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Multi-Criteria Prioritization of Watersheds for Post-Fire Restoration Using GIS Tools and Google Earth Engine: A Case Study from the Department of Santa Cruz, Bolivia

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Abstract: The Santa Cruz department in Bolivia is characterized by a wide range of ecosystems and by its richness in water resources. In recent years, extended drought caused by climate change has led to extensive fire events. Combined with deforestation, this is resulting in the degradation of the region's ecosystems and water resources. To address restoration needs from both a land- and water-management perspective, this study proposes to prioritize restoration areas by applying a multi-criteria analysis (MCA) based on two main principles: (1) using the watershed as the main study unit and (2) involving stakeholders in the definition of priority watersheds. Local stakeholders selected criteria representing water resources, biophysical characteristics, land management, productive areas, and fire disaster threats, and reclassified the spatial information based on perceived importance. Different prioritization scenarios were developed and compared in a Google Earth Engine (GEE) application. Priority restoration areas largely depend on the weighting scheme. Focusing solely on past fires leads to prioritizing the south-east basins, while the conservation of the western watersheds becomes more important when increasing the weight of the water resources criteria. This study represents the first step in developing a participatory MCA tool at the watershed scale in Santa Cruz. Highlighting the impact of different prioritization criteria can support collective decision-making around land and watershed restoration.

Keywords: watershed management; forest restoration; criteria and indicators; priority areas; participatory process

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1. Introduction

Water in Latin America is both an environmental and an economic resource and its management is critical for sustainable development in the 21st century [1,2]. Though the region is rich in abundant water resources, the security of water quantity and quality is subject to population growth and urbanization, increasing demands for irrigated agriculture, combined with financial and institutional issues [3]. In addition, forest resources and ecosystems are also suffering from irreversible degradation caused by deforestation and wildfires of increasing frequency and magnitude [4].

Human-induced changes to land cover and forests are resulting in a loss of biodiversity [5] and likely further impacting the water resources [6]. For instance, forest cover affects the interception of rain and other components of the water balance and thus plays a key role for water resources [7]. The loss of forest cover could lead to increases in surface water runoff and decreased groundwater recharge [8]. In addition, water quality is impacted by changes resulting from soil erosion and increased nutrient and sediment loading in rivers following riparian wetland loss [9]. There is a link between the forest, water, and energy cycles, in the sense that forests are key to mitigating water scarcity and global warming [10]. Consequently, it is essential to focus on ecosystem restoration, as it will benefit both water resources and biodiversity.

In recent years, interests in ecological restoration have grown considerably in Latin America, with a large focus on Brazil, Mexico, Chile, and Argentina, leading to a great number of ecosystem prioritization studies that aim to select areas best suited for restoration [11]. From a technical point of view, site selection and decision-making for environmental restoration, ecosystem management, and nature conservation objectives may involve a large number of possible alternatives and evaluation criteria. For this reason, many studies have stressed the benefits of multi-criteria analysis (MCA) and Geographic Information Systems (GIS) for prioritizing areas for restoration due to the spatial aggregation and criteria combination possibilities [12–14]. Indeed, coupling MCA and GIS is an efficient approach when solving spatial and environmental problems, as it makes it possible to consider many choice criteria, diverse stakeholder values, and spatial datasets that characterize the studied landscape [15]. The main factors considered in the MCAs are typically species richness, ecosystem diversity, forest degradation, land use, and various socioeconomic factors [16]. Valente et al. [12] focused on water ecosystem services but noted that few other restoration prioritization studies in Brazil have included water resources.

From a social perspective, decision-making around biodiversity, land use change, and climate change is complex as it is influenced by individual values and perceptions of the problems [17]. Successful restoration efforts depend on the technical assessment of the landscape's characteristics and the analytical decision-making framework, as well as on local perceptions of the restoration goals [18]. Stakeholder consultation can be combined with MCA approaches to integrate local knowledge with regional case studies and cross-sector management plans [19]. It is therefore useful to involve local experts in the process of identifying and prioritizing suitable restoration actions [20,21].

In terms of the spatial aggregation scale, watersheds are the basic unit for water management [22]. For example, in Europe, the river basin is the reference unit for major policy frameworks for water resources management, such as the Water Framework and the Floods Directives, which integrate both water resources protection and safety in the face of extreme events [23]. Though less common for land management, there are examples of spatial prioritization studies at the watershed scale based on soil erosion, groundwater recharge potential, water quality, and conservation purposes. Gumma et al. [24] prioritized watersheds for agricultural development and proper natural resources management in Mali. In India, Javed et al. [25] prioritized subwatersheds for natural resources conservation using morphometric characteristics and land cover and Kumar et al. [26] prioritized watersheds on the basis of soil erosion.

In Bolivia, river basin planning is still in its earlier stages of development and implementation [27]. Despite the fact that restoration is a national priority [28], the associated planning tools are insufficient. Watershed management is complex due to the large number of public entities involved with overlapping and conflicting roles and to tensions between the various governance levels [29].

Santa Cruz, the largest of the nine departments in Bolivia, is facing crucial socio-environmental sustainability issues. Both its Key Biodiversity Areas [30] and forest areas [28] have been significantly affected by wildfires in the last two decades. In response to the major forest fires of 2019, the Autonomous Departmental Government of Santa Cruz (Gobierno Autónomo Departamental de Santa Cruz—GADSC), in conjunction with the Bolivian National Government, developed the Plan for the Recovery of Areas Affected by Fires [31]. Although there are notable advances in the prioritization of burned areas in the department [32], there is still no study that allows for the prioritization of impacted ecosystems at the watershed level. Thus, there is potential to innovate by adopting a comprehensive view of land and water resources management and developing spatial-analytical tools that connect information that is useful across institutions.

This paper aims to identify relevant criteria for the prioritization of forest restoration areas and watershed management plans in the department of Santa Cruz, Bolivia. The study combines spatial analysis in ArcMap and Google Earth Engine (GEE) with MCA tools and the input from GIS experts, natural resources specialists, and regional authorities, collected during participatory workshops, to compare different restoration scenarios in Santa Cruz.

2. Materials and Methods

2.1. Study Area

The study area corresponds to the department of Santa Cruz in eastern Bolivia, at the border of Brazil and Paraguay. This department covers 370,621 km^2, representing close to one third of the country's territory. In terms of population, the department is home to almost 3.5 million people [33] with the majority located in the capital city of Santa Cruz de la Sierra. Santa Cruz is the driver for Bolivia's economic development, contributing to 30% of the country's gross domestic product thanks to its timber, oil and gas reserves, cattle farming, and recently, soy and sugar production [34].

The region sits between two major basins: the Amazon Basin in the north and the La Plata Basin in the south (Figure 1). It is divided into 16 macrowatersheds [35]. In the north, the main rivers are the Iténez River, which is the longest in the department, the Río Grande, the Piraí River, and the Itonomas River. In the southern basin, the primary rivers are the Paraguay River and its tributaries. The area is also home to several significant lakes, including Mandioré, Uberaba, La Gaiba, Marfil, Concepción, and San Jorge.

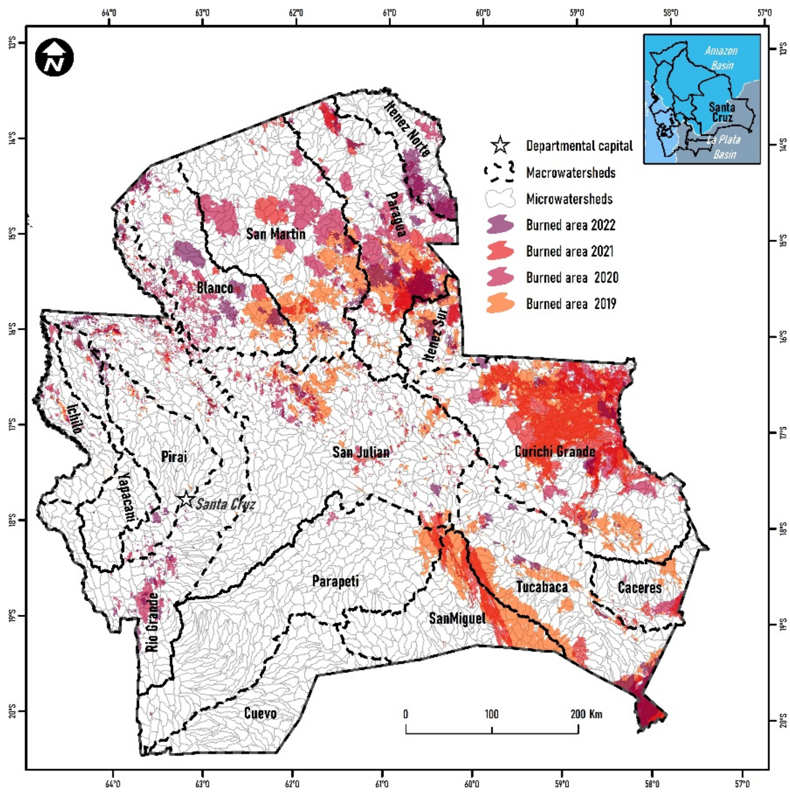


Figure 1. Watersheds of the department of Santa Cruz and burned area scars from fires between 2019 and 2022.

This region of Bolivia is characterized by a great variety of ecosystems, described by Ibisch and Mérida [36]. In the western part, there are temperate sub-Andean valleys, while to the north and south, there are two distinct lowland regions: the Beni and the Chaco regions. The flat areas to the north-east are known as the Chiquitania region, which is characterized by a low elevation and a few hills up to 1250 m high. In the far east, there are small portions of the enormous Pantanal wetland.

The forests and ecosystems in Santa Cruz are under threat from habitat conversion and fragmentation due to agricultural expansion and unplanned colonization [37], infrastructure development, and uncontrolled logging. In the last two decades, and in particular since 2019 (Figure 1), an increasing trend in the frequency, intensity and magnitude of wildfires has been observed [28], which can be linked to temperature increases, drought events, and fragmentation processes [38]. The resulting loss and degradation of primary forests is transforming the watersheds in Santa Cruz in ways that could potentially impact the quality and availability of the area's water resources [39].

2.2. MCA Methodology and Datasets

MCA methods include a range of techniques designed to help structure decisions and evaluate alternative options through the definition and weighing of measurable criteria [15]. A broad categorization divides the methods into non-compensatory and compensatory approaches: the former imply fixed limits for including or excluding options, while the latter allow for trade-offs and compensation between the analysis criteria [40]. A preliminary screening of fire-affected watersheds was applied (Section 2.2.1) followed by a compensatory MCA (Sections 2.2.2–2.2.6) to select priority watersheds.

2.2.1. Selection and Analysis of the Santa Cruz Watersheds

The watershed prioritization uses two different scales of analysis: micro- and macrowatersheds. The prioritization area was narrowed down to a spatial selection of the watersheds in which fires occurred between 2019 and 2022. The watershed level 12 dataset from the HydroSHEDS product was used for the microwatersheds (Table 1). The macrowatersheds layer was generated by the GADSC with the watershed name attributes corresponding to the main Santa Cruz rivers [35]. The watershed layers were processed in ArcMap to identify the watersheds impacted by fires using the Fundación para la Conservación del Bosque Chiquitano's (FCBC) fire scar maps from the years 2019 to 2022 (Table 1). This selection was used to create a mask for the spatial aggregation. The total burned area and area burned in each macrowatershed was calculated with ArcMap raster calculations and zonal statistic tools.

Table 1. Overview of datasets, sources, and pre-processing.

Layer Used in the MCA	Input Dataset	Processing Tool in ArcMap	Input Source	Source Link or Reference
Macrowatersheds	Gobierno Autónomo Departamental de Santa Cruz's (GADSC) macrowatersheds	Spatial selection and intersection with the Fire occurrence layer	GADSC	[35]
Microwatersheds	HydroSHEDS product, level 12	Spatial selection and intersection with the Fire occurrence layer	World Wide Fund (WWF)	https://www.worldwildlife.org/pages/hydrosheds (accessed on 12 April 2022)
Proximity to surface water	2021 Landsat-based vegetation cover and deforestation product.	Extracting the water class, Euclidean distance	Landsat; Fundación para la Conservación del Bosque Chiquitano (FCBC)	[38]
Well density	Well site coordinates (points)	Kernel Density tool	GADSC, local water cooperatives, municipalities	
Precipitation	Average precipitation for 1970–2000, WorldClim version 2.1	Re-scaling to the department level	WorldClim	https://www.worldclim.org (accessed on 10 April 2022)
Land cover	Land cover map	Reclassification into five land cover classes	FCBC	
Elevation	Aster Global Digital Elevation Map (GDEM) version 2 sensor scenes	Mosaic to New Raster tool	National Aeronautics and Space Administration (NASA)/Japan Space Systems	https://ssl.jspacesystems.or.jp/ersdac/GDEM/E/4.html (accessed on 11 March 2023)

Table 1. *Cont.*

Layer Used in the MCA	Input Dataset	Processing Tool in ArcMap	Input Source	Source Link or Reference
Slope	Aster GDEM version 2 sensor scenes	Slope tool	NASA/Japan Space Systems	https://ssl.jspacesystems.or.jp/ersdac/GDEM/E/4.html (accessed on 11 March 2023)
Protected areas	Maps of national, regional and municipal protected areas	Raster conversion and reclassification	GADSC	
Land ownership	Landowner mapping	Raster conversion and reclassification	National Institute of Agrarian Reform (INRA)	
Proximity to roads and infrastructure	Digitized roads	Euclidean distance tool	FCBC	
Population density	2012 population census	Kernel Density tool	National Statistics Institute (INE)	http://geo.gob.bo/portal (accessed on 23 March 2023)
Fire occurrence	4 fire scar maps: 2019, 2020, 2021, 2022	Cell statistics tool	FCBC	
Fire intensity	Fire Radiative Power, MODIS Collection 6.1 product	Interpolation using the Inverse Distance Weighted (IDW) technique [30]	NASA's Fire Information for Resource Management System (FIRMS)	https://firms.modaps.eosdis.nasa.gov (accessed on 12 April 2022)

2.2.2. Analytical and Participatory Framework

The main technique applied in the prioritization methodology is a conventional compensatory MCA that entails defining objectives and selecting, ranking, and weighting the variables that support the objectives in order to evaluate different prioritization alternatives. For spatial problems, this process involves the translation of geographic data into priority assessments and preferences using GIS [41].

To reflect local expertise, stakeholders were involved in every step of the process, from design to tool testing (Figure 2). Collaborating with stakeholders and decision-makers in a participatory approach ensures that their values and preferences are accounted for in the MCA and decision-making process [14,20]. The consultation engaged representatives of civil society and non-profit organizations, experts in water and natural resources management, environmental planners, and representatives of the regional and municipal governments. This inclusive approach provided valuable insights into local expectations regarding forest and watershed management and ensured that the prioritization methodology was based on the unique context of the study area.

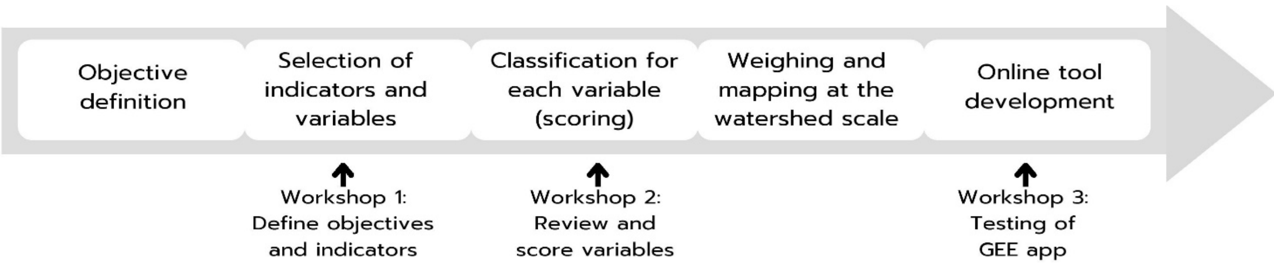


Figure 2. Steps in the development of the prioritization framework and tool.

2.2.3. Prioritization Objectives

The initial step towards the development of the prioritization framework was to agree upon the objectives of the analysis. While some burned areas in Santa Cruz can be restored through natural regeneration processes, others call for assisted restoration [30]. The agreed scope of the prioritization was to select restoration areas for active interventions rather than passive and natural regeneration, which corresponds to the definition of ecological restoration used by Mansourian et al. [42]. The primary aim established with stakeholders was to identify watersheds that exhibit richness in biodiversity and water resources while also taking into account the threats posed by human activities and the risk of wildfires. In this way, the prioritization framework addresses the conservation of water resources and ecosystems and identifies the areas most in need of restoration based on existing environmental and human-made risks.

2.2.4. Variable Selection

The set of indicators or criteria for the prioritization was selected in line with the study objectives, the scientific literature, and in dialogue with local experts. The first facilitated workshops with conservation and GIS experts led to the grouping of variables into five indicator categories: water resources, biophysical characteristics, land ownership and management, vulnerability to human impacts, and exposure to natural hazards. For each indicator group, the contributing variables were chosen according to data availability at the scale of the department of Santa Cruz. In total, 12 variables (i.e., 12 raster layers) were used in the analysis. All the input datasets were processed with ArcMap tools (Table 1) and resampled to a spatial resolution of 30 m.

1. Water Resources Conservation

Together with local experts and authorities, proximity to surface water and groundwater were identified as key factors in determining the value of an area for water resources. Restoration actions close to water bodies protect both ecosystems and water resources [43]. Due to the limited access to stream flow and groundwater data, proxy variables such as the proximity to streams and the density of wells were used. The surface water class was obtained from a Landsat-based vegetation cover and deforestation product developed by the FCBC for the year 2021 [38]. The proximity to streams was then calculated using Euclidean distance (in m). In addition, well data was provided by the GADSC and by technicians at water cooperatives and municipalities. The well density map was generated using the ArcMap Kernel Density tool (km^2). Stakeholders also chose precipitation as an indicator of water availability, as described by Ianni and Geneletti [44]. The average precipitation data (mm) for 1970–2000 were downloaded from WorldClim version 2.1 and re-scaled to a 30 m pixel.

2. Biophysical Characteristics

To represent the landscape's biophysical characteristics, land cover data were included, as one aim of the prioritization was to restore forest and vegetation areas. The FCBC's land cover map was reclassified into five classes: non-vegetated area, other non-forest natural formation, wetlands, forest, and flooded forest. In addition, the restoration of ecosystems that are located on a high slope and at higher elevation was prioritized, as steeper areas are more susceptible to erosion and to the impacts of human activities and natural hazards [45,46]. The elevation (m.a.s.l.) and slope (degrees) layers were obtained from Aster Global Digital Elevation Map (GDEM) version 2 sensor scenes.

3. Managed and Protected Areas

Protected landscapes are key areas for biodiversity conservation and for the preservation of cultural and social values [47]. Protected areas were included in the analysis to prioritize areas with a high conservation value and to support the ecosystem services they provide. All governance levels (national, regional, municipal) were considered and obtained from mapping data provided by the GADSC. Moreover, a land-ownership dataset provided by National Institute of Agrarian Reform (INRA) was added to prioritize community and indigenous-owned land.

4. Human Activity Threats

In terms of threats from human activities, the analysis considered population density and proximity to roads and built infrastructure. The Euclidean distance to roads and productive areas was calculated (in m) using FCBC's maps of anthropogenic land use. Population density (per km^2) was calculated using the 2012 population census from the

National Statistics Institute [33] and the Kernel Density tool. Populated areas and productive areas were prioritized to reflect stakeholders' preference to restore ecosystem services in the vicinity of urban centers and human activities. Generally, studies do not prioritize locations close to roads or urban areas [45,48] as these are considered a disturbance that reduces the restoration's feasibility factor [13].

5. Vulnerability to Wildfire Hazards

Fire occurrence and fire intensity were selected to prioritize the restoration of the most exposed watersheds. It was assumed that the intensity of fires and the number of recurring fires may determine whether the vegetation will be able to regenerate naturally or not and that active restoration should focus on the ecosystems most impacted by fire. Using the FCBC's fire scar maps, a layer sum operation was applied to calculate the recurrence of fire events over the 2019–2022 period. The intensity of the fires was obtained using the Fire Radiative Power (FRP) (in MW) in the MODIS Collection 6.1 product (1 km resolution), from NASA's Fire Information for Resource Management System (FIRMS). An interpolation of the FRP data was performed using the Inverse Distance Weighted (IDW) technique to obtain the intensities [30].

2.2.5. Variable Scores

During the second stakeholder workshop, the values of each variable were ranked from very low to very high importance for the prioritization. For both quantitative and qualitative variables, the values were distributed into five classes. This participatory ranking process captured the local preferences regarding each criterion and was also complemented with examples from the literature. The subsequent scoring step allowed for the comparison between the different variables by transforming the values of each spatial dataset into a common scale. Specifically, the ArcMap reclassification tool was used to assign variable scores ranging from 1 (least important for restoration) to 5 (most important) as shown in Table 2.

Table 2. Ranking of prioritization variables.

Category	Variables/Importance	1-Very low	2-Low	3-Medium	4-High	5-Very high
Water resources	Distance to rivers/water bodies (m)	>10,000	5000–10000	2000–5000	1000–2000	<1000
	Density of water wells (km^2)	<0.01	0.01–0.02	0.02–0.05	0.05–0.07	>0.07
	Precipitation (mm)	<500	500–1000	1000–1500	1500–2000	>2000
Ecosystems and biophysical criteria	Elevation (m a.s.l.)	<100	100–250	250–500	500–1000	>1000
	Slope (°)	<30	30–40	40–50	50–60	>60
	Land cover type	Non-vegetated area	Other non-forest natural formation	Wetland	Forest	Flooded forest
Land governance	Protected areas (national, regional or municipal)	No protected area	N/A	N/A	N/A	Protected
	Land ownership	Urban	Small to large private property	Community-owned	Indigenous territories	State-owned
Human activities	Distance to productive areas, roads, population centers (m)	>2000	1500–2000	1000–1500	500–1000	<500
	Population density (inhabitants/km^2)	<10	10–20	20–40	40–1000	>1000
Fire threat	Recurrence of fires between 2019–2022 (4 years)	0	1	2	3	4
	Intensity of fire (MW)	0	1–250	250–500	500–1000	>1000

2.2.6. Aggregation to Microwatersheds and Macrowatersheds

To aggregate the classified and scored variables, a Weighted Linear Combination (WLC) method was applied. This method has been validated for forest restoration and conservation by a number of authors [43,49–51]. It consists of multiplying each standardized criterion's spatial layer (i.e., pixels) by an assigned weight and then summing the weighted criteria to produce a final result layer. The WLC can be applied in one step or hierarchically to aggregate variables within a group before combining groups together [40]. Applying the latter approach, equal weights were assigned to the variables in each indicator group. Then, another set of indicator weights was assigned to each group of variables (Figure 3).

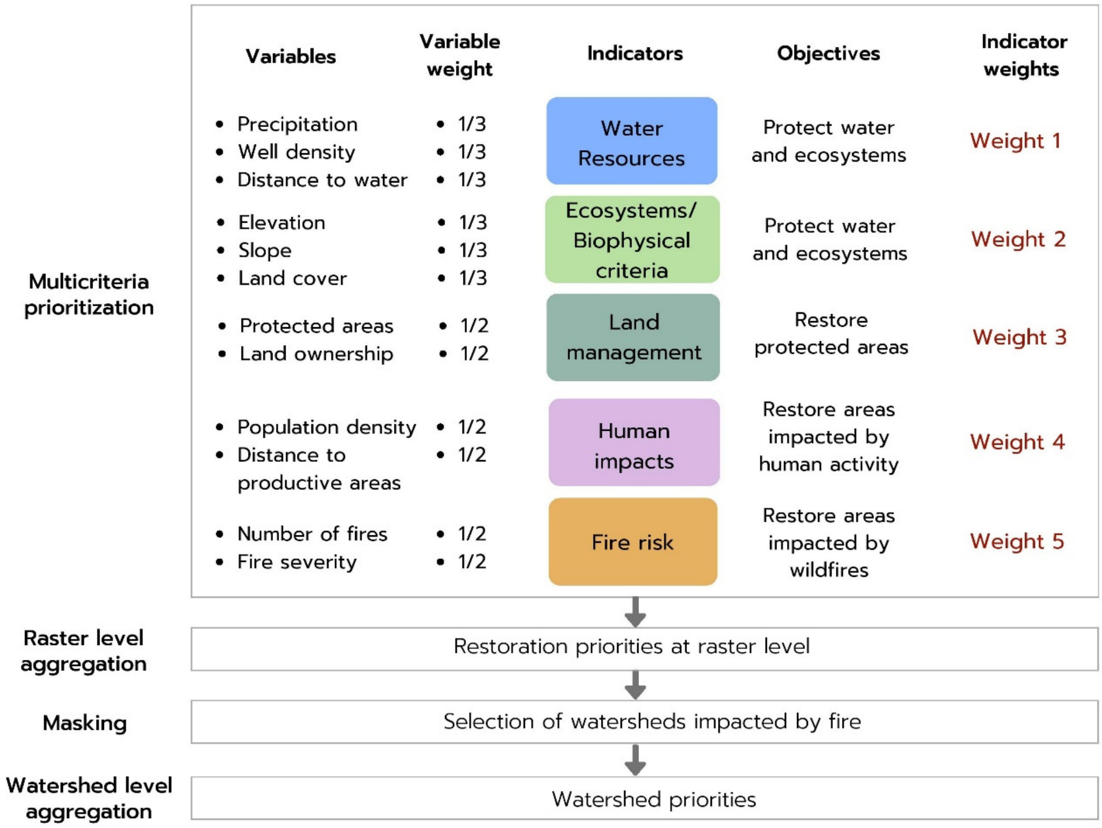


Figure 3. Prioritization-tree developed with technical experts and government authorities during the workshops.

The overall priority P for each pixel is calculated following the algebraic operations (1) and (2), where j is a variable contributing to indicator i, P_j is the corresponding pixel value, n is the number of variables in a group, P_i is the pixel-level priority for indicator i and W_i is the weight assigned to indicator group i:

$$\text{Indicator group priority } P_i = \sum\nolimits_{j\,=\,1 \text{ to } n} P_j \times 1/n \quad (1)$$

$$\text{Overall priority } P = \sum\nolimits_{i\,=\,1 \text{ to } 5} (W_i \times P_i)/\sum W_i \quad (2)$$

In this case study, examples of the contribution of different indicator weights in the prioritization of watersheds are illustrated. A total of 12 scenarios were considered: the first five (A–E) focus on a single indicator group, while scenario F shows the result of equally valuing all five groups. The remaining scenarios (G–L) give equal priority to two or three indicator groups (Table 3). It must be noted that these are only illustrations of possible weight combinations and that different weight values and combinations of indicators could be considered.

Table 3. Prioritization scenarios.

Scheme 1	W1	W2	W3	W4	W5
A—water	1	0	0	0	0
B—ecosystems	0	1	0	0	0
C—management	0	0	1	0	0
D—human activities	0	0	0	1	0
E—natural hazards	0	0	0	0	1
F—all combined	1	1	1	1	1
G—water + ecosystems	1	1	0	0	0
H—water + ecosystems + management	1	1	1	0	0
I—human impacts + fire	0	0	0	1	1
J—water + human impacts	1	0	0	1	0
K—water + fire	1	0	0	0	1
L—ecosystems + fire	0	1	0	0	1

When averaging all weighted indicators to obtain the restoration priority map, minimum to maximum stretching was applied to obtain results between 1 and 5. Therefore, the prioritization gives a relative priority associated with a set of weights rather than an absolute priority across all weighing schemes. Finally, the raster level results were averaged at the microwatershed and macrowatershed scale using zonal statistics, corresponding to the masking and aggregation steps in Figure 3.

All the MCA steps were implemented using GEE. The GEE platform offers interactive and user-friendly interfaces designed for conducting spatial analyses using either Earth Engine's data catalog or uploaded datasets [52]. First, the spatial layers representing the ranked variables were imported into the GEE database. Then, a Javascript code was developed in the code editor to read-in the spatial data and perform the aggregation, weighting, and mapping of the prioritized watersheds. For the purpose of accessibility and the potential for local hosting, the code was used to create an online application (https://jeannefdz.users.earthengine.app/view/watershed-prioritizer-sc, updated on 7 August 2023). The tool was presented to local stakeholders during the testing workshop, and this provided an opportunity for potential users to review the prioritization framework and discuss future developments.

3. Results

3.1. Watersheds Impacted by Wildfires

The results of the GIS analysis of recent fire scars in the department of Santa Cruz show that the area impacted by wildfires varies annually, but in the year 2019 an extreme series of fire events burned 42,005 km^2. This was the largest burned area in the last four years (2019–2022). The absolute total area impacted by fires between 2019 and 2022 in Santa Cruz was 73,481 km^2. Of this total, the macrowatershed of Curichi Grande represents 21,225 km^2 (29%), San Martin accounts for 10,464 km^2 (14%) and Paragua accounts for 9109 km^2 (12%) (Figure 4). The watersheds in Figure 4 are sorted according to the fraction of the watershed area impacted by wildfires in 2019–2022. Based on this, over 25% of the surface area in Itenez Sur, Paragua, San Miguel, San Martin and Tucabaca was affected by fires, reaching 50% in Curichi Grande. If focusing primarily on burned areas, restoration activities would be centered around these watersheds. At the microwatershed scale, 1765 watersheds of the 3004 (59%) were affected by wildfires in at least one of the four years (2019–2022).

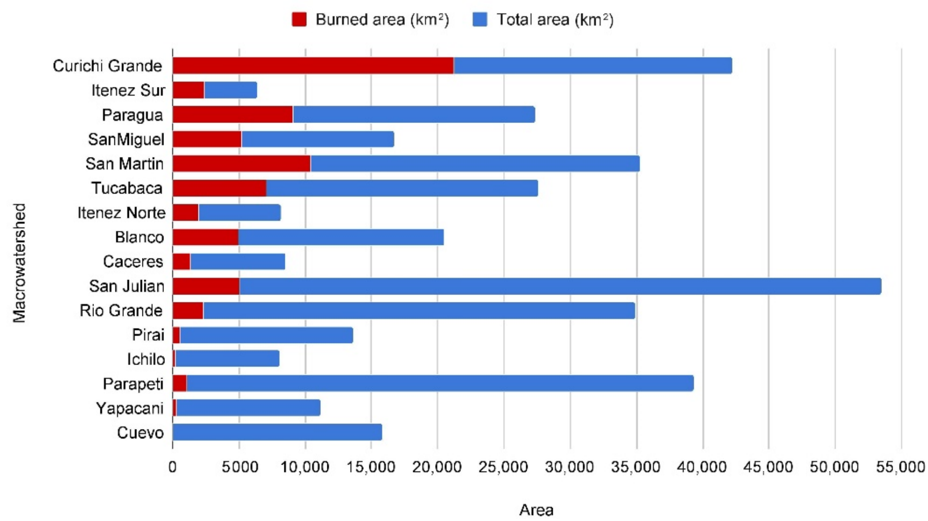
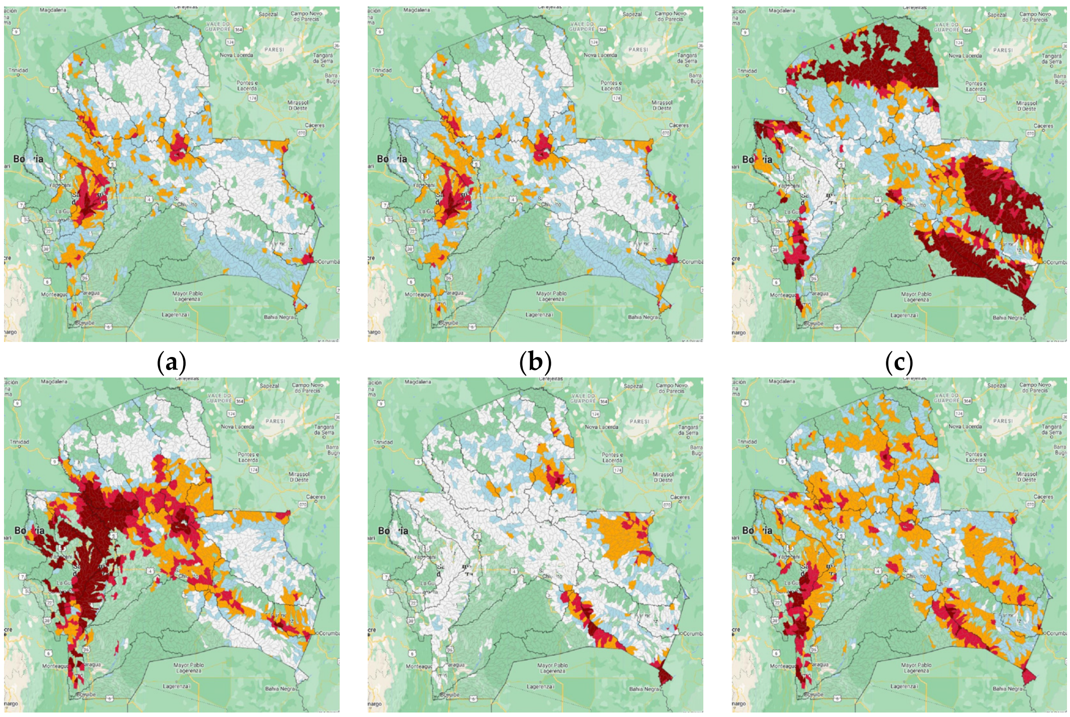


Figure 4. Burned areas in the watersheds of the department of Santa Cruz and their relation to the total watershed area (km^2).

3.2. Priority Watersheds in Santa Cruz

The MCA results give an overview of the priority watersheds for each example scenario considered in this case study. The series of maps in Figures 5 and 6 depict the priority levels of the Santa Cruz watersheds, ranging from very low priority (1—light gray) to very high priority (5—dark red). Figure 5 shows the 12 example scenarios at the microwatershed level and Figure 6 shows six examples at the macrowatershed level.

For scenarios A to F, summary data are provided in Tables 4 and 5 with information on the number of medium–high-priority watersheds (weighted indicator average >3.4) and the total medium–high-priority area they cover.



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

Figure 5. *Cont.*

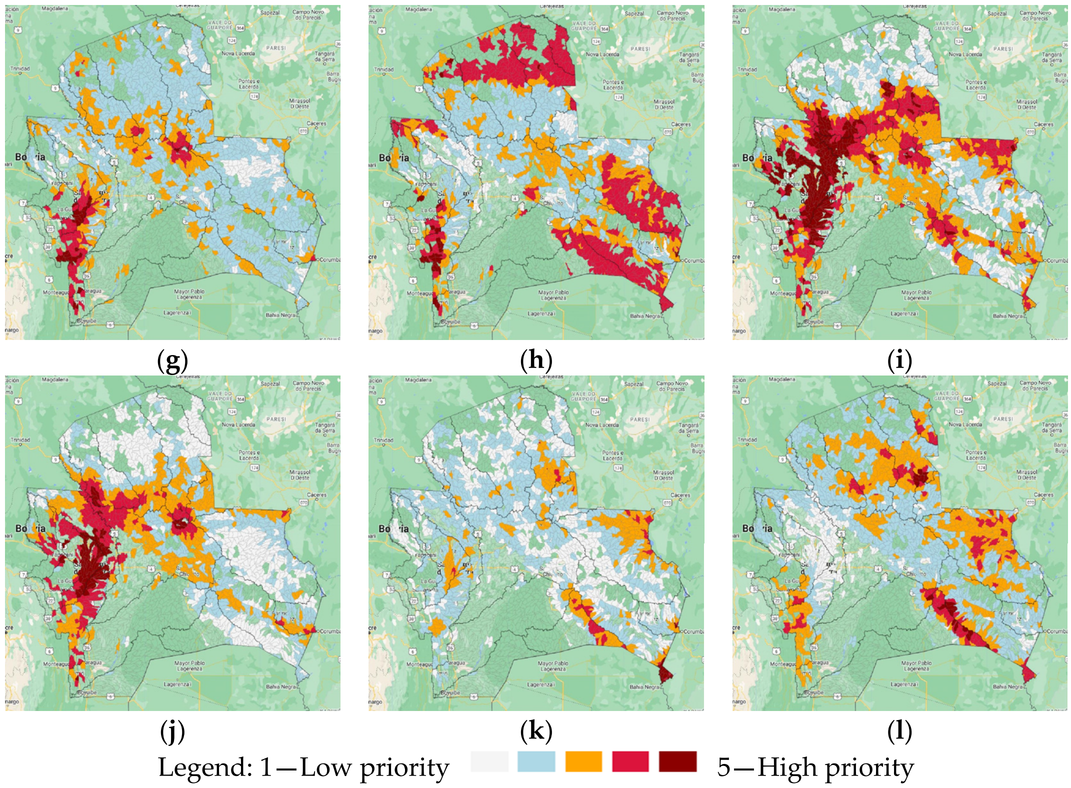


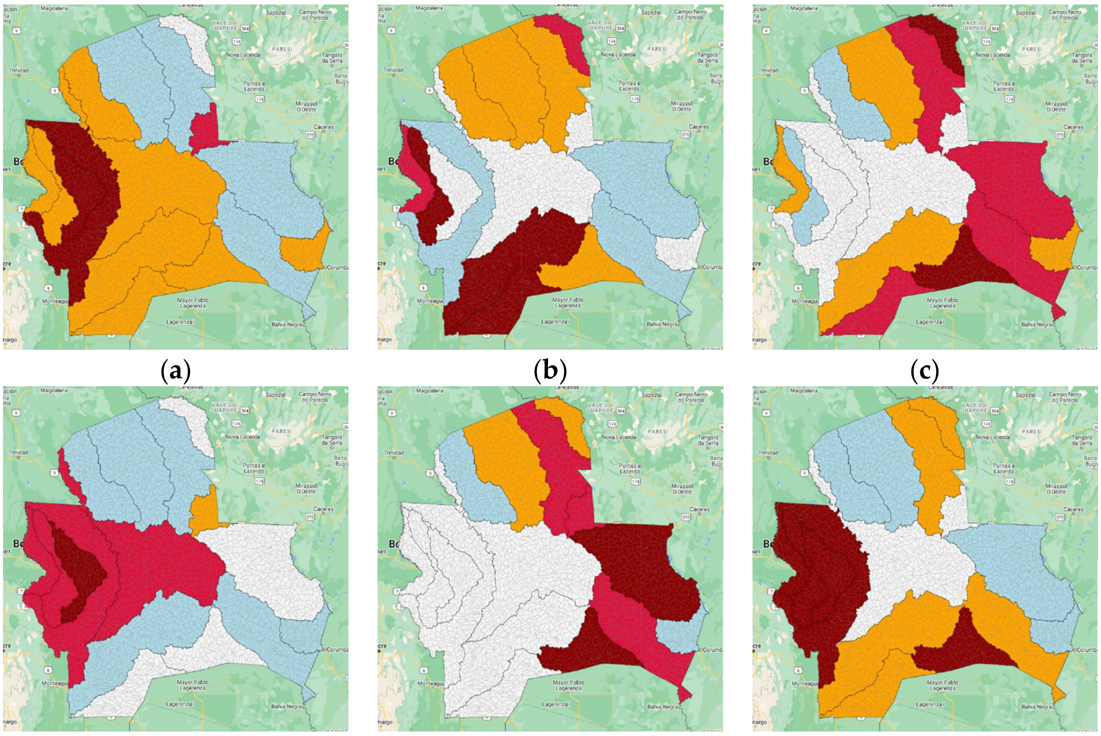
Figure 5. Microwatershed level priority maps for scenarios A-L. (**a**) Scenario A—water; (**b**) Scenario B—ecosystems; (**c**) Scenario C—management; (**d**) Scenario D—human activities; (**e**) Scenario E—natural hazards; (**f**) Scenario F—all combined; (**g**) Scenario G—water + ecosystems; (**h**) Scenario H—water + ecosystems + management; (**i**) Scenario I—human impacts + fire; (**j**) Scenario J—water + human impacts; (**k**) Scenario K—water + fire; (**l**) Scenario L—ecosystems + fire.

Table 4. Microwatershed level priority area summary for example scenarios A–F.

Scheme 2	High-Priority Area (km^2)	Priority Watersheds (Count)
A—water	16,061	80
B—ecosystems	34,322	156
C—management	102,756	457
D—human activities	82,145	310
E—natural hazards	16,140	99
F—all combined	19,905	88

Table 5. Macrowatershed level priority area summary for example scenarios A–F.

Scenarios	High-Priority Area (km^2)	Priority Watersheds (Count)	Priority Macrowatersheds (Names)
A—water	54,911	3	Pirai, Rio Grande, Itenez Sur
B—ecosystems	82,389	5	Itenez Norte, Yapacani, Ichilo, Cuevo, Parapeti
C—management	137,698	6	Itenez Norte, San Miguel, Paragua, Curichi Grande, Tucabaca, Cuevo
D—human activities	121,136	5	Pirai, Yapacani, Rio Grande, San Julian, Ichilo
E—natural hazards	120,193	5	Paragua, Itenez Sur, Curichi Grande, San Miguel, Tucabaca
F—all combined	84,366	5	Rio Grande, San Miguel, Pirai, Yapacani, Ichilo



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

Legend: 1—Low priority 5—High priority

Figure 6. Macrowatershed level priority maps for scenarios A-F. (**a**) Scenario A—water; (**b**) Scenario B—ecosystems; (**c**) Scenario C—management; (**d**) Scenario D—human activities; (**e**) Scenario E—natural hazards; (**f**) Scenario F—all combined.

Based on scenarios A–E, which correspond to a single indicator group prioritization, it appears that 80 out the 1765 fire-affected microwatersheds in Santa Cruz are important in terms of water resources alone, 156 are a high priority for ecosystems, and 457 are important under existing forms of land management. In terms of threats, 310 microwatersheds are in the vicinity of human activity, infrastructure, or populated centers and 99 were exposed to wildfires in the past four years (Table 4). The priority areas range between 16,061 km^2 and 102,756 km^2 depending on the prioritized indicator group (between 4% and 28% of the Santa Cruz Department). Compared to the results at the macrowatershed level, which vary between 54,911 km^2 and 137,698 km^2 (15% to 37% of the department), the area is much smaller, in accordance with the smaller analysis unit (Table 5).

In scenario C—management, the number of medium-high-priority watersheds can be explained by the high ranking given to protected areas by stakeholders in the variable classification process and by the large surface of the Santa Cruz department that is protected at either municipal, regional, or national level. In scenarios A and E, less than 100 microwatersheds have a medium–high importance which is again due to the classification step and the variables considered in the water and ecosystems indicator groups.

Scenario F—all combined shows fewer microwatersheds with a medium–high priority compared to all other scenarios except scenario A. When combining multiple indicator groups, the priority microwatersheds are rather scattered out across the department. This is due to the aggregation and equal weighing of all indicator groups, as well as to the limited spatial overlap between the analysis variables. This tends to give an average priority to all watersheds when combining all criteria equally.

3.3. Importance of Water Resources

The area that is important for water resources, based on scenario A, is primarily located in the western part of Santa Cruz, in particular in the macrowatersheds of Pirai and Rio Grande. These watersheds are also high priority in terms of human impacts due to the proximity with the city of Santa Cruz de la Sierra. In addition, the priority watersheds in scenario A which are located in the middle of the department correspond to areas with more wells and possibly groundwater resources, while in the south-west, the priority watersheds correspond to higher precipitation regions. In terms of overlap with ecosystems and biophysical characteristics, the middle of the map is characterized by the presence of the dry tropical Chiquitano forest and the landscape in the south-west, by a high slope and elevation. The protected areas prioritized in scenario C—management do not overlap with priority areas for water resources. Finally, the watersheds most affected by fires in 2019–2022 (scenario E) do not correspond to the priority watersheds in scenario A, defined by the proximity to surface water, the density of wells, and by the annual rainfall.

3.4. Impacts of the Analysis Unit

The results clearly show the impacts of scale when working with microwatersheds versus macrowatersheds. While at the microwathershed scale, the microwatersheds that were not impacted by fires were filtered out of the analysis, a similar filtering process could not be applied to macrowatersheds as there have been fires in all macrowatersheds, even in Cuevo (less than 1% of the area) (Figure 4). Thus, the entire Cuevo and Parapeti watersheds in the south-west, are ranked as important in prioritization scenario B—ecosystems when only a fraction of the microwatersheds, i.e., a much smaller surface, is included in Figure 5 for the same scenario.

In Scenario F—all combined, the macrowatershed level aggregation does not capture any priorities in the larger watersheds of Curichi Grande, San Julian, San Martin, and Blanco. This is because the macrowatershed's total area influences the aggregation and the few high-priority microwatersheds no longer appear as important at this scale. The size of the microwatersheds ranges from 0.5 km^2 to 3206 km^2 (with an average of 230.1 km^2 and a standard deviation of 241.8 km^2) and the size of the macrowatersheds varies from 6409 km^2 to 53,442 km^2 (average: 23,048 km^2 and standard deviation: 14,496 km^2). Thus, the microwatershed unit is a finer scale with less dramatic variations in surface area. It can better capture landscape changes compared to larger management units (macrowatersheds or municipalities).

3.5. Online Application

The online GEE application incorporates the key indicators and objectives applied to the watershed prioritization in Santa Cruz. The application includes the set of spatial datasets that were collaboratively selected and that can be combined at the watershed level. As shown in Figure 7, the interface consists of a Google Maps layer, which is centered on the department of Santa Cruz. The user can select spatial datasets to be displayed by clicking on layer names located in the drop-down list, e.g., "Precipitation". The map and legend are updated according to the chosen indicator.

The main weights can be assigned to the prioritization indicators so that different scenarios can be compared. To assign weights, the user may input values between 0 and 5 into the text boxes. Upon clicking on the "Apply weights" button, cloud-based spatial analyses are launched to create a microwatershed or macrowatershed ranking map utilizing the user-defined weights and the selected scale. The watershed ranking for the restoration ranges from low to high priority. When clicking on "View high priority summary", the number of medium-to high-priority watersheds and the area they cover are shown.

The running time to load the data layers or to apply weights on a regular computer with a stable internet connection is less than one minute. The application can be accessed online by individuals, both experts and non-experts, without a Google account.

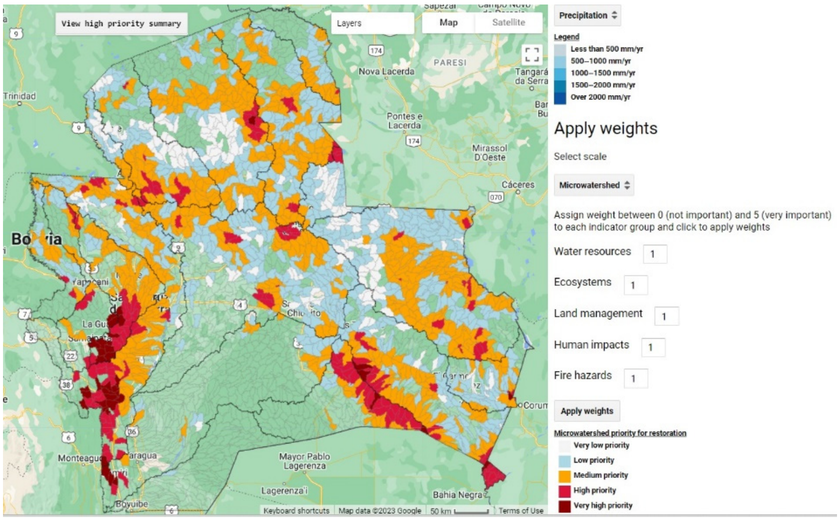


Figure 7. GGE application interface after applying weights.

4. Discussion

4.1. Addressing a Need for Integrative Restoration Methodologies

In Bolivia, the restoration of ecosystems impacted by fires is a high priority, in compliance with international commitments and agreements [53]. However, restoration actions and prioritization are usually based on the areas burned annually in each administrative unit and do not consider the multiple indicators that can impact the need for restoration. The current study offers a valuable foundation for prioritizing restoration efforts in the Santa Cruz department in Bolivia, by integrating water resources into restoration planning and aggregating a comprehensive set of indicators at a scale that is relevant to both ecological and hydrological processes [54]. The outcomes have significance for advancing the development of restoration frameworks in Bolivia that are both integrative and aligned with watershed plans.

We mapped areas of importance for water resources, land cover and biophysical parameters, existing land management, proximity to threats from human activities, and exposure to fire hazards. We found that the Curichi Grande, San Martin, Paragua, and Tucabaca macrowatersheds were the most impacted by fires in terms of the cumulative burned area between 2019 and 2022. These four watersheds were the ones most affected by the 2019 fires, according to the GADSC's post-fire restoration report [31]. Although fires are more frequent in the eastern and south-eastern part of the department, towards the Brazil and Paraguay borders, this does not mean that these are the highest-priority areas for restoration. We found that the priority microwatersheds in terms of water and social factors are located mainly in the west, in the Pirai and Rio Grande watersheds. This confirms that the use of a single criterion to perform prioritization can be highly biased, in accordance with restoration strategies that emphasize the benefits of multiple criteria rather than single objectives [13].

Restoration actions can be ranked at multiple scales from the national to stream-reach level and the ranking can identify either areas for restoration or individual projects [55]. Based on the interest of the stakeholders, we focused on the entire Santa Cruz department. The results show that working at a finer analysis scale (microwatersheds rather than macrowatersheds) could allow for a better representation of the variation in the landscape characteristics. The average microwatershed size in Santa Cruz being over 200 km^2, it is clear that this is still a relatively large unit that is not suited for individual projects. Indeed, Scenario F, combining multiple indicator groups, prioritizes 19,905 km^2 which is a lot larger than the 575 km^2 of land identified for assisted restoration in the GADSC's pixel-scale analysis [31]. Therefore, our classification of areas for restoration is adequate for prioritizing watersheds at the regional level. It can be considered a preliminary assessment which can be built upon to refine the prioritization of measures within selected watersheds.

4.2. The Participatory MCA Methodology

The application of MCA and a simple WLC approach in GEE proved to be an efficient and flexible solution for the multi-indicator prioritization of watersheds. However, the method presents both advantages and limitations which depend on several factors: the quality of the input information, the scoring, weighting and aggregation processes, and the actors included [56].

First, accessing high-quality datasets representing MCA indicators can be a challenge [13,57]. One of the significant difficulties faced during the MCA was the limited availability of datasets to represent critical indicators such as access to water resources. This reduced our ability to extend existing research that integrates water into restoration prioritization. As in other studies, the proximity to the drainage network was considered [43,58,59]. However, a more systematic mapping of small springs and mountain slopes, which are the main water access points in the rural areas of Santa Cruz and currently are not registered by the National Meteorological and Hydrological Services (SENAMHI), could help refine the water resources indicator. If groundwater recharge maps were available, these could represent groundwater resources better than well density maps.

Researchers have also incorporated water balance and water-quality modeling results into MCA studies [60] and prioritization exercises [61]. In the future, if water cooperatives and communities agree to share the location of water supplies, with water quality and quantity data, and if well-calibrated water balance results are available for the Santa Cruz region, this could greatly improve the main water resources indicator. We expect this would lead to a higher prioritization of the Chiquitano forest, in the west of Santa Cruz, where many fragile water sources are exposed to drought and deforestation [62].

Regarding the WLC technique, its strength is that it is easy to apply and replicate and as such, it is the most common MCA method [63]. The weights in the WLC method represent the importance of an indicator relative to the others and control trade-offs between indicators. Instead of assigning fixed weights to the analysis as in other studies [12,43,45,48], we created scenarios by varying criteria weights to observe the trade-offs.

As described, scenario F combines all the main criteria, some of which have limited overlap in terms of the highly important areas. The resulting priority watersheds are rather scattered out across the department. This illustrates an inherent limitation of the WLC in achieving restoration objectives when there is some incompatibility between concurrent goals [64]. Also, the scenarios that include the management indicator (C and H) were largely controlled by the high ranking of 5 given to protected areas. This is due to the linear operations in the WLC that allow high values from one criterion to compensate for low values in another [65].

In this initial study, we chose simplicity over more complex calculations which are more difficult to communicate to a broad audience [55]. However, the WLC aggregation is often compared to Ordered Weighted Averaging (OWA) which introduces order weights on a location-by-location basis to govern the trade-offs between criteria [15,65–67]. Adding OWA operators has been found to bring nuance to the GIS-based restoration scenarios [59,68,69].

Finally, the MCA method presents a certain amount of subjectivity related to the selection and valuation of each criterion. The participatory process is key, but it is not simple, as individuals or institutions may have different motivations or interests [70]. In terms of the criteria identified with stakeholders, these generally corresponded to variables commonly listed in the literature (land cover, protected areas, distance to water bodies, etc.) [21]. During the workshops, stakeholders discussed and ranked variables based on their perceived importance. This means that the ranking process reflects the preferences of the participants and that revisiting the choice of indicators or the ranking of each variable could provide a new prioritization result.

The subjectivity of the MCA method is generally acknowledged and welcomed by scientists and decision-makers, as it enriches the analyses with otherwise overlooked knowledge from the public and from local communities [19,71,72]. Although the participatory approach was successful in collecting useful input from GIS experts and local authorities, the participation in the hybrid workshops was limited to actors who were able to attend either in person, in Santa Cruz de la Sierra, or remotely. Thus, a more robust stakeholder analysis and participation could give a more complete picture of the actors and their interests in ecosystem restoration [44].

4.3. GEE as an Effective Result-Viewing Platform

What does an online interactive tool bring to this spatial analysis? In this study, we used GEE to combine various layers of spatial information and assign main weights to each indicator group in order to obtain and compare different scenarios. The incorporation of adjustable weights helps highlight the complexity of the spatial prioritizing of restoration interventions. The tool was found to be effective in providing decision-makers with a quick and straightforward overview of the challenges associated with the prioritization of restoration efforts, serving as a useful starting point for regional planning discussions. This, as emphasized by Malczewski [63] is the goal of GIS-based decision-making: to generate a shared understanding rather than claim there is a single exact solution.

At this stage, the pre-processing of the datasets (for example, reclassification) was computed in ArcMap. But this step could be directly coded into GEE. The application could also include additional summaries by macrowatershed or by municipality depending on user preferences. Moreover, the grouping of variables into indicator categories limits the number of user-assigned weights to five and the impact of this on the prioritization could be further studied. But what is gained from adding features to restoration prioritization tools must be balanced with simplicity and ease of use considerations [55].

It is obvious that cloud computations require a stable internet network which may not be available to stakeholders in remote areas. Furthermore, the Earth Engine platform imposes a quota per project on the number of simultaneous interactive requests [52]. But overall, in remote working conditions, online applications and web-based solutions allow for interactivity and flexibility [73]. The future of such cloud-based approaches for GIS-based MCA and their incorporation as an element of participatory GIS is promising, especially when local knowledge is included [40].

4.4. Considerations for Future Restoration Studies

Forest restoration has become an effective conservation tool to restore ecological processes as well as to reduce the effects of climate change [74]. Depending on the state of degradation of an ecosystem, a number of management approaches have been proposed, ranging from restoration to natural regeneration, though interventions are subject to the available time frame as well as the financial investments [74]. This study considers restoration preferences, but the criteria were not translated into economic values. In practice, cost-effective restoration needs to balance the benefits (landscape connectivity, carbon storage, biodiversity, etc.) with the associated costs [75]. In the case of watersheds, successful restoration planning also depends on whether the conceptual framework takes into account the functional interactions, at all spatial levels, within the river landscape system, as well as nutrient exchange processes and effects on natural habitats and biota [76]. For this purpose, MCA may be combined with economic assessments and complementary tools such as Cost–Benefit Analysis (CBA) [77].

Though large-scale studies of restoration benefits provide arguments for increased investments [78], there are many unanswered questions about the economic impacts of dry forest restoration in Latin America [79], especially given that the cost-effectiveness of active restoration depends on how non-market benefits to communities and ecosystems are measured compared to productive activities [80]. To translate our study into concrete recommendations for the Santa Cruz department, it would be valuable to expand the input from local stakeholders and better account for ecosystem services and practical and economic feasibility [13,14,54].

5. Conclusions

The proposed prioritization methodology using multi-criteria analysis (MCA) can be regarded as an effective and easily reproducible approach to forest and ecosystem restoration. The prioritization results can support regional decision-makers in the Santa Cruz department, Bolivia, in planning protection and restoration actions in affected or at-risk watersheds. The web-based tool built in Google Earth Engine (GEE), a spatial analysis platform that provides spatial analytical capacity in the cloud, enables users to visualize various land and water resources datasets and to select the priority indicators and aggregation scale (microwatershed or macrowatershed). It then classifies watersheds based on the indicators and user-defined weights, which represent the importance of each indicator for the prioritization. Though still a prototype, the tool could be further developed with additional input from local stakeholders, with enhanced land cover and fire risk data, as well as with a more comprehensive modeling of water resources in the region. A limitation of this study is that it does not consider the economic impacts of restoration. Future research should consider the feasibility and cost–benefits of ecosystem restoration, which would allow for more advanced policy-planning. In conclusion, the use of collaborative methods to prioritize watersheds for restoration has the potential to support effective decision-making processes and to guide watershed restoration plans in Bolivia and in other fire-prone regions globally.

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Data Availability Statement: The datasets used in the GEE application are publicly available through the GEE platform. The application script is available on demand.

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