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Spatial dynamics of biophysical trade-offs and synergies among ecosystem services in the Himalayas

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ABSTRACT

The production of ecosystem services (ES) is highly dependent on the current state of spatial distribution, pattern of occurrence, and interaction among them, which is barely studied in the Hindu-Kush Himalayas (HKH). Taking a case of a multifunctional landscape in the central HKH region, we aimed to assess the biophysical production possibilities of major ES, their relationships and co-occurrence, and dynamic interactions at different spatial scales. We quantified and mapped six major ES (crop production, timber production, carbon sequestration, soil conservation, water yield, and habitat quality) at two spatial scales: landscape level (functional unit) and watershed level (management unit). Further, we analysed the relationship and interactions among all the possible pairs of the considered ES. All six ES were found to have a positive correlation, except crop production which showed a significant negative correlation with soil conservation. Moreover, we delineated 186 watersheds in the landscape and clustered them based on their biophysical potentials for the supply of ES. Gap statistics from K-means clustering identified three main clusters of watersheds (i.e., agriculture-dominated, poor-performing uplands, and multifunctional). The supply of ES from downstream watersheds was substantially higher than that of the upstream watersheds. We then discussed the interrelationships among ES at various spatial scales and suggested policy instruments for ecosystem management. The relationship among ES shows dynamic forms of spatial distribution, which need to be sustainably managed for minimizing trade-offs and maximizing synergies through the consideration of an integrated watershed management approach, improved agronomy practices, and global climate actions.

1. Introduction

Ecosystem services (ES) can be referred as nature's benefits to human well-being. ES is a concept introduced by a couple of publications in 1997 (Costanza et al., 1997; Daily, 1997), which was materialized in the policy discourse after the Millennium Ecosystem Assessment, and is now popularly used in sustainability science to cater to various provisioning and non-provisioning services of nature to the mankind (Bennett et al., 2015; MEA, 2005; Wu, 2021). Global loss of natural resources, economic progress at the environmental cost, multi-dimensional socio-cultural values, climatic uncertainties, and compelling demand for sustainable development have persuaded environmental decision-makers for the management of ES to satisfy both socioeconomic aspirations and ecological integrity (Balvanera et al., 2014; Ramzan et al., 2022; van Niekerk, 2018; Wood et al., 2018). Accordingly, assessment and analysis of ES at various spatial and temporal scales have been a growing research agenda among conservation scholars and development practitioners worldwide (Aryal et al., 2022; Costanza et al., 2017; Fulford et al., 2022).

Assessment of ES is contingent on various domains of its characterization. First, the categorization and classification of ES are based on the supply nature of goods and services derived from the nature, ranging from provisioning and non-provisioning (i.e., regulating, cultural, and supporting ES). Various well-known classification schemes are available to understand the nature of ES; for example, the Millennium Ecosystem Assessment (MEA, 2005), Common International Classification of ES-CICES (Haines-Young and Potschin, 2012), The Economics of Ecosystem and Biodiversity- (TEEB, 2010), the system of nature's contribution to

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people- NCP (Pascual et al., 2017), and Final Ecosystem Goods and Services-FEGS (Landers and Nahlik, 2013). Second, the 'resource' and 'reserve' of ES, as well as existing institutional arrangement for plausible extraction of ES, posits further challenges in the quantification and mapping of ES. Resource denotes the eventual existence of ES which cannot be fully extracted, whereas reserve implies the current possible extraction of ES (Farley, 2012; Winterstetter et al., 2015). Further, various national and international environmental policies and institutional arrangements (i.e., policy choices) add to the restriction or relaxation regarding the extraction of ES, thereby complicating the quantification of ES in the real ground (Corbera and Brown, 2008; Nahuelhual et al., 2018). Third, the areal extent for the assessment and characterization of ES is also important in understanding the existing and extractable amounts of ES (Bagstad et al., 2018; Liu et al., 2022). For example, a site-based assessment might not capture the ES that is reflected or can be visualized at the broader basin or landscape level.

From among the numerous lists of ES nomenclatures, many developing countries in the South are concerned with provisioning ES (i.e., food and fibre including crop and timber production) and few non-provisioning ES (i.e., water regulation, soil conservation, climate regulation, biodiversity, and habitat support) that are important to their livelihoods and crucial for local and regional development (Aryal et al., 2023; Awasthi et al., 2020; Dhungana et al., 2022; Guo et al., 2010; Turkelboom et al., 2018). Similarly, people might not be interested in how much nature has, which is sometimes beyond the capacity of estimation, but might be interested in how much they are getting and what is the optimum level of supply from nature (Fernández Martínez et al., 2020; Scheffer et al., 2000; Srichaichana et al., 2019). Alternatively, the notion of the concurrent institutional interface of the supply of ES and ecological frontiers (i.e., optimum level of supply of ES) might be a real concern for the public as well as the environmental decision-makers (Aryal et al., 2019a; Boisvert et al., 2013; Costanza et al., 2017; Mann et al., 2015). Besides, a composite overview of ES at both the landscape level (ecological functional unit) and watershed level (i.e., management intervention unit) is important rather than the small-scale site-level assessment or the large-scale basin-level assessment in isolation (Hein et al., 2006; Lindborg et al., 2017; Qiu et al., 2018).

Studies about ES have been increasing, but only spinning around the general assessment, quantification, and valuation at the broader basin level (Acharya et al., 2019; Costanza et al., 2017; Wang et al., 2021a). Mountains represent critical ecosystems because of their socioecological configurations, biophysical interactions, climate sensitivity, and strong connection to livelihood in mountains be it in African mountains, Hindu Kush Himalaya (HKH), or European Alps (Bhattarai et al., 2022; Ndayizeye et al., 2020; Payne et al., 2020; Sapkota et al., 2021; Shrestha et al., 2022). Some of the previous research have assessed landscape dynamics and multiple interactions among ES in European Alps (Egarter Vigl et al., 2016; Jäger et al., 2020) and in African mountains (Finch et al., 2017; Peters et al., 2019). However, studies about the relationship among ES are very few in the HKH region (Aryal et al., 2021; Mengist et al., 2020). Yet, a review by Kandel et al. (2021) found a substantial number of research about ES in the HKH region. The studies were basically the snapshot approach to ES quantification, which is insufficient to explain and visualize the relationship and interaction from 'whole to part' of the landscape (Ikematsu and Quintanilha, 2020; Obiang Ndong et al., 2020). Besides, the studies on ES were concentrated in temperate and humid regions with a very low representation of highly biodiverse ecosystems in the tropics (Muenchow et al., 2018). Studies about mapping and trade-offs in ES are not adequate in heterogenous mountain landscapes, including the HKH regions (Chaudhary et al., 2016; Mengist et al., 2020; Xu et al., 2019a).

Various global policy frameworks, such as UN Sustainable Development Goals (2030), Decade on Ecosystem Restoration (2021–2030), and Post-2020 Global Biodiversity Conservation Framework have envisioned accelerated movements in ecosystem management and restoration. However, on one hand, many of the existing ecosystem management approaches are based on developed countries in the humid region (for example, Bernués et al., 2022; Schwaiger et al., 2019; Sun et al., 2020; Zulian et al., 2018). On the other hand, we barely see studies on mapping and quantification of ES, its interaction (trade-offs and synergies), and interrelationships in the Himalayas (Acharya et al., 2019; Aryal et al., 2022; Mengist et al., 2020), which are the foundation for planning and sustainable management of ES. In this scenario, there are chances of policy failures in the management of ES in the Himalayas, if we adopt the exogenous ES management models without a critical assessment of ES, their pattern of occurrence, and interaction in an integrated way (Elizalde et al., 2020; Sitas et al., 2014). Furthermore, no studies have been done on the Himalayas to understand the current state, competitive interaction (i.e., trade-offs and synergies), and dynamics of ES at the various scales: (1) broader landscape level, (2) smaller watershed level, and (3) clusters of watersheds (i.e., similar ecological characteristics and production functions to ease priority of management interventions), simultaneously.

This study aimed to overcome the research gaps on the Himalayas by analysing and examining the composite overview of major ES and their inter-relationship at the heterogenous and multifunctional landscapes. Taking the case of the HKH, we aimed to quantify and compare the current state, distribution, and interaction of ES at multiple spatial scales. The findings of this study will be crucial in fulfilling the knowledge gap of ecosystem gradient in the Himalayan landscape, especially downscaling of ES from whole to part (i.e., from landscape to watershed), the upstream–downstream ecological gradient of the landscape, and understanding production possibilities of the functional units of landscape (i.e., clustering of watersheds based on the coexistence of ES). Further, this study is expected to support environmental decision-makers for sustainable management of heterogenous landscapes in the HKH region and beyond such as for managing African mountains and the European Alps.

2. Methods

2.1. Study area

This research was conducted in Chitwan Annapurna Landscape (CHAL) area of Nepal, occupying an area of 31,700 km^2 at the centre of Hindu-Kush Himalayan (HKH) region (Fig. 1). CHAL area overlaps (i.e., >95 % area coverage) the hydrological gradient of Gandaki river basin, a transboundary river system having a large portion of it situated in Nepal (WWF Nepal, 2013). Gandaki river basin is the second largest river basin of Nepal, which drains along the *trans*-Himalaya, mountain, and lowlands of Nepal, finally into the Ganges of India (Rai et al., 2018). Gandaki river basin has about 1500 glaciers and 300 lakes (Bajracharya et al., 2011). We selected CHAL (~ Gandaki river basin) area for a number of reasons: (a) it is a unique multifunctional landscape stretching north–south ecological gradients (100 m - >8000 m above mean sea level), (b) it follows a river basin so as to capture the effect of upstream–downstream linkages, (c) it represents one of the highly biodiverse ecosystems including six protected areas (one listed in World Heritage Site), three wetlands of international importance (listed in Ramsar site), three protected forests, and a fragile geological landscape (*Chure* region), and (d) it includes four of the 200 global eco-regions (WWF Nepal, 2013). Notably, ecosystems in the study area are also identified as vulnerable to climate stress and water-induced hazard, and a 32.7 million USD project from Green Climate Fund is being implemented to improve climate resilient communities and ecosystems. It characterizes climatic zones ranging from tropical lowlands to alpine cold semi-desert; average minimum and maximum temperature of 4.9 °C to 39.9 °C, respectively; and average annual rainfall ranging from 165 mm (Lomanthang, Mustang) to 5,244 mm (Lumle, Kaski) (Luitel et al., 2020; WWF Nepal, 2013).

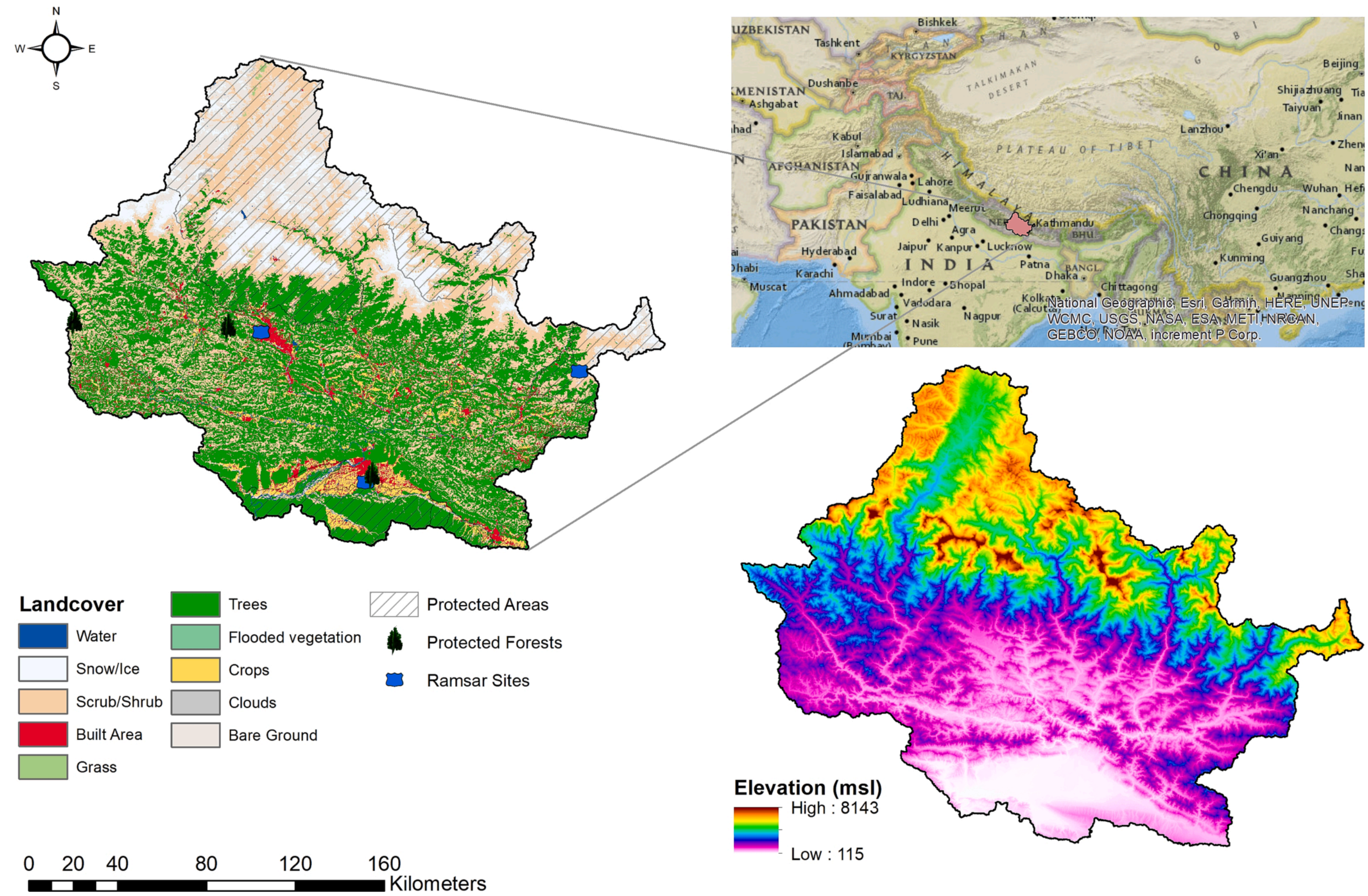

Fig. 1. Land cover map of the study area, including the spatial information about protected areas, protected forest and Ramsar listed wetlands. Bottom right map shows elevation range (meter above mean sea level). Map to the top right corner is base map of National Geographic extracted from ArcGIS 10.8.1.

2.2. Watershed delineation and characterization

Flowchart of the research methods, including watershed delineation, quantification of ES, and data analysis is presented in Fig. 2. River basin occupies a big area; however, landscape management is viable in watersheds of relatively smaller size (i.e., sub-division of a drainage basin), which are considered as the management unit under the functional domain of a river basin (Jha et al., 2004; Khan et al., 2001). To ease the

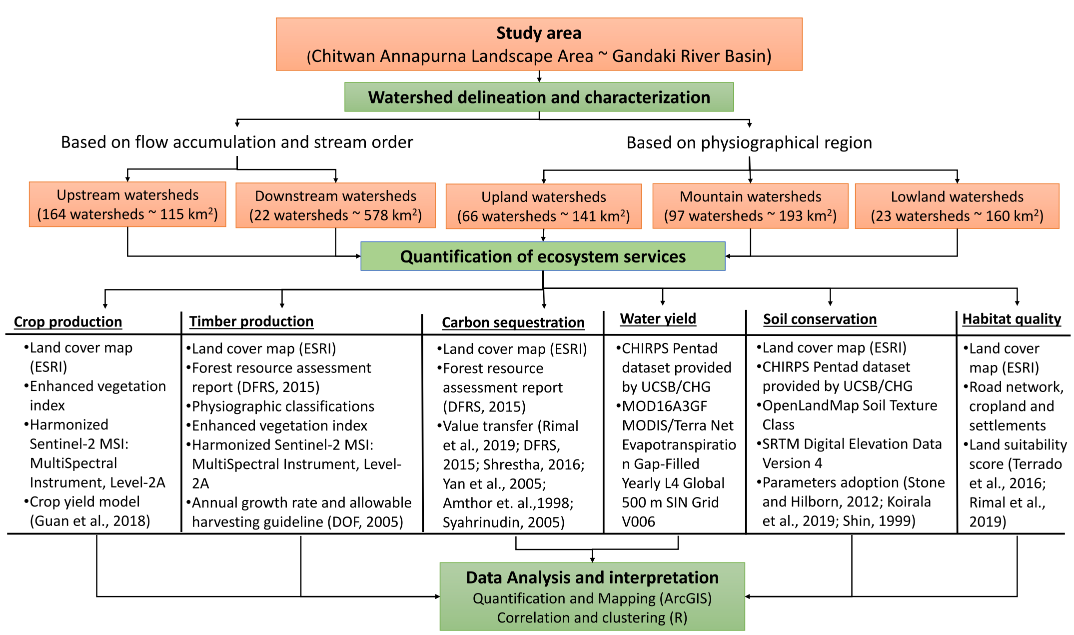

Fig. 2. Flowchart of the research methods.

visualization of ES at the management unit level, we divided the study area into 186 watersheds of varying sizes, using SRTM Digital Elevation Data Version 4 (Jarvis et al., 2008). Watershed delineation was done, using ArcGIS 10.8.1, based on the flow accumulation threshold of the river networks, which was set differently to the upstream and downstream sides of the basin. Upstream watersheds are characterized by the small flow accumulation (i.e., at the outlet or pour point) of initial stream orders, whereas downstream watersheds are characterized by a higher flow accumulation value, along with bigger confluence effects in the lower elevation gradient of the river networks. We identified 164 watersheds in the upstream and 22 in the downstream with an average size of 115 km^2 and 578 km^2, respectively (Fig. 3). Besides, the watersheds were also characterized based on the physiographic region such as upland watersheds (located in high mountains and Himal), mountain watersheds (located in mid-hills and mountains), and lowland watersheds (located in Terai and Siwalik).

2.3. Data acquisition and analysis

Data were taken from various primary and secondary sources. Because a large proportion of ES depends on the land cover types (i.e., ecosystem assets), we first acquired the land cover map of the study area. To access a suitable and more accurate land cover map, we compared two freely available fine resolution (i.e., 10 m) global land cover products developed by Environmental Systems Research Institute (ESRI) and European Space Agency (ESA). In order to compare the accuracy of the maps in our study area, we generated 300 random sample points throughout the study area in Google Earth Engine (GEE). Land cover types of the sample points were identified through visual interpretation of GEE-enabled high-resolution images. The land cover classes of each sample point were then compared against ESRI and ESA map products, which resulted in 89 % overall accuracy for ESRI product and 74 % for that of the ESA product. So, we selected ESRI land cover map (ESRI, Microsoft & Impact Observatory, 2021), and clipped our study area using GEE as a reference to quantify various ES. The scripts that are used to access the land cover maps and the comparison are mentioned in Supplementary file A.

Among the various types of ES, our study was focused on the quantification of six major ES in the study area (MOFE Nepal, 2015; WWF Nepal, 2016, 2013); (1) crop production, (2) timber production, (3) carbon sequestration, (4) water yield, (5) soil conservation, and (6) habitat quality which are the proxies to the classification of ES as recommended by MEA as food, fibre, climate regulation, water regulation, erosion control, and biodiversity conservation, respectively (MEA, 2005). Forest products, carbon, and habitat quality are important ES in the study area because about half of the study area is occupied by forestland, including protected areas (MOFE Nepal, 2015; WWF Nepal, 2016). The representation of a fragile landscape and a north–south stretching river basin signifies the importance of soil conservation and water yields in the study area (Mainali and Chang, 2021). Grain production from the croplands is crucial in terms of feeding about five million people (MOFE Nepal, 2015). About 80 % of the total energy consumption in the study area is based on traditional biomass sources (WWF Nepal, 2016). Because of the multi-functionality of the landscape in the study area, consideration of multiple ES (i.e., provisioning and non-provisioning ES), its quantity, and spatial pattern of occurrence is of utmost importance for spatial planning and landscape conservation.

2.3.1. Crop production

We quantified the crop production (i.e., cereal crops) from satellite

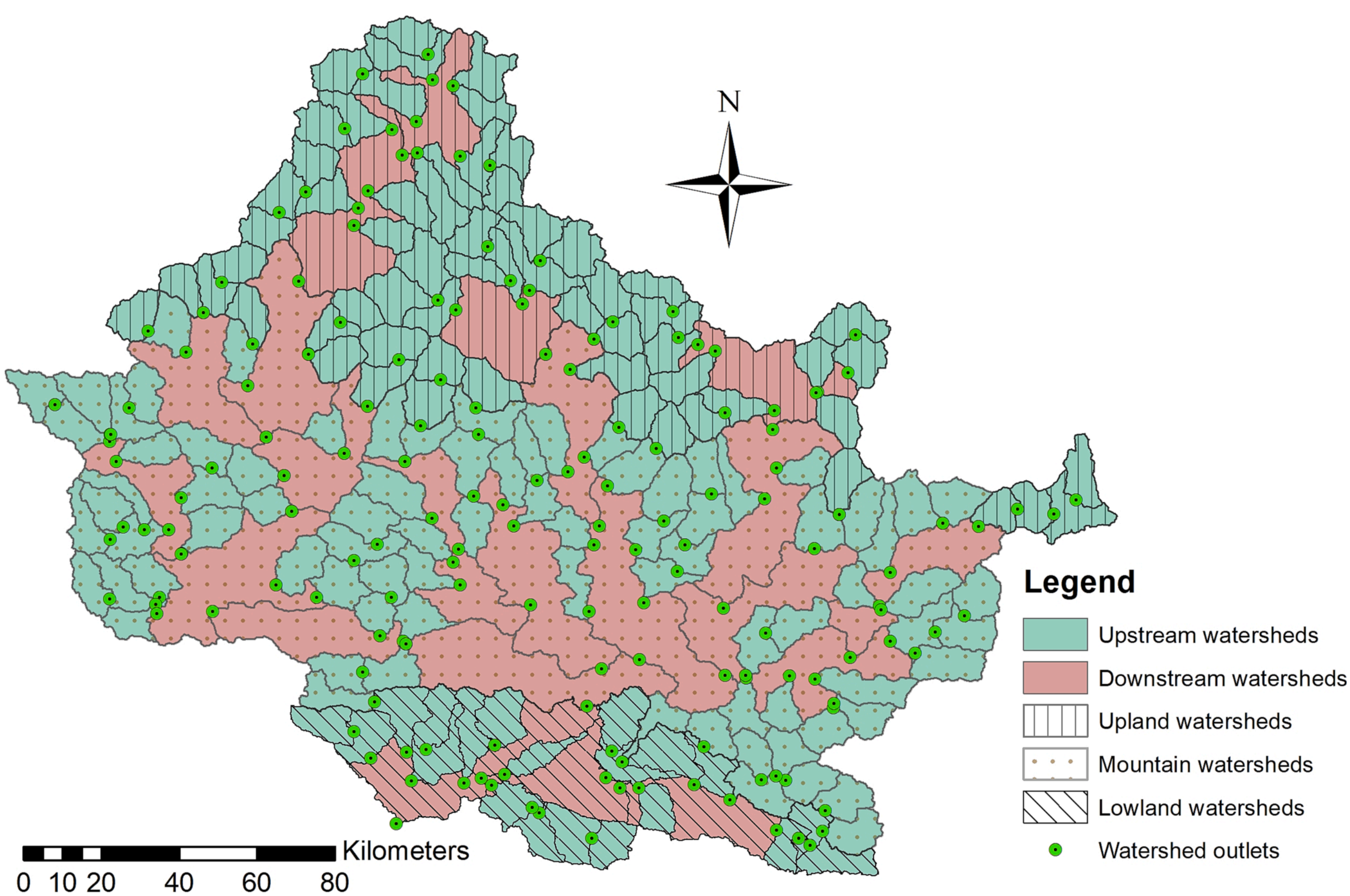

Fig. 3. Map showing 186 watersheds in the study area: (1) identifying upstream and downstream watersheds based on continuous flow accumulation and (2) upland, mountain and lowland watersheds based on physiographic region.

images. Land cover types were the main reference to estimate crop production, and vegetation indices further support explaining the variability of production from the study area (Kern et al., 2018; Panda et al., 2010). From the 10 land cover types of the ESRI land cover map we extracted, only the cropland area was used to quantify crop production from the study area. From among the vegetation indices, we used the enhanced vegetation index (EVI) of the cropland because EVI corrects noises from atmospheric conditions, the canopy background, and it is more sensitive in areas with dense vegetation (Wu et al., 2011; Xue and Su, 2017). Considering the diversity of crop species in the study area and their differing growing season at the river basin level, we considered only the peak EVI values of the pixel of cropland. EVI for the cropland was accessed from 'Harmonized Sentinel-2 MSI: MultiSpectral Instrument, Level-2A' (provided by European Union/ESA/Copernicus) through GEE for the year 2020. To predict the crop yield, we followed the crop yield model developed by Guan et al. (2018) and adopted by Kibret et al. (2021) for tropical agriculture based on peak EVI value:

[Crop yield (tons/ha) = 7.76 * peak EVI – 0.66].

The average production of crops and grains from the study area was then validated to the national average production of crops and grains for the year 2020 (MoALD, 2021). Although the model was developed in other countries, the ecosystem gradient and environmental scale as well as cropping pattern are similar to those of our study area. For instance, the model was primarily based on the paddy crop, which is the primary crop in terms of area and production (i.e., >50 % of the net cultivated area) in Nepal, including our study area (Basyal et al., 2019; MoALD, 2021). Further, crop production in our study area is concentrated in the lowlands of Nepal, where paddy is the most grown crop species due to the access to arable land and irrigation. We find that the crop yield model developed by Guan et al. (2018) is more accurate in terms of assessing crop production from the study area. Because other available approaches to estimate crop yield are irrelevant to our study area, for example, we could have used the crop data from the agricultural atlas of Nepal as adopted by Rimal et al. (2019), but when referred to the cropland area (as assessed by ESRI land cover product) the average production showed > 80 tons/ha, which is much higher than the national average of 3.2 tons/ha (MoALD, 2021). Alternatively, we also examined the crop yield model developed by Kuri et al. (2014) and adopted by Zhao et al. (2018) based on dry dekads (i.e., >10 consecutive dry days, calculated from vegetation condition indices). The 'Global (shared) linear model' for the crop yield however does not assume crop production can go > 0.8 tons/ha, which is again very low from the national average of Nepal.

2.3.2. *Timber production*

Timber production was assumed as the proxy for the forest product collection from the study area. We first extracted the forestland of the study area from ESRI land cover product and classified based on physiographic region (i.e., uplands, mountains, and lowlands). Within the classified region, we obtained the average stem volume of the study area from the FRA report of Nepal (DFRS, 2015), which was disaggregated based on the physiographic region. EVI was used to characterize the variations at the pixel level within each physiographic region of the forestland because EVI is correlated with above-ground biomass and growing stock as identified by previous studies (Hawryło and Wężyk, 2018; Pandit et al., 2018). After the assessment of average stem volume at the pixel level, we followed the annual growth rate to timber as recommended by the government of Nepal (i.e., 3 %) considering medium-quality forests with the timber species of medium growth rate (DOF, 2005). Further, as per the working guideline of the government of Nepal, we quantified the annual allowable harvest amount of timber as 60 % of the annual increment for medium-quality forest (DOF, 2005), such as:

[Annual allowable harvest (m^3/ha) = Average stem volume * 0.03 *0.6].

Due to the unavailability of location-specific forest quality information for the whole landscape, we assumed that all types of forestlands in the study area can resemble the national medium-quality forests of Nepal.

2.3.3. *Carbon sequestration*

Quantification of carbon sequestration was done based on land cover types and physiographic regions. Carbon sequestration values for: (1) the forestland and shrubland were acquired from FRA report (DFRS, 2015); and (2) other land cover types were adopted from other published sources, for example, Shrestha (2016) for grassland, Rimal et al. (2019) for cropland and snow and ice, Yan et al. (2015) for settlements, Amthor et al. (1998) for waterbodies, and Syahrinudin (2005) for bare grounds. Carbon sequestration was quantified for above-ground biomass, below-ground tree components, soil organic matter, and dead organic matter including litter and debris. Some land cover types are crucial for retaining greenhouse gases such as water, and wetland resources are important in retaining methane (Castillo et al., 2017), but we restricted our focus to carbon only, so we did not consider other greenhouse gases.

2.3.4. *Water yield*

Water yield was considered as the proxy to quantify the value of the hydrological regulation potential of the study area. Water yield was estimated using the formula:

[Water yield = precipitation - evapotranspiration ± Δ Storage]

Average annual precipitation data were accessed from CHIRPS Pentad dataset provided by UCSB/CHG (Funk et al., 2015). Similarly, actual evapotranspiration data were accessed from MOD16A3GF MODIS/Terra Net Evapotranspiration Gap-Filled Yearly L4 Global 500 m SIN Grid V006 (Running, Steve et al., 2019) using AppEEARS software (AppEEARS Team, 2022). The annual average of the precipitation and actual evapotranspiration was calculated from the average annual value of the last 10 years (2011–2020) because we focused on quantifying ES for the year 2020, and single-year data may contain the climate extremes. We considered the changes in storage as negligible, following the theoretical framework mentioned by Zhang et al. (2004) and also adopted by (Li et al., 2017) that the changes in water storage at regional and basin scales can be neglected.

2.3.5. *Soil conservation*

Soil conservation value was estimated by calculating the difference between potential soil erosion and actual soil erosion, which is supposed to be due to the factors of management practice, cropping pattern, and vegetation management (Li et al., 2017). We followed the Revised Soil Loss Equation (RUSLE) to estimate soil erosion (Wischmeier and Smith, 1965):

[Soil Conservation = Potential erosion (R × K × L × S) – Actual erosion (R × K × L × S × C × P)]

where, R indicates rainfall erosivity factor measured in MJ mm/ha/hour/year; K is the soil erodibility factor measured in tons hour/MJ mm; LS is the slope length factor; C is crop and management factor; and P denotes the conservation practice factor. Data sources for the quantification of soil conservation value were CHIRPS pentad dataset for rainfall erosivity (Funk et al., 2015), OpenLandMap Soil Texture Class (Hengl, 2018) for soil erodibility, and SRTM Digital Elevation Data Version 4 (Jarvis et al., 2008) for slope length factor. Parameters for quantification of soil conservation were obtained from various sources such as Stone and Hilborn (2012) for soil erodibility coefficient based on soil texture classes in the study area, C factor was adopted from Koirala et al. (2019) who have applied to a Nepal's case that is similar to our study area, the P factor was adopted by assuming contours as the only conservation practice as suggested by Shin (1999) and also implemented by Koirala et al. (2019) in Nepal.

2.3.6. Habitat quality

Habitat quality is the indication of the ability of the landscape to support wildlife habitat and biodiversity. The habitat quality of the study area is measured in terms of index 0 to 1, where 0 denotes poor habitat quality and 1 denotes excellent habitat quality. We considered three factors to quantify the habitat quality i.e., land cover suitability, threats to the habitat, and sensitivity of the land use to the threats (Terrado et al., 2016). The land cover suitability score based on the land cover types was adopted from Terrado et al. (2016), except for the forest and bare ground which was adopted from Rimal et al. (2019). Land cover suitability was assessed not based on the species preference, but the attributes of land cover to support biodiversity from a general perspective. Settlement, cropland, and road were considered threats to the habitat. The relative weightage of the threat values was adopted from Terrado et al. (2016), while the effective distance of the threats to the land cover was adopted from Rimal et al. (2019), which resembles Nepal's context that fits with our study area. The combined effects of threats and sensitivity to the threats were deducted from land cover suitability, based on the distance of the threats to the land cover classes.

2.4. Data processing and presentation

The quantitative value of ES was assigned at the pixel level. Due to the differences in the availability of data sources, the value of crop production, timber production, carbon sequestration, and habitat quality were assigned at the pixel of 10*10 m^2, whereas water yield and soil conservation were assigned at the pixel of 500*500 m^2. Landscape level mapping of the ES was done and visualized at the pixel level using ArcGIS 10.8.1. After the mapping of ES, we summed up the value of ES at the watershed level to perform a correlation analysis of ES and clustering of watersheds, using zonal statistics tools of ArcGIS. Because of the differences in the size of the watersheds, we calculated the average value of ES for each watershed per unit area for further analysis. Spearman correlation test was performed to understand the relationship among 15 pairs of ES at the watershed level, using R software (R Core team, 2021). We employed K-means clustering (i.e., the spatial distribution of ES) to categorize the watersheds based on the coexistence and production potentials of ES, using R software. Gap statistics of K-means clustering (i.e., the goodness of clustering measure) was used to define the optimal number of clusters (i.e., "fviz_nbclust" to determine the optimal number using within cluster sums of squares, and "fviz_gap_stat ()" to visualize the gap statistic using 'factoextra' package in R). Details of the library package and script used for the analysis are presented in Supplementary file A. Mean value of the ES in each cluster is transformed through min/max normalization (i.e., on a scale of 0–1) and then presented in a Radar chart.

3. Results

3.1. Quantification and spatial mapping of ES

In the study area of 31,700 km^2, the annual crop production was estimated to be 0.43 million tons (MT). Likewise, the estimated production of timber in the study area was 3.4 million m^3 (MCM). About 300 MT of carbon and 47 billion m^3 (BCM) of water yield were estimated in the study area. About 128 MT of soil was found to be conserved through vegetation, contouring, and various cropping and management practices. The overall habitat quality of the study area was found to be relatively low (i.e., 0.36) on a scale of 0–1. As the study area is heterogenous in terms of climate (i.e., sub-tropical to alpine) physiography (i.e., southern lowlands to *trans*-Himalayan region), and elevation range (about 100 m to 8000 m above mean sea level), the supply of ES is also found to be highly heterogenous. Southern lowland region was found to be supplying a substantive amount of crop and timber production. On the other hand, the northern uplands, which are mostly covered with bare ground, snow and ice, and shrublands are very poor in supplying various ES. The mountain region was found to supply multiple ES simultaneously. The average supply of the six ES according to various watershed types is presented in Table 1. It shows that lowland watersheds have higher crop production and timber production but low soil conservation. The mountain watersheds were found to have a higher value of carbon sequestration, while upland watersheds were found to be poor in supplying all six ES except water yield. Regarding the upstream/downstream watersheds, downstream watersheds were found to supply higher values of ES as compared with the upstream watersheds.

Fig. 4 shows the spatial distribution of the average production of six ES in the study area. Crop production is restricted to only a few areas in the middle and southern parts of the study area. The average production of the crop in the cropland areas was found to be ranging from about 0.1 tons to > 6 tons/ha. Timber production was observed throughout the study area with an average value of 2–4 m^3/ha, except in the northern uplands and some agriculture-dominated landscapes in the southern lowlands. Carbon sequestration, water yield, and soil conservation were measured throughout the study area, with the average value of 90 tons, 15,000 m^3, and 40 tons per ha, respectively. The habitat quality was measured good in the southern foothills and in the northern part of the hilly region, which is relatively far from the threats to habitat (i.e., roads, settlements, and croplands).

3.2. Relationship among ES

ES in the study area is found to be differently associated with each other, ranging from a correlation coefficient of 0.85 to 0.08. The average quantity of ES was measured for all 186 watersheds. All the ES are significantly positively correlated with each other except crop production (Fig. 5). The correlation of habitat quality and carbon sequestration is highest ($r = 0.85$) followed by timber production and carbon sequestration ($r = 0.83$), timber production and habitat quality ($r = 0.74$), soil conservation and water yield ($r = 0.71$), and others. We found crop production was negatively correlated with soil conservation ($r = -0.15$). Our study found no spatial relationship between crop production and water yield. The ellipse of the scatter plot and regression line for crop production is found to be coarser because about one-third of the total watershed, especially in the northern upland regions, had no farmland and hence no production of cereal crops.

3.3. Clustering of watersheds based on co-occurrence of ES

We grouped the watersheds within the study area into three functional categories: (1) agriculture watersheds, (2) multifunctional watersheds, and (3) poor-performing uplands. Agriculture-dominated watersheds, with a relatively high supply of crop production, were depicted in the southern lowlands of the study area. Poor-performing upland watersheds, located on the northern side of the study area, were characterized by the low supply of all ES, except soil conservation value, which is lower in agriculture watersheds. The mean value of crop production in agriculture-dominated landscape was 0.67 tons/ha, while that of the poor-performing uplands was very negligible. Similarly, the mean values of carbon sequestration (37.37 tC/ha), timber production (0.06 m^3/ha), and habitat quality index (0.17) of poor-performing uplands were substantially lower than those of multifunctional and agriculture-dominated watersheds. As compared with the agriculture-dominated watersheds, carbon sequestration, timber production, and soil conservation values are substantially higher in multifunctional watersheds. The range normalized value of the cluster mean of each watershed cluster is presented in Fig. 6. The figure shows that the multifunctional watershed cluster is an ecologically productive area having higher values except for crop production. The difference in timber production between multifunctional watersheds and agriculture

Table 1
Average quantity of ecosystem services based on watershed types.

Types of watersheds	Timber production (m^3/ha)	Carbon sequestration (tC/ha)	Crop production (tons/ha)	Water yield ('000 m^3/ha)	Habitat quality	Soil conservation (tons/ha)
Upland	0.16	46.59	0.00	85.74	0.21	33.20
Mountain	1.44	117.83	0.10	146.64	0.44	42.40
Lowland	1.67	92.97	0.65	52.28	0.44	12.14
Upstream	0.98	87.43	0.13	113.14	0.35	33.47
Downstream	1.29	105.54	0.16	115.05	0.41	50.47
Overall mean of the landscape	1.01	89.48	0.13	113.36	0.35	35.39

watersheds is found to be very low.

4. Discussion

In this study, we quantified and mapped the spatial distribution of ES at various spatial scales. Besides, we found that the major ES in the multifunctional landscape in the Himalayas exhibits different forms of spatial relationships. For example, crop production and timber production were spatially exclusive at the pixel level (i.e., the difference in land cover types) but exhibit a positive correlation at the watershed levels. Conversely, the interaction among timber production, carbon sequestration, soil conservation, water yield, and habitat quality were found to be synergistic at both pixel and watershed level. Besides, we showed watersheds can be grouped into three clusters based on the average ecological functions and production possibilities, implying different kinds of management interventions for different clusters.

4.1. Quantity, spatial distribution, and interaction of ES

Our finding of average crop production (0.13 tons/ha) of the whole study area (i.e., not only the cropland area) is very low from a previous study by Rimal et al. (2019) in the Eastern part of Nepal, who found about 2.85 tons/ha for the whole Koshi River basin. Although the consideration of crop species (i.e., cereal crops) of the two studies is the same, the difference in production might be due to the differences in the quantification approach, as well as the differences in the availability of cropland area. It is because the margin of difference is very low when compared with the crop production per cropland area only (i.e., 3.77 tons/ha in our case and 8.05 tons/ha in the study done by Rimal et al. (2019)). Nevertheless, our estimation is close to the national average cereal crop production of 0.74 tons/ha because the cropland area in our study area was lower (i.e., 3 %) than that of the cropland area nationwide (i.e., 21 %) (MoALD, 2021, p. 20). Unlike crop production, our estimation of average carbon sequestration (i.e., 89.47tC/ha) is much higher than that estimated by a comparable study Rimal et al. (2019) in Eastern Nepal as 55 tons/ha and a little higher than the national average of 71.52tC/ha (DFRS, 2015). One reason behind the higher value might be that the proportion of forestland and shrubland is higher as compared with the other land cover types in our study area, which sequester a relatively high amounts of carbon.

The average timber production from the study area is estimated to be about 1.0 m^3/ha which is substantially higher than the national record of timber collection of about 0.02 m^3/ha for the fiscal year of 2019/2020 (Basnyat et al., 2020). The higher difference in the values is attributed to the policy provisioning of allowable timber collection and actual timber collection. Further, the national accounting of timber production largely misses the household and community consumption of timber, especially in the rural areas (Aryal et al., 2020). In addition, a report by FAO/UNDP/UNEP and MSFC Nepal (2014) stated that only 2.5 % of the potential timber production is actually harvested in Nepal. Our estimation of the overall habitat quality of the study area (0.35) is lower than that of a study by Rimal et al. (2019) who noted a habitat quality of 0.44 for Koshi river basin, probably due to the presence of a higher proportion of bare ground, shrublands, and snow and ice cover in the high altitude zones of our study area. In addition, a large part of the study area in the uplands is designated as 'conservation area', which is primarily to represent the Himalayan landscape rather than the biodiversity hotspots. Further, the widespread development of road network, settlement, and cropland in the study area might have attributed to the lower score for habitat quality in this region. The average water yield in our study area (i.e., 110,000 m^3/ha) is higher than that of a study by Bastola et al. (2019) who estimated 15000 m^3/ha in Bagmati river basin. This difference in water yield is probably because of concentrated high rainfall in our study area as it includes high rainfall pocket areas of Nepal (i.e., Pokhara receives mean annual rainfall of > 5000 mm) (Karki et al., 2016). In this regard, we argue that the supply of various ES from a heterogenous and multifunctional landscape is not unidirectional but contingent on multiple natural processes and human interventions.

Major ES are found to exhibit a distinct pattern of occurrence in the study area. Crop production is at its peak in the southern lowlands of the study area, average in the middle part and almost absent in the northern uplands. It is because the land cover types, slope gradient, water availability as well as environmental factors for crop production are favourable in the lowland and not suitable in the uplands (Budhathoki et al., 2020; Pokhrel and Soni, 2019; Shrestha et al., 2013). Timber production has a distinct form of distribution, which has its high value in the southern lowlands and at the edges of mountain and upland watersheds in the upper half part of the study area (Fig. 4). Our finding is in line with the national assessment of stem volume of timber that has the highest value in the uplands and lowest in the mountains (DFRS, 2015) but at the same time, forestland in the uplands is confined only to its southern part (ESRI, Microsoft & Impact Observatory, 2021). These two provisioning ES (crop and timber) included in this study are found to be mutually exclusive at the pixel level because of the land cover consideration; however, the production of both ES is found to be higher in southern lowlands and almost absent in the northern part of the study area. Non-provisioning ES, especially carbon sequestration and habitat quality were found to follow the spatial pattern of land cover classes, while soil conservation and water yield were found to be dependent on multiple factors, including land cover, slope, and elevation.

We observed that land cover types, altitudinal gradients, slopes, and soil classes are the major determinants of spatial patterns of ES in the Himalayas. Land cover is the major determinant of ES supply which has been supported by numerous previous studies (Chen et al., 2019; Makwinja et al., 2021; Qiao et al., 2019; Rimal et al., 2019; Sharma et al., 2019). As observed in our study, Rahmonov et al. (2021) and Ma et al. (2021) believe that elevation and terrain gradient highly influence the distribution of ES in mountains. Similarly, a few other studies (i.e., Li et al., 2021; Wang et al., 2021b) noted slope has a significant effect on the distribution of ES. Nevertheless, as opposed to their findings of slope having a positive influence on ES, we found the slope as having a negative effect on the availability of ES in our study area. For example, the northern upland part of the study area with high altitude and higher slope percentage has low ES distribution. The presence of mountains (i.e., covering > 90 % of the study area) implying a higher slope percent have different consequences on ES than having a gentle slope in plain land, peatlands, or waterlogging areas. The influence of soil on ES has also been evident from previous studies (Ellili-Bargaoui et al., 2021;

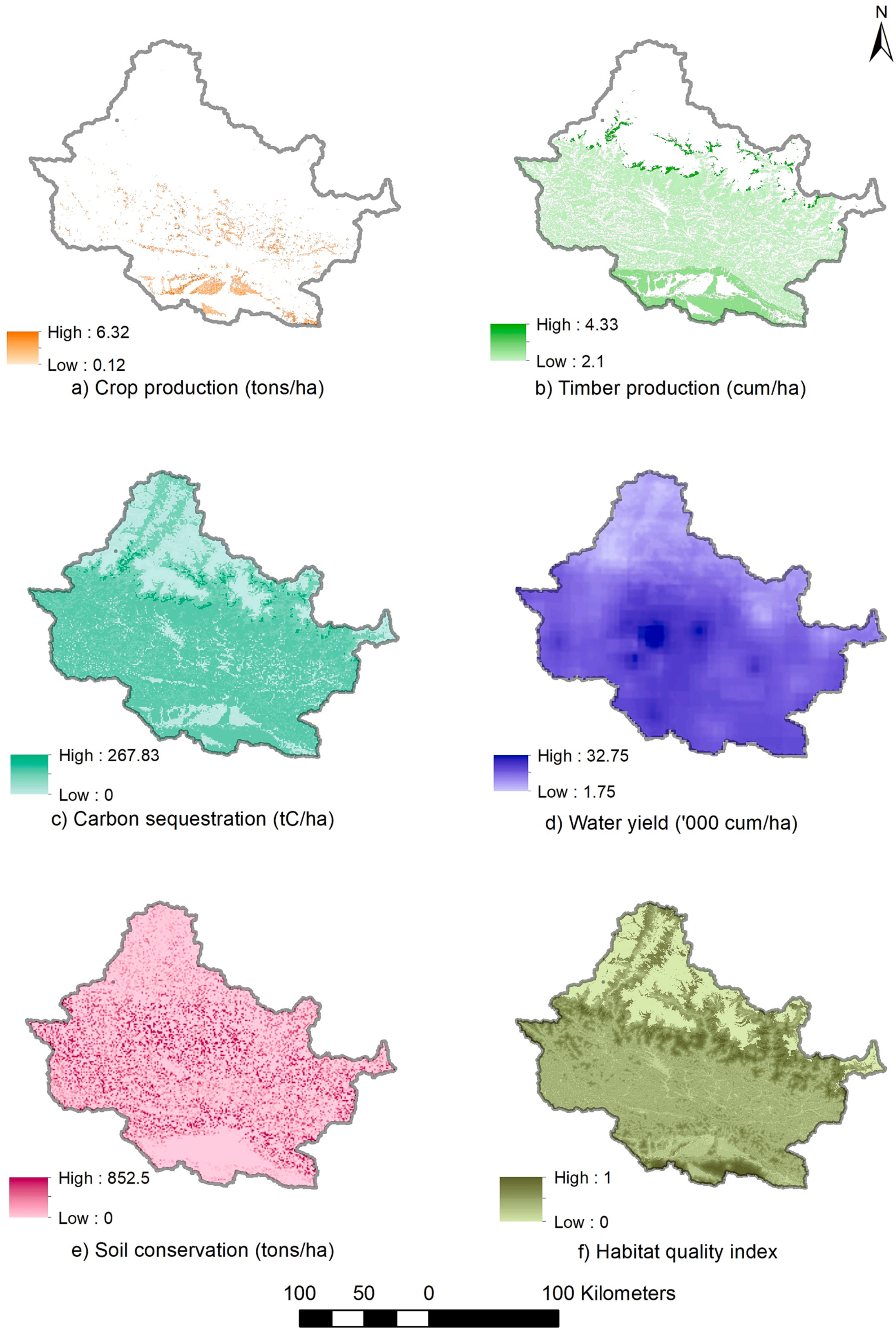

Fig. 4. Spatial distribution of six ecosystem services in the study area.

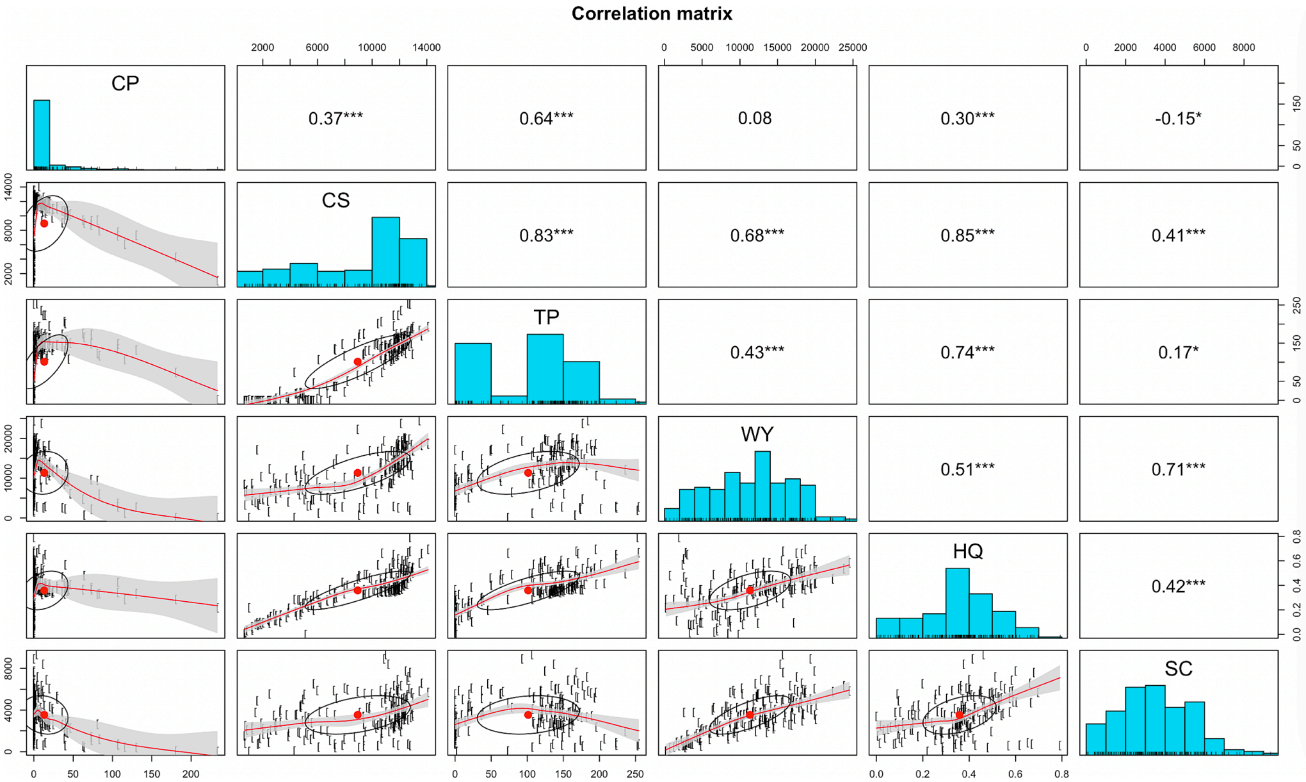

Fig. 5. Correlation matrix of the six ES (with Locally Estimated Scatterplot Smoothing line in red having 95 % confidence interval in grey shading and ellipse, histogram of data density, and correlation coefficient with significance level). CP = crop production; CS = carbon sequestration; TP = timber production; WY = water yield; HQ = habitat quality; and SC = soil conservation. Significance code * = P value [0.01, 0.05]; and *** = P value [0, 0.001].

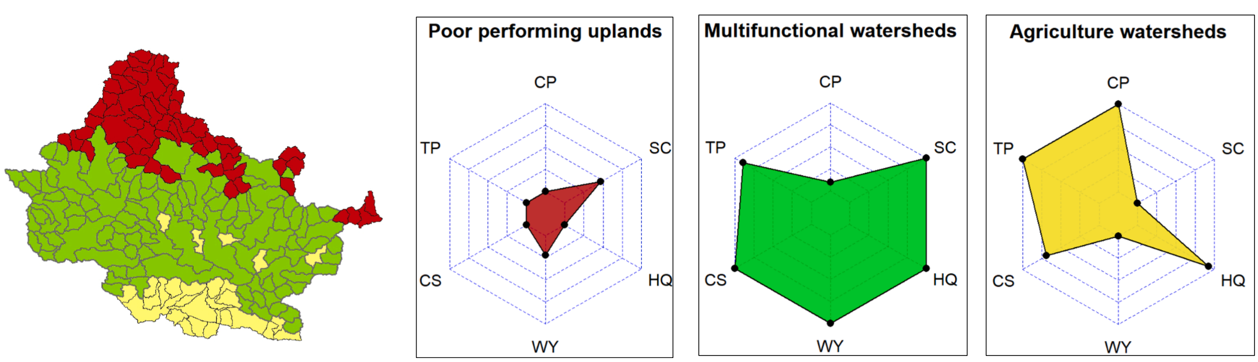

Fig. 6. Three clusters of watersheds. Map shows the distribution and visualization of each cluster types throughout the study area. The diagram shows the range normalized value (0 for the inner segment to 1 for the outer segment) of the mean values of six ES in each cluster of watersheds. CP = crop production; CS = carbon sequestration; TP = timber production; WY = water yield; HQ = habitat quality; and SC = soil conservation.

Paul et al., 2021; Ziter and Turner, 2018). We found that the spatial pattern of ES is dependent not only on a single determinant but composite interactions of land cover types, soil, topography, and other environmental factors.

Among the 15 pair-wise correlations between ES, 13 positive and one negative interaction were detected, whereas one pair (i.e., crop production and water yield) was found to be uncorrelated (Fig. 5). We found timber production, carbon sequestration, and habitat quality to be highly correlated with each other. The negative correlation of crop production with other ES, such as soil conservation, supports the notion that agricultural land use limits the availability of other ES (Foley et al., 2005; Turner et al., 2014). Various previous studies have mentioned that crop production is negatively correlated with carbon sequestration (Jeong et al., 2019; Johnson et al., 2014; Ridzuan et al., 2020) and habitat quality (Adhikari et al., 2022; Berta Aneseyee et al., 2020; Di Pirro et al., 2021; Xu et al., 2019b); however, in our case, it was not negatively correlated with carbon sequestration and habitat quality. One explanation could be the habitat consideration of agrobiodiversity and the choice of crop and cropping practices (Ostle et al., 2009). A negative correlation between crop production and soil conservation is also evident from other previous studies (Zhong et al., 2020), which can be minimized through proper conservation and management practices.

The trade-off between timber production and carbon sequestration is evident in many previous studies (Lin and Ge, 2020; Seidl et al., 2007; Soimakallio et al., 2021), but we found it positively correlated because the estimation of timber production was based on the institutional provision of allowable timber collection from a forest area in Nepal. However, the relationship among ES can also be reversed depending on time, space, and socio-economic factors (Wu et al., 2021). For example, the synergistic relationship between carbon sequestration and material production turned into trade-offs in the Yellow River Delta in China due to the changes in socioeconomic factors (Yang et al., 2018). Similarly, the strength of the relationship can also be changed through management interventions as evident through the fire management regimes in minimizing trade-offs between biodiversity conservation and greenhouse gas emissions in Australia (Maraseni et al., 2016). In this regard, we would suggest empirical field-based research on actual timber harvest and its carbon counterpart for a better understanding of the interaction among the ES. Positive correlation among major ES as observed in our study indicates that, at the landscape level, careful planning and integrated management of natural resources might have a synergistic effect on other ES rather than putting individual sector efforts on managing the ES (Chaudhary et al., 2019; Kandel et al., 2021). Similarly, trade-offs between crop production and other ES can be minimized using landscape-friendly cropping practices, proper selection of crop species, and the use of improved cropping technologies suitable to the site and/or landscape.

4.2. Supply potentials and its implication for landscape management in the Himalayas

Although various policy prescriptions advocate for win–win scenarios for contradictory pairs of ES, not all ES can indefinitely be supplied from a landscape in the real-world scenario (Turkelboom et al., 2018). There exist some production possibilities and optimum supply potentials of certain landscapes and/or basins. To illustrate, few previous studies have depicted the production possibilities between carbon sequestration and soil conservation in China (Wu et al., 2021), crop production and soil carbon in Western Australia (Kragt and Robertson, 2014), forest cover and crop production in Tanzania (King et al., 2015), and forest, agriculture and freshwater in Eastern Himalayas (Chettri et al., 2021). As we observed in our study, watersheds within the landscape can broadly be classified into three categories, such as agriculture-dominated, multifunctional, and poor-performing uplands (Fig. 6). Agriculture-dominated watersheds, mostly observed in the southern lowlands of the study area, have to be compromised for soil conservation. Nevertheless, improvements in cropping practices and the use of advanced technologies can reduce soil erosion caused by agronomic practices as can be seen in other places, such as agroforestry practices in Nepal, India, and other humid regions of the tropics (Aryal et al., 2019b; Bastakoti et al., 2017; Dhakal et al., 2015, 2012; Muchane et al., 2020), terracing and strip cultivation in Northeast China (Liu et al., 2011), organic farming and green manuring in Pakistan (Kousar and Abdulai, 2016), and many other agronomic and mechanical practices throughout Asia (Nasir Ahmad et al., 2020). Considering the suitability of the particular landscape for crop production, which is the immediate and most important ES for rural communities, especially in developing countries, the optimization of ES and accordingly the landscape management prescription needs to be adaptive to address the demand of local people and the biophysical capacity of the landscape. Supply limitation of other ES, such as habitat quality, in the agriculture-dominated watersheds can be improved by enriching the practices of agrobiodiversity, which have been practiced in European countries (Mouysset, 2017), Iran (Monfared and Armaki, 2015), Ethiopia (Erenso and Andemo, 2022), India (Das and Das, 2020), and other developing tropical countries (Andersen, 2016; Montenegro de Wit, 2016; Mwavu et al., 2016). Accepting the inevitable element that higher crop production is as necessary as the preservation of other provisioning and non-provisioning ES, the future course of actions in agriculture-dominated watersheds must be focused on refining agronomic practices, the adaptation of improved technologies, and introduction of agrobiodiversity enrichment programs to buffer its trade-offs with soil conservation and habitat quality.

The clustering of the watershed is found to be largely determined by the altitudinal gradient. The supply of ES from poor-performing uplands (i.e., watersheds in the high-altitude areas) of the study area is very low as compared with other clusters of watersheds. Such types of watersheds are common in the Himalayas landscape. Primarily, harsh topography, snow-capped mountains, ice cliffs, and the presence of rock and bare grounds in the northern uplands of the study area, to a large extent, limit the supply of ES (Parsons et al., 2016; Paudel et al., 2016; Pellicciotti et al., 2015). Besides, snow-capped mountains and glaciers in the upland regions are highly responsive to climate change, causing the frequent incidences of glacier lake outburst floods, and landslides further diminishing the ecological productivity of the upland areas (Bajracharya et al., 2018; Gentle et al., 2018; Kraaijenbrink et al., 2021; Mainali and Pricope, 2017). Moreover, a study by Chaudhary et al. (2020) found that > 90 % of the farmlands in the uplands of Nepal is irreversibly deteriorated due to farmland abandonment and associated land degradation (i.e., landslides, soil erosion). In this regard, intensive management and human interventions in the upland watersheds for the supply of diversified ES might be less efficient or even counter-productive due to its fragile topography and ecological sensitivity. Rather, management prescriptions for those watersheds might include greening of the mountain landscapes (Mishra and Mainali, 2017), minimizing land use change (Bastola et al., 2020; Chaudhary et al., 2016; Shrestha et al., 2022), nature-based solutions (Keesstra et al., 2018), grazing and rangeland management (Danvir et al., 2018), climate action in mountains (Karki et al., 2019; Laudari et al., 2021; Marahatta et al., 2021), and high-altitude horticulture (Chisanga et al., 2018). Nevertheless, global climate action is indeed crucial to maintain the ecological integrity of the mountain watersheds of Nepal's Himalayas.

Multifunctional watersheds in the middle part of the study area are relatively rich in supplying varying ES. Multifunctional watersheds support ecological protection while creating socio-economic resilience (Hibbard et al., 2015). The supply of various provisioning and non-provisioning ES in those watersheds can be managed and enriched to get a win–win solution to trade-offs in ES (Kong et al., 2018; Poppenborg and Koellner, 2013). We observed higher mean values of carbon sequestration, soil conservation, water yield, and habitat quality in the multifunctional watersheds, yet we see trade-offs with crop production as compared with the agriculture-dominated landscape. Watershed management activities such as improved cropping practice, soil and water conservation, sustainable forest management, disaster risk management, nature-based solutions, and climate change adaptation might improve the productivity of those watersheds (Aryal et al., 2023, 2019b; Devkota et al., 2017; Laudari et al., 2022; Maraseni et al., 2022; Thapa et al., 2022). In this regard, we recommend integrated watershed management (considering social, ecological, and policy aspects) in the multifunctional watersheds, which can further be eased by the institutional development of community organization.

An important yet rarely discussed issue in ES interaction is the dispute in understanding the difference between potential supply and actual supply of ES. For example, we found that the average timber production in the study area is about 1 m^3/ha; however, the actual timber production and supply might have differed from the estimated value. Similarly, although we consider carbon sequestration as an important non-provisioning ES, our estimates of about 90tC/ha in the study area might have a different value (monetary and other) to the different communities from different perspectives. In such kind of complicated scenarios of understanding natural resources, potential extraction value, and actual supply of ES might create confusion and ambiguity in quantification (Clec'h et al., 2016; Newton et al., 2018). However, consideration of the relationship and interactions among the ES simplifies the landscape management confusion by portraying clear objectives of optimizing ES through maximizing synergies and minimizing trade-offs. The optimum supply of provisioning and non-provisioning ES is ever getting important also because of the rapidly changing socio-economic context, complex ecological functions and processes, and emerging climatic uncertainties to satisfy both local and non-local ES beneficiaries in a sustainable manner.

Having discussed the dynamics of ES supply and interaction, we acknowledge a few limitations of this research that can be improved in future studies. For example, field-based empirical assessment of the ES might enhance the findings rather than using estimates and adopting parameters from other studies (Aryal et al., 2022; Mach et al., 2015). Further, our quantification and mapping of ES are based on the land cover map which might contain up to 11 % error (i.e., 89 % accuracy of the land cover product), and this margin of error should be reminded while using the finding of this research in planning and management of ES in this region and beyond. The addition of temporal variations and interactions among ES might widen the general applicability of our findings (Hein et al., 2016; Rau et al., 2018). Analysis of the co-occurrence of ES at different clusters, depicting production possibility frontiers of the clusters of watersheds, would be insightful for understanding trade-offs in ES, which we recommend for future research. Moreover, the incorporation of socio-economic aspects, including political science, of ES quantification and trade-offs complement the study for sustainable landscape management (Cavender-Bares et al., 2015; Kandel et al., 2021; King et al., 2015). The economic valuation of ES (i.e., putting price tags) could provide an even clearer picture that enhances the applicability of the findings (Acharya et al., 2019; Rai et al., 2018). Nevertheless, our findings show that the management intervention in the Himalayas depends not only on the types of the landscape but the pattern of occurrence of ES within the landscape and their unique characteristics as observed in three clusters of watersheds in our study area. To ensure sustainability in ES from the Himalayas landscape, future research work must be focused on depicting production possibility frontiers of the landscape, socio-cultural perspective and economic valuation of trade-offs in ES, and scenario modelling of different policy alternatives to satisfy the varying demands of divergent stakeholders from the limited production possibilities of the landscape.

5. Conclusions

Scholarship on the assessment and valuation of ecosystem services (ES), as a snapshot approach, provide sufficient reasons to study the spatial dynamics of ES in the Himalayas. What has been previously discovered was insufficient to understand the relationship and interaction among ES from whole to part (i.e., broader functional unit to smaller management unit) of the landscape. In this paper, we quantified six important ES (namely, crop production, timber production, carbon sequestration, soil conservation, water yield, and habitat quality) at the landscape and watershed levels. Further, we categorized the watersheds into three clusters based on their bio-physical potential for producing the ES. Our results show that the study area has a production potential of 0.43 MT of crops, 3.4 MCM of timber, 300 MT of carbon, 47 BCM of water yield, 128 MT of soil conservation, and average habitat quality index of 0.36 on a scale of 0–1. The ES are not proportionately distributed in the Himalayas. For example, southern lowlands were rich in crop and timber production, while the northern uplands were poor in supplying those ES. All the ES were positively correlated to each other, except crop production, which had a significant negative correlation with soil conservation. The nature of interrelationships among the ES was also found to be changing based on the differing spatial scale, such as crop production and timber production being mutually exclusive at the pixel level, but we observed them to have a positive correlation at the watershed level.

Based on the supply potentials of ES, all the delineated watersheds in the landscape were divided into three clusters. Agriculture-dominated watersheds were found to have a higher proportion of crop production but lower values of soil conservation and habitat quality. However, the poor-performing uplands were found to have lower values for all major ES due to the presence of bare ground, snow and ice in the high-altitude area. Multifunctional watersheds in the middle part of the study area showed the highest supply potentials for carbon sequestration, soil conservation, and timber production.

Based on the peculiarity of the clusters of watersheds, we suggest: (1) technological interventions, improved agronomic practices, and agrobiodiversity programs in agriculture-dominated landscapes in the southern lowlands, (2) integrated watershed management activities in multifunctional watersheds in the middle region, and (3) global climate actions in poor-performing uplands to protect the critical high-altitude ecological integrity of the watersheds. To get a deeper insight of ES interactions, we recommend future research on depicting production possibility frontiers of the Himalayan landscape, varying sociocultural utility values of ES, and evaluation of various policy alternatives for landscape management. The Himalayan landscape is heterogenous and multifunctional not only in terms of its ecological characteristics but also based on its differing supply potentials at varying spatial scales. Thus, we conclude that sustainable ecosystem management in the Himalayas, be it at the landscape or watershed level, should focus on minimizing trade-offs and maximizing synergies among ES holistically.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2022.101503.

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