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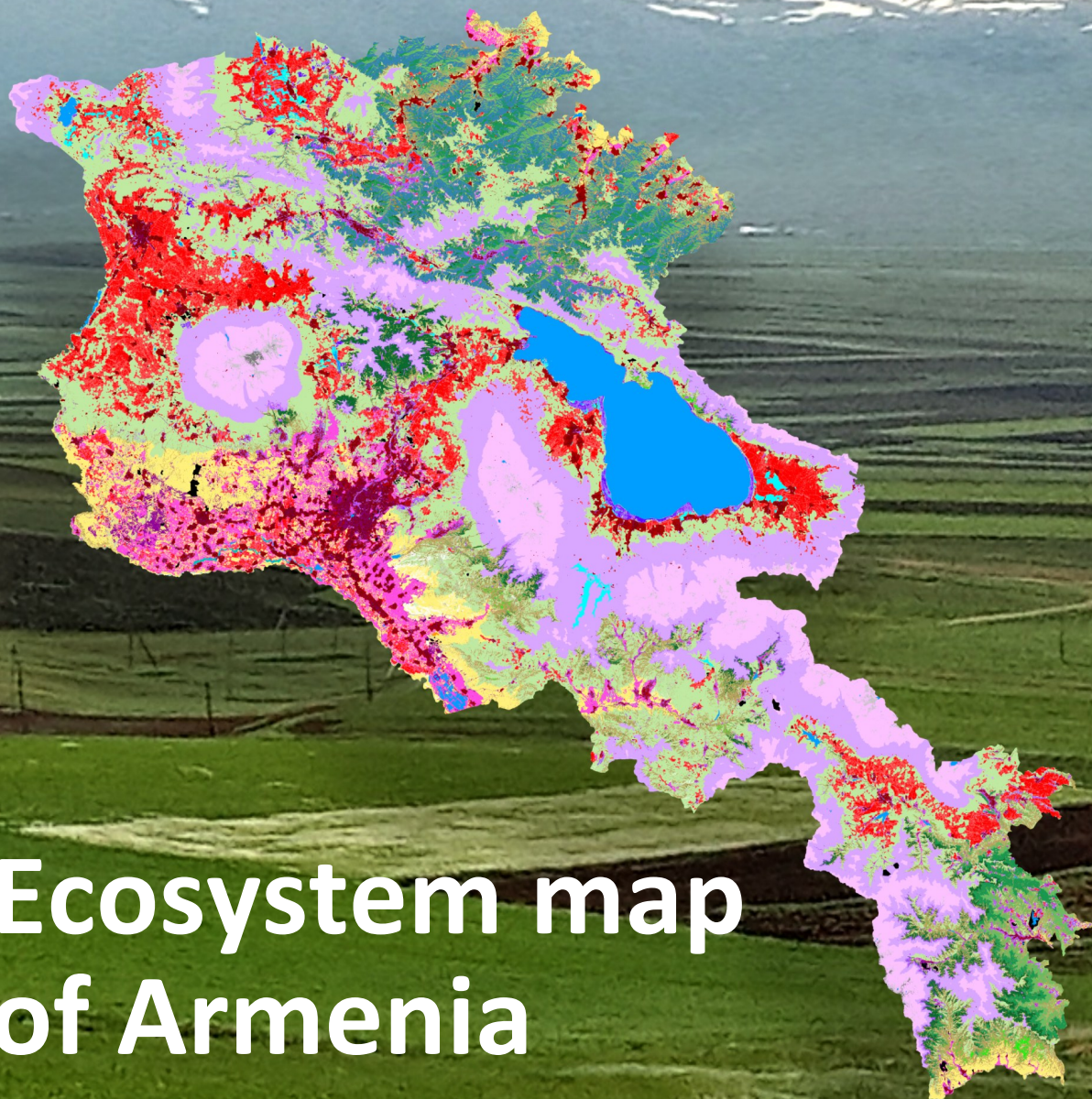
**TAKING ACTION
FOR NATURE**



Leibniz Institute of
Ecological Urban and
Regional Development



Institute
of Botany
NAS RA



Ecosystem map of Armenia

Terrestrial ecosystems

Methodology and results

Yerevan 2026

Ecosystem accounting in Armenia: Setting the scene

Part 2 – Ecosystem map of Armenia



Leibniz Institute of
Ecological Urban and
Regional Development



Institute
of Botany
NAS RA

The project is being implemented by the Biodiversity Conservation Center (BCC Armenia), in collaboration with the Leibniz Institute of Ecological Urban and Regional Development (IOER, Germany), with the participation of experts from leading scientific organizations in Armenia.



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Summary

This publication accompanies the **interactive Ecosystem map of Armenia**, available at <https://armenia-woodlands.projects.earthengine.app/view/ecosystem-map-of-armenia>.

Two versions of the map are freely available (licence: CC BY 4.0) for download:

(1) the map using the **detailed ecosystem classification** developed specifically for this map http://biodiversity-armenia.am/wp-content/uploads/2026/09/Ecosystem_Map_of_Armenia.zip;

(2) the map crosswalked to the **IUCN Global Ecosystem Typology (IUCN GET)** http://biodiversity-armenia.am/wp-content/uploads/2026/09/IUCN_GET_Map_of_Armenia.zip.

The Ecosystem Map of Armenia – Terrestrial Ecosystems was developed by experts from **BCC Armenia** and the **Institute of Botany** of the National Academy of Sciences of the Republic of Armenia within the framework of the **Armenian-German project “Ecosystem Accounting in Armenia: Setting the Scene”**. The map addresses a major data gap: the absence of an up-to-date, national-scale digital ecosystem map needed to support ecosystem accounting and international biodiversity reporting.

The Ecosystem map of Armenia comprises an **interactive online map and two downloadable layers** — one based on the ecosystem classification developed specifically for this map and one crosswalked to the IUCN Global Ecosystem Typology (IUCN GET). Both layers can be freely downloaded under the CC BY 4.0 licence (link above). The interactive map (link above) allows users to explore thematic layers, switching individual layers on and off.

The map provides a spatially explicit representation of natural and anthropogenic terrestrial ecosystems across Armenia. It includes **19 classes of natural ecosystems**: 6 forest, 3 woodland, 5 grassland, 2 wetland, and 3 sparsely vegetated ecosystem classes. It also includes **11 classes of anthropogenic ecosystems**: 5 classes of human-made woody vegetation, 1 cropland class, and 5 classes of built-up and technogenically disturbed areas. Water bodies are mapped as a separate class, but the ecosystem classification itself covers terrestrial ecosystems only. Reclassification according to the IUCN Global Ecosystem Typology resulted in **12 Ecosystem Functional Groups**.

Supplementary informational layers were also developed to characterize broader human influence, including human-modified landscapes and potential grazing-pressure zones around livestock farmyards, as well as national protected areas, Ramsar sites, and Emerald Network sites.

The map was produced at **10 m spatial resolution** by integrating a **potential vegetation** framework with current **land-cover information derived primarily from satellite imagery**, machine-learning classification, open-access spatial datasets, and expert interpretation. The potential distribution of the main vegetation zones was defined using topographic and geological parameters. The current distribution of woody vegetation and croplands was mapped using Random Forest probability models. Wetlands, sparsely vegetated ecosystems, anthropogenic woody vegetation, built-up and technogenically disturbed areas, and other ecosystem classes were delineated using combinations of satellite-derived indicators, existing spatial datasets, and manual interpretation of high-resolution imagery.

The map provides estimates of **ecosystem extent** across Armenia. At the level of aggregated ecosystem categories, more than half of Armenia is covered by grasslands of different types, ranging from high-mountain grasslands to semi-deserts; forests and woodlands cover about 18 %, and water bodies 4.6 %. When the ecosystem map is crosswalked to the IUCN GET, temperate subhumid grasslands (T4.5) cover almost 40 % of Armenia, followed by deciduous temperate forests (T2.2), temperate alpine grasslands and shrublands (T6.4), temperate woodlands (T4.4), and semi-desert steppes (T5.1), each accounting for approximately 6–11 % of the country.

Of the 19 natural ecosystem types included in the map, 10 can be considered **rare ecosystems**, each occupying less than 1 % of Armenia. These include desert ecosystems, natural pine forests, both wetland types, all types of natural sparsely vegetated habitats, and pure *Quercus iberica* forests.

The map also allows **the degree of anthropogenic transformation** of Armenia’s territory to be assessed. Clearly identifiable human-made ecosystems mapped as distinct classes occupy about 23 % of Armenia. However, when broader areas of human influence are considered—including landscapes where irregularly used croplands and hay-fields occur as scattered patches interspersed with natural ecosystems, as well as potential grazing-pressure zones—anthropogenic influence extends across approximately 68 % of the country.

Comparison with government-reported land-cover statistics showed substantial differences for some individual classes, reflecting differences in classification objectives, definitions, and mapping approaches. However, when ecosystem and land-cover classes were aggregated into four broad categories—Non-woody areas, Trees, Crops, and Built—the differences between the Ecosystem Map and government statistics were considerably smaller, ranging from 1.5 % to 10 % for terrestrial classes. This level of agreement supports the reliability of the map at a generalized level, while further harmonization will require a more detailed crosswalk between ecosystem and national land-cover and cadastral categories and access to spatial datasets used by forestry and agricultural authorities.

1 Introduction

This publication accompanies the Ecosystem map of Armenia, which includes two versions — the detailed ecosystem classification version and the IUCN GET version — as well as the interactive map, which allows users to explore thematic layers by switching individual layers on and off (links above). The publication is intended for researchers, environmental practitioners, public authorities, and other users interested in Armenia's ecosystems and their spatial distribution. It explains the methodology and data sources used to develop the map, describes its ecosystem classification, and presents the main results on ecosystem extent and the comparison of map-derived land-cover areas with Armenia's official land-cover statistics.

An up-to-date ecosystem map is essential for informed spatial environmental decision-making and provides the fundamental basis for ecosystem accounting. Armenia is taking first steps towards implementing the System of Environmental-Economic Accounting (SEEA), including the compilation of water accounts (United Nations..., 2024). However, ecosystem accounts have not yet been developed. An important step has already been taken with the Decision of the Government of the Republic of Armenia (2019)¹, which established a framework for the statistical accounting of the main land-cover classes: cultivated lands, grasslands, tree-covered areas, shrub-covered areas, water-covered areas, and vegetation-free areas. However, modern ecosystem accounting requires more than statistical data on the area of broad land-cover classes. Ecosystems need to be spatially delineated in digital form so that their extent, distribution, and changes can be quantified and linked to biodiversity, ecosystem condition, and ecosystem services.

A major obstacle currently hindering the development of ecosystem accounts in Armenia is therefore the absence of a consistent, digital, and regularly updatable ecosystem map covering the entire country. This information gap also has direct implications for Armenia's international biodiversity reporting. In the Seventh National Report to the Convention on Biological Diversity (2026)², Armenia reported that no data were available for headline indicator A.2, "Extent of natural ecosystems", attributing this to "the absence of a nationally agreed ecosystem classification and comprehensive, spatially harmonized ecosystem mapping at the national scale". Headline indicator A.1, "Red List of Ecosystems", which requires spatially explicit ecosystem mapping, is not reported in the report. No data were reported either for headline indicator B.1, "Services provided by ecosystems", as their comprehensive assessment requires spatial mapping and quantification based on a spatially explicit ecosystem map.

The Ecosystem map of Armenia was developed as a first step towards filling this gap. It brings together existing national knowledge on Armenia's terrestrial ecosystems with available spatial datasets and Earth observation data to produce a consistent national-scale representation of terrestrial ecosystems.

The ecosystem classification largely builds on approaches previously adopted in the National Atlas of Armenia (2007) and in the Fifth national report of the Republic of Armenia to the Convention on Biological Diversity (2014). Rather than digitizing any existing paper-based academic map of potential vegetation, we developed a new digital potential vegetation layer based on academic knowledge of the relationships between vegetation and environmental parameters, primarily topography. This approach is consistent with modern digital mapping technologies, provides a reproducible spatial framework, and allows the layer to be readily refined in the future by incorporating additional environmental parameters, including climatic variables, and improved spatial data as they become available.

The potential vegetation layer was combined with layers derived from Earth observation and other geospatial datasets to represent the current spatial distribution of ecosystems. The use of digital and regularly updated data sources provides a basis for rapid and systematic updating of the ecosystem map as new data become available.

To link national information with global biodiversity monitoring and reporting initiatives, the Ecosystem map of Armenia can be crosswalked to international ecosystem classifications. In particular, we developed a layer corresponding to the IUCN Global Ecosystem Typology (IUCN GET) to facilitate the integration of Armenia's ecosystem data into the Global Ecosystems Atlas³ and its use for SEEA Ecosystem Accounting (SEEA EA) reporting.

Interactive Ecosystem map of Armenia, available at <https://armenia-woodlands.projects.earth-engine.app/view/ecosystem-map-of-armenia>. The maps illustrating individual spatial layers in this booklet reproduce the layers that can be viewed separately in the interactive map which allows users to view individual map layers and compare them with two versions of the Ecosystem Map: one based on the detailed nationally adapted ecosystem classification and the other corresponding to the IUCN Global Ecosystem Typology (IUCN GET). Both versions of the map are freely available for download under the CC BY 4.0 licence:

http://biodiversity-armenia.am/wp-content/uploads/2026/09/Ecosystem_Map_of_Armenia.zip;

http://biodiversity-armenia.am/wp-content/uploads/2026/09/IUCN_GET_Map_of_Armenia.zip.

The ecosystem map is intended for a broad range of users, including public authorities, environmental and spatial-planning institutions, researchers, practitioners involved in biodiversity monitoring and ecosystem accounting. It

¹ <https://www.arlis.am/hy/acts/135631>

² <https://ort.cbd.int/national-reports/nr7/E2E02104-BB22-9C03-73B7-C1834A695F67#section4>

³ <https://www.globalecosystemsatlas.org/>

provides a spatial basis for assessing the distribution and extent of ecosystems, supporting biodiversity conservation and protected-area planning, identifying areas of natural and human-modified ecosystems, and developing ecosystem accounts. The map can also support international biodiversity reporting. The map is intended not as a static final product, but as a framework that can be regularly refined and updated.

The map was created by the Biodiversity Conservation Center (BCC Armenia), jointly with the Institute of Botany after A. Takhtajyan of the National Academy of Sciences of the Republic of Armenia and the Leibniz Institute of Ecological Urban and Regional Development (IOER). The project is funded by the German Federal Environment Ministry's Advisory Assistance Program (AAP) for environmental protection in the countries of Central and Eastern Europe, the Caucasus and Central Asia and other countries neighboring the European Union. It is supervised by the Federal Agency for Nature Conservation (BfN) and the German Environment Agency (UBA).

2 Methodology

The overall workflow integrates two main types of spatial information (Fig. 1): 1) a potential vegetation map developed from academic knowledge of vegetation types and their relationships with topographic and geological parameters; 2) layers reflecting the current state of land cover, derived from satellite imagery and open-access datasets. The ecosystem types represented on the map and the main approaches used for their spatial delineation are presented in Table 1. The national boundary of Armenia and the administrative boundaries of the marzes were obtained from the Forest Atlas of Armenia⁴.

Table 1. Ecosystem types, data sources and criteria used for their spatial delineation in the ecosystem map

Map layers		Altitude				Exposure	
		North- ern zone	Central zone	Southeast- ern zone	Southern zone	North- ern zone	All other zones
Grasslands	Semi-desert	<700	<1300	<800	<1300		
	Steppe	1300-2200					
	Subalpine	2200-2700					
	Alpine	2700-3500					
	High mountain	>3500					
Wetlands	Fens and wet meadows	Satellite-derived					
	Wetland waterbodies in the Ararat Valley	Manually delineated from high-resolution imagery					
Natural forests	<i>Fagus orientalis</i> + <i>Carpinus</i> , <i>Tilia</i> , etc.	Satellite-derived forest, <1800				N	-
	<i>Quercus macranthera</i> + <i>Carpinus</i> , <i>Tilia</i> , etc.	Satellite-derived forest, 1400-1800				S	N,S
	<i>Quercus macranthera</i>	Satellite-derived forest, >1800				S	N,S
	<i>Quercus iberica</i> + <i>Carpinus</i> , <i>Tilia</i> , etc.	Satellite-derived forest, 1000-1400				S	N,S
	<i>Quercus iberica</i>	Satellite-derived forest, <1000				S	N,S
	<i>Pinus kochiana</i> (natural stands)	Ranges based on Institute of Botany data					
	Coniferous natural and planted stands	Satellite-derived					
Natural open woodlands	Subalpine woodlands	Satellite-derived woodlands, >2200					
	Deciduous and mixed woodlands	Other satellite-derived woodlands, <2200					
	Juniper woodlands	Satellite-derived					
Anthropogenic woody vegetation	Closed-canopy forest plantations	Satellite-derived forest and woodland within boundaries manually delineated from high-resolution imagery					
	Open-canopy forest plantations						
	Forest-like veg. in human-modified landscapes						
	Open woodland-like veg. in human-modified lands.						
	Tree, vine and shrub crops						
Sparse vegetation	High-mountain	Satellite-derived near-zero NDVI, >3500					
	Rocky habitats	Satellite-derived near-zero NDVI, rocky geological substrate					
	Sandy and clay habitats	Satellite-derived near-zero NDVI, sand and clay substrate					
Agricultural areas	Actively used croplands	Satellite-derived					
	Actively cultivated landscapes	Morphological closing of active croplands					
Built-up and technogenically disturbed areas	Buildings	ESA 2021 land cover data and OpenStreetMap (OSM) data					
	Settlements	Morphological closing of buildings					
	Quarries	OpenStreetMap (OSM) data					
	Landfills	OpenStreetMap (OSM) data					
	Sparse vegetation in human-modified landscapes	Satellite-derived near-zero NDVI within boundaries manually delineated from high-resolution imagery					
Supplementary information layers	Human-modified landscapes	Satellite-derived areas, manually refined using high-resolution imagery					
	Livestock camps and grazing zones	OpenStreetMap (OSM) data; 3 km buffers around livestock camps					
	Settlement names	OpenStreetMap (OSM) data					
	National protected areas, Emerald Network Sites, Ramsar Sites	UNEP-WCMC and IUCN (2026). Protected Planet: WDPA and WD-OECM. Available at: protectedplanet.net.					

⁴ <https://forestatlas.am/>

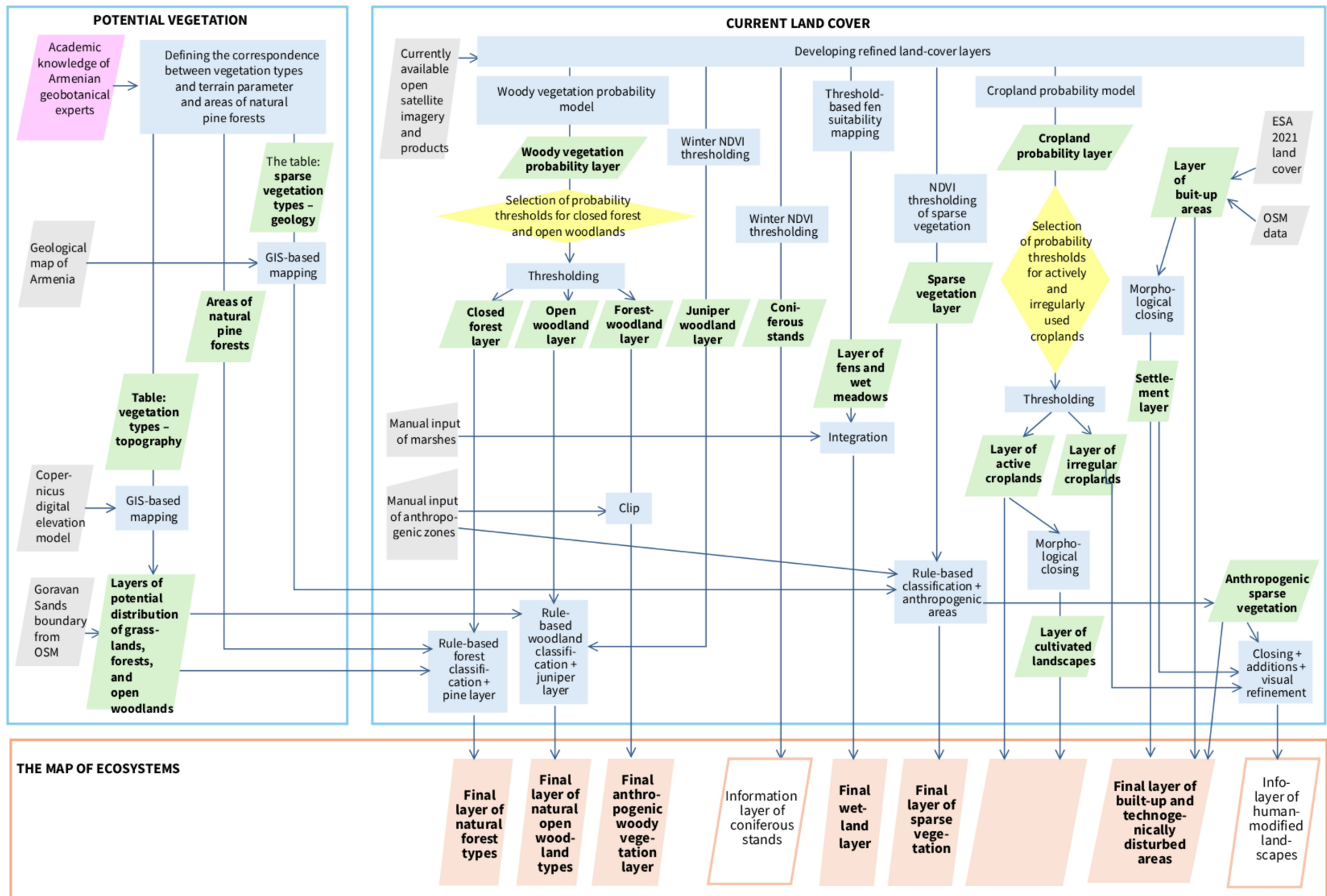


Figure 1. Flowchart of the ecosystem map development

2.1 Potential distribution of natural ecosystems

The potential vegetation map was developed based on the academic expertise of George Fayvush and Alla Aleksanyan, specialists from the Takhtajyan Institute of Botany of the National Academy of Sciences of Armenia. Climatic conditions, and consequently vegetation patterns in Armenia, are determined primarily by topography. Therefore, topography was used as the principal basis for developing the potential vegetation map. Potential distribution of grasslands and forests were defined according to altitudinal belts and aspect (Table 1). Topographic parameters were derived from the 30 m Copernicus Global Digital Elevation Model (COPERNICUS DEM GLO-30).

Because climatic conditions differ among macro-slopes of major mountain systems with different orientations, resulting in regional differences in the altitudinal distribution of vegetation, four zones were distinguished for ecosystem mapping in Armenia: the northern macroslope of the Lesser Caucasus (Northern Zone), the eastern macroslope of the Zangezur Range (Southeastern Zone), the slopes surrounding the Ararat Valley (Central Zone) and the southern macroslope of the Zangezur Range (Southern Zone) (Fig. 2).

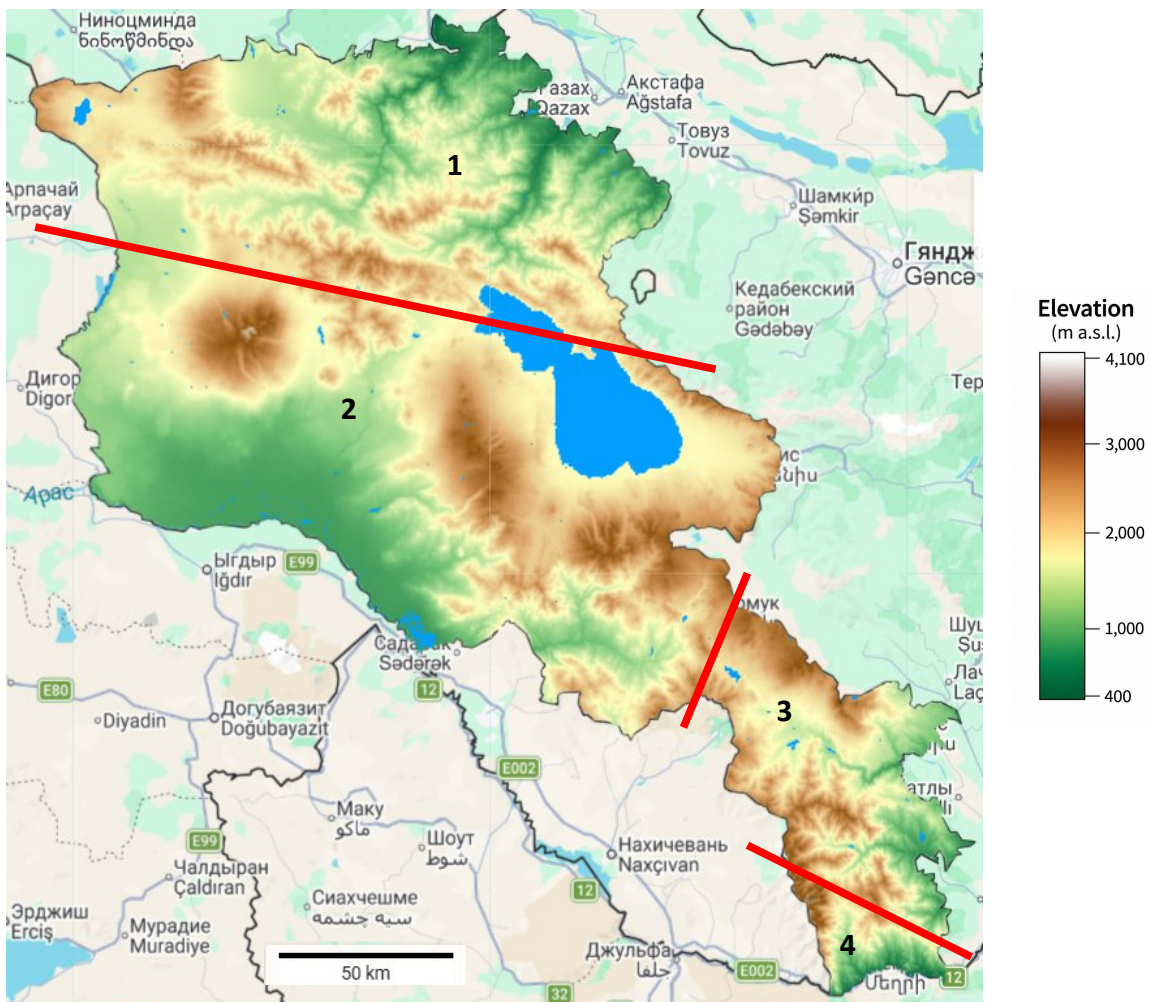


Figure 2. Ecological zones used for potential vegetation mapping in Armenia: 1) Northern; 2) Central; 3) Southeastern; 4) Southern.

The potential distribution of grasslands was determined based on altitudinal belts, with regionalization applied to the upper elevational boundary of semi-deserts. The upper boundary of the semi-desert belt was set at 700 m in the Northern Zone, 800 m in the Southeastern Zone, and 1,300 m in the Central and Southern Zones, based on the observed regional distribution of semi-desert vegetation (Table 1). Areas between these regional thresholds and 2,200 m were classified as steppe ecosystems. Vegetation occurring between 2,200 and 2,700 m was classified as subalpine, and vegetation above

2,700 m as alpine (Fig. 3a). The resulting raster represented the initial spatial framework for all open terrestrial ecosystems and was subsequently refined by overlaying sparse vegetation, woodland, forest, anthropogenic woody vegetation, cropland, settlement, and water layers.

The potential distribution of different forest types was determined based on altitudinal zonation and slope aspect, with the relationship between deciduous forest types and slope exposure differing between the Northern zone and all other zones. Beech forests were considered to occur only in the Northern zone (Table 1, Fig. 3b).

The potential distribution of open woodlands was defined as follows:

- Subalpine woodlands — within the subalpine zone, i.e., above 2,200 m;
- Deciduous, juniper, and mixed woodlands — throughout the remaining territory.

The current distribution of forests and woodlands was then determined by intersecting the satellite-derived forest and woodland masks (Section 2.2.3) with the potential distribution areas described above.

Although Armenian official statistics on land-cover class areas include a shrubland class, at this stage we did not attempt to distinguish shrub vegetation using satellite imagery because of the substantial methodological challenges involved (see Section 4 below).

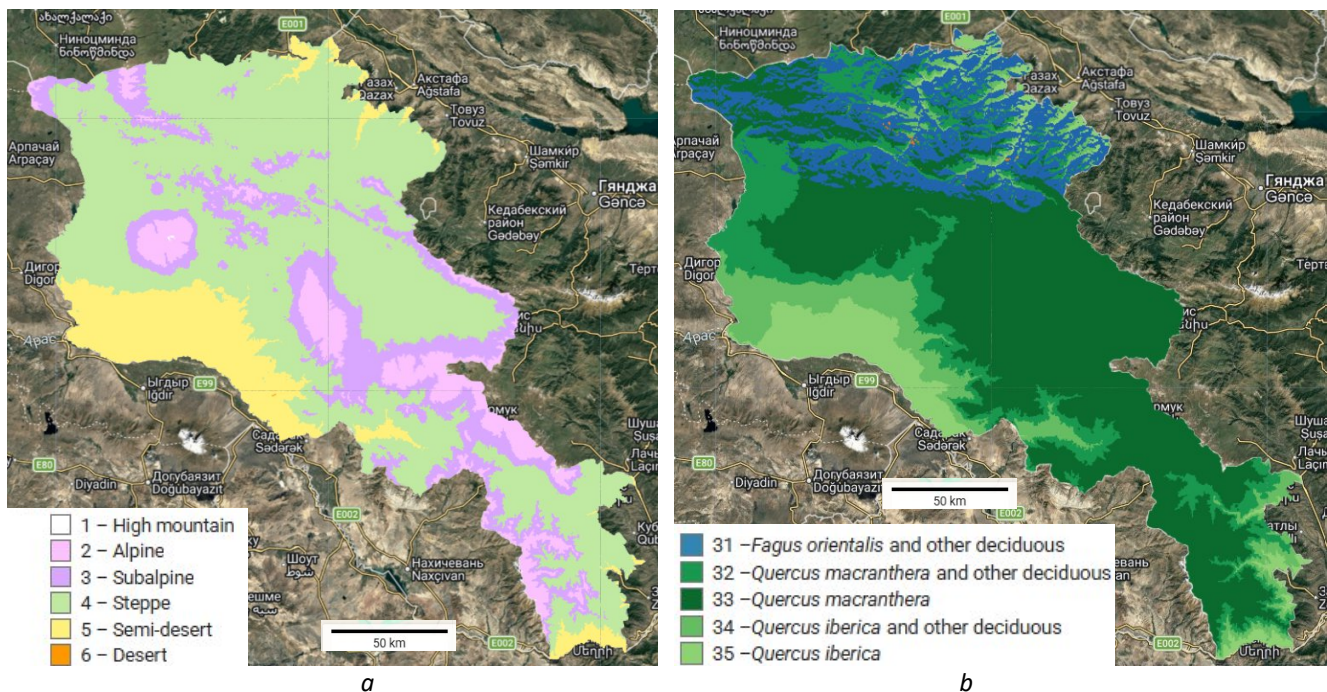


Figure 3. Layers of potential vegetation: a) grasslands; b) forests

2.2 Mapping current ecosystem distribution

To reflect the current distribution of ecosystems, a set of land-cover layers was developed in Google Earth Engine using AI-assisted script development, machine-learning classification, and rule-based geospatial analysis. Dedicated training datasets and sets of predictor variables were prepared separately for the respective machine-learning models.

Two principal probability layers—forest and woodland probability and cropland probability—were developed using Random Forest classification. A separate built-up layer was derived from satellite and OpenStreetMap (OSM) data and further processed using morphological operations to consolidate built-up areas and fill small gaps between individual built-up pixels.

In addition to the main grassland, forest, and woodland types, whose potential distribution was defined based on topographic parameters (Section 2.1), the map included a number of ecosystem types delineated using specific satellite-derived features or mapped manually:

- a small unique patch of natural sandy desert delineated within the Goravan Sands Sanctuary, whose boundary was obtained from OSM;
- natural pine forests (*Pinus kochiana*) based on data provided by experts from the Takhtajyan Institute of Botany;

- inferred distribution of juniper woodlands identified using satellite imagery (Section 2.2.3);
- inferred distribution of natural and planted coniferous stands identified using satellite imagery (Section 2.2.3);
- two wetland types identified using satellite data and manually digitized from high-resolution imagery (Section 2.2.4);
- three types of natural sparsely vegetated ecosystems identified using satellite data, elevation, and the geological map of Armenia (Section 2.2.5).

2.2.1 Training dataset

For machine-learning classification, a training dataset was created using a regular grid of 60×60 m cells distributed across Armenia. Each cell was visually interpreted based on high-resolution imagery and manually assigned to the appropriate land-cover class. Training cells were classified into the following land-cover classes:

- non-forest (including all non-forested areas without clear signs of human land use);
- cropland (cells showing visible characteristics of agricultural fields or hay meadows in high-resolution imagery, including both actively used and potentially abandoned agricultural land);
- forest-woodland (including closed forest and open woodlands);
- orchards and vineyards.

Built-up and other technogenically disturbed areas were not assigned to any of the training classes, as these land-cover types were mapped separately using dedicated data sources and methods (see Section 2.2.6).

Grid cells rather than individual points were used as training units because one of the key objectives of the classification was to identify not only closed forests but also open woodlands. Woodland represents a spatial pattern of relatively sparse tree cover and therefore cannot be reliably characterized by a single point or pixel. A 60×60 m cell provided sufficient spatial context to visually assess the presence and density of woody vegetation while remaining small enough to limit the inclusion of heterogeneous land-cover types. This cell size also corresponded to a 2×2 block for predictor layers with a spatial resolution of 30 m. The 60 m cell size was used only for the preparation of the training dataset and did not determine the spatial resolution of the resulting probability maps, which were produced at a 10 m spatial resolution.

The complete reference dataset comprised 108,007 manually classified cells: 43,800 non-forest cells, 36,454 cropland cells, 24,383 forest cells, 752 orchard cells, and 2,618 vineyard cells (Fig. 4). Orchard and vineyard classes were retained in the reference dataset but were not used for training the forest and woodland or cropland classification models.

The same grid-based training dataset served as the reference dataset for both the forest–woodland and cropland classification models.

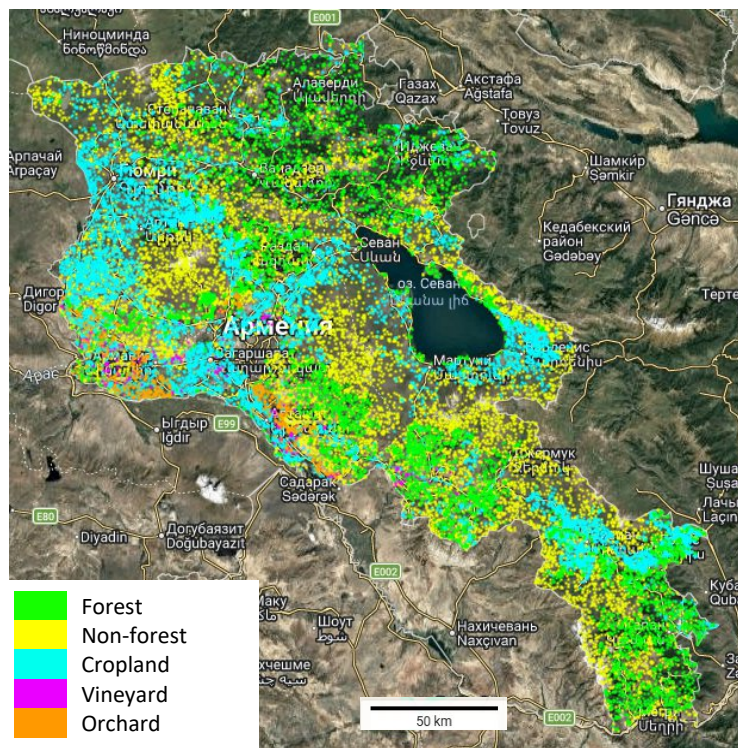


Figure 4. Spatial distribution of manually classified training cells across Armenia.

2.2.2 Predictor feature stacks for forest-woodland and cropland probability mapping

Initial feature stack

An initial feature stack was developed from multiple remote-sensing and topographic data sources. The predictor layers had different spatial resolutions, depending on the source data and the method used for their derivation. Spatial resolution therefore refers to the resolution of the predictor layer used in the feature stack rather than the native resolution of the source dataset. All predictor layers were spatially aligned and resampled as required for model training and subsequent probability mapping.

The initial feature stack comprised 84 predictor variables (Appendix Table S1), including Sentinel-2 spectral and texture metrics, Sentinel-1 radar metrics, topographic variables, seasonal vegetation dynamics, and custom spectral and spatial heterogeneity metrics.

Three custom spectral indices, denoted as MIR (mid-infrared; based on the Sentinel-2 SWIR bands B11 and B12), SOIL (soil-related), and RESWIR (red-edge–SWIR), were calculated as:

$$\begin{aligned}MIR &= (B11 - B12) / (B11 + B12); \\SOIL &= ((B11 + B4) - (B8 + B2)) / ((B11 + B4) + (B8 + B2)); \\RESWIR &= (B8A - B11) / (B8A + B11).\end{aligned}$$

For each index, a spatial heterogeneity metric (textstd3) was calculated as the local standard deviation of continuous index values within a 3×3 moving window at the native spatial resolution of the corresponding input bands. Texture metrics were calculated before resampling to the common 10 m analysis grid. This procedure produced six custom predictors: three spectral indices and their corresponding texture layers.

Three additional Sentinel-2 local texture metrics (S2X_p50_textstd3, S2X_p50_textstd5, and S2X_p50_textstd7) represented local standard deviation calculated within 3×3 , 5×5 , and 7×7 moving windows, respectively.

Seasonal vegetation dynamics were characterized using three NDVI-based metrics. NDVI was calculated from the B8 and B4 bands after cloud and shadow masking. A time series of NDVI composites was generated at 10-day intervals using median NDVI within a 20-day moving window centred on each date.

Seasonal NDVI dynamics were represented by harmonic amplitude (NDVI_harm_amp_30), harmonic phase (NDVI_harm_phase_30), and minimum daily NDVI slope (NDVI_min_slope_day_30). Harmonic amplitude and phase were derived by fitting a first-order harmonic model:

$$NDVI(t) = a_0 + a_1 \cos(2\pi t) + b_1 \sin(2\pi t),$$

where t is the fractional year. Harmonic amplitude was calculated as:

$$Amplitude = \sqrt{a_1^2 + b_1^2},$$

and harmonic phase as:

$$Phase = \text{atan2}(b_1, a_1).$$

The minimum daily NDVI slope represents the strongest decline in NDVI during the analysed period. For each pair of consecutive 10-day composites, the daily slope was calculated as:

$$Slope = (NDVI_{t+10} - NDVI_t) / 10,$$

and the minimum value across the seasonal time series was retained.

Other spectral indices and statistical metrics included in the feature stack were calculated using standard definitions. Temporal percentile statistics (p10, p50, and p90), interquartile range (IQR), mean, minimum, maximum, range, standard deviation, amplitude, skewness, and kurtosis were derived from the corresponding temporal image series.

Predictor selection and feature stack for cropland probability mapping

Predictor selection for the cropland model was performed iteratively. A baseline Random Forest model containing the full predictor set was trained and evaluated using an independent validation dataset, and variable importance was used to identify the most informative predictors. Reduced predictor sets were subsequently constructed by retaining high-ranking variables and removing redundant or weakly informative predictors.

The reduced models were evaluated using the same training and validation datasets, Random Forest parameters, and sampling strategy. Additional experiments involved excluding specific groups of predictors to assess their contribution to classification performance. Model variants were compared using overall accuracy, Cohen's kappa coefficient, confusion matrices, and variable-importance rankings.

The predictors retained through this optimization procedure provided the basis for constructing a dedicated multi-year cropland feature stack. Five-year versions of selected spectral, temporal, and texture metrics were generated from Sentinel-2 observations for 2021–2025 and complemented by multi-year NDVI phenology and spatial heterogeneity metrics.

The final stack comprised 27 predictor variables (Appendix Table S2), spatially aligned to a common 10 m grid in EPSG:32638.

The MIR, SOIL, and RESWIR indices defined above were calculated separately for each year from 2021 to 2025 using Sentinel-2 median composites for April–October. Annual index layers were then aggregated using the median to obtain five-year representations of each index. Their corresponding 3 × 3 texture metrics were likewise calculated annually and subsequently aggregated using the median across the five years.

A separate five-year median NDVI predictor was derived for 2021–2025. For each year, NDVI composites were generated for June–October at 10-day intervals using median NDVI within 20-day moving windows. These composites were aggregated to obtain an annual median NDVI image, followed by calculation of the median across the five annual images.

Multi-year vegetation phenology was represented by four metrics derived from annual NDVI dynamics: harmonic amplitude, harmonic phase, magnitude of the strongest seasonal NDVI decline, and day of year of the strongest decline. Harmonic amplitude, decline magnitude, and decline timing were aggregated across the five years using the arithmetic mean, whereas harmonic phase was aggregated using the circular mean. Spatial heterogeneity in the five-year mean magnitude of the strongest NDVI decline was additionally characterized as local standard deviation within a 3 × 3 pixel moving window (30 × 30 m).

Two groups of selected Sentinel-2 predictors were also calculated separately for each year and aggregated using the median across 2021–2025. Temporal series were represented by 20-day moving-window median composites generated at 10-day intervals.

The first group comprised seven extended spectral, temporal, and spatial metrics: the 10th percentiles of NIRv and spectral brightness, median SWIR ratio (B11/B12), temporal standard deviation of B12, temporal NDVI skewness, and local standard deviation of annual median NDVI within 3 × 3 and 7 × 7 pixel windows. NIRv was calculated as $\text{NDVI} \times \text{B8}$, and spectral brightness as the mean of B2, B3, B4, B8, B11, and B12.

The second group comprised eight core Sentinel-2 metrics: median NDRE2, median and 90th-percentile NDWI-Gao, interquartile range and median of B11, and the 10th percentiles of B5, B11, and B12:

$$\text{NDWI-Gao} = (B8A - B11) / (B8A + B11),$$

$$\text{NDRE2} = (B8A - B6) / (B8A + B6).$$

Predictor selection and feature stack for woody vegetation probability mapping

For woody vegetation mapping, a simpler predictor-selection procedure was applied. Preliminary Random Forest models were trained using the initial predictor set, and variable importance was used to rank the predictors. The 60 highest-ranking predictors were retained for the final woody vegetation model (Appendix Table S3).

The predictor set included Sentinel-2 spectral and texture metrics, Sentinel-1 radar metrics, topographic variables, seasonal vegetation dynamics, custom spectral and spatial heterogeneity metrics, and Dynamic World tree-cover probability.

The selected predictors were generated using remote-sensing data representing conditions in 2025 and were subsequently used for model training, validation, and probability mapping. Predictor layers with spatial resolutions coarser than 10 m were resampled to and aligned with the common 10 m output grid.

2.2.3 The layers of woody vegetation

Training of the woody vegetation model and probability mapping

A continuous woody vegetation probability layer was developed using supervised machine-learning classification in Google Earth Engine. A Random Forest classifier was trained using the manually prepared reference dataset (Section 2.2.1) and the 60-predictor feature stack selected for woody vegetation mapping (Section 2.2.2).

For binary classification, the reference classes were regrouped into woody vegetation and non-woody land cover. The woody vegetation class comprised cells manually classified as forest, including both closed forest and open woodlands, whereas the non-woody class comprised cells classified as non-forest or cropland. Orchard and vineyard cells retained as separate classes in the reference dataset were not used for training the woody vegetation model.

Five sample points were generated within each 60 × 60 m reference cell to extract predictor values for model training and validation. To minimize spatial dependence between the training and validation samples, the dataset was partitioned at the level of the original reference cells rather than individual sample points. Consequently, all five points generated within a given cell were assigned exclusively to either the training or validation subset. Approximately 80 % of the reference cells were used for model training and 20 % for independent validation.

To reduce the influence of random sampling and Random Forest initialization on the resulting probability estimates, the classification procedure was repeated in 10 independent runs. In each run, the Random Forest classifier contained 250 trees and used the same set of 60 predictors and model settings, while both the Random Forest seed and the random selection of training points were varied. Up to 9,000 training points per class were randomly selected for each run. The validation subset was kept fixed across all runs, with up to 2,500 points per class, allowing the resulting models to be evaluated against the same reference sample.

Each trained classifier was applied to the common 10 m predictor stack to generate an independent continuous woody vegetation probability map for the entire territory of Armenia. Water pixels were assigned a probability of zero. Pixel values represent the estimated probability of membership in the woody vegetation class.

The 10 probability maps were subsequently spatially aligned to an identical 10 m grid and combined by calculating the arithmetic mean of pixel-level probabilities. The mean was calculated only for pixels for which predictions were available from all 10 runs. The resulting ensemble layer represented the mean estimated probability of woody vegetation occurrence (Fig. 5 a) and was used as the basis for subsequent delineation of forests and open woodlands.

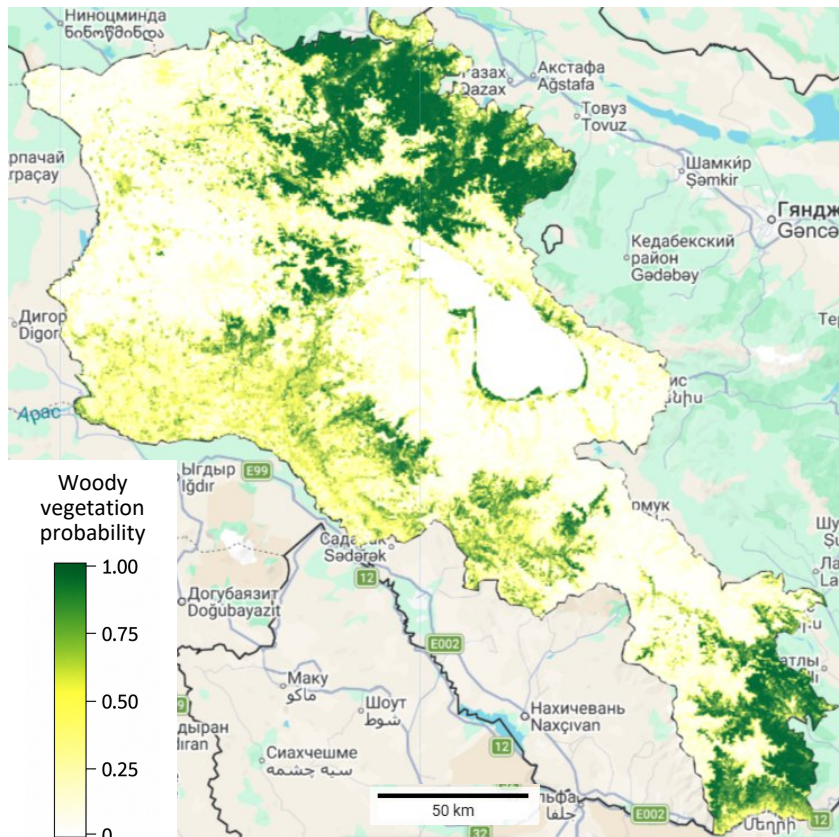


Figure 5. The layer of woody vegetation probability

Validation demonstrated high discriminatory performance of the woody vegetation probability model across a broad range of probability thresholds. At a threshold of 0.50, overall accuracy was 94.17 % (Fig. 6a), with false-positive and false-negative rates of 6.16 % and 5.18 %, respectively (Fig. 6b). Increasing the threshold progressively reduced false-positive errors but increased omission of woody vegetation. This validation characterizes the ability of the model to distinguish the combined woody vegetation class (forest and open woodland) from non-woody areas. The threshold analysis was used to assess the performance and sensitivity of the probability model rather than to define the final forest and open woodland classes. Instead, the continuous probability surface was subsequently used to delineate these two classes using visually determined probability thresholds.

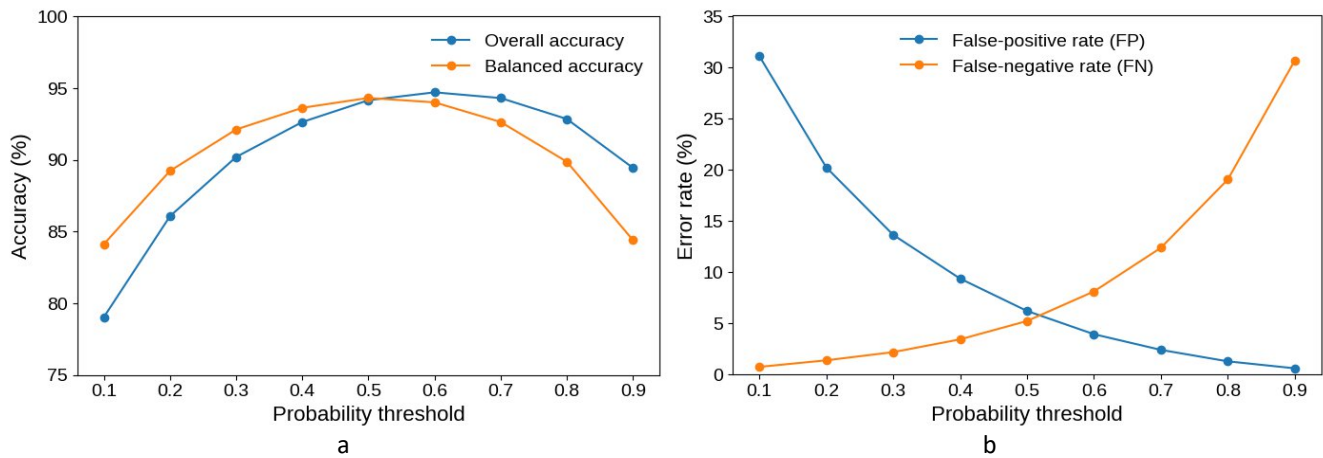


Figure 6. Sensitivity of woody vegetation classification performance to the probability threshold.

The probability thresholds were determined by visual comparison of the probability layer with high-resolution satellite imagery. Closed forest was defined as areas with a woody vegetation probability >0.98. Open woodland was initially delineated using different probability ranges for areas of extensive orchards and vineyards and for the rest of Armenia. Within areas characterized by extensive orchards and vineyards (Fig. 7a), a broader probability range of 0.25–0.98 was applied to ensure that woody cover associated with orchards and vineyards of different ages was not omitted. Across the remainder of Armenia, a more conservative probability range of 0.75–0.98 was applied. This procedure resulted in two separate woody vegetation masks: closed forest and open woodland (Fig. 7b). Orchards and vineyards were subsequently removed from the open woodland mask and assigned to a separate class of tree, vine and shrub crops.

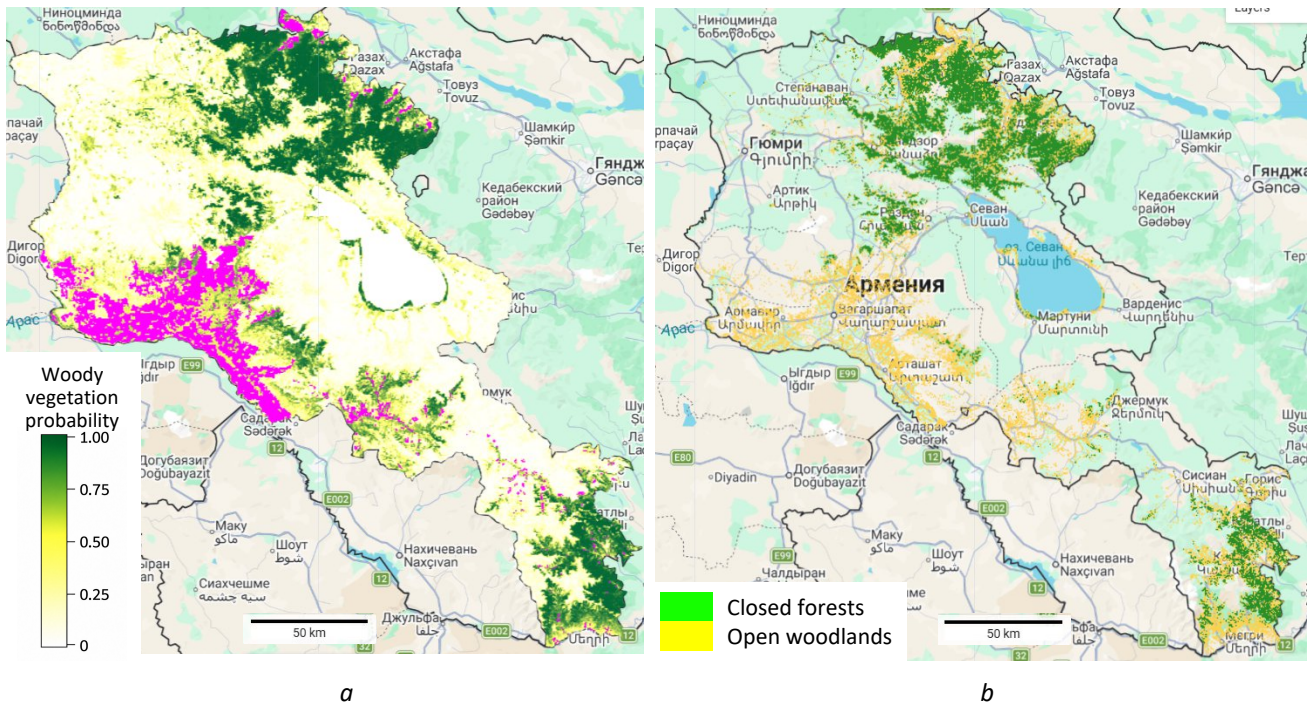


Figure 7. Delineation of woody vegetation classes: a) areas of orchards and vineyards where the extended woodland probability range was applied are shown in purple; b) resulting closed forest and open woodland masks.

Forest layer

Specific forest ecosystem types were delineated by applying the rule-based potential vegetation classification (Table 1) to the closed forest mask. Consequently, individual forest ecosystem types were assigned only within areas identified as closed forest. The distribution of natural pine forests was derived from spatial data provided by experts from the Takhtayan Institute of Botany. This procedure resulted in the map of current forest ecosystem types shown in Figure 8.

For further methodological development of the ecosystem map, an additional layer representing forests dominated by coniferous species was delineated. A multi-year January NDVI composite was calculated as the median of cloud-masked Sentinel-2 observations acquired in January from 2020 to 2024. Candidate coniferous stands were identified within the mapped woody vegetation area based on their persistent winter greenness, using January NDVI values between 0.5 and 0.9. The resulting layer showed good spatial correspondence with the distribution of coniferous forests presented in the Forest Atlas of Armenia.

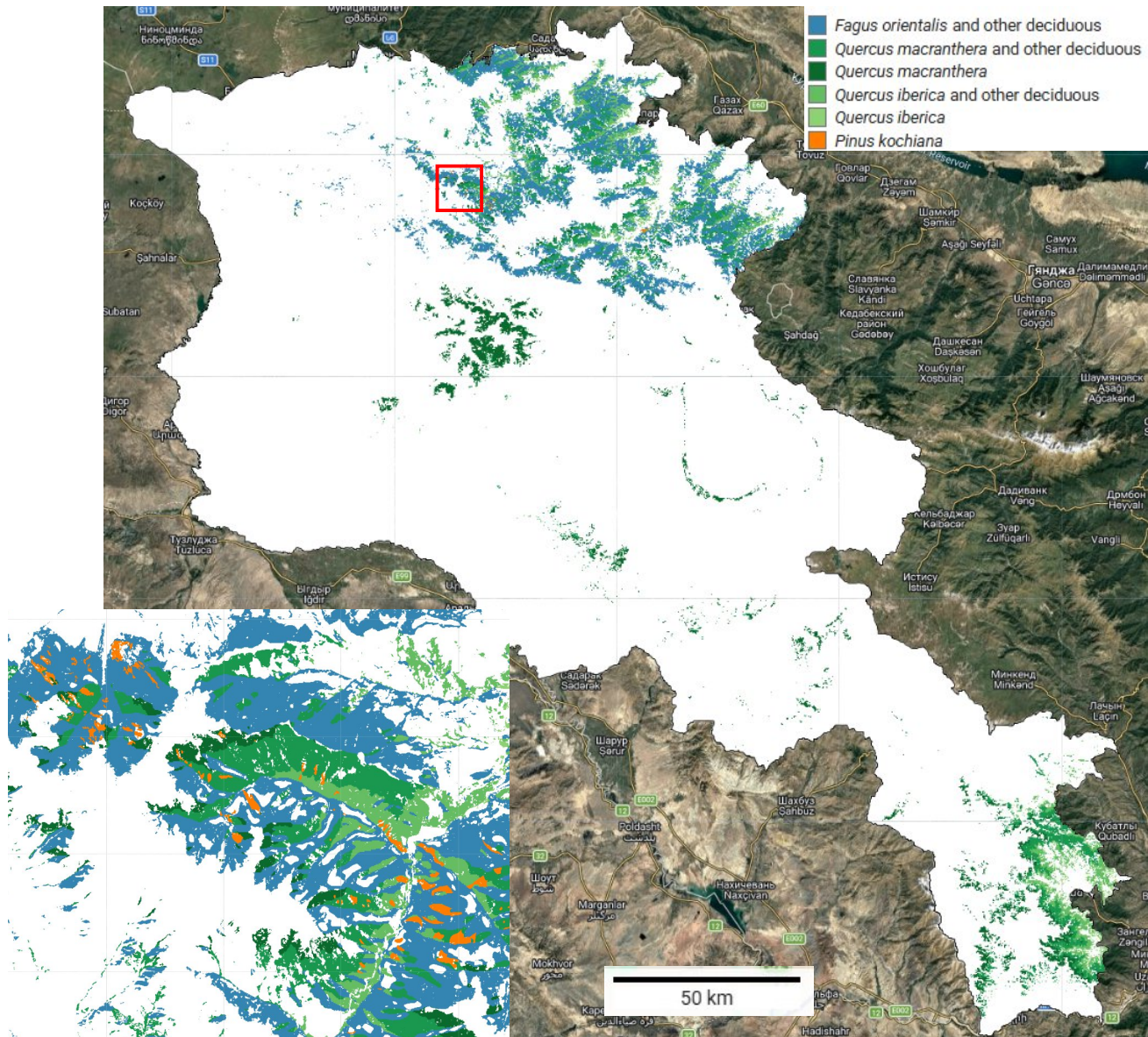


Figure 8. Current forest types.

The inset shows an enlarged view of the area indicated by the red rectangle on the main map.

Open woodland layer

Current open woodland ecosystems were delineated within the mapped open woodland mask according to the rules defining their potential distribution (Table 1). Juniper woodlands were identified using satellite imagery. In contrast to the predictor stack used for woody vegetation probability modeling, a ten-year Sentinel-2 time series was used for the identification of juniper woodlands. The longer observation period (2016–2025) was required to minimize data gaps in winter NDVI caused primarily by cloud and snow cover and to obtain a spatially more complete and robust representation of winter vegetation greenness. To characterize persistent winter greenness, two reference NDVI layers were calculated from Sentinel-2 observations for 2016–2025: multi-year mean NDVI and multi-year maximum NDVI. All valid NDVI observations acquired during the ten-year period were combined after masking clouds, cloud shadows, cirrus, and snow/ice, and pixel-wise mean and maximum values were calculated. A multi-year winter NDVI composite was calculated from Sentinel-2 observations acquired between 15 December and 30 January over ten winters (2015/2016–2024/2025). The median of all valid observations was used to further reduce data gaps and produce a robust winter greenness layer. Winter NDVI was then normalized by the multi-year mean and maximum NDVI to derive the ratios of winter NDVI to multi-year mean NDVI and winter NDVI to multi-year maximum NDVI. These metrics were used to characterize persistent winter greenness and distinguish juniper-dominated woody vegetation from deciduous vegetation. The following thresholds were applied to identify juniper woodlands: a minimum winter-to-annual mean NDVI ratio of 0.001, a minimum winter-to-annual maximum NDVI ratio of 0.53, and an annual mean NDVI ranging from 0.10 to 0.50. This procedure resulted in the delineation of three current open woodland ecosystem types: subalpine woodlands, juniper woodlands, and other deciduous and mixed woodlands (Fig. 9).

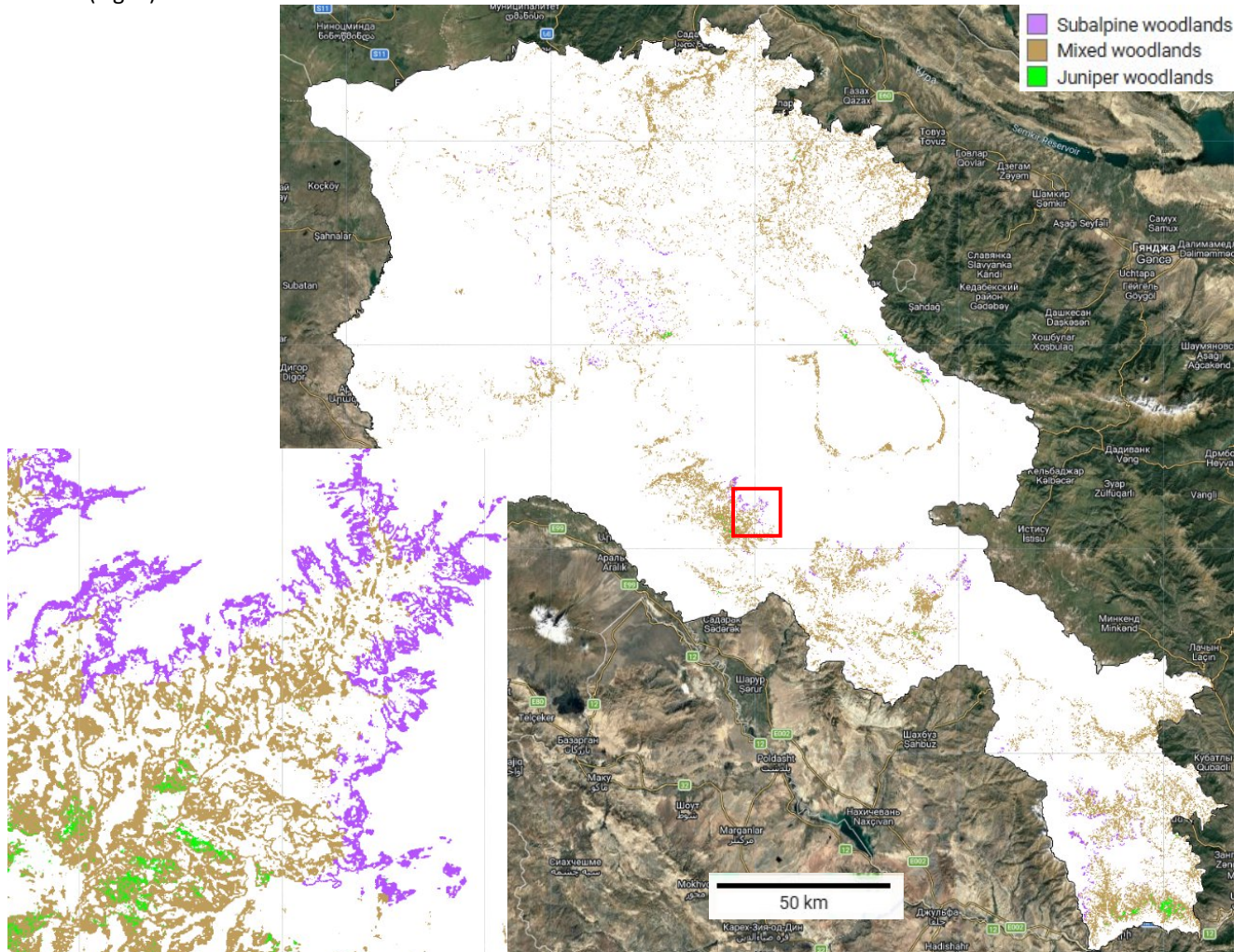


Figure 9. Current open woodland ecosystem types.

The inset shows an enlarged view of the area indicated by the red rectangle on the main map.

Anthropogenic woody vegetation

In addition to natural forests and open woodlands, five types of anthropogenic woody vegetation were distinguished: closed planted forests, open planted woodlands, tree, vine and shrub crops (predominantly orchards and vineyards), and other forest-like and open woodland-like vegetation in human-modified landscapes (Fig. 10).

Closed planted forests, open planted woodlands, and areas predominantly occupied by orchards, vineyards, and other perennial woody and shrub crops were manually delineated using high-resolution satellite imagery. Closed planted forests and open planted woodlands were identified by intersecting the respective manually delineated areas with the closed forest and open woodland masks. Forest-like and open woodland-like vegetation in human-modified landscapes was similarly identified by intersecting manually delineated human-modified areas with the closed forest and open woodland masks. Tree, vine and shrub crops were identified within manually delineated areas of orchards, vineyards, and other perennial woody and shrub crops using the combined closed forest and open woodland mask.

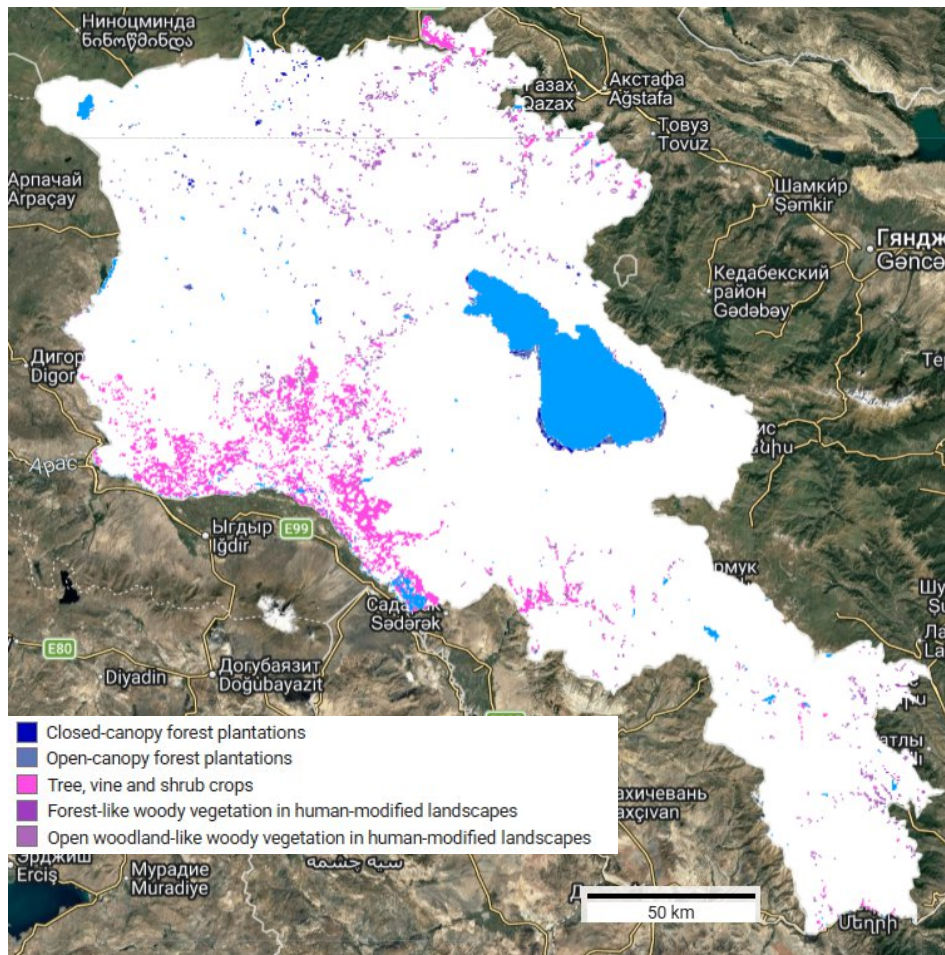


Figure 10. Anthropogenic woody vegetation

2.2.4 Wetlands

Although the map focuses on terrestrial ecosystems, we considered it useful to include two wetland types that are assigned to the terrestrial–freshwater realm in the IUCN GET. We distinguished two wetland types: 1) fens and wet meadows; 2) permanent marshes in the Ararat Valley. Fens and wet meadows potentially occupied substantial areas in the past, but most of these areas have now been converted to cropland and thus transformed into terrestrial agricultural ecosystems. Permanent marshes in the Ararat Valley are of particular conservation importance as part of the Metsamor Emerald Network site, but only a small proportion of their area is represented by the water layer derived from the ESA land-cover

dataset. We therefore considered it useful to delineate these marshes manually to ensure that they were represented on the ecosystem map rather than being obscured by the anthropogenic layers. Peat ecosystems corresponding to IUCN GET type TF1.6, Boreal, temperate and montane peat bogs, do not occupy substantial areas in Armenia and were therefore not included as a separate wetland type in the map. The identification and mapping of other wetland ecosystem types in Armenia is a task for future work, as part of a broader effort to map rare ecosystem types that cannot be readily distinguished using satellite imagery alone.

For mapping fens and wet meadows, areas of their potential distribution were first identified using a rule-based approach combining hydrological, topographic, and climatic indicators. Candidate areas were selected based on low Height Above Nearest Drainage (HAND), elevated topographic wetness (TWI proxy), low slope, high summer evapotranspiration (ET), and relatively low summer land surface temperature (LST), representing environmental conditions favorable for persistent wet habitats. Threshold values of $HAND \leq 12$ m, $TWI \geq 3.5$, $slope \leq 3^\circ$, $ET \geq 245$ mm, and $LST \leq 28^\circ C$ were selected through visual calibration against preserved fens and wet meadows represented on the vegetation map developed within the Prototype of Ecosystem Accounting in Armenia (BCC Armenia, 2026). The resulting potential distribution layer (Fig. 11) was subsequently constrained by the current anthropogenic land-cover classes to derive the current distribution of fens and wet meadows.

Permanent marshes in the Ararat Valley, located within the Metsamor Emerald Site, were manually delineated from high-resolution satellite imagery.

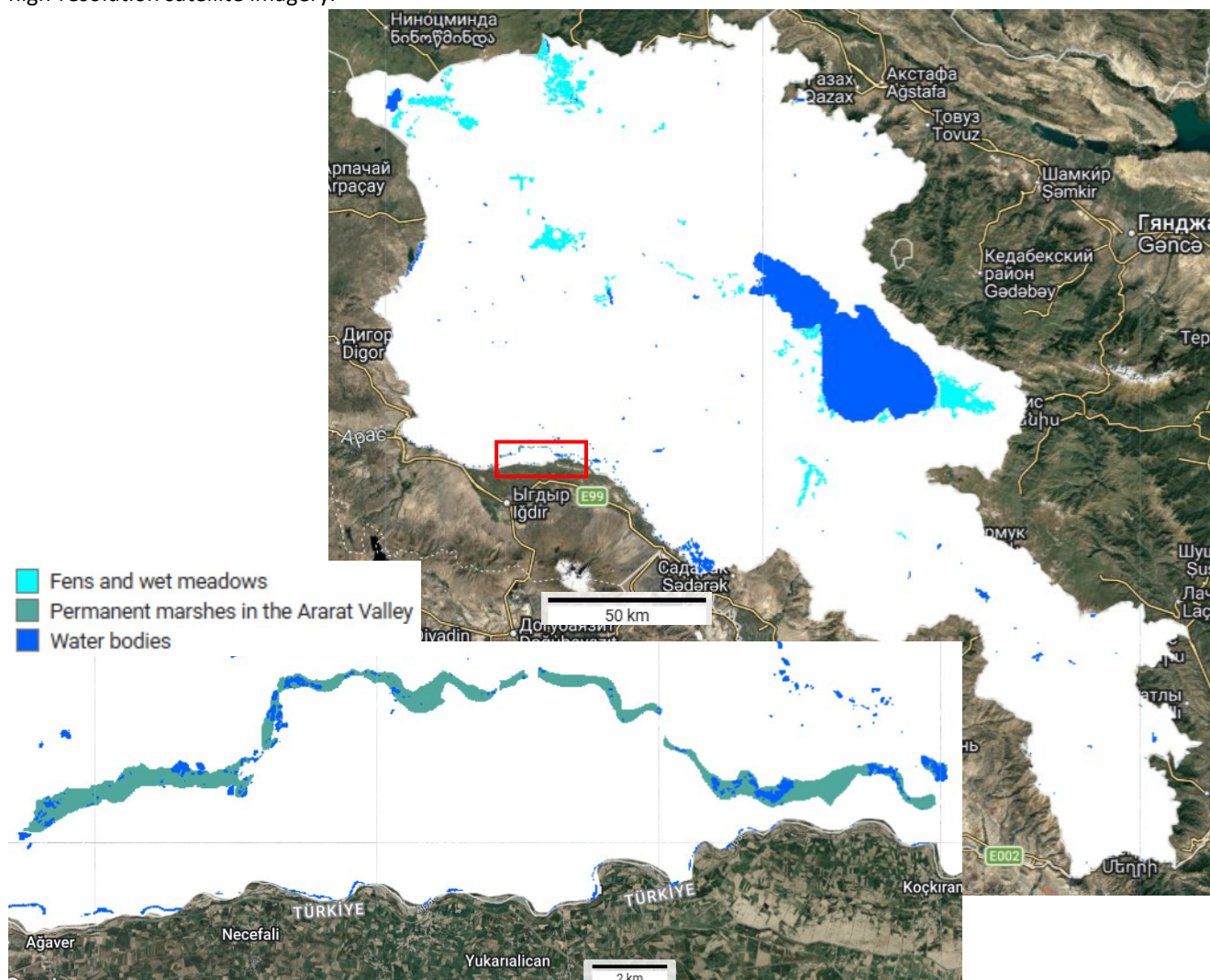


Figure 11. Wetlands. Potential distribution is shown for fens and wet meadows, whereas current distribution is shown for permanent marshes. The inset shows an enlarged view of a part of the permanent marshes indicated by the red rectangle.

2.2.5 Sparsely vegetated areas

Sparsely vegetated areas were identified using a threshold on maximum annual NDVI, with low peak vegetation greenness used as an indicator of persistently sparse vegetation cover. The maximum NDVI threshold for the sparse vegetation class was set at 0.2, as this value is lower than the maximum NDVI observed at a natural desert site within the Goravan Sands Sanctuary (0.2–0.4).

Natural sparsely vegetated ecosystems were further subdivided into three habitat types based on elevation and generalized geology: (1) high-mountain sparse habitats above 3500 m; (2) rocky habitats; and (3) sandy and clay habitats (Fig. 12). The generalized geology layer was derived from the Geological Map of Armenia available through the Forest Atlas of Armenia (<https://forestatlas.am/>).

In addition to natural ecosystems, a separate anthropogenic class of sparse vegetation was identified (Section 2.2.6).

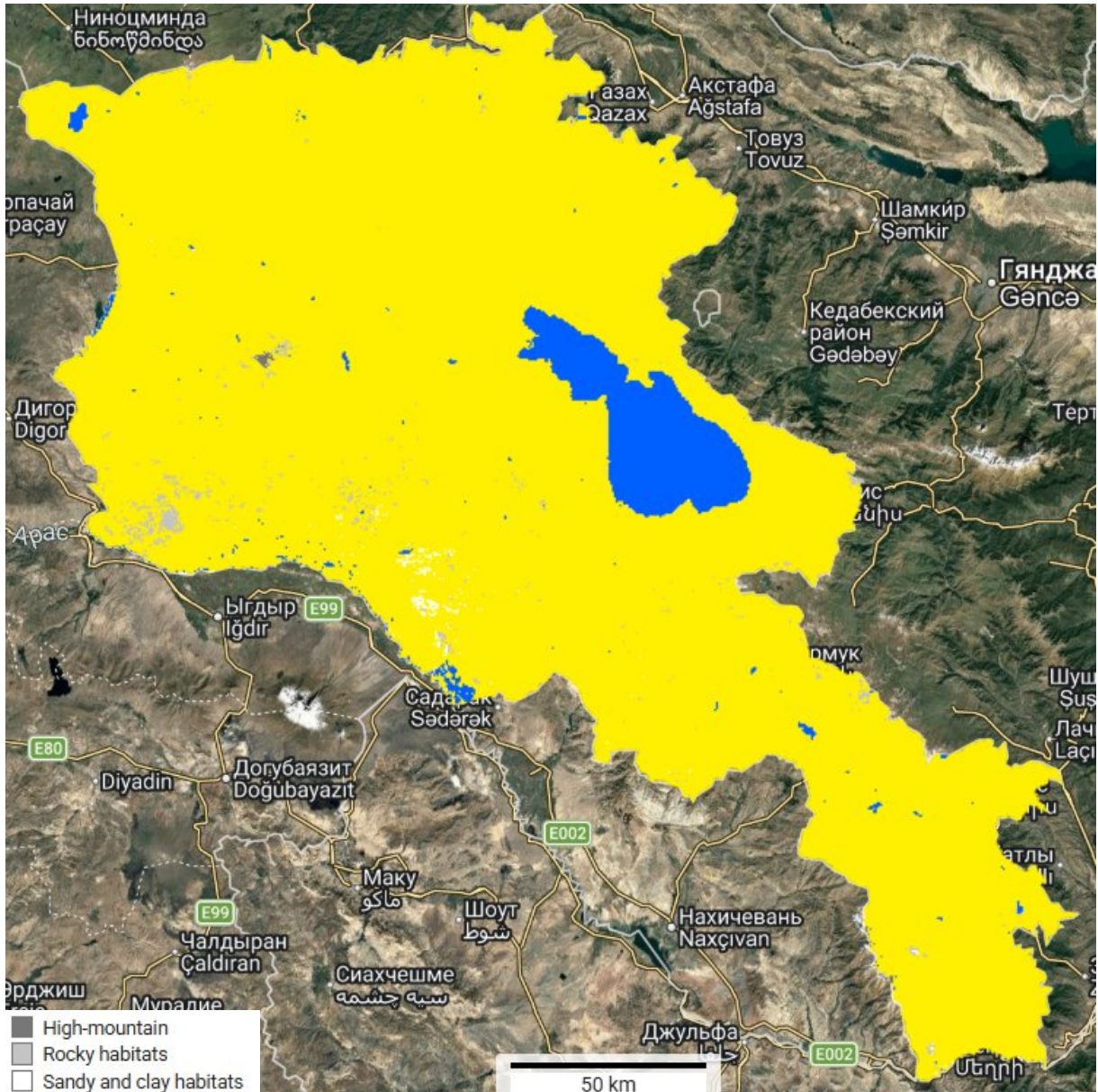


Figure 12. Sparsely vegetated ecosystems. A uniform yellow background is used solely to enhance the visibility of the different sparsely vegetated ecosystem types.

2.2.6 Anthropogenic areas and impacts

Croplands

The cropland probability layer was developed using supervised machine-learning classification in Google Earth Engine. A Random Forest classifier was trained to distinguish cropland from non-cropland areas using the manually prepared training dataset and the unified geospatial predictor stack described above.

For model training, all cells assigned to the cropland class in the training dataset were combined into one class, while cells representing all other ecosystem and land-cover types were combined into the non-cropland class. The generation of training and validation samples, their separation into training and validation subsets, and the construction of the predictor stack followed the same general methodology as described above for the woody vegetation probability model.

Cropland probability maps were generated at 10 m resolution using the predictor layers described above, with coarser-resolution predictors resampled bilinearly where required. To reduce the influence of random variation in sample selection and model fitting, the classification was repeated in 10 independent Random Forest runs using different random seeds.

The Random Forest classifier was configured to produce continuous probability outputs rather than discrete class assignments. The probability maps from the 10 runs were averaged pixel-wise to produce the final cropland probability layer, representing the mean estimated probability of cropland occurrence for each 10 m pixel (Figure 13).

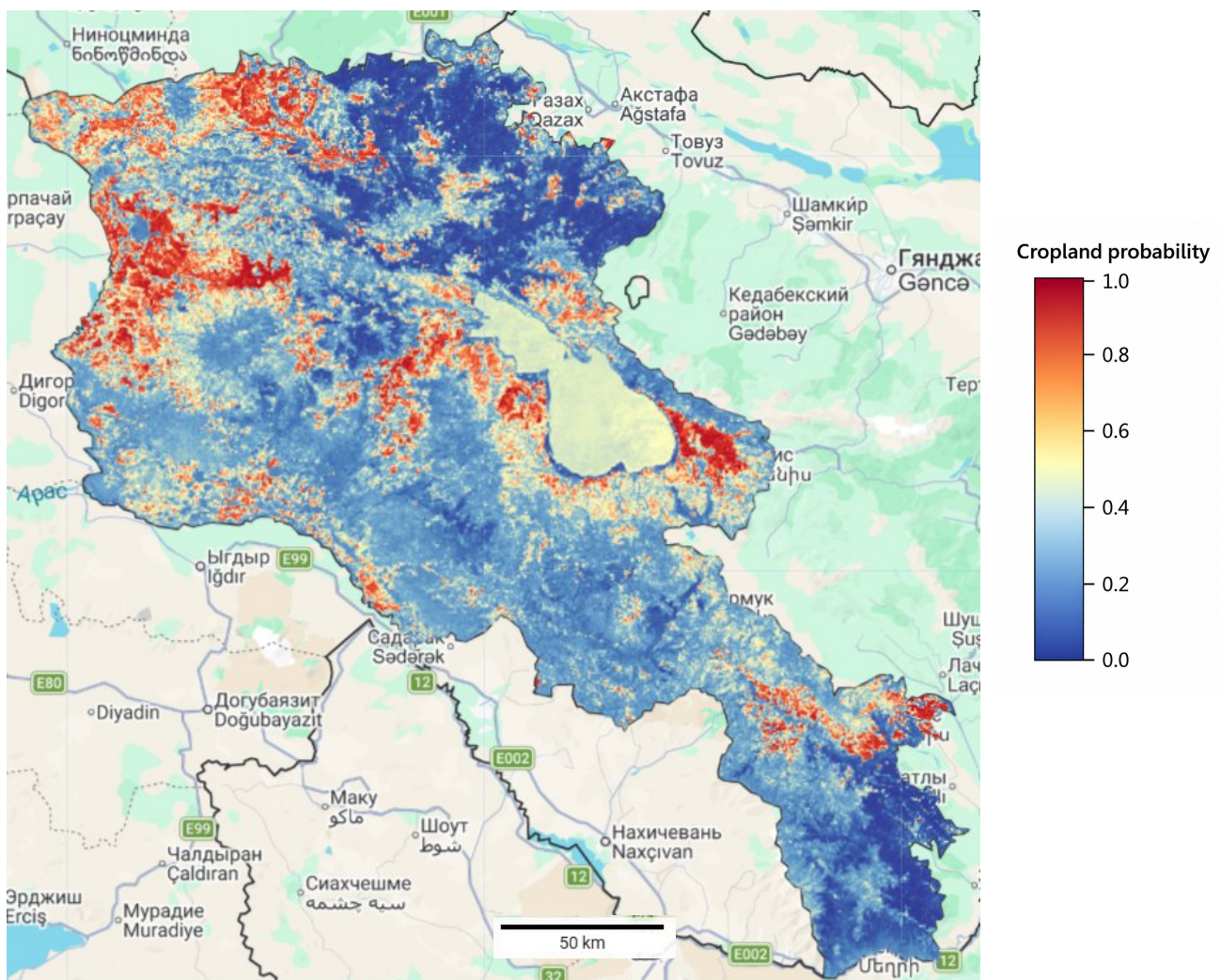


Figure 13. Cropland probability layer

Validation of the cropland probability layer demonstrated good discriminatory performance across a broad range of probability thresholds. At a threshold of 0.60, the overall accuracy reached its maximum value of 90 % (Fig. 14a) with false-positive and false-negative rates of 5.2 % and 19.2 %, respectively (Fig. 14b). Increasing the probability threshold reduced false-positive errors but increased omission of cropland, while overall accuracy declined at higher thresholds.

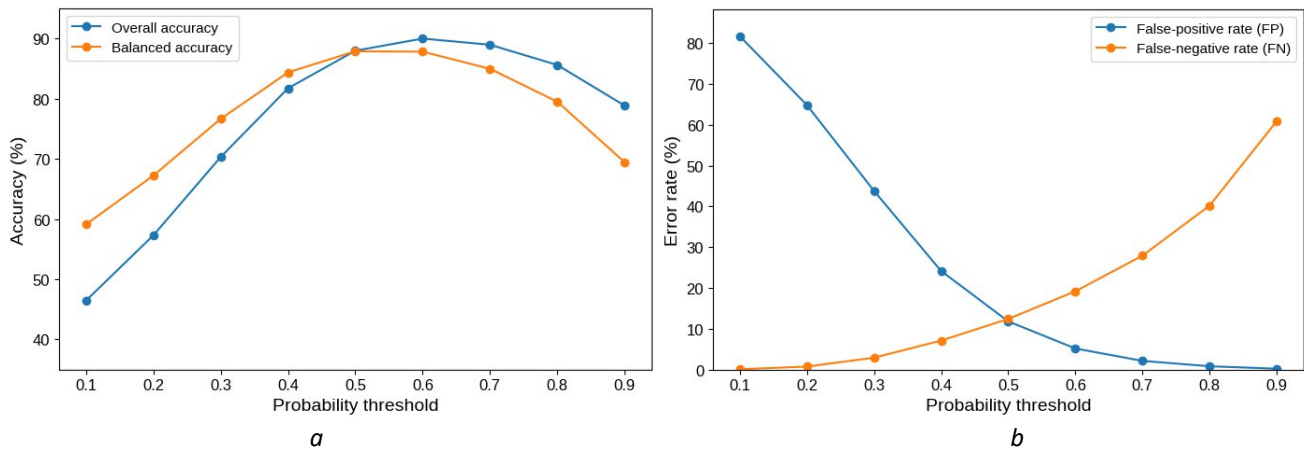


Figure 14. Sensitivity of cropland classification performance to the probability threshold.

High cropland probability values predominantly corresponded to fields that were actively and regularly used during the five-year period, whereas lower probability values represented a heterogeneous mosaic of irregularly used or abandoned fields and hay meadows. The decline in accuracy at higher probability thresholds can therefore be explained by the composition of the reference dataset, in which a substantial proportion of cropland cells represented irregularly used fields or hay meadows which received lower probability.

The continuous cropland probability surface was subsequently converted into two cropland classes using probability thresholds supported by the validation results and visual interpretation of high-resolution imagery: actively and regularly used fields (≥ 0.80) and irregularly used fields and hay meadows (≥ 0.60 and < 0.80).

High-probability (≥ 0.80) cropland areas generally corresponded closely to clearly identifiable agricultural field boundaries visible in high-resolution imagery. In contrast, lower-probability croplands (≥ 0.60 and < 0.80) identified by the model showed a more spatially diffuse pattern and did not necessarily coincide with the boundaries of individual fields identifiable in high-resolution imagery. Therefore, this class should be interpreted not as a delineation of specific agricultural fields, but rather as an indication of broader areas characterized by irregular cropland use and hay meadows. Actively used cropland pixels were subsequently aggregated into actively cultivated landscapes using the same spatial procedure as for settlement delineation. First, a 50 m outer buffer was applied to the active cropland mask to connect nearby cultivated fields. Morphological closing with a 150 m radius was then used to fill small internal gaps and produce spatially continuous agricultural landscape units. This procedure incorporated small non-cropland elements embedded within the cultivated landscape mosaic, such as roads, small shelterbelts and other woody strips, small streams, and irrigation canals (Fig. 15).

The layer of irregularly used fields and hay meadows was subsequently used as a basis for delineating human-modified landscapes (Section 2.2.7).

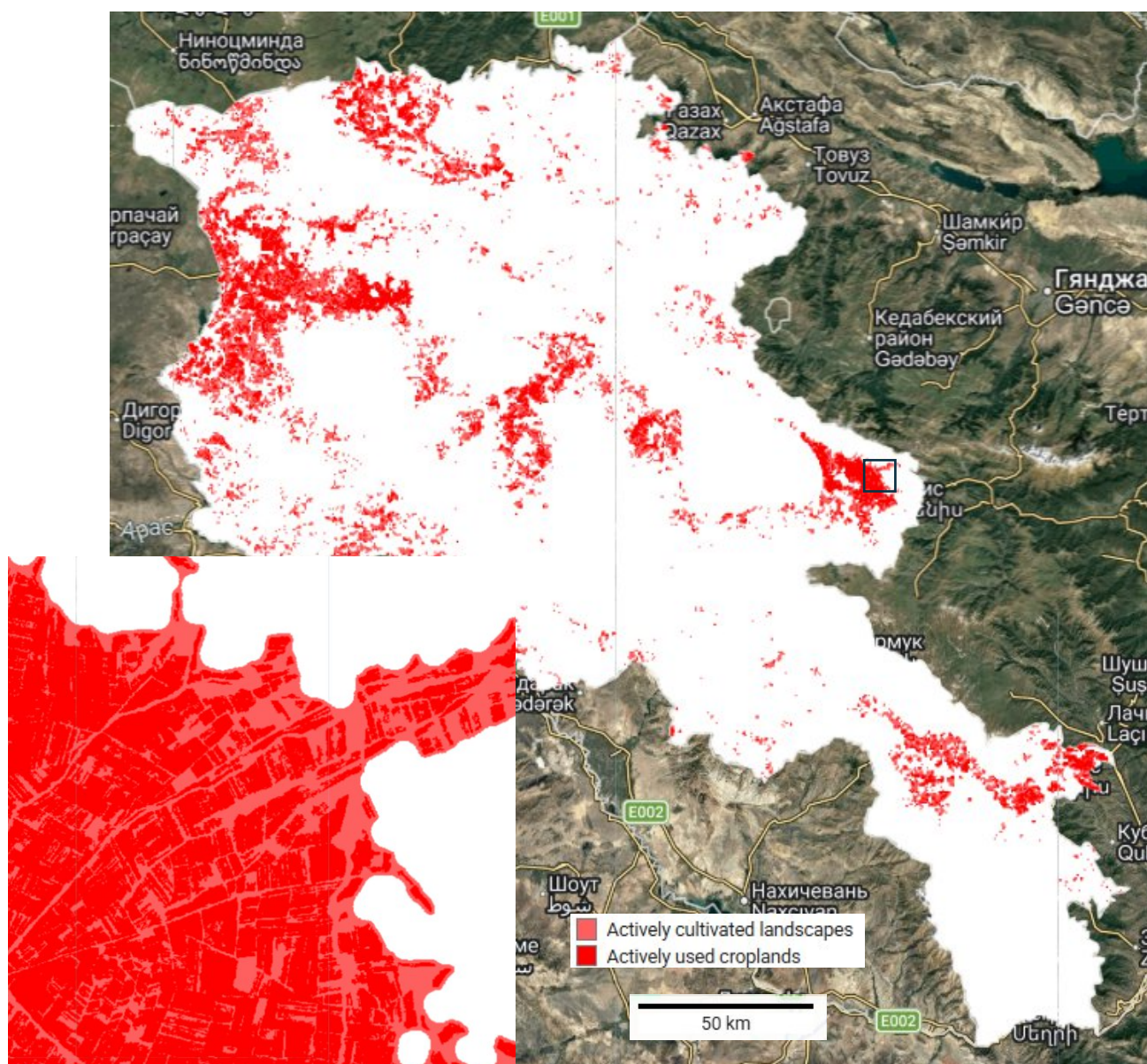


Figure 15. Actively used croplands and actively cultivated landscapes.
The inset shows an enlarged view of the area indicated by the black rectangle on the main map.

Built-up and technogenically disturbed areas

Settlement areas were delineated as follows. ESA Built-up data and OSM Buildings were combined to create an initial layer of buildings and built-up surfaces. False linear built-up features in the ESA layer associated with transport infrastructure were removed. The resulting cleaned built-up layer was then spatially aggregated by applying a 50 m outer buffer followed by morphological closing with a 150 m radius. This procedure connected closely spaced built-up areas and incorporated small internal gaps between buildings. The resulting raster was interpreted as the spatial extent of settlements rather than as the footprints of individual buildings.

Quarries and landfills were derived from OpenStreetMap (OSM) data. In addition, areas of sparse vegetation with maximum annual NDVI below 0.2 located within human-modified landscapes (see Section 2.2.7) were classified as technogenically disturbed areas (Fig. 16).

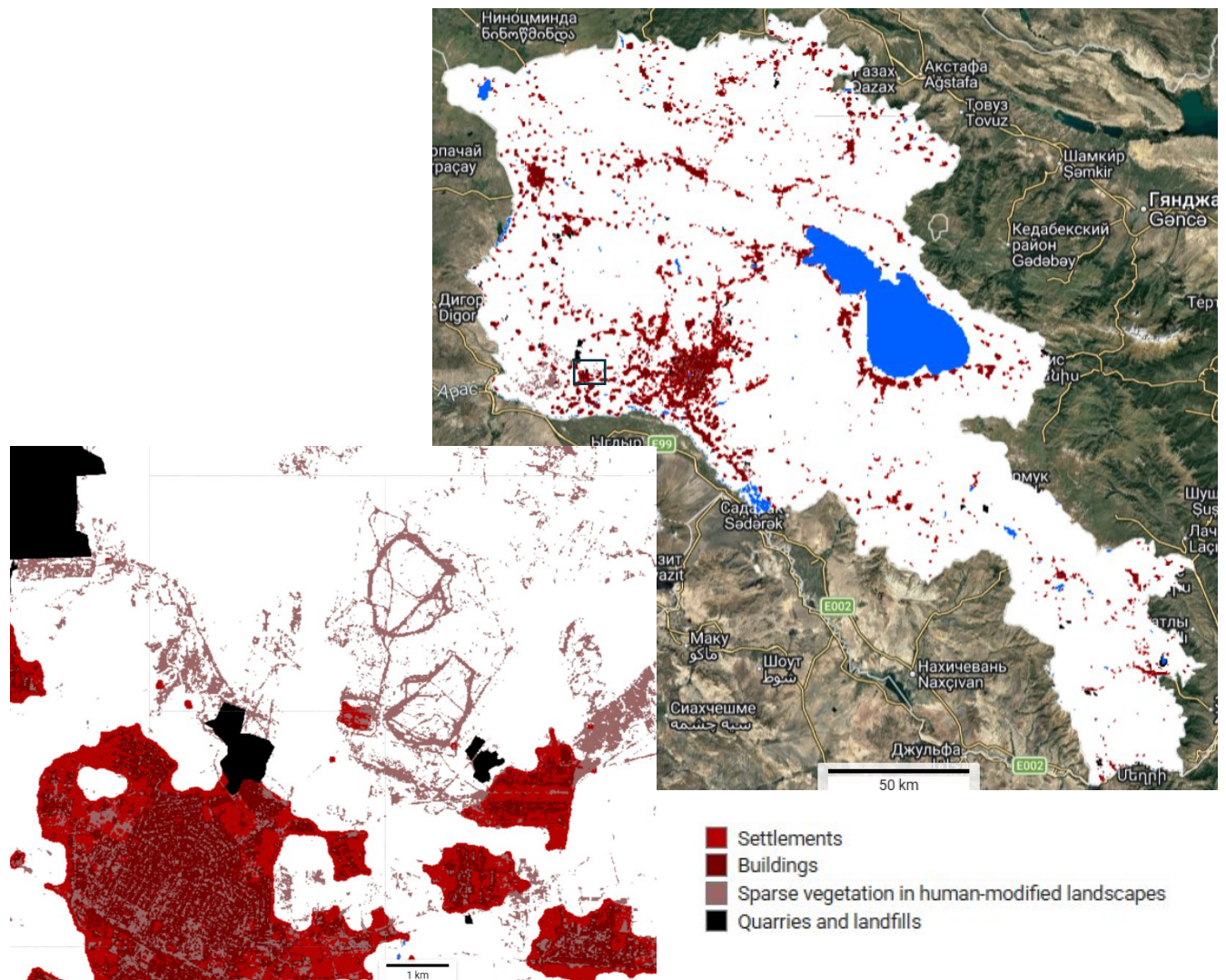


Figure 16. Built-up and technogenically disturbed areas.

The inset shows an enlarged view of the area indicated by the black rectangle on the main map

2.2.7 Informational layers: human-modified landscapes, grazing zones, protected areas

Human-modified landscapes (Fig. 17a) were delineated using the lower-probability cropland layer (≥ 0.60 and < 0.80) described in Section 2.2.6 as the principal spatial indicator. Because these lower-probability croplands formed a spatially diffuse pattern rather than clearly delineated individual fields, they were aggregated to represent broader areas of agricultural transformation. A 100 m outer buffer was first applied to connect nearby fragments, followed by morphological closing with a 500 m radius to fill internal gaps and form spatially continuous human-modified landscape units. The resulting layer was subsequently visually inspected and manually refined using high-resolution satellite imagery, including historical imagery available in Google Earth. This allowed the boundaries of human-modified landscapes to be corrected in areas where current land-cover patterns alone did not clearly indicate previous or irregular agricultural use. During this refinement, areas of abandoned and degraded croplands, orchards and vineyards, as well as technogenically disturbed areas, were manually delineated and incorporated into the human-modified landscape layer. All built-up areas described above were also included in this layer.

The resulting human-modified landscape layer broadly encompasses a heterogeneous mosaic of croplands, orchards, vineyards, hay meadows, settlements, and anthropogenically degraded areas, together with fragments of natural vege-

tation remaining between them. Because this layer represents a spatial mixture of anthropogenic and natural ecosystems rather than a distinct ecosystem type, it was retained as an informational layer and was not incorporated as a separate class into the integrated ecosystem map.

Livestock camps and grazing zones (Fig. 17b) were mapped as an informational layer representing areas potentially subject to livestock grazing. A total of 1,445 livestock farmyards were identified from OpenStreetMap (OSM) land-use data, and a 3 km buffer was generated around each farmyard. The selected distance is consistent with empirical studies showing that most sheep remain within approximately 3 km of watering points (Fensham & Fairfax, 2008; James et al., 1999), although the total distance travelled during a day may be several times greater. The resulting buffers were interpreted as potential grazing-pressure zones rather than as areas uniformly or continuously grazed by livestock.

Overlapping buffers were retained, as they indicate areas potentially influenced by livestock originating from multiple farmyards. The resulting layer should therefore be interpreted as an indicator of potential grazing influence rather than as a delineation of actual grazed areas or grazing intensity. The accuracy of this layer could be further improved by verifying individual farmyards using high-resolution satellite imagery. Some of the mapped farmyards appear to be abandoned, whereas many others show clear signs of current use, including maintained buildings, well-defined vehicle tracks and, in some cases, visible livestock herds. Such verification could allow inactive farmyards to be excluded and provide a more accurate representation of current grazing influence.

Additional informational layers show national protected areas, Emerald Network sites, and Ramsar sites. Clicking on an area displays its name (Fig. 18).

Marz boundaries and settlement names, which become readable when zooming in, are shown in dedicated layers to facilitate spatial orientation and interpretation of the ecosystem map (Fig. 19).

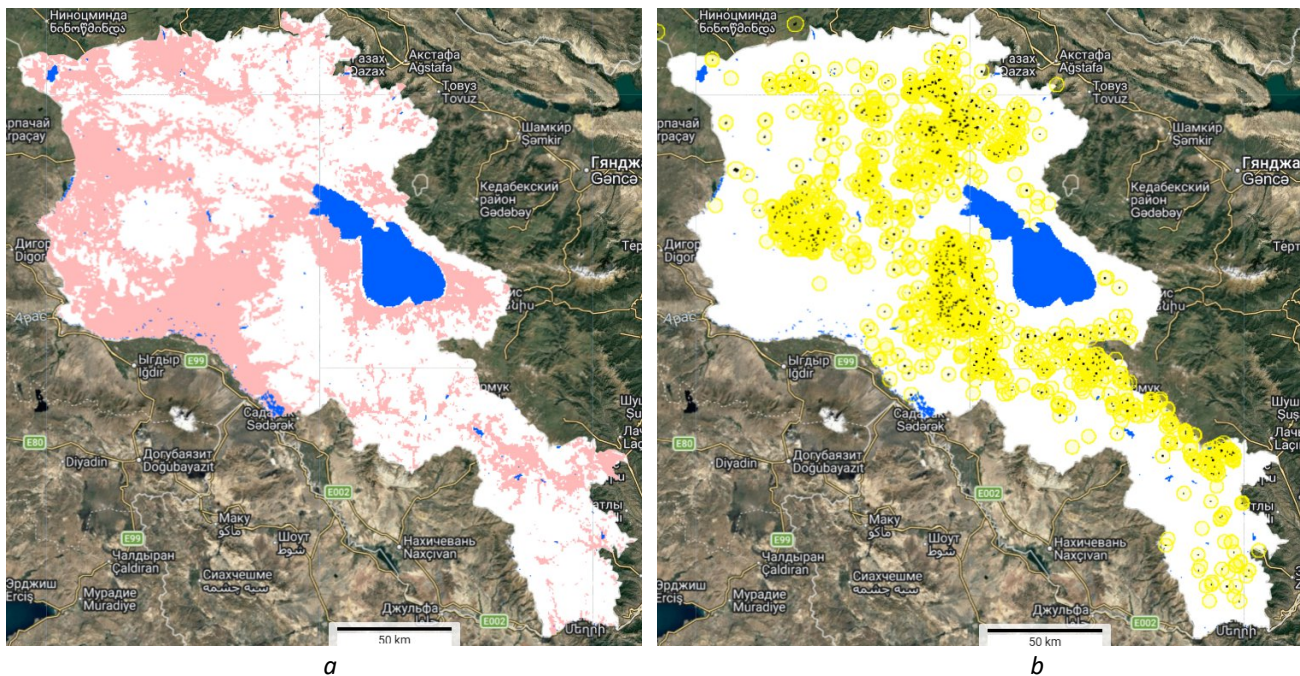


Figure 17. Spatial layers of anthropogenic influence: a) human-modified landscapes; b) livestock camps (black dots) and potential grazing-pressure zones represented by 3 km buffers (yellow circles).

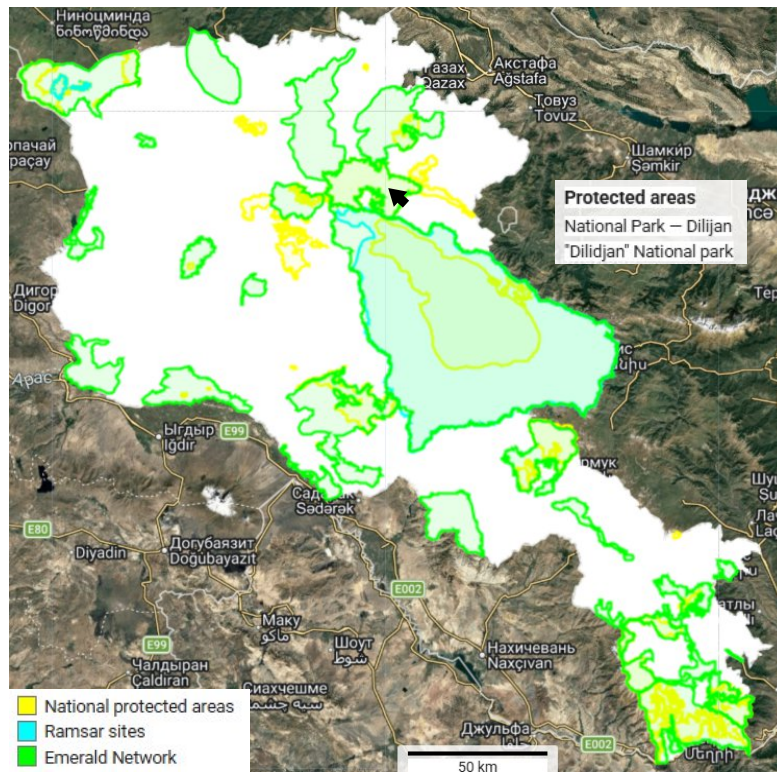


Figure 18. National protected areas, Emerald Network sites, and Ramsar sites.

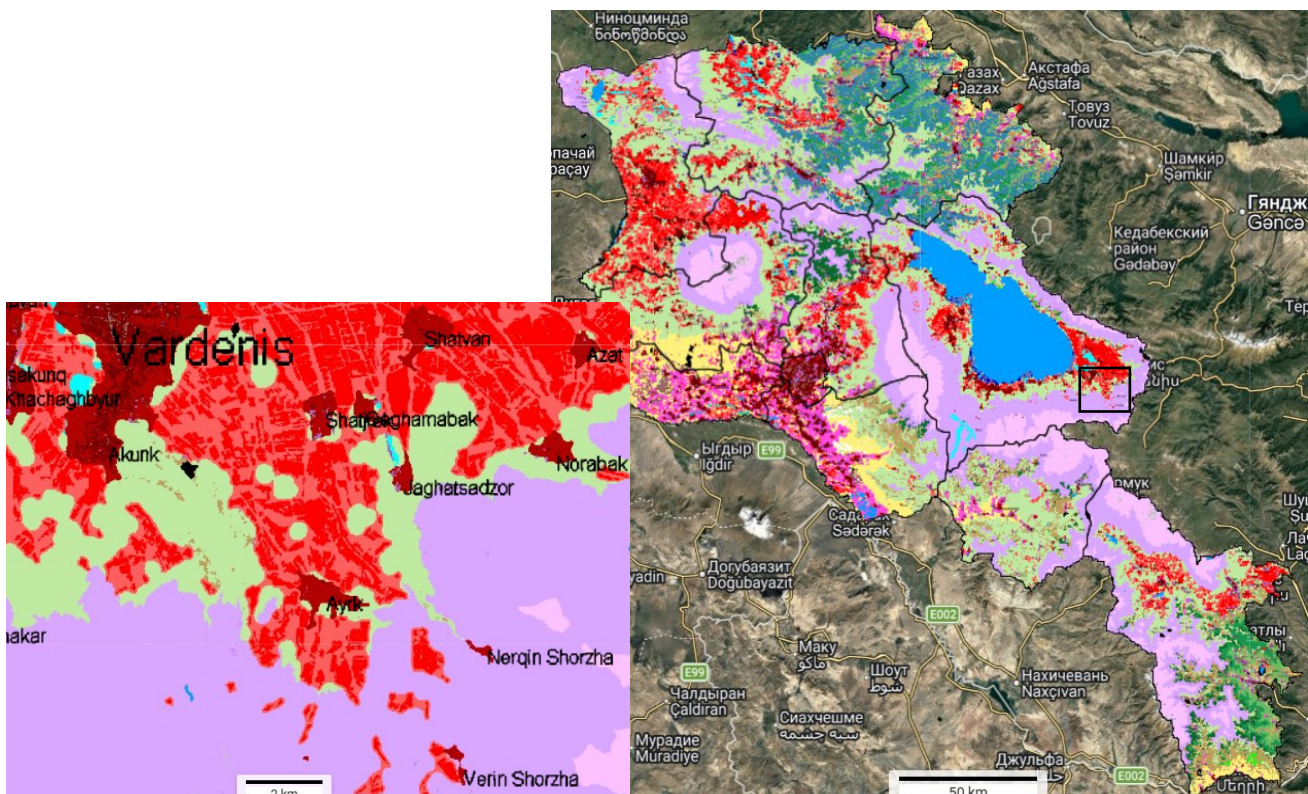


Figure 19. Marz boundaries and settlement names.

The inset shows an enlarged view of the area indicated by the black rectangle on the main map

2.3 Integrated layer of the Ecosystem map of Armenia

The ecosystem layers described above were combined into a single integrated layer (Fig. 20), which is available for download at http://biodiversity-armenia.am/wp-content/uploads/2026/09/Ecosystem_Map_of_Armenia.zip.

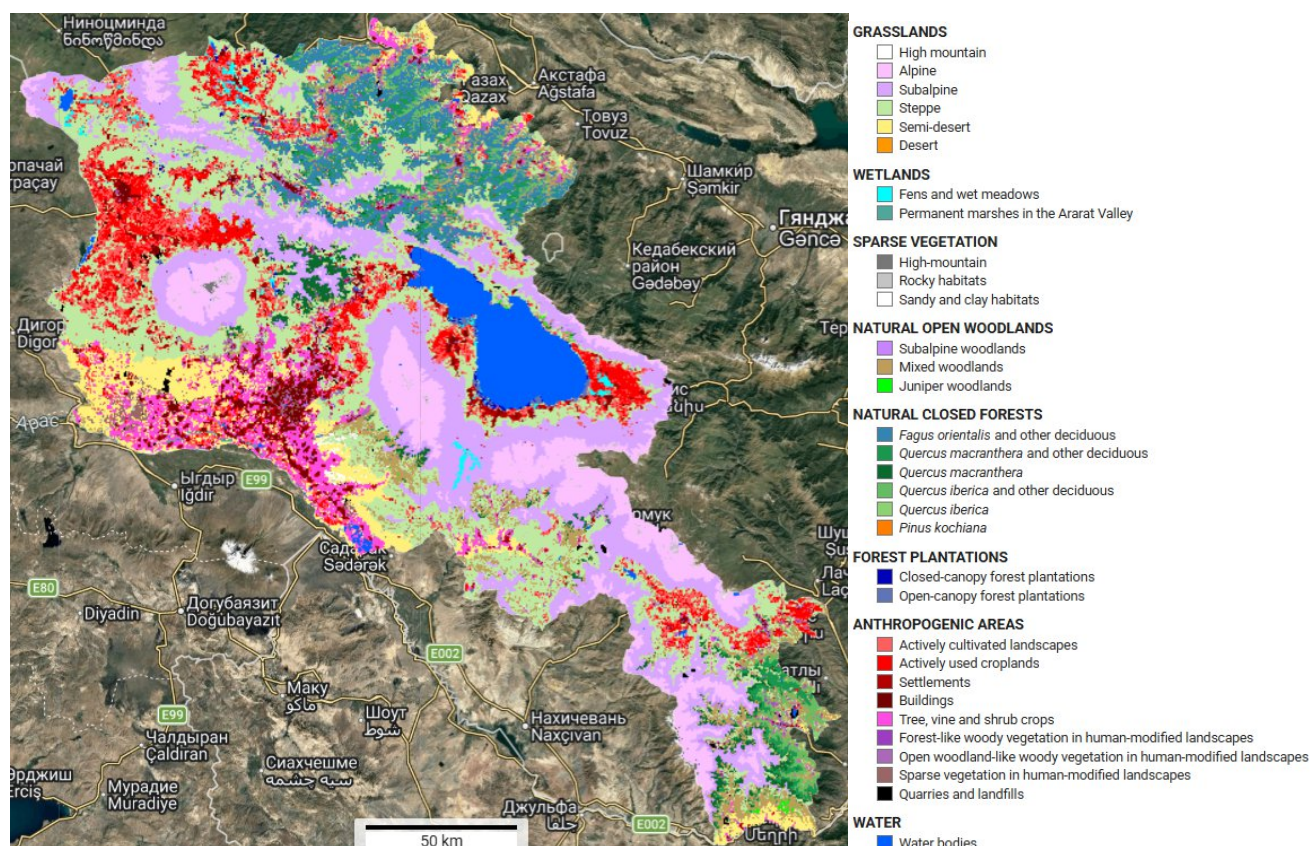


Figure 20. View of the integrated ecosystem layer in the interactive Ecosystem map of Armenia.

To produce the integrated layer, individual ecosystem layers were combined using a hierarchical overlay procedure (Fig. 21). The potential grassland layer formed the lowest layer of the map and was overlain by all other layers in the following sequence:

- 1) Potential fens and wet meadows were overlaid on the grassland layer, replacing the corresponding grassland classes within their mapped extent.

- 2) The layers of actively cultivated landscapes, including actively used croplands (Crops in Fig. 21), and settlement areas, including buildings (Built in Fig. 21), were overlaid on the potential grasslands, fens and wet meadows, replacing much of their area

- 3) Sparsely vegetated areas, which had previously been divided into natural and anthropogenic areas, together with quarries and landfills, were then overlaid on the potential grasslands and built-up areas. These areas did not overlap with wetlands or croplands.

- 4) Woody vegetation layers—including natural and anthropogenic woody vegetation—were overlaid on the resulting mosaic of grasslands, fens and wet meadows, actively cultivated landscapes, and settlement areas, replacing the underlying classes. Woody vegetation did not overlap with sparsely vegetated areas. Within the woody vegetation layer, seven classes were spatially exclusive and therefore did not overlap with one another: natural forests, natural woodlands, and the five types of anthropogenic woody vegetation (Section 2.2.3). Areas of natural *Pinus kochiana* forest were overlaid on the other forest ecosystem types. This priority was applied because *P. kochiana* forests represent a distinct and rare ecosystem type mapped separately. Similarly, within the woodland layer, satellite-derived juniper woodlands were

overlaid on and replaced the underlying woodland classes within their mapped distribution. The satellite-derived coniferous forest layer was retained as an informational layer and was not incorporated into the integrated ecosystem map.

5) Permanent marshes in the Ararat Valley were overlaid on the surrounding croplands and built-up areas, replacing these classes within the mapped marsh boundaries.

6) Finally, the layer of water bodies derived from the ESA WorldCover 2021 dataset was overlaid on all ecosystem layers, replacing all underlying classes within its mapped extent.

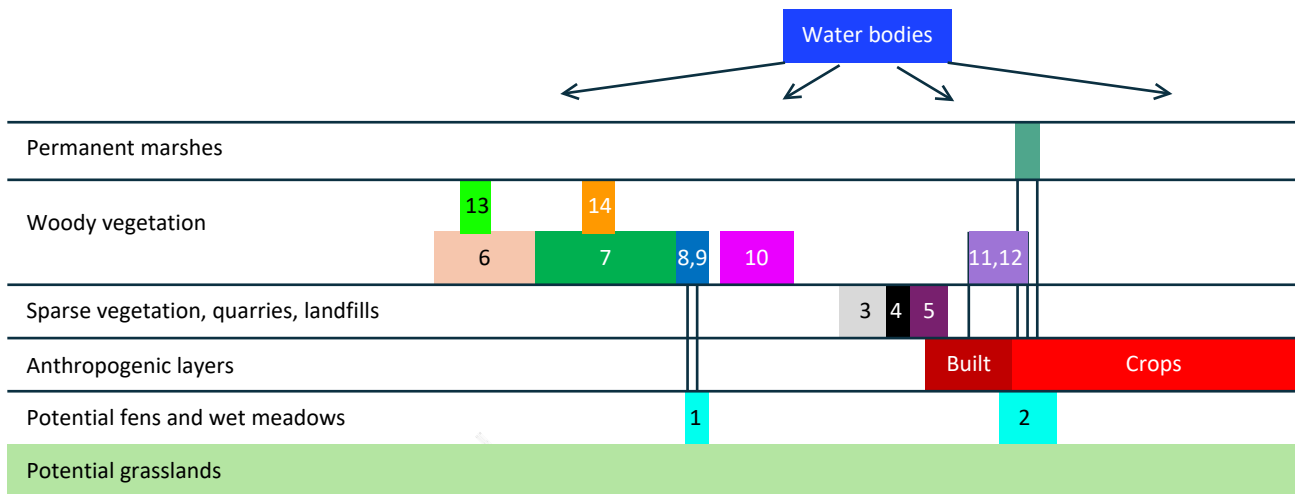


Figure 21. Hierarchical assembly of the integrated ecosystem layer. Layer overlaps are shown schematically; bar dimensions are illustrative and do not represent the actual relative areas of ecosystem types. 1 — Unploughed remnants of potential fens and wet meadows partly overlapped by woody vegetation; 2 — Potential fens and wet meadows converted to croplands; 3 — Natural sparse vegetation; 4 — Quarries and landfills; 5 — Sparse vegetation in human-modified landscapes; 6 — Natural woodlands; 7 — Natural forests; 8 — Closed-canopy forest plantations; 9 — Open-canopy forest plantations; 10 — Tree, vine and shrub crops; 11 — Forest-like vegetation in human-modified landscapes; 12 — Open woodland-like vegetation in human-modified landscapes; 13 — Juniper woodlands; 14 — Natural *Pinus kochiana* forests.

2.4. Crosswalk of the Ecosystem map of Armenia to the IUCN GET

To facilitate its inclusion in the Global Ecosystems Atlas and international reporting on ecosystem extent, the Ecosystem map of Armenia was crosswalked to the IUCN Global Ecosystem Typology (GET) (Table 2, Fig. 22).

Because the ecosystem classification used in the national map does not correspond directly to the IUCN GET classification, the integrated national ecosystem layer could not be reclassified into GET classes through simple one-to-one recoding. Instead, the individual ecosystem layers used to construct the national map were reclassified separately according to the correspondence rules presented in Table 2 and subsequently combined to produce the IUCN GET map.

High-mountain and alpine grasslands were combined into EFG T6.4 Temperate alpine grasslands and shrublands. Sub-alpine and steppe grasslands were assigned to EFG T4.5 Temperate subhumid grasslands, while semi-deserts and the small desert area were assigned to EFG T5.1 Semi-desert steppes. All types of natural and anthropogenic woodlands were combined into EFG T4.4 Temperate woodlands, and all types of natural and anthropogenic forests into EFG T2.2 Deciduous temperate forests. All ecosystem types occurring within the delineated settlement areas, as well as quarries and landfills, were assigned to EFG T7.4 Urban and industrial ecosystems. Because some ecosystem types with sparse vegetation represented in the national map, such as sandy habitats and anthropogenically degraded areas, have no direct equivalents in the GET, these classes were assigned to the EFGs corresponding to the vegetation zones in which they occur.

The grassland layers were first reclassified and used as the underlying layer of the GET map. The wetland and sparsely vegetated ecosystem layers were subsequently overlaid on the grassland layer. Sandy and clay habitats, as well as anthropogenic sparsely vegetated areas, were not retained as separate classes; their areas within the semi-desert and steppe zones were reassigned to the corresponding GET grassland classes.

The actively used cropland layer was then overlaid and reclassified as T7.1 Annual croplands. The broader Actively cultivated landscapes layer and the Livestock camps layer were not included in the GET map. Forest and woodland masks, including anthropogenic woody vegetation and planted forests and woodlands, were subsequently overlaid on the preceding layers. This ensured that closed forest and open woodland areas assigned to anthropogenic woody vegetation classes in the national map were reassigned to the corresponding forest or woodland GET classes. The Tree, vine and shrub crops layer was then overlaid and reclassified as T7.3 Plantations.

Finally, the settlement layer was overlaid on all preceding ecosystem layers. Consequently, all ecosystem and land-cover types occurring within the delineated settlement areas were assigned to T7.4 Urban and industrial ecosystems. Quarries and landfills were likewise assigned to T7.4.

GET functional group T7.5 Derived semi-natural pastures and old fields, corresponding to part of the informational human-modified landscape layer, was not included in the GET map because, at the present stage, its spatial distribution cannot be reliably delineated within the heterogeneous mosaic of the human-modified landscape.

GET functional groups of the freshwater biome occurring in Armenia were not mapped because the project scope was limited to terrestrial ecosystems; therefore, surface water was retained on the GET map without reclassification.

Table 2. Crosswalk of ecosystem types from the Ecosystem map of Armenia to the IUCN GET.

National ecosystem map of Armenia		IUCN GET Ecosystem Functional Group (EFG)
Grasslands	Desert	T5.1 Semi-desert steppes
	Semi-desert	
	Steppe	T4.5 Temperate subhumid grasslands
	Subalpine	T6.4 Temperate alpine grasslands and shrublands
	Alpine	
Wetlands	Fens and wet meadows	TF1.7 Boreal and temperate fens
	Permanent marshes in the Ararat Valley	TF1.3 Permanent marshes
Natural forests	<i>Fagus orientalis</i> + <i>Carpinus</i> , <i>Tilia</i> , etc.	T2.2 Deciduous temperate forests
	<i>Quercus macranthera</i> + <i>Carpinus</i> , <i>Tilia</i> , etc.	
	<i>Quercus macranthera</i>	
	<i>Quercus iberica</i> + <i>Carpinus</i> , <i>Tilia</i> , etc.	
	<i>Quercus iberica</i>	
	<i>Pinus kochiana</i> (natural stands)	
Natural open woodlands	Subalpine woodlands	T4.4 Temperate woodlands
	Deciduous and mixed woodlands	
	Juniper woodlands	
Anthropogenic woody vegetation	Planted forests and woodlands	T2.2 Deciduous temperate forests
	Forest-like vegetation in human-modified landscapes	T2.2 Deciduous temperate forests
	Open woodland-like vegetation in human-modified landscapes	T4.4 Temperate woodlands
	Tree, vine and shrub crops	T7.3 Plantations
Sparse vegetation	High-mountain	T6.2 Polar-alpine rocky outcrops
	Rocky habitats	T3.4 Rocky pavements, scree and lava flows
	Sandy and clay habitats	Areas within the vegetation zones were reclassified into the corresponding grassland EFG
Agricultural areas	Actively used croplands	T7.1 Annual croplands
	Actively cultivated landscapes	
Built-up and technogenically disturbed areas	Buildings	T7.4 Urban and industrial ecosystems
	Settlements	
	Quarries	
	Landfills	
	Sparse vegetation in human-modified landscapes	Areas within the vegetation zones were reclassified into the corresponding grassland EFG

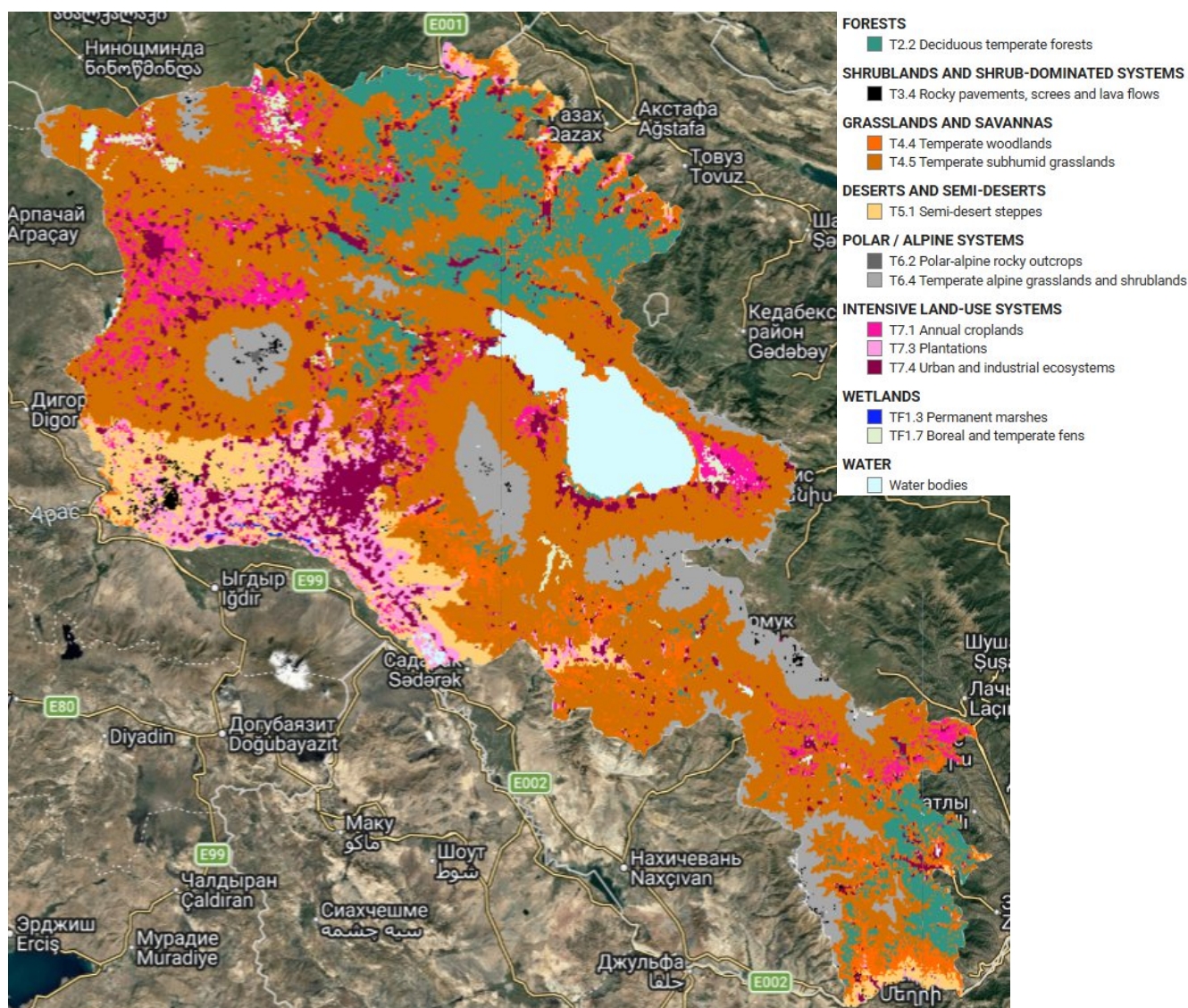


Figure 22. Ecosystem map of Armenia crosswalked to the IUCN Global Ecosystem Typology (GET).

2.5. Interactive map

The Ecosystem map of Armenia is available as an interactive online map (link above) that allows users to explore the map at different spatial scales, display different versions of the ecosystem map, examine individual ecosystem layers, and access additional spatial information (Fig. 23). The interactive map provides three main map modes:

“EXPLORE INDIVIDUAL LAYERS” allows users to display individual ecosystem layers separately and switch them on and off using the corresponding checkboxes.

“ECOSYSTEM MAP OF ARMENIA” displays the integrated ecosystem layer using the ecosystem classification developed for this map.

“IUCN GLOBAL ECOSYSTEM TYPOLOGY MAP” displays the integrated ecosystem layer crosswalked to the IUCN Global Ecosystem Typology (GET).

Each map mode has its own legend, which can be displayed or hidden independently. Multiple map modes and their corresponding legends can be displayed simultaneously by selecting the relevant checkboxes. This allows users to visually compare the different map layers and explore their spatial relationships.

When only one map mode is enabled, clicking on the map displays the ecosystem type at the selected location. In “EXPLORE INDIVIDUAL LAYERS” mode, the information corresponds to the uppermost visible ecosystem layer at the selected location.

Additional information can be displayed independently of the selected map mode. Settlement names, marz boundaries, and elevation can be switched on and off to facilitate spatial orientation and interpretation of the map. The map also includes national protected areas, Emerald Network sites, and Ramsar sites; clicking on these areas displays their names and, where available, additional information. Two layers provide supplementary information on human influence on natural landscapes: human-modified landscapes and potential grazing-pressure zones. These layers can be switched on and off independently and compared with the ecosystem layers.

The map can be explored by zooming and panning. Because the ecosystem layers are displayed at high spatial resolution, map rendering may take a few moments after zooming or moving.

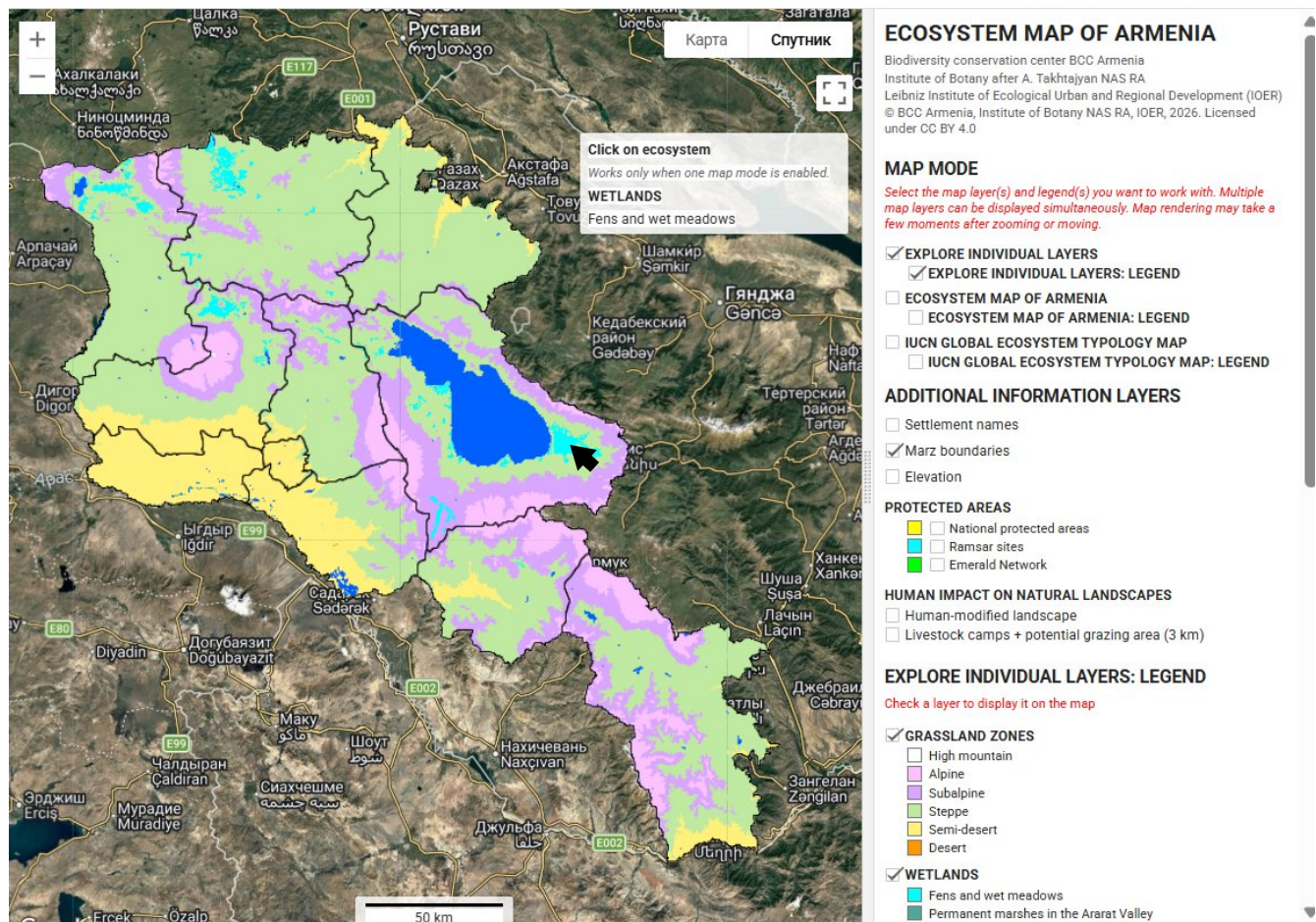


Figure 23. View of the interactive map in “EXPLORE INDIVIDUAL LAYERS” mode, with the grassland and fen layers displayed together with the “Marz boundaries” information layer. The information panel shows the ecosystem type at the selected location within the fen layer.

2.6 Computational environment and resources

Spatial data processing, model implementation, and map development were carried out primarily in Google Earth Engine (GEE). The workflow involved repeated processing of large national-scale raster datasets, including satellite imagery, environmental predictor layers, probability maps, and intermediate and final ecosystem layers. Most raster processing and the final map production were performed at a spatial resolution of 10 m.

Several stages of the workflow were computationally demanding, particularly the generation and processing of large predictor stacks, machine-learning-based probability mapping, spatial filtering and refinement of raster layers, and integration of multiple datasets into the final ecosystem map. Because the methodology was developed iteratively, many of these operations had to be repeated as classification rules, thresholds, and intermediate layers were tested and refined.

As the workflow became increasingly computationally demanding, the cumulative computational demand eventually exceeded the resources available under the Google Earth Engine Contributor Tier, resulting in restricted processing capacity and preventing us from continuing the most demanding national-scale operations. Access to the Google Earth Engine Partner Tier, provided by the Google Earth Engine team to our non-commercial project, offered the additional computational capacity needed to resume and complete these operations and to implement the workflow at the 10 m spatial resolution and national extent used for the final map.

We gratefully acknowledge the Google Earth Engine team for providing access to the Partner Tier, which offered the computational capacity required for the development of the Ecosystem map of Armenia.

3 Ecosystem extent and spatial distribution

3.1 Area statistics of the Ecosystem map of Armenia

According to the Ecosystem map of Armenia, more than half of the country's area is covered by grasslands of different types, ranging from high-mountain grasslands to semi-deserts. Anthropogenic areas account for approximately 27 % of the country, while forests and woodlands cover about 18 %. Wetlands and areas with sparse vegetation each account for less than 1 %, while water bodies cover 4.6 % of Armenia (Table 3, Fig. 24).

Table 3. Ecosystem extent in Armenia

Ecosystems	Area_km ²	Share in Armenia, %
High mountain vegetation	1.13	0.00
Alpine vegetation	2377.00	8.00
Subalpine grasslands	5112.98	17.20
Steppe	6595.66	22.19
Semi-desert	1491.79	5.02
Desert	0.96	0.00
Grasslands subtotal	15579.52	52.41
Fens and wet meadows	148.36	0.51
Permanent marshes in the Ararat Valley	11.36	0.04
Wetlands subtotal	161.72	0.54
High-mountain sparse vegetation	14.73	0.05
Rocky habitats with sparse vegetation	158.48	0.53
Sand and clay habitats with sparse vegetation	75.79	0.25
Ecosystems with sparse vegetation subtotal	248.994221	0.84
Subalpine woodlands	139.21	0.47
Mixed woodlands	1877.77	6.32
Juniper woodlands	55.94	0.19
Natural open woodlands subtotal	2072.92	6.97
Forests: Fagus orientalis and other deciduous	1344.27	4.52
Forests: Quercus macranthera and other deciduous	671.05	2.26
Forests: Quercus macranthera	530.45	1.78
Forests: Quercus iberica and other deciduous	494.25	1.66
Forests: Quercus iberica	90.19	0.30
Forests: Pinus kochiana	5.40	0.02
Forests subtotal	3135.62	10.55
Closed forest plantations	51.47	0.17
Open woodland plantations	91.81	0.31
Forest plantations subtotal	143.29	0.48
Actively cultivated landscapes	1932.11	6.49
Actively used croplands	1615.50	5.43
Actively cultivated landscapes subtotal	3545.61	11.93
Tree, vine and shrub crops	1036.00	3.48
Settlements	807.19	2.72
Buildings	479.72	1.61
Quarries and landfills	78.63	0.26
Forest-like woody vegetation in human-modified landscapes	167.54	0.56
Open woodland-like woody vegetation in human-modified landscapes	624.05	2.10
Sparse vegetation in human-modified landscapes	272.14	0.92
Urban and technogenically disturbed areas subtotal	2429.27	8.17
Water bodies	1376.10	4.63

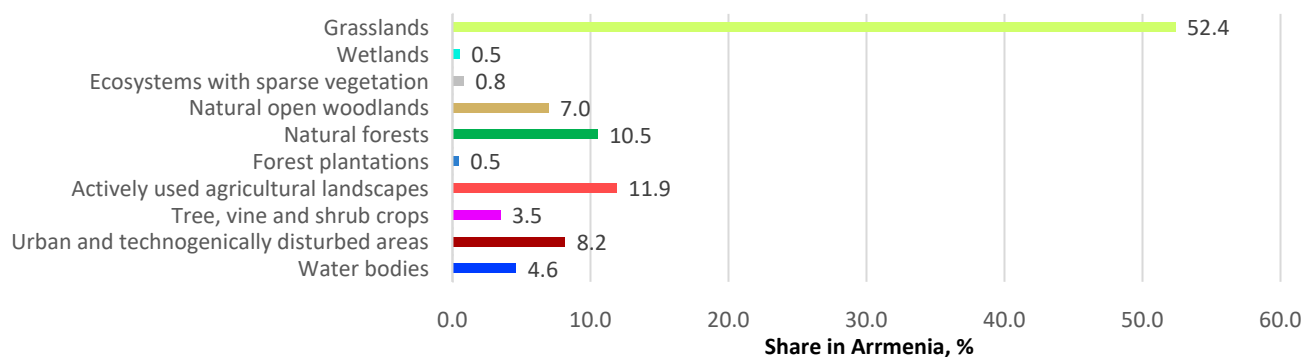


Figure 24. Aggregated ecosystem extent statistics

The area of all ecosystem types included in the Ecosystem map of Armenia for the entire country is shown in Figure 25. Steppes are the most widespread ecosystem type, followed by subalpine and alpine ecosystems. Woodlands are predominantly represented by mixed deciduous–coniferous types, while subalpine and juniper woodlands occupy relatively small areas. Among forests, deciduous forests dominated by *Fagus orientalis*, which are widespread in northern Armenia, have the largest extent, whereas natural forests dominated by *Pinus kochiana* have the smallest extent. The remaining types of natural ecosystems occupy relatively small areas.

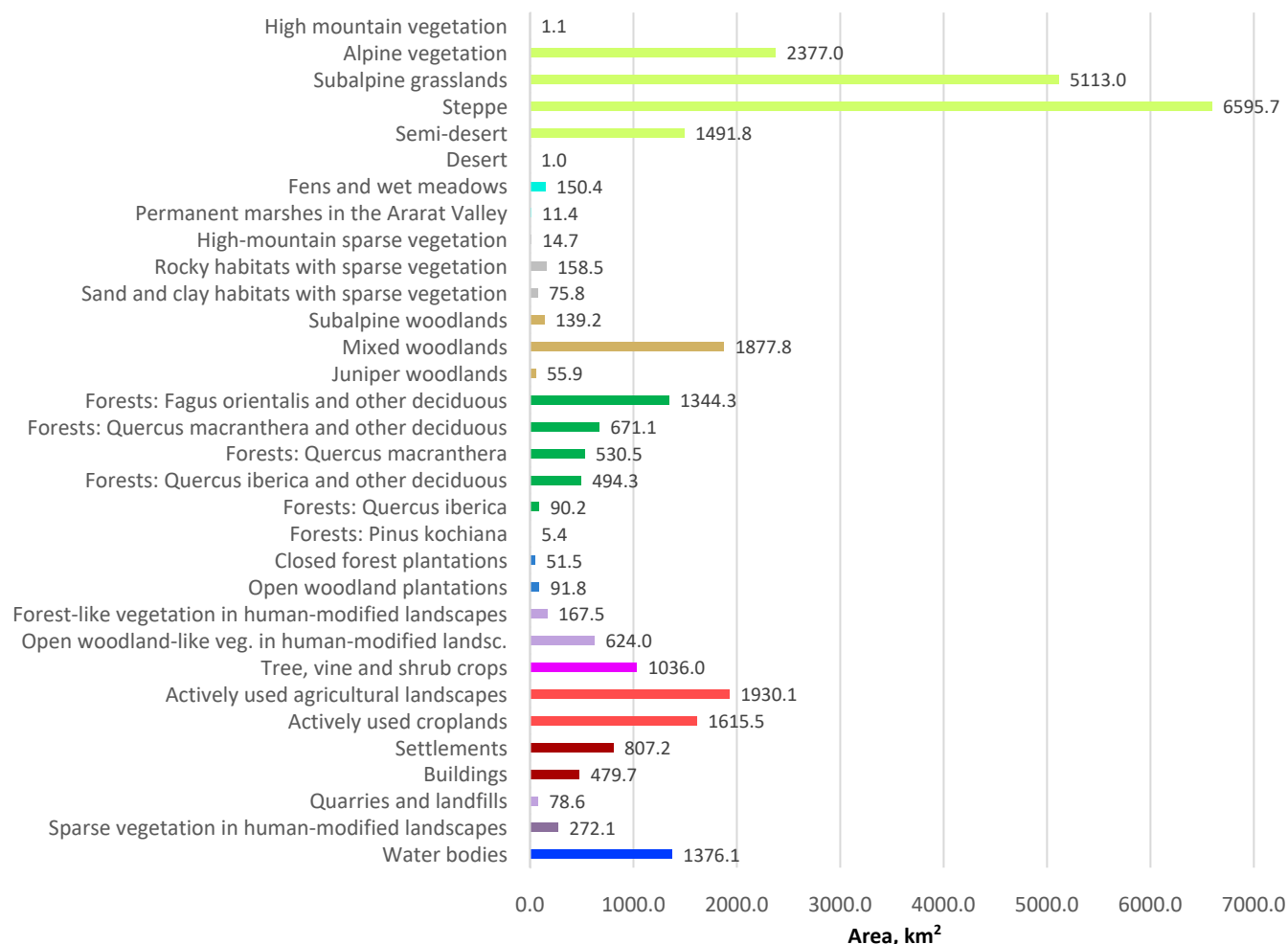


Figure 25. Extent of all ecosystem types in Armenia

Ecosystem extent varies considerably among marzes (Figure 26, Table 4). In all marzes except Tavush and Vayots Dzor, a substantial proportion of the area is occupied by anthropogenic systems. The largest areas of subalpine and alpine ecosystems occur in Gegharkunik and Syunik, while steppe ecosystems are most extensive in Lori. Semi-desert ecosystems occupy their largest areas in Armavir, Ararat, and Aragatsotn. In Armavir, almost the entire marz is occupied by anthropogenic areas and remaining patches of semi-desert ecosystems. Woodlands, including juniper woodlands, are most extensive in Syunik. Beech forests are concentrated mainly in Tavush and Lori. Oak forests have their largest extent in Syunik, while substantial areas also occur in Tavush and Lori.

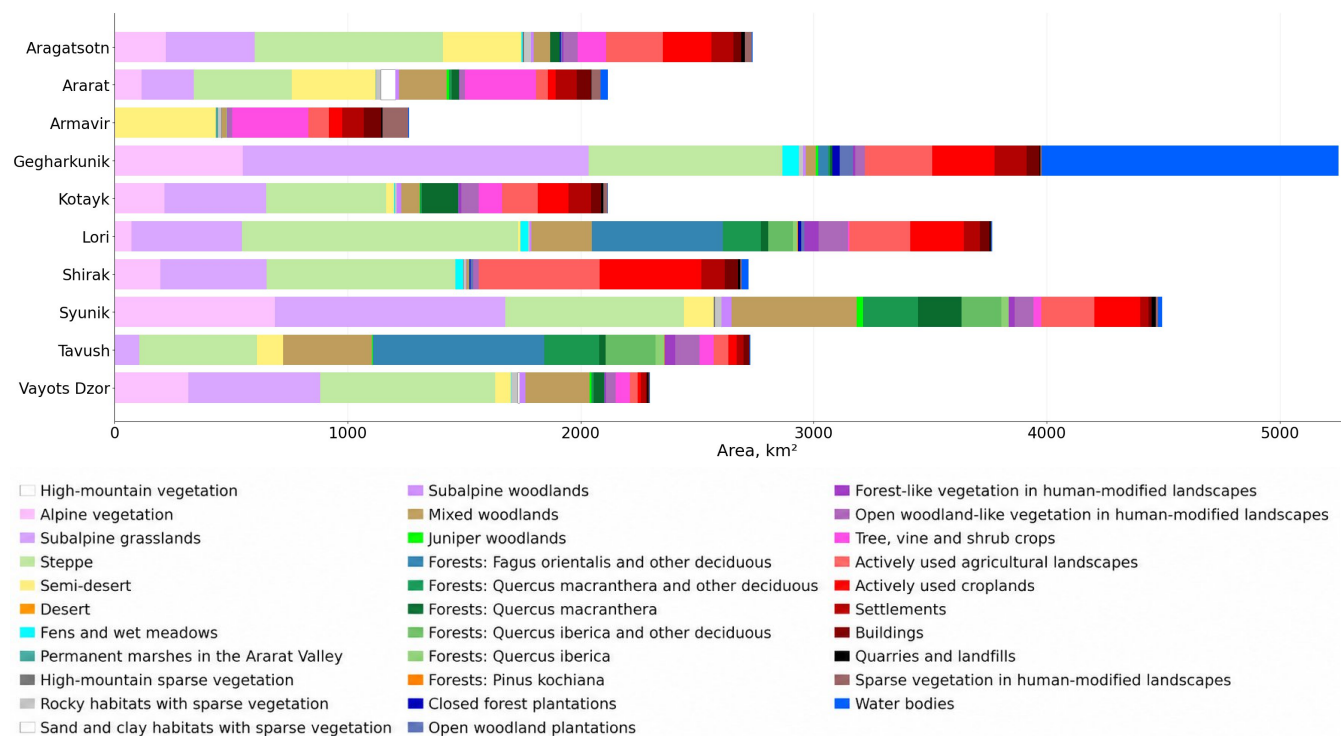


Figure 26. Ecosystem extent across marzes

Table 4. Extent of all ecosystem types in Armenia and across marzes, km²

	Aragatsotn	Ararat	Armavir	Gegharkunik	Kotayk	Lori	Shirak	Syunik	Tavush	Vayots Dzor	Yerevan	Armenia
High mountain vegetation	0.6	0.0	0.0	0.0	0.0	0.0	0.2	0.3	0.0	0.0	0.0	1.1
Alpine vegetation	219.5	116.3	0.0	550.3	214.2	73.6	195.9	688.3	2.0	316.9	0.0	2377.0
Subalpine grasslands	380.6	223.7	0.0	1484.7	437.2	472.9	456.6	987.4	104.2	565.9	0.0	5113.1
Steppe	809.0	420.7	0.5	831.7	513.6	1185.2	808.7	767.0	504.6	750.8	3.7	6595.6
Semi-desert	335.5	359.0	433.1	0.0	33.8	9.4	0.0	127.6	112.4	66.9	13.9	1491.7
Desert	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
Fens and wet meadows	6.5	0.0	0.0	69.7	3.5	34.2	34.3	0.0	0.0	0.2	0.0	150.4
Permanent marshes in the Ararat Valley	0.0	1.2	10.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.4
High-mountain sparse vegetation	6.4	0.0	0.0	0.1	0.2	0.0	2.7	5.4	0.0	0.0	0.0	14.7
Rocky habitats with sparse vegetation	29.1	20.7	13.7	17.5	7.3	4.7	9.8	28.2	0.2	27.3	0.0	158.5
Sand and clay habitats with sparse vegetation	0.3	63.1	2.0	1.0	0.2	0.2	0.2	0.9	0.0	7.9	0.0	75.8
Subalpine woodlands	11.5	15.3	0.0	11.2	21.2	9.2	1.4	43.4	0.3	25.7	0.0	139.2
Mixed woodlands	69.5	204.9	20.9	43.5	78.1	258.3	10.6	535.3	381.3	275.5	0.0	1877.8
Juniper woodlands	0.0	8.0	0.0	8.5	1.2	0.4	0.0	28.5	3.0	6.4	0.0	55.9
Forests: <i>Fagus orientalis</i> and other	0.0	0.0	0.0	44.1	0.0	562.6	2.0	0.0	735.5	0.0	0.0	1344.2
Forests: <i>Quercus macranthera</i> and other	1.0	12.7	0.0	7.3	8.0	161.9	0.1	235.2	235.3	9.6	0.0	671.1
Forests: <i>Quercus macranthera</i>	41.3	30.7	0.0	10.4	155.0	31.9	0.2	186.9	28.7	45.4	0.0	530.4

Forests: <i>Quercus iberica</i> and other	0.6	1.3	0.1	0.9	0.5	106.5	0.0	170.1	213.2	1.1	0.0	494.3
Forests: <i>Quercus iberica</i>	0.0	0.0	0.5	0.0	0.0	18.3	0.0	32.5	38.9	0.0	0.0	90.2
Forests: <i>Pinus kochiana</i>	0.0	0.0	0.0	0.0	0.0	3.8	0.0	0.0	1.6	0.0	0.0	5.4
Closed forest plantations	3.3	0.0	0.0	30.5	0.3	12.5	4.8	0.0	0.0	0.1	0.0	51.5
Open woodland plantations	6.1	0.1	0.0	56.5	2.4	15.0	10.7	0.0	0.0	1.0	0.0	91.8
Forest-like vegetation in human-modified landscapes	5.6	1.1	0.7	10.6	12.0	59.8	1.7	24.9	44.0	5.8	1.2	167.5
Open woodland-like vegetation in human-modified landscapes	60.9	23.3	24.4	41.5	74.0	126.5	22.4	81.7	105.3	41.0	23.1	624.1
Tree, vine and shrub crops	122.4	305.9	324.9	0.0	99.5	6.6	0.0	32.5	59.6	61.6	23.0	1036.0
Actively used agricultural landscapes	243.9	49.7	88.4	289.3	153.0	261.1	519.9	228.8	63.1	34.6	0.3	1930.1
Actively used croplands	208.0	34.6	57.5	266.4	133.4	230.4	435.7	196.9	36.9	15.4	0.4	1615.5
Settlements	93.2	89.9	92.0	138.7	95.0	68.7	100.3	34.7	28.6	21.6	44.6	807.2
Buildings	34.0	60.5	74.8	53.8	44.4	40.6	56.8	12.7	25.2	5.9	71.2	479.8
Quarries and landfills	15.8	2.5	5.3	4.9	8.9	6.4	9.1	17.8	0.6	4.6	2.6	78.6
Sparse vegetation in human-modified landscapes	28.5	38.7	110.3	5.3	17.1	1.8	6.6	10.5	0.3	4.6	48.4	272.1
Water bodies	4.9	31.9	5.3	1273.4	2.6	3.4	29.4	18.3	3.5	2.5	0.8	1376.1

Of the 19 natural ecosystem types included in the map, 10 can be considered rare, as each occupies less than 1 % of Armenia's area. These include desert ecosystems, natural pine forests, both wetland types, all types of natural sparse-vegetation habitats, and pure *Quercus iberica* forests occurring along the lower boundary of the forest belt (Figure 27).

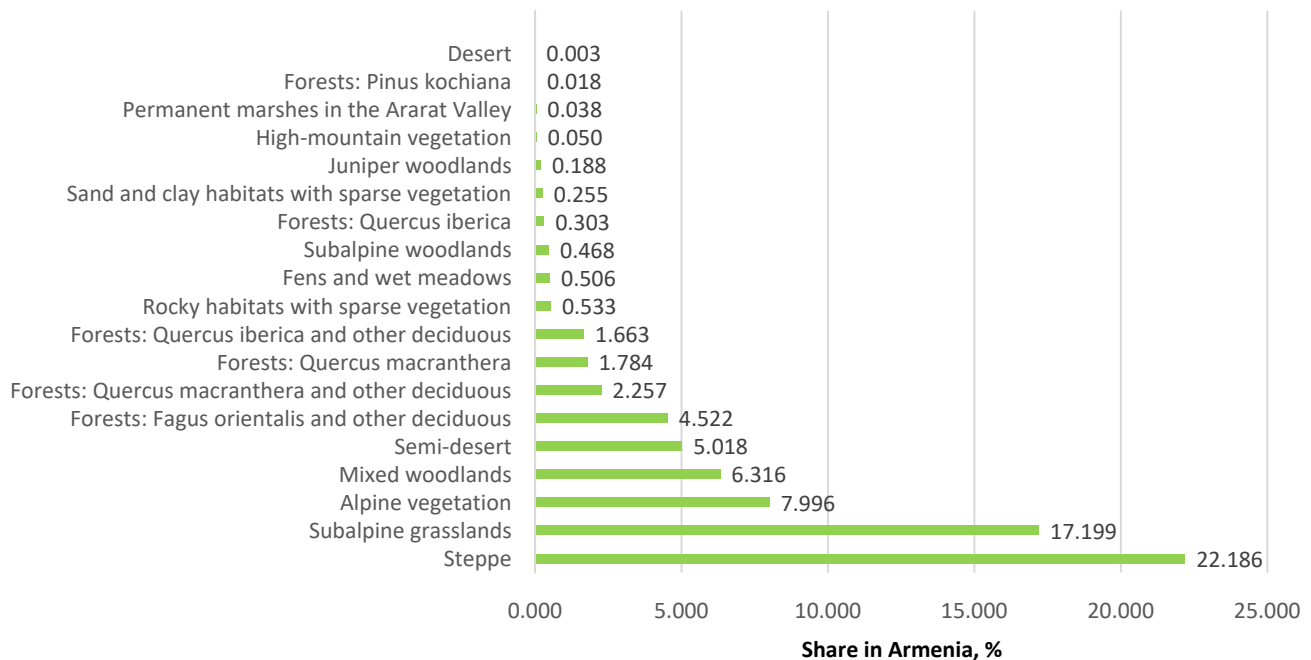


Figure 27. Ranking of natural ecosystem types by rarity

Ecosystem extent accounting based on the ecosystem map makes it possible to assess how rare ecosystems are distributed among marzes. This information can support the optimal allocation of conservation efforts aimed at maintaining ecosystem diversity within the territorial management system. Overall, the largest total area of different rare ecosystem types occurs in Syunik, while the smallest occurs in Armavir (Fig. 28). Nevertheless, Armavir contains almost all permanent marshes of the Ararat Valley. Syunik supports the largest areas of the identified juniper and subalpine woodlands, as well as pure *Quercus iberica* stands. Fens and wet meadows occur primarily in Gegharkunik, with substantial areas also found in Lori and Shirak. Sandy habitats are concentrated in Ararat, while rocky habitats are most extensive in Aragatsotn and Syunik, with smaller areas occurring in other marzes. The small area of desert ecosystem is located within the Goravan Sands protected area in Ararat.

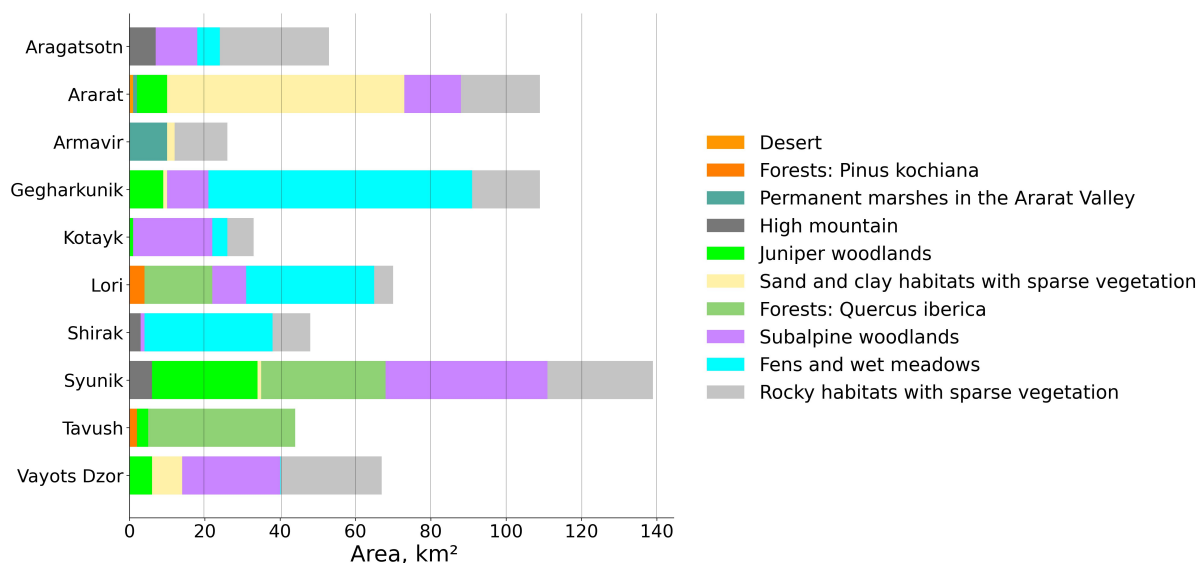


Figure 28. Extent of rare ecosystems across marzes

Some types of rare ecosystems are distributed across almost all marzes, such as Rocky habitats with sparse vegetation and subalpine woodlands. Other types, in contrast, occur in only one or two marzes. The only remaining area of sandy desert in Armenia is located in Ararat marz, which also contains most of the sand and clay habitats with sparse vegetation. Permanent marshes are concentrated mainly in Armavir marz, while natural pine forests persist in only two marzes—Lori and Tavush (Fig. 29).

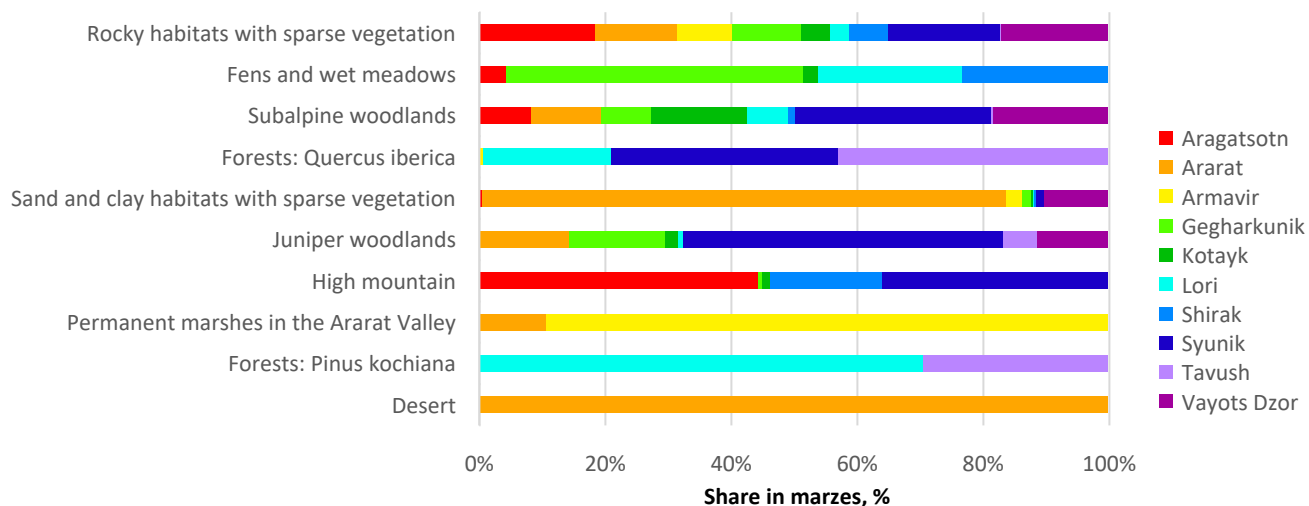


Figure 29. Distribution of the total area of rare ecosystem types among the marzes of Armenia.

3.2 Degree of anthropogenic transformation of vegetation zones

The layer-based structure of the interactive map retains the potential distribution of grassland and fen ecosystem types separately from anthropogenic layers. This makes it possible to overlay anthropogenic land cover on the potential ecosystem distribution and to assess the degree of anthropogenic transformation of these ecosystem types both visually and quantitatively. In this study, we were unable to assess the degree of anthropogenic transformation of forests and woodlands, as this would require a map of their potential pre-anthropogenic distribution, which was not available.

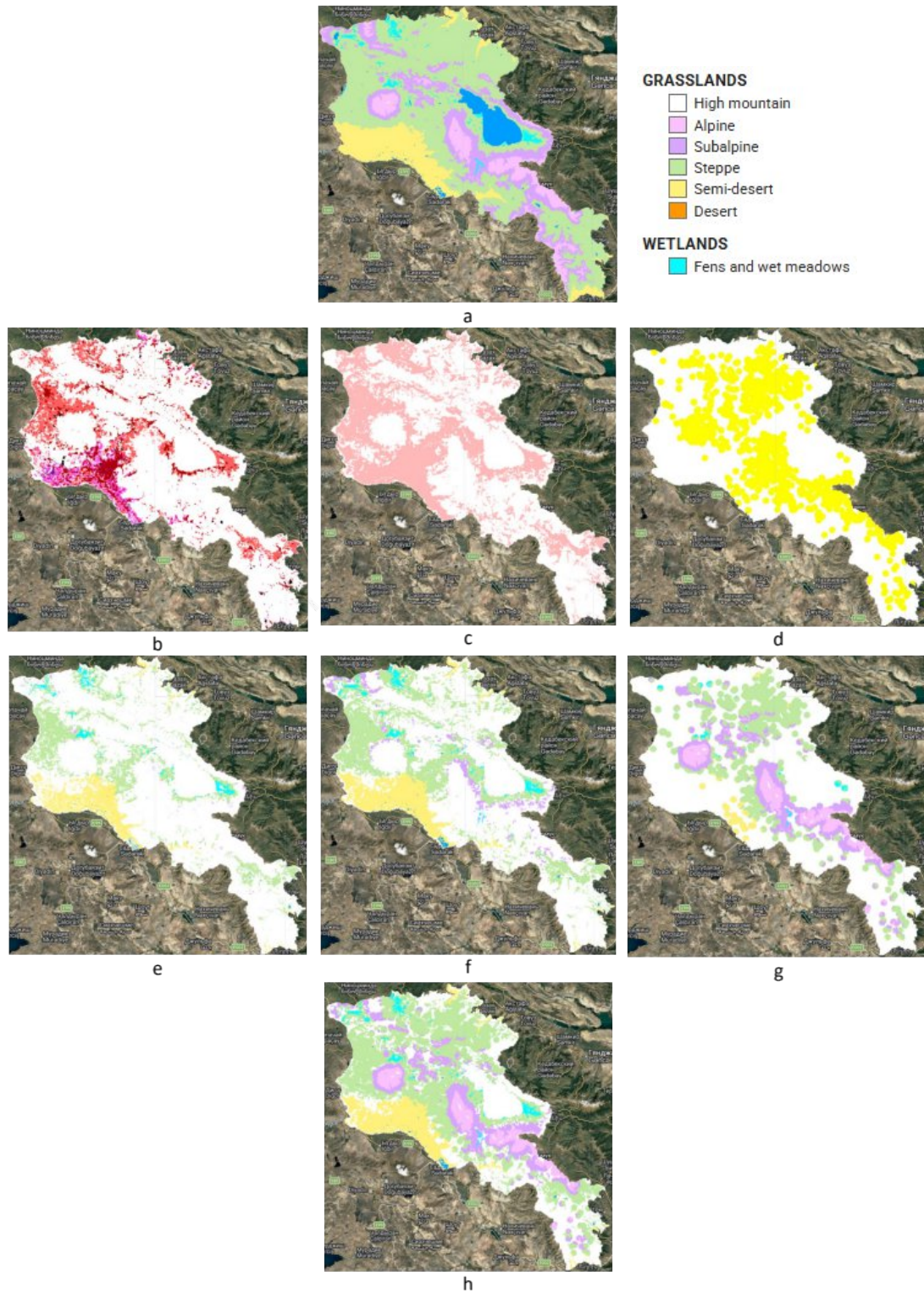


Figure 30. Mapping of anthropogenic transformation of ecosystems: a) assessed potential vegetation zones; b) actively cultivated landscapes, tree, vine and shrub crops, urban and technogenically disturbed areas; c) human-modified landscapes; d) potential grazing areas; e–g) areas of potential vegetation zones affected by the types of anthropogenic influence shown in panels b–d, respectively; h) areas of potential vegetation zones affected by one or more types of anthropogenic influence. In panels b–h, areas unaffected by the anthropogenic influences considered here are shown in white.

We assessed the anthropogenic influence on the potential distribution areas of six grassland ecosystem types, as well as fens and wet meadows (Fig. 30a). For this purpose, three layers representing different types of anthropogenic influence were used: 1) intensively used anthropogenic areas, including actively cultivated landscapes, tree, vine and shrub crops, settlements, anthropogenic sparse-vegetation areas, quarries, and landfills (Fig. 30b); 2) broad human-modified landscapes, which represent a mosaic of anthropogenic areas and the natural patches between them (Fig. 30c); and 3) potential grazing areas, mapped as 3-km buffers around livestock camps (Fig. 30d).

These layers were used to determine the areas of grasslands and fens affected by these types of anthropogenic influence. In Fig. 30e–h, the affected areas are shown according to their potential ecosystem type, using the same colors as in Fig. 30a, while areas unaffected by the anthropogenic influences considered here are shown in white:

- areas converted to intensively used anthropogenic land (Fig. 30e), which are most extensive within the steppe and semi-desert zones (light green and yellow in Fig. 30e) and also occupy a large proportion of the potential distribution area of fens and wet meadows (cyan in Fig. 30e);
- areas located within broad human-modified landscapes (Fig. 30f), which cover even larger areas of steppe, semi-desert, and fens, and also extend into the subalpine zone (purple in Fig. 30f);
- areas potentially affected by grazing (Fig. 30g), which are most extensive in the steppe zone, as well as in the alpine and subalpine zones (shown by the corresponding colors of these zones in Fig. 30g);
- areas affected by one or more types of anthropogenic influence (Fig. 30h), representing the combined footprint of anthropogenic influence, cover most of Armenia, with the most noticeable remaining patches unaffected by these influences occurring in the south of the country, particularly in Syunik and Vayots Dzor marzes.

According to our map, intensively used anthropogenic areas occupy 24 % of Armenia, while human-modified landscapes, comprising a mosaic of transformed and natural areas, cover 37%, and potential grazing areas cover 42 %. Areas free from these types of anthropogenic influence account for 32 % of the assessed territory. The percentages exceed 100 % because areas of considered anthropogenic influence overlap (Table S4; Fig. 31a).

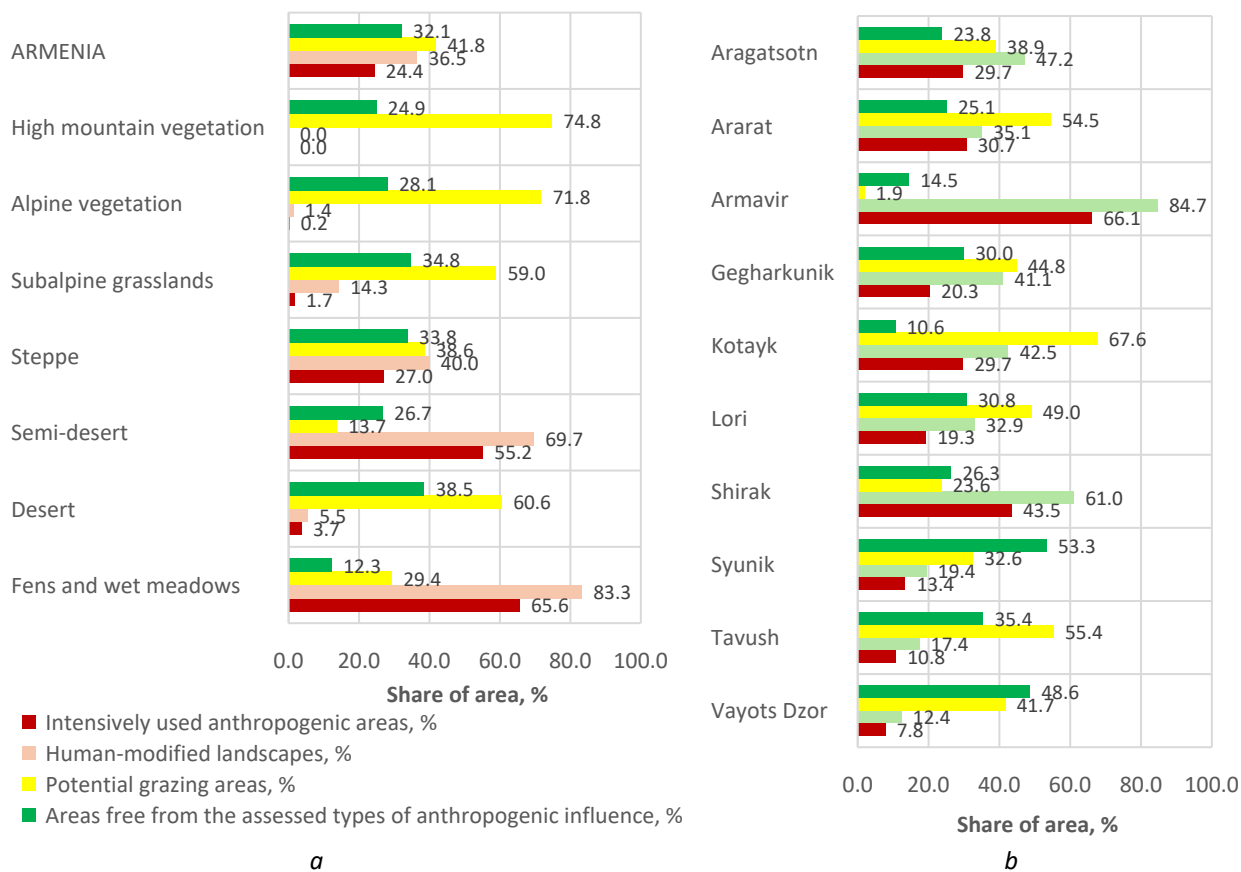


Figure 31. Proportion of the area of potential vegetation zones affected by anthropogenic influence: a) across vegetation zones; b) across marzes.

Fens and wet meadows are the most affected by anthropogenic influence, with only 12 % of their potential area remaining free from the types of anthropogenic influence considered here. They also have the highest proportion of intensively used anthropogenic areas, i.e. areas converted to cropland and built-up land. The semi-desert, alpine, and high-mountain zones are also substantially affected, with only about 20–30 % of their potential area remaining free from the assessed anthropogenic influences. In the semi-desert zone, the main forms of anthropogenic influence are intensive land use and broader human modification of landscapes, whereas in the alpine and high-mountain zones, livestock grazing is the dominant influence. The steppe and subalpine zones are less affected, with more than 30 % of their potential area remaining free from the assessed anthropogenic influences.

The relatively high proportion of the potential desert zone classified as free from anthropogenic influence should not be interpreted as indicating low anthropogenic pressure for two reasons. First, all mapped desert ecosystems occur within the small Goravan Sands State Sanctuary. Second, our method identifies potential grazing areas only within buffers around livestock camps, whereas livestock from nearby settlements may also graze within the sanctuary and such grazing is therefore not fully captured by our assessment.

Among the marzes, Kotayk and Armavir are the most affected by anthropogenic influence, with only 11 % and 14 % of their territories, respectively, remaining free from the types of anthropogenic influence considered here (Fig. 31b). However, the dominant types of anthropogenic influence differ between the two marzes. In Armavir, the main factor is intensive land use, including conversion to croplands, orchards and vineyards, and built-up areas, whereas in Kotayk, livestock grazing is the dominant influence. Syunik and Vayots Dzor are the least affected, with 53 % and 49 % of their territories, respectively, remaining free from the assessed anthropogenic influences; in both marzes, livestock grazing represents the main type of anthropogenic influence. The other marzes occupy intermediate positions with respect to these indicators.

A more detailed analysis of the factors driving intensive anthropogenic transformation shows that such transformation is virtually absent in the high-mountain, alpine, subalpine, and desert zones (Table 5; Fig. 32). However, it should be kept in mind that a large proportion of these zones is potentially affected by livestock grazing. The highest degree of intensive transformation is observed for fens and wet meadows, where more than 60 % of their potential extent is currently occupied by croplands. The semi-desert zone is the next most intensively transformed, with more than 50 % of its area occupied primarily by tree, vine and shrub crops and settlements, including Yerevan. The semi-desert zone also contains a substantial proportion of anthropogenically degraded areas characterized by sparse vegetation and near-zero NDVI. In the steppe zone, less than 30 % of the potential extent is occupied by actively cultivated landscapes and settlements.

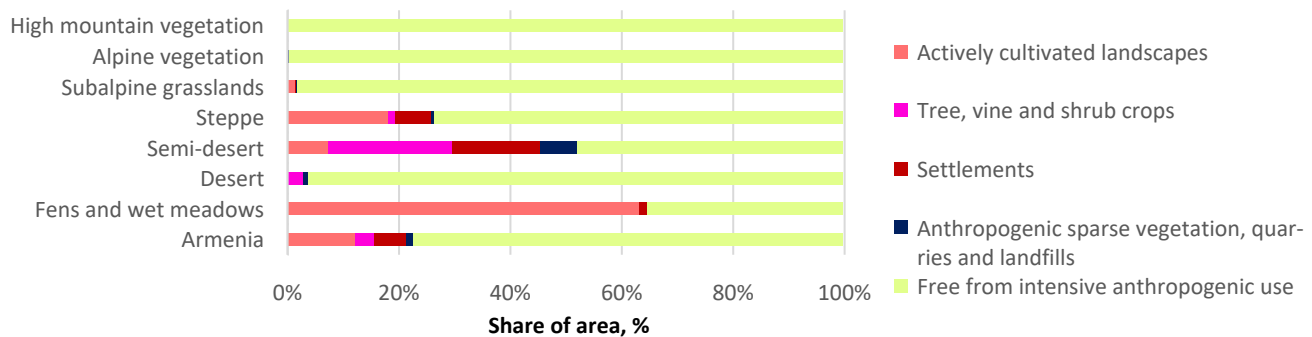


Figure 32. Share of potential vegetation zone area transformed by different types of anthropogenic land use, %

Table 5. Share of potential vegetation zone area transformed by different types of anthropogenic land use, %

	Actively cultivated landscape	Tree, vine and shrub crops	Settlements	Anthropogenic sparse vegetation, quarries and landfills	Not transformed
High mountain vegetation	0.00	0.00	0.00	0.00	100.00
Alpine vegetation	0.00	0.00	0.06	0.18	99.76
Subalpine grasslands	1.38	0.00	0.13	0.16	98.32
Steppe	18.15	1.09	6.56	0.52	73.67
Semi-desert	7.37	22.17	15.85	6.52	48.09
Desert	0.00	2.76	0.00	0.92	96.32
Fens and wet meadows	63.11	0.00	1.36	0.09	35.43
Armenia	12.10	3.48	5.67	1.24	77.51

3.3 Ecosystem representation in protected areas

The representation of ecosystem types within Armenia's protected-area (PA) network was assessed as the proportion of the total area of each ecosystem type occurring within PAs. The analysis included national parks, state reserves, and state sanctuaries, which were combined to estimate the overall PA coverage of each ecosystem type (Table 6).

Table 6. Area and proportion of ecosystem types within Armenia's protected areas

Ecosystems	Total area in Armenia, km ²	Area in national parks and reserves, km ²	Share of area in national parks and reserves, %	Area in sanctuaries, km ²	Share of area in sanctuaries, %	Share of area in all PAs, %
High mountain vegetation	1.13	0.05	4.39	0.22	19.79	24.18
Alpine vegetation	2377.05	80.60	3.39	257.44	10.83	14.22
Subalpine	5113.06	177.13	3.46	196.17	3.84	7.30
Steppe	6603.60	210.90	3.19	31.23	0.47	3.67
Semi-desert	1493.50	30.97	2.07	0.69	0.05	2.12
Desert	0.96	0.00	0.00	0.85	88.32	88.32*
Fens and wet meadows	148.35	15.59	10.37	0.00	0.00	10.37
Permanent marshes in the Ararat Valley	11.36	0.00	0.00	0.00	0.00	0.00
High-mountain	14.73	0.99	6.72	3.90	26.47	33.20
Rocky habitats	158.53	7.40	4.67	9.21	5.81	10.48
Sandy and clay habitats	75.77	2.58	3.41	0.05	0.07	3.48
Subalpine woodlands	137.83	16.51	11.98	27.15	19.70	31.68
Other woodlands	1890.89	271.03	14.33	74.17	3.92	18.26
Juniper woodlands	56.38	23.86	42.33	4.51	8.00	50.32
<i>Fagus orientalis</i> and other deciduous	1339.32	138.95	10.37	81.98	6.12	16.50
<i>Quercus macranthera</i> and other deciduous	663.91	135.12	20.35	30.65	4.62	24.97
<i>Quercus macranthera</i>	521.56	101.56	19.47	109.46	20.99	40.46
<i>Quercus iberica</i> and other deciduous	493.90	51.49	10.42	16.37	3.32	13.74
<i>Quercus iberica</i>	90.57	1.96	2.17	2.89	3.20	5.36
<i>Pinus kochiana</i>	5.45	0.47	8.59	0.79	14.56	23.15
Closed-canopy forest plantations	48.10	25.83	53.70	0.00	0.00	53.70
Open-canopy forest plantations	87.30	48.38	55.41	0.00	0.00	55.41

* The Desert ecosystem was delineated using the boundary of the Goravan Sands sanctuary and would therefore be expected to be 100 % protected. The lower calculated value (88.32 %) results from a spatial mismatch between the boundary used for ecosystem delineation and that provided by the protected-area dataset used in this analysis.

Weak negative relationships were observed between ecosystem area and its representation within the PA network (Fig. 33). The proportion of ecosystem area under protection tended to decrease with increasing total ecosystem area. For rare ecosystem types occupying small total areas in Armenia, the relationship indicates a protected proportion of around 30 %, whereas for extensive ecosystems, such as subalpine grasslands and steppes, it decreases to less than 10 %. Thus, smaller and spatially restricted ecosystem types tended, on average, to have a higher proportion of their area under protection, whereas the largest ecosystem types were generally less well represented. However, rare ecosystem types showed very high variability in their representation within the PA network, ranging from almost 0 % to 88 %.

Despite the different shapes of the linear and nonlinear relationships, several ecosystem types were underrepresented relative to both: fens and wet meadows, permanent marshes, rocky habitats, sand and clay habitats, *Pinus kochiana* and *Quercus iberica* forests, and semi-deserts. Desert and juniper woodlands largely followed the nonlinear relationship but nevertheless represent notable examples of ecosystem types with a very high proportion of their area under protection.

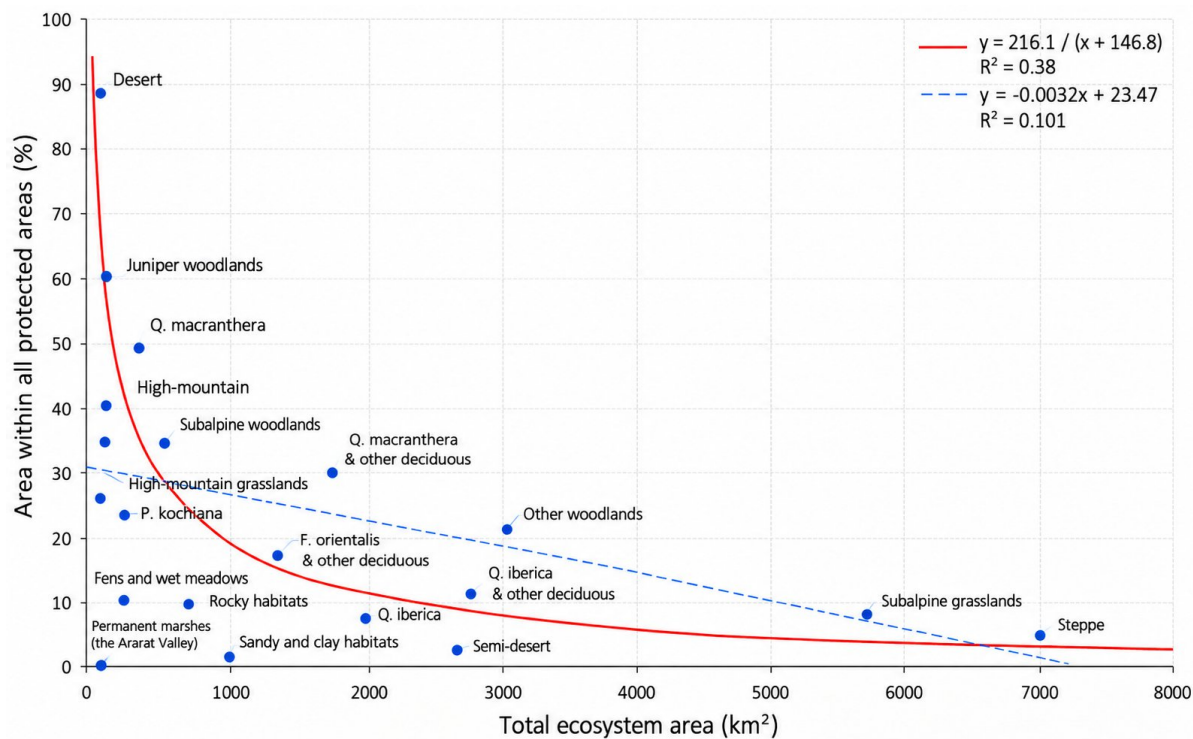


Figure 33. Relationship between ecosystem area and its representation within Armenia's PA network.

3.4 Ecosystem extent according to the IUCN Global Ecosystem Typology

Ecosystem extent in the GET-compatible map corresponds to the extent of the respective ecosystem types in the Ecosystem map of Armenia, either directly reclassified or aggregated into GET Ecosystem Functional Groups according to the methodology described in Section 2.4 (Table 7, Figure 34).

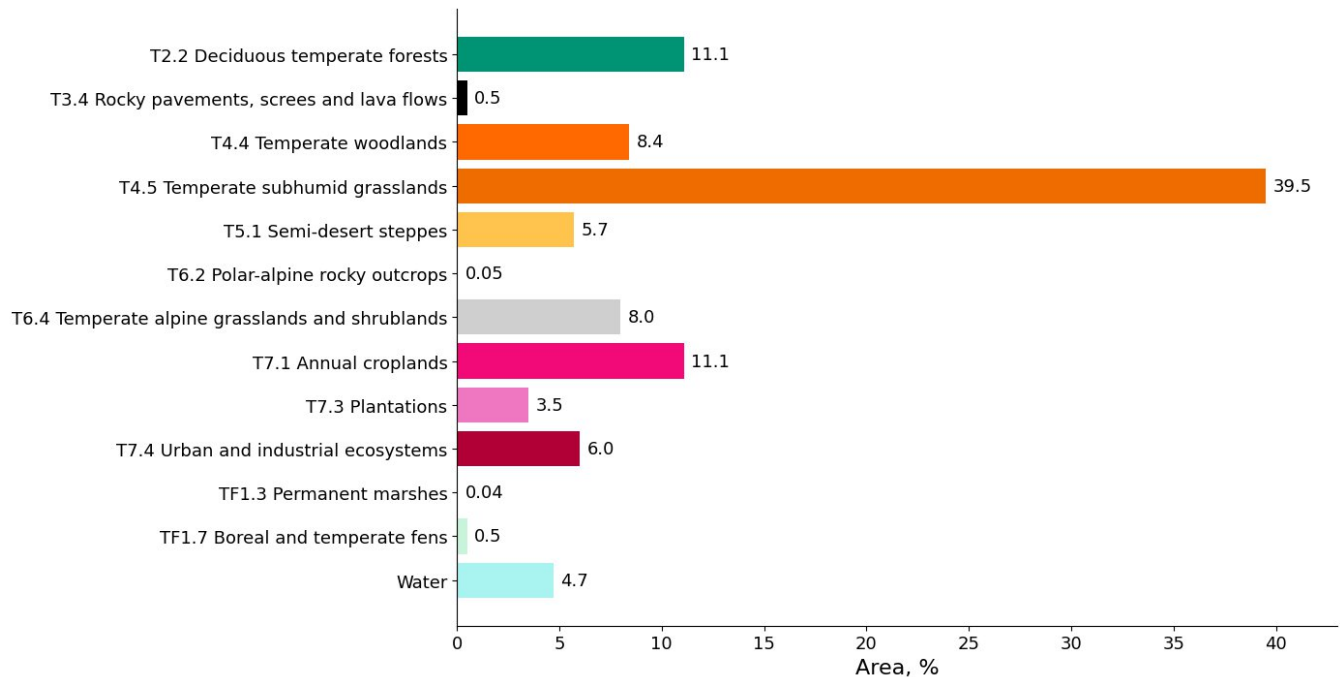


Figure 34. Proportional extent of ecosystem types in the GET-compatible Ecosystem Map of Armenia.

Table 7. Cross-referencing and extent of ecosystem types in the national Ecosystem Map of Armenia and the GET-compatible map.

Ecosystem map of Armenia						IUCN GET map							
Ecosystem types		Area, km²	%	Subtotal		EFG	Area, km²	%					
				Area, km²	%								
High mountain	High mountain vegetation	1.1	0.0	2379.8	8.0	T6.4 Temperate alpine grasslands and shrublands	2379.8	8.0					
Alpine	Alpine vegetation	2377.0	8.0										
	Sparse vegetation on sand and clay substrates	0.6	0.0										
	Human-modified sparse vegetation	1.1	0.0										
Subalpine	Subalpine grasslands	5113.0	17.2	11753.1	39.5	T4.5 Temperate subhumid grasslands	11753.1	39.5					
	Sparse vegetation on sand and clay substrates	0.5	0.0										
	Human-modified sparse vegetation	1.5	0.0										
Steppe	Steppe grasslands	6595.7	22.2						1683.6	5.7	T5.1 Semi-desert steppes	1683.6	5.7
	Sparse vegetation on sand and clay substrates	26.2	0.1										
	Human-modified sparse vegetation	16.2	0.1										
Semi-desert	Semi-desert grasslands	1491.8	5.0	Desert	Desert	1.0	0.0						
	Sparse vegetation on sand and clay substrates	49.6	0.2		Sparse vegetation on sand and clay substrates	0.0	0.0						
	Human-modified sparse vegetation	141.2	0.5		Human-modified sparse vegetation	0.0	0.0						
Wetlands	Fens and wet meadows	148.4	0.5	150.4	0.5	TF1.7 Boreal and temperate fens	148.4	0.5					
	Permanent marshes in the Ararat Valley	11.4	0.0	11.4	0.0	TF1.3 Permanent marshes	11.4	0.04					
Sparse vegetation	High-mountain sparse vegetation	14.7	0.0	14.7	0.1	T6.2 Polar-alpine rocky outcrops	14.7	0.05					
	Rocky habitats	158.5	0.5	158.5	0.5	T3.4 Rocky pavements, scree and lava flows	158.5	0.5					
Open woodlands	Subalpine woodlands	139.2	0.5	2509.9	8.4	T4.4 Temperate woodlands	2509.9	8.4					
	Juniper woodlands	55.9	0.2										
	Mixed woodlands	1877.8	6.3										
	Open-canopy forest plantations	91.8	0.3										
	Woodland in human-modified landscapes	345.2	1.2										
Closed forests	<i>Fagus orientalis</i> and other deciduous	1344.3	4.5	3312.8	11.1	T2.2 Deciduous temperate forests	3312.8	11.1					
	<i>Quercus macranthera</i> and other deciduous	671.1	2.3										
	<i>Quercus macranthera</i>	530.5	1.8										
	<i>Quercus iberica</i> and other deciduous	494.3	1.7										
	<i>Quercus iberica</i>	90.2	0.3										
	<i>Pinus kochiana</i>	5.4	0.0										
	Closed-canopy forest plantations	51.5	0.2										
	Forest-like woody veget. in human-modified landscapes	125.7	0.4										
Croplands	Actively cultivated landscapes	1932.1	6.5	3547.6	11.1	T7.1 Annual croplands	3547.6	11.1					
	Actively used croplands	1615.5	5.4										
Tree, vine and shrub crops		1036.0	3.5	1036.0	3.5	T7.3 Plantations	1036.0	3.5					
Urban and technogenically disturbed areas	Settlements	807.2	2.7	1798.6	6.0	T7.4 Urban and industrial ecosystems	1798.6	6.0					
	Buildings	479.7	1.6										
	Quarries and landfills	78.6	0.3										
	Sparse vegetation in settlements	112.4	0.4										
	Woodlands in settlements	278.9	0.9										
	Forest-like vegetation in settlements	41.8	0.1										
Water		1376.1	4.6	1376.1	4.6	Water	1376.1	4.7					
TOTAL		29729	100	29729	100		29729	100					

4 Comparison with government-reported land-cover statistics

The comparison of ecosystem extent was conducted against government-reported data on the extent of land-cover classes for 2024, published on the Unified Website for Publication of Draft Legal Acts of Armenia⁵ (Table 8).

The total area of Ecosystem map of Armenia (29,729.2 km²) closely corresponds to the total area represented in the government statistics (29,742.6 km²), differing by only 13.4 km² (0.045 %). This minor discrepancy in total area is likely attributable to differences in the representation of the state boundary.

Differences in the extent of individual land-cover classes reflect the different aims and methodological approaches used. The Ecosystem Map of Armenia was designed to represent the spatial distribution and extent of terrestrial ecosystem types, with a primary focus on natural ecosystems, and combines the potential distribution of natural ecosystems with satellite observations used to delineate tree cover and anthropogenic areas. In contrast, government data are primarily intended for land-use statistics and are derived from land-accounting categories and functional land-use designations. Consequently, direct correspondence between the two classification systems is neither expected nor required, and differences in the estimated extent of individual classes should be interpreted in this context.

The two systems also differ substantially in their level and type of classification detail. The Ecosystem Map does not include the detailed subcategories related to land designation and cadastral classification represented in the government statistics. At the same time, its classification of natural ecosystems is substantially more detailed. The map distinguishes six types of natural forests and three types of natural woodlands, whereas the government statistics include a single class of tree-covered areas. The map also includes five types of natural grasslands, whereas grasslands in the government statistics are divided into 12 categories according to their use (hayfields and pastures) and cadastral classification. The map includes four types of sparsely vegetated areas—three natural and one anthropogenic—whereas vegetation-free areas in the government statistics are divided into 13 categories according to their cadastral classification. These differences prevent a one-to-one correspondence between natural ecosystem types and cadastral categories. For example, agricultural lands or special-purpose lands may contain different types of natural grasslands, while the same natural grassland type may occur on lands assigned to different cadastral categories.

The ecosystem type “shrublands”, represented as a separate land-cover class in the government statistics and covering 1.2 % of Armenia, was not included in the current version of the Ecosystem Map because shrub cover could not be reliably delineated using the available data and within project resources. The use of global land-cover datasets was not considered sufficiently reliable, as the analysis conducted during the development of the Prototype Ecosystem Accounts for Armenia (BCC Armenia, 2026) showed that their estimates of shrubland extent differ several-fold from the government-reported data (Table S5). Reliable mapping of shrub vegetation should therefore be considered one of the tasks for the future development of the Ecosystem Map of Armenia. This will require addressing both remote-sensing and classification challenges. Shrub vegetation is particularly difficult to distinguish using satellite imagery because its spectral characteristics often overlap with those of grasslands, open woodlands, and sparsely vegetated areas. An important prerequisite is also the harmonization of the criteria used to define shrubland in official land-cover statistics with those applied in ecosystem mapping.

In natural landscapes, shrub vegetation may occur in contrasting habitats. For example, CORINE distinguishes three major classes that include a substantial proportion of shrub vegetation alongside herbaceous vegetation, bare surfaces, and trees: 322 Moors and heathland; 323 Sclerophyllous vegetation; and 324 Transitional woodland-shrub. These vegetation types occur under very different environmental conditions and have distinct geographical distributions. CORINE does not distinguish a separate class consisting exclusively of shrub vegetation (Kosztra et al., 2019).

The EUNIS habitat classification explicitly distinguishes ecologically defined scrub and shrub-dominated habitat types within the broader group of heathland, scrub and tundra habitats. These types are differentiated according to their vegetation composition and ecological conditions rather than simply by the presence of shrub cover. The EUNIS-based classification of Armenian habitats (Fayvush & Aleksanyan, 2016) distinguishes several ecologically different shrub-dominated habitat types. These include temperate and Mediterranean-montane scrub (F3), with several types of deciduous thickets, as well as thorny cushion shrub communities (F7.4), including diverse tragacanth communities dominated by species of *Astragalus*, *Onobrychis* and *Acantholimon*. This illustrates that ecologically meaningful mapping of shrub vegetation requires its differentiation into distinct vegetation and habitat types rather than treating all shrub-covered areas as a single land-cover class.

⁵ <https://www.e-draft.am/projects/7902/about>

Table 8. Comparison of the Ecosystem map of Armenia with government-reported land-cover statistics for 2024.

Major ecosystem and land-cover classes	Ecosystem map			Government land-cover statistics		
	Ecosystems	Area, km²		Land-cover classes and subclasses	Area, km²	
Grasslands	High mountain grasslands	1.1	15728.0	Shrubs	343.7	13786.6
	Alpine grasslands	2377.0		Agricultural lands — hayfields	1212.9	
	Subalpine grasslands	5113.0		Agricultural lands — pastures	10482.4	
	Steppe	6595.7		Agricultural lands — other grasslands	777.6	
	Semi-desert	1491.8		Grasslands on lands of PAs	608.4	
	Desert	1.0		Grasslands on special-purpose lands	149.0	
				Forest lands — hayfields	92.0	
				Forest lands — pastures	109.0	
		Fens and wet meadows		148.4	Forest lands — other frasslands	
Forests	Forest - <i>Fagus orientalis</i> and other	1344.3	3187.3	Tree-covered areas		3823.6
	Forest - <i>Quercus macranthera</i> and other	671.1				
	Forest - <i>Quercus macranthera</i>	530.5				
	Forest - <i>Quercus iberica</i> and other	494.3				
	Forest - <i>Quercus iberica</i>	90.2				
	Forest - <i>Pinus kochiana</i>	5.4				
	Closed forest plantations	51.5				
Open wood-lands	Subalpine open woodlands	139.2	2164.7	Ambiguous assignment: - Tree-covered areas - Grasslands		
	Mixed open woodlands	1877.8				
	Juniper woodlands	55.9				
	Open woodland plantations	91.8				
Natural sparse veg- etation	High-mountain sparse vegetation	14.7	249.0	Vegetation-free areas — forest lands	46.3	240.0
	Rocky sparse vegetation	158.5		Vegetation-free areas — lands of PAs	167.7	
	Sandy and clay sparse vegetation	75.8		Vegetation-free areas — water lands	26.0	
Croplands	Actively cultivated landscapes	1932.1	3547.6	Arable land	4405.9	4408.5
	Actively used croplands	1615.5		Arable forest lands	2.6	
Perennial crops and orchards	Tree, vine and shrub crops	1036.0	1036.0	Perennial crops	419.1	447.2
				Orchards	28.1	
Settlement area	Settlement area	807.2	807.2	Grasslands on settlement lands, mixed devel- opment	5.0	734.5
				Grasslands on public-use settlement lands	57.3	
				Grasslands on settlement lands, public devel- opment	27.9	
				Grasslands on other settlement lands	103.7	
				Grasslands on household plots	540.5	
Buildings	Buildings	479.7	479.7	Settlement lands — residential development excluding household plots	427.1	503.3
				Public development	53.7	
				Mixed development	22.5	
Woody vegetation in human-modified landscapes	Woodland-like vegetation in human-mod- ified landscapes	624.1	791.6	Ambiguous assignment: - Tree-covered areas - Perennial crops		
	Forest-like vegetation in human-modified landscapes	167.5				
Sparse vegetation in human-modified landscapes	Sparse vegetation in human-modified landscapes	272.1	350.8	Other anthropogenic vegetation-free lands	133.7	967.5
	Quarries and landfills	78.6		Public-use vegetation-free lands	127.2	
				Vegetation-free lands for industry, subsoil use, and other production purposes	402.0	
				Vegetation-free lands for energy, communi- cations, transport, and utility infrastructure	145.1	
				Special-purpose vegetation-free lands	153.3	
				Reserve vegetation-free lands	6.2	
Vegetation-free agricultural lands	Ambiguous assignment: - Croplands - Grasslands - Natural sparse vegetation			Vegetation-free agricultural lands	3110.3	3110.3
Water	Permanent marshes in the Ararat Valley	11.4	1387.47	Water-covered areas	1721.2	1721.2
	Water bodies	1376.1				
	TOTAL		29729.3			29742.6

Exact correspondence between ecosystem types in the map and land-cover subcategories in the government statistics cannot always be established, because the two classifications use different criteria. For the comparison, shrub-covered areas reported in the government statistics were included in the area of grassland group in the map. In contrast, no corresponding government category was assigned to open woodlands, as these may be classified either as tree-covered areas or as grasslands. Woody vegetation in human-modified landscapes was likewise left without a corresponding category because it may be represented in government statistics as either tree-covered areas or perennial crops. Conversely, the government subcategory “vegetation-free agricultural lands” was left without a corresponding map class because it may include areas mapped as grasslands, croplands, or anthropogenic sparsely vegetated areas.

The observed discrepancies largely reflect differences in the classification of ecosystem and land-cover subcategories. The largest differences were found for grasslands and for the two categories without direct correspondence: open woodlands in the Ecosystem Map and “vegetation-free agricultural lands” in the government statistics (Table 9; Fig. 35). Grassland extent is larger in the map, indicating that some areas mapped as grasslands are likely classified as vegetation-free areas in the official statistics. The smaller extent of sparsely vegetated areas in the map may similarly reflect the use of more restrictive biomass and vegetation-cover thresholds. Forest extent is also lower in the map, possibly because some areas included as tree-covered land in the government statistics are represented as open woodlands or woody vegetation within human-modified landscapes. Finally, cropland extent is lower in the map, whereas the area of perennial crops is larger, suggesting that some areas reported as cropland in the government statistics may have been identified as perennial crops in the Ecosystem Map.

Table 9. Differences between Ecosystem Map estimates and government-reported land-cover statistics.

Major ecosystem and land-cover classes	Ecosystem map, km ²	Government data, km ²	Difference, km ²	Difference, % relative to government data
Grasslands	15728.0	13786.6	1941.4	14.1
Forests	3187.3	3823.6	-636.3	-16.6
Open woodlands	2164.7	0.0	2164.7	100.0
Natural sparse vegetation areas	249.0	240.0	9.0	3.8
Croplands	3547.6	4408.5	-860.9	-19.5
Perennial crops	1036.0	447.2	588.8	131.7
Settlement area	807.2	734.5	72.7	9.9
Buildings	479.7	503.3	-23.6	-4.7
Woody vegetation in anthropogenic landscape	791.6	0.0	791.6	100.0
Anthropogenic vegetation-free areas	350.8	967.5	-616.7	-63.7
Vegetation-free agricultural areas	0.0	3110.3	-3110.3	-100.0
Water	1387.5	1721.2	-333.7	-19.4

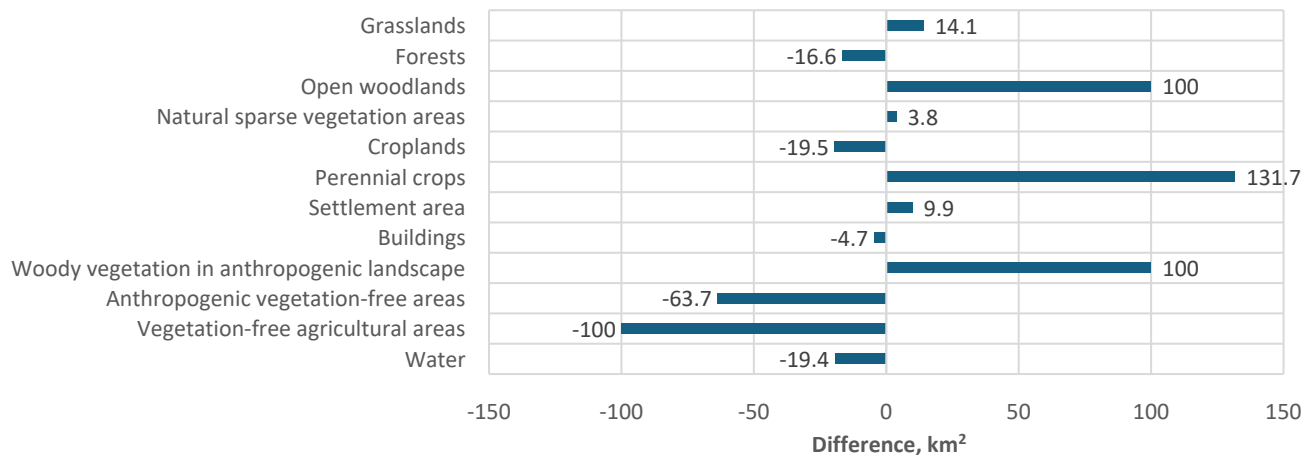


Figure 35. Differences between ecosystem map estimates and government-reported land-cover statistics. Negative values indicate that the area estimated by the map is smaller, while positive values indicate that it is larger than the area reported in government statistics.

Comparison of the broad generalized classes—non-woody areas, trees, crops, and built-up areas—shows substantially smaller discrepancies, ranging from 2 % to 6 % relative to the government-reported data for terrestrial classes (Table 10). In our view, this represents a good level of agreement for a map derived primarily from satellite imagery. In contrast, comparison of the global land-cover datasets ESA 2021, Esri 2023, GLAD 2020, and Dynamic World 2022 with government statistics, conducted during the development of the Prototype ecosystem accounting of Armenia (BCC Armenia, 2026), revealed substantially larger discrepancies, which in most cases exceeded 10 % and exceeded 30 % for croplands. The largest discrepancy between map and government statistics was observed for water-covered areas (19 %). The map uses the water layer derived from ESA WorldCover 2021, which apparently did not identify some of the water bodies included in the government statistics.

Table 10. Differences between generalized classes of Ecosystem Map and government-reported land-cover statistics.

Generalized classes	Major ecosystem and land-cover classes	Ecosystem map, km ²	Government data, km ²	Difference, km ²	Difference, % relative to government data
Non-woody areas	Grasslands	18492.5	18104.4	388.1	2.1
	Natural sparse vegetation areas				
	Anthropogenic vegetation-free areas				
	Vegetation-free agricultural areas				
	Open woodlands				
Trees	Forests	3978.9	3823.6	155.3	4.1
	Woody vegetation in anthropogenic landscape				
Crops	Croplands + Perennial crops	4583.6	4855.7	-272.1	-5.6
Built	Settlement area + Buildings	1286.9	1237.8	49.1	4.0
Water	Water	1387.5	1721.2	-333.7	-19.4

The correspondence between ecosystem types in the Ecosystem map of Armenia, the GETmap and land-cover subcategories in the government statistics is presented in Table 11. The generalized groups are indicated by different colors: forests, natural sparse vegetation, grasslands, open woodlands, settlements and industry, anthropogenic vegetation-free areas, croplands, perennial croplands, and water-covered areas. Ecosystem types that are assigned to different groups in the ecosystem map and the government statistics are shown in white.

Overall, these results indicate that, despite substantial differences in classification approaches and the definition of individual classes, the Ecosystem Map provides a robust representation of the broad spatial distribution and extent of terrestrial ecosystems in Armenia.

Further harmonization with government statistics will require the development of an agreed crosswalk between ecosystem types and national land-cover and cadastral categories, supported by spatial comparison of the underlying datasets and clarification of the criteria used to define individual classes. Access to spatial datasets used by the forestry and agricultural authorities, as well as official spatial data on built-up areas and other anthropogenic features, would be particularly valuable for this purpose, allowing direct comparison of mapped ecosystem types with the corresponding government records.

Table 11. Cross-referencing and extent of ecosystem types and land-cover subcategories in the national Ecosystem Map of Armenia, GET-compatible map and government land-cover statistics.

IUCN GET map		Ecosystem map			Government statistics		
EFG	Area, km ²	Area, km ²	Ecosystem types	Area, km ²	Land-cover categories	Area, km ²	
T2.2 Deciduous temperate forests	3312.8	3187.1	Natural forests and plantations	3187.1	3354.6	Tree-covered areas	3823.6
		125.7	Forest-like veg. in human-modified landsc. except settlem	125.7			
			Forest-like in settlements	41.8			
T6.2 Polar-alpine rocky outcrops	14.7	14.7	High-mountain sparse vegetation	14.7	249.0	Vegetation-free forest lands Vegetation-free lands of PAs Vegetation-free water lands	240.0
T3.4 Rocky pavements, screes and lava flows	158.5	158.5	Rocky sparse vegetation	158.5			
Distributed between EFG T4.5, T5.1, T6.6			Sandy/clay sparse vegetation in four vegetation zones	75.8			
T 6.4. Temperate alpine grasslands and shrublands	2379.8	1.1	High mountain vegetation	1.1	18237.9	Shrubs	343.7
		2377.0	Alpine vegetation	2377.0		Agricultural lands — hayfields	1212.9
		0.6	Sandy/clay sparse veget. -high mountain and alpine			Agricultural lands — pastures	10482.4
T4.5. Subhumid grasslands	11753.1	1.1	Human-modified sparse veg.			Agricultural lands — other grasslands	777.6
		5113.0	Subalpine grasslands	5113.0		Grasslands on lands of PAs	608.4
		6595.7	Steppe	6595.7		Grasslands on special-purpose lands	149.0
		0.5	Sandy/clay sparse veget. In sub-alpine and steppe			Forest lands — hayfields	92.0
		26.2				Forest lands — pastures	109.0
T5.1.Semi-desert steppes	1683.6	1.5	Human-modified sparse veg.			Forest lands — other grasslands	11.6
		16.2				Vegetation-free agricultural lands	3110.3
		1491.8	Semi-desert	1491.8			
		1.0	Desert	1.0			
TF1.7. Boreal and temperate fens	148.4	49.6	Sandy/clay sparse veget. In desert and semi-desert				
		141.2	Human-modified sparse veg.				
T4.4 Temperate woodlands	2509.9	2164.7	Natural woodlands and plantations	2164.7			
		345.2	Woodland-like veg. in human-modified lands. except settlem.	345.2			
T7.4. Urban and industrial ecosystems	1798.6	278.9	Woodland-like veg. in settlem.	278.9	1086.1	Grasslands on settlement lands, mixed development	5.0
		41.8	Forest-like veg. in settlements			Grasslands on public-use settl.	57.3
		807.2	Settlement area	807.2		Grasslands on settlement lands, public development	27.9
						Grasslands on other settl. lands	103.7
						Grasslands on household plots	540.5
		479.7	Buildings	479.7	479.7	Settlement lands — residential excluding household plots	427.1
						Public development	53.7
						Mixed development	22.5
		112.4	Sparse vegetation in settlements	112.4	351.0	Vegetation-free - public-use	127.2
		78.6	Quarries and landfills	78.6		Vegetation-free - industry, sub-soil and other purposes	402.0
						Vegetation-free - energy, communications, transport, etc.	145.1
			Human-modified sparse veg. Except settlements	160.0		Special-purpose veg.-free lands	153.3
						Reserve vegetation-free lands	6.2
						Other anthropogenic vegetation-free lands	133.7
T7.1 Annual croplands	3547.6	3547.6	Actively cultivated landscapes	1932.1	3547.6	Arable lands	4405.9
			Actively used croplands	1615.5		Arable forest lands	2.6
T7.3 Plantations	1036.0	1036.0	Tree, vine and shrub crops	1036.0	1036.0	Perennial crops	419.1
						Orchards	28.1
TF1.3. Permanent marshes	11.4	11.4	Permanent marshes	11.4	1387.5	Water covered areas	1721.2
Water	1376.1	1376.1	Water bodies	1376.1			
TOTAL	29729	29729	TOTAL	29729	29729		29743

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6 Appendix

Table S1. Predictor variables included in the initial feature stack

Predictor group	Band names
Sentinel-2 core spectral statistics (S2C)	S2C_B5_p10, S2C_B6_p10, S2C_B7_p10, S2C_B8A_p10, S2C_B11_p10, S2C_B12_p10, S2C_NDWI_GAO_p10, S2C_NDRE2_p10; S2C_B5_p50, S2C_B6_p50, S2C_B7_p50, S2C_B8A_p50, S2C_B11_p50, S2C_B12_p50, S2C_NDWI_GAO_p50, S2C_NDRE2_p50; S2C_B5_p90, S2C_B6_p90, S2C_B7_p90, S2C_B8A_p90, S2C_B11_p90, S2C_B12_p90, S2C_NDWI_GAO_p90, S2C_NDRE2_p90; S2C_B5_iqr, S2C_B6_iqr, S2C_B7_iqr, S2C_B8A_iqr, S2C_B11_iqr, S2C_B12_iqr, S2C_NDWI_GAO_iqr, S2C_NDRE2_iqr
Sentinel-2 extended spectral / texture metrics (S2X)	S2X_NIRv_p10, S2X_NIRv_p50, S2X_NIRv_p90, S2X_NIRv_iqr; S2X_Brightness_p10, S2X_Brightness_p50, S2X_Brightness_p90, S2X_Brightness_iqr; S2X_std, S2X_range, S2X_mean, S2X_min, S2X_max, S2X_amp; S2X_SWIR_ratio_p50, S2X_Red_NIR_ratio_p50; S2X_B8_std, S2X_B11_std, S2X_B12_std, S2X_NDWI_GAO_std, S2X_EVI2_std, S2X_NDRE2_std; S2X_skew, S2X_kurt; S2X_p50_texstd3, S2X_p50_texstd5, S2X_p50_texstd7
Sentinel-1 radar metrics (S1)	S1_VV_p10, S1_VV_p50, S1_VV_p90, S1_VV_iqr; S1_VH_p10, S1_VH_p50, S1_VH_p90, S1_VH_iqr; S1_VV_VH_ratio_p50; S1_RVI_p50; S1_VV_std, S1_VH_std, S1_VV_range
Topographic variables (DEM)	DEM_elev, DEM_slope, DEM_aspect
Custom spectral and texture metrics	MIR, SOIL, RESWIR; MIR_texstd3, SOIL_texstd3, RESWIR_texstd3
Seasonal vegetation dynamics	NDVI_harm_amp_30, NDVI_harm_phase_30, NDVI_min_slope_day_30

Table S2. Predictor variables included in the cropland probability feature stack

Predictor group	Predictor	Description	No.
Five-year custom spectral indices	MIR_median_2021_2025	Five-year median MIR (mid-infrared; B11 and B12)	
	SOIL_median_2021_2025	Five-year median soil-related spectral index	
	RESWIR_median_2021_2025	Five-year median red-edge–SWIR index	3
Custom spectral-index textures	MIR_texstd3_median_2021_2025	Median of annual local SD of MIR, 3 × 3 window	
	SOIL_texstd3_median_2021_2025	Median of annual local SD of SOIL, 3 × 3 window	
	RESWIR_texstd3_median_2021_2025	Median of annual local SD of RESWIR, 3 × 3 window	3
Five-year median vegetation index	NDVI_median_2021_2025	Median of annual median NDVI, 2021–2025	1
NDVI phenology	NDVI_harm_amp_mean_2021_2025	Five-year mean harmonic amplitude	
	NDVI_harm_phase_circmean_2021_2025	Five-year circular mean harmonic phase	
	NDVI_min_slope_value_mean_2021_2025	Five-year mean magnitude of strongest NDVI decline	
	NDVI_min_slope_day_mean_2021_2025	Five-year mean day of strongest NDVI decline	4
Phenology texture	PHENO_minSlope_mean_texstd3	Local SD of five-year mean strongest NDVI decline, 3 × 3 window	1
Sentinel-2 extended metrics (S2X)	S2X_NIRv_p10	Five-year median of annual NIRv p10	
	S2X_Brightness_p10	Five-year median of annual brightness p10	
	S2X_SWIR_ratio_p50	Five-year median of annual B11/B12 p50	
	S2X_B12_std	Five-year median of annual temporal SD of B12	
	S2X_NDVI_skew	Five-year median of annual temporal NDVI skewness	
	S2X_NDVI_p50_texstd3	Five-year median of annual NDVI p50 local SD, 3 × 3 window	
	S2X_NDVI_p50_texstd7	Five-year median of annual NDVI p50 local SD, 7 × 7 window	7
Sentinel-2 core metrics (S2C)	S2C_NDRE2_p50	Five-year median of annual NDRE2 p50	
	S2C_NDWI_GAO_p50	Five-year median of annual NDWI-Gao p50	

Predictor group	Predictor	Description	No.
	S2C_NDWI_GAO_p90	Five-year median of annual NDWI-Gao p90	
	S2C_B11_iqr	Five-year median of annual B11 IQR	
	S2C_B11_p50	Five-year median of annual B11 p50	
	S2C_B5_p10	Five-year median of annual B5 p10	
	S2C_B11_p10	Five-year median of annual B11 p10	
	S2C_B12_p10	Five-year median of annual B12 p10	8
Total			27

Table S3. Predictor variables selected for the final woody vegetation probability model (60 predictors)

Predictor group	Band names	No.
Dynamic World tree-cover probability	treeProb_DW_smooth	1
Topographic variables (DEM)	DEM_elev, DEM_slope, DEM_aspect	3
Seasonal vegetation dynamics	NDVI_harm_amp_30, NDVI_harm_phase_30, NDVI_min_slope_day_30	3
Custom spectral and texture metrics	MIR, MIR_texstd3, SOIL, SOIL_texstd3, RESWIR, RESWIR_texstd3	6
Sentinel-1 radar metrics (S1)	S1_VV_p10, S1_VV_p50, S1_VV_p90, S1_VV_iqr; S1_VH_p10, S1_VH_p50, S1_VH_p90, S1_VH_iqr; S1_VV_VH_ratio_p50, S1_RVI_p50, S1_VV_std, S1_VH_std, S1_VV_range	13
Sentinel-2 core spectral statistics (S2C)	S2C_NDWI_GAO_p10, S2C_NDWI_GAO_p50, S2C_NDWI_GAO_p90, S2C_NDWI_GAO_iqr; S2C_NDRE2_p10, S2C_NDRE2_p50, S2C_NDRE2_p90, S2C_NDRE2_iqr; S2C_B11_p10, S2C_B11_p50, S2C_B11_iqr; S2C_B12_p10, S2C_B12_p50, S2C_B12_p90, S2C_B12_iqr; S2C_B5_iqr, S2C_B6_iqr, S2C_B8A_p50	18
Sentinel-2 extended spectral and texture metrics (S2X)	S2X_p50_texstd5, S2X_skew, S2X_kurt; S2X_NIRv_p10, S2X_NIRv_p50, S2X_NIRv_iqr; S2X_Brightness_p50, S2X_Brightness_iqr; S2X_NDWI_GAO_std, S2X_NDRE2_std, S2X_B11_std, S2X_B12_std; S2X_SWIR_ratio_p50, S2X_Red_NIR_ratio_p50; S2X_mean, S2X_range	16
Total		60

Table S4. Anthropogenic influences by potential vegetation zone and marz, km²

Ecosystem Accounting Areas	Potential vegetation zones	Total land area	Intensively used anthropogenic areas	Human-modified landscapes	Potential grazing areas	Areas free from the assessed types of anthropogenic influence
Yerevan	High mountain vegetation	0.0	0.0	0.0	0.0	0.0
	Alpine vegetation	0.0	0.0	0.0	0.0	0.0
	Subalpine grasslands	0.0	0.0	0.0	0.0	0.0
	Steppe	24.2	20.5	21.9	1.3	2.3
	Semi-desert	208.4	198.5	204.9	30.5	2.4
	Desert	0.0	0.0	0.0	0.0	0.0
Lori	Fens and wet meadows	0.0	0.0	0.0	0.0	0.0
	High mountain vegetation	0.0	0.0	0.0	0.0	0.0
	Alpine vegetation	77.6	0.0	0.0	19.0	58.6
	Subalpine grasslands	487.2	1.7	48.6	306.3	157.4
	Steppe	3022.7	612.0	1045.0	1471.7	922.5
	Semi-desert	42.5	14.7	20.7	18.5	14.9
Vayots Dzor	Desert	0.0	0.0	0.0	0.0	0.0
	Fens and wet meadows	132.4	96.6	124.7	28.3	3.8
	High mountain vegetation	0.0	0.0	0.0	0.0	0.0
	Alpine vegetation	328.4	2.7	3.0	283.2	45.0

	Subalpine grasslands	604.6	3.4	26.0	344.1	249.6
	Steppe	1215.6	115.5	175.6	326.6	754.1
	Semi-desert	144.9	54.8	76.7	1.7	67.9
	Desert	0.0	0.0	0.0	0.0	0.0
	Fens and wet meadows	2.3	2.3	2.2	0.8	0.1
Shirak	High mountain vegetation	1.1	0.0	0.0	0.7	0.4
	Alpine vegetation	207.0	0.2	0.3	135.5	71.5
	Subalpine grasslands	487.8	28.5	190.3	177.5	176.4
	Steppe	1913.1	1093.5	1372.2	307.0	457.5
	Semi-desert	0.0	0.0	0.0	0.0	0.0
	Desert	0.0	0.0	0.0	0.0	0.0
	Fens and wet meadows	81.8	47.5	79.6	13.8	2.1
Ararat	High mountain vegetation	0.0	0.0	0.0	0.0	0.0
	Alpine vegetation	118.7	0.2	0.4	118.3	0.4
	Subalpine grasslands	246.1	0.2	0.3	213.7	32.4
	Steppe	710.3	24.9	35.5	414.4	272.9
	Semi-desert	1008.5	613.9	695.0	387.9	216.7
	Desert	1.1	0.0	0.1	0.7	0.4
	Fens and wet meadows	0.0	0.0	0.0	0.0	0.0
Kotayk	High mountain vegetation	0.0	0.0	0.0	0.0	0.0
	Alpine vegetation	219.9	0.2	0.2	197.7	22.2
	Subalpine grasslands	497.1	3.3	27.5	456.3	39.3
	Steppe	1300.6	568.5	785.1	753.0	155.7
	Semi-desert	88.4	51.9	80.3	21.2	4.5
	Desert	0.0	0.0	0.0	0.0	0.0
	Fens and wet meadows	7.8	3.7	5.0	1.5	2.6
Tavush	High mountain vegetation	0.0	0.0	0.0	0.0	0.0
	Alpine vegetation	2.0	0.0	0.0	1.2	0.8
	Subalpine grasslands	105.0	0.4	7.6	88.8	16.2
	Steppe	2377.1	209.1	378.2	1403.6	802.8
	Semi-desert	240.8	85.2	89.5	14.6	145.9
	Desert	0.0	0.0	0.0	0.0	0.0
	Fens and wet meadows	0.0	0.0	0.0	0.0	0.0
Syunik	High mountain vegetation	0.6	0.0	0.0	0.1	0.5
	Alpine vegetation	721.3	1.8	5.3	355.4	363.6
	Subalpine grasslands	1057.9	9.5	71.2	430.6	594.2
	Steppe	2422.4	553.6	739.5	653.6	1219.0
	Semi-desert	275.2	35.7	52.0	17.7	210.9
	Desert	0.0	0.0	0.0	0.0	0.0
	Fens and wet meadows	0.0	0.0	0.0	0.0	0.0
Armavir	High mountain vegetation	0.0	0.0	0.0	0.0	0.0
	Alpine vegetation	0.0	0.0	0.0	0.0	0.0
	Subalpine grasslands	0.0	0.0	0.0	0.0	0.0
	Steppe	0.8	0.3	0.7	0.0	0.1
	Semi-desert	1258.4	832.2	1065.9	23.6	182.3
	Desert	0.0	0.0	0.0	0.0	0.0
	Fens and wet meadows	0.0	0.0	0.0	0.0	0.0
Aragatsotn	High mountain vegetation	2.7	0.0	0.0	2.5	0.2
	Alpine vegetation	246.2	0.2	0.3	235.8	10.4
	Subalpine grasslands	417.3	11.3	31.7	359.6	53.2
	Steppe	1376.7	475.6	764.7	406.2	392.1
	Semi-desert	618.4	258.9	422.4	17.8	193.2
	Desert	0.0	0.0	0.0	0.0	0.0
	Fens and wet meadows	71.7	65.7	69.9	40.8	1.5
Gegharkunik	High mountain vegetation	0.0	0.0	0.0	0.0	0.0
	Alpine vegetation	565.5	0.7	24.3	438.2	126.7
	Subalpine grasslands	1536.6	35.1	374.0	829.5	572.7
	Steppe	1658.4	652.3	1088.4	447.7	440.8
	Semi-desert	0.0	0.0	0.0	0.0	0.0
	Desert	0.0	0.0	0.0	0.0	0.0
	Fens and wet meadows	218.1	121.3	146.7	65.7	53.0

Table S5. Comparison of shrub-cover area estimates from government statistics and global land-cover datasets by marz (from BCC Armenia, 2026)

Marz	GOV 2022, km ²	ESA 2021, km ²	ESA difference, %	ESA / GOV	DW 2022, km ²	DW difference, %	DW / GOV
Aragatsotn	3.925	0.000	-100.0	0.000×	361.594	+9,112.6	92.1×
Ararat	24.962	0.001	-100.0	<0.001×	387.490	+1,452.3	15.5×
Armavir	6.341	0.001	-100.0	<0.001×	58.548	+823.3	9.2×
Gegharkunik	36.351	0.000	-100.0	0.000×	611.396	+1,581.9	16.8×
Kotayk	23.135	0.000	-100.0	0.000×	372.450	+1,509.9	16.1×
Lori	48.307	0.057	-99.9	0.001×	345.520	+615.3	7.2×
Shirak	0.000	0.000	—	—	246.146	—	—
Syunik	157.423	1.042	-99.3	0.007×	1147.185	+628.7	7.3×
Tavush	29.433	8.913	-69.7	0.303×	310.120	+953.6	10.5×
Vayots Dzor	11.479	0.000	-100.0	0.000×	843.881	+7,251.5	73.5×