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Socio-Ecological Systems (SESs)—Identification and Spatial Mapping in the Central Himalaya

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Abstract: The Himalaya is a mosaic of complex socio-ecological systems (SESs) characterized by a wide diversity of altitude, climate, landform, biodiversity, ethnicity, culture, and agriculture systems, among other things. Identifying the distribution of SESs is crucial for integrating and formulating effective programs and policies to ensure human well-being while protecting and conserving natural systems. This work aims to identify and spatially map the boundaries of SESs to address the questions of how SESs can be delineated and what the characteristics of these systems are. The study was carried out for the state of Uttarakhand, India, a part of the Central Himalaya. The presented approach for mapping and delineation of SESs merges socio-economic and ecological data. It also includes validation of delineated system boundaries. We used 32 variables to form socio-economic units and 14 biophysical variables for ecological units. Principal component analysis followed by sequential agglomerative hierarchical cluster analysis was used to delineate the units. The geospatial statistical analysis identified 6 socio-economic and 3 ecological units, together resulting in 18 SESs for the entire state. The major characteristics for SESs were identified as forest types and agricultural practices, indicating the influence and dependency of SESs on these two features. The database would facilitate diverse application studies in vulnerability assessment, climate change adaptation and mitigation, and other socio-ecological studies. Such a detailed database addresses particularly site-specific characteristics to reduce risks and impacts. Overall, the identified SESs will help in recognizing local needs and gaps in existing policies and institutional arrangements, and the given methodological framework can be applied for the entire Himalayan region and for other mountain systems across the world.

Keywords: clustering; ecological units; mapping; PCA; socio-ecological systems; socio-economic units

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1. Introduction

Understanding complex interactions and interrelations between humans and their environment is necessary for planning and policy formulation for attaining sustainable development goals. Human systems and natural ecosystems are closely linked in a given space and time [1], forming a socio-ecological system (SES) [2,3], which is referred to in earlier studies as coupled human–environment systems [4] or coupled natural and human systems [3,5,6]. Nowadays, the terms "socio-ecological system" and "social-ecological system" are used synonymously in environmental sciences to represent the interrelationship and dynamics between ecological and social systems. In an SES, social entities interact and alter natural resources of the ecological systems in multiple ways and at different levels [5,6]. In previous empirical studies, these interactions have been examined without accounting for the dynamics and the complexity of the coupled systems [7–12], which is rarely understood and documented [13,14]. Such a lack of understanding is due to incoherent separation between social and ecological sciences, leading to insufficient comprehensive analyses for sustainability [15,16]. The differences in associations between social and ecological systems can cause unsustainable use of resources [6,17]. Thus, the understanding of these associations in an SES is pertinent in achieving sustainability [18]. Although some researchers have studied coupled systems shaped by insights from complex adaptive systems [19–21], most of the previous works have been theoretical rather than empirical. Thus, SES research needs innovative transdisciplinary methodologies to understand the characteristics and associations of its two domains [6].

The spatial mapping of coupled SESs was a subject of interest in earlier studies [1,10,11,22]. These were either to a limited geographical extent or focused on a particular characteristic of a system. However, many studies have a limited focus on the socio-economic aspects and their implications on ecosystem states in the mapping. In cross-disciplinary studies, interactions between different levels of SESs and their components and decision-makers are often not addressed. The mapping of SESs has the potential to reveal the complex relationships between the social and ecological systems. Martín-López et al. [1] mapped the SESs at the local scale for understanding and assessing whole-system interactions to operationalize the concept of SESs in landscape planning. Various mapping approaches used the actors and institutions of the social system and ecosystems, creating SES models [23,24]. There are no spatial mapping studies of the SES that focus on the Himalayan region where multiple social systems are intricately linked to their respective ecological systems through complex linkages. The characterization of SESs based on socio-economic and ecological components can be identified by a specific indicator or a set of indicators to help in formulating policies and for other assessments [25], e.g., poverty in economic development [26], and conservation in the ecoregion [27,28]. To date, converting theoretical concepts into practical tools such as spatial mapping of SESs and ecosystem services assessment allows identifying and understanding the complex processes and dynamics, non-linear feedback processes, and interactions across scales [29]. Each SES has a distinctive feature, in which a social system has a distinct association with the surrounding ecological systems [21]. In different SESs, the usage of natural resources by the communities is different as their association and dependence vary among them [30]. Spatial mapping of SESs through maps can never characterize their dynamics and complexity [31], but it can help in identifying the spatial characteristics and features to understand the dynamics of the SESs.

Mountains are complex SESs characterized by ecological fragility, limited accessibility, geological instability, social marginality, and natural diversity [32–35]. Unprecedented changes such as climate change, soil erosion, biodiversity loss, forest fires, glacial melting, etc., occurring in different mountain ecosystems are being reported across the world [36,37]. These changes increase the stress on the systems with ample effects on the environment, biodiversity, and socio-economic conditions [38]. The number of studies has increased in the past few years to understand the social-ecological interactions [39,40], particularly in a mountainous region [12].

The Himalaya, one of the youngest and the most fragile arrays of mountains, are important for economic growth and human well-being [41]. The region has several challenges for humans such as inaccessibility, remoteness, and poor development [42] and is also prone to many catastrophic events [43]. The geography and socio-economic settings make this region highly vulnerable to climate change, risks, and hazards [35]. The Central Himalaya is a distinctive entity with undulating topography, rugged and mountainous terrain, fragile ecosystems, and high population density [44,45]. Uttarakhand, one of the hilly states of the Central Himalaya, with above-average warming of 0.46 °C during the 20th century is one of the most vulnerable regions to climate-mediated risks [35,46]. Over the last few years, the state has seen a rapid increase in the incidence and intensity of extreme weather events such as increased temperature, altered precipitation patterns, more recurrent episodes of drought and floods, and negative biotic influences such as pest outbreaks, invasive species, forest fires, forest fragmentation, etc. [46–49]. The changes in the climate have resulted in diverse impacts and disasters [50,51] and, thus, have impacted the functioning and productivity of the SESs. The changes in productivity, especially in agriculture and forestry severely affect the prevailing livelihood options of the Himalayan community [52]. These problems are accelerated through unplanned and unsustainable development activities, such as rapid urbanization, road constructions, and hydro-power plants [53]. Additionally, the net increase in temperature in the region in the 2030s is forecast to be between 1.7 and 2.2 °C with respect to the 1970s, and temperatures are also forecast to rise in all seasons [46,54]. As a result, these changes along with already existing changes in the climate systems make the Himalayan regions more exposed to high levels of climate change and variability, threatening biodiversity, agriculture, social systems, and other natural resources [52]. Impacts of climate change are linked to the interactions within and among the social and natural systems [55]. Thus, it is essential to understand how the vulnerability of different types of SESs will respond to climate change.

The objective of the presented research is to identify and spatially map the boundaries of SESs to understand the delineation and characteristics of these systems using the methodological approach, proposed by Martín-López et al. [1], on a large and heterogeneous area such as the Himalaya region, using Uttarakhand as an example. Our suggested delineation approach is based on large numbers of variables that characterize the major SES types and their characteristic socio-economic and environmental features. The results support and provide a database for further meta-analysis and generate recommendations for decision-making and policy planning for the preparation of climate change adaptation plans by providing insights on key factors that enhance the vulnerability of the different SES types.

2. Materials and Methods

2.1. Study Area

The study area focuses on the Uttarakhand State in the Central Himalaya. Geographically, it is situated between 28°43′24″ to 31°27′50″ North latitude and 77°34′27″ to 81°02′22″ East longitude with an area of 53,485 km^2, accounting for 1.62% of the total area of the country (Figure 1). The elevation of the region ranges from 210 to 7817 m. Administratively, the state is divided into 13 districts falling into two administrative divisions, Garhwal (north-west portion) and Kumaon (south-east portion). The entire state is characterized by a wide range of intraregional variations in topography, geology, soil, and climate as well as in socio-economic structure and living standards and development. It has an immense diversity of altitude, climate, natural resources, biodiversity, ethnicity, culture, and farming systems.

The state has a diverse topography and fragile terrain. It can broadly be divided into three physiographic zones, the Greater Himalaya (Himadri), the Lesser Himalaya (Himachal), and the Outer Himalaya (Shivaliks) running parallel to each other from northwest to southeast. The forest cover is 45.44% of its geographical area, with 9.44% very dense forest, 23.94% moderately dense forest, and 12.06% open forest [56]. The major forest types present are Himalayan moist temperate forest (31.64%), subtropical pine forest (29.87%), and tropical moist deciduous (20.29%) forest.

According to the Census of India (2011), the population of Uttarakhand amounts to 10.11 million inhabitants with a population density of 189 individuals per km^2. Population distribution in the state is very uneven depending upon the physiography. The state has a sex ratio of 963 females for every 1000 males and a literacy rate of 79.63%. Uttarakhand is predominantly a rural state (69.45% population lives in rural areas) with 16,826 villages, of which 12,699 or 81% have a population of fewer than 500 people. The region is sparsely populated in small settlements with high dependence on rainfed agriculture and adjoining forests. Subsistence agriculture is the main source of livelihood [57,58]. People lack basic facilities such as services and institutions in the region, making them highly dependent on natural resources [59].

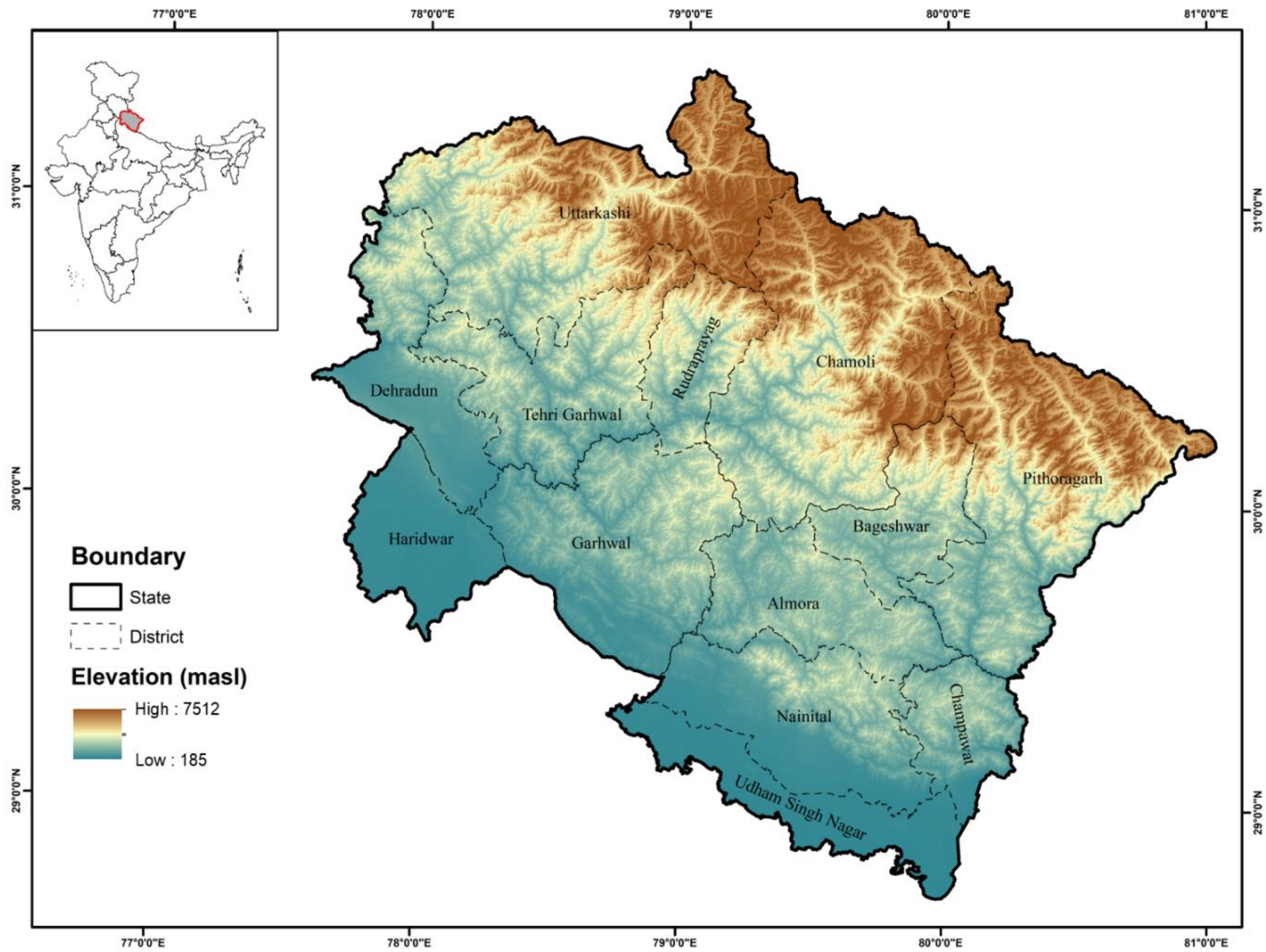

Figure 1. Map showing districts of Uttarakhand state in the Indian Himalayan region (IHR).

2.2. Data Collection

In all, 92 socio-economic variables, such as demography, economy, education, infrastructure, technology, health, etc., and 28 ecological variables addressing climate, geomorphology, biophysical environment, lithology, topography, and land use/cover were collected for the study area based on the earlier mountain-specific literature [35,57,60], discussions with scientific community, and ground observations for a holistic understanding of the considered region (see Tables A1 and A2 in Appendix A for the complete list of all the variables used). Highly correlated variables were dropped after correlation analysis, resulting in 32 socio-economic and 14 ecological variables (Tables 1 and 2). For the socio-economic variables, the village was taken as the data collection unit, and the entire database on ecological variables was resampled to 30 m cell size for consistency. Data were collected from different reliable secondary sources namely Census of India (2011), WorldClim database (1970–2000), National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Forest Survey of India (2015), Biodiversity Characterization program (IIRS/NRSC), National Resource Repository Survey (NRSC), ASTER-GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer—Global Digital Elevation Model), MODIS (Moderate Resolution Imaging Spectroradiometer), and a database generated in our laboratory and by others to delineate the boundaries of SESs.

Table 1. List of variables used for socio-economic units (source: Census of India, 2011).

Type	Variable Name	Code	Numeric/ Categorical (N/C)	Mean	Standard Deviation
Demographic	Total Geographical Area (in Hectares)	G_area	N	200.30	31.77
	Total Households	Hshld	N	84.82	19.60
	Total Population of Village	Vil_pop	N	418.82	10.80
Education	Primary Education	Prm__edu	N	0.85	0.85
	Secondary Eduction	Sec_edu	N	0.56	1.15
	Higher Education	Hgh_edu	N	0.01	0.12
Health	HealthCare	Hlth_cr	N	0.32	0.78
	Govt. Health Program	Hlth_prg	C	1.40	0.49
Water	Tap Water	Tp_wtr	C	1.11	0.31
	Well	Well	C	1.97	0.18
	Hand Pump/Tube wells	Hnd_pmp	C	1.69	0.46
	Spring	Sprng	C	1.96	0.18
	River/Canal/Tank/Pond/Lake	Rvr_cnl_tk	C	1.78	0.41
Post Office	Post Office	Pst_offc	C	1.84	0.37
Communication	Communication	Comm	C	1.11	0.31
Transportation	Transportation	Trnsprt	C	1.56	0.50
Road	Road Connectivity	Road	C	1.59	0.49
Bank Services	Bank Services	Bnk_srvc	C	1.96	0.20
	Credit Societies	Crdt_soc	C	1.71	0.45
Market	Market	Mrkt	C	1.96	0.19
	Public Distribution System (PDS) Shop	Pblc_dst	C	1.67	0.47
Information	Media	Media	C	1.96	0.20
	Information	Info	C	1.79	0.41
Electricity	Power Supply for Domestic Use	Pwr_dom	C	1.08	0.27
	Power Supply for Agriculture Use	Pwr_agri	C	1.86	0.34
Agriculture	Total Unirrigated Land Area (in Hectares)	Unirrgt	N	30.06	2.78
	Area Irrigated by Source (in Hectares)	Irrigt	N	18.63	6.00
	Culturable Waste Land Area (in Hectares)	Cltr_wst	N	18.05	4.18
	Fallows Land Other Than Current Fallows Area (in Hectares)	Fllw_lnd	N	2.92	0.74
	Current Fallows Area (in Hectares)	Fllw_crnt	N	2.47	1.60
	Net Area Sown (in Hectares)	Nt_swn	N	46.61	8.22
	Agriculture Equipment	Agri_eqp	C	1.93	0.26

Table 2. List of variables used to form ecological units.

Type	Variable Name	Code	Source	Resolution
Climatic	Climatic Annual Mean Temperature	B1	WorldClim	1 km
	Mean Diurnal Range	B2	WorldClim	1 km
	Isothermality (BIO 2/BIO 7) (×100)	B3	WorldClim	1 km
	Temperature Seasonality (Standard Deviation × 100)	B4	WorldClim	1 km
	Temperature Annual Range (BIO 5–BIO 6)	B7	WorldClim	1 km
	Annual Precipitation	B12	WorldClim	1 km
	Precipitation of Driest Month	B14	WorldClim	1 km
	Precipitation Seasonality (Coefficient of Variation)	B15	WorldClim	1 km
	Precipitation of Driest Quarter	B17	WorldClim	1 km
Geomorphologic	Aspect	Asp	ASTER-GDEM	30 m
	Slope	Slp	ASTER-GDEM	30 m
Pedologic	Soil type	Soil	National Bureau of Soil Survey and Land Use Planning	1:50,000
Land Use/ Land Cover	LULC	LULC	National Remote Sensing Center	1:50,000
Forest Cover	Forest Types	Frst	Forest Survey of India	1:50,000

2.3. Data Processing and Analysis

The SES boundary delineation and mapping were carried out with modifications in the methodological approach proposed by Martín-López et al. [1] on a large and heterogeneous area. It was performed in four steps (Figure 2) (a) socio-economic unit identification and characterization, (b) ecological unit identification and characterization, (c) delineation of SES boundaries, and (d) characterization of SES boundaries. R-studio software was used for statistical analysis of the data collected from primary and secondary sources. ArcGIS (ver. 10.1) was used for mapping and spatial analysis.

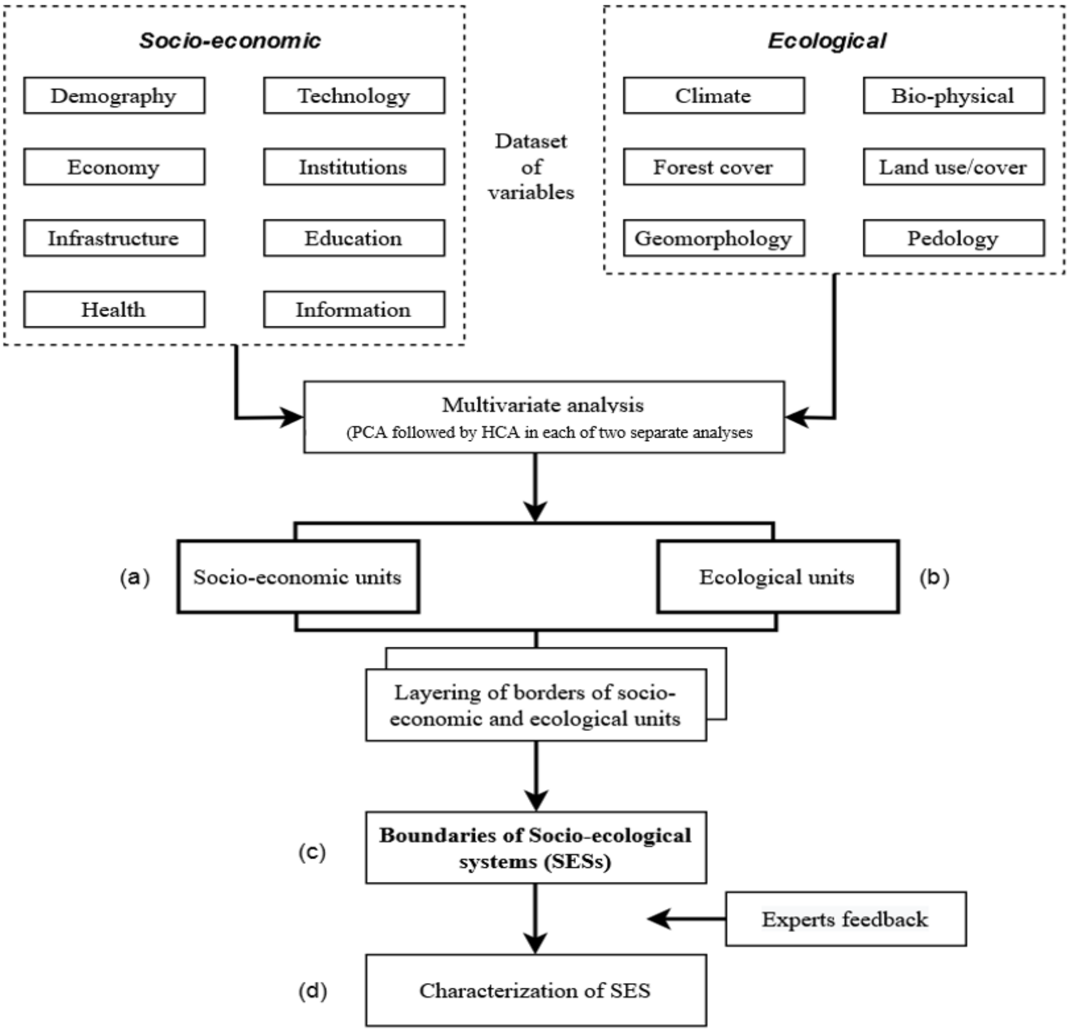

Figure 2. The methodological framework used to identify and delineate socio-ecological system boundaries. In multivariate analysis, PCA is followed by HCA for both datasets of variables in a separate analysis (adapted from Martín-López et al. [1]).

Multivariate data analysis was performed in R-studio using the "FactoMineR", "factoextra", and "ggplot2" packages. Standardization of the variables with different units was done before the analysis, as variables are measured at different scales, which do not contribute equally to the analysis and might end up creating a bias. The Kaiser–Meyer–Olkin (KMO) test [61] was performed to measure sampling adequacy of both datasets of variables (Equation (1)). The KMO test indicates the proportion of variance in variables that might be caused by underlying factors. The KMO test is represented as

$$KMO_j = \frac{\sum_{i \neq j} r_{ij}^2}{\sum_{i \neq j} r_{ij}^2 + \sum_{i \neq j} u} \quad (1)$$

where r_{ij} is the correlation matrix and u_{ij} is the partial covariance matrix. The KMO value range between 0 to 1, and if the value is lower than 0.6, then the sampling is not adequate. Bartlett's test of sphericity [62] was done to test the hypothesis that the correlation matrix is an identity matrix, which indicates that variables are unrelated and, therefore, unsuitable for structure detection. Small values ($p < 0.05$) of the significance level indicate that data are suitable for principal component analysis (PCA).

For socio-economic units, the villages were considered for clustering since they represent the lowest administrative level. For the delineation of the ecological entities, the state was divided into 250 m grid cells to maintain the data uniformity, and the values for each biophysical variable were calculated for each cell. Subsequently, the values of the variables for socio-economic and ecological units (Tables 1 and 2) were used in PCA to extract key components for the joint delineation of the SESs. PCA identifies linear independent dimensions by analyzing the similarities between the data points (Equation (2)). PCA is done before clustering for efficiency purposes as algorithms that perform clustering are more efficient for lower-dimensional data. The main objective of PCA is to reduce a dataset (X dataset with m individuals and n variables) with a smaller number of uncorrelated variables ($X < n$) while retaining as much information as possible. Let $X = [x_i]$ be any $k \times 1$ random vector. We define a $k \times 1$ vector $Y = [y_i]$, where for each i the ith principal component of X is

$$y_i = \sum_{j=1}^{k} \beta_{ij} x_j \quad (2)$$

For some regression coefficients β_{ij}. Since each y_i is a linear combination of the x_i, Y is a random vector.

Sequential agglomerative hierarchical cluster analysis (HCA) was applied to the PCs with an eigenvalue greater than 1 (Kaiser criteria), using Euclidean distance and Ward's method [63] to compute the similarity. It is a stepwise algorithm in which two objects with the least dissimilarity are merged at each step (Equation (3)). The basic concept behind the clustering is Minimize = (Within cluster variance/between cluster variance).

$$sim(X_1, X_2 \ldots n_i) = \left[\left(\frac{|X_1| \times |X_2|}{|X_1| + |X_2|}\right)\right] \times \sum \left[dist\left(M_i, M_j \ldots x_k\right)\right]^2 \quad (3)$$

where, X_1, X_2, … n_i are clusters and M_i, M_j, … x_k are points. The similarity of clusters X_1, X_2, … n_i is equal to the maximum of the similarity between points M_i, M_j, … x_k such that M_i belongs to X_1, and M_j belongs to X_2 cluster and n belongs to x_k belongs to n_i cluster.

The outcome of this analysis is a binary tree, also called a dendrogram, with $n-1$ nodes characterizing the homogeneous characteristics of a cluster. Usually, the clusters are represented on the y-axis and the similarity or the distance is depicted on the x-axis. The lines that depart from each cluster are linked according to the degree of similarity at which the linkage between clusters happens. The obtained results from separate analyses provide homogeneous socio-economic and ecological units. The socio-economic and ecological units were layered and stored in a fishnet of 250 m grid size. The grid was clustered using the HCA to determine the boundaries of the SESs. For characterization of the mapped SESs, variable contribution in each socio-economic and ecological unit was determined using the variable loadings of the respective PCA. Prominent variables were selected as characteristic features of the SESs. The nomenclature for the SESs was derived using feedback on characteristics from domain experts such as scientists and environmental managers working in the Himalaya through discussions and informal meetings. The feedback helped in the nomenclature and characterization of the SESs.

3. Results

3.1. Socio-Economic Units

The KMO test result gave a value of 0.82, and Bartlett's test of sphericity showed $p < 2.22 \times 10^{-16}$ for the socio-economic variables. Socio-economic data were accounted for by the first nine PCs with 51.62% of the variability. Performing HCA on these components generated six socio-economic cluster units based on the common grouping of characteristics as illustrated in Figure 3. The distribution of eigenvalues and variability explained by each PCA component is presented in Appendix A (Table A3).

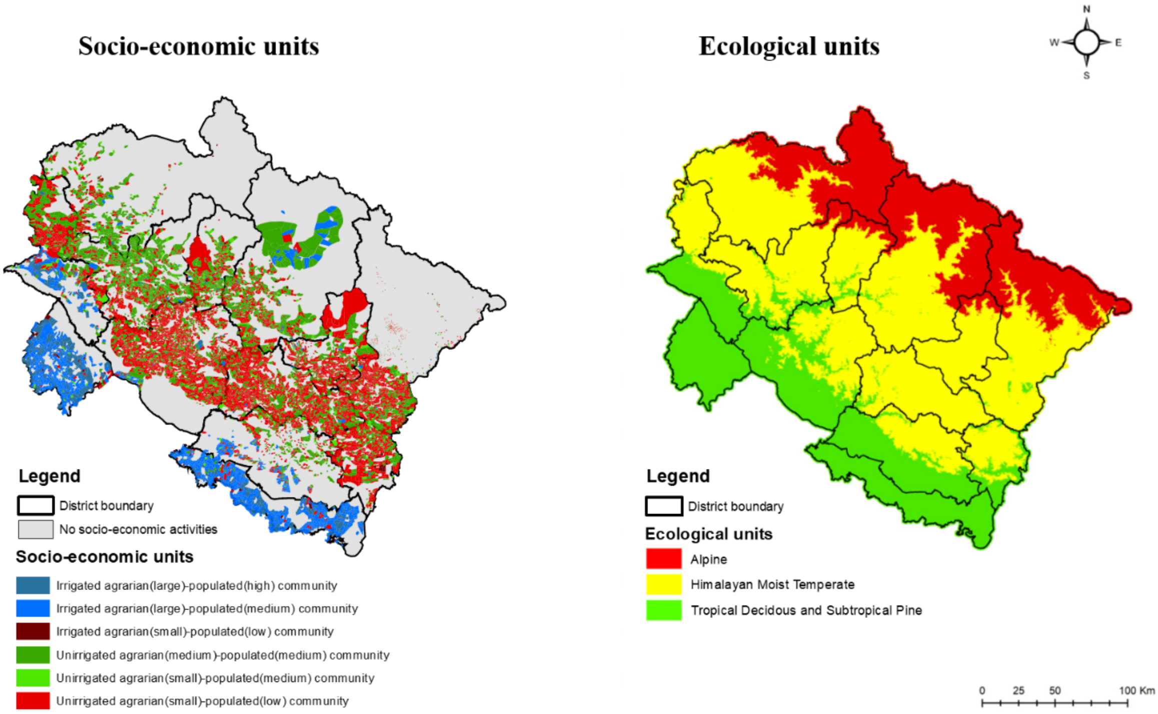

Figure 3. Socio-economic and ecological units of the Uttarakhand state. Six types of socio-economic and three types of ecological units were identified through the analysis.

Based on the variable loading for each cluster (Table 3), dominant characterizing features were used for the naming of the units (Table 4). The categorization of these features is presented in Appendix A (Table A4). For instance, Unit 1 (irrigated agrarian (large)–populated (high) community) represents the villages that are large and have well-irrigated land for agriculture. This unit occurs mostly in the plains at the foothills of the Himalaya known as *Tarai* and *Bhabar*, covering 1.82 percent of the geographical area. Unit 2 (irrigated agrarian (large)–populated (medium) community) represents the villages that have irrigated land and are modest in size. This unit is mostly present in the lower Himalaya and the valleys of the upper Himalaya covering together 8.82 percent of Uttarakhand. Unit 3 (irrigated agrarian (small)–populated (low) community) represents the villages that have a high population with unirrigated land for agriculture. This unit is distributed in the middle Himalayan region within the elevation range of 1000–2500 m, covering 31.72 percent of the land, thus, being the second-largest unit. Unit 4 (unirrigated agrarian (medium)–populated (medium) community) represents the villages that are small in area and have unirrigated land for agriculture. It is distributed throughout the middle Himalaya covering 4 percent of the area. Unit 5 (unirrigated agrarian (small)–populated (medium) community) represents the small villages, with a high population and unirrigated land for agriculture. It is distributed in the middle and upper Himalaya. It is the dominant unit covering 53.07 percent of the land in the state. Unit 6 (unirrigated agrarian (small)–populated (low) community) represents the villages that have irrigated land with better road connectivity and communication infrastructure. It is the smallest unit covering only 0.51 percent of land and is scattered throughout the Himalaya. In most of the cluster types, agriculture, geographical area, and population were the main epicenters around which the socio-economic strata reforms.

Table 3. Major variable contribution in the socio-economic unit clustering from units 1 to 6; and in the ecological unit clustering from units A to C. See Figure A1 in Appendix A for full variable loadings.

Type	Unit	Major Variable Contributor	Variable Loading
Socio-economic units	1	Total geographical area (G_area); Net area sown (Nt_swn); Area irrigated by source (Irrigt)	>12
	2	Area irrigated by source (Irrigt); Net area sown (Nt_swn)	≥14
	3	Net area sown (Nt_swn); Total households (Hshld)	>12
	4	Total geographical area (G_area); Total households (Hshld); Total unirrigated land area (Unirrgt); Net area sown (Nt_swn)	≥10
	5	Total geographical area (G_area); Total households (Hshld); Net area sown (Nt_swn)	>10
	6	Area irrigated by source (Irrigt); Communication (Comm); Transportation (Trnsprt)	>10
Ecological units	A	Forest types (Frst); Land use/Land cover (LULC); Soil type (Soil); Isothermality (B3)	>10
	B	Forest types (Frst); Land use/Land cover (LULC); Isothermality (B3)	>10
	C	Forest types (Frst); Land use/Land cover (LULC); Precipitation of driest month (B14); Precipitation of driest quarter (B17)	≥9

Table 4. Characterization of socio-economic units and ecological units.

	Cluster	No. of Villages/ Grids	Area (%)	Unit Description	Code
Socio-economic units	1	278	1.82	Irrigated agrarian (large)–populated (high) community	1
	2	1357	8.88	Irrigated agrarian (large)–populated (medium) community	2
	3	78	0.51	Irrigated agrarian (small)–populated (low) community	3
	4	4849	31.72	Unirrigated agrarian (medium)–populated (medium) community	4
	5	611	4.00	Unirrigated agrarian (small)–populated (medium) community	5
	6	8112	53.07	Unirrigated agrarian (small)–populated (low) community	6
Ecological units	1	173,244	20.95	Alpine	A
	2	437,384	52.89	Himalayan moist temperate	B
	3	216,397	26.16	Tropical deciduous and subtropical pine	C

3.2. Ecological Units

For the ecological variables, the KMO test result gave a value of 0.65, and Bartlett's test of sphericity showed $p < 2.22 \times 10^{-16}$. The distribution of eigenvalues and variability of PCA components is presented in Appendix A (Table A5). In Uttarakhand state, the HCA identified three ecological units illustrated in Figure 3. Based on the variable loadings of cluster units (Table 3), forest types and land use land cover (LULC) classes were identified as the characterizing feature (Table 4). Unit 1 (alpine) represents the alpine-dominated forest group in the state. It covers 20.95 percent of the state area in the upper Himalaya (>2500 m). Unit 2 (Himalayan moist temperate) represents the Himalayan moist temperate forest group and is the largest unit in the state by covering 52.89 percent of the land area. This unit occurs in the middle Himalaya (1000–2500 m). Unit 3 (tropical deciduous and subtropical pine) covers 26.16 percent of the land and occurs in the lower and outer Himalaya (<1000 m).

3.3. Socio-Ecological Systems

The intersection of borders of socio-economic and ecological units determined the SES boundaries. After the delineation, 18 SES classes were generated and identified as shown in Figure 4 (see also Table 5). The key socio-economic and ecological characteristics were selected based on the methodological approach defining SESs in the Himalayan state. The major contributing ecological variable was identified as forest types and the most important socio-economic variable was agricultural practices. These two variables were determinant factors to characterize the generated 18 types of SESs (Table 3). The alpine-forest-based SESs are situated in the upper Himalayan region covering 21.71 percent of the land area, and the majority of this is covered with snow throughout the year. The Himalayan moist temperate forest–based SESs are situated in the middle Himalaya and are the major groups in the state covering 52.29 percent of the state area. Tropical deciduous and subtropical pine–based SESs are situated in the foothills and lower Himalaya covering 26 percent of the land area.

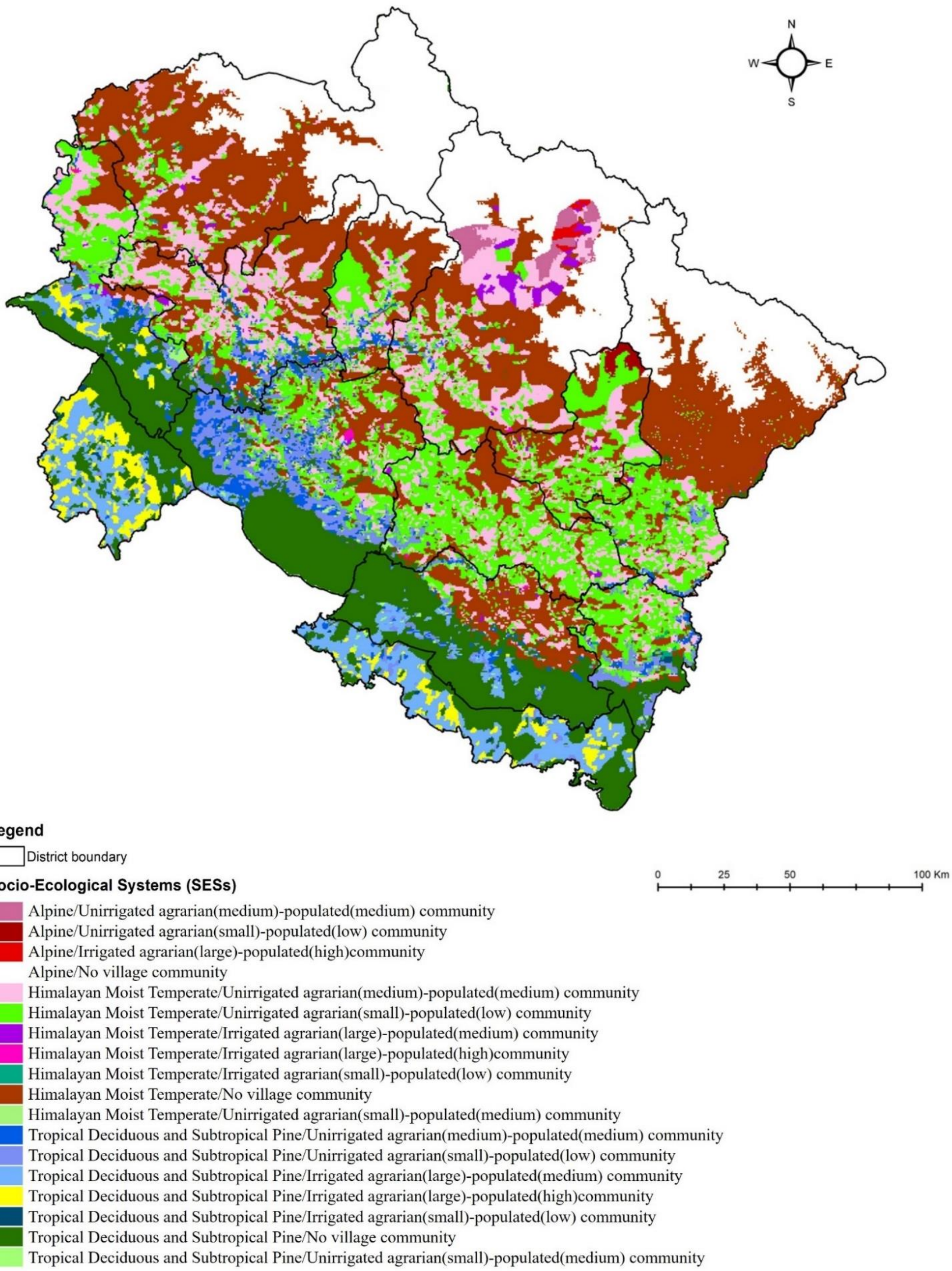

Figure 4. Spatial distribution of socio-ecological systems in Uttarakhand state.

Table 5. Characterization of the socio-ecological systems.

S. No.	Socio-Ecological System Description	Code	Area (%)
1	Alpine/Unirrigated agrarian (medium)–populated (medium) community	A4	0.63
2	Alpine/Unirrigated agrarian (small)–populated (low) community	A6	0.22
3	Alpine/Irrigated agrarian (large)–populated (high) community	A2	0.2
4	Alpine/No village community	A0	20.66
5	Himalayan moist temperate/Unirrigated agrarian (medium)–populated (medium) community	B4	11.55
6	Himalayan moist temperate/Unirrigated agrarian (small)–populated (low) community	B6	13.38
7	Himalayan moist temperate/Irrigated agrarian (large)–populated (medium) community	B2	0.6
8	Himalayan moist temperate/Irrigated agrarian (large)–populated (high) community	B1	0.08
9	Himalayan moist temperate/Irrigated agrarian (small)–populated (low) community	B3	0.1
10	Himalayan moist temperate/No village community	B0	25.46
11	Himalayan moist temperate/Unirrigated agrarian (small)–populated (medium) community	B5	1.13
12	Tropical deciduous and subtropical pine/Unirrigated agrarian (medium)–populated (medium) community	C4	1.91
13	Tropical deciduous and subtropical pine/Unirrigated agrarian (small)–populated (low) community	C6	3.71
14	Tropical deciduous and subtropical pine/Irrigated agrarian (large)–populated (medium) community	C2	4.51
15	Tropical deciduous and subtropical pine/Irrigated agrarian (large)–populated (high) community	C1	1.99
16	Tropical deciduous and subtropical pine/Irrigated agrarian (small)–populated (low) community	C3	0.14
17	Tropical deciduous and subtropical pine/No village community	C0	13.40
18	Tropical deciduous and subtropical pine/Unirrigated agrarian (small)–populated (medium) community	C5	0.34

The Himalayan moist temperate/unirrigated agrarian (small)–populated (low) community (B6) within the middle Himalaya is the major socio-ecological system with 13.38% cover in the state. This system has small villages with low farm holdings in a temperate climate. The other major system is the Himalayan moist temperate/unirrigated agrarian (medium)–populated (medium) community (B4) covering 11.55% in the middle Himalaya. In this system, the villages have a moderate population linked with a temperate climate. These two systems with temperate climate are located in the middle Himalaya. The villages are sparsely populated and have mostly unirrigated agriculture, making the communities highly dependent on forest resources due to the geographical setting of the region. In the lower Himalaya, the major SESs are the tropical deciduous and subtropical pine/irrigated agrarian (large)–populated (medium) community (C2) with 4.51% and the tropical deciduous and subtropical pine/unirrigated agrarian (small)–populated (low) community (C6) with 3.71%.

The spatial mapping shows two pertinent aspects of the Himalaya, the ecosystem and the society. Our mapping highlights the interactions and linkages between the ecological subsystems and social systems (Figure 5). The alpine ecological unit is dominated by social systems with large-to-medium irrigated land and medium population density (A2, A4, and A6). These are more in the high altitudes of the mountain systems. The Himalayan moist temperate forest shows a much wider range of linkages across the social units of the region. These are dominated by villages with low-to-medium population with unirrigated agrarian practices (B1, B2, B3, B4, B5, and B6). However, it also supports other social units. These ecological systems range from low-to-medium altitude with select pockets in high-altitude regions. The tropical deciduous and subtropical pine forests also share a wider linkage across all the social units of the Central Himalaya. These exhibit a stronger linkage with irrigated large agrarian–medium population communities (C1, C2, C3, C4, C5, and C6). Unlike the Himalayan moist temperate forest, these do not have a wider distribution and are restricted much to lower altitudes and a few ranges of middle altitude.

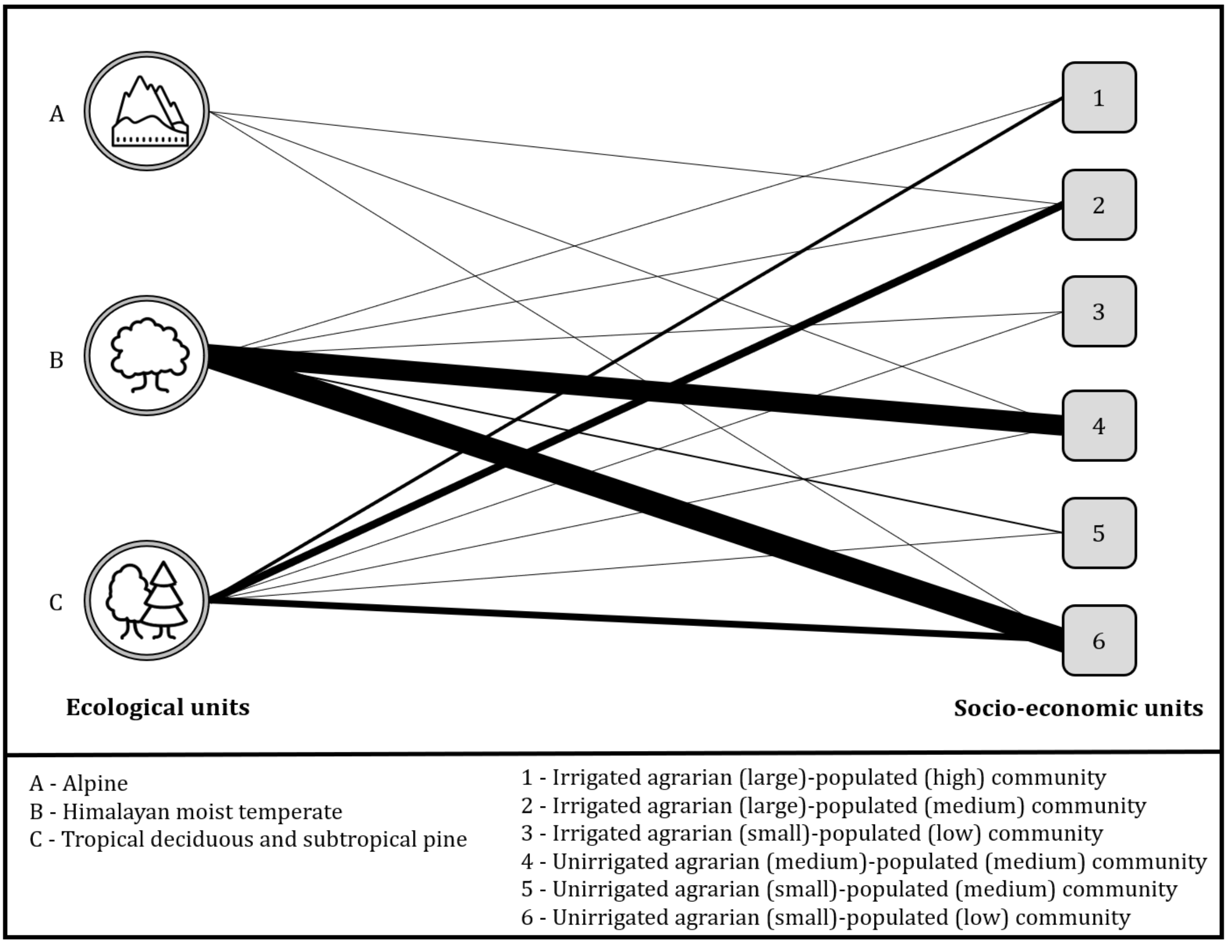

Figure 5. The linkage between the ecological units and socio-economic units based on their association. The width of the linkage represents the magnitude of the interaction between the units.

4. Discussion

Identification and spatial mapping of SESs at the regional level is demanding since administrative borders often do not coincide with natural variables that determine how nature is managed by people. Therefore, an interdisciplinary approach is required that supports integrating a wide range of variables considering social and ecological interactions. Most of the earlier studies [1,5,10,11,22] have mapped these for a smaller geographical area (e.g., regional, municipality, national park) or with a focus on particular system types. Martín-López et al. [1] identified SESs at a local level to understand the interaction at the local level, which can be useful for meta-analysis of the individual SESs. In addition to the understanding of the cross-disciplinary approaches, the geospatial tools and data integration capability have enhanced opportunities to analyze potential and complex relationships and interactions between social and ecological systems [64,65]. Researchers have leveraged such capabilities to identify and map different ecological units [66–68]. The identification and spatial mapping of SESs in the Central Himalaya presented in this study is one of the first attempts to develop an indicator-based model. It extends previous efforts of mapping SESs [1,11,22], in that it takes a broader range of both social and ecological variables into account. Such an attempt has multiple advantages and a few limitations, which can assist researchers to replicate, reproduce, and enhance it over time to identify changes in social-ecological systems, essential to policy planning [22].

These intricate linkages between the ecological and social systems indicate the distinct vulnerability and adaptive capacities of the communities to climate change. The relationships also explain the dependence of the socio-economic units on the ecological units, indicating higher dependence on forests. For example, Himalayan moist temperate forests are known for the resource utilization structures, processes, and patterns in the region, and thus these are highly associated with the forests, farmland, and livestock [69,70]. Similarly, the dependence is higher on the tropical deciduous and subtropical pine forest and the least on the alpine ecological units. Such relationships also indicate the services and support rendered by these ecological units to the socio-economic units in the Central Himalaya. These provide multiple ecosystem services including much of the supporting and regulating services for such communities, e.g., biomass production, soil formation and retention, nutrient cycling, provisioning of habitat, and regulation of climate and water [71].

4.1. Advancement in Methods

The presented methodological framework combines the multivariate analysis of both biophysical and socio-economic variables using GIS to identify and characterize the SESs [1]. The study generated SESs at the regional level with characteristics features though the SESs are nested at multiple spatial levels [3]. The modified methodology has similar limitations that have been noted by others in their studies [1,22,72]. Few of the variables' data were not available at the local level in the study, so that they had to be downscaled, and this increased the data-borne uncertainty of the mapping exercise [73]. Our analysis suggests that there is a need to carefully consider scale to generate SES units. Analyses at multiple spatial scales will reveal different patterns of complexity and dynamics, thus, limiting the recognition of the complex dynamics of SESs. Our approach is limited by the availability of data. For example, factors responsible for governance are not included in the approach [6]. In order to interpret large datasets, methods are required to drastically reduce their dimensionality in an interpretable way, such that most of the information in the data is preserved. It gives the best possible representation of a p-dimensional dataset in q dimensions ($q < p$) in the sense of maximizing variance in q dimensions. A disadvantage is, however, that the new variables that it defines are usually linear functions of all p original variables, and there is a trade-off between interpretability and variance [74]. In this study, since the original random variables are non-Gaussian distributed, their linear combinations were non-Gaussian distributed, and uncorrelated principal components were independent. The removal of outliers does create a normal distribution in some of the variables, but for some variables, outliers are informative about the subject area and data collection process, which was essential in the study to understand the spatial complexity.

The framework helps in replacing the general administrative boundary criteria used in adaptation and landscape planning using a socio-ecological approach. From a social scientific point of view, the boundaries on a map do not correspond with the association of the physical and social world [75]. The perceived boundaries of SESs can vary among actors considering their landscape-scale usage patterns [1]. Cross-scale modeling concepts have emerged in landscape ecology as a way to better capture complex system characteristics to support science and practitioner interactions [76]. These abstractions of the real-world address different types of governance, how resources are influenced, and how human action or behavior affects the ecosystem's performance [77].

4.2. Relevance and Applicability of the Method

This study provides a robust methodology to delineate and characterize SESs, which could be adopted in the entire Himalayan arc and in other mountain ecosystems of the world. Mapped SESs can provide a basic template for studies in mountain ecosystems related to climate change impacts, vulnerability assessment, adaptation planning, risk and hazards assessment, the resilience of communities to multiple stressors, natural resource management, and policy- and decision-making. Characterizing multilevel interactions from local communities to national decision-makers encourages robust policy-making to ensure sustainable resource management [78]. Combining practitioners' knowledge with socio-economic and environmental changes in modeling platforms acts as a vehicle toward proactive spatial assessment and planning. Pivotal for policy-making is a better recognition of cross-disciplinary models to ensure information and communication flows for developing landscape as well as adaptation planning strategies [79]. The mapped SESs help in recognizing local needs and gaps in existing policies and institutional arrangements. Taking SES as a coupled system will help policymakers to look at two fronts as a single unit. Beyond these practicum usages, the study fills a wide gap in SES approaches for vulnerability assessment in mountain ecosystems as it considers the differences and associations of socio-economic and ecological system characteristics and acts as a tool for policy implementation to reduce vulnerability [80]. This would pave the pathways for future academic and research-based studies. Understanding the SESs can help in explaining the natural resource usage pattern by the communities of socio-economic units and major ecosystem services. Homogenous ecological units have similar kinds of services and usage patterns. This helps in analyzing and modeling SES interactions to better understand feedback, non-linearity, and the future dynamics of drivers across multiple scales [81].

4.3. Outlook

India is classified into 15 agroclimatic zones by the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP). These zones are classified based on climatic factors, soil properties, physiographic settings, geological formation, climate, cropping patterns, and development of irrigation and mineral resources. Uttarakhand state is classified as a Western Himalayan agroclimatic zone. It is further divided into two subclasses, namely Hill (AZ26) and Bhabar and Tarai (AZ27). Our approach identified seven different types of SESs in the Bhabar and Tarai (AZ27) zone and eleven types of SESs in the Hill (AZ26) zone with distinct features providing more details for planning. Agroclimatic zonation and other similar approaches such as biome [66] and bio-geographical zone [82] mapping mainly address ecological settings but do not take into account the association of communities and institutions. To our knowledge, this is the first time that census data on resource use have been used to identify and map SESs in the Himalayan landscape. Therefore, the developed database and method can be used as a tool for locally adapted actors and institutions for efficient planning and management. The studied cases of Uttarakhand state showed that there is a need for locally suitable adaptation planning and management to avoid a one size fits all strategy [17,83] in social and ecological aspects. The SESs provide variation and specific features pertinent to the interlinked network of resource systems and actors [6].

A study by Dressel et al. [22] used PCA on multiple socio-ecological variables to understand the socio-ecological context of natural resource management. Martín-López et al. [1] identified SES boundaries to explain their importance in landscape planning for managing ecosystem services. Our approach used a similar principle but focused on characterizing a larger geographical entity in mountain systems to provide SESs boundaries and improve the understanding of the characteristics that define the SESs.

5. Conclusions

The study has demonstrated an approach to identify and spatially map socio-ecological systems in the Central Himalaya. It developed an indicator-based model on an understanding of the intricate relationship between social systems and ecological systems and by explaining the characteristic features over a large heterogeneous area. This is the first time that census data on resource and biophysical variables on ecological distribution area were used to identify and map SESs in the Himalayan region. The approach differs from earlier attempts at mapping ecological units and linking with social data to describe the socio-ecological system. The SESs mapping will help in improving the currently practiced mapping approach in the Himalayan region for socio-economic and ecological planning and management. The approach presented here may be a practical tool that can be replicated and reproduced across mountain ecosystems. The subsequent understandings will, therefore, support the preparation of adaptation plans to cope with the impacts of climate change in the Himalayan region and sustainable natural resource management. Our approach is a beneficial tool to analyze and represent the multidimensional systems of mountainous regions to help decision- and policymakers develop site-specific policies. The future challenges in SES research involve the understanding of dynamics at multiple scales and the development of credible measures of evaluation, corporate governance, and promotion of adaptation. To understand the complexity of the SESs, a further meta-analysis by integrating participatory methods for each system is necessary. Overall, a rigorous and in-depth approach is necessary to combat these situations.

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Appendix A

Table A1. List of total variables used to form ecological units.

Type	Variable Name	Code	Data Source
Climatic	Climatic Annual Mean Temperature	BIO 1	WorldClim
	Mean Diurnal Range	BIO 2	WorldClim
	Isothermality (BIO 2/BIO 7) (×100)	BIO 3	WorldClim
	Temperature Seasonality (Standard Deviation × 100)	BIO 4	WorldClim
	Max. Temperature of Warmest Month	BIO 5	WorldClim
	Min. Temperature of Coldest Month	BIO 6	WorldClim
	Temperature Annual Range (BIO 5-BIO 6)	BIO 7	WorldClim
	Mean Temperature of Wettest Quarter	BIO 8	WorldClim
	Mean Temperature of Driest Quarter	BIO 9	WorldClim
	Mean Temperature of Warmest Quarter	BIO 10	WorldClim
	Mean Temperature of Coldest Quarter	BIO 11	WorldClim
	Annual Precipitation	BIO 12	WorldClim
	Precipitation of Wettest Month	BIO 13	WorldClim
	Precipitation of Driest Month	BIO 14	WorldClim

Table A1. *Cont.*

Type	Variable Name	Code	Data Source
	Precipitation Seasonality (Coefficient of Variation)	BIO 15	WorldClim
	Precipitation of Wettest Quarter	BIO 16	WorldClim
	Precipitation of Driest Quarter	BIO 17	WorldClim
	Precipitation of Warmest Quarter	BIO 18	WorldClim
	Precipitation of Coldest Quarter	BIO 19	WorldClim
Geomorphologic	Elevation	Elv	ASTER-GDEM
	Aspect	Asp	ASTER-GDEM
	Slope	Slp	ASTER-GDEM
Pedologic	Soil type	Soil	National Bureau of Soil Survey and Land Use Planning
Land use/Land cover	LULC	LULC	National Remote Sensing Center
Forest Cover	Forest Types	Frst	Forest Survey of India
Biophysical	Normalized Difference Vegetation Index	NDVI	MODIS
	Enhanced Vegetation Index	EVI	MODIS
	Normalized Difference Water Index	NDWI	MODIS

Table A2. List of total variables used to form socio-economic units (source: Census of India, 2011).

Type	Variables				
Demographics	Total Geographical Area (in Hectares)	Total Households	Total Population of Village		
Primary Education (Numbers)	Govt. Preprimary School (Nursery/LKG/UKG)	Private Preprimary School (Nursery/LKG/UKG)	Govt. Primary School	Private Primary School	
Secondary School (Numbers)	Govt. Middle School	Private Middle School	Govt. Secondary School	Private Secondary School	
	Govt. Senior Secondary School	Private Senior Secondary School			
Higher Education (Numbers)	Govt. Arts and Science Degree College	Private Arts and Science Degree College	Govt. Engineering College	Private Engineering College	
	Govt. Medical College	Private Medical College			
Healthcare (Numbers)	Community Health Center	Primary Health Center	Primary Health Subcenter	Maternity And Child Welfare Center	Family Welfare Center
	Hospital—Allopathic	Hospital—Alternative Medicine	Dispensary	Mobile Health Clinic	
Toilet	Toilet Complex (including Bath)				
Tap Water	Tap Water—Treated	Tap Water—Untreated			
Well	Covered Well	Uncovered Well			
Hand Pump/Tube Wells	Hand Pump	Tube Wells/Borehole			
River/Canal/Tank/Pond/Lake	River/Canal	Tank/Pond/Lake	Spring		
Post Office	Post Office	Sub-Post Office	Post and Telegraph Office		
Communication	Public Call Office/Mobile (PCO)	Mobile Phone Coverage	Internet Cafes/Common Service Center (CSC)	Telephone	
Transportation	Public Bus Service	Private Bus Service	Railway Station	Auto/Modified Autos	Taxi
Road Connectivity	Black Topped (pakka) Road	Gravel (kuchha) Roads	Water-Bound Macadam		
	All-Weather Road	State Highway	National Highway		
Bank Services	ATM	Commercial Bank	Cooperative Bank		
Credit Societies	Agricultural Credit Societies	Self-Help Group (SHG)			

Table A2. *Cont.*

Type	Variables			
Market	Mandis/Regular Market	Weekly Haat	Public Distribution System (PDS) Shop	
Govt. Health Program	Nutritional Centers—Anganwadi Center	ASHA		
Waste Disposal	Waste Disposal System after House-to-House Collection	Bio-gas or Recycling of Waste for Production Use		
Media	Community Center with/without TV	Sports Club/Recreation Center	Cinema/Video Hall	
Information	Public Library	Public Reading Room	Daily Newspaper Supply	Assembly Polling Station
Agriculture Infrastructure	Agriculture Equipment	Tractors	Carts Driven by Animals	
Electricity	Power Supply for Domestic Use	Power Supply for Agriculture Use	Power Supply for Commercial Use	
Agricultural Land	Culturable Waste Land Area (in Hectares)	Fallows Land other than Current Fallows Area (in Hectares)	Current Fallows Area (in Hectares)	
	Net Area Sown (in Hectares)	Total Unirrigated Land Area (in Hectares)	Area Irrigated by Source (in Hectares)	
Land	Forest Area (in Hectares)	Area under Non-Agricultural Uses (in Hectares)	Barren and Un-cultivable Land Area (in Hectares)	
	Permanent Pastures and Other Grazing Land Area (in Hectares)	Land under Miscellaneous Tree Crops, etc., Area (in Hectares)		

Table A3. Distribution of eigenvalues and variability by PCA components for socio-economic units.

Component	Eigenvalue	Percentage of Variance	Cumulative Percentage of Variance
1	5.0205182	16.19522	16.19522
2	2.4833644	8.010853	24.20607
3	1.5594366	5.030441	29.23651
4	1.4401137	4.645528	33.88204
5	1.1921083	3.845511	37.72755
6	1.1492132	3.707139	41.43469
7	1.1019871	3.554797	44.98949
8	1.0516104	3.392292	48.38178
9	1.0066872	3.247378	51.62916
10	0.9893615	3.191489	54.82065
11	0.9703779	3.130251	57.9509
12	0.9557607	3.083099	61.034
13	0.9076826	2.928008	63.96201
14	0.8888257	2.86718	66.82919
15	0.8738607	2.818906	69.64809
16	0.8603775	2.775411	72.4235
17	0.8536764	2.753795	75.1773
18	0.8078302	2.605904	77.7832
19	0.7867955	2.53805	80.32125
20	0.7492632	2.416978	82.73823
21	0.699398	2.256123	84.99435
22	0.6863401	2.214	87.20835
23	0.6332295	2.042676	89.25103
24	0.5855329	1.888816	91.13984

Table A3. *Cont.*

Component	Eigenvalue	Percentage of Variance	Cumulative Percentage of Variance
25	0.556595	1.795468	92.93531
26	0.5209481	1.680478	94.61579
27	0.4585095	1.479063	96.09485
28	0.4205302	1.356549	97.4514
29	0.4058192	1.309094	98.7605
30	0.2451117	0.790683	99.55118
31	0.1391345	0.448821	100

Table A4. Categorization of the socio-economic units with their mean households and area per village.

Socio-Economic Unit	Number of Villages	Mean Area per Village (in Hectares)	Large/Medium/ Small	Mean Households per Village	High/Medium/Low
Irrigated agrarian (large)–populated (high) community	278	452.3	L	646	H
Irrigated agrarian (large)–populated (medium) community	1357	165.19	L	188	M
Irrigated agrarian (small)–populated (low) community	78	85.23	S	13	L
Unirrigated agrarian (medium)–populated (medium) community	4849	104.79	M	74	M
Unirrigated agrarian (small)–populated (medium) community	611	79.6	S	51	M
Unirrigated agrarian (small)–populated (low) community	8112	57.35	S	27	L

Table A5. Distribution of eigenvalues and variability by PCA components for ecological units.

Component	Eigenvalue	Percentage of Variance	Cumulative Percentage of Variance
1	4.8433	34.595	34.595
2	3.37687	24.1205	58.7155
3	1.59367	11.3834	70.0989
4	1.00264	7.16174	77.2607
5	0.83842	5.9887	83.2494
6	0.7459	5.32784	88.5772
7	0.57257	4.08978	92.667
8	0.47321	3.38008	96.0471
9	0.32444	2.31741	98.3645
10	0.13174	0.94098	99.3054
11	0.05924	0.42316	99.7286
12	0.02881	0.20579	99.9344
13	0.00758	0.05415	99.9886
14	0.0016	0.01145	100

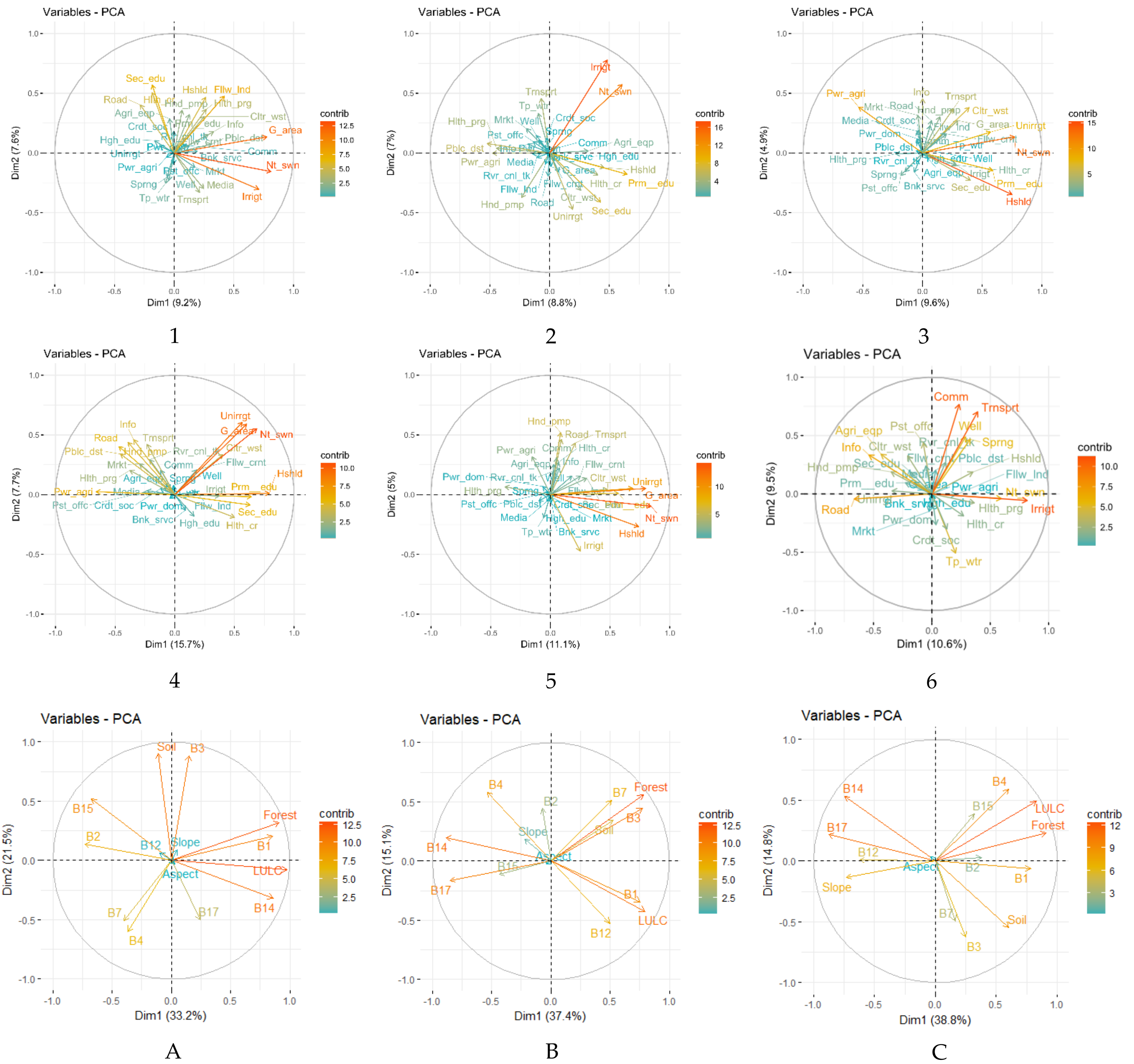

Figure A1. Variable contribution in the socio-economic unit clustering from units (**1**–**6**); and in the ecological unit clustering from units (**A**–**C**).

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