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Understanding production possibility frontiers and utility values of ecosystem services in the Himalayas: An analysis of the supply-demand divide

Kishor Aryal [a,b], Tek Maraseni [a,c,*], Armando Apan [a,d]

[a] University of Southern Queensland, Toowoomba, 4350, Queensland, Australia
[b] Ministry of Industry, Tourism, Forests, and Environment, Sudoorpaschim Province, Nepal
[c] Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, China
[d] Institute of Environmental Science and Meteorology, University of the Philippines Diliman, Quezon City, Philippines

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ABSTRACT

Nature's services to humanity – ecosystem services (ES) – have been at the centre of natural resource management scholarship for the last few decades. Yet, quantification of ES supply and its economic valuation have dominated the academia. Spatial associations of multiple ES and their mutual production possibilities, social dimensions of ES demand, and the gaps between supply and demand of ES have not been sufficiently articulated in the literature, especially for the Himalayan landscapes. In this context, using satellite images, secondary data, and household survey (n = 300), we identified the supply-demand divide of ES by assessing production possibility frontiers and social demand of ES in the central regions of Hindu-Kush Himalayas. Among the six major ES that we considered in this research (crop production, timber production, carbon sequestration, water yield, soil conservation, and habitat quality), production possibilities of the other five ES get diminished with the increasing supply of crop production. Timber production, carbon sequestration, habitat quality, and soil conservation can be mutually incremental through the allocation of sufficient forestland areas. Local people's demand of water yield and crop production is very high as compared to those of the others, yet the current state of supply potential of those ES is largely inadequate to meet the demands. Instead of generalized management prescriptions, we recommend for the people- and place-based interventions in ecosystem management. Nonetheless, improved agronomic practices and integration of farming with forestry, carbon, and climate actions might be the safe operating space for sustainable landscape management in the Himalayas.

1. Introduction

Ecosystem services (ES) are the benefits to human wellbeing provided by Nature (Costanza et al., 2017; Daily et al., 2009; de Groot et al., 2012). Depending on biophysical properties, ecological processes, climatic characteristics, and human interferences, a landscape supports various ES (i.e., provisioning, regulating, cultural, and supporting) at varying scales and intensities (Englund et al., 2017; Sharma et al., 2019). ES ranges from direct provisioning services such as food and fibre, and cultural and spiritual values, yet these are not standing alone but depend on interactions among each other. The interactions among ES can be synergistic or trade-offs which can be observed at various spatial and temporal scales (Ikematsu and Quintanilha, 2020; Qiao et al., 2019). The presence of one ES might impact on the abundance or scarcity of others, including its further ecological dynamics or the environmental equilibrium (Foster et al., 2022; Mori et al., 2017; Pandey et al., 2023). Besides, the social dimension of the landscapes, including the demand of ES and their utility functions (Cavender-Bares et al., 2015; King et al., 2015), plays a crucial role in characterizing the spatio-temporal mosaics of ecosystems needed to examine landscape sustainability.

Sustainability framework of ES must consider both ecological supply potentials of the landscapes, as well as the social demand of the local communities (Aryal et al., 2022; Torralba et al., 2018). Unlike any industrial farming where production of goods or services is independent of

Abbreviations: ES, Ecosystem services; PPF, production possibility frontiers; CP, rop production; TP, timber production; CS, carbon sequestration; WY, water yield; SC, soil conservation; HQ, habitat quality; CHAL, Chitwan Annapurna landscape; ESRI, Environmental Systems Research Institute, Inc.

* Corresponding author. Block: Q 525, University of Southern Queensland, Toowoomba, 4350, Queensland, Australia.
E-mail address: Tek.Maraseni@usq.edu.au (T. Maraseni).

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other, the production potential of one ES is dependent on the concurrent production of other ES (Kumar et al., 2013; Le Provost et al., 2022). The interface of socio-ecological tradeoffs in ES which is crucial in understanding the supply-demand divide of multiple ES is presented in Fig. 1. Biophysical constraints or the production potentials of a landscape cannot be measured for a single ES but should be understood as its productive capacity with respect to the increase or decrease of the other ES known as "production possibility frontiers" (PPF) (Martinez-Harms et al., 2015; Vallet et al., 2018; Yang et al., 2022). Although the concept of PPF is commonly used in economics as "a transcendental function of the logarithms of its arguments, the quantities of net outputs" (Christensen et al., 1973), it can also be used to explain concurrent production possibilities of two ES from a given landscape with the existing institutional arrangements. PPF indicates the maximum pairwise production limits of various combinations of ES with either trade-offs or synergistic relationships (Joly et al., 2021; Yang et al., 2022). In this regard, analysis of PPF is important to understand the maximum supply potentials of ES and to evaluate various measures to stretch out the curves of PPF.

In addition to ecological supply potentials, the social demand of ES is equally important to understand the extraction of ES, as well as the potential human intervention/influences through socio-ecological system framework (Manley, 2022; Torralba et al., 2018). People might have different preferences and demand values, depending on various socio-demographic characteristics, for different pairs of ES (Drake et al., 2013; Wang et al., 2019; Yin et al., 2023). Although the demand values of each ES are difficult to quantify in terms of exact units of those ES, it can be measured in terms of relative importance and utility functions – demand isoclines or indifference curves (Cavender-Bares et al., 2015; King et al., 2015). Indifference curves indicate the points of equal utility throughout the possible band of mutual ES demand (King et al., 2015; Samuelson, 1956). Scale measurement of the utility functions of various pairs of ES would ease to understand which ES are on high demand as compared to the others, and whether the ecological supply potential is matching the social demand of the respective pairs of ES (Wei et al., 2021; Yin et al., 2023). PPF and demand isoclines however assume that some ES can be maximized at the complete loss of other (Sickles and Zelenyuk, 2019; Stosch et al., 2019). But this assumption is unrealistic because some ES are inevitably present even at the maximum attainment of the other ES. For example, even if forestland is converted to farmland, the value of carbon sequestration, biodiversity and soil retention cannot be reduced to zero. In this case, instead of the curves or isoclines, ellipses of the area covering pairwise production possibilities of ES better represent various combinations of the supply amount of two ES.

There has been a plethora of research about ES since the late 20th century. Publications about the importance of ES to society by Daily (1997) and valuation of global ES by Costanza et al. (1997) have onboarded ES in the mainstream environmental studies. Afterwards, other aspects have been studied, such as the structured understanding of ES (MEA, 2005), general assessment of ES as a decision support tool (Costanza et al., 2017; Dang et al., 2021), economic valuation and conceptual framework of ES (Valencia Torres et al., 2021), relationship among multiple ES (Bennett et al., 2009; Obiang Ndong et al., 2020; Vallet et al., 2018), role of ES in sustainable development (Aryal et al., 2023b; Yuan and Lo, 2020), supply potentials of ES (Fischer and Eastwood, 2016; Le Provost et al., 2022), and social demand of ES (Castro et al., 2016; Wei et al., 2021). However, very few studies have done the integrated assessment of relationship among ES, along with the ecological supply and social demand perspective (Wu et al., 2022). There has been some studies about ecological supply and social demand of ES (Baró et al., 2015; Wei et al., 2017; Zhang et al., 2017), but many are from the theoretical perspective (Cavender-Bares et al., 2015; King et al., 2015). A composite overview and holistic understanding of relationship among ES, and integrated assessment of ecological supply and social demand of ES is lacking, especially in the mountain landscapes of Hindu-Kush-Himalayas.

In the context of knowledge gaps of the supply-demand nexus of ES in the Himalayas, we aim to (1) depict pairwise production potentials of ES from the ecological perspective, (2) understand the social demand of ES and their relative importance to the local people, and (3) identify the gap between ecological supply and social demand of ES. We have employed various quantitative research tools in this study including data collection from various secondary sources (i.e., satellite images, extraction of high-resolution global land cover maps, global as well as regional databases, policy documents, and literature), and primary sources (household survey). This research has examined whether the current state of ES supply is adequate to meet the social demand, and which pair of ES is confronted with the gap between demand and supply. Further, we discuss policy implications of the mismatches between

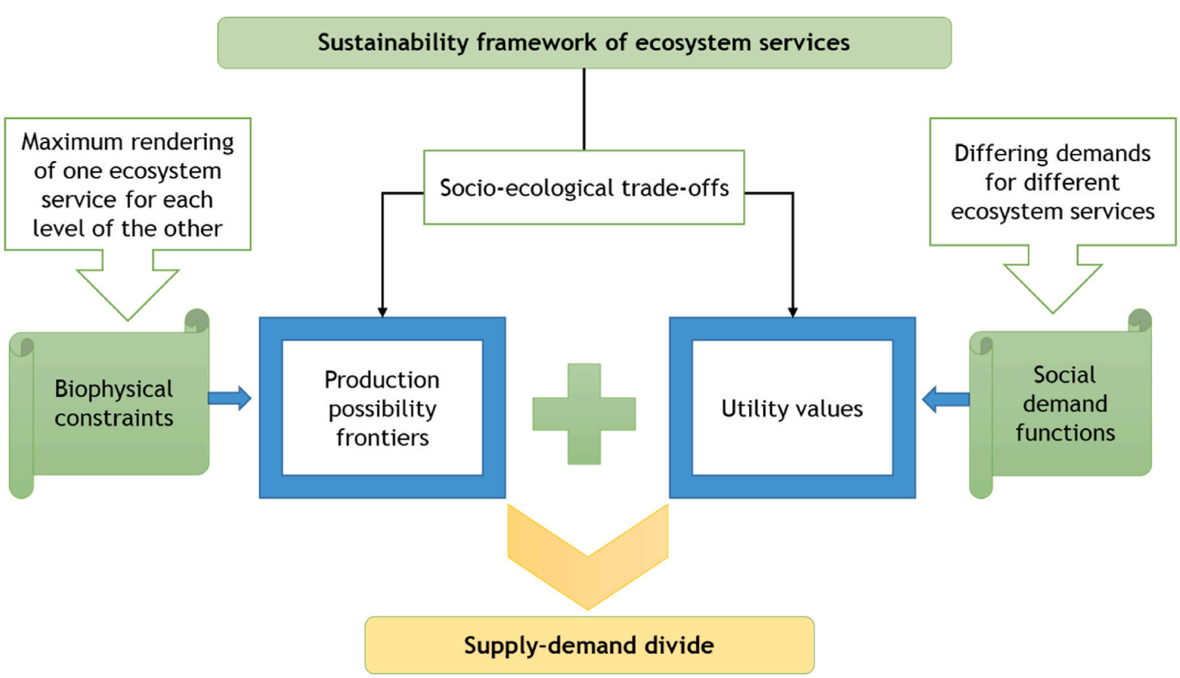

Fig. 1. Sustainability framework of socio-ecological trade-offs in ES (conceptual framework of the study).

demand and supply, which will be helpful for decision-makers in sustainable management of natural resources in the Himalayas.

Following this introduction, we have described the study area and methods in Section 2. Section 3 presents the main results of the research, including PPF, utility values, and the comparison ellipses of ES supply and demand. Section 4 contains discussion of the findings. Finally, Section 5 concludes the study.

2. Methods

2.1. Study area

The study was carried out in a multifunctional landscape in the central part of Hindu-Kush Himalayan regions (Fig. 2). The land cover map of the study area was extracted from ESRI, Microsoft and Impact Observatory (2021). The study area is representative of two domains of environment conservation, such as from the biodiversity perspective and water regime management perspective (Aryal et al., 2023c). From the biodiversity perspective, it is known as Chitwan Annapurna Landscape (CHAL), which connects the lowland biodiversity hotspot of Nepal (i.e., Chitwan National Park) to the snow-capped mountain ecosystem (i.e., Annapurna Conservation Area). The connection is designed from the river corridor perspective, which is known as Gandaki River Basin. Depending on the core value of organizational objectives, this area is called the Gandaki River Basin by water resource management institutions and CHAL by biodiversity giants. But the area is the same, except few areas of CHAL (i.e., <3% of the total area) which do not come under the catchment zone of Gandaki River Basin. In any case, the study area is crucial in terms of understanding socio-ecological interdependencies, dynamics of climate and water regime, the nexus of biodiversity and livelihoods, and representative of the mountain and Himalayan landscapes (Aryal et al., 2023c). Considering the climate sensitivity of the landscape, a USD 32.7 million project to support climate-resilient communities and ecosystems has been implemented by Green Climate Fund (FP131) in the study area (GCF, 2020). Among the study area of 31,700 sq.km, Forestland is the major land cover type (45.7%) followed by Shrubland (27.5%), Bare ground (12.2%), and Snow and ice (6.6%) (ESRI, Microsoft and Impact Observatory, 2021). More details of the study area, altitude and geographical position, land cover, climatic characteristics, biodiversity, and socio-demographic information can be found in Aryal et al. (2023a, 2023c).

2.2. Data collection

The CHAL area supplies various ES, among which our research was focused on the ecological supply and social demand of six ES, namely, crop production (CP), timber production (TP), carbon sequestration (CS), water yield (WY), soil conservation (SC), and habitat quality (HQ) that are important in the study area (Aryal et al., 2023c). To quantify the ES, we divided the study area into 186 watersheds based on the flow

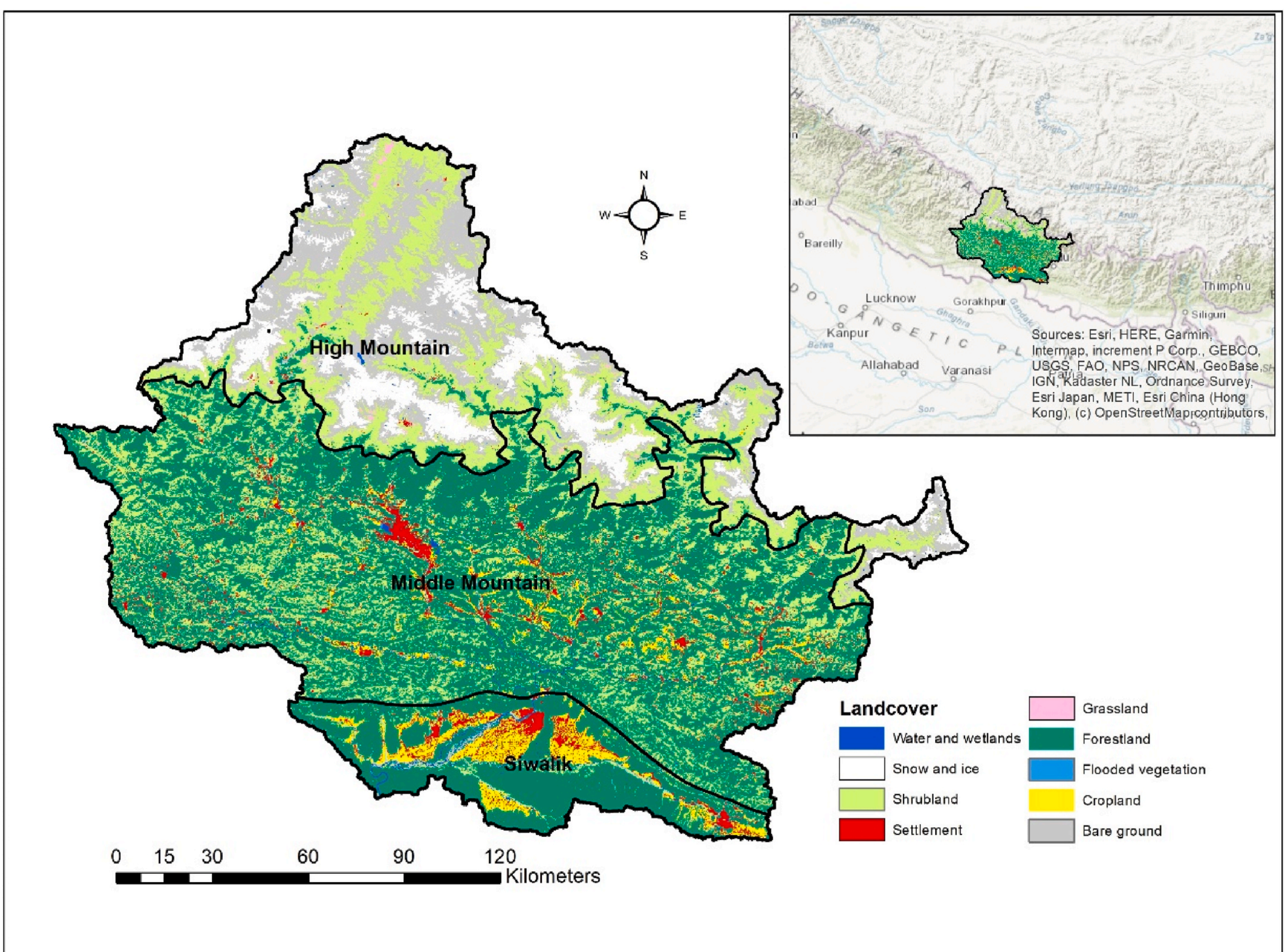

Fig. 2. Map of the study area, showing land cover and physiographic zones.

accumulation threshold using ArcGIS 10.8.1. Flow accumulation threshold was different for upstream (i.e., small flow accumulation at the pour point) and downstream watersheds (i.e., larger flow accumulation at the pour point). Average area of upstream and downstream watersheds was 115 sq.km and 578 sq.km, respectively. Specification of flow accumulation threshold in mountain landscapes is challenging because of the confluence effect of high gradient river networks, yet our approach is the representative of mountain watersheds in the Hindu-Kush Himalayan region. The quantitative value of each ES was assessed at the watershed level, and average production of the ES per unit area for each watershed was determined based on various secondary and primary sources, including but not limited to the collection of satellite images, extraction of high-resolution global land cover maps, and use of various global as well as regional databases about precipitation, evapotranspiration, forest resource assessment, digital elevation model, soil map, and infrastructure development pattern of the study area.

The quantification of CP was based on ESRI land cover product (ESRI, Microsoft and Impact Observatory, 2021), from which the cropland was extracted to calculate enhanced vegetation index (i.e., based on the 'Harmonized Sentinel-2 MSI: MultiSpectral Instrument, Level-2A'). The vegetation index was then used to predict crop yield based on the model developed by (Guan et al., 2018) and adopted by (Kibret et al., 2021) for tropical agriculture. TP was estimated based on various sources, such as ESRI land cover product, the Forest Resource Assessment Report of Nepal (DFRS, 2015), physiographic zones, enhanced vegetation index, and annual growth rate and allowable harvesting guidelines of Nepal (DOF, 2005). Similarly, CS was based on ESRI land cover product, the Forest Resource Assessment Report of Nepal (DFRS, 2015), and value transfer from various sources (i.e., Amthor et al., 1998; DFRS, 2015; Rimal et al., 2019; Shrestha, 2016; Syahrinudin, 2005; Yan et al., 2015). Water yield model was used to quantify WY based on the CHIRPS Pentad dataset provided by UCSB/CHG (Funk et al., 2015) and actual evapotranspiration data accessed from MOD16A3GF MODIS/Terra Net Evapotranspiration Gap-Filled Yearly L4 Global 500 m SIN Grid V006 (Running et al., 2019). We adopted the Revised Soil Loss Equation (RUSLE) to quantify soil conservation (Wischmeier and Smith, 1965), while HQ was quantified in terms of the quality index based on land cover suitability, threats to the habitat, and sensitivity of the land use to the threats (Terrado et al., 2016). Further details of the data collection and procedures for the quantitative assessment of the ES can be found in a paper by Aryal et al. (2023b).

Moreover, we carried out household survey (HHS, n = 300) to understand the social demand of ES in the study area. Stratified simple random sampling was employed for this research. As an approach to stratification, we classified the settlements in the study area into five categories based on their proximity to the five major land cover classes (i.e., forestlands, shrublands/grasslands, water and wetlands, croplands, and urban settlements). Those land cover types were identified in both the predetermined upstream and downstream watersheds. In this way, we randomly selected ten settlements (five land cover types * two watershed categories). HHS was carried out from randomly selected 30 households each the selected settlements. An information sheet was supplied to the respondents before doing the survey to facilitate them about the understanding of nature and characteristics of ES. We developed and tested a semi-structured questionnaire which was reviewed and approved by the Human Research Ethics Committee of a university (the name of the university has been withheld for the review process). Pre-tested questionnaire was then translated into local language and administered to the respondents by trained personnel in the relevant field. Section of the semi-structured questionnaire for household survey is provided in Supplementary file A. Readers are referred to the paper (Aryal et al. 2023e) for additional details of the HHS. In addition to biophysical quantification of ES and social survey, relevant data were collected through literature review and the review of policy and program documents related to our study area to discuss the dynamics of supply and demand of various ES.

2.3. Data analysis and visualization

Data analysis was done based on various statistical and visualization tools. After assessing the average production per unit area (i.e., sq.km) of ES at the watershed level, for all the identified 186 watersheds, we prepared scatter plots for each pair of ES based on their quantitative values at the watershed level. The scatter plots were prepared for all 15 pairs of ES for 186 watersheds in the study area. The highest attainable combinations of ES supply were picked up to draw PPF curves for each pair of ES.

Similarly, polar plots were prepared to understand the relative importance of ES from the demand perspective. Because the research participants were asked to pick the desirable demand (i.e., point coordinate) for all the 15 pairs of ES, the respondents gave the relative value for each ES five times (i.e. to specify their demand of 1 ES at the desirable level of every other five ES). Six polar plots were prepared, using R software, taking 1 ES at a time with its average desirable level compared to the relative weightage of the other five counterparts, on a scale of 1–10. The parameters were then calculated based on their respective arithmetic mean of the point coordinates, focusing on 1 ES at a time.

Further, to superimpose the social demand of ES with the biophysical supply potential, we recalibrated the average production of ES on a scale of 0–100 based on its percentage to the maximum value (i.e., the relative percentage of ES for each watershed as compared to the maximum attainable value for the specific ES among the 186 watersheds). Likewise, the point coordinate of the desirable demand was also rescaled from 0 to 100 from its original value of 0–10 by multiplying it by 10. Since the watersheds in our study area were highly varying based on their production possibilities, we classified watersheds based on gap statistics from K-means clustering, which is basically carried out to divide the total number of observations into certain clusters based on their dimensionality so that the sum of squares within the cluster is minimized (Hartigan and Wong, 1979). Based on the clustering, we depicted three optimum levels of watershed clusters. One of the clusters characterised the northern uplands of the study area, which is covered with bare ground, snow/ice, and shrublands that barely supply ES (no or minimum supply of crop, timber, and carbon), and therefore, we excluded northern uplands from our analysis, and the remaining two clusters (agriculture-dominated lowland watersheds, and multifunctional mountain watersheds) were considered for further analysis to visualise supply sphere of ES. Ellipses of the three values: (1) productive capacity of lowland watersheds, (2) productive capacity of mountain watersheds, and (3) social demand were then prepared using R software, showing three different levels of concentration (i.e., central circle = 50%, middle circle = 75% and outer circle = 95% of all the combination of ES supply and demand).

3. Results

3.1. Pairwise production potentials of the ES in the Himalayan landscape

The production possibility of ES is varying depending on topographical and landscape characteristics, ecological processes, climatic factors, and external anthropogenic influences. Nevertheless, the presence and absence of one ES also play a dominant role in determining the amount and intensity of the production possibilities of other ES. Fig. 3 shows the pairwise production possibilities of ES for different possible pairs of the six ES. The area under the curve represents the pairwise production possibilities in the Himalayan landscape, meaning that production of ES cannot exceed the limit set by the PPF. For instance, TP of about 250 cum/sq.km is possible at the cost of zero CP, whereas CP of about 230 tons/sq.km is possible at the cost of zero TP. If both TP and CP are required, the maximum possible production of CP is 100 tons/sq.km

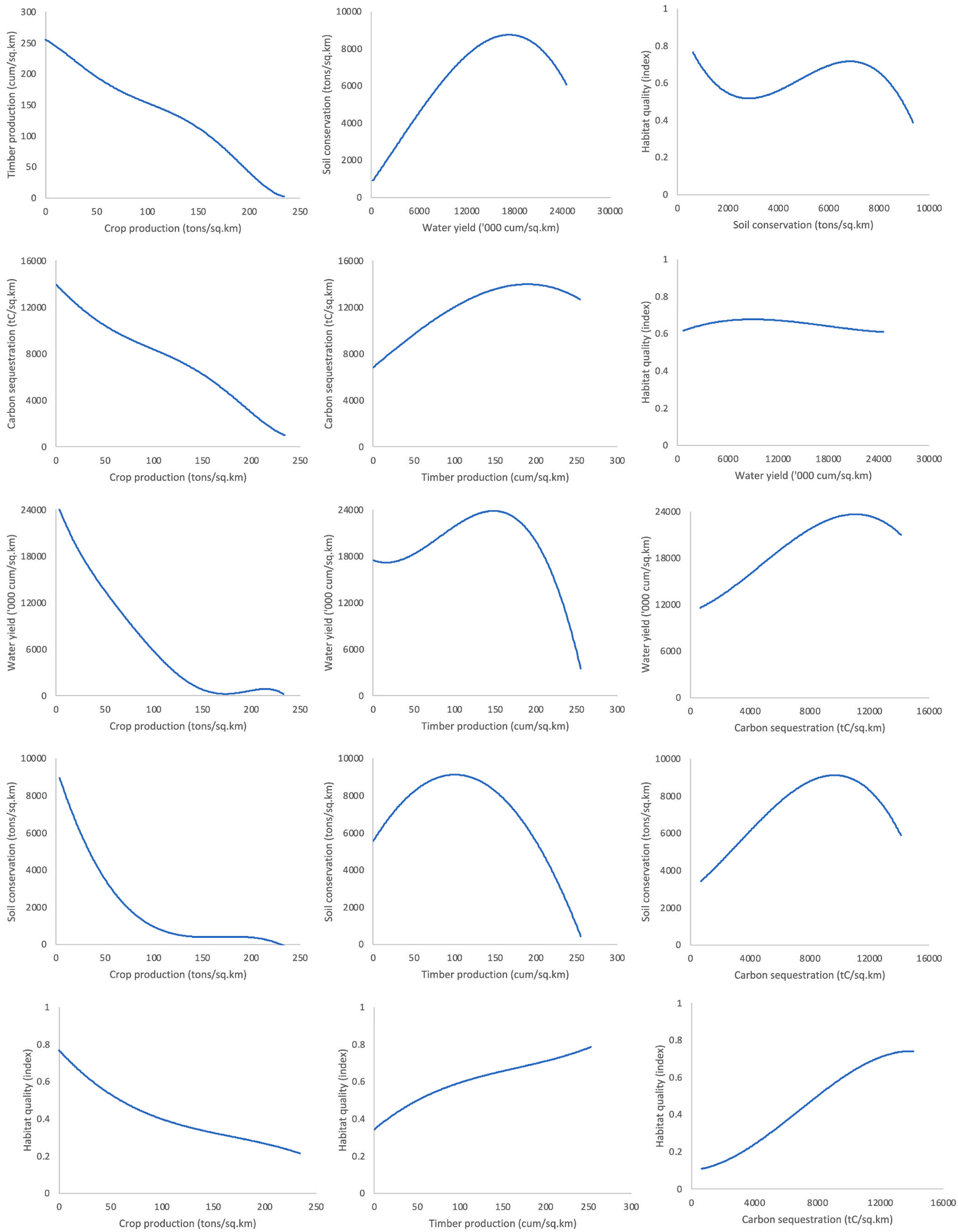

Fig. 3. Curves of the production possibility frontier for the 15 pairs of ecosystem services in the study area. Supply of ecosystem services cannot go beyond those curves unless any intervention is applied.

while TP is 150 cum/sq.km. This kind of inverse relationship of the pairwise production possibility is pertinent with CP as compared to the other ES, including CS, WY, and SC. However, even if we approach the maximum value of CP, the HQ index of the landscape cannot be less than 0.22.

For some pairs of ES, the production potential of one ES increases as the production potential of the other ES increases. For example, pairwise production potential increases for both ES of the pair in the case of TP and HQ as well as CS and HQ. The curves of PPF show that some pairs of ES are mutually increasing with the increase of one another until some point and then decline in 1 ES at the increase of other ES. This trend can be observed in the pairs of WY and SC, TP and CS, WY and CS, and SC and CS. For example, both WY and SC mutually increase until the concurrent supply of about 15.5 million cum/sq.km WY and 9500 tons/sq.km SC, but with the further increase in the supply of WY, SC decreases. Likewise, the mutual production of CS and SC was highest when CS is about 11 thousand tC/sq.km and SC is about 9400 ton/sq.km, but the production of SC decreases as the production capacity of CS increases further.

The PPF curves for some pairs of ES are unique in their shape. The production potential of HQ was not affected by the increase in WY, but showed an unpredictable change with the increase in SC. Likewise, there was a small increase in SC and WY with the increase of TP, but both ES (SC and WY) showed a precipitous fall with the further increase in TP. For example, the highest production potential of WY (>24 million cum/sq.km) was observed when TP was about 185 cum/sq.km, but WY rapidly declined with further increases in TP. Similarly, SC increased from about 5500 tons/sq.km to the highest (>9000 tons/sq.km) when TP was about 100 cum/sq.km, then it showed a decreasing trend. In general, the curves of PPF (Fig. 3) showed that eight pairs of ES showed inverse relationships and five pairs showed mutually increasing relationships when considering the combination of maximum pairwise production potentials. Alternatively, the remaining two pairs were more or less unchanged with the increase of the others.

3.2. Social demand of ES and their relative importance to local people

The relative weightage of utility values of ES, which is based on the social demand, is presented in Fig. 4. WY had the highest average utility value (8.99), followed by CP (8.57), SC (6.86), and TP (6.63). CS had the lowest average utility value among the ES with a score of 5.73 on a scale of 1–10. Alternatively, the utility value of WY is at its highest (9.01) when it was jointly valued with SC and lowest (8.96) when compared with that of the CP. Similarly, CP is at its highest value (8.96) when it was jointly valued with WY, and lowest (8.53) when it was concurrently valued with CS. The order of priority of ES (as expressed by the score of utility values) remained unchanged irrespective of its comparison with different ES and was found as WY > CP > SC > TP > HQ > CS.

3.3. Gaps between supply and demand of ES

Pairwise production possibilities of ES are different with the varying landscape characteristics, which can be observed through different ellipses representing the productive capacity of lowland watersheds and mountain watersheds in Fig. 5. Ellipses of the social demand for respective pairs of ES indicate social aspirations for the availability of those ES. Fig. 5 also shows that the current state of the productive capacity of the ES is not adequate to meet the social demand of many ES,

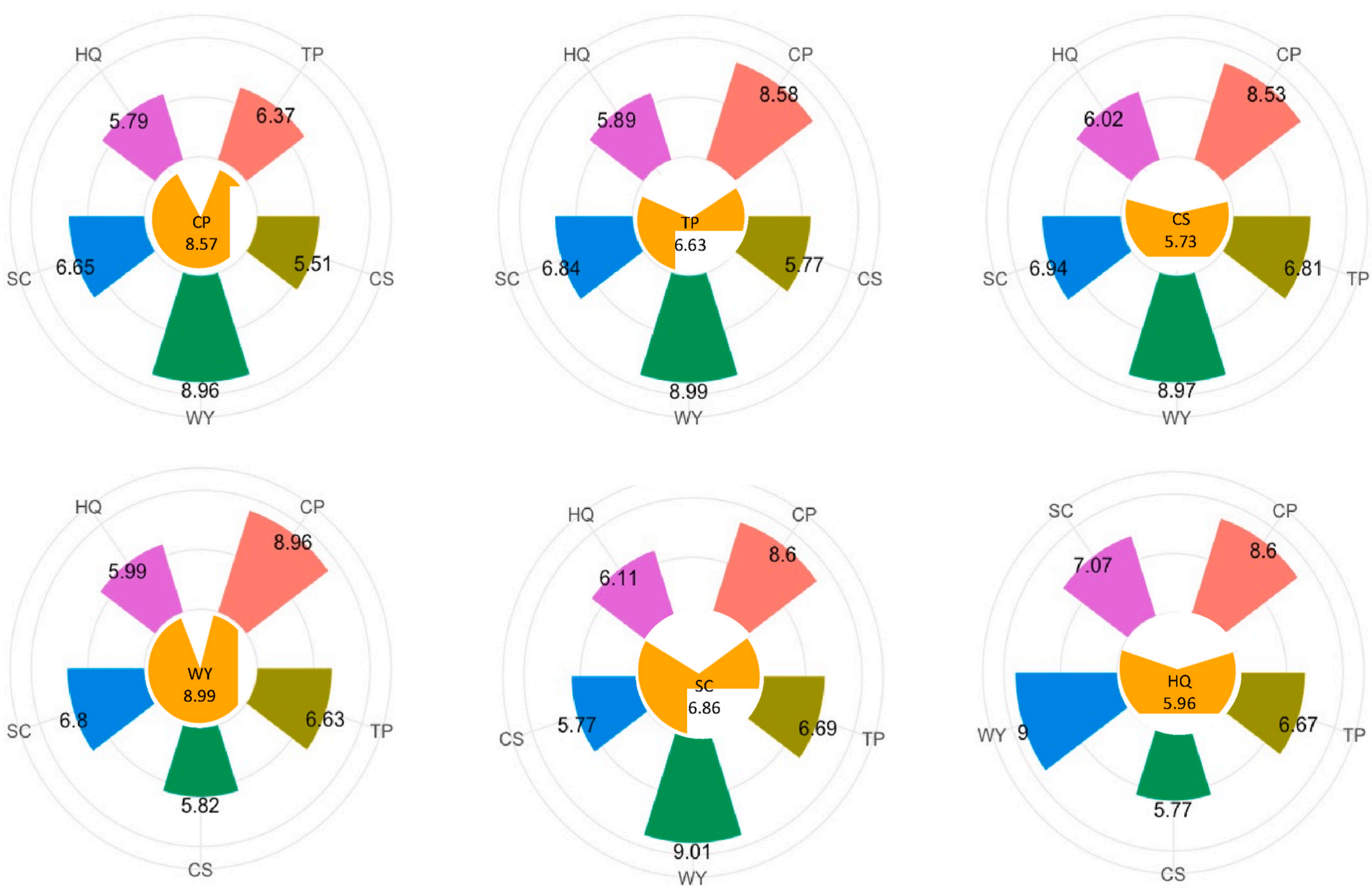

Fig. 4. Relative weightage of utility values of ES for local people on a scale from 1 to 10. Six different polar plots show the relative weightage of other five ES when taking the collective average of one ecosystem services (mentioned at the center of each plot). Abbreviations: CP = crop production, TP = timber production, CS = carbon sequestration, WY = water yield, SC = soil conservation, and HQ = habitat quality.

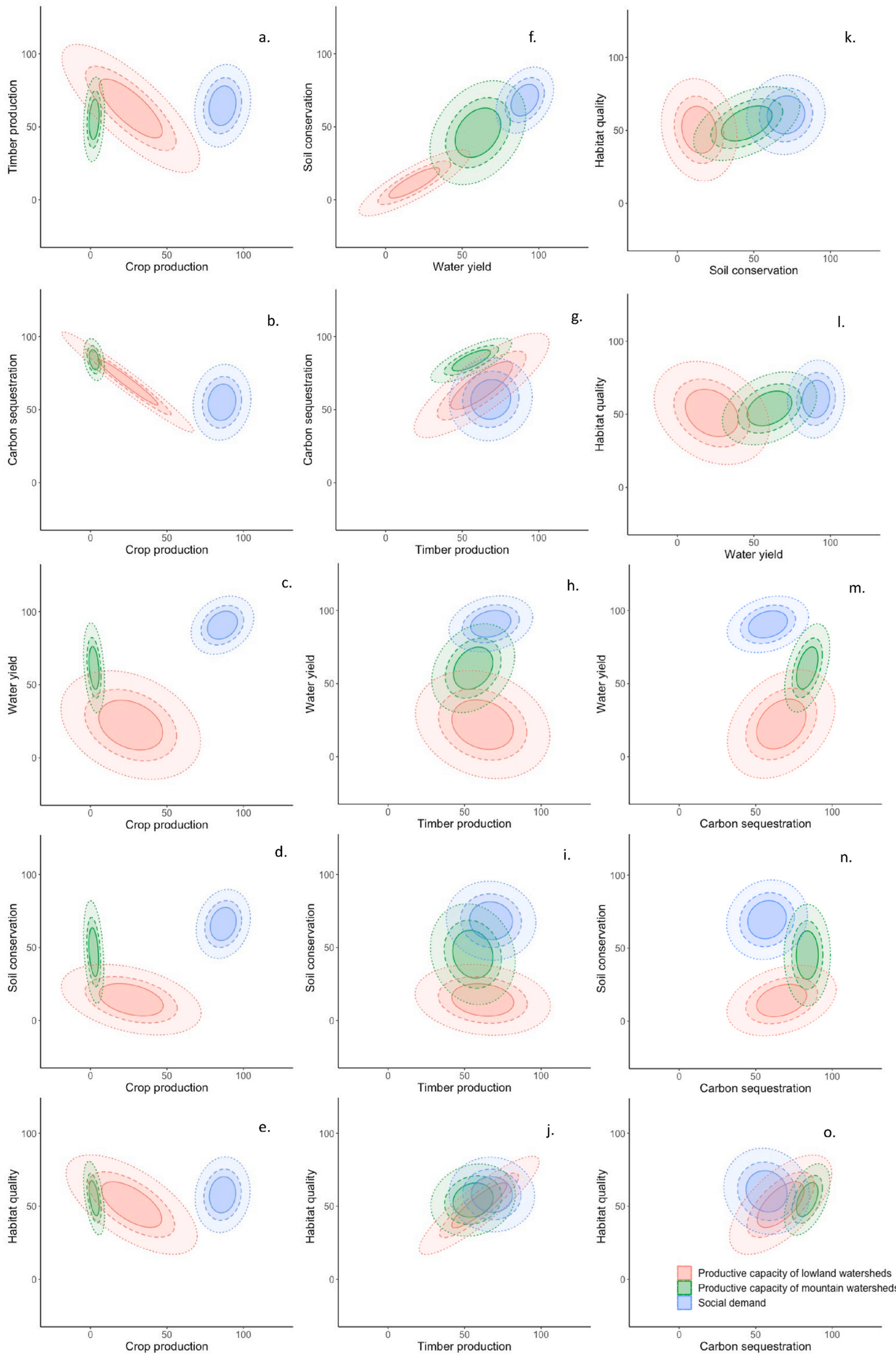

Fig. 5. Ellipses of the social demand and supply of lowland and mountain watersheds in the study area. The core circle includes 50% of the observation, the middle circle includes 75%, and the outer circle of each ellipse includes 95% of the observation in both social demand and the current supply of ecosystem services. Value > 100 and < 0 should not be considered because those are just the effect of the ellipse and no data exist over there (i.e., maintained for the aesthetic purpose of the figure). Both the x-axis and y-axis represent the percentage relative to the maximum value for both social demand and ecological supply.

especially CP, because none of the ellipse (lowland watersheds and mountain watersheds) overlaps with the ellipse of the social demand of CP (Fig. 5: a, b, c, d, and e). Furthermore, the productive capacity of mountain watersheds seems to be very poor in meeting the social demand as compared to that of the lowland watersheds. Although the productive potential of mountain watersheds is near to satisfy the social demand, the gap between social demand and the productive capacity of WY in the lowland watershed is very high (Fig. 5: c, f, h, l, and m). Interestingly, there is not a big gap between the supply potential and demand of TP (Fig. 5: a, g, h, i, and j). The same is the case for HQ where the social demand and the productive capacity of both lowland watersheds and mountain watersheds are not much different. Conversely, the production potential of CS is at least well met or more than the social demand as we can see in Fig. 5 (b, g, m, n, and o). Biophysical production potential and social demand overlap in the case of the pairwise production of TP and HQ (Fig. 5: j), indicating an ideal condition for landscape management in the Himalayas.

4. Discussion

Production potential of one ES is dependent on that of the other associated ES. Some pairs of ES have illustrated a positive relationship because the increase in the production of one ES support the increase in the production of the other, while some pair of ES have shown an inverse relationship (Brown et al., 2015; Chen et al., 2019). For example, the attainment of maximum production potentials of CP was found to be contingent on the reduced production of TP, CS, WY, SC, and HQ. While the increase in CS was found to be contingent on the increase in supply potentials of HQ, TP, WY, and SC. Those relationships might just be the representation of the spatial associations in the Himalayas. Cause-effect and functional interaction, however, can be different according to the differing intensity of interactions between people and places (Rugani et al., 2019; Torralba et al., 2018). The social demand of WY was found to be of the highest importance, followed by CP, SC, and TP. The relative importance of CS and HQ was found to be low from the local people's perspective. The gap between the ecological supply and social demand is pertinent in the case of CP, the demand of which was hardly met by the supply potential of agriculture-dominated lowland watersheds. The gap between the supply potential of CP from mountain watersheds and its social demand is even wider, which was found to be nearly impossible to meet even at the expense of all the other ES. Ideally, the ecological supply potential was found to meet its social demand, regarding the pair of TP and HQ in the Himalayas.

4.1. Supply and demand dynamics of ES

In terrestrial ecosystems, ecosystem assets (i.e., land cover types and land use practices) play a decisive role in the concurrent supply of various ES, at differing scales and intensities (Li et al., 2022; Sannigrahi et al., 2020). Abundance of some types of ecosystem assets (i.e., forestland) is crucial to supply multiple ES (i.e., including TP, CS, SC, and HQ) while others, such as cropland, opted to produce a single ES (i.e., CP). Nonetheless, a landscape is a mosaic of different ecosystem assets, allowing a mix of production of various ES in which some of them are mutually exclusive while others can be mutually supportive (Aryal et al., 2022; Laudari et al., 2022; Wang et al., 2022; Yu et al., 2021). Based on the biophysical characteristics and properties of ES, the increase in the production of one ES is only possible at the reduction of other ES, as we observed CP can only be maximized at the reduction of TP, CS, WY, SC, and HQ. Not only in our case, but the increment in CP also has sufficient examples of the reduction in other ES, for example, crucial environmental services in West Africa (Vaast and Somarriba, 2014), wetland health in the U.S. and Mid-Atlantic region (Bostian and Herlihy, 2014), forestry services in Swiss mountains (Briner et al., 2013), and biodiversity in India (Hinz et al., 2020). Likewise, West et al. (2010) found that one more ton of crop yield has contributed to the emission of three tons of carbon annually in the temperate zone. Although Clough et al. (2011) detected little association between crop production and biodiversity, we found that the increase in CP incurred a decrease in HQ of the landscape. Yet, the HQ index rarely gets to zero because farmlands also support various forms of agrobiodiversity. Trade-offs relationship is prominent in contested landscapes where agriculture expansion is common, especially in the financially challenged countries in the Global South (Li et al., 2020; Winkler et al., 2021). Although a study by Aryal et al. (2023b) stated the significant trade-off relationship only between CP and SC, the inverse curve of PPF (as shown in Fig. 3) for all the five pairs of ES (i.e., CP with other five ES) indicate that agriculture development strategy and cropping practices must be seriously examined to safeguard the multifunctionality of the Himalayan landscapes. While doing so the policy maker may seek for the program alternatives that not only focus on the increase in CP but concurrently support biodiversity conservation, soil erosion and land productivity enhancement, land sharing approach, and cleaner production pathways (Li et al., 2021; Ma et al., 2021; Nath et al., 2021; Wang et al., 2011). As demonstrated by Aryal et al. (2023a), for example, integrated agroforestry practice can be a promising alternative to address the trade-offs in ES, especially from the production of crops and grains.

Mutually incremental pairwise production potentials have been detected for a few pairs, such as TP and HQ, CS and HQ, and TP and CS. It might be attributed to the availability of forestland because a landscape with forestland can increasingly supply TP, HQ, and CS, simultaneously. To illustrate, Petrasek et al. (2015) valued forestland for its combined TP and CS market in the and Benz et al. (2020) stressed the multifunctionality of forests not only to supply timber and carbon but to deal with climate change, livelihood support, and other societal demands in China and Germany. Likewise, Gustafsson et al. (2020) recommended 'retention forestry' for integrated biodiversity conservation in Europe, implying a strong connection between forest and biodiversity. Some pairs of ES were found to be mutually increasing to some extent and then the amount of one ES decreases with the increase in another, as evident in our case of pairs of WY and SC, WY and TP, SC and TP, and CS and SC (Fig. 3). Water availability improves soil quality and hence soil retention (Kramer and Boyer, 1995; Mahajan et al., 2021); however, the excess amount of WY might trigger erosion (Chalise et al., 2019; García-Ruiz et al., 2017), and the value of SC might have decreased beyond the value of 15 MCM/sq.km of WY. Unlike the general assumption that forestland produces a good amount of TP and also improves SC of the landscape (Ding et al., 2022; Shono et al., 2007), we found SC has decreased when TP goes beyond 100 cum/sq.km. This might indicate two crucial remarks that excessive load of trees in the mountains might be counterproductive to soil retention in slopes which has also been claimed by other researchers (i.e., Giadrossich et al., 2019; Lan et al., 2020; Satchell, 2018). Alternatively, SC might be attainable at its maximum not only with the forestland but with the integrated management of forestland, grassland, wetlands, and improved agronomic practices, simultaneously in the contested landscapes.

The social demand for ES is dependent on multiple socioeconomic factors (Bidegain et al., 2019; Campbell, 2018; Terrado et al., 2016). Human-dominated landscapes in the Himalayas, including the CHAL area, are characterised by heterogenous communities with different economic classes, origin and ethnicity, caste and language, and multi-cultural and social hierarchy (MOFE Nepal, 2015; WWF Nepal, 2013). Preference and social demand might differ from place to place and community to community, but landscape-level planning and management must consider the holistic view of social demand (Acharya et al., 2019 & 2021). Our findings of relatively high demand of WY, followed by CP and SC, corroborate with the previous findings of Castro et al. (2016) who claimed that water availability is the most essential and highly demanded ES among all types of ES beneficiaries. Similarly, Chang et al. (2013) emphasized the importance of water demand and water quality variables in Columbia River Basin. Alongside, based on the choice experiment approach, Khan and Zhao (2019) found WY as the most preferred ES in inland river basins of China. Although Eitelberg et al. (2016) urge the demand for carbon storage and biodiversity to influence future land use scenarios, our findings affirm that it is very unlikely to create this kind of scenario because CS and HQ were among the least preferred and low-demanded ES for local people. Because our finding is based on the preference of local people who are prompt to put values to local ES, policy and management framework however should be strategic to incorporate non-local ES for integrated and sustainable landscape management.

The gap between demand and supply of ES must be one of the greatest concerns for policymakers and landscape management practitioners (Laca, 2021; Larondelle and Lauf, 2016). We found that the most distant gap between the ellipses of demand and supply is for the pair of CP and WY (Fig. 5c), followed by the pair of CP and SC (Fig. 5d). In those cases, the ellipse of the demand of the ES pair is neither touched by the supply ellipse from lowland watersheds nor that of the mountain watersheds. The demand for CP is much higher than the supply potential from the global perspective as well (Ray et al., 2013; Sands et al., 2014). For instance, South Asian countries are facing severe challenges in meeting food demand (Rasul, 2016; Sodhi et al., 2010), as well as food security has become a growing agenda in African countries (Asenso-Okyere and Jemaneh, 2012; Sasson, 2012). It might be a different case in developed countries, such as Kroll et al. (2012) found that the food supply is much higher than its demand in European nations. Furthermore, a site-based assessment might show a different result as Wang et al. (2019) found that the supply of WY is higher than its demand in China's Hainan Island. But the gap between social demand and concurrent supply of CP and WY has been a pressing issue in human-dominated landscapes in the Himalayas.

Although the productive capacity of lowland watersheds is close to the social demand in the case of CP, the productive capacity of mountain watersheds tends to meet the social demand of various other ES such as WY, SC, and TP. It might be because the lowland watersheds are characterized by the plainlands which are suitable for farming and potentially irrigation facilities. Nevertheless, the supply of CP is not sufficient for sustainable landscape management, and therefore, concurrent supply of various provisioning and non-provisioning services is indeed important to supply local and non-local demand for ES. In this regard, multifunctional watersheds in the mountains, which are the common features of Himalayan landscapes, should be managed carefully. In line with our observation, Accatino et al. (2019) also recommended expanding multifunctional areas to allow the concurrent production of multiple ES. Having mentioned the supply-demand perspective, it should bear in mind that the supply and demand of ES are dynamic and changes over time and space (González-García et al., 2020; Kroll et al., 2012), which need to be carefully scrutinized. Whatsoever, the generalization of supply and demand of ES, as well as the blueprint approach to ecosystem management might be counter-productive (Aryal et al., 2023d), thus people and place-based ecosystem management should be considered based on the supply-demand dynamics in the Himalayas.

4.2. Policy and management alternatives to constrict the supply-demand divide

Civilization and human settlement have been dependent on the easy availability of natural resources and ES. People used to live in and develop settlements in the Himalayas where they can have easy access to ES such as forest resources, land for crop production, and water resource availability (Chidi, 2009; Fang et al., 2018). However, the availability of the resources must have changed with the rate of consumption and the trends of human interventions, changes in socio-demographic characteristics, and changes in climatic and natural processes. In this regard, the recovery of multiple ES must not be an impossible task but should be cautious to consider non-local ES while minimizing the gap between the supply and demand of ES. To illustrate, rotational cropping and agroforestry practices have been widely recommended to minimize the trade-offs between CP and other services (Aryal et al., 2023b; Clough et al., 2011; Maraseni and Cockfield, 2011; Vaast and Somarriba, 2014). Similarly, Wang et al. (2019) suggested intercropping to reduce the supply-demand gap in Hainan Island of China. Moreover, Castro et al. (2016) believed in integrated watershed management as a solution to achieve the higher social demand for ES in Kiamichi watershed of Oklahoma. Likewise, Yin et al. (2023) recommended zoning, classification, and hierarchical governance for integrated management of ES to address the mismatches between the demand and supply of ES in the Yellow River Basin of China. Further, Wei et al. (2021) proposed a driver-based framework of integrated management to address the gap between demand and supply of ES in dryland catchments. Alternatively, Holt et al. (2016) recommended providing incentives for multiple ES management to address the demand-supply divide of ES. Nonetheless, a single sectoral intervention might not be adequate for the sustainable management of ES, so policy and management alternatives to minimize the gap between supply and demand must be based on the structure and pattern of the interdependencies of society and nature at large.

There has been a long-lasting discussion about various measures to deal with the trade-offs in ES, and to fulfill the gap between demand and supply. Aryal et al. (2022) identified some measures through a systematic literature review, such as management interventions, technology and innovation, incentives and compensation, and empowerment of the community institutions for sustainable resource management. However, policy alternatives and management interventions must be guided by the principles but not the prescriptions, such as a successful management model in one site might not be successful in another site and vice-versa (Polasky and Segerson, 2009; Rosenberg and McLeod, 2005; Tallis et al., 2008). Further, an approach to landscape management should be guided by the broader framework of nature-based solutions to solve the problems of a huge gap between demand and supply of the ES (Cohen-Shacham et al., 2019; Lafortezza et al., 2018). Improved agronomic practices might lessen the gap between CP and other ES as observed in our study; however, the interventions should be guided by the principles of integrated watershed management (Aryal et al., 2019; Haregeweyn et al., 2012) and the adoption of an integrated approach to agroforestry as suggested by Aryal et al. (2023a). Additionally, farming practices should be integrated with forestry, carbon, and climate actions to safeguard the multifunctionality of the landscapes to supply both provisioning and non-provisioning ES, simultaneously.

Integrated conservation and development programs have succeeded in various parts of the Himalayan landscape to conserve nature while satisfying the development need of local people (Alpert, 1996; Aryal et al., 2020; Godar Chhetri, 2012; Upadhaya et al., 2022). This approach can be adopted to minimize the gap between the supply and demand of CP because the demand pressure of CP can also be reduced by engaging local communities in various livelihood support and off-farm income-generating activities. Alternatively, policy alternatives should consider technological development and innovation in farming practices (Coccia, 2019; Duru et al., 2015), which might help in increasing the supply of CP and other ES without compromising the productivity of non-provisioning ES. Likewise, coordination among multiple institutions and good governance while implementing landscape management activities must also be a prime concern (Cadman and Maraseni, 2012). We acknowledge a few limitations of our study that the understanding of social demand in terms of its quantitative value (i.e., amount of ES per household per year) would give a clear picture which we recommend for future studies. We believe that the findings based on relatively small samples (as compared to the area of the landscape) might be cautiously taken while generalizing its policy implications at a wider scale. In addition to the consideration of six ES, incorporation of the other ES would further enlighten supply-demand dynamics of ES in the Himalayas. Further, a one-time assessment of supply and demand might be inadequate because the supply and demand of ES is changing over time and space. In this regard, we suggest periodic monitoring of the socio-demographic characteristics and the dynamics of ES flow to ease planning and management of the landscape. Moreover, the relationship of one ES to other, as shown in Fig. 3, should not be considered as just the two-way interactions but based on various other socio-ecological factors of the landscapes. Yet, the future course of action should be the empowerment of community institutions, acknowledgment of indigenous practices of natural resource management, and harmonized policy interventions to minimize trade-offs and maximize synergies among ES to constrict the supply-demand divide in human-dominated landscapes in the Himalayas.

5. Conclusions

Himalayan landscapes, where ecosystem assets are disproportionately distributed along altitudinal gradients, are under pressure due to the increasing demand for ES. Understanding the spatial associations of ES and their pairwise production possibilities, social demand of ES, and examination of the supply and demand gaps are therefore vital for landscape planning and management. In this paper, we have depicted the PPF of all possible pairs of six different ES. An increase in crop production was found to be possible at the expense of timber, carbon, soil, water, and habitat quality. There has been a mutual increase of ES for all the possible pairs of timber production, carbon sequestration, and habitat quality. While some other pairs of ES showed mutual increase until some points of threshold and then the further increase in one ES triggered the decrease in other ES (i.e., timber production and soil conservation, water yield and soil conservation, carbon sequestration and soil conservation, and timber production and water yield).

Local people tend to put more value on water yield and crop production, and less on carbon sequestration and habitat quality. The demand for all pairs of ES with crop production has never been met according to the current state of the pairwise biophysical supply potential of the ES. The productive capacity of mountain watersheds is much lower than the lowland watershed in terms of crop production, whereas the productive capacity of mountain watersheds is much higher than the lowlands for water yield and soil conservation. The current supply potential of timber production, carbon sequestration, and habitat quality is adequate to meet its social demand. To minimize the trade-offs in production and to meet the demand for ES, we recommend various policy and management interventions, including improved agronomic practices and integrated agroforestry approach to combine farming practices with forestry and climate actions, nature-based solutions, integrated conservation and development program, as well as livelihood support to generate off-farm employment opportunities, technology and innovations, and empowerment of the community institutions. From the theoretical perspective, assessment of the trade-offs from the sustainability framework (social and ecological perspective) has been found to be a promising approach to understand the supply and demand dynamics of ES. Nevertheless, we recommend future research on periodic monitoring of the landscape variabilities and differing socio-demographic characteristics over time and space. We believe that policy and management alternatives should be guided by the principles of ecosystem management but not the experimental prescriptions that might have been successful in some parts of the world. Instead of a blueprint approach of management prescriptions, interventions should be based on society and site-specific ecological environment and must ensure that the restoration of one ecosystem service does not compromise the basics of other crucial ecosystem services in the landscape. Besides, we argue that people- and place-based ecosystem management can be considered as a safe operating space for sustainable and cleaner production of ecosystem services in the Himalayas.

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CRediT authorship contribution statement

Kishor Aryal: Conceptualization, Visualization, Data curation, Formal analysis, Methodology, Validation, Writing – original draft, preparation, Writing – review & editing. **Tek Maraseni:** Writing – review & editing, Supervision. **Armando Apan:** Writing – review & editing, Supervision.

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

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References

Accatino, F., Tonda, A., Dross, C., Léger, F., Tichit, M., 2019. Trade-offs and synergies between livestock production and other ecosystem services. Agric. Syst. 168, 58–72. https://doi.org/10.1016/j.agsy.2018.08.002.

Acharya, R., Maraseni, T.N., Cockfield, G., 2019. Local users and other stakeholders' perceptions on the identification and prioritization of ecosystem services in fragile mountains: a case study of Chure region of Nepal. Forests 10, 421. https://doi.org/10.3390/f10050421.

Acharya, R., Maraseni, T.N., Cockfield, G., 2021. Estimating the willingness to pay for regulating and cultural ecosystem services from forested Siwalik landscapes: perspectives of disaggregated users. Ann. For. Sci. 75 https://doi.org/10.1007/s13595-021-01046-3.

Alpert, P., 1996. Integrated conservation and development projects. Bioscience 46, 845–855. https://doi.org/10.2307/1312970.

Amthor, J.S., Dale, V., Edwards, N., Garten, C., Gunderson, C., Hanson, M., Huston, M., King, A., Luxmoore, R., McLaughlin, S., 1998. Terrestrial Ecosystem Responses to Global Change: a Research Strategy. Report by the Ecosystems Working Group. Environmental Sciences Division Publication.

Aryal, K., Thapa, P.S., Tamang, P., Bhattarai, D., Chaudhary, S.K., Mandal, R.A., 2019. Effect of integrated watershed management on vegetation cover, soil organic carbon and soil fertility in mid-hills of Nepal. Agriculture and Forestry Journal 3, 23–29. https://doi.org/10.5281/zenodo.3239260.

Aryal, K., Dhungana, R., Silwal, T., 2020. Understanding policy arrangement for wildlife conservation in protected areas of Nepal. Hum. Dimens. Wildl. 1–12. https://doi.org/10.1080/10871209.2020.1781983.

Aryal, K., Maraseni, T., Apan, A., 2022. How much do we know about trade-offs in ecosystem services? A systematic review of empirical research observations. Sci. Total Environ. 806, 151229 https://doi.org/10.1016/j.scitotenv.2021.151229.

Aryal, K., Apan, A., Maraseni, T., 2023a. Comparing global and local land cover maps for ecosystem management in the Himalayas. Remote Sens. Appl.: Society and Environment 30, 100952. https://doi.org/10.1016/j.rsase.2023.100952.

Aryal, K., Maraseni, T., Apan, A., 2023b. Transforming agroforestry in contested landscapes: a win-win solution to trade-offs in ecosystem services in Nepal. Sci. Total Environ. 857, 159301 https://doi.org/10.1016/j.scitotenv.2022.159301.

Aryal, K., Maraseni, T., Apan, A., 2023c. Spatial dynamics of biophysical trade-offs and synergies among ecosystem services in the Himalayas. Ecosyst. Serv. 59, 101503 https://doi.org/10.1016/j.ecoser.2022.101503.

Aryal, K., Maraseni, T., Apan, A., 2023d. A call for 'management authorship' in community forestry. Environ. Sci. Pol. 139, 204–208. https://doi.org/10.1016/j.envsci.2022.10.023.

Aryal, K., Maraseni, T., Apan, A., 2023e. Preference, perceived change, and professed relationship among ecosystem services in the Himalayas. J. Environ. Manag. 344, 118522. https://doi.org/10.1016/j.jenvman.2023.118522.
Asenso-Okyere, K., Jemaneh, S., 2012. Increasing Agricultural Productivity and Enhancing Food Security in Africa: New Challenges and Opportunities. Intl Food Policy Res Inst.
Baró, F., Haase, D., Gómez-Baggethun, E., Frantzeskaki, N., 2015. Mismatches between ecosystem services supply and demand in urban areas: a quantitative assessment in five European cities. Ecol. Indicat. 55, 146–158. https://doi.org/10.1016/j.ecolind.2015.03.013.
Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12, 1394–1404. https://doi.org/10.1111/j.1461-0248.2009.01387.x.
Benz, J.P., Chen, S., Dang, S., Dieter, M., Labelle, E.R., Liu, G., Hou, L., Mosandl, R.M., Pretzsch, H., Pukall, K., Richter, K., Ridder, R., Sun, S., Song, X., Wang, Y., Xian, H., Yan, L., Yuan, J., Zhang, S., Fischer, A., 2020. Multifunctionality of forests: a white paper on challenges and opportunities in China and Germany. Forests 11, 266. https://doi.org/10.3390/f11030266.
Bidegain, I., Cerda, C., Catalán, E., Tironi, A., López-Santiago, C., 2019. Social preferences for ecosystem services in a biodiversity hotspot in South America. PLoS One 14, e0215715. https://doi.org/10.1371/journal.pone.0215715.
Bostian, M.B., Herlihy, A.T., 2014. Valuing tradeoffs between agricultural production and wetland condition in the U.S. Mid-Atlantic region. Ecol. Econ. 105, 284–291. https://doi.org/10.1016/j.ecolecon.2014.06.016.
Briner, S., Huber, R., Bebi, P., Elkin, C., Schmatz, D.R., Grêt-Regamey, A., 2013. Trade-offs between ecosystem services in a mountain region. Ecol. Soc. 18.
Brown, G., Helene Hausner, V., Lægreid, E., 2015. Physical landscape associations with mapped ecosystem values with implications for spatial value transfer: an empirical study from Norway. Ecosyst. Serv. 15, 19–34. https://doi.org/10.1016/j.ecoser.2015.07.005.
Cadman, T., Maraseni, T.N., 2012. The governance of REDD+: an institutional analysis in the asia pacific region and beyond. J. Environ. Plann. Manag. 55 (4), 617–635.
Campbell, E.T., 2018. Revealed social preference for ecosystem services using the eco-price. Ecosystem Services, SI: Human-Nature nexuses 30, 267–275. https://doi.org/10.1016/j.ecoser.2017.04.009.
Castro, A.J., Vaughn, C.C., Julian, J.P., García-Llorente, M., 2016. Social demand for ecosystem services and implications for watershed management. JAWRA Journal of the American Water Resources Association 52, 209–221. https://doi.org/10.1111/1752-1688.12379.
Cavender-Bares, J., Polasky, S., King, E., Balvanera, P., 2015. A sustainability framework for assessing trade-offs in ecosystem services. Ecol. Soc. 20.
Chalise, D., Kumar, L., Kristiansen, P., 2019. Land degradation by soil erosion in Nepal: a review. Soil Systems 3, 12. https://doi.org/10.3390/soilsystems3010012.
Chang, H., Jung, I.-W., Strecker, A., Wise, D., Lafrenz, M., Shandas, V., Moradkhani, H., Yeakley, A., Pan, Y., Bean, R., Johnson, G., Psaris, M., 2013. Water supply, demand, and quality indicators for assessing the spatial distribution of water resource vulnerability in the Columbia River Basin. Atmos.-Ocean 51, 339–356. https://doi.org/10.1080/07055900.2013.777896.
Chen, W., Chi, G., Li, J., 2019. The spatial association of ecosystem services with land use and land cover change at the county level in China, 1995–2015. Sci. Total Environ. 669, 459–470. https://doi.org/10.1016/j.scitotenv.2019.03.139.
Chidi, C.L., 2009. Human settlements in high altitude region Nepal. Geographical Journal of Nepal 7, 1–6. https://doi.org/10.3126/gjn.v7i0.17436.
Christensen, L.R., Jorgenson, D.W., Lau, L.J., 1973. Transcendental logarithmic production frontiers. Rev. Econ. Stat. 55, 28–45. https://doi.org/10.2307/1927992.
Clough, Y., Barkmann, J., Juhrbandt, J., Kessler, M., Wanger, T.C., Anshary, A., Buchori, D., Cicuzza, D., Darras, K., Putra, D.D., Erasmi, S., Pitopang, R., Schmidt, C., Schulze, C.H., Seidel, D., Steffan-Dewenter, I., Stenchly, K., Vidal, S., Weist, M., Wielgoss, A.C., Tscharntke, T., 2011. Combining high biodiversity with high yields in tropical agroforests. Proc. Natl. Acad. Sci. USA 108, 8311–8316. https://doi.org/10.1073/pnas.1016799108.
Coccia, M., 2019. Why do nations produce science advances and new technology? Technol. Soc. 59, 101124 https://doi.org/10.1016/j.techsoc.2019.03.007.
Cohen-Shacham, E., Andrade, A., Dalton, J., Dudley, N., Jones, M., Kumar, C., Maginnis, S., Maynard, S., Nelson, C.R., Renaud, F.G., Welling, R., Walters, G., 2019. Core principles for successfully implementing and upscaling Nature-based Solutions. Environ. Sci. Pol. 98, 20–29. https://doi.org/10.1016/j.envsci.2019.04.014.
Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260. https://doi.org/10.1038/387253a0.
Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., Grasso, M., 2017. Twenty years of ecosystem services: how far have we come and how far do we still need to go? Ecosyst. Serv. 28, 1–16. https://doi.org/10.1016/j.ecoser.2017.09.008.
Daily, G.C., 1997. Nature's Services: Societal Dependence on Natural Ecosystems, the Future of Nature. Yale University Press.
Daily, G.C., Polasky, S., Goldstein, J., Kareiva, P.M., Mooney, H.A., Pejchar, L., Ricketts, T.H., Salzman, J., Shallenberger, R., 2009. Ecosystem services in decision making: time to deliver. Front. Ecol. Environ. 7, 21–28. https://doi.org/10.1890/080025.
Dang, A.N., Jackson, B.M., Benavidez, R., Tomscha, S.A., 2021. Review of ecosystem service assessments: pathways for policy integration in Southeast Asia. Ecosyst. Serv. 49, 101266 https://doi.org/10.1016/j.ecoser.2021.101266.
de Groot, R., Brander, L., van der Ploeg, S., Costanza, R., Bernard, F., Braat, L., Christie, M., Crossman, N., Ghermandi, A., Hein, L., Hussain, S., Kumar, P., McVittie, A., Portela, R., Rodriguez, L.C., ten Brink, P., van Beukering, P., 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosyst. Serv. 1, 50–61. https://doi.org/10.1016/j.ecoser.2012.07.005.
DFRS, 2015. State of Nepal's Forests. Forest Resource Assessment (FRA) Nepal. Department of Forest Research and Survey (DFRS), Kathmandu, Nepal.
Ding, X., Liu, X., Liu, G., Xiao, P., Liu, R., Gou, Z., Zhao, Y., 2022. Comprehensive assessment of soil conservation measures by rough set theory: a case study in the yanhe River Basin of the loess plateau. Water 14, 2213. https://doi.org/10.3390/w14142213.
DOF, 2005. Directives of Community Forest Resource Inventory.
Drake, B., Smart, J.C.R., Termansen, M., Hubacek, K., 2013. Public preferences for production of local and global ecosystem services. Reg. Environ. Change 649–659.
Duru, M., Therond, O., Martin, G., Martin-Clouaire, R., Magne, M.-A., Justes, E., Journet, E.-P., Aubertot, J.-N., Savary, S., Bergez, J.-E., Sarthou, J.P., 2015. How to implement biodiversity-based agriculture to enhance ecosystem services: a review. Agron. Sustain. Dev. 35, 1259–1281. https://doi.org/10.1007/s13593-015-0306-1.
Eitelberg, D.A., van Vliet, J., Doelman, J.C., Stehfest, E., Verburg, P.H., 2016. Demand for biodiversity protection and carbon storage as drivers of global land change scenarios. Global Environ. Change 40, 101–111. https://doi.org/10.1016/j.gloenvcha.2016.06.014.
Englund, O., Berndes, G., Cederberg, C., 2017. How to analyse ecosystem services in landscapes—a systematic review. Ecol. Indicat. 73, 492–504. https://doi.org/10.1016/j.ecolind.2016.10.009.
ESRI, Microsoft & Impact Observatory, 2021. Esri Land Cover [WWW Document]. URL. https://livingatlas.arcgis.com/landcover. (Accessed 21 April 2022).
Fang, Y., Ceola, S., Paik, K., McGrath, G., Rao, P.S.C., Montanari, A., Jawitz, J.W., 2018. Globally universal fractal pattern of human settlements in river networks. Earth's Future 6, 1134–1145. https://doi.org/10.1029/2017EF000746.
Fischer, A., Eastwood, A., 2016. Coproduction of ecosystem services as human–nature interactions—an analytical framework. Land Use Pol. 52, 41–50. https://doi.org/10.1016/j.landusepol.2015.12.004.
Foster, S.L., Kharouba, H.M., Smith, T.W., 2022. Testing the assumption of environmental equilibrium in an invasive plant species over a 130 year history. Ecography 2022, e12933. https://doi.org/10.1111/ecog.06284.
Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J., 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Sci. Data 2, 150066. https://doi.org/10.1038/sdata.2015.66.
García-Ruiz, J.M., Beguería, S., Lana-Renault, N., Nadal-Romero, E., Cerdà, A., 2017. Ongoing and emerging questions in water erosion studies. Land Degrad. Dev. 28, 5–21. https://doi.org/10.1002/ldr.2641.
GCF, 2020. FP131: Improving Climate Resilience of Vulnerable Communities and Ecosystems in the Gandaki River Basin. Nepal.
Giadrossich, F., Cohen, D., Schwarz, M., Ganga, A., Marrosu, R., Pirastru, M., Capra, G.F., 2019. Large roots dominate the contribution of trees to slope stability. Earth Surf. Process. Landforms 44, 1602–1609. https://doi.org/10.1002/esp.4597.
Godar Chhetri, S., 2012. Climate Change, its Impacts on Rural Livelihood: Adaptation Strategies from Siwalik to Terai Region. Lambert Academic Publishing.
González-García, A., Palomo, I., González, J.A., López, C.A., Montes, C., 2020. Quantifying spatial supply-demand mismatches in ecosystem services provides insights for land-use planning. Land Use Pol. 94, 104493 https://doi.org/10.1016/j.landusepol.2020.104493.
Guan, K., Hien, N.T., Li, Z., Rao, L.N., 2018. Measuring Rice Yield from Space: the Case of Thai Binh Province, Viet Nam (SSRN Scholarly Paper No. 3188560). Social Science Research Network, Rochester, NY. https://doi.org/10.2139/ssrn.3188560.
Gustafsson, L., Bauhus, J., Asbeck, T., Augustynczik, A.L.D., Basile, M., Frey, J., Gutzat, F., Hanewinkel, M., Helbach, J., Jonker, M., Knuff, A., Messier, C., Penner, J., Pyttel, P., Reif, A., Storch, F., Winiger, N., Winkel, G., Yousefpour, R., Storch, I., 2020. Retention as an integrated biodiversity conservation approach for continuous-cover forestry in Europe. Ambio 49, 85–97. https://doi.org/10.1007/s13280-019-01190-1.
Haregeweyn, N., Berhe, A., Tsunekawa, A., Tsubo, M., Meshesha, D.T., 2012. Integrated watershed management as an effective approach to curb land degradation: a case study of the enabered watershed in northern Ethiopia. Environ. Manag. 50, 1219–1233. https://doi.org/10.1007/s00267-012-9952-0.
Hartigan, J.A., Wong, M.A., 1979. Algorithm AS 136: a K-means clustering algorithm. Journal of the Royal Statistical Society. Series C (Applied Statistics) 28, 100–108. https://doi.org/10.2307/2346830.
Hinz, R., Sulser, T.B., Huefner, R., Mason-D'Croz, D., Dunston, S., Nautiyal, S., Ringler, C., Schuengel, J., Tikhile, P., Wimmer, F., Schaldach, R., 2020. Agricultural development and land use change in India: a scenario analysis of trade-offs between UN sustainable development goals (SDGs). Earth's Future 8, e2019EF001287. https://doi.org/10.1029/2019EF001287.
Holt, A.R., Alix, A., Thompson, A., Maltby, L., 2016. Food production, ecosystem services and biodiversity: we can't have it all everywhere. Sci. Total Environ. 573, 1422–1429. https://doi.org/10.1016/j.scitotenv.2016.07.139.
Ikematsu, P., Quintanilha, J.A., 2020. A review of ecosystems services trade-offs, synergies and scenarios modelling for policy development support. Desenvolv. Meio Ambiente 54. https://doi.org/10.5380/dma.v54i0.72871.
Joly, F., Benoit, M., Martin, R., Dumont, B., 2021. Biological operability, a new concept based on ergonomics to assess the pertinence of ecosystem services optimization practices. Ecosyst. Serv. 50, 101320 https://doi.org/10.1016/j.ecoser.2021.101320.
Khan, I., Zhao, M., 2019. Water resource management and public preferences for water ecosystem services: a choice experiment approach for inland river basin management. Sci. Total Environ. 646, 821–831. https://doi.org/10.1016/j.scitotenv.2018.07.339.

Kibret, K.S., Marohn, C., Cadisch, G., 2021. Improved food-insecurity prediction in smallholder-dominated landscapes using MODIS enhanced vegetation index and google earth engine: a case study in South Central Ethiopia. European Journal of Remote Sensing 54, 625–641. https://doi.org/10.1080/22797254.2021.1999176.

King, E., Cavender-Bares, J., Balvanera, P., Mwampamba, T.H., Polasky, S., 2015. Trade-offs in ecosystem services and varying stakeholder preferences: evaluating conflicts, obstacles, and opportunities. Ecol. Soc. 20.

Kramer, P.J., Boyer, J.S., 1995. Water Relations of Plants and Soils. Academic Press.

Kroll, F., Müller, F., Haase, D., Fohrer, N., 2012. Rural–urban gradient analysis of ecosystem services supply and demand dynamics. Land Use Pol. 29, 521–535. https://doi.org/10.1016/j.landusepol.2011.07.008.

Kumar, P., Brondizio, E., Gatzweiler, F., Gowdy, J., de Groot, D., Pascual, U., Reyers, B., Sukhdev, P., 2013. The economics of ecosystem services: from local analysis to national policies. Current Opinion in Environmental Sustainability, Terrestrial systems 5, 78–86. https://doi.org/10.1016/j.cosust.2013.02.001.

Laca, E.A., 2021. Multi-scape interventions to match spatial scales of demand and supply of ecosystem services. Front. Sustain. Food Syst. 4.

Lafortezza, R., Chen, J., van den Bosch, C.K., Randrup, T.B., 2018. Nature-based solutions for resilient landscapes and cities. Environ. Res. 165, 431–441. https://doi.org/10.1016/j.envres.2017.11.038.

Lan, H., Wang, D., He, S., Fang, Y., Chen, W., Zhao, P., Qi, Y., 2020. Experimental study on the effects of tree planting on slope stability. Landslides 17, 1021–1035. https://doi.org/10.1007/s10346-020-01348-z.

Larondelle, N., Lauf, S., 2016. Balancing demand and supply of multiple urban ecosystem services on different spatial scales. Ecosyst. Serv. 22, 18–31. https://doi.org/10.1016/j.ecoser.2016.09.008.

Laudari, H.K., Aryal, K., Maraseni, T., Pariyar, S., Pant, B., Bhattarai, S., Kaini, T.R., Karki, G., Marahattha, A., 2022. Sixty-five years of forest restoration in Nepal: lessons learned and way forward. Land Use Pol. 115, 106033 https://doi.org/10.1016/j.landusepol.2022.106033.

Le Provost, G., Schenk, N.V., Penone, C., Thiele, J., Westphal, C., Allan, E., Ayasse, M., Blüthgen, N., Boeddinghaus, R.S., Boesing, A.L., Bolliger, R., Busch, V., Fischer, M., Gossner, M.M., Hölzel, N., Jung, K., Kandeler, E., Klaus, V.H., Kleinebecker, T., Leimer, S., Marhan, S., Morris, K., Müller, S., Neff, F., Neyret, M., Oelmann, Y., Perović, D.J., Peter, S., Prati, D., Rillig, M.C., Saiz, H., Schäfer, D., Scherer-Lorenzen, M., Schloter, M., Schöning, I., Schrumpf, M., Steckel, J., Steffan-Dewenter, I., Tschapka, M., Vogt, J., Weiner, C., Weisser, W., Wells, K., Werner, M., Wilcke, W., Manning, P., 2022. The supply of multiple ecosystem services requires biodiversity across spatial scales. Nat Ecol Evol 1–14. https://doi.org/10.1038/s41559-022-01918-5.

Li, Z., Deng, X., Jin, G., Mohmmed, A., Arowolo, A.O., 2020. Tradeoffs between agricultural production and ecosystem services: a case study in Zhangye, Northwest China. Sci. Total Environ. 707, 136032 https://doi.org/10.1016/j.scitotenv.2019.136032.

Li, S., Zhu, C., Lin, Y., Dong, B., Chen, B., Si, B., Li, Y., Deng, X., Gan, M., Zhang, J., Wang, K., 2021. Conflicts between agricultural and ecological functions and their driving mechanisms in agroforestry ecotone areas from the perspective of land use functions. J. Clean. Prod. 317, 128453 https://doi.org/10.1016/j.jclepro.2021.128453.

Li, J., Dong, S., Li, Y., Wang, Y., Li, Z., Li, F., 2022. Effects of land use change on ecosystem services in the China–Mongolia–Russia economic corridor. J. Clean. Prod. 360, 132175 https://doi.org/10.1016/j.jclepro.2022.132175.

Ma, S., Qiao, Y.-P., Jiang, J., Wang, L.-J., Zhang, J.-C., 2021. Incorporating the implementation intensity of returning farmland to lakes into policymaking and ecosystem management: a case study of the Jianghuai Ecological Economic Zone, China. J. Clean. Prod. 306, 127284 https://doi.org/10.1016/j.jclepro.2021.127284.

Mahajan, G.R., Das, B., Manivannan, S., Manjunath, B.L., Verma, R.R., Desai, S., Kulkarni, R.M., Latare, A.M., Sale, R., Murgaonkar, D., Patel, K.P., Morajkar, S., Desai, A., Barnes, N., Mulla, H., 2021. Soil and water conservation measures improve soil carbon sequestration and soil quality under cashews. Int. J. Sediment Res. 36, 190–206. https://doi.org/10.1016/j.ijsrc.2020.07.009.

Manley, K., 2022. Understanding social–ecological systems using social media data. Nat. Rev. Earth Environ. 3, 497. https://doi.org/10.1038/s43017-022-00320-w. –497.

Maraseni, T.N., Cockfield, G., 2011. Crops, cows or timber? Including carbon values in land use choices'. Agric. Ecosyst. Environ. 140, 280–288.

Martinez-Harms, M.J., Bryan, B.A., Balvanera, P., Law, E.A., Rhodes, J.R., Possingham, H.P., Wilson, K.A., 2015. Making decisions for managing ecosystem services. Biol. Conserv. 184, 229–238. https://doi.org/10.1016/j.biocon.2015.01.024.

MEA, 2005. In: Ecosystems and Human Well-Being: Synthesis. Island Press, Washington, DC.

Mori, A.S., Lertzman, K.P., Gustafsson, L., 2017. Biodiversity and ecosystem services in forest ecosystems: a research agenda for applied forest ecology. J. Appl. Ecol. 54, 12–27. https://doi.org/10.1111/1365-2664.12669.

Nath, A.J., Sileshi, G.W., Laskar, S.Y., Pathak, K., Reang, D., Nath, A., Das, A.K., 2021. Quantifying carbon stocks and sequestration potential in agroforestry systems under divergent management scenarios relevant to India's Nationally Determined Contribution. J. Clean. Prod. 281, 124831 https://doi.org/10.1016/j.jclepro.2020.124831.

Nepal, W.W.F., 2013. Chitwan Annapurna Landscape (CHAL): A Rapid Assessment.

Nepal, M.O.F.E., 2015. Strategy and Action Plan 2016-2025. Chitwan-Annapurna Landscape, Nepal.

Obiang Ndong, G., Therond, O., Cousin, I., 2020. Analysis of relationships between ecosystem services: a generic classification and review of the literature. Ecosyst. Serv. 43, 101120 https://doi.org/10.1016/j.ecoser.2020.101120.

Pandey, H.P., Aryal, K., Aryal, S., Maraseni, T.N., 2023. Understanding local ecosystem dynamics in three provinces of the lowlands of Nepal. Sci. Total Environ. 867, 161501 https://doi.org/10.1016/j.scitotenv.2023.161501.

Petrasek, S., Perez-Garcia, J., Bare, B.B., 2015. Valuing forestlands with stochastic timber and carbon prices. Ann. Oper. Res. 232, 217–234. https://doi.org/10.1007/s10479-013-1389-1.

Polasky, S., Segerson, K., 2009. Integrating ecology and economics in the study of ecosystem services: some lessons learned. Annu. Rev. Resour. Econ. 1, 409–434. https://doi.org/10.1146/annurev.resource.050708.144110.

Qiao, X., Gu, Y., Zou, C., Xu, D., Wang, L., Ye, X., Yang, Y., Huang, X., 2019. Temporal variation and spatial scale dependency of the trade-offs and synergies among multiple ecosystem services in the Taihu Lake Basin of China. Sci. Total Environ. 651, 218–229. https://doi.org/10.1016/j.scitotenv.2018.09.135.

Rasul, G., 2016. Managing the food, water, and energy nexus for achieving the sustainable development goals in South asia. Environmental Development 18, 14–25. https://doi.org/10.1016/j.envdev.2015.12.001.

Ray, D.K., Mueller, N.D., West, P.C., Foley, J.A., 2013. Yield trends are insufficient to double global crop production by 2050. PLoS One 8. https://doi.org/10.1371/journal.pone.0066428.

Rimal, B., Sharma, R., Kunwar, R., Keshtkar, H., Stork, N.E., Rijal, S., Rahman, S.A., Baral, H., 2019. Effects of land use and land cover change on ecosystem services in the Koshi River Basin, Eastern Nepal. Ecosyst. Serv. 38, 100963 https://doi.org/10.1016/j.ecoser.2019.100963.

Rosenberg, A.A., McLeod, K.L., 2005. Implementing ecosystem-based approaches to management for the conservation of ecosystem services. Mar. Ecol. Prog. Ser. 300, 270–274.

Rugani, B., Maia de Souza, D., Weidema, B.P., Bare, J., Bakshi, B., Grann, B., Johnston, J. M., Pavan, A.L.R., Liu, X., Laurent, A., Verones, F., 2019. Towards integrating the ecosystem services cascade framework within the Life Cycle Assessment (LCA) cause-effect methodology. Sci. Total Environ. 690, 1284–1298. https://doi.org/10.1016/j.scitotenv.2019.07.023.

Running, Steve, Mu, Qiaozhen, Zhao, Maosheng, Moreno, Alvaro, 2019. MOD16A3GF MODIS/Terra Net Evapotranspiration Gap-Filled Yearly L4 Global 500 M SIN Grid V006. https://doi.org/10.5067/MODIS/MOD16A3GF.006.

Samuelson, P.A., 1956. Social indifference curves. Q. J. Econ. 70, 1–22. https://doi.org/10.2307/1884510.

Sands, R., Jones, C., Marshall, E.P. (Eds.), 2014. Global Drivers of Agricultural Demand and Supply, Economic Research Report. https://doi.org/10.22004/ag.econ.186137.

Sannigrahi, S., Zhang, Q., Joshi, P.K., Sutton, P.C., Keesstra, S., Roy, P.S., Pilla, F., Basu, B., Wang, Y., Jha, S., Paul, S.K., Sen, S., 2020. Examining effects of climate change and land use dynamic on biophysical and economic values of ecosystem services of a natural reserve region. J. Clean. Prod. 257, 120424 https://doi.org/10.1016/j.jclepro.2020.120424.

Sasson, A., 2012. Food security for Africa: an urgent global challenge. Agric. Food Secur. 1, 2. https://doi.org/10.1186/2048-7010-1-2.

Satchell, D., 2018. Report - Trees for Steep Slopes.

Sharma, R., Rimal, B., Baral, H., Nehren, U., Paudyal, K., Sharma, S., Rijal, S., Ranpal, S., Acharya, R.P., Alenazy, A.A., Kandel, P., 2019. Impact of land cover change on ecosystem services in a tropical forested landscape. Resources 8, 18. https://doi.org/10.3390/resources8010018.

Shono, K., Cadaweng, E.A., Durst, P.B., 2007. Application of assisted natural regeneration to restore degraded tropical forestlands. Restor. Ecol. 15, 620–626. https://doi.org/10.1111/j.1526-100X.2007.00274.x.

Shrestha, K., 2016. Variation in soil organic carbon within highland grasslands of Langtang National Park, Nepal. International Journal of Environment 5, 57–65. https://doi.org/10.3126/ije.v5i3.15704.

Sickles, R.C., Zelenyuk, V., 2019. Measurement of Productivity and Efficiency: Theory and Practice, first ed. Cambridge University Press. https://doi.org/10.1017/9781139565981.

Sodhi, N.S., Koh, L.P., Clements, R., Wanger, T.C., Hill, J.K., Hamer, K.C., Clough, Y., Tscharntke, T., Posa, M.R.C., Lee, T.M., 2010. Conserving Southeast Asian forest biodiversity in human-modified landscapes. Biological Conservation, Conserving complexity: Global change and community-scale interactions 143, 2375–2384. https://doi.org/10.1016/j.biocon.2009.12.029.

Stosch, K.C., Quilliam, R.S., Bunnefeld, N., Oliver, D.M., 2019. Quantifying stakeholder understanding of an ecosystem service trade-off. Sci. Total Environ. 651, 2524–2534. https://doi.org/10.1016/j.scitotenv.2018.10.090.

Syahrinudin, 2005. The Potential of Oil Palm and Forest Plantations for Carbon Sequestration on Degraded Land in Indonesia. Cuvillier Verlag.

Tallis, H., Kareiva, P., Marvier, M., Chang, A., 2008. An ecosystem services framework to support both practical conservation and economic development. Proc. Natl. Acad. Sci. USA 105, 9457–9464. https://doi.org/10.1073/pnas.0705797105.

Terrado, M., Sabater, S., Chaplin-Kramer, B., Mandle, L., Ziv, G., Acuña, V., 2016. Model development for the assessment of terrestrial and aquatic habitat quality in conservation planning. Science of the Total Environment, 5th Special Issue SCARCE: river Conservation under Multiple stressors: integration of ecological status. pollution and hydrological variability 540, 63–70. https://doi.org/10.1016/j.scitotenv.2015.03.064.

Torralba, M., Fagerholm, N., Hartel, T., Moreno, G., Plieninger, T., 2018. A social-ecological analysis of ecosystem services supply and trade-offs in European wood-pastures. Sci. Adv. 4, eaar2176 https://doi.org/10.1126/sciadv.aar2176.

Upadhaya, S., Tiwari, S., Poudyal, B., Chhetri, S.G., Dhungana, N., 2022. Local people's perception of the impacts and importance of ecotourism in Central Nepal. PLoS One 17, e0268637. https://doi.org/10.1371/journal.pone.0268637.

Vaast, P., Somarriba, E., 2014. Trade-offs between crop intensification and ecosystem services: the role of agroforestry in cocoa cultivation. Agrofor. Syst. 88, 947–956. https://doi.org/10.1007/s10457-014-9762-x.

Valencia Torres, A., Tiwari, C., Atkinson, S.F., 2021. Progress in ecosystem services research: a guide for scholars and practitioners. Ecosyst. Serv. 49, 101267 https://doi.org/10.1016/j.ecoser.2021.101267.

Vallet, A., Locatelli, B., Levrel, H., Wunder, S., Seppelt, R., Scholes, R.J., Oszwald, J., 2018. Relationships between ecosystem services: comparing methods for assessing tradeoffs and synergies. Ecol. Econ. 150, 96–106. https://doi.org/10.1016/j.ecolecon.2018.04.002.

Wang, Y., Liu, J., Hansson, L., Zhang, K., Wang, R., 2011. Implementing stricter environmental regulation to enhance eco-efficiency and sustainability: a case study of Shandong Province's pulp and paper industry, China. J. Clean. Prod. 19, 303–310. https://doi.org/10.1016/j.jclepro.2010.11.006.

Wang, L., Zheng, H., Wen, Z., Liu, L., Robinson, B.E., Li, R., Li, C., Kong, L., 2019. Ecosystem service synergies/trade-offs informing the supply-demand match of ecosystem services: framework and application. Ecosyst. Serv. 37, 100939 https://doi.org/10.1016/j.ecoser.2019.100939.

Wang, Q., Wang, H., Zeng, H., Chang, R., Bai, X., 2022. Understanding relationships between landscape multifunctionality and land-use change across spatiotemporal characteristics: implications for supporting landscape management decisions. J. Clean. Prod. 377, 134474 https://doi.org/10.1016/j.jclepro.2022.134474.

Wei, H., Fan, W., Wang, X., Lu, N., Dong, X., Zhao, Yanan, Ya, X., Zhao, Yifei, 2017. Integrating supply and social demand in ecosystem services assessment: a review. Ecosyst. Serv. 25, 15–27. https://doi.org/10.1016/j.ecoser.2017.03.017.

Wei, Y., Wu, S., Jiang, C., Feng, X., 2021. Managing supply and demand of ecosystem services in dryland catchments. Current Opinion in Environmental Sustainability, The dryland social-ecological systems in changing environments 48, 10–16. https://doi.org/10.1016/j.cosust.2020.08.007.

West, P.C., Gibbs, H.K., Monfreda, C., Wagner, J., Barford, C.C., Carpenter, S.R., Foley, J. A., 2010. Trading carbon for food: global comparison of carbon stocks vs. crop yields on agricultural land. Proc. Natl. Acad. Sci. USA 107, 19645–19648. https://doi.org/10.1073/pnas.1011078107.

Winkler, K., Fuchs, R., Rounsevell, M., Herold, M., 2021. Global land use changes are four times greater than previously estimated. Nat. Commun. 12, 2501. https://doi.org/10.1038/s41467-021-22702-2.

Wischmeier, W.H., Smith, D.D., 1965. Predicting Rainfall-Erosion Losses from Cropland East of the Rocky Mountains: Guide for Selection of Practices for Soil and Water Conservation. Agricultural Research Service. U.S. Department of Agriculture.

Wu, J., Huang, Y., Jiang, W., 2022. Spatial matching and value transfer assessment of ecosystem services supply and demand in urban agglomerations: a case study of the Guangdong-Hong Kong-Macao Greater Bay area in China. J. Clean. Prod. 375, 134081 https://doi.org/10.1016/j.jclepro.2022.134081.

Yan, Y., Kuang, W., Zhang, C., Chen, C., 2015. Impacts of impervious surface expansion on soil organic carbon – a spatially explicit study. Sci. Rep. 5, 17905 https://doi.org/10.1038/srep17905.

Yang, Y., Zhang, S., Xia, F., Yang, Y., Li, D., Sun, W., Wang, Y., Xie, Y., 2022. A comprehensive perspective for exploring the trade-offs and synergies between carbon sequestration and grain supply in China based on the production possibility frontier. J. Clean. Prod. 354, 131725 https://doi.org/10.1016/j.jclepro.2022.131725.

Yin, D., Yu, H., Shi, Y., Zhao, M., Zhang, J., Li, X., 2023. Matching supply and demand for ecosystem services in the Yellow River Basin, China: a perspective of the water-energy-food nexus. J. Clean. Prod. 384, 135469 https://doi.org/10.1016/j.jclepro.2022.135469.

Yu, Y., Li, J., Zhou, Z., Ma, X., Zhang, X., 2021. Response of multiple mountain ecosystem services on environmental gradients: how to respond, and where should be priority conservation? J. Clean. Prod. 278, 123264 https://doi.org/10.1016/j.jclepro.2020.123264.

Yuan, M.-H., Lo, S.-L., 2020. Ecosystem services and sustainable development: perspectives from the food-energy-water Nexus. Ecosyst. Serv. 46, 101217 https://doi.org/10.1016/j.ecoser.2020.101217.

Zhang, L., Peng, J., Liu, Y., Wu, J., 2017. Coupling ecosystem services supply and human ecological demand to identify landscape ecological security pattern: a case study in Beijing–Tianjin–Hebei region, China. Urban Ecosyst. 20, 701–714. https://doi.org/10.1007/s11252-016-0629-y.