognize here after the full socio-ecoregion as the sum of all polygons corresponding to a single combination of and HDI condition and an ecoregion (Fig. 1, lower map).

Fig. 1. Method for mapping socio-ecoregions. Each ecoregion is overlaid on each socioregion (i.e. a group of municipalities with the same Human Development Index condition); the areas where both intersect are then chosen and identified as the socio-ecoregion. Each of the polygons of that intersection can be analyzed separately; the sum of all these polygons is the whole socio-ecoregion.



The resulting socio-ecoregions were tagged according to their ecoregion (*e.g.* Mediterranean California, MC) and their HDI level (*e.g.* 4) to obtain their socio-ecoregion identity (*e.g.* MC4).

2.3. Applying the social-ecological spatial framework at two contrasting scales

The third step was to reproduce the identification of national scale socio-ecoregions at the scale of a single state. It is well-know that social-ecological systems are interconnected across spatial scales and the dynamics of the system cannot be understood without taking into account scales above and below those of studied (Walker *et al.* 2006). On the other hand, policy decisions need to be made at a range of nested scales, ranging from federal to municipal and below. Rather than assessing a wide range of scales we just show how the concepts developed here can be applied at different spatial scale than the federal one, and chose the state of Oaxaca for doing so.

Also, for illustrative purposes, we decided to use a different resolution (*i.e.* the area of the smallest unit analyzed). At the scale of a single state, rather than merging all the polygons corresponding to a unique combination of ecoregion and HDI condition we analyzed all the different. To illustrate the potential application of the framework at different spatial scales we focus on two scales: i) the whole country, and ii) one state. We focused on the state of Oaxaca, because of it is a state that is very heterogeneous both in terms of its ecological and social heterogeneity. There, the municipalities are very small and very contrasting in terms of their culture, history and governance, and most of the ecoregions are represented within the state.

2.4 Using the social-ecological spatial framework for designing transversal policies

The fourth step was to envision how the socio-ecoregions map at the two spatial scales and resolutions could be used to design transversal policies. We used two contrasting data sources that inform on the way ecosystems are managed: a) an ecosystem transformation gradient, and b) the identification of indigenous territories. We then linked these two data sources explicitly to the socio-ecoregions map to explore how policies aimed at more sustainable management of resources could be operationalized using the socio-ecoregions map. We focused largely on how examples on the way the results from the socio-ecoregions map would lead to policies that would be more adequate to the particular social-ecological context and relevant towards their sustainable stewardship.

2.4.1. Ecosystem Transformation Gradient (T). The attributes of social-ecological systems are given by the way that land is managed (Collins *et al.* 2010). The Land cover information is the most widely available and commonly used indicator of the interactions between ecosystems and societies (Ellis and Ramankutty 2008) and the management decisions that have been taken to foster particular ecosystem services (Carpenter *et al.* 2009).

Here we chose to assess a transformation gradient based on productivity and technification data, as well as land cover/land use data; seven categories ranging from extremely low (T1) transformation to very high (T7) transformation were identified. The approach was inspired by an assessment of productivity and technification of agricultural areas (Feige and Urban 2008) that classified agricultural lands based on technology use (fertilizer, tillage implements and improved seeds), and the destination of agricultural production (from subsistence to country wide commercialization). Data was drawn from the agricultural and land cover/land use data available for the country (INEGI 2005a; Acosta López 2007).

We classified the territory into the following transformation classes:

- T1-primary and secondary forests, scrublands, mangroves and natural grasslands;
- T2- rain-fed agriculture;
- T3- induced grasslands;
- T4- moisture agriculture (a semi-intensive agriculture that manages for the maintenance of soil moisture levels;
- T5- long-lived monocultures (*e.g.* fruits);
- T6- irrigated crops and
- T7- urban and permanent infrastructure.

We calculated the percentage of the total area of each polygon and each socio-ecoregion within each T class.

2.4.2. Indigenous territories (IT). Traditional ecological knowledge has been shown to be key for the adaptive governance of social-ecological systems (Folke *et al.* 2005). Areas with an elevated proportion of indigenous people and where the language has been conserved are likely to host a traditional ecological knowledge that is particularly knowledgeable of the context and particularities of their social-ecological system (Leff 2002). In particular in Mexico, indigenous territories often represent areas where local institutions and the rationale for management can be very different to that imposed by global, national and state level policies (Cabrero Mendoza 2000).

Indigenous territories were defined as those encompassing localities with more than 40% of the indigenous population that are contiguous (Boege 2006). These areas where the indigenous population tend to be moderately to strongly dominant preserve some of the traditional institutional arrangements to manage their resources. The Mexican government recognizes many of these traditional institutional arrangements as "traditional uses and customs". Such arrangement are respected at municipal level even if conflict with other state and federal level regulations.

3. Results

3.1 The socio-ecoregions

3.1.1 National scale. The large heterogeneity of the country was summarized into 24 different socio-ecoregions in Mexico (Fig. 2).[1] The resulting map shows that ecoregions (such as the Tropical Humid Forest region along the eastern Pacific Coast) contain various socioregions (*e.g.* the poorest-HDI1 areas in the mountain ranges in the northwestern extreme of the country and the richest-HDI4 areas around the touristic area of Cancun in the southwestern extreme). Similarly, the same socioregions were found within different ecoregions (*e.g.* HDI1 areas in the northwestern part of the country into Southern Semiarid Hills and Temperate Sierras).

Contrasting social and ecological conditions can clearly be visualized throughout the country with this tool. The wealthy areas in the northern part of the country correspond to the Great Plains and North American Deserts ecoregions with high to very high HDI where Monterrey is located (3 in Fig. 2). The central part of the country, where Mexico City is located (1 in Fig. 2), has intermediate to high HDIs nested into Temperate Sierras. The areas with the lowest HDI in the south and southeastern part of the country, where Oaxaca is located (4 in Fig. 2), range from Temperate Sierras to Tropical Dry Forest regions.

The configuration of socio-ecoregions in space varied as a function of topographic heterogeneity and size of the municipality. The northern part is less topographically heterogeneous, and municipalities are big; as a result only a few ecoregions dissect each municipality, and resulting socio-ecoregions are quite large. Instead the southern part of the country is very heterogeneous topographically and municipalites are small, resulting in a complex mosaic of socio-ecoregions.

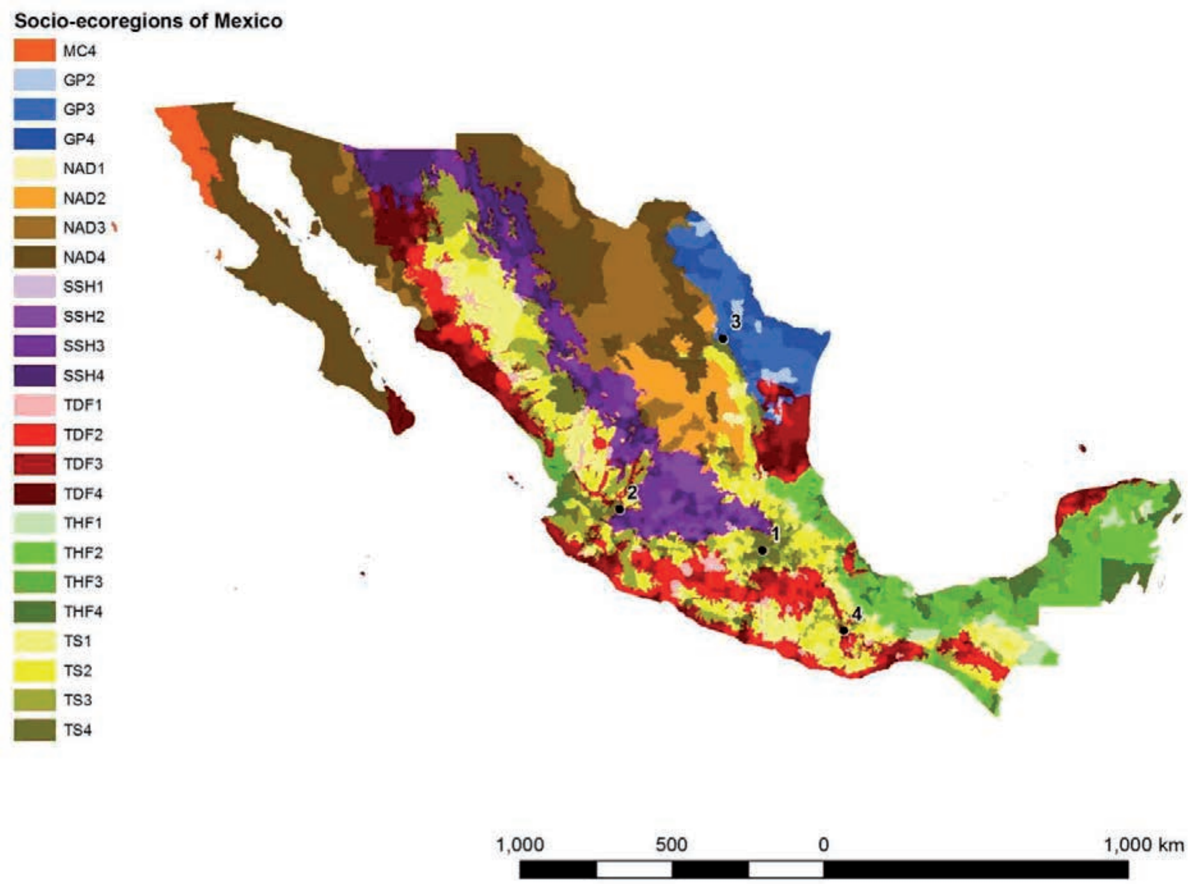
Very contrasting contexts, drivers, and dynamics can be anticipated across the country with this socio-ecoregions map. Also, solutions towards sustainability are likely to be highly contrasting across the country.

3.1.2 State scale. Zooming into Oaxaca, one of the most diverse states, patterns emerging from the socio-ecoregions frameworks can be further observed (Fig. 3). Twelve of the 24 socio-ecoregions were found there, corresponding to three of the eight ecoregions and to the four HDI conditions. Polygons belonging to the same socio-ecoregion were spatially disaggregated into separate sections of municipalities (*e.g.* TS3 found both at the northwestern and the southeastern sections of the state). Small municipalities and high environmental heterogeneity contributed to this highly dissected pattern, where very different contrasting ecosystem conditions and societal needs can be found.

Particular challenges arise for the understanding and build alternatives towards sustainability in these very heterogeneous regions. On one hand, by summarizing the complexity into a few, though small and spatially disconnected, contrasting socio-ecoregions, can help characterize the types of challenges associated to particular social-ecological contexts. On the other hand, the deep dissection of the region into very small spatial units calls for approaches that operate within small relatively homogeneous areas. Also, the resulting mosaic suggests strong interactions among ad-

[1] The corresponding files can be found at Conabio.gob.mx/información/gis.

Fig. 2. Socio-ecoregions of Mexico. These are given by a combination of ecoregions (letters) and Human Development Index (HDI) values of municipalities (numbers). Ecoregions include: Mediterranean California (MC), North American Deserts (NAD), Southern Semi-arid Highlands (SSH), Great Plains (GP), Tropical Humid Forests (THF); Tropical Dry Forests (TDF) and Temperate Sierras (TS). HDI levels: low (1), intermediate (2), high (3) and very high (4). Cities: 1- Mexico City, 2- Guadalajara, 3- Monterrey, 4- Oaxaca. (Note the corresponding shape file will be made available if published).



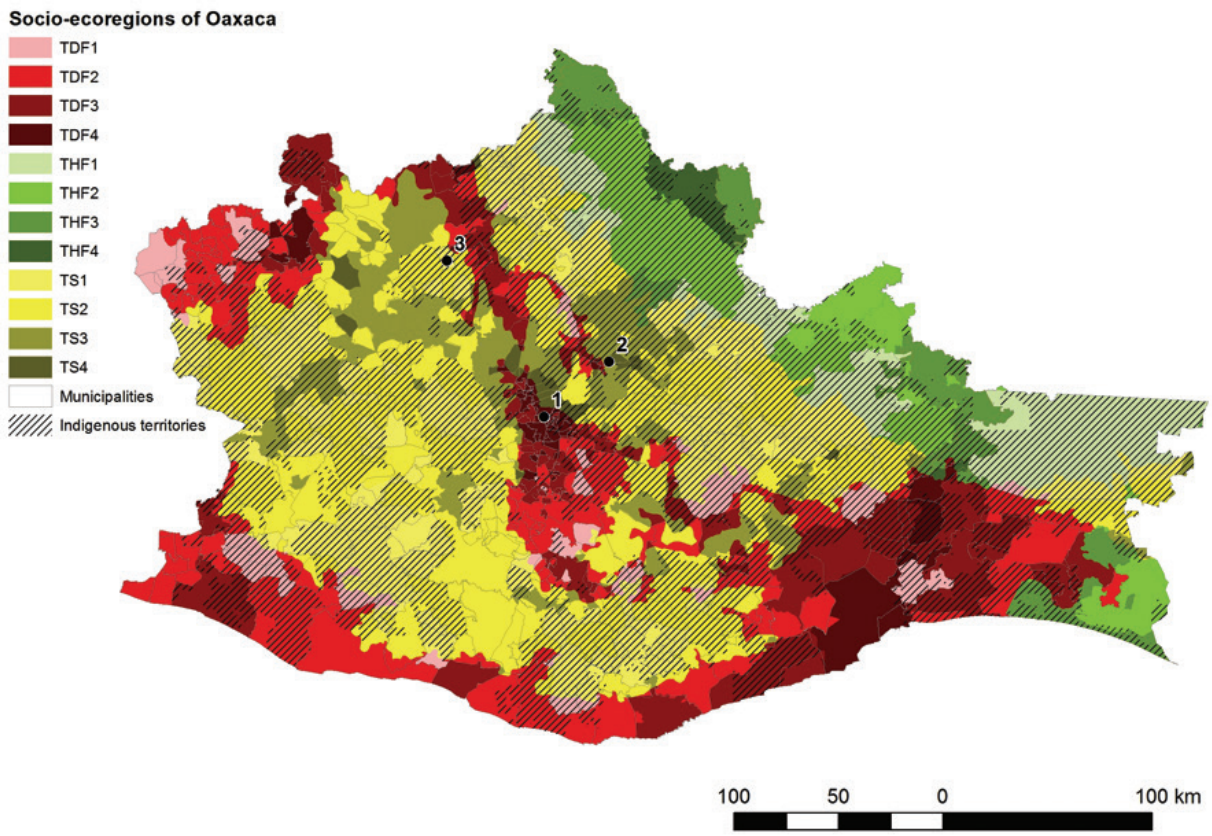
jacent but very contrasting socio-ecoregions, calling then for multi-scale approaches that encompass less to higher amount of social-ecological heterogeneity.

3.2 Using the social-ecological spatial framework for designing policies towards sustainability

3.2.1 National scale-coarse resolution. At the national scale a policy towards sustainability could be aimed at: i) ameliorating people's livelihood by targeting areas with the lowest HDI, and ii) suggesting and promoting management alternatives that are better suited to the particular conditions of the ecosystems within such areas.

Targeting areas with lowest HDI in the northeastern part of the country would mean focusing, for example, within the GP ecoregion east of Monterrey on the GP2 socio-ecoregion. Given that in general the GP area is quite well conserved, showing elevated proportions of T1 (Table 1), and that the GP2 patches are relatively small, development policy responses within those patches could rely on ecosystem transformation, while conserving the rest of the GP area, securing for ecosystem service provision of GP. Ecoregions with climates that show high evapotrans-

Fig. 3. Socio-ecoregions of Oaxaca. Results from Ecoregions (letters) and Human Development Index (HDI) values of municipalities (numbers). Ecoregions: Tropical Humid Forests (THF); Tropical Dry Forests (TDF) and Temperate Sierras (TS). HDI levels: low (1), intermediate (2), high (3) and very high (4). Towns: 1- Oaxaca, , 2- Calpulalpan, 3- San Miguel Huautla. Areas where indigenous populations dominate, the indigenous territories (IT), are shaded.



pirative demand, as those found in the northwestern part of the country, could be identified as those that would be more vulnerable to water scarcity, and thus those where agricultural production would be more at risk under alternative. Particular adaptive strategies aimed at dealing with such water scarcity (Miralles-Wilhelm *et al.* 2010) could be developed for these particular climatic conditions and coupled with the characteristics of the socio regions. Areas with low HDI could indicate those where more vulnerable populations would require more support for the state government. Areas with high HDI could indicate those where opportunities for more costly technological interventions to address water stress could be developed.

Targeting areas with lowest HDI in the central and southeastern part of Mexico, would mean focusing, for example, on the TRF found along the Gulf of Mexico and South into Guatemala, and focusing on the TRF1 socio-ecoregion. These areas correspond to the water divide of the Sierra Madre Oriental and are characterized by very steep conditions (INEGI 2005a). These areas are much better conserved than the adjacent TRF2 and TRF3 areas (Table 1), and host a very large biodiversity (Meave del Castillo 1998), yet they encompass small areas that are scattered from central Mexico all the way to the border with Guatemala. Development policy responses in this socio-ecoregion should make compatible the maintenance of this biodiversity and the assurance of income to ameliorate people's livelihoods, therefore, supporting actions with low ecosystem transformation, which could include, for example, ecotourism or sustainable forestry strategies (Arreola *et al.* 2009).

Table. 1. Values of the ecosystem management indicators for the twenty four socio-ecoregions. The names of socio-ecoregions include the ecoregion they belong to, as well as the socioregion, given by the Human Development Index (HDI) categories (1-low, 2- intermediate, 3- high, 4- very high). EMI = Ecosystem management intensity (1 low, 5 very high; percent of the total area of the socio-ecoregion under each management intensity), PPV (Primary production value, as a proportion of the national primary production in thousands of Mexican Pesos), IT (percent area covered by indigenous territories), UP (percent urban population). Highlighted rows are explicitly mentioned in the text.

Socio-ecoregion	EMI1	EMI2	EMI3	EMI4	EMI5	IT	UP
North American Deserts HDI1	0.00	44.49	55.51	0.00	0.00	0.00	0.00
Southern Semi-arid Highlands HDI1	0.16	26.53	72.74	0.14	0.42	21.98	0.00
Temperate Sierras HDI1	40.00	42.88	16.44	0.67	0.01	65.82	0.01
Tropica Dry Forests HDI1	34.26	41.02	20.74	3.93	0.05	36.13	0.02
Tropical Rain Forests HDI1	6.16	33.21	46.31	14.32	0.00	89.11	0.00
Great Plains HDI2	0.00	15.34	3.49	80.81	0.36	0.00	0.00
North American Deserts HDI2	2.29	31.98	23.88	37.65	4.21	0.27	0.00
Southern Semi-arid Highlands HDI2	3.29	10.78	37.94	43.26	4.72	1.31	0.06
Temperate Sierras HDI2	27.97	26.11	26.57	14.83	4.53	19.89	0.02
Tropical Dry Forests HDI2	9.70	22.11	26.77	20.40	21.02	13.85	0.02
Tropical Humid Forest HDI2	7.48	20.91	29.43	37.11	5.06	50.95	0.03
Great Plains HDI3	0.00	0.01	9.81	53.27	36.91	0.00	0.01
North American Deserts HDI3	3.26	9.80	19.89	22.77	44.28	2.06	0.02
Southern Semi-arid Highlands HDI3	1.80	3.42	24.62	52.65	17.51	1.35	0.14
Temperate Sierras HDI3	20.86	28.60	24.47	22.36	3.70	6.11	0.16
Tropical Dry Forests HDI3	4.32	10.79	15.87	35.65	33.37	10.64	0.12
Tropical Rain Forests HDI3	3.70	12.72	39.86	34.16	9.56	24.63	0.13
Great Plains HDI4	0.00	0.70	21.53	26.23	51.54	0.15	1.31
North American Deserts HDI4	0.00	8.94	9.17	15.03	66.86	2.40	0.20
Mediterranean California HDI4	0.00	0.00	0.00	14.33	85.67	2.32	0.69
Southern Semi-arid Highlands HDI4	0.82	4.90	12.22	60.02	22.04	0.21	0.77
Temperate Sierras HDI4	22.58	17.02	20.85	37.16	2.38	2.51	4.66
Tropical Dry Forests HDI4	5.45	4.92	9.03	28.47	52.14	4.31	0.87
Tropical Rain Forest HDI4	11.84	24.07	45.37	17.39	1.32	20.13	0.78

A federal level policy could then be tailored based on assessments as those above for each of the ecoregions and their corresponding HDI1 and HDI2 areas.

3.2.2 State scale-fine resolution. Given the prevalence of indigenous territories in the State of Oaxaca and that of the TS ecoregion (Figure 3) dominated by temperate forests a policy towards sustainability could be aimed at: i) targeting the indigenous territories, and ii) strengthening or maintaining their capacity for sustainable community forestry management.

Community forest management in that area has been shown to be successful at maintaining biodiversity and carbon stocks (Porter-Bolland *et al.* 2012) while sustaining people's livelihoods (Bray 2013) as long as it is supported by strong local institutions (Cronkleton *et al.* 2011). That is the case of Calpulalpan (2 in Fig. 3), dominated by Zapotec (indigenous) inhabitants, with a high HDI, that has preserved the forest cover of its territory (96% into T1 and T2). They have secured communal ownership for their forests through tight community institutional arrangements that rule social interactions and forestry management; emigration is low and local livelihoods are being sustained

(Ganz and Burckle 2002, and on ongoing field work by E. Lazos).

Most urgent interventions would then be targeted towards areas with both low HDI and extensive forest transformation. For example, San Miguel Huautla, a Mixtecan community (3 in Fig. 3), with low HDI preserves a low percentage of their original forest cover (34% of the area into T1 and T2) as a result of over-exploitation of forests for wood and charcoal. Such devastation arose from the lack of community level institutional arrangements for the use of forests. As a consequence, job opportunities are scarce leading to high emigration rates (Ganz and Burckle 2002, and on ongoing field work by E. Lazos). There, reforestation, forest management capacity and institutional strengthening would be simultaneously needed towards sustainability (Bray 2013).

A federal level policy could be tailored based on assessments as those above for each of the ecoregions and their corresponding HDI1 and HDI2 areas. A state level policy could be tailored based on approaches such as the ones described above by combining information from the socio-ecoregions map with data on indigenous territories (IT) and transformation intensity (T) and complemented with information about institutional arrangement practices.

4. Discussion

4.1 Mapping socio-ecoregions in Mexico

The socio-ecoregions map synthesized some key dimensions of the ecological and social heterogeneity of Mexico. By combining information on the ecoregions and the HDI levels, the nature of this mosaic, with important societal contrasts within similar biophysical conditions, or important biophysical contrasts for similar societal conditions, can be clearly observed. The texture of this mosaic is better appreciated when zooming into the state of Oaxaca that reveals the very fine scale at which very contrasting biophysical or societal conditions are found, even in adjacent areas.

The information provided by the socio-ecoregions maps is likely to be very relevant to guide research and decision-making in Mexico. At present, very useful and synthetic information is readily available on the abiotic and biotic conditions of the country (http://www.conabio.gob.mx/informacion/gis/) to researchers and decision makers interested in sustainability and other environmental issues. While many societal indicators are periodically gathered (www.inegi.gob.mx), such information is not so readily accessible in a spatially explicit way. Nor is this information available in a format that allows for assessing cross-sectoral initiatives.

4.2 Using the social-ecological spatial framework for designing policies towards sustainability

Policies that better integrate sustaining life-support systems while meeting the multiple human needs can benefit from social-ecological spatial frameworks such as the one designed here for Mexico. We showed how information on the location and extent of the different socio-ecoregions could support federal level or state level policy design. By combining the socio-ecoregions map with land use maps, in this case classified into a transformation intensity gradient, and with social variables such as the presence of indigenous territories, could further inform the design of such policies.

4.3 Advantages and limitations of the socio-ecoregions approach beyond Mexico

The socio-ecoregions approach aimed at identifying those key variables that would be most relevant to predict contrasting dynamics among social-ecological systems. It is well know that slow variables, those that change gradually though directionally, play a paramount role in the dynamics of complex systems relative to that of fast ones, those that change constantly and in many directions (Folke 1997). The socio-ecoregions map relies on ecoregions and municipality boundaries that are relatively static (though some changes do occur at least in the case of Mexico). Instead, currently available approaches (Ellis and Ramankutty 2008; Halpern *et al.* 2008) rely on land cover or human impacts which account for accumulating effects, but can also change very dynamically over a few years in areas under rapid transformation. Yet, the classification of municipalities among socioregions given by HDI factors can also be dynamic and have the same limitation.

HDI is of course no panacea but is very useful and easy to use. The use of HDI has strongly being critiqued for its limitations to truly convey the complexities involved in human development and for methodological reasons (Kovacevic 2011). The information contained within HDI provides indirect indication of the drivers underpinning ecosystem management that operate at the municipality level. It does not provide any information on the local governance, including land tenure right or informal institutional arrangements for the management of these systems. Yet, it does provide a quick overview of societal conditions with readily available information. Detailed assessment of the range of societal drivers underpinning ecosystem management that operate at the local scale and that interact with other operating at larger scales could be done a posteriori.

Despite above limitations, we believe that socio-ecoregions maps contribute to the previously identified need for integrated social-ecological frameworks that take into account the role of the particular ecological and societal context and the key ecological and social drivers in their dynamics. Societal attributes had not been explicitly been part of previous approaches, but were just surrogates to explain impacts on ecosystems. Here we used HDI as a summary of those conditions, but other indicators of societal conditions could be used in similar initiatives.

The methodology suggested here to build the spatial socio-ecoregions framework can easily be applied to other areas of the world, at multiple spatial scales. Ecoregions have been identified at global, national and subnational scales (CEC 1997), and the Human Development Index is available for all countries and municipalities in many of them (UNDP 2010). These indicators have been widely used by scientists, by national and international agencies, as well as governmental and non-governmental organizations.

The development of socio-ecoregions at multiple spatial scales can better contribute to the development of policies towards sustainability. While the national scale map was useful to summarize the amazing heterogeneity of the country into only 23 contrasting socio-ecoregions, the state level map was useful to tease apart the heterogeneity and emphasize the contrasts. Federal policies are often homogeneous across the country, and often influenced by global policies and global corporations. A generic classification of the country or the globe into a few contrasting socio-ecoregions could lead to the adevelopment of a small set of policies and technologies towards sustainability that are particularly suited to specific contexts. A more focused and detailed classification at the state and municipal level could allow to understand how similar context have led to very contrasting current conditions of the social-ecological system, and vice-versa. It would allow us to understand better the limitations of generic approaches and address the particularities of each social-ecological system.

The socio-ecoregions approach could be modified to best suit the specific characteristics of each country. Global, national and state level socio-ecoregions maps could be produced. Socio-ecoregions could be developed for explorations and policy design within individual countries them, or for comparisons among countries and the generation of global strategies. Socio-ecoregions could also be used to contrast progress towards biodiversity conservation targets, such as the Aichi ones (Walpole *et al.* 2009), or the soon to be developed Sustainable Development Targets (Griggs *et al.* 2013).

5. Conclusions

In this paper we have developed a map of socio-ecoregions that takes into account boundaries given by major biophysical conditions, political boundaries (municipalities in this case) and societal conditions (HDI- Human Development Index). We applied this to Mexico and showed how it summarized the spatial ecological heterogeneity of the country and a very diverse state.

The socio-ecoregions approach is different to previous analogous efforts because it addresses both the conditions of the ecosystem and that of societies. This approach can easily be used to map socio-ecoregions for the whole globe, or at subnational scales.

Socio-ecoregions maps can further be used for research and policy design. It can support comparative research on the state of social-ecological systems across contrasting ecological and societal conditions, or further explorations of the relative contribution of social and ecological drivers to the way ecosystems are managed. They can also be used for integrated policy design allowed for societal and economic development while maintaining biodiversity and ecosystem functioning. We showed a couple of examples of how this could be done at federal and state levels.

Further integration of ecological and social perspectives is most needed in the search for sustainability. The socio-ecoregions framework constitutes one of the tools towards achieving such goal.

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