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Using Social, Economic and Land-Use Indices to Build a Local Sustainability Index in a Mining Region of the Sierra Tarahumara, Mexico

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Abstract: Ore mining has served as a predictor of economic wellbeing since it brought development to countries. However, these benefits do not always extend to all localities that comprised the center of this industry. This paper examined the contribution of mining to local communities. An index of local sustainability was constructed based on economic, social, and land-use data from twelve localities where mining and forestry are their major economic activities. Land-use variables were obtained from Landsat Thematic Mapper (TM 5) images for 2000, and Landsat Operational Land Imager (OLI8) for 2014, while the socio-economic variables were collected in twelve localities with an 85-question survey. A sustainability index was developed for each group of variables—economic (ESI), social (SSI) and land-use sustainability index (LUSI)—to further build a local sustainability index (LSI). Three localities showed the highest ESI (0.61, 0.53 and 0.43) and SSI (0.90, 0.79 and 0.78), while two localities had the lowest values in the ESI and SSI. In contrast, the highest value of LUSI was found in two other different localities and in one with lower SSI. Income from mining activities is positively associated with the ESI and SSI, but there was no evidence of linear association with the LUSI. A local index of sustainability provides useful information for planning and development strategies.

Keywords: Chihuahua; sustainability; rural development

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1. Introduction

Metal ore extraction has been important for the economic development of nations even before industrialization. More recently, low- and middle-income countries have increased their Gross Domestic Product (GDP) [1] and consequently higher human development indices have been achieved due to mining industry [2]. However, there is debate about the economic benefits offered by mining and the high underlying costs of the environmental degradation produced by its operations [3–6]. The extraction of mineral resources, especially surface mining, causes numerous environmental and social impacts [7–9]. The most common is degradation to some landscapes [10], which, along with the increasing land-use change patterns and forest fragmentation, drastically affects equilibrium in ecosystems [11–13]. Consequently, there is a loss of soil productivity [14] that further impacts the livelihood of rural localities [15]. Other forms of social impacts are due to changes in infrastructure networks, non-balanced industrial development, resettlement and changes in the economic and social structure of the local population, family disruption, schooling drop offs [16], and loss of cultural heritage [16].

The large economic benefits associated with large foreign investment, exports and fiscal revenues [2] of mining have made possible the development of polices and technologies to mitigate and remediate those impacts [17]. Mining companies are committed to reducing the amount of water and energy needed for their operations and research has improved the treatment of acid rock drainage and wastewater; in addition, land reclamation is included into their business plans as suggested by international standards [18]. While these sustainable practices have been steadily implemented around the world, the degree of the impacts and contribution of mining depends on different factors that are more relevant at the local level [19]. Consequently, assessments at the local level are important to better allocate resources and solutions that will enhance the quality of life of inhabitants around mining operations. In this sense, measuring sustainability as a metric that encompasses economic, social, and land use variables, of areas under ore extraction should be a requirement to develop strategies that favor production and natural resource management [20]. Sustainability indicators and composite indices are instrumental to communicate complex information [21] and serve to monitor and evaluate sustainable strategies [22,23]; in addition, they provide guidance to decision makers [24] when developing public policies [25]. Furthermore, indicators and indices can also be used to make comparisons among countries and regions [26]. At the regional and local level sustainability indices serve to assess the contribution of mining to small rural and indigenous localities, which are frequently the owners of the intervened land [27].

Land-use planning implies the evaluation of forest landscape impacts to further understand the dynamic of the social, economic, and ecological component associated to it [28]. Land-use indices based on GIS are good predictors of changes in landscape patterns [29] and help to design strategies for restoration [30]; while socioeconomic indices reflect the contribution of natural resources to wellbeing. Incorporating socioeconomic indices to land-use patterns at the local level is critical for decision-making in areas under mining extraction. Recently, most of the rural projects to restore or ameliorate the environmental impacts of mining highly rely on community participation; communities will be prompt to participate according to the degree of the benefits and impacts perceived [31]. Although there is a large body of research that has studied the impact and benefits of mining, research using GIS to explore land use changes and its connection to socioeconomic wellbeing at the local level is exiguous. Most of the studies that address the social component of mining has revolved around the assessment of socioeconomic benefits and costs, and the effects to development if closing the mines [32] partially reflecting the real impacts and benefits to stakeholders.

Mining is one of the oldest economic activities developed in Mexico after the Spanish conquest. In recent decades, Mexican gold and silver have substantially reached the international markets [11] occupying first and seventh rank of silver and gold production with an estimated market value of 2.4 and 4.3 thousand millions United States Dollars, respectively [33]. The state of Chihuahua is characterized for its forestry and mineral richness, in particular along the Sierra Tarahumara; those two activities comprise more than 50% of the state's income [34]. While forest harvesting has stagnated lately, mining has expanded. In 2015 the extraction of gold in the municipality of Ocampo was of 9640 tons, around 7.2% of the total production of Mexico [33]; similarly, this municipality is known for its large areas of forest cover.

In Mexico, most of the studies related to mining have been done at the state level; there are not studies at the local level that provide information of the real contribution/impacts of mining to society. This study aimed to evaluate the impacts of mining to the landscape at the local level. To accomplish this goal, we constructed indices of sustainability for the social, economic, and land-use dimensions to further develop an index of local sustainability. Building local indices would help policy makers and industry to develop mitigation and adaptation strategies that directly benefit the affected localities.

2. Methodology

2.1. Study Site

The Ocampo mining region is located at the heart of Sierra Tarahumara in the state of Chihuahua, Mexico. This region is comprised of three municipalities Ocampo, Temosachi, and Moris with a GPS coordinates of 28.49 N, 108.49 E and 28.08 N, 107.91 E (Figure 1). About 80% of the region is composed of steep mountains, while the other 20% is covered by plateaus and valleys [34] with elevations between 458 and 2911 meters above the sea level (masl). Three rivers (Balloreca, Concheño and Apituychi) flow through the mountains systems, irrigating the agricultural land of the state of Sonora to finally discharge into the Pacific Ocean [35]. Due to biological and physical characteristics of the region, there are two Natural Protected Areas (Parque Nacional Basaseachi and the Área de Protección de Flora y Fauna Tutuaca) that are home to a large number of species of flora and fauna.

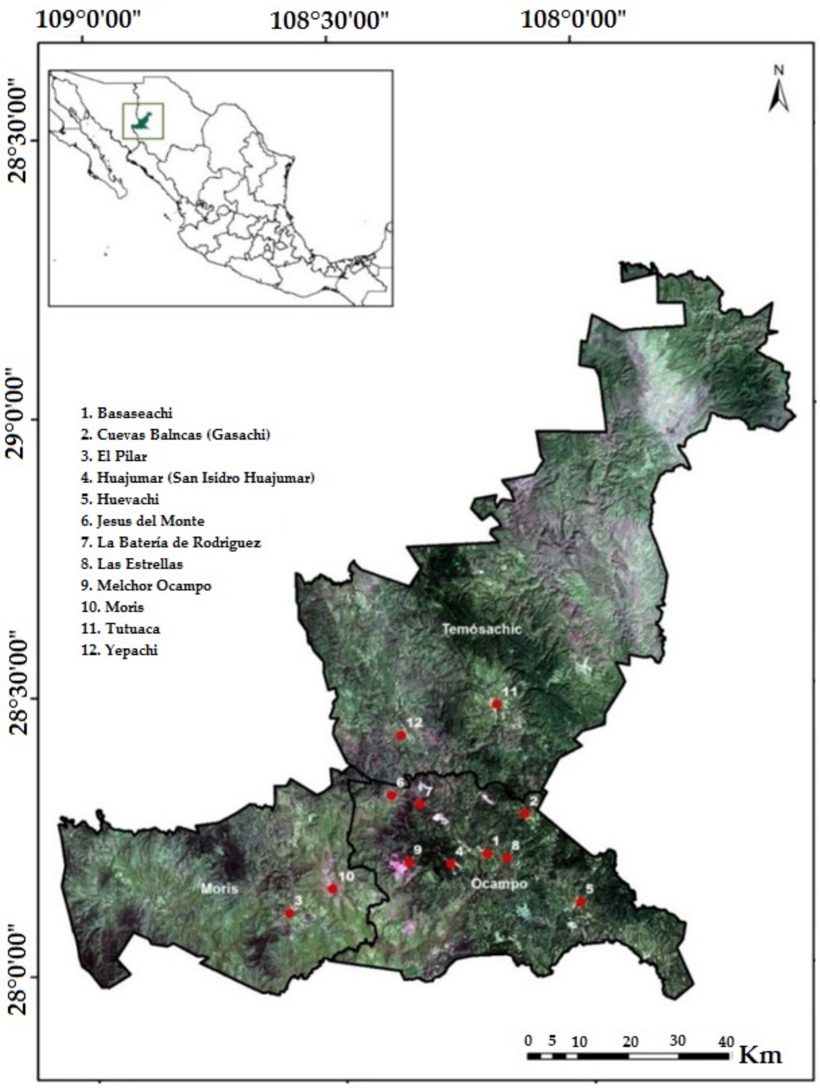

Figure 1. Location of the 12 study sites in the municipalities of Temosachic, Ocampo and Moris in the mining region of Ocampo.

In economic terms, the region produced 35% of the gold extracted from the Sierra Tarahumara [36]. In 2015, despite of the historical importance of forest production in the Sierra Tarahumara, the value of gold production was three times higher than the forest production [36,37]. At national level, the Ocampo region occupies 3rd place for gold production with 451 million USD and 2nd place of forest production with an estimate of 157 million USD. The region is currently facing a fast process of degradation and fragmentation due to the extraction of gold and timber harvesting principally; this situation is aggravated by forest clear cut for agriculture and cattle, and forest fires [34,38].

2.2. Data Collection

2.2.1. Land Use Indices

The land-use change, number of patches, Shannon and Simpson indices, Normalized Difference Vegetation Index (NDVI) and the rate of erosion were obtained after processing four scenes of Landsat Images TM 5 for the year 2000 and Landsat OLI for 2014 under the path/row 33/40, 33/41, 34/40 and 34/41 with their respective radiometric and atmospheric correction [39]. The images were acquired for free from the United States Geological Survey and registered under the Universal Transversal Mercator (UTM) on the zone 12 N with datum World Geodesic System of 1984. Each band has a resolution of 30m. To compare images of different years the Top Atmosphere (TOA) process was used to convert digital numbers (DN) to values of reflectance. Differences of atmospheric conditions were corrected with the dark object subtraction method (DOSM) [40]. To adjust the localization error a geometric re-sampling with a linear polynomic of first grade was used until obtaining the square root of the medium error at 1.0 pixel.

In addition, the land use classification and vegetation was determined through the supervised analyzing method using the Euclidian distance to measure pixels' similarity [41]. Using the Gaussian probabilistic model we obtained maps for 2000 and 2014. Once we had land use, a Patch Analysis module Arcgis® (Redlands, CA, USA) was conducted to determine fragmentation [42]. Landscape fragmentation was represented by the number of patches in the area (NumP). Patches were then analyzed as individual polygons or as group of nearby neighborhood. The two images were converted to vectors before the calculation of de indices.

2.2.2. Socioeconomic Data

Data were collected at the household level in 12 localities of three municipalities comprising the Ocampo mining region. A questionnaire of 85 questions was designed and divided in 10 sessions to obtain information on: general household information, sources of income, expenditure, type of house, water availability, way to dispose waste, agricultural, livestock and forestry production, and perceptions about food security, from which we derived the final 12 economic and the 10 social indicators (Table 1). The sample population was randomly selected using the reference of [43]. A total of 130 questionnaires were administered in the localities. The number of questionnaires varied in each locality due to the total number of households for each of them. Four graduate and undergraduate students were trained to serve as interviewers.

Table 1. Indicators selected for the economic, social and environmental components.

Indicators	Components	Unit of Measurement
Annual income per mining activity	Economic	$
Annual income from forestry activities	Economic	$
Annual income from government programs	Economic	$
Income from agricultural activities	Economic	$
Income from other wages	Economic	$
Other sources of income	Economic	$
Costs per dress	Economic	$
Food expenses	Economic	$

Table 1. *Cont.*

Indicators	Components	Unit of Measurement
Expenses for services	Economic	$
Recreation expenses	Economic	$
Household expenses	Economic	$
Expenditure on productive activities	Economic	$
Households with water availability	Social	%
Level of overcrowding	Social	%
Homes with electricity	Social	%
House with earthen floor	Social	%
Households with waste collection	Social	%
Household drainage	Social	%
Egg consumption per week	Social	None
Chicken consumption per week	Social	None
Consumption of beef per week	Social	None
Milk consumption per week	Social	None
Number of patches	Environmental	No
Erosion rate	Environmental	Ton/ha^{-1}
Shannon Index	Environmental	Index
Simpson Index	Environmental	Index
Land-use change	Environmental	%
Differential normalized vegetation index (NDVI)	Environmental	Index

2.2.3. Developing the Sustainability Indices (IS)

Data from the questionnaires were processed in Excel to further standardized measuring units for each variable. A relative index was created for each component (Equation (1)), [22].

$$\text{R. I.} = 1 - (X_i - X_{min})/(X_{max} - X_{min}) \tag{1}$$

where: R. I. Relative index, X_i value of variable *i* in the locality *X*; while, X_{max} and X_{min} are maximum and minimum values for the variable *i* in all localities.

Thus, values range from 0 to 1, being 1 the locality in better condition. However, due the characteristics of some variables, in which 1 does not imply positive connotation such: level of housing crowding, type of flooring in the house, number of patches, Shannon and Simpson indices, % of land-use change, and vegetation index, a factor correction was needed to be able to standardize the meaning of the values 0 and 1 (see Equation (2)).

$$\text{R.I.} = (X_i - X_{max})/(X_{max} - X_{min}) \tag{2}$$

For example, if the house flooring is of dirt, the index should have a value close to 0 to show that this kind of flooring is less desirable. Then, economic (ESI), social (SSI) and land use (LUSI) sustainability indices were computed to then comprised them in an index of local sustainability (*LSI*). The following equation (Equation (3)) was used to calculate the *LSI*.

$$LSI = \frac{\sum_{i=1}^{n} RI_E}{12} + \frac{\sum_{i=1}^{n} RI_S}{10} + \frac{\sum_{i=1}^{n} RI_L}{6} \tag{3}$$

where: *LSI* = Local sustainability index, *RI* = Relative index.

2.3. Assessment of Sustainability Indices

A principal component analysis (PCA) was used to observe relations between social, economic, and land use variables. PCA showed the contribution of each variable to each of the sustainability indices and explained the total observed variable; it also helped to observe contrasts among the localities. SAS® CORR (SAS, Cary, NC, USA) procedure was run to find the lineal association between pair of components [44]. A cluster analysis for the localities was used to estimate the closest sustainability index and to validate the PCA procedure [45]. Finally, data was represented with the radar diagram to ease understanding.

3. Results and Discussion

3.1. Land Use Sustainability Index (LUSI)

Maps showed 10 different types of land use and vegetation (Figure 2): Mining; Open Lands; Oak Forest; Pine Forest; Oak-pine Forest; Pine-oak Forest; Shrubs; Waters Bodies; Deciduous Forest, and Crops Lands. Land-use change, Shannon and Simpson indices, NDVI, and erosion were correlated to landscape fragmentation. The number and average size of patches of forest cover also showed forest fragmentation. Ocampo presented a number of patches of 115, a Shannon index of 1.34 and a Simpson index of 0.67 indicating the presence of fragmentation. The oak forest (OF) showed greater number of patches (537) and pine forest (PF) the lowest (see Table 2). There was a decreased of the average size of patches as a response of the number of patches. From 2000 to 2014 land-use changed as gold mining increased in the localities of Ocampo and Moris. A steady increase of fragmentation could be the response of continuous fuelwood harvesting, opening of roads and changes in land use by expansion of the mining industry, and human settlements [45].

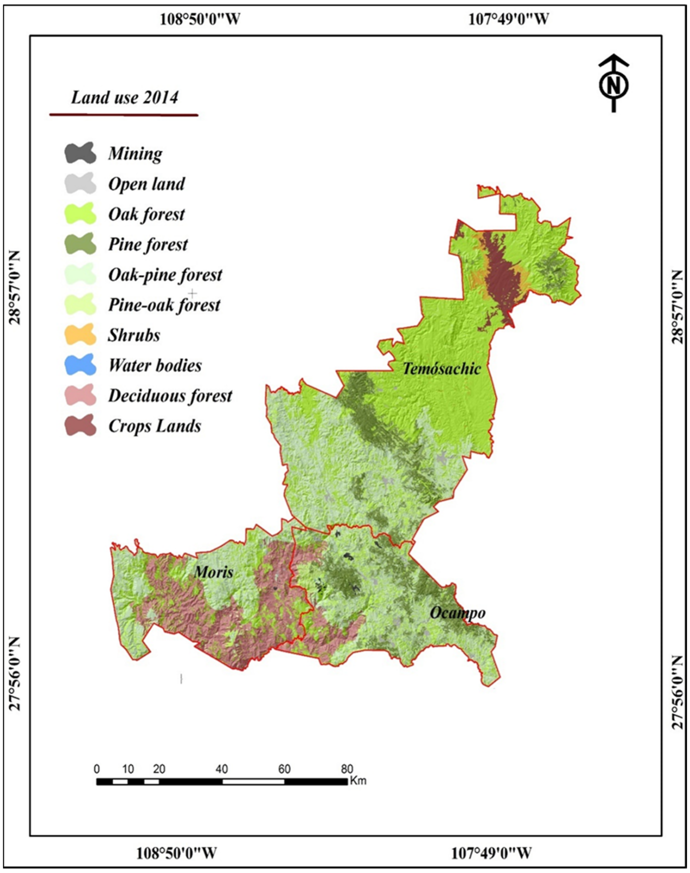

Figure 2. Mapping of land use classification with Landsat OLI8 images from year 2014.

Higher values of LUSI were present in the localities of Yepachi (0.74), La Batería de Rodríguez (0.74) and Moris (0.66), this can be explained due to low levels of erosion and drastic changes in the land-use. In contrast, Gasachi (0.47), Jesús del Monte (0.40) and Ocampo (0.21) showed the lowest values of LUSI. Ocampo is a locality where both mining and forest harvesting are the main sources of income; which highly exceeds the income of the localities nearby.

Table 2. Number of patches by coverage classification for scenes 2000 and 2014.

Municipality	Coverage	Number of Patches	
		2000	**2014**
Temósachi	Mining	0	0
	Open land	7	11
	Oak forest	12,850	13,387
	Pine forest	100	105
	Oak-pine forest	1041	1063
	Pine-oak forest	2476	2543
	Shrubs	131	183
	Water bodies	0	0
	Deciduous forest	0	0
	Crops lands	23	23
Moris	Mining	2	4
	Open land	2	11
	Oak forest	3726	3945
	Pine forest	2	2
	Oak-pine forest	930	1073
	Pine-oak forest	207	230
	Shrubs	0	0
	Water bodies	0	0
	Deciduous forest	687	710
	Crops lands	0	0
Ocampo	Mining	0	37
	Open land	24	30
	Oak forest	3723	3913
	Pine forest	57	57
	Oak-pine forest	1108	1250
	Pine-oak forest	1688	1748
	Shrubs	0	0
	Water bodies	0	3
	Deciduous forest	192	283
	Crops lands	0	0

3.2. Economic Sustainability Index (ESI)

The localities of Huajumar (0.61), Gasachi (0.53) and Ocampo (0.43) showed the highest values for this index, due principally to their higher income compared to the rest of the localities. Huajumar and Ocampo are closer to mining camps and also have a good road system; therefore, more than 50% of the population's income comes from mining activities. As opposed to El Pilar (0.23), Huevachi (0.20) and Tutuaca (0.03) that showed lower values for this index, operation camps are farther down.

3.3. Social Sustainability Index (SSI)

This index showed a similar tendency of ESI, localities with higher incomes registered higher SSI values, Gasachi (0.91), Huajumar (0.79) and Ocampo (0.78). Higher income, as expected allows people to have better houses with faucet water and more access to food. In contrast, the localities of Huevachi (0.44), La Batería de Rodríguez (0.42) and Tutuaca (0.28) showed the lowest values of the 12 localities of this study. Variables associated to housing were more relevant for the SSI. A decent housing that allows a person to satisfy their basic needs should have faucet water, electrical energy, sewer and solid waste system; concrete flooring material, and enough number of rooms to harbor each member of the family [46,47]. The localities that exhibited low social index are consistent with those localities considered under extreme poverty [47], meaning that besides decent housing, there is also a lack of education or health services.

In regard to food security as an indicator of wellbeing, availability and consumption of animal products such, chicken, beef, poultry, dairy products and eggs the following data was found. The localities of Gasachi, Huajumar and Ocampo showed a major consumption of these products with a frequency of "at least once a week", eggs and milk were products that are consumed 4 days of the week. In contrast, the localities of Huevachi, Batería de Rodríguez, and Tutuaca showed lower consumption of these products due to their lower income that limited the access to these products.

3.4. Local Sustainability Index (LSI)

We constructed a composite index using land-use and socioeconomic variables. The LSI for the localities of El Pilar, Huevachi and Tutuaca showed the lowest values (0.39, 0.35 and 0.24 respectively). The large distance from the mining activities limits the access to basic needs and food, it also has influence on income; which is reflected on lack of education, and precarious housing for these localities. In contrast, Huajumar, Gasachi and Las Estrellas exhibited higher values (0.67, 0.65 and 0.53 respectively). These localities presented higher incomes and better housing condition; which imply that income from mining is expended in goods and services for household [27].

3.5. Assessment of Sustainability Indices

The values of the sustainability indices are presented in Table 3. Income was a determinant for the ESI ($p = 0.0057$) and for SSI ($p = 0.001$); however, there was not an empirical evidence of its impact to LUSI ($p = 0.8121$). Figure 3 shows the sensibility of indices to changes in income from mining. The ESI showed an increase of 0.017% per year for every 10 thousand Mexican pesos; meanwhile, the SSI increase in 0.022%. Although the LUSI showed a negative value (−0.002), this was not statistically significant ($p = 0.8121$). A similar trend was observed when comparing localities. Mining as a major activity had an impact on the ESI ($p = 0.0150$) and the SSI ($p = 0.0012$) but no for the LUSI ($p = 0.8881$). We also analyzed the impact of natural protected areas on the indices due to the fact that some localities are within the limits of natural protected areas. There was not significant evidence for the ESI ($p = 0.2183$) and the LUSI ($p = 0.313$); however, there is a significant correlation on the SSI ($p = 0.0392$).

Table 3. Indices composed of economic, social and land use sustainability determined in the mining region of Ocampo, Chihuahua, Mexico.

Locality	ESI	SSI	LUSI	LSI
Basaseachi	0.42	0.59	0.57	0.51
El Pilar	0.23	0.45	0.58	0.39
Gasachi	0.53	0.91	0.47	0.65
Huajumar	0.61	0.79	0.58	0.67
Huevachi	0.20	0.44	0.51	0.35
Jesús del Monte	0.30	0.51	0.40	0.40
La Batería de Rodríguez	0.26	0.42	0.74	0.42
Las Estrellas	0.30	0.74	0.64	0.53
Moris	0.30	0.68	0.66	0.51
Ocampo	0.43	0.78	0.21	0.51
Tutuaca	0.03	0.28	0.60	0.24
Yepachi	0.27	0.53	0.74	0.47

ESI = Economic Sustainability Index. *SSI* = Social Sustainability Index. *LUSI* = Land use Sustainability Index. *LSI* = Local Sustainability Index.

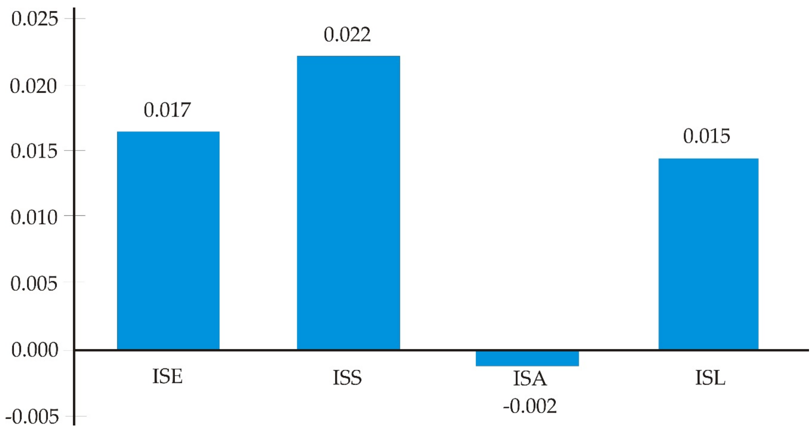

Figure 3. Values of the B1 estimator for the region's sustainability indices miner of Ocampo.

The principal component analysis showed contrast within the localities of Gasachi and Tutuaca (Figure 4); the latter, observed the lowest value of the component 1 (−5.07), which is consistent with the lowest value for the LSI (0.24). The localities of Huajumar and Ocampo showed similar trends with high values on ESI in comparison with Tutuaca and Huevachi that presented the lowest values. Low income in these localities is considered a barrier to access goods and services such food and decent housing. Long distance to mining operations is one of the major problems for these localities, as observed by [19] as well. Meanwhile, Huajumar showed a medium value in the component 1 (2.39) and a high value on component 2 (3.97) indicating that there was a balance among the three indices, which in turn, was exhibited with a highest value in the LSI (0.67).

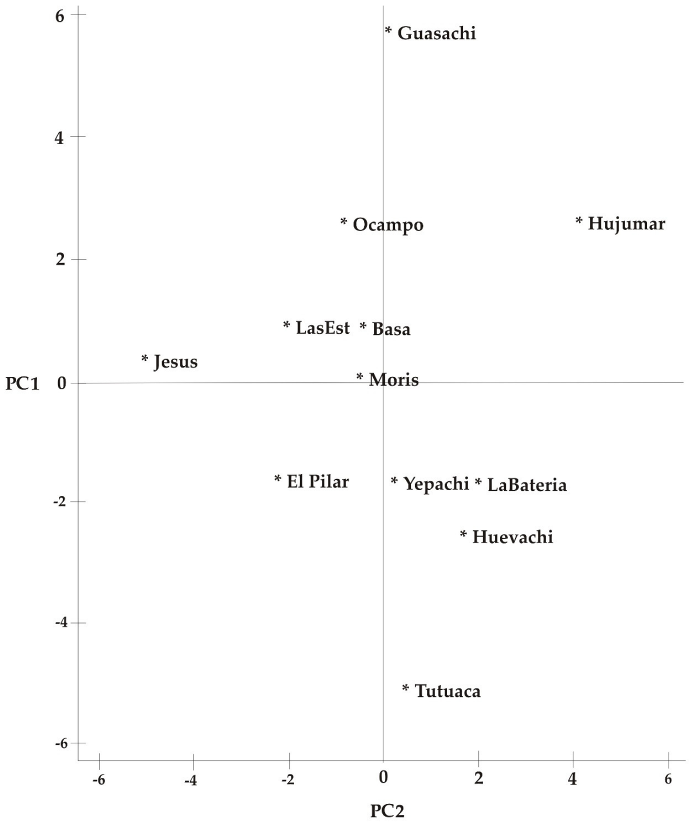

Figure 4. PCA ordination showing the localities along the first and the second principal component axes. These axes explained 47% of the total variation.

The radar diagram compiles and summarizes the relationship among the indices obtained from the PCA (Figure 5). It can be seen how the localities identified with the highest incomes showed the values closest to unity in the economic and social indices, while the land-use index behaved differently. As an example, localities such as Ocampo and Basaeachi, that presented high values of ESI and SSI showed low values in the LUSI, due to the fact that they presented changes of forestland use.

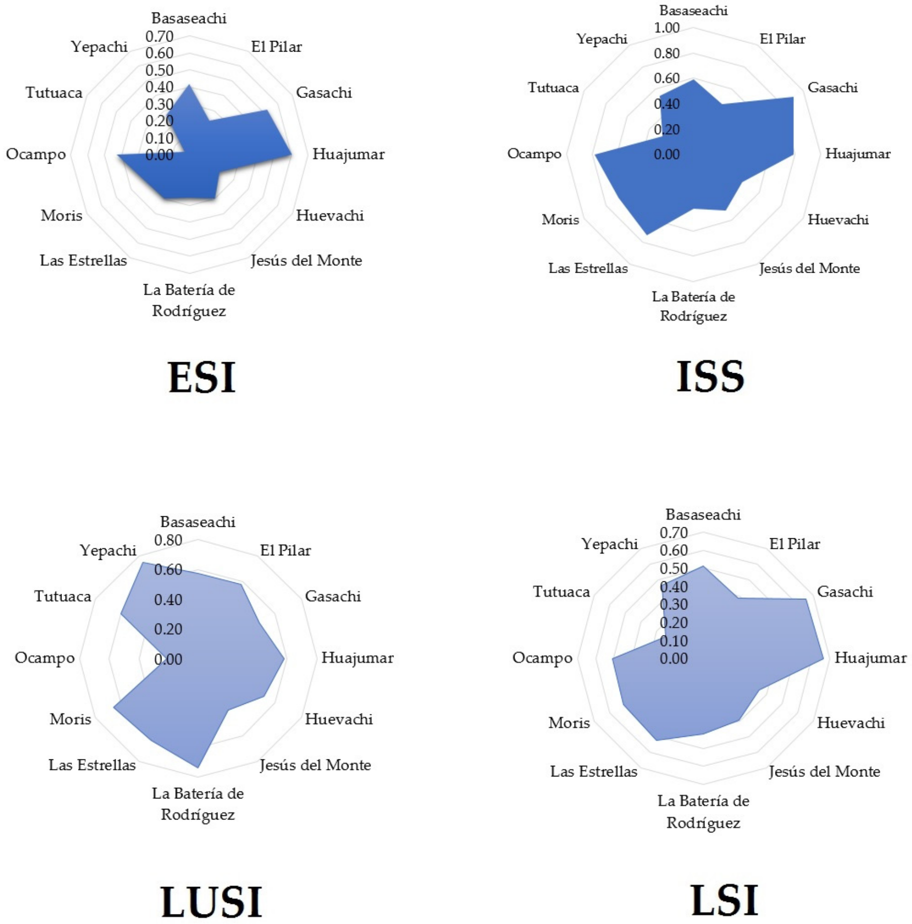

Figure 5. Radar diagram showing the distribution of assessed sustainability indices.

In this study, the SSI followed the same pattern since the indicators of human wellbeing are associated to income. Consumption of beef per week, chicken consumption per week and annual income per mining activities showed the highest values of contribution to main component 1 (Table 4). In contrast, the main component 2 is more influenced by the number of patches, annual income from forestry activities and NDVI. In this way we can associate the main component 1 as an indicator of economic development, and the main component 2 as an indicator of ecological development. The analysis of LSI confirmed the tendency of localities of Huajumar and Gasachi accordingly to the results obtained by the PCA. Therefore, it can be concluded that the extraction of gold contributed to economic benefits that enhance the quality of life of people in terms of housing, water availability, education, and road network. Although there was evidence of landscape fragmentation, this was not significant to those documented at regional level [48].

Table 4. Contribution of the indicators to the main components PC1 and PC2.

Indicator	PC1	PC2
Annual income per mining activity	0.29	0.09
Annual income from forestry activities	0.08	0.29
Annual income from government programs	0.11	0.15
Income from agricultural activities	0.01	0.27
Income from other wages	0.07	−0.06
Other sources of income	0.21	−0.14
Costs per dress	0.19	−0.22
Food expenses	0.27	−0.25
Expenses for services	0.04	0.12
Recreation expenses	0.25	0.11
Household expenses	0.27	0.11
Expenditure on productive activities	0.24	0.03
Households with water availability	0.03	0.29
Level of overcrowding	−0.18	0.2
Homes with electricity	0.2	0.25
House with earthen floor	−0.1	−0.1
Household drainage	0.19	−0.22
Households with waste collection	0.23	0.07
Egg consumption per week	0.15	0.22
Chicken consumption per week	0.32	−0.15
Consumption of beef per week	0.32	−0.08
Milk consumption per week	0.23	−0.06
Number of patches	0.04	−0.38
Erosion rate	0.1	−0.14
Shannon Index	0.09	−0.11
Simpson Index	0.19	0.13
Land-use change	0.14	0.21
Differential normalized vegetation index (NDVI)	0.12	0.27

Mining in the Ocampo region was the first predictor of erosion and fragmentation; a previous study reported high levels of trace elements at the runoff water due to mining [34]. Although there were degrees of land disturbance at the local level, these were not significant to those documented at the surface scale of the Sierra Tarahumara [48].

The extraction of mineral resources, especially surface mining, causes numerous negative environmental externalities and socio-economic impacts, i.e., land use changes, ecosystem disturbances, watercourse relocation, and a decrease in ground water level [8], and changes in the economic and social structure of the local population. In recent year public controversies about mining and sustainability have arose, due to the contribution of mining to socioeconomic development versus the environmental degradation [49]. Gold mining, in particular, has a negative image due to low contribution to local localities [50] that has been a determinant of illegal mining which in turn, has detrimental consequences to landscape such high levels of fragmentation, water pollution and loss of aquatic biodiversity [12].

Despite mining seeming to enhance quality of life in economic terms, there is a level of inequality of income among the localities and households. Although there are groups of people who live in the mining operation centers, their income is not necessary a product of their jobs on the mine, leaving them more vulnerable to access goods and services in economic terms [19]. The same situation arises for localities a little further from the mining operation centers; in these cases, localities do not have both physical and economic access to those services [20].

The accessibility dimension of food security is associated with income and a good road system principally; in this regard, our study corroborated what [19] also found, that localities far from production centers have limited access to animal products due to the lack of income and distance.

Local sustainability indices are important to understand regional dynamics in the three dimensions of sustainability. In localities with an indigenous population, where culture and community are intrinsically linked to the management of forest and mining resources, social and economic indicators become more important. The challenge for natural resource management is to balance ecological functioning of natural systems with an increasingly diverse set of demands imposed on those systems by human needs [51]. These include employment, subsistence goods, recreational opportunities, tourism-based economic development, as well as spiritual connections, heritage values, social meanings and aesthetics [52]. Our study confirmed what was previously found by [53] in 71 localities in Australia.

4. Conclusions and Recommendations

Sustainable development in the Sierra Tarahumara is becoming more important in particular for the localities that depend on the forest and mining industry. To respond to many sustainability challenges, these localities must be able to measure their progress towards sustainable development.

The framework of local-level sustainability indicators generated in this study could be used as baseline information to assess the level of sustainability of localities dependent on mining in temperate forests and deciduous forests of the Sierra Tarahumara. Nine of the twelve localities had the lowest ESI (<0.40) implying that their level of sustainability is low or unsustainable. The remaining three localities had ESI values of 0.61, 0.53 and 0.43 suggesting a medium level of sustainability. This could be explained by the annual income from economic activities, food expenses and housing costs. The SSI showed the same trend for the same localities (0.90, 0.79 and 0.78). These values indicate that income from mining activity is associated with housing affordability, access to communication and food, in particular animal products as a source of protein.

Localities with low sustainability indices in ESI and SSI showed better behavior in LUSI (>0.66). This is explained by the fact that they did not present a significant change in soil use and their erosion rate was low. Three others localities with intermediate values of economic and social sustainability also presented intermediate values in the LUSI. This is due to the fact that, in addition to participating in mining activities, towns and villages are developing alternative activities such as self-consumption agriculture.

The LSI integrated by ESI, SSI and LUSI showed that three of the twelve localities presented the lowest sustainability indices (<0.39). This may be due to the fact that these localities are far from large population centers and therefore they lack on fixed and well-paid jobs, which is reflected in the precarious housing conditions, poor access to basic services and healthy food.

Although there is a dynamic in the change of coverage of forestland to the use of mining land, there was still insufficient evidence to affirm that the activity implies a process of forest degradation in the region studied, perhaps due to its surface area. We also concluded that mining activity did not have a significant impact on the LUSI component in the two natural protected areas. The condition of being within an area with a protected natural area category had only impacts on the social sustainability index. This is probably due to the distance from the localities to the mining centers. This implies that conservation may halt social development in the region, as an expression of decent housing, water availability, and access to food. Then, there is a dilemma that needs to be resolved: while mining provides immediate social benefits in terms of jobs, income, and infrastructure, conservation runs short on it, and therefore, mining would be more attractive for people under poverty. This dilemma urges the finding of sustainable programs for those localities, such as ecotourism or payments for environmental services to compensate for those benefits that mining could not bring in the short run.

Although mining wealth appears to improve the quality of life for localities in the Ocampo mining region, it is necessary to extend these scales of study to the other mining regions of the Sierra Tarahumara where indigenous workers prevail. It is also necessary to obtain information related to the perception of the local residents in relation to their opinion by the economic, social and environmental impacts.

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