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# Land Use-Based Participatory Assessment of Ecosystem Services for Ecological Restoration in Village Tank Cascade Systems of Sri Lanka

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**Abstract:** Village Tank Cascade System (VTCS) landscapes in the dry zone of Sri Lanka provide multiple ecosystem services (ESs) and benefits to local communities, sustaining the productivity of their land use systems (LUSs). However, there is a lack of adequate scientific research on the ESs of LUSs, despite the recent land use changes that have greatly impacted the provisioning of ESs. Collection of baseline ESs data is a pre-requisite for decision making on ESs-based ecological restoration and management of the VTCS. Thus, this study aimed at assessing ESs of the Mahakanumulla VTCS (MVTCS) located in the Anuradhapura district of Sri Lanka by using a participatory approach involving the integration of local knowledge, expert judgements and LUSs attribute data to assess the ESs. The methodology was designed to integrate the biodiversity and land degradation status of LUSs in a way that is directly linked with the supply of ESs. The study identified twenty-four ESs of the MVTCS based on community perceptions. The identified ESs were assessed as a function of LUSs to develop an ecosystem service supply (ESS) and demand (ESD) matrix model. The results reveal that the current overall ESD for regulating and supporting ESs is higher than the ESS capacity of MVTCS. The assessment also revealed that land degradation and biodiversity deterioration reduce the capacity to provide ESs. Downstream LUSs of the meso-catchment were found to be more vulnerable to degradation and insufficient to provide ESs. Further, the study established that ESs in the MVTCS are generated through direct species-based and biophysical-based providers. In addition, it emerged that social and cultural engagements also played an important role in association with both providers to generate certain types of ESs. Therefore, it can be concluded that VTCS ecological restoration depends on the extent to which integrated effort addresses the levels of ecological complexity, as well as the social engagement of communities and stakeholders. The results of this study provide a scientific basis that can inform future land use decision making and practices that are applicable to successful ESs-based ecological restoration and management of the VTCSs in the dry zone of Sri Lanka.

**Keywords:** village tank cascade system; ecosystem services; land use systems; ecosystem services mapping; ecosystem services trade-offs; ecosystem services-based ecological restoration

## 1. Introduction

In Sri Lanka, the Village Tank Cascade Systems (VTCSs) are considered unique social-ecological systems (SESs) that have also been recently recognised as one of the Globally Important Agricultural Heritage Systems (GIAHSs) attributed to complex hydrological and social-ecological relationships at different spatial scales [1]. Land use systems (LUSs) of VTCSs have evolved through unique biophysical-social interactions and are inexorably linked with rich biodiversity and ecosystem services (ESs) for their sustainability and resilience [2,3]. Ecosystem services provide the foundation for food and nutrition security to smallholder farming communities in the VTCSs by maintaining and improving ecosystem health and climate change resilience [4]. Over the last few years, there has been increased attention in the scientific literature to the value of ESs in SESs, leading to a better understanding of their contribution to human well-being and ecosystem health in the face of global environmental changes [5–8]. Moreover, after the Millennium Ecosystem Assessment (MEA) [8], the ESs concept has been broadened into a framework and increasingly adopted as a decision-making tool for the sustainable management of natural resources [9]. The VTCSs provide a model of a sustainable landscape in which human well-being was maintained in harmony with nature, despite environmental shocks during the past two millennia [10,11]. Thus, studying the ESs of the VTCSs provides insight into how people interact within a unique social-ecological system (SES) to obtain ESs for their survival and well-being, and helps guide efforts to maintain them into an uncertain future [12].

The Village Tank Cascade System (VTCS) comprises a mosaic of small-scale social-ecological LUSs, including smallholder farming systems and ecologically sensitive areas. About 23.3% of the agricultural lands (approximately 228,000 hectares of paddy lands) of the country are located in VTCSs, therefore sustainable maintenance of VTCSs is of great importance in enhancing the agricultural productivity of the country [13]. However, sustainability of the VTCSs will not be achieved if its ecosystem functions and ESs are not properly maintained and protected within the system. Some of the ESs associated with VTCSs have been identified and economically valued. Provisioning ESs are largely recognised at present, while other ESs—regulating, supporting and cultural services of the VTCSs—have not been adequately assessed and are mostly ignored [14–18].

A critical current challenge for maintaining the sustainability of VTCSs is how to increase their agricultural productivity in an environmentally sustainable way [12]. During the past two decades, devastating land use changes have caused biodiversity loss in VTCS landscapes, which have degraded ESs. Some of the land-use changes have resulted in the irreversible collapse of socio-ecological interactions and LUSs–ESs connections. [10,19–21]. Different LUSs may have different capacities for generating ESs [22]. Thus, the supply capacity variations of ESs across LUSs should be well understood in order to initiate sustainable strategies for ecosystem services-based ecological restoration and management of VTCSs. Increasing the ecological productivity of a VTCS through improving ESs could be one of the sustainable solutions for enhancing agricultural productivity [13,23]. In this context, a clear understanding of ESs and their associations with the land use system (LUS) attributes is important. However, research on VTCS ecology, its functions at different levels and the capacity of different ecological components to generate ESs is inadequate. For example, a review of published literature shows only two studies where the biodiversity of the VTCSs has been systematically quantified [24,25].

Ecosystem services assessment and mapping approaches have gained increasing attention, especially since 2000, in the global literature [26]. The essence of the ESs concept is described as the contribution of nature to human well-being [27,28]. Recent studies that have adopted participatory approaches to estimate and map ecosystem service supply and demand include those by Burkhard, Müller [29]; Burkhard, Kroll [30]; Casado-Arzuaga, Madariaga [31]; Burkhard, Kroll [32]; Jacobs, Wolfstein [33]; Burkhard, Kandziora [34]; Reyers, Biggs [35]; Paudyal, Baral [36]; Palomo, Felipe-Lucia [37]; Baral, Keenan [38]; Orsi, Ciolli [39]. Among others, Brück, Abson [9] noted that the majority of ESs assessments have focused on the overall value of ESs for society, rather than the intersection of ecosystem service (ES) values across space, time and user groups. Though there is an increasing trend of ESs assessment studies in Sri Lanka since 2000, research that quantifies the value of ESs through community engagements remains scant in the country [40]. Most ES bundles are generated in social-ecological systems as a result of the integrated outcomes of interacting social, ecological and cultural elements of the system [23,35,37,41–44]. Fisher, Turner [7] emphasised that people are the most important users and beneficiaries of ESs. Thus, participatory approaches that utilise peoples' perceptions could be more appropriate because the value of ESs is determined by the beneficiaries of the LUSs. On the other hand, most existing ES studies have focused on biophysical assessment and quantification of ecological and economic impacts due to land use changes in large-scale landscapes through advanced GIS and remote-sensing techniques [45,46]. Limited studies have taken into consideration the quantitative measurement of social perceptions that reflect the real beneficiary value of ESs [26,47] and other important ES components, such as biodiversity [26,45,48] and land health [49–51]. Therefore, a mixed approach, with the integration of social factors and local knowledge, is more effective for the assessment and mapping of ESs in a complex small-scale social-ecological system [52–54].

The present paper analyses the ESs of different LUSs of Mahakanumulla VTCS in Sri Lanka through community perceptions, expert estimations and biophysical indicators—species diversity and land degradation of LUSs. The specific objectives were to (i) identify and prioritise ESs; (ii) determine ES supply (ESS) and ES demand (ESD) varying across the LUSs; and (iii) map hotspots and bright spots of biodiversity, land degradation and ESS across the LUSs. The findings of this study will provide valuable and much-needed scientific information that could be applied to future land use decision making and practices in regard to ESs-based ecological restoration and management of the VTCSs in Sri Lanka.

## 2. Materials and Methods

### *2.1. Study Area*

The Mahakanumulla Village Tank Cascade System (MVTCS) is located in the Anuradhapura district within the Malwathuoya River Basin of the north-central province of Sri Lanka (8°5′–8°15′ N and 80°20′–80°35′ E). There are 12 villages and 28 village tanks within the MVTCS, which covers a cascade area of about 4450 ha, with a water surface area of about 557 ha and an irrigation command area of about 758 ha. The population of the area is 3432 (47.8% male and 52.2% female) and 1193 households. There are ten farmer organisations within the MVTCS. The MVTCS landscape is characterised by a tropical monsoonal climate with a well-defined bi-modal rainfall pattern. The annual average rainfall of the area is 1445 mm and the average daily ambient temperature is 27 °C. The terrain of the MVTCS landscape is undulating and is characterised by slopes and valleys which determine the water movement. Three major soil groups (Reddish Brown Earths—Rhodustalfs (60%), Low Humic Gley—Tropaqualfs (30%) and Alluvials (10%)) are found in the area, which create different drainage conditions that provide favourable conditions for farmers to adopt three-fold traditional farming systems (lowland paddy, rain-fed upland and homestead gardens) in the MVTCS. The farming systems of the MVTCS are heavily fragmented and the majority of farm plots are less than two hectares. Intra-annual variation in rainfall (875 to 1875 mm) enables farmers to adapt two major cultivation seasons consisting of combinations of monsoonal and inter-monsoonal climatic seasons. These farming practices have symbiotic relationships with a rich array of biodiversity associated with traditional knowledge and the cultural practices of the area. The above social-ecological, hydrological and geomorphological features of the MVTCS contribute immensely to reducing climate stresses and maintaining sustainable food production. However, long-term land use changes and frequent intra-annual climate variations have impacted significantly the supply of ESs in the study area [12,13]. Altogether, five LUSs and ten major land use types (LUTs) could be identified from a 1:10,000 digital land use map of the study area obtained from the Land Use Policy Planning Department (LUPPD) of Sri Lanka (Table 1 and Figure 1).

**Table 1.** Land use system categories used for the ESs assessment.

| **Land Use System (LUS)** | **Land Use Type (LUT)** | **Code** | **Scale** | **Functions** |
|---|---|---|---|---|
| Agricultural lands | Paddy | P | Macro | Irrigated paddy agro-ecosystem. |
| | Sparsely used crop land/Shifting cultivation (Chena) | SUCL | Macro | Rain-fed shifting cultivation with very few scattered trees. |
| | Seasonal crops | SC | Macro | Seasonal crop farming based on climatic seasons. |
| Forest lands | Dense forest | DF | Macro | Catchment forest (tropical dry mixed evergreen forest—habitat for wild animals). |
| | Open forest | OF | Macro | Secondary (sparse) forest trees and shrubs. Patches of Damana grasslands associated with tree vegetation. |
| | Scrub land | SL | Macro | Open areas with low vegetation, covered with small trees and shrubs—habitats for small wild species (amphibians, reptiles etc.). |
| | Forest plantation | FP | Macro | Dominant Acacia (*Acacia auriculiformis*) and monoculture Teak (*Tectona grandis*) plantation. |
| Water bodies | Tank/Minor reservoir | T/MNR | Macro | Village tanks. Four geometrical phases of the tank (dead storage, deep-phase, shallow-phase and high flood phase) provide habitats and support the survival of aquatic flora and fauna. |
| Rocky areas | Area with exposed rocks | RARE | Macro | Rocks and rock outcrops—habitat for few wild species (amphibians, reptiles, etc.). |
| Built-up areas | Home garden/Homestead | HG | Macro | Houses, home gardens with horticulture, vegetable and animal husbandry. |
| Micro-land uses (Ecological commons) | Upstream tree belt (Gasgommana) | UTB | Micro | Strip of trees found at the periphery of the tank bed. Functioning as a wind barrier, fish breeding habitat, silt filter, habitats for birds and small wild animals. |
| | Downstream reservation (Kattakaduwa) | DR | Micro | Diverse vegetation function as natural bio-filter to reduce salinity in seepage water before it reaches into the paddy fields. Habitat for many species. |
| | Upstream soil ridges (Isweti or Potaweti) | USR | Micro | Upstream earth ridges to prevent sediment inflow. |

**Table 1.** *Cont.*

| Land Use System (LUS) | Land Use Type (LUT) | Code | Scale | Functions |
|---|---|---|---|---|
| | Upstream water hole (Godawala) | UWH | Micro | Human-made water hole aims to trap sediment run-off and provides water to wild animals. |
| | Deep phase (Diyagilma) | DP | Micro | Central part of the tank bed. Various aquatic plants are grown in this area. Lotus and hydrilla species are dominant. Invasive aquatic plants such as water hyacinth, azolla, salvenia and water lettuce are also present. |

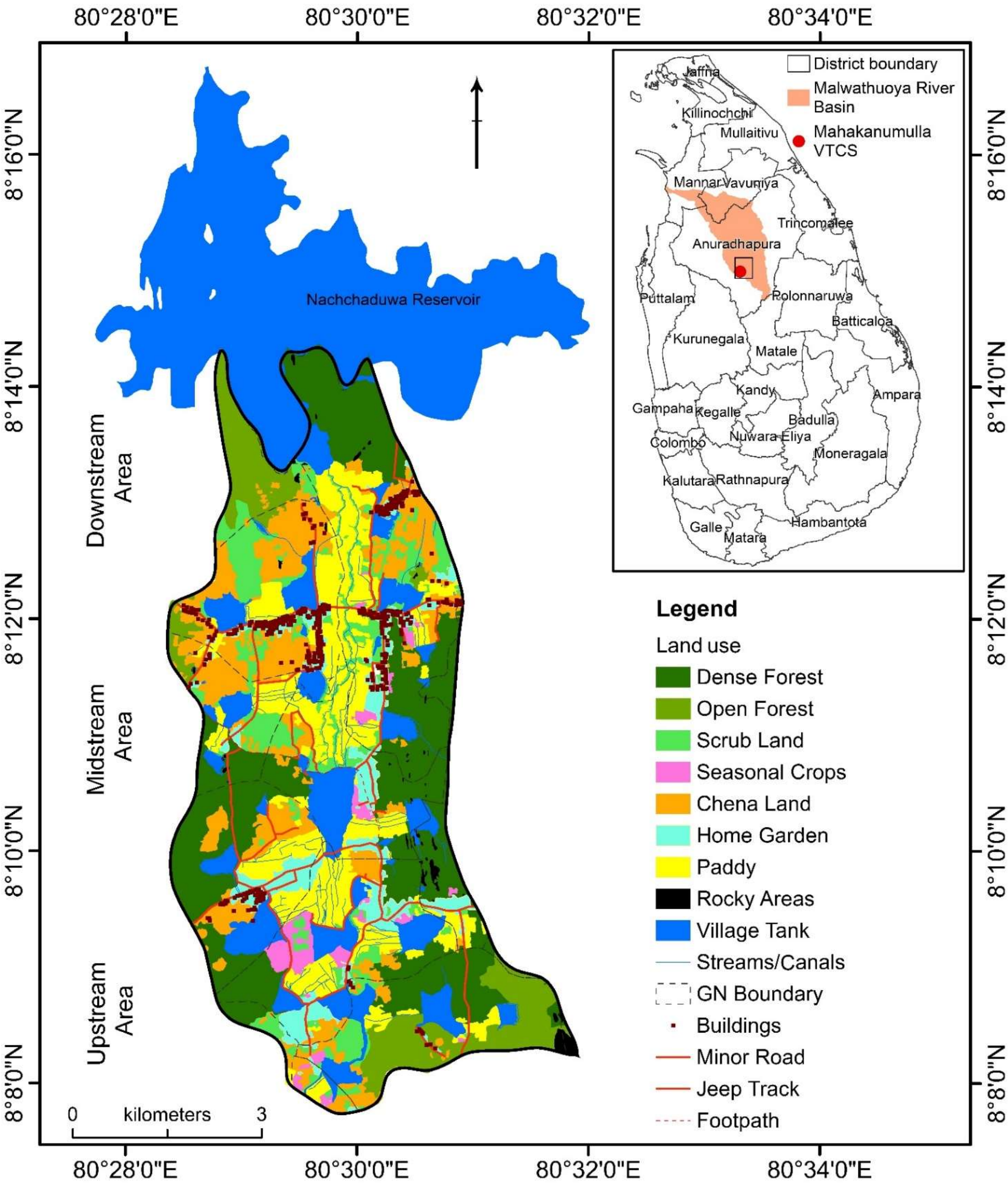


**Figure 1.** Location of the study area and major land use types.

### 2.2. Approach and Data Collection

The study utilised both qualitative and quantitative data collection methodologies. Participatory Rapid Appraisal (PRA) techniques were used to determine community perception of values they consider, while prioritising ESs and assessing the supply and demand of ESs provided by the LUSs of the MVTCS. An on-site field survey was carried out to assess the impact of land degradation on ESS of different LUTs. Biodiversity data were obtained from the biodiversity baseline survey of the MVTCS [55]. Land degradation and biodiversity data were integrated to map the ESS capacities of the MVTCS. Data were analysed using graphical and numerical summary measures and exploratory data analysis methods. On-site field survey data collection and participatory assessments were carried out with the support of the Natural Resources Management Centre (NRMC) of the Department of Agriculture and Wayamba University of Sri Lanka in December 2021 and May 2022, respectively.

### 2.3. Preparation of LUS Units Field Basemap

The LUSs digital map (1:10,000) layer (shapefile) of the study area was overlaid on the basemap of Google Earth imagery and the study area was selected as a Keyhole Markup Language (KML) file. On-screen digitising was undertaken by employing ArcMap (version 10.8.1) software from the Environmental Systems Research Institute, Redlands, California, USA, to demarcate fine-scale LUS units of the study area using the Google Earth image (KML file) accessed on 20 June 2021. In the basemap, each LUS unit was assigned a unique ID. The completed LUSs units field basemap was (i) uploaded as a KML file into Google Earth to use for navigation purposes through a smartphone to find the location of LUSs units and (ii) used as a reference basemap during on-site field assessment of ESs [56]. The methodological approach used in this study is elaborated in Figure 2.

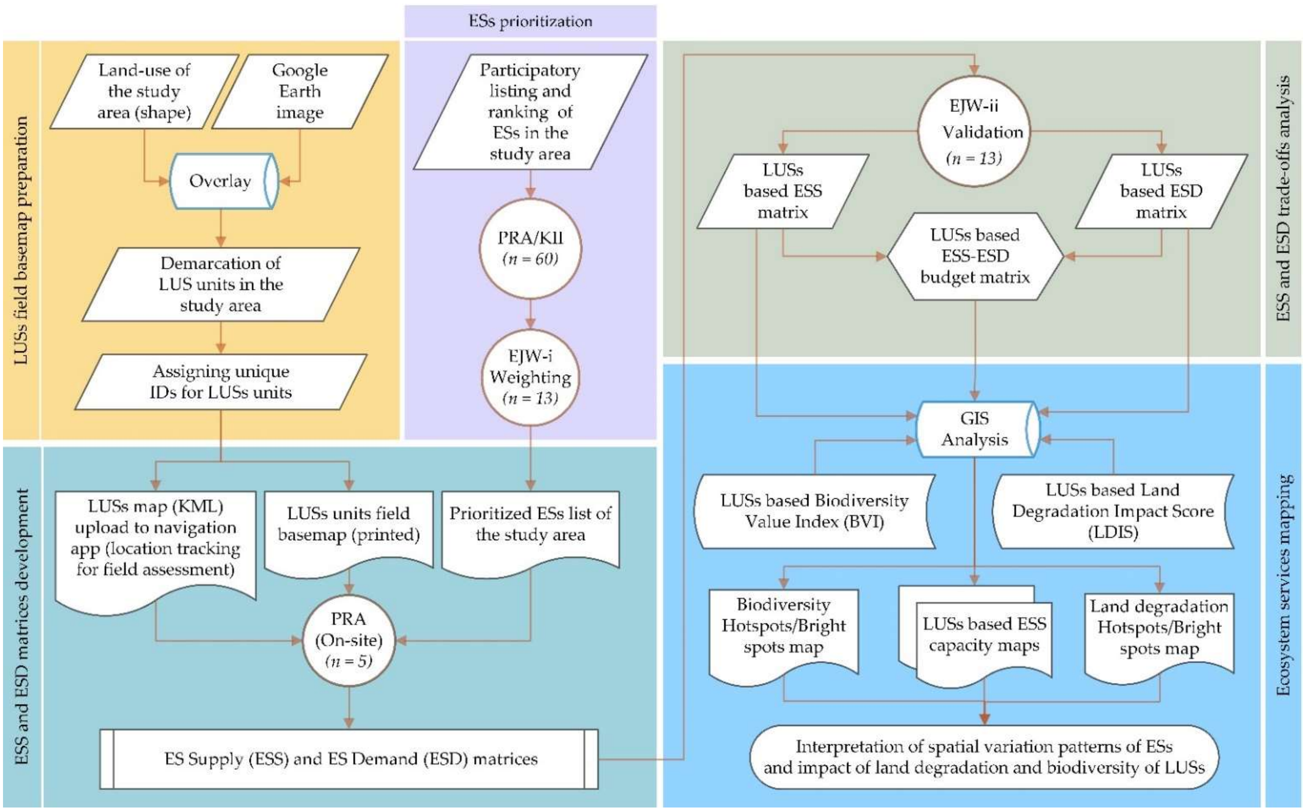


**Figure 2.** Methodological approach used to assess ecosystem services in the MVTCS. LUSs = Land Use Systems; ES = Ecosystem Service; KML = Keyhole Markup Language; PRA = Participatory Rapid Appraisal; KII = Key Informant Interviews; EJW = Expert Judgement Workshop.

### 2.4. Inventorying and Prioritisation of ESs

A review of the literature was first undertaken to screen and list out potential ESs associated with VTCS landscapes. In addition, participatory ESs screening was performed in the community to refine the initial list and prioritise ESs in the MVTCS. The prioritised ESs were organised under four main ESs categories: (i) Provisioning (P); (ii) Regulating (R); (iii) Cultural (C) services; and (iv) Supporting functions (S), based on the Common International Classification of Ecosystem Services (CICES—V5.1) [8,57].

The prioritisation of ESs was carried out through the adoption of a rapid participatory listing and ranking approach through PRA techniques [58,59]. The PRA was conducted by selecting community members of upstream, midstream and downstream areas of the MVTCS meso-catchment. An initial explanation of the ESs and their benefits to society was given by the facilitators. Community members were organised into groups and convened to identify ES indicators linked to different LUSs types; they were asked to score each ecosystem service based on its importance in providing benefits to society and to give reasons for the scores. Validated and analysed perception data were visualised using the 'ggplot2' package in R statistical software version 4.1.2 [60].

Often, the community members were uncertain how to convert their perception into a numerical score value, and therefore facilitators had to note down and convert their opinion on a scale of zero to five, where the higher the value, the higher the importance. The results were further validated through key informant interviews (KII), including government authorities and senior community members of the area. The first expert judgement workshop (EJW-i) was conducted to assign weights (%) for each ES based on their knowledge and experience. On-site biodiversity field survey data were analysed to verify the species-based ESs providers. Finally, on-site field verification exercises were conducted parallel to field data collection with the PRA members and experts to further verify the results.

### 2.5. Assessment of ESs' Supply and Demand

This study refers to the ESs' supply (ESS) capacity as the current potential of individual LUS units to provide different ESs bundles to the local beneficiaries. Ecosystem services' demand (ESD) refers to the amount of all ESs currently consumed or used in both the local area where they are generated or in areas outside local areas over a given period of time [30,53,61]. The study assessed 430 LUS units in the MVTCS which belonged to various macro and micro LUTs (Table 1). Ecosystem services' supply and demand values for particular LUS units were derived from on-site PRA exercises with key informants. The derived values (scores) were transferred to a pre-defined scale from zero to five—where the higher the value (score), the higher the demand or supply for the quantification of ESD and ESS for a particular LUS unit. All values were arranged in a matrix model to link ESs (y-axis) and the LUTs (x-axis). To reduce the uncertainties and improve the confidence level of perceived values by the community, a second expert judgement workshop (EJW-ii) was conducted to validate the ESS and ESD scores by integrating: (i) on-site observations to ensure real evidence and (ii) expert verification to reach a high level of scientific agreement on the final scores of the matrix model [62], thus increasing the scientific quality of the matrix model outcomes [63]. Validated and analysed perception data were visualised using the 'ggplot2' and 'fmsb' packages in R statistical software version 4.1.2 [60,64].

### 2.6. Mapping of ESS Capacity

Ecosystem service supply scores of the matrix were linked with the attributes of LUSs units' polygons using the 'unique code field' of the LUSs units as a common identifier field for the map production process. The mapping of ESs was carried out based on the values of the ESS matrix scores, Biodiversity Value Index (BVI) and Land Degradation Impact Score (LDIS) of each LUSs unit in the ArcMap version 10.8.1 GIS platform. The study used on-site biodiversity field survey data to derive the BVI by calculating the Simpson Diversity Index for shrubs, small plants, trees, crop plants, medicinal plants and aquatic flora and fauna for the LUTs level [65]. Land Degradation Impact Scores for each LUS unit were calculated based on land degradation field assessment survey data. The land degradation assessment adopted LUS-based LADA–WOCAT–QM (Land Degradation Assessment in Drylands–World Overview of Conservation Approaches and Technologies–Questionnaire for Mapping) approach for on-site assessment of the land degradation indicators in the MVTCS [50,66,67]. The study developed the LUTs and ESs matrix for a grid (100 m × 100 m)-based calculation of ESS capacity values. All ESS, BVI and LDIS values were normalised (rescaled) to be between 0 and 1 to develop raster maps of ESS capacity, biodiversity and land degradation hotspot and bright spot areas in the MVTCS landscape (Figure 3).

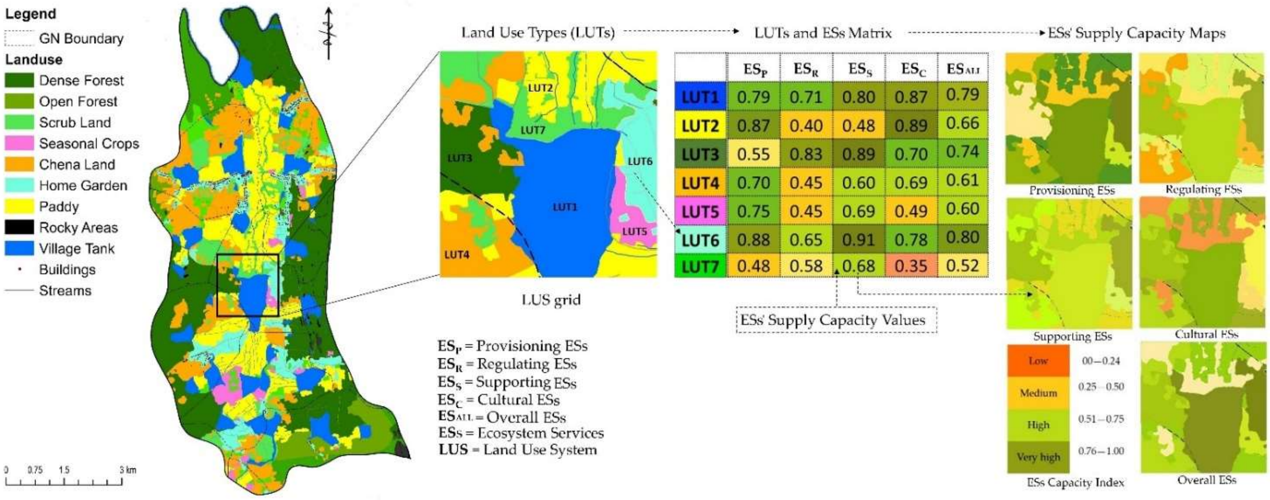


**Figure 3.** An illustration of the process used to map ecosystem services.

## 3. Results

### *3.1. Informants of the PRA*

Community assessments through PRA and KII involved 60 people (68% male and 32% female) who had different interactions with MVTCS, including the village community and local government officers. Expert judgement workshops involved 13 experts from NRMC, LUPPD, academia and research institutions. Among the community members who participated in the assessment, 88% were members and/or office bearers of the farmer organisations established in the MVTCS that were directly involved in the local governance of village tanks and associated livelihood activities in harmony with local government organisations. The age distribution of the informants ranged from 30 to 85 years. Most informants were seniors and had been living in the area for more than two generations, which indicates that they had firsthand information—key informants on the ecosystem benefits being received from the LUSs of the MVTCS. All informants were engaged in paddy cultivation in the MVTCS, while about 74% of them were found to be practicing upland farming, including shifting cultivation and home garden horticulture. The age distribution and the number of generations that the community members had been living in this area are shown in Figure 4.

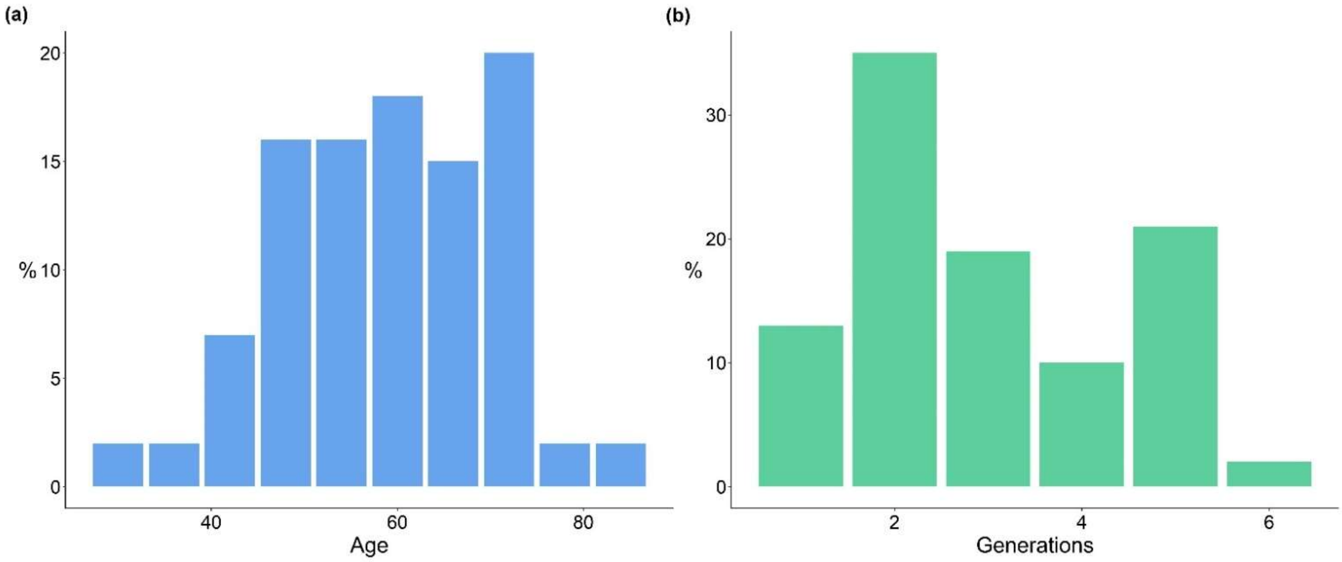


**Figure 4.** Age (**a**) and the generations (**b**) of the informants.

### 3.2. Establishment of ESs Priorities

This study revealed that the MVTCS landscape has provided a wide range of ES benefits to the local communities. Participatory listing of ESs by local community members identified twenty-four ESs—nine provisioning services, nine regulating services, four cultural services and two supporting functions. The findings also revealed that the community could identify key providers of ESs and had a strong relationship with biodiversity and biophysical elements of LUSs of the MVTCS. During the EJW-i, experts identified potential indicators to quantify the ESs identified in the participatory listing. The list of ESs perceived by local communities of the MVTCS is given in Table 2. The ranking of the ESs based on the community's perceived scores and experts' weighting values are provided in Figure 5.

**Table 2.** Summary of ecosystem services/functions and their key providers that emerged from the participatory rapid appraisal.

| Ecosystem Service | Description | Key Providers | Potential Indicators Identified for ESs Quantification |
|---|---|---|---|
| Food production (P) | Cultivated food crops (paddy, cereals, lentils, pulses, vegetables, tubers and other seed crops). | - Crop species<br>- Soil organisms<br>- Biophysical elements | - Agrobiodiversity<br>- Soil biodiversity<br>- Crop productivity<br>- Dietary diversity |
| Water for domestic use (P) | Capacity to provide clean water. | - Biophysical elements | - Soil health/land degradation<br>- Pollution indicators<br>- Groundwater recharge |
| Water for irrigation (P) | Capacity to provide water for agriculture. | - Biophysical elements | - Water productivity |
| Inland fisheries (P) | Edible fish species for food and nutrition. | - Fish species | - Biodiversity<br>- Fish productivity<br>- Dietary diversity |
| Livestock (P) | Reared livestock species for livestock products for food and nutrition.<br>Provide organic manure for crop cultivation. | - Livestock species | - Livestock diversity<br>- Livestock productivity<br>- Dietary diversity<br>- Soil organic matter content |

**Table 2.** *Cont.*

| Ecosystem Service | Description | Key Providers | Potential Indicators Identified for ESs Quantification |
|---|---|---|---|
| Fodder and grasses (P) | Existence of grazing lands (pastures) used in the diets of domestic herbivores. | - Plant species | - Biodiversity<br>- Biomass productivity |
| Raw materials (P) | Plant species used as raw materials. | - Plant species | - Biodiversity<br>- Biomass productivity |
| Medicinal plants (P) | Medicinal plants and materials. | - Plant species | - Biodiversity |
| Fruits and wild edibles (P) | Fruit species and wild edible plants. | - Plant species<br>- Soil organisms | - Biodiversity<br>- Soil biodiversity |
| Control of floods (R) | Capacity of LUSs to capture storm water and reduce runoff. | - Biophysical elements<br>- Plant species of vegetative cover | - Land use, land degradation, soil health<br>- Vegetative cover |
| Ground water recharge (R) | Capacity of LUSs to capture runoff water and enhance aquifer recharge. | - Biophysical elements | - Land use, land degradation, vegetative cover, soil health |
| Water purification (R) | Plant species capable to purify polluted water. | - Plant species | - Bioiversity—species richness |
| Local climate regulation (R) | Capacity of VTCS ecosystems to reduce negative effects of climate change and regulate air quality. | - Plant species | - Biodiversity—species richness<br>- Ecological productivity/resilience |
| Global climate regulation (R) | Capacity of VTCS ecosystems to enhance carbon sequestering, and reduce GHG emissions. | - Biophysical elements | - Land use, vegetative cover, soil organic carbon<br>- Ecological productivity/resilience |
| Pollination (R) | Capacity to maintain insects, birds and animal species as pollinators and seed dispersal animals that support crop pollination—food production and their contribution to gene flows and ecological restoration. | - Insect, bird, animal and host plant species | - Biodiversity—species richness<br>- Habitat fragmentation<br>- Pollution (soil, water, air) |
| Soil nutrient regulation (R) | Capacity of ecological components to maintain soil fertility and soil properties. | - Biophysical elements | - Land use, land degradation, vegetative cover, soil health |
| Soil erosion regulation (R) | Capacity of LUSs to provide soil retention, runoff control and reduce soil erosion. | - Biophysical elements | - Land use, land degradation, vegetative cover, soil health |
| Pests and diseases control (R) | Capacity to maintain of biological control agents to minimise incidence of pest and diseases outbreak. | - Insect, bird and vertebrate species | - Biodiversity—species richness<br>- Pollution (soil, water, air) |
| Landscape diversity (S) | Capacity of LUSs to maintain ecologically and social-ecologically important habitats. | - Biophysical elements | - Landscape/habitat diversity<br>- Landscape performance/resilience |
| Biodiversity (S) | Capacity of VTCS ecosystems to maintain globally and locally important biodiversity to support ecosystem processes and functions. | - Plant and animal species<br>- Biophysical elements | - Biodiversity<br>- Ecological productivity |
| Aesthetic and recreational values (C) | Capacity of landscape to provide areas of outstanding aesthetic beauty and quality. It provides environment for villagers and eco-travellers to relax—recreation and educational potentials. | - Plant and animal species<br>- Biophysical elements | - Biodiversity<br>- Landscape/habitat diversity |
| Traditional knowledge and values (C) | Existence of traditional knowledge systems and practices in the VTCS. | - Plant and animal species<br>- Social elements | - Biodiversity<br>- Biocultural diversity |

**Table 2.** *Cont.*

| Ecosystem Service | Description | Key Providers | Potential Indicators Identified for ESs Quantification |
|---|---|---|---|
| Cultural customary values (C) | Cultural traditions, customs and rituals connected with socio-cultural and ecological elements of the VTCS. | - Plant and animal species<br>- Biocultural elements | - Biodiversity<br>- Biocultural diversity |
| Spiritual and religious values (C) | Spiritual and religious customs associated with a sense of places in the VTCS environment. | - Biophysical elements<br>- Biocultural elements | - Landscape/habitat diversity<br>- Biocultural diversity |

Note: P = Provisioning ES; R = Regulating ES; C = Cultural ES; S = Supporting ES functions.

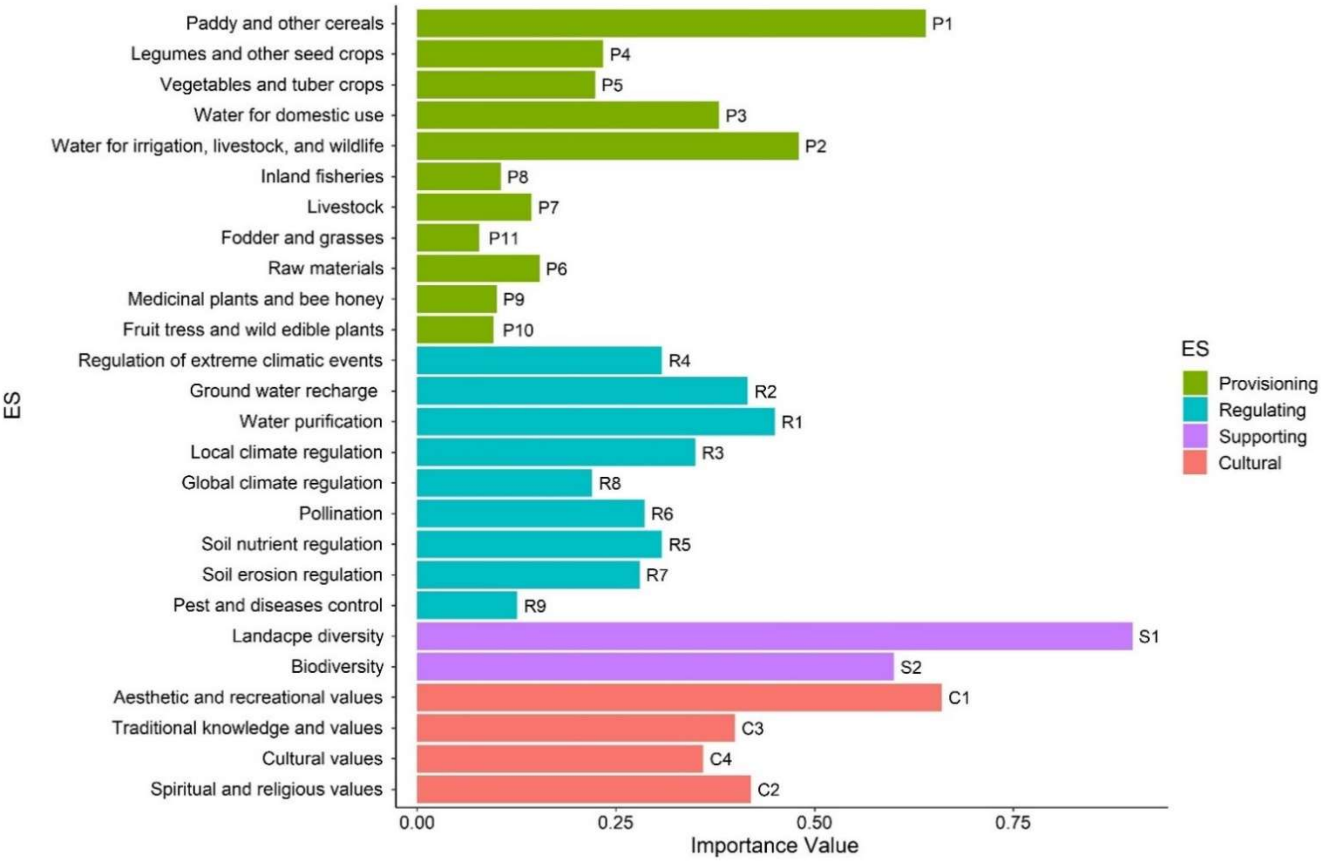


**Figure 5.** Community-perceived ranking of ecosystem services in MVTCS. ES = Ecosystem service; Importance value = Community perceived score; P = Provisioning ES; R = Regulating ES; C = Cultural ES; S = Supporting ES; Number (P1) = Rank within the ES category.

It was observed that the majority of food provisioning and regulating ESs identified are associated with direct species-based ESs providers (Table 2). Thus, further analysis of the biodiversity baseline survey data revealed that 276 plant species belonging to shrubs, small plants and trees, and 191 faunal species belonging to mammals, reptiles, birds, amphibians, land snails, butterflies and dragonflies, are found in various LUSs of the MVTCS. Many species are found to be common in several LUSs, while some species are multifunctional and multipurpose. Home garden LUSs record the highest number of plant species, while natural forest and downstream reservation areas accommodate many ecologically sensitive plant species important for providing regulating and supporting ESs. The baseline survey data also revealed that MVTCS is rich in agrobiodiversity, including 150 actively managed crop plant species bearing edible components of fruits, seeds, leaf, yam and bark. Most of these species are grown in home gardens and shifting cultivation (Chena) LUSs. Much of the diversity of crop species consists of crop landraces (110 landraces) maintained by the community. The distribution of plants, animals and crop species among different LUTs in MVTCS is visualised in Figure 6.

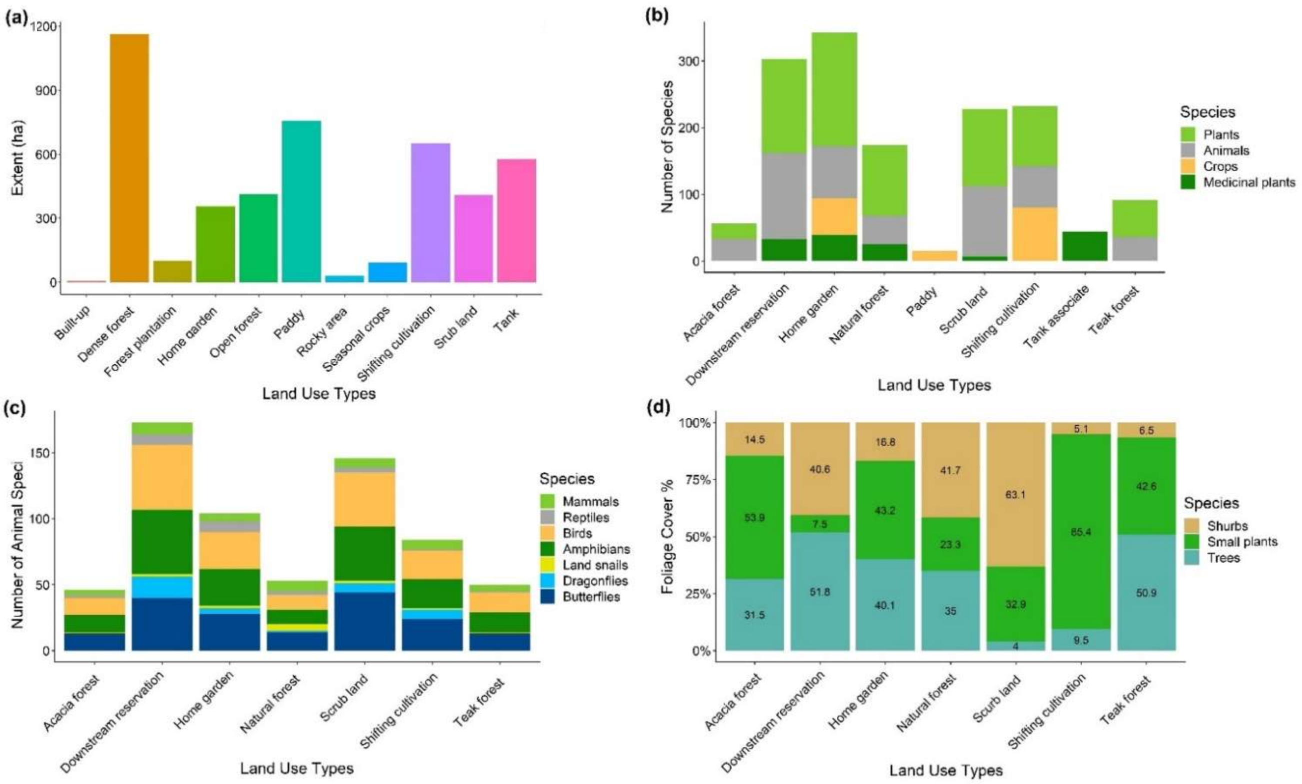


**Figure 6.** Land use types and species associations in the MVTCS: (**a**) land use types, (**b**) species occurrence (cumulative) in different habitats, (**c**) number of animal species and (**d**) foliage cover percentage of species.

### *3.3. Ecosystem Services' Supply and Demand*

The current capacity to supply provisioning ESs ranges from zero to four. Home gardens, paddy fields and tanks are prominent in providing provisioning ESs. As far as the tanks are concerned, they still have some capacity to supply water for agriculture. The supply of ESs by shifting cultivation lands recorded low values. During on-site field verification, it was noticed that farmers practised agro-wells-assisted irrigation for their shifting cultivation for commercial purposes. To the extent that regulating ESs are valued, upstream tree belt (UTB), upstream soil ridge (USR), tanks and catchment forests were identified as ecologically important LUTs. The ESS matrix showed that most of the LUTs in the MVTCS have at least some capacity to maintain supporting ES functions. The tanks, paddy fields and home gardens are reported as the LUTs with the highest capacity to supply cultural ESs (Figure 7a). Demand for provisioning ESs ranged from zero to four. ESD matrix values indicated high demand for irrigation water from tanks to paddy fields. Compared to the demand for provisioning ESs, a fairly high demand for regulating ESs from all LUTs was recorded. There is a high demand from upstream soil ridge (USR) for regulating ESs. It was observed that the fairly high ESD values for regulating ESs were associated with food production LUTs. There were high ESD values that were observed to maintain biodiversity in the LUSs. Out of the four cultural ESs assessed, the most valued cultural ESs were the aesthetic and recreational services arising from particular LUTs (Figure 7b).

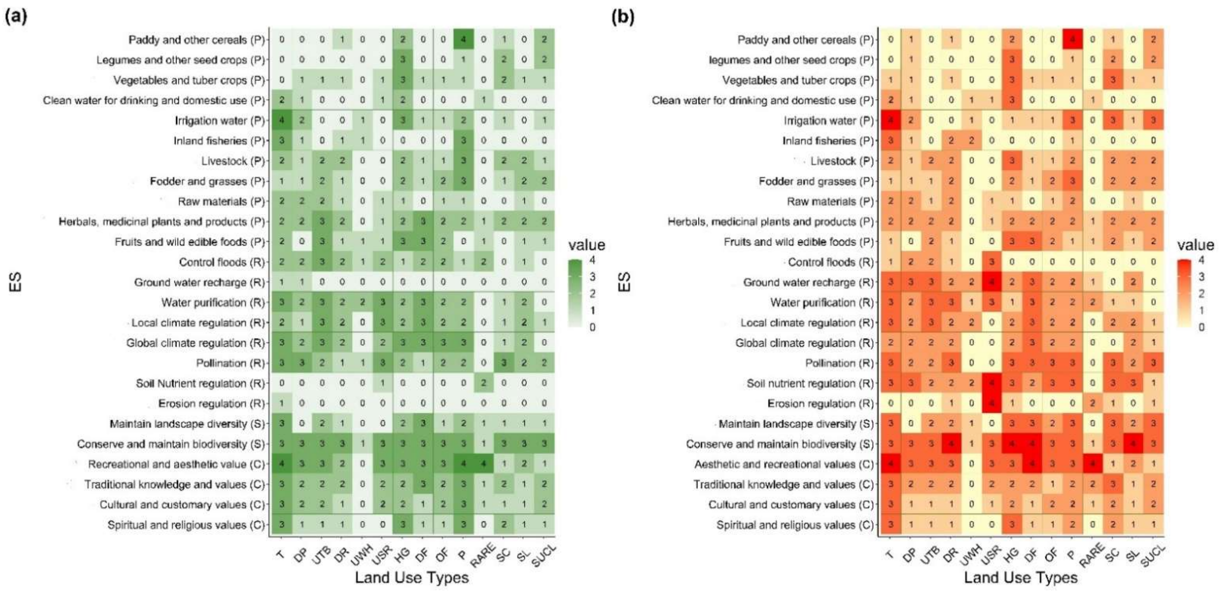


**Figure 7.** Ecosystem service supply (ESS) capacity evaluation matrix (**a**) and ecosystem service demand (ESD) evaluation matrix (**b**) based on different land use types in the MVTCS. T = Tank; DP = Deep-phase (Diyagilma); UTB = Upstream tree belt (Gasgommana); DR = Downstream reservation (Kattakaduwa); UWH = Upstream water hole (Godawala); USR = Upstream soil ridge (Iswetiya); HG = Home gardens; DF = Dense forests; OF = Open forests; P = Paddy; RARE = Area with exposed rocks; SC = Seasonal crop farming lands; SL = Scrublands; SUCL = Sparsely used crop lands (Chena); ES = Ecosystem service; P = Provisioning ES; R = Regulating ES; C = Cultural ES; S = Supporting ES.

The analysis of ESS and ESD trade-offs showed that the ESs' demand exceeds the supply capacity of the majority of the LUTs in the MVTCS (Figure 8). Negative values indicate occasions where demand exceeds supply (undersupply) and positive values indicate situations where supply exceeds demand (oversupply) (Figures 8c and 9a). Provisioning of all regulating ESs across all LUTs was recorded as undersupply (Figure 8c). There was a comparatively high undersupply of groundwater recharge and soil nutrient regulation ESs in the LUTs recorded (Figure 9b). In addition, the matrix analysis showed a decrease in pollinator services across most of the LUTs (Figure 9a). More importantly, LUTs that are central for generating supporting ES functions in the MVTCS recorded negative trade-off values (Figure 8c). It was observed that the natural forest LUS of the MVTCS has some supply capacity to provide all four ESs categories (Figure 8a). Further, ESD analysis revealed that the demand for tank-associated micro-land uses of upstream water holes (UWH), upstream soil ridges (USR) and downstream reservations (DR) was very high (Figure 8b). The field investigation revealed that the majority of micro-land uses were degraded.

### 3.4. Spatial Variation in ESS

This study produced ESS capacity maps in different LUTs in MVTCS to understand the spatial variation in current ESS capacities (Figure 10). The spatial pattern in ESS capacities across the MVTCS meso-catchment showed degradation of regulating and supporting ESs towards the downstream and valley bottom areas (Figure 10b,c). Overall, it emerged that the downstream and valley bottom LUSs of the meso-catchment have more capacity to provide provisioning ESs (Figure 10a), while midstream LUSs are important for providing cultural ESs linked with the rich biodiversity of these areas (Figure 10d). Based on the estimation of BVI and LDIS values, the study developed hotspot and bright spot maps of the spatial distribution of BVI and LDIS to understand the impact of biodiversity and land degradation on the ESS capacity of the MVTCS landscape (Figure 11). More hotspot areas impacted by land degradation on ESs were found in downstream and valley bottom areas of the meso-catchment (Figure 11b) and high-value biodiversity areas—bright spots were concentrated in the midstream areas (Figure 11a). Generally, ESS-rich, bright spot areas were found in the midstream areas, while more vulnerable areas of ESs degradation, hotspots, were found towards the downstream areas of the meso-catchment (Figure 11c).

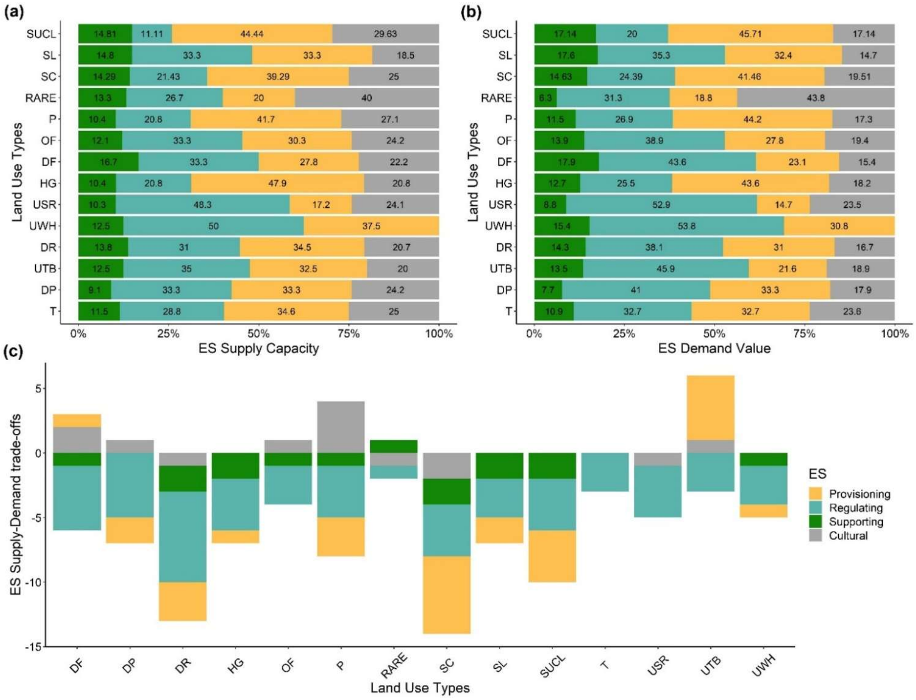


**Figure 8.** Percentage contributions of current supply (**a**), demand (**b**) and trade-offs (**c**) in four ecosystem service categories of different LUTs in the MVTCS based on community-perceived values. T = Tank; DP = Deep-phase (Diyagilma); UTB = Upstream tree belt (Gasgommana); DR = Downstream reservation (Kattakaduwa); UWH = Upstream water hole (Godawala); USR = Upstream soil ridge (Iswetiya); HG = Home gardens; DF = Dense forests; OF = Open forests; P = Paddy; RARE = Area with exposed rocks; SC = Seasonal crop farming lands; SL = Scrublands; SUCL = Sparsely used crop lands (Chena); ES = Ecosystem service.

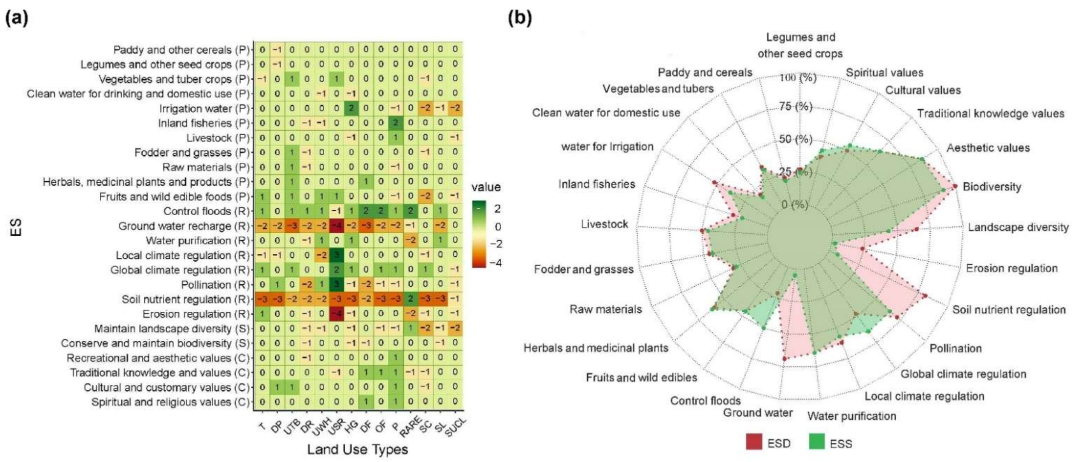


**Figure 9.** Ecosystem service supply (ESS) and ecosystem service demand (ESD) budget evaluation matrix (**a**); radar chart of ESS and ESD variations with different LUTs (**b**). T = Tank; DP = Deep-phase (Diyagilma); UTB = Upstream tree belt (Gasgommana); DR = Downstream reservation (Kattakaduwa); UWH = Upstream water hole (Godawala); USR = Upstream soil ridge (Iswetiya); HG = Home gardens; DF = Dense forests; OF = Open forests; P = Paddy; RARE = Area with exposed rocks; SC = Seasonal crop farming lands; SL = Scrublands; SUCL = Sparsely used crop lands (Chena); ES = Ecosystem service; P = Provisioning ES; R = Regulating ES; C = Cultural ES; S = Supporting ES.

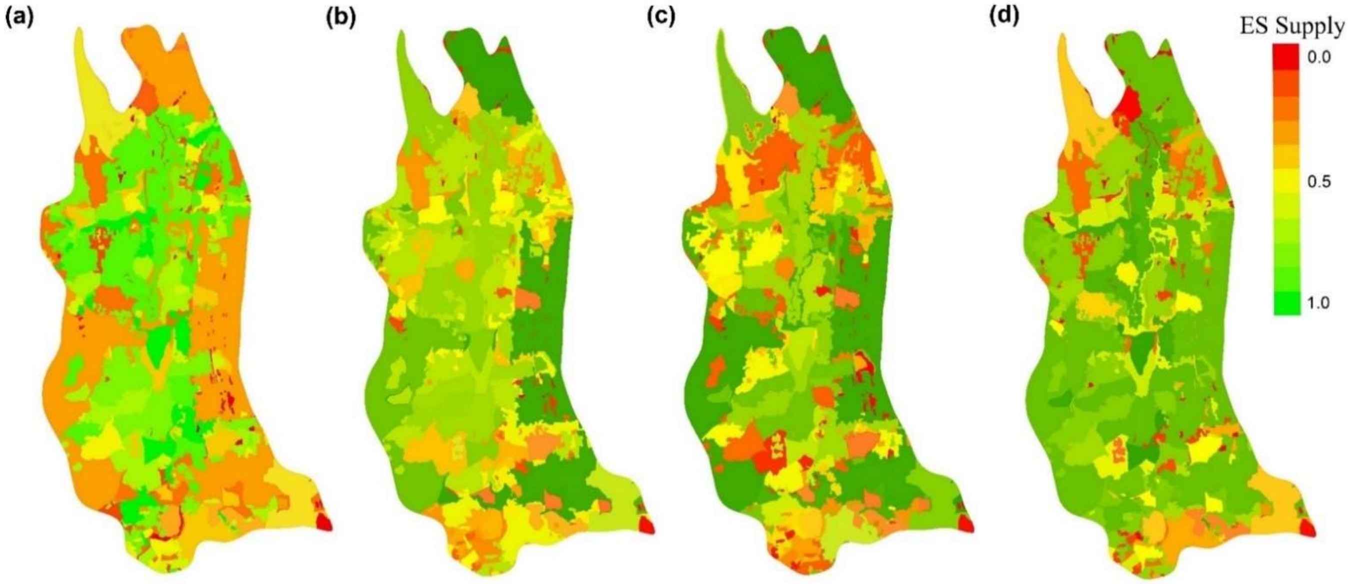


**Figure 10.** Ecosystem service supply capacities of different land use systems in the MVTCS: (**a**) provisioning, (**b**) regulating, (**c**) supporting and (**d**) cultural.

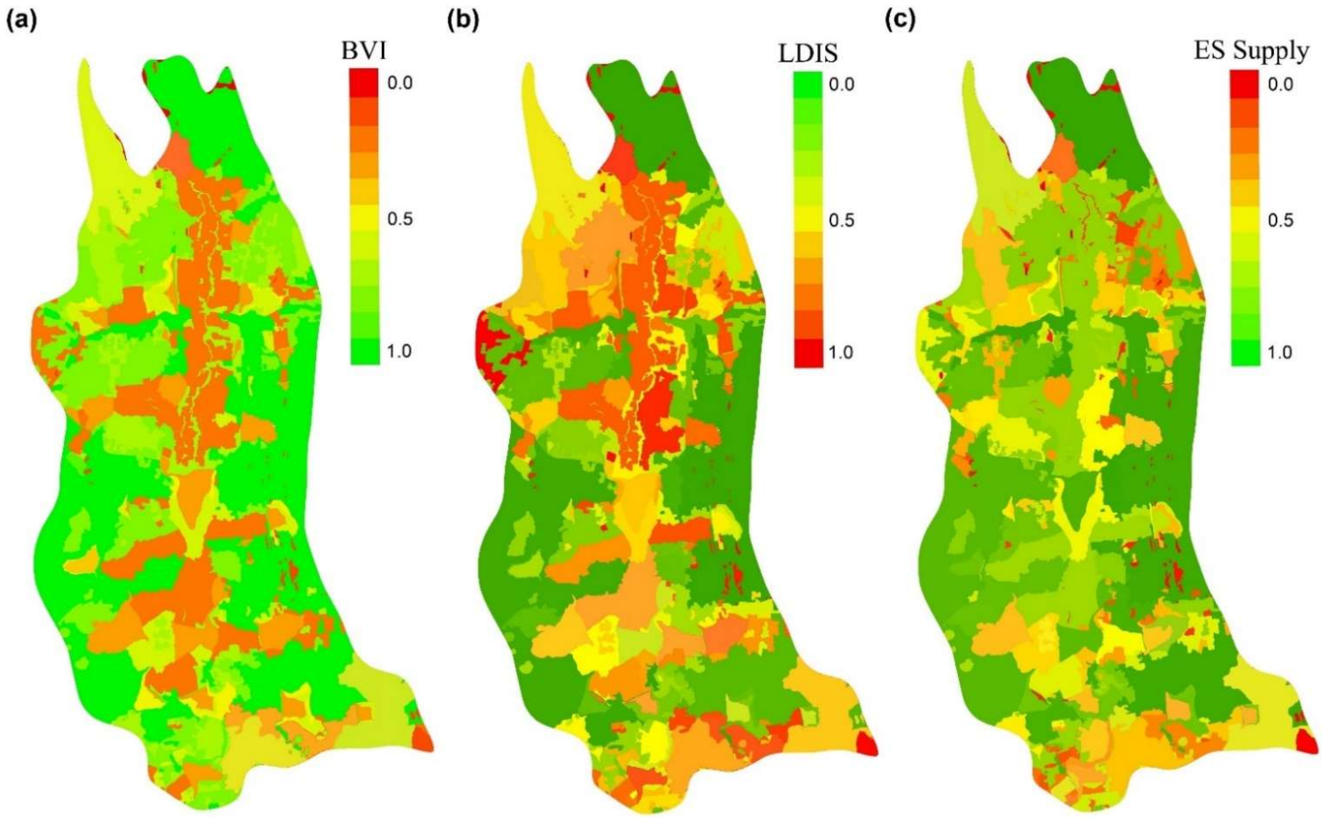


**Figure 11.** Ecosystem service supply hotspots and bright spots in the MVTCS: (**a**) biodiversity, (**b**) land degradation, and (**c**) overall ecosystem services supply. BVI = Biodiversity Value Index; LDIS = Land Degradation Impact Score.

## 4. Discussion

This study estimated the capacities of twenty-four ESs for the fourteen macro and micro-land use types identified in the MVTCS. The results show that the species-based ESs providers play an important role in generating ESs associated with biophysical elements of the land uses of the MVTCS. The majority of food provisioning ESs were established to be crop-based generated by interaction with biophysical elements of the LUSs in association with social engagements. The community prioritised food and water-related ESs as the straightforward ESS from the LUSs. Further, all regulating ESs identified had a substantial relationship with food and water provisioning in the MVTCS. This could be the reason the community placed considerable weight on most of the regulating services provided by the LUSs [13,68]. It indicated that the community perceptions appeared to favour their land use management practices and related ES benefits from the LUSs [31]. However, they ranked the role of ESs in pests and diseases control and global climate regulation at a lower level. This could be the reason the majority of community members failed to recognise the effectiveness of regulating ESs of the VTCS in terms of global climate change mitigation and biological control of pests and diseases.

Biodiversity and landscape diversity were identified as the key supporting ES functions from the MVTCS during the participatory listing. The study also found that all cultural ESs are generated as an integrated outcome of the biodiversity and social engagements of the VTCS. Further, it was observed that about 50% of the regulating ESs identified are associated with direct species-based ESs providers. This confirms the findings of [69–71] who established that, biodiversity and the species composition of LUSs is vital for maintaining the ecological balance of the VTCSs. Regaining the lost biodiversity in the VTCSs could be one of the most important steps in the ecological restoration of ESs that supports sustainable agricultural productivity. The significance of ESs restoration in global LUSs has been recognised by the United Nations (UN), declaring 2021–2030 as the Decade on Ecosystem Restoration [72,73]. Reassembling or re-creation of the original ecological components that once occupied VTCS–LUSs in the past is fundamental to ESs-based ecological restoration and management of VTCSs. This could involve assisting the recovery of degraded or fragmented ecological components of the VTCS land uses with a strong ecosystem structure to generate a variety of ecosystem functions and services [23,72,74–76]. However, it could be argued that the restoration of the ecological components/ESs to their past status is unattainable, given social-economic, political, institutional, technological and environmental changes in VTCSs, which in itself is a useful future research question.

Mapping of spatial variation of ESS across the MVTCS–LUSs showed a spatial distribution of areas of high ecological value and social-ecologically important land uses of the MVTCS, which is important in determining future land use and ESs trade-off decisions. Hotspot and bright spot maps of the study area demonstrate that overall ESs' generation capacity is influenced by biodiversity and the land degradation impacts of the land use. Further, it was observed that the degradation of ESs is high in the downstream and valley bottom areas of the meso-catchment. The high impact of land degradation and high social demand for provisioning ESs in the downstream LUSs could be one of the reasons affecting the downstream ESs. Impacts of land use change on biodiversity often lead to declines in ESs [77,78]. Thus, ESs supply-based land health indicators are important for the assessment of ESS capacity at the landscape level in the context of global change scenarios, such as climate, land use and socio-economic changes [79–83]. Therefore, this research provides an integrative, participatory bottom-up ESs assessment framework to apply in highly fragmented, diverse, small-scale SESs, based on their multifunctional LUSs. The resultant assessments can then inform future ecological restoration decision making and practices in the VTCSs. In contrast to conventional participatory ESs assessments, this study accounted for key ecological and land health indicators of the LUSs that directly link with the supply capacity of ESs.

Pre-testing of the participatory ESs screening questionnaire used in the study showed that prioritisation of ESs varied according to the community knowledge and the awareness of the ESs' use by the local communities. Participatory appraisal methods, although having both advantages and disadvantages, have been widely adopted in social-ecological research carried out in rural communities over the last two decades [84]. On the contrary, ESs demand–supply matrices have some limitations associated with the need for more quantitative methods to estimate perception scores [62,85]. In addition, although on-site field assessment of ESs is straightforward and maybe more accurate, it takes more resources and time [36]. Therefore, to minimise such biases, initial awareness workshops for informants were conducted and the perception scores cross-validated through on-site field verifications and expert consultations. The diversity, complexity and fragmented nature of the arrangements of MVTCS–LUSs could create challenges to the production of quantitative species-based ESs data in a systematic manner.

Process-based biophysical models and toolkits, such as InVest—Integrated Valuation of Ecosystem Services and Tradeoffs, ARIES—ARtificial Intelligence for Ecosystem Services, MIMES—Multi-scale Integrated Models of Ecosystem Services, SolVES—Social Values for Ecosystem Services and MESH—Mapping Ecosystem Services to Human Well-Being, are popular for systematic modelling of ESs in data-rich, large-scale landscapes [53,78,86–90]. However, limitations were found in using such models for the assessment of ESs in small-scale SESs, such as VTCSs, due to the lack of baseline spatial data on biodiversity and land use systems. Thus, a complete survey of biodiversity associated with all LUSs, especially micro-land uses and aquatic environs, is required for a complete understanding of the vital relationships between land use and species interactions.

## 5. Conclusions

Ecosystem services are central to the existence and optimal multi-functioning of the LUSs of VTCSs. Thus, a comprehensive understanding of ESs is required to achieve optimum productivity of the VTCSs. This study demonstrated the use of the mixed-methods approach to assess, model and map ESs by integrating local knowledge and scientific estimations of land degradation and biodiversity indicators of LUSs of the VTCSs. The study introduced the process of combining biophysical data (biodiversity and land degradation) with social perception data into the ESs mapping process. Although the ESs mapping exercise is challenging due to some limitations, the study managed to map the spatial variation of ESs in the MVTCS using a bottom-up participatory data collection approach. Spatial variation of ESs' supply across LUSs revealed that the demand for all ESs was higher than the ESs' supply capacity of the MVTCS landscape. There was a fairly high demand for regulating and supporting ESs from all LUSs of the MVTCS. The study found that biodiversity plays an important role in generating ESs associated with LUSs. ESs maps revealed that loss of biodiversity and land degradation in the LUSs was directly linked to the overall ESS capacity. The success of the ecological restoration of VTCSs depends on the extent to which strategies address the diverse levels of cascade ecological complexity, as well as the social engagement of local communities. The study approach could be improved by integrating more biophysical and socio-economic data of the VTCSs that provide support to the successful ESs-based ecological restoration and management. Future research should focus not only on ESs assessments, but also consider their applicability to integrate potential ES indicators into ongoing ecological restoration planning processes in the VTCSs in Sri Lanka.

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