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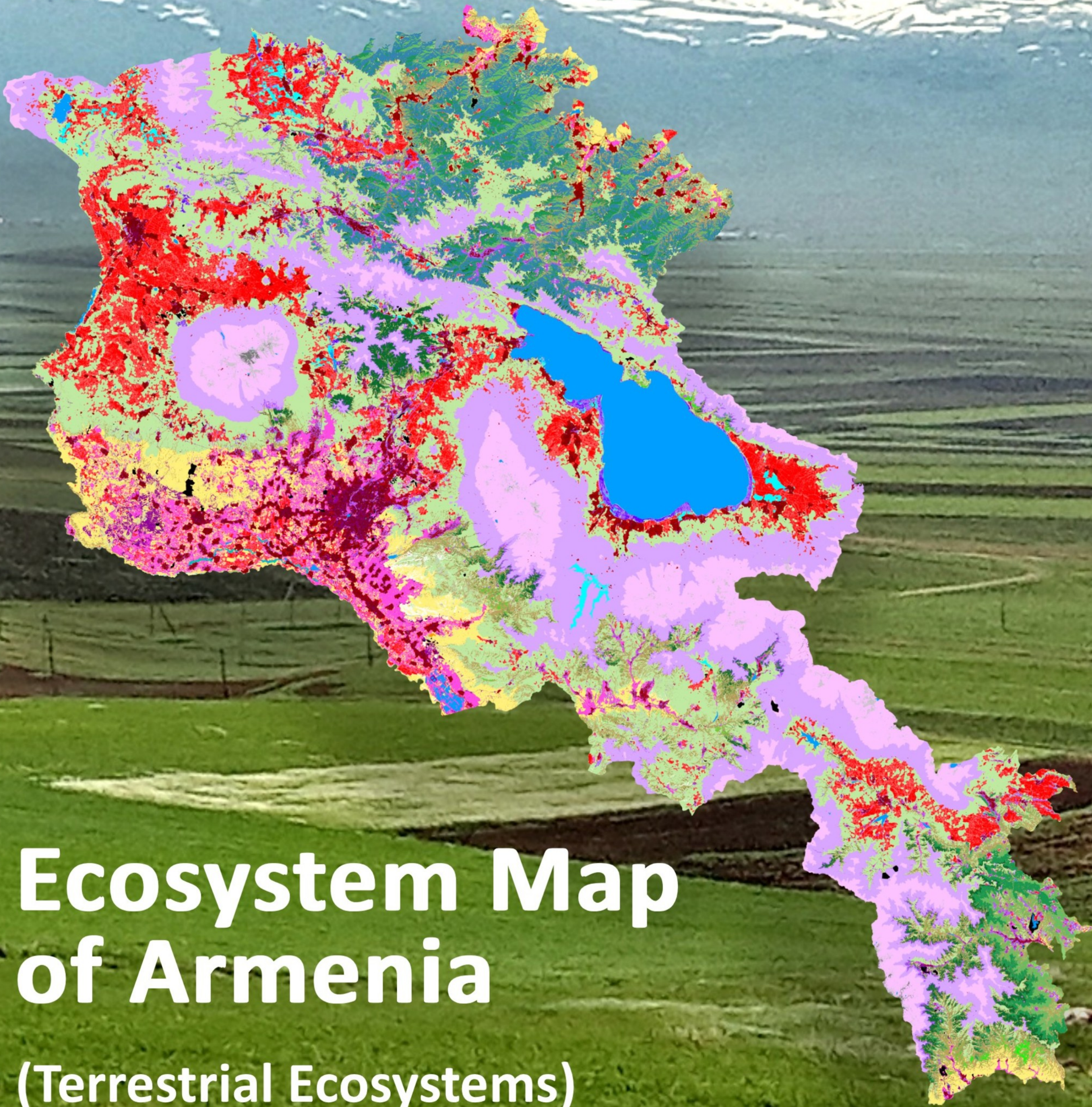

Ecosystem Map of Armenia

(Terrestrial Ecosystems)

Yerevan 2026

Ecosystem Accounting in Armenia: Setting the Scene
Part 2

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

Current interactive version of the Ecosystem Map

https://armenia-woodlands.projects.earthengine.app/view/ecosystem-map-of-armenia-v2

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 Armenia within the continuation of the project “Ecosystem Accounting in Armenia: Setting the Scene”. The map comprises two versions: (1) a detailed version based on the national ecosystem classification, and (2) a version reclassified according to the IUCN Global Ecosystem Typology (GET) for inclusion in the Global Ecosystems Atlas.

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 natural zones was defined using topographic and geological parameters, while 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 resulting map provides a spatially explicit representation of both natural and anthropogenic terrestrial ecosystems across Armenia. In addition to the ecosystem classes included in the integrated map, supplementary layers were developed to characterize broader human influence, including human-modified landscapes and potential grazing-pressure zones around livestock farmyards, as well as areas of special conservation importance.

The Ecosystem Map of Armenia covers and classifies terrestrial ecosystems only. It includes 19 classes of natural ecosystems: 6 forest, 3 woodland, 5 grassland, 2 wetland, and 3 sparsely vegetated ecosystem classes.The map also includes 9 classes of anthropogenic ecosystems: 3 classes of human-made woody vegetation, 1 cropland class, and 5 classes of built-up and technogenically disturbed areas.

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%. Of the 19 natural ecosystem types included in the map, 10 can be considered rare, 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.

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 hayfields occur as scattered patches interspersed with natural ecosystems, as well as potential grazing-pressure zones, anthropogenic influence extends across approximately 68% of the country.

Reclassification of the national ecosystem map according to the IUCN Global Ecosystem Typology resulted in 12 Ecosystem Functional Groups (EFGs). Temperate subhumid grasslands (T4.5) are the dominant EFG, covering almost 40% of Armenia. Among natural ecosystems, they are 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. Other mapped natural EFGs each occupy less than 1% of Armenia. The three anthropogenic EFGs—annual croplands (T7.1), plantations (T7.3), and urban and industrial ecosystems (T7.4)—together cover approximately 21.7% of the country, with annual croplands being the most extensive.

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. Methodology

The overall workflow integrates academic knowledge of vegetation types with current land-cover data two main types of spatial information (Figure 1):

- a potential vegetation map based on topographic and geological parameters;
- 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 used throughout the study were obtained from the Forest Atlas of Armenia.

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

Map layers		*Altitude*				*Exposure*	
		Northern zone	*Central zone*	*Southeastern zone*	*Southern zone*	*Northern 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	*Fagus orientalis + Carpinus, Tilia, etc.*	Satellite-derived forest, <1800				N	-
	Quercus macranthera + Carpinus, Tilia, etc.	Satellite-derived forest, 1400-1800				S	N,S
	Quercus macranthera	Satellite-derived forest, 1800-2400				S	N,S
	Quercus iberica+ Carpinus, Tilia, etc.	Satellite-derived forest, 1000-1400				S	N,S
	Quercus iberica	Satellite-derived forest, <1000				S	N,S
	Pinus kochiana (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	Planted forests and woodlands	Satellite-derived forest and woodland within boundaries manually delineated from high-resolution imagery					
	Woody veg. in human-modified landscapes						
	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	Areas with satellite-derived ≥60% cropland and built-up areas, followed by generalized manual delineation by high-resolution imagery					
	Livestock camps and grazing zones	OpenStreetMap (OSM) data; 3 km buffers around livestock camps					
	Settlement names	OpenStreetMap (OSM) data					
	Areas of Special Conservation Importance: National protected areas Emerald Network Sites Ramsar Sites	UNEP-WCMC and IUCN (2026), Protected Planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM), Cambridge, UK: UNEP-WCMC and IUCN. Available at: www.protectedplanet.net.					

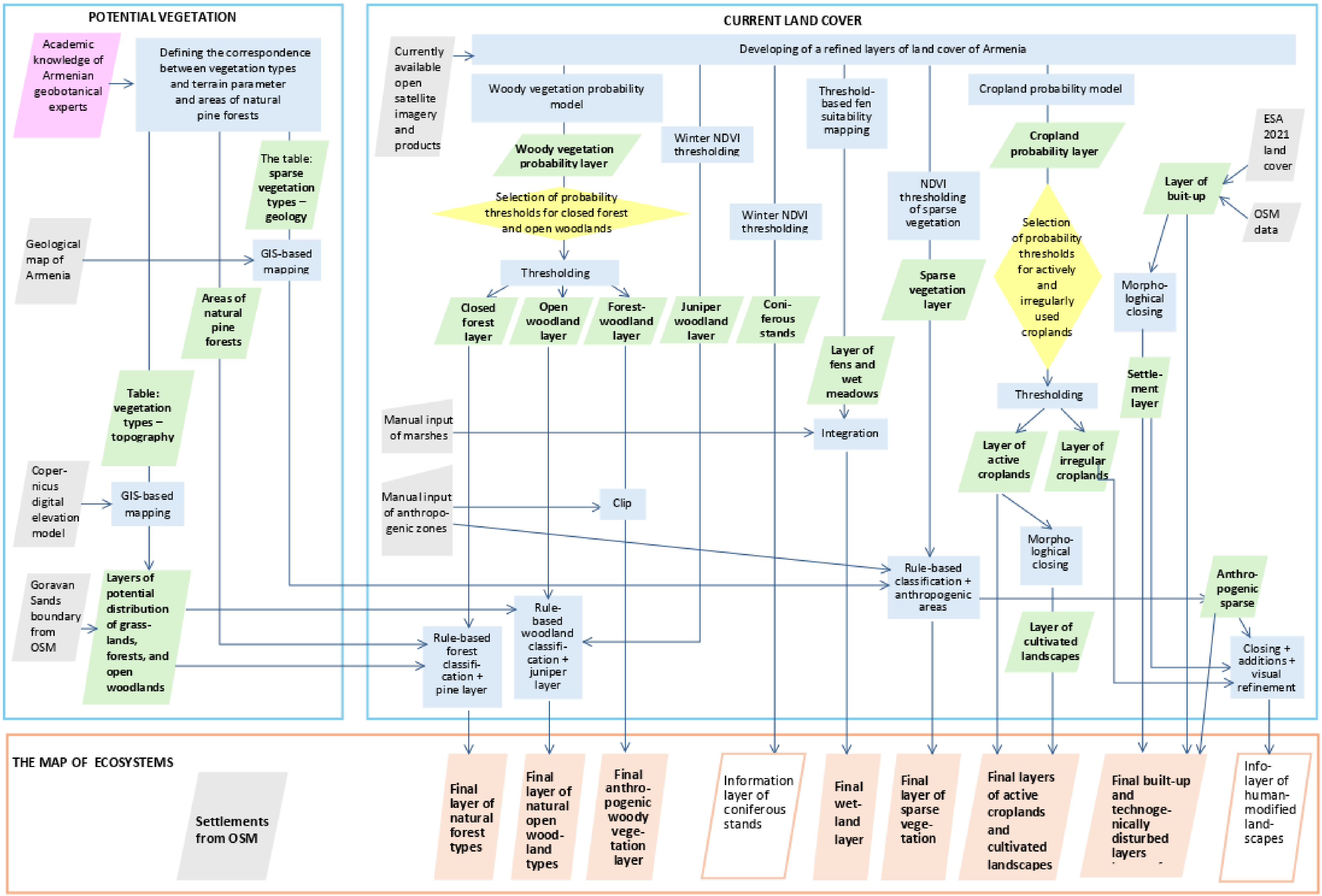


Figure 1. Flowchart of ecosystem map creation

1.1. Potential Distribution of Natural Ecosystems

The potential vegetation map was developed based on the academic expertise of specialists from the Takhtajyan Institute of Botany of the National Academy of Sciences of Armenia George Fayvush and Alla Aleksanyan. Climatic conditions, and consequently vegetation patterns in Armenia, are determined primarily by topography. Therefore, topograpy was used as the principal basis for developing the potential vegetation map. Zones of 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 on the southern macroslope of the Zangezur Range (Southern Zone) (Figure 2).

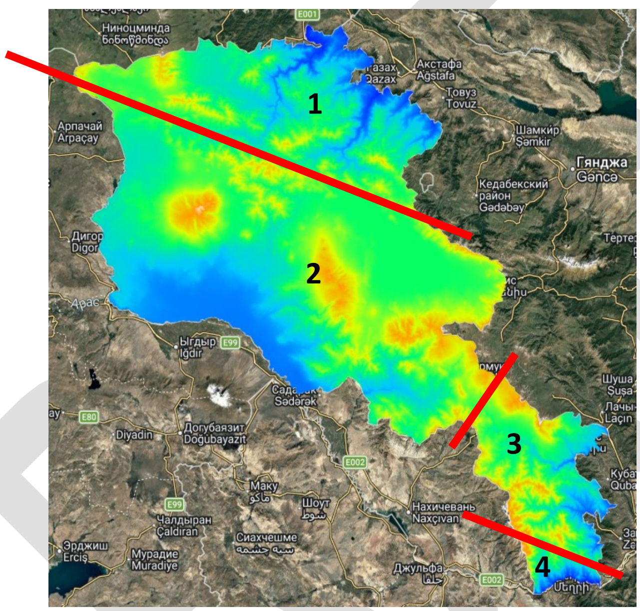


Figure 2. Ecological zones used for potential vegetation mapping in Armenia: 1) Nothern; 2) Central; 3) Southeastern; 3) Southern.

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. 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 Northern zone and all other zones. Beech forests were considered to occur only in Northern zone (Table 1. Figure 2).

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 2.3) with the potential distribution areas described above.

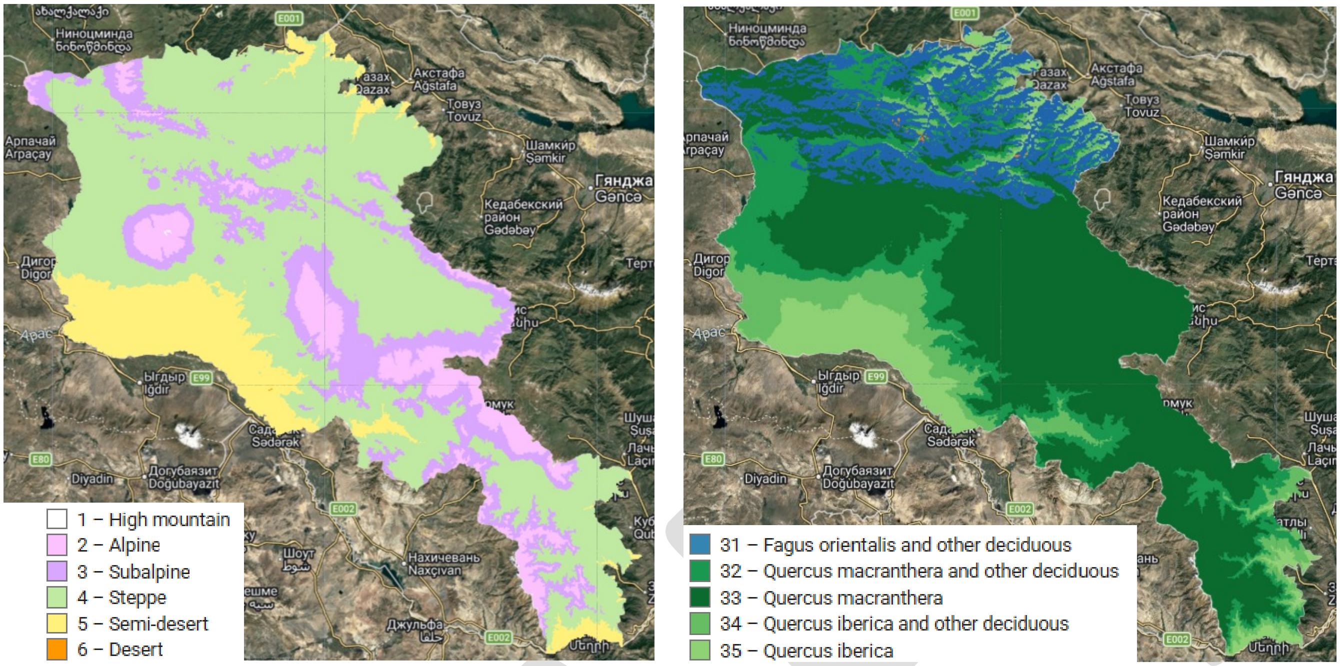


Figure 2. Potential distribution of differen types of grasslands and forests

1.2. Mapping of 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 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 2.3.3);
- inferred distribution of natural and planted coniferous stands identified using satellite imagery (Section 2.3.2);
- two wetland types identified using satellite data and manually digitized from high-resolution imagery (Section 3.4);
- three types of natural sparsely vegetated ecosystems identified using satellite data, elevation, and the geological map of Armenia (Section 2.5).

1.2.1. 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 technologically 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 2.6.2).

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 (Figure 3). 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.

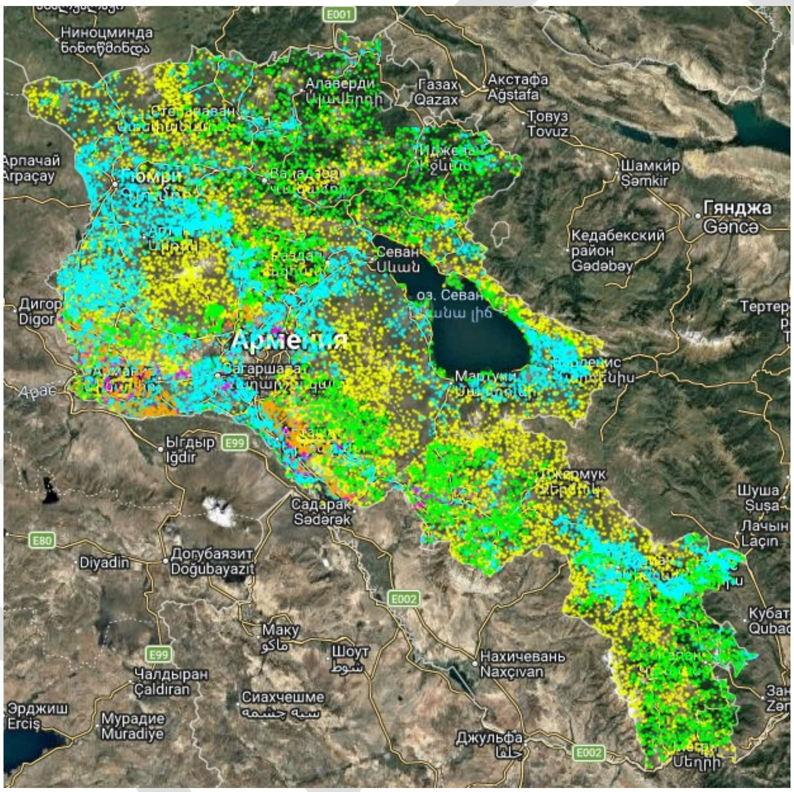


Figure 3. Spatial distribution of manually classified training cells across Armenia.

1.2.2. 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:

$$MIR = (B11 - B12) / (B11 + B12);$$
$$SOIL = ((B11 + B4) - (B8 + B2)) / ((B11 + B4) + (B8 + B2));$$
$$RESWIR = (B8A - B11) / (B8A + B11).$$

For each index, a spatial heterogeneity metric (`texstd3`) 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_texstd3`, `S2X_p50_texstd5`, and `S2X_p50_texstd7`) 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:

$$Phase = atan2(b_1, a_1).$$

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 NDVI × 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:

$$NDWI\text{-}Gao = (B8A - B11) / (B8A + B11),$$
$$NDRE2 = (B8A - B6) / (B8A + B6).$$

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 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 and aligned to the common 10 m output grid.

1.2.3. 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 described in Section 2.1 and the 60-predictor feature stack selected for woody vegetation mapping as described in Section 2.2.3.

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.

The Random Forest classifier was trained using the fixed set of 60 predictors selected as described in Section 2.2.3. 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 same 60 predictors were used for model training, validation, and probability mapping, with predictor layers of coarser spatial resolution resampled and aligned to the common 10 m analysis grid.

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 (Figure 4) and was used as the basis for subsequent delineation of forests and open woodlands.

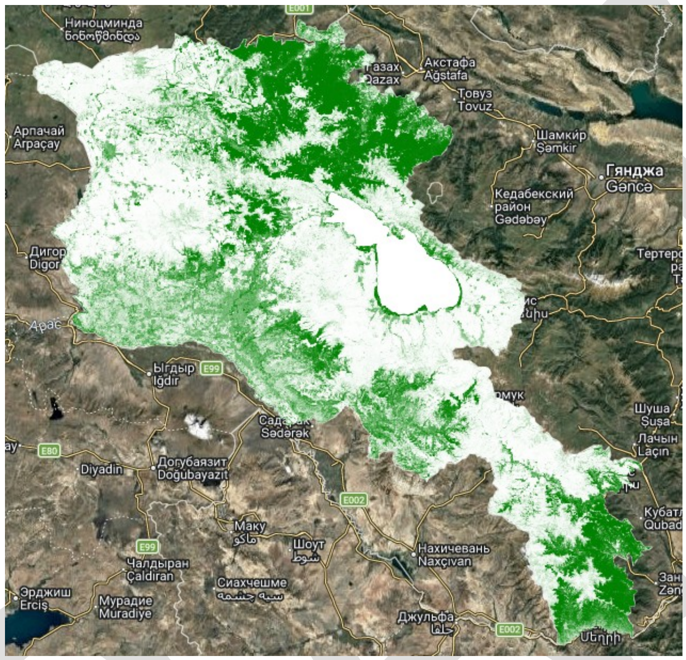


Figure 4. The layer of woody vegetation probability

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%, with false-positive and false-negative rates of 6.16% and 5.18%, respectively. Increasing the threshold progressively reduced false-positive errors but increased omission of woody vegetation (Fig. 5). 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.

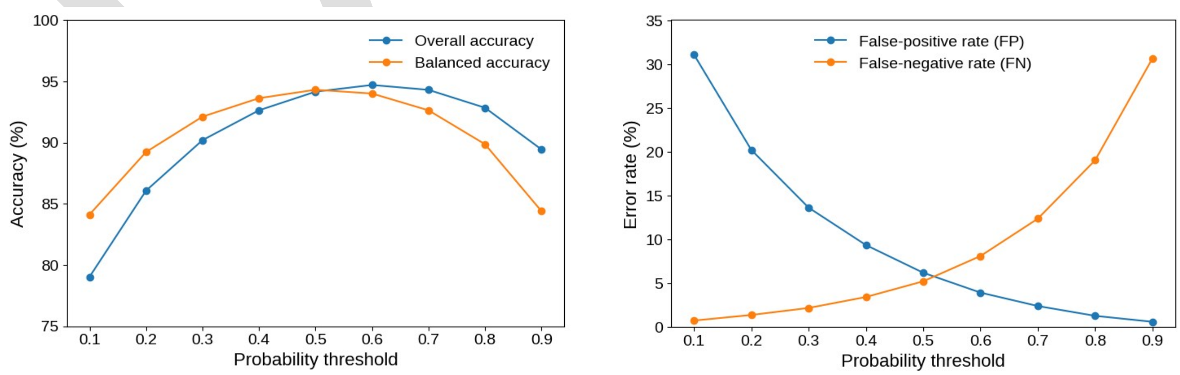


Figure 5. Sensitivity of woody vegetation classification performance to the probability threshold.

The probability thresholds were determined by visual comparison of the probability layer with high-resolution satellite imagery. Closed forest was defined as areas with woody vegetation probability >0.98. Open woodland was initially delineated using region-specific probability ranges. Within areas characterized by extensive orchards and vineyards (Fig. 6a), 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 at this stage. Orchards and vineyards were subsequently identified and removed from the open woodland mask and assigned to a separate class of cultivated woody vegetation. Across the remainder of Armenia, a more conservative probability range of 0.75–0.98 was used. This procedure resulted in two separate woody vegetation masks: closed forest and open woodland (Fig. 6b).

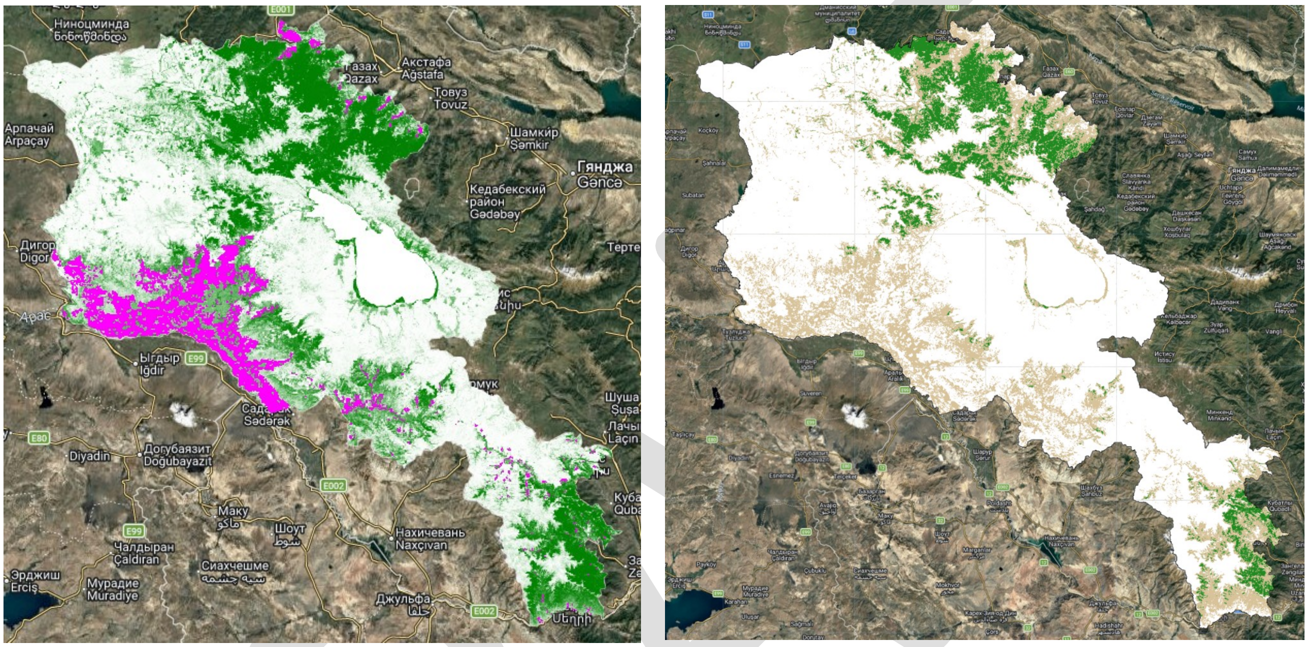


Figure 6. Delineation of woody vegetation classes: (a) zones of orchards and vineyards where the extended woodland probability range was applied; (b) resulting closed forest (green) and open woodland (beige) masks.

Forest layer

Specific forest ecosystem types were delineated by applying the rule-based potential vegetation classification described in 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 Takhtajyan Institute of Botany. This procedure resulted in the map of current forest ecosystem types shown in Figure 7.

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 during 2020–2024. 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.

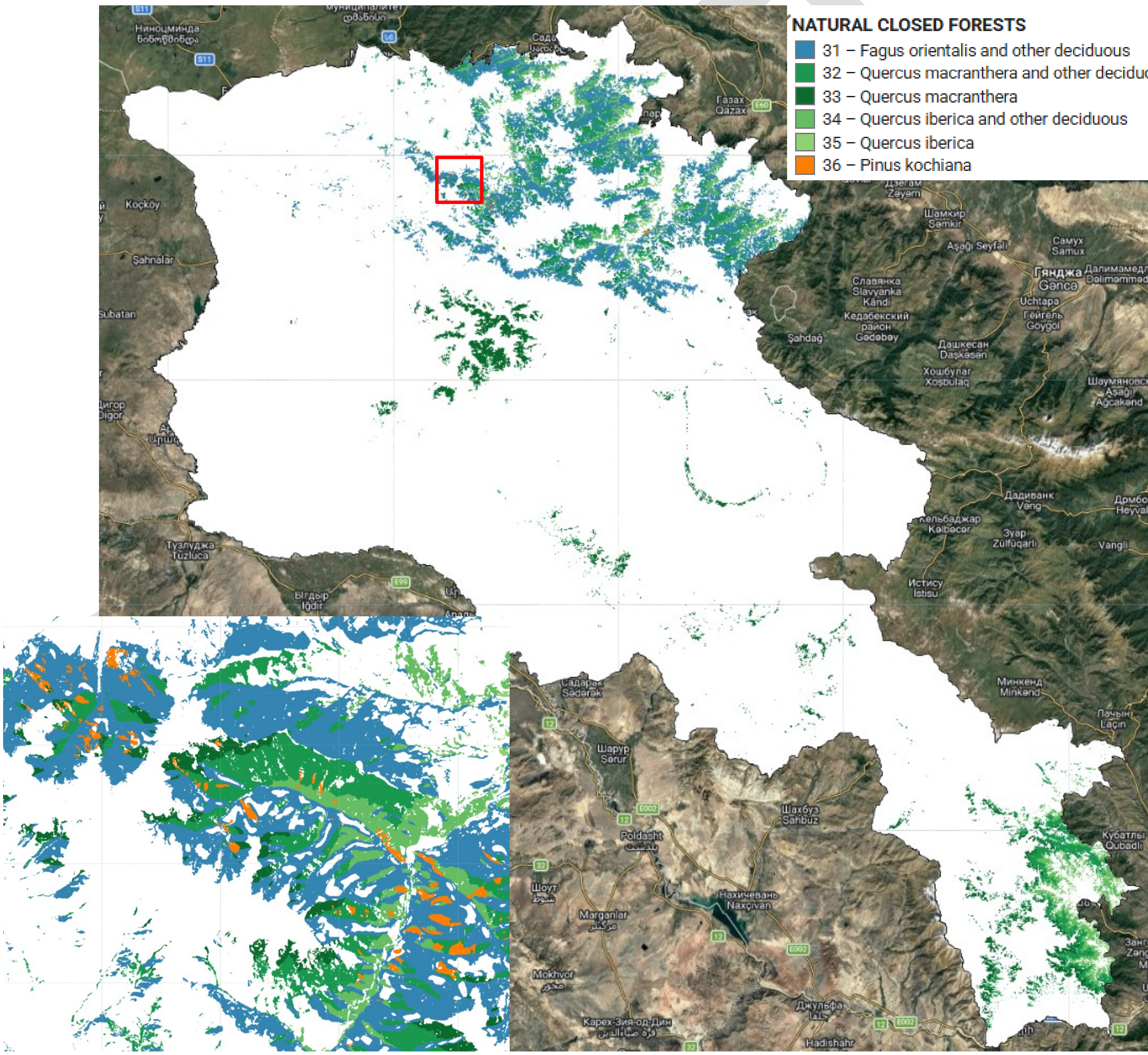


Figure 7. Current forest types.
The inset shows an enlarged view of the area indicated by the red rectangle on the main map.

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 modelling, 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. This procedure resulted in the delineation of three current open woodland ecosystem types: subalpine woodlands, juniper woodlands, and other deciduous and mixed woodlands (Fig. 8).

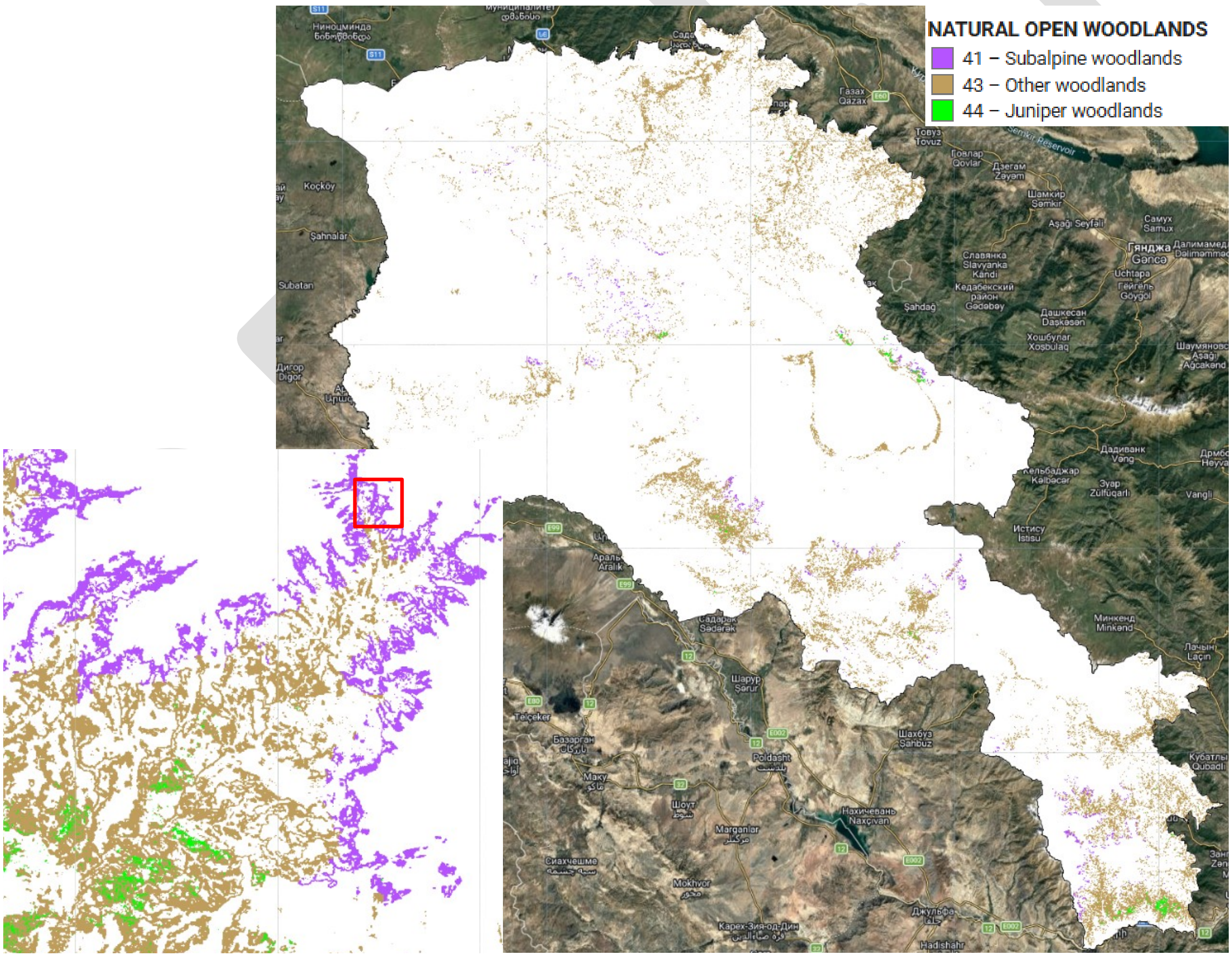


Figure 8. Current open woodland ecosystem types.
The inset shows an enlarged view of the area indicated by the red rectangle on the main map.

Anthropogenic woody vegetation

In addition to natural forests and open woodlands, four types of anthropogenic woody vegetation were distinguished: closed planted forests, open planted woodlands, tree, vine and shrub crops (predominantly orchards and vineyards), and other woody vegetation in human-modified landscapes (Fig. 9).

Closed planted forests, open planted woodlands, and zones 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. Tree, vine and shrub crops were identified within the corresponding manually delineated zones using the combined closed forest and open woodland mask. Other woody vegetation in human-modified landscapes was similarly identified using the combined closed forest and open woodland mask within the human-modified landscape layer described in Section 2.6.3.

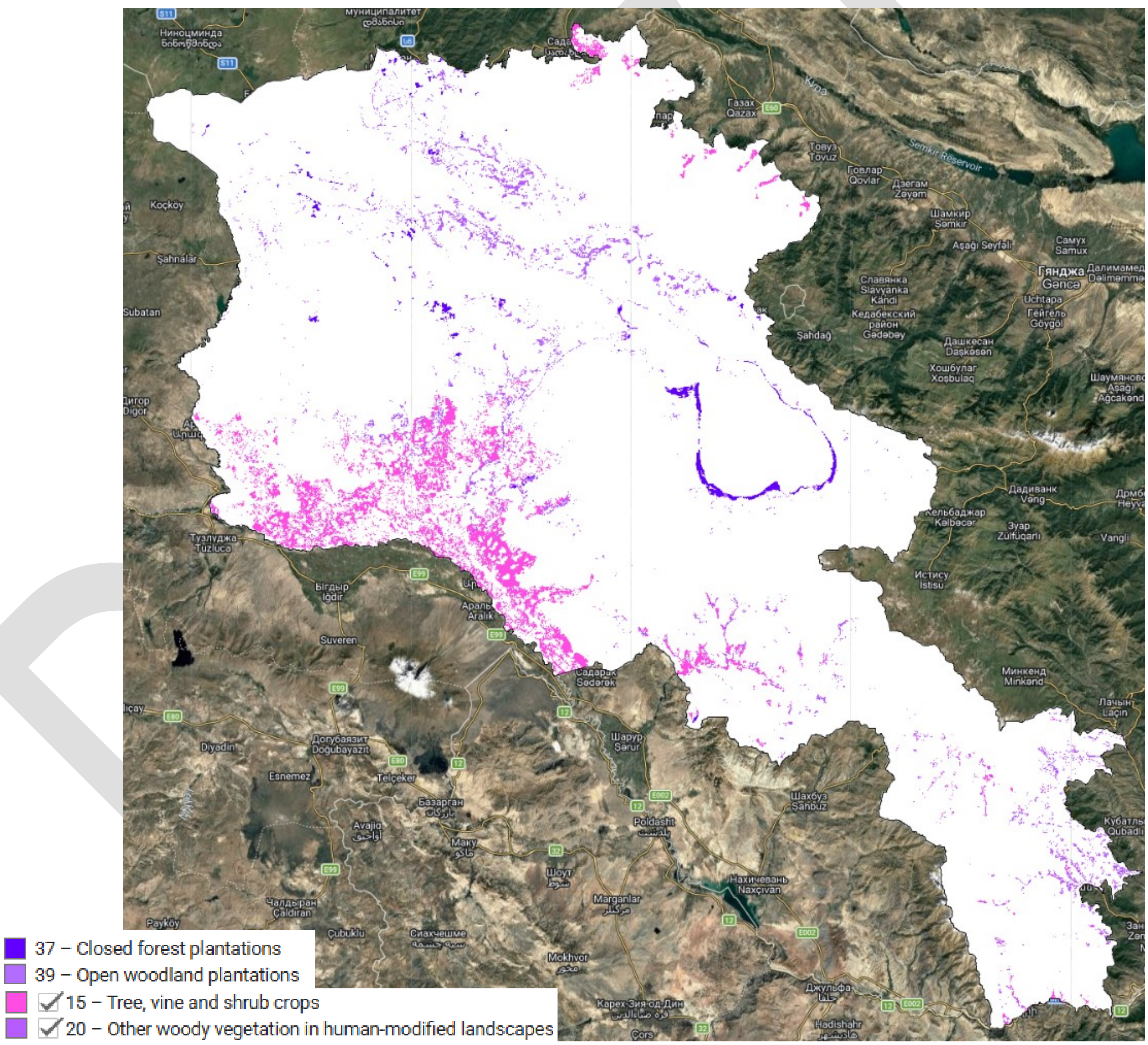


Figure 9. Anthropogenic woody vegetation

1.2.4. Wetlands

Two wetland ecosystem types were distinguished: fens and wet meadows, and wetland waterbodies in the Ararat Valley. Potential areas suitable for fens and wet meadows were initially 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 ≤ 12 m, TWI ≥ 3.5, slope ≤ 3°, ET ≥ 245 mm, and LST ≤ 28°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 (https://biodiversity-armenia.am/).The resulting potential distribution layer (Fig. 10) was subsequently constrained by the current land-cover classes. Areas occupied by cropland and other incompatible ecosystem types were excluded, so that the final fens and wet meadows layer represents their estimated current distribution rather than their full potential extent.

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

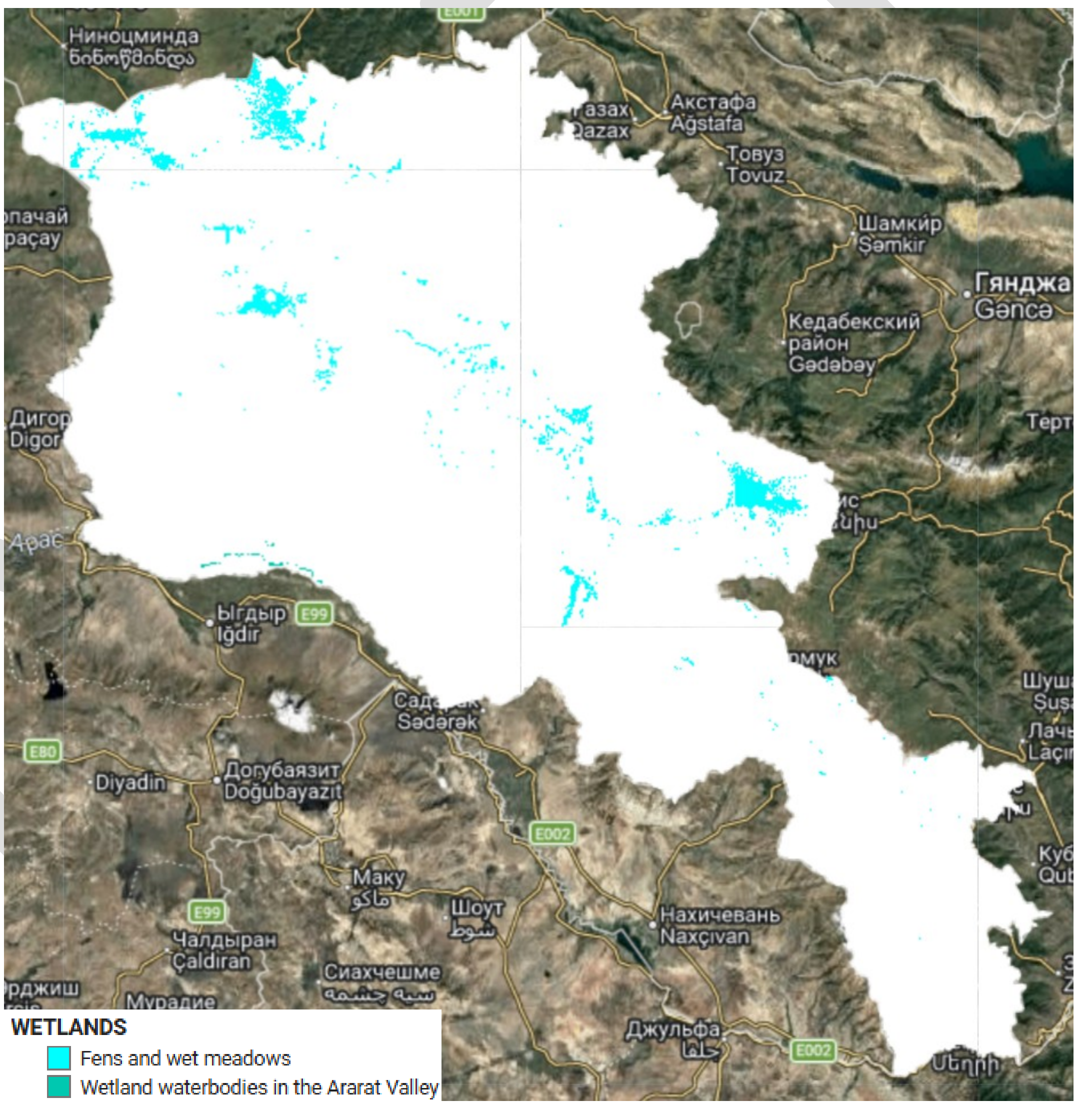


Figure 10. Wetlands. The potential distribution is shown for fens and wet meadows.

1.2.5. 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. 11). The generalized geology layer was derived from the Geological Map of Armenia available through the Forest Atlas of Armenia (https://forestatlas.am/).

In addition, a separate anthropogenic class was created by combining quarry areas and other unvegetated artificial surfaces. The resulting sparse vegetation layer was subsequently overlaid on the grassland layer, replacing grassland classes wherever sparse substrates formed the dominant ecosystem.

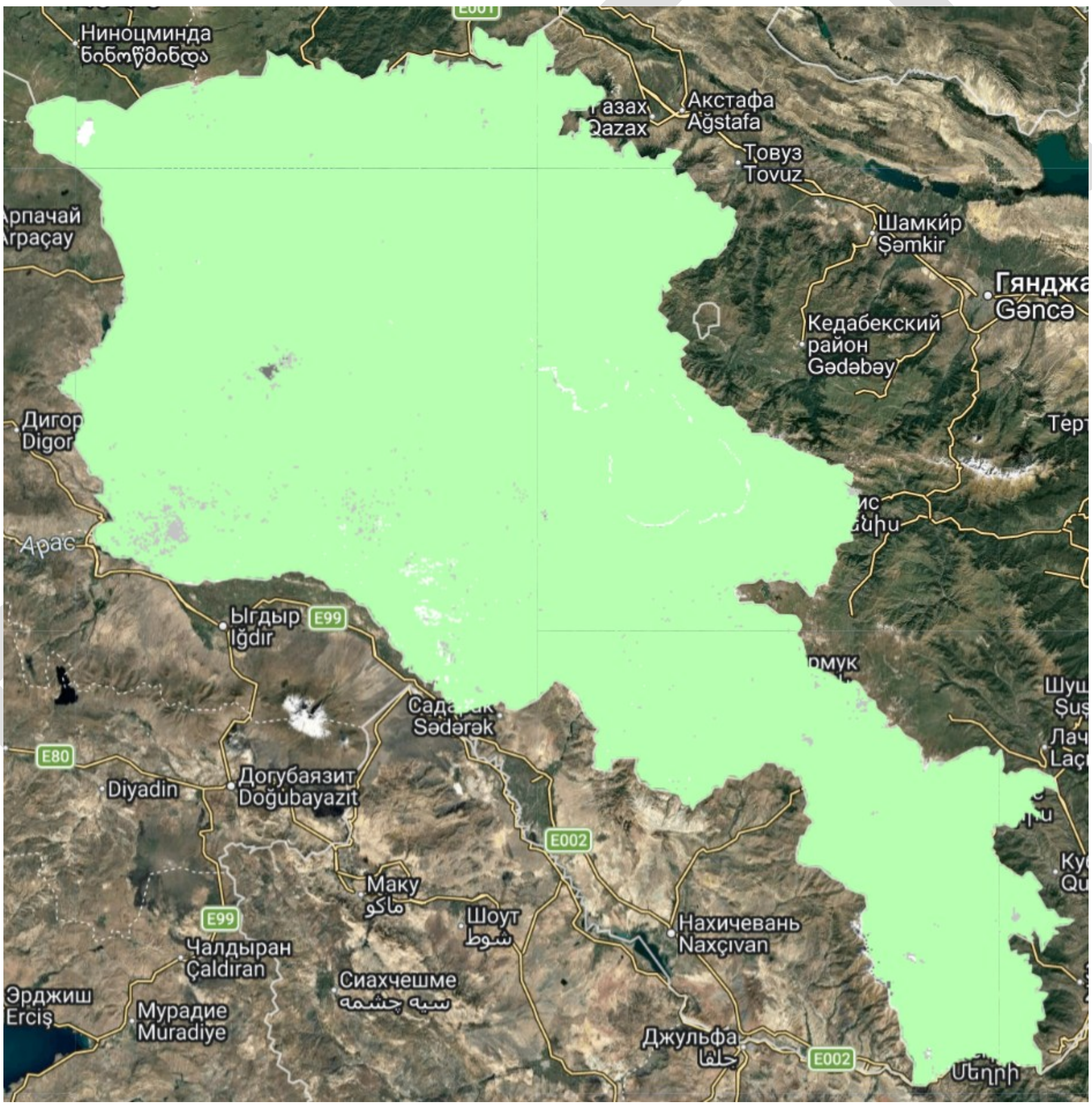


Figure 10. Sparsely vegetated ecosystems. A uniform green background is used solely to enhance the visibility of the different sparsely vegetated ecosystem types.

1.2.6. 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.

The model was trained using the 30 m predictor stack (TrainStack30), while cropland probability maps were generated at 10 m resolution using the corresponding high-resolution predictor layers, 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 11).

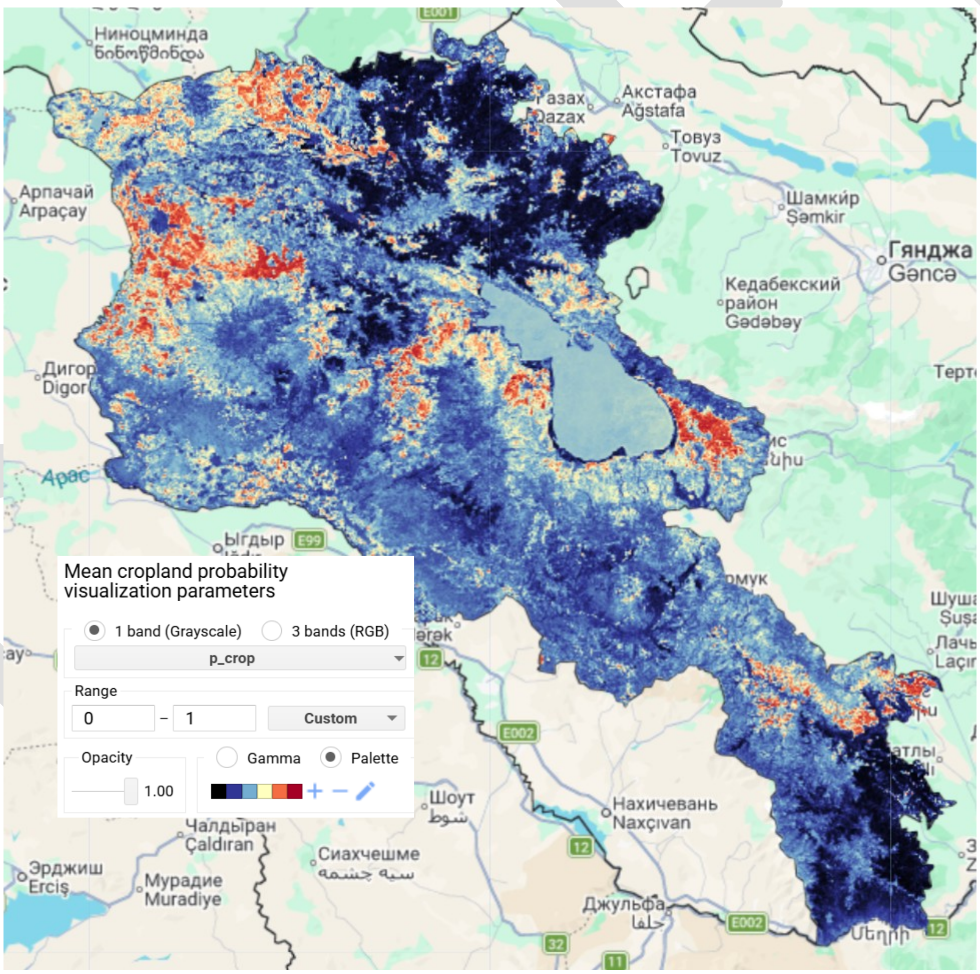


Figure 11. Cropland probability layer

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 89.99%, with false-positive and false-negative rates of 5.18% and 19.20%, respectively. Increasing the probability threshold progressively reduced false-positive errors but increased omission of cropland, while overall accuracy declined at higher thresholds (Fig. 12).

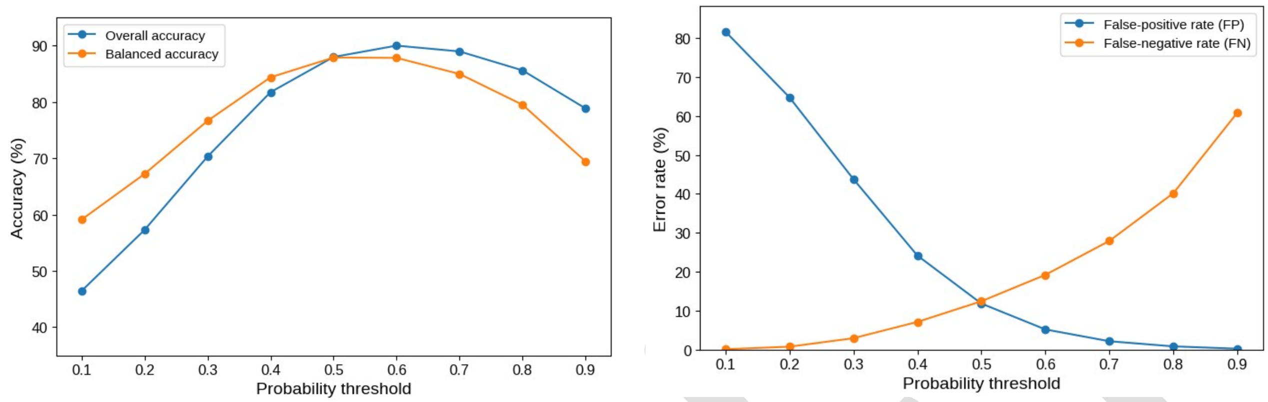


Figure 12. Sensitivity of cropland classification performance to the probability threshold.

High cropland probability values predominantly corresponded to fields that were actively and regularly cultivated 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 cultivated 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 cultivated cropland pixels were subsequently aggregated into actively cultivated agricultural 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. 13).

The layer of irregularly used fields and hay meadows was subsequently used as a basis for delineating human-modified landscapes (Section 2.6.3).

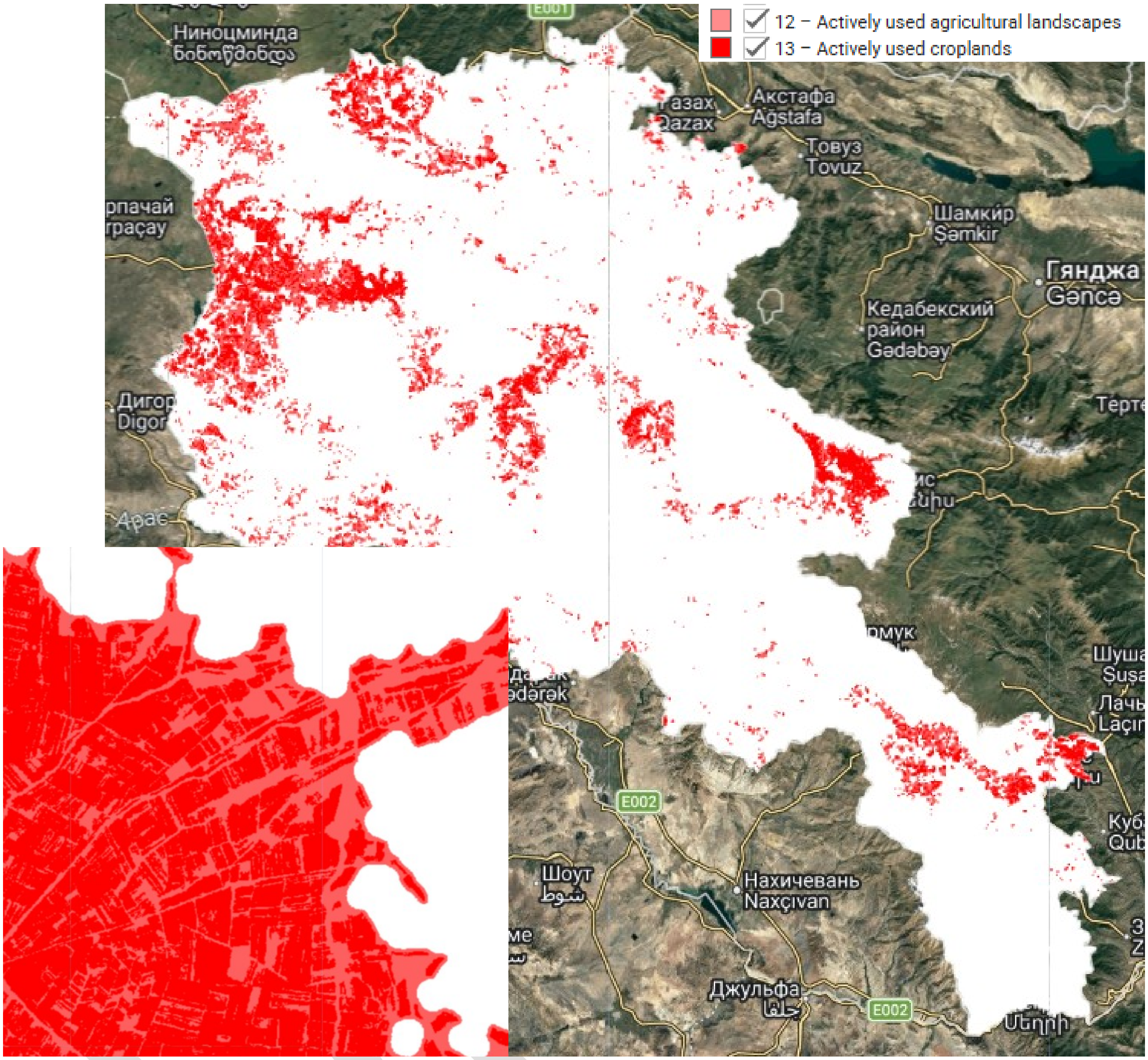


Figure 13. Actively used croplands and actively cultivated agricultural landscapes.

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 2.6.3) were classified as technogenically disturbed areas (Fig. 14).

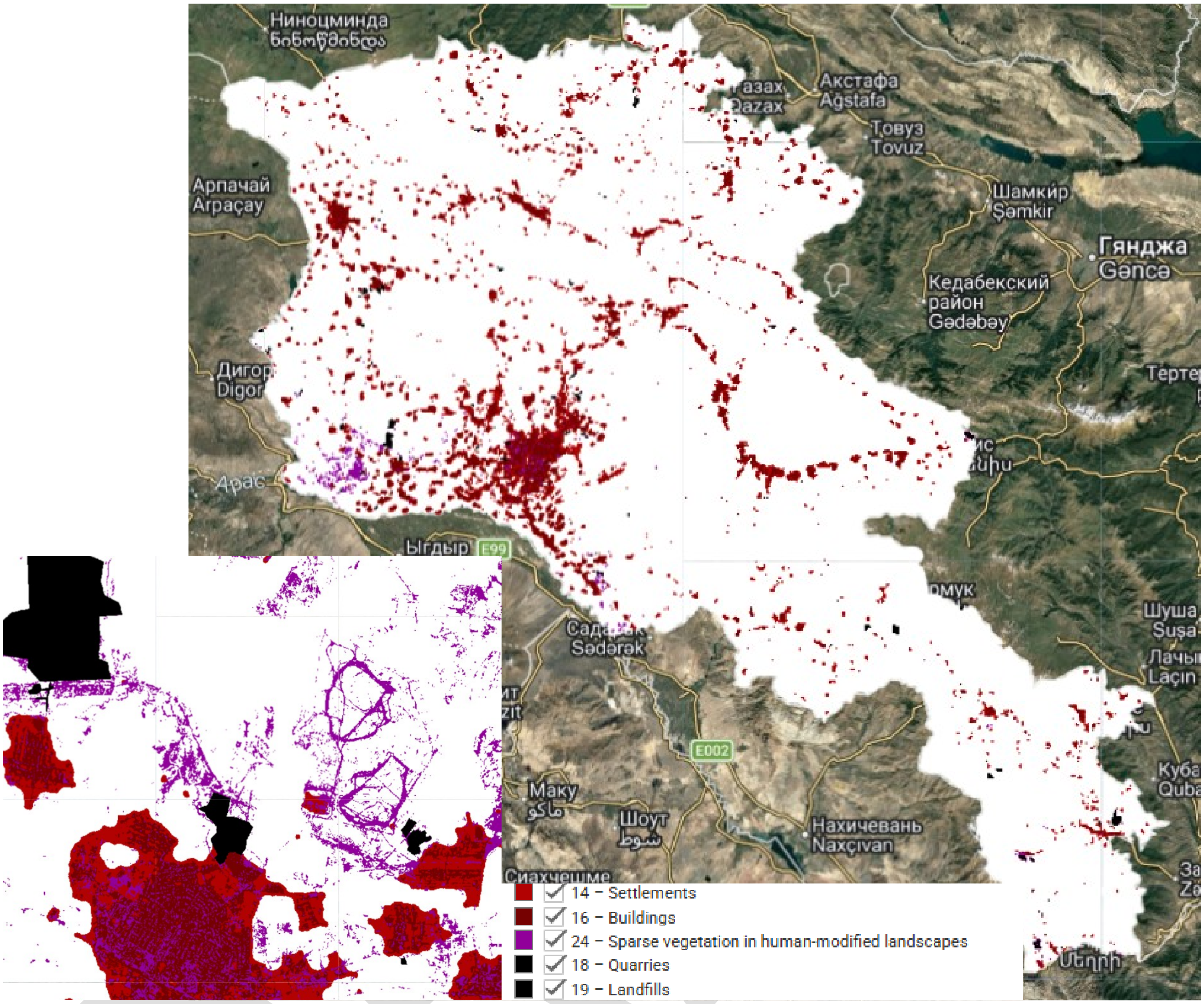


Figure 14. Built-up and technogenically disturbed areas. The inset shows an area north of the city of Armavir.

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

Human-modified landscapes (Fig. 15 a) were delineated using the lower-probability cropland layer (≥ 0.60 and < 0.80) described in Section 2.6.1 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. The resulting layer was subsequently visually inspected and manually refined using high-resolution satellite imagery, including historical imagery available in Google Earth. 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 vegetation 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. 15 b) were mapped as an informational layer representing areas potentially subject to regular livestock grazing. A total of 1,445 livestock farmyards were identified from OpenStreetMap (OSM) land-use data (farmyard), and a 3 km buffer was generated around each farmyard. The 3 km distance was used as a conservative estimate of the area regularly accessible to grazing livestock from farmyards. 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. Further refinement of this layer should include verification of 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 would allow inactive farmyards to be excluded and improve the representation of current grazing influence.

An additional informational layers showing the areas of special conservation importance (national PAs, Emerald network sites, and Ramsar sites names) and settlement names was included to facilitate spatial orientation and interpretation of the ecosystem map.

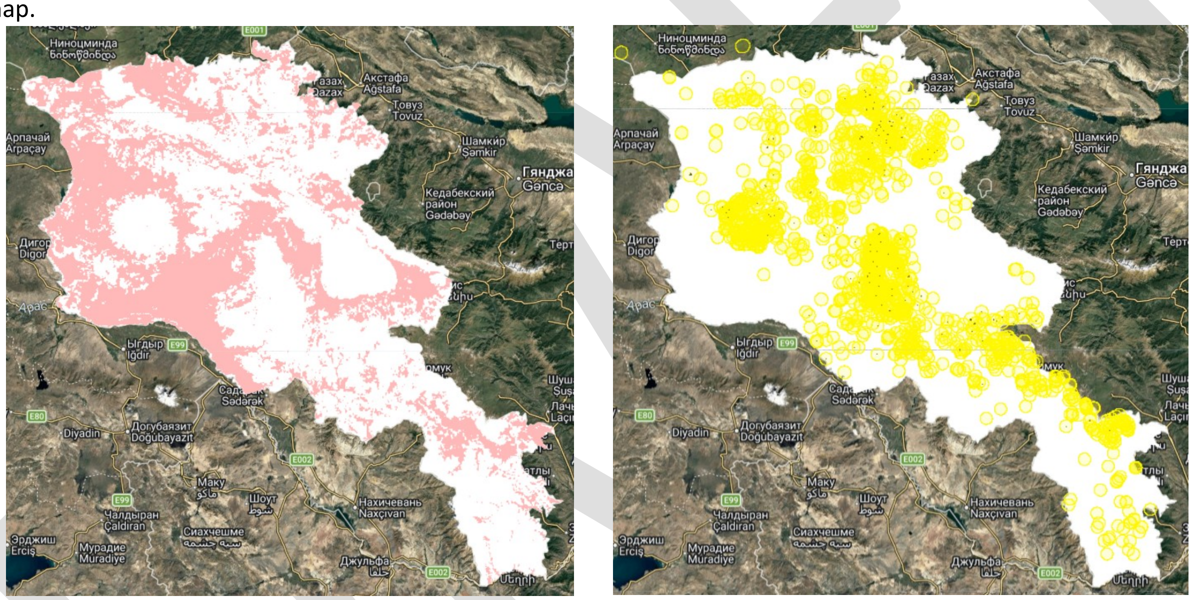


Figure 15. Human-modified landscapes and grazing zones

1.3. Integrated ecosystem map of Armenia

The ecosystem layers described above were integrated into a single spatially explicit ecosystem map of Armenia at 10 m resolution (Fig. 16). The layers were combined using a hierarchical overlay procedure following the same bottom-to-top sequence as presented in the map legend. Thus, classes appearing higher in the legend were generally overlaid on and, where spatial overlap occurred, replaced the underlying classes.

The potential grassland map formed the underlying natural ecosystem layer. Potential fens and wet meadows were overlaid on this layer, replacing the corresponding grassland classes within their mapped extent. Sparsely vegetated ecosystems were also overlaid on the grassland layer and similarly replaced the underlying grassland classes. No priority rule was required between wetlands and sparsely vegetated ecosystems, as these classes occur under contrasting environmental conditions and their mapped distributions neither overlapped nor were spatially adjacent.

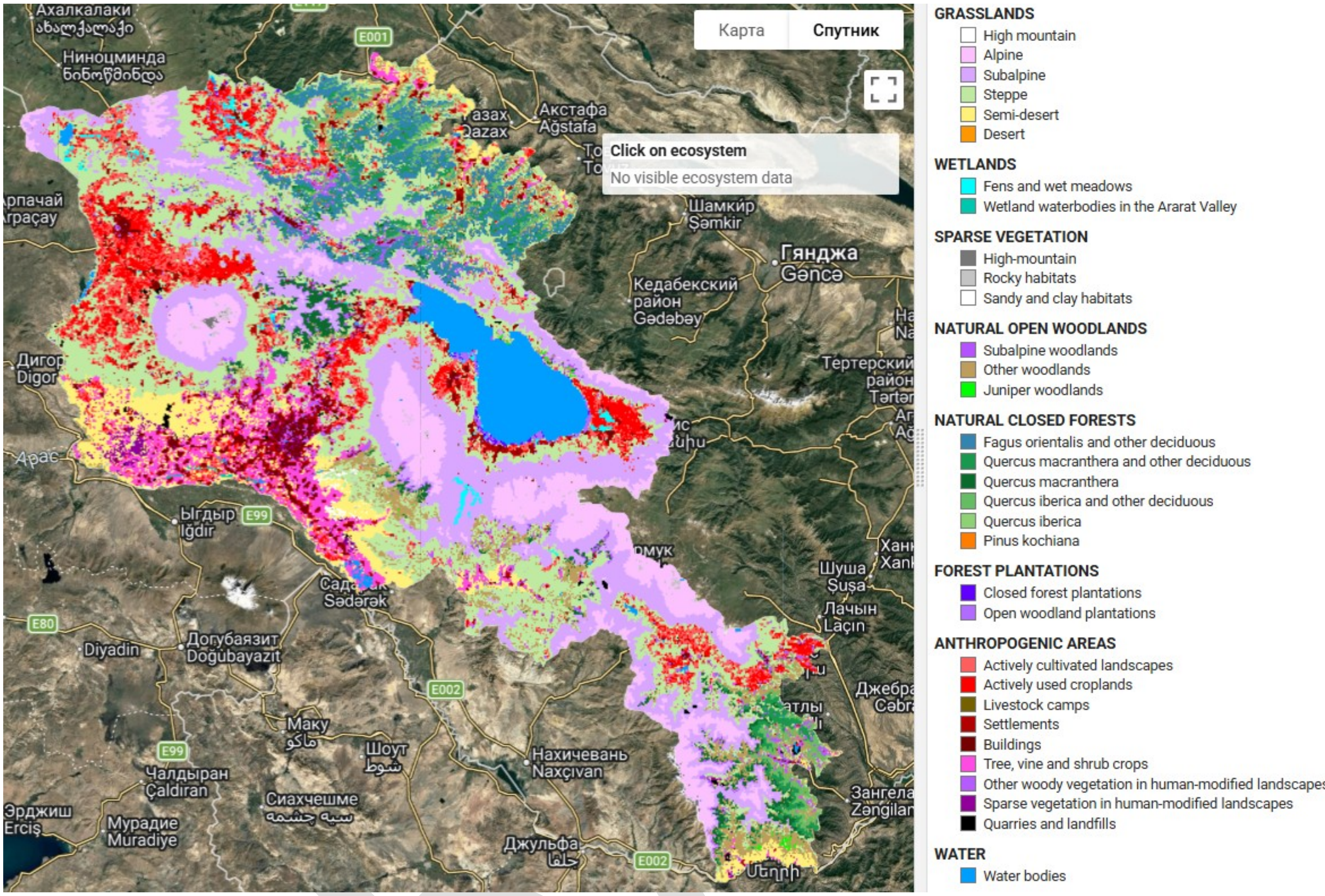


Figure 16. Integrated ecosystem map of Armenia.

Natural woody vegetation layers—including natural forests and natural woodlands—were overlaid on the grassland layer, replacing the underlying grassland classes. The forest and woodland layers were spatially exclusive and therefore did not overlap with one another. Within the forest layer, areas of natural *Pinus kochiana* forest were assigned the highest priority and overlaid on the other forest ecosystem types. 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.

Anthropogenic layers were subsequently overlaid on the grassland layer, replacing the underlying grassland classes where they occurred. However, natural forest and woodland classes were retained and were not replaced by the anthropogenic layers. The anthropogenic group comprised ten layers incorporated into the integrated ecosystem map and two additional informational layers that were not included as ecosystem classes:

- (1) Human-modified landscapes formed the lowest layer in the anthropogenic hierarchy. This layer was retained for informational purposes only and was not incorporated as an ecosystem class into the integrated map.

- (2) Actively cultivated landscapes were overlaid above the human-modified landscape layer, while (3) actively cultivated fields were placed above them. Thus, individual high-confidence cultivated fields remained distinguishable within the broader actively cultivated agricultural landscape.

- (4) Livestock farmyards were overlaid on natural grasslands. The associated (5) grazing zones were retained as an informational layer only and were not incorporated as an ecosystem class into the integrated map.

- (6) Settlement areas were overlaid on grasslands, while (7) buildings were placed above the settlement areas, preserving the locations of individual built-up structures within the broader settlement extent.
- (8) Sparse vegetation in human-modified landscapes was overlaid on both grasslands and settlement areas.
- (9) Quarries and (10) landfills were overlaid on grasslands.
- (11) Tree, vine and shrub crops were overlaid on grasslands and, in some areas, on cropland classes.
- (12) Other woody vegetation in human-modified landscapes was overlaid on grasslands and settlement areas.

Layers 4, 7, 8, 9, 10, 11, and 12 were spatially exclusive and did not overlap with one another.

The surface water layer derived from the ESA WorldCover 2021 dataset was subsequently overlaid on the ecosystem layers. It primarily replaced underlying grassland classes, as well as occasional individual pixels of other ecosystems along waterbody margins.

Thus, the individual ecosystem layers were combined into an integrated spatial layer representing the current distribution of natural and anthropogenic ecosystems across Armenia (Fig. 16).

1.4. Reclassification of the Ecosystem Map of Armenia into the IUCN GET

To facilitate its inclusion in the Global Ecosystems Atlas, the national ecosystem map of Armenia was reclassified according to the IUCN Global Ecosystem Typology (GET) (Table 2, Fig.17).

Table 2. Reclassification of ecosystem types from the national ecosystem map of Armenia into the IUCN GET.

National ecosystem map of Armenia		*IUCN GET*
Grasslands	Desert	T5.1 Semi-desert steppes
	Semi-desert	
	Steppe	T4.5 Temperate subhumid grasslands
	Subalpine	
	Alpine	T6.4 Temperate alpine grasslands and shrublands
Wetlands	Fens and wet meadows	TF1.7 Boreal and temperate fens
	Wetland waterbodies in the Ararat Valley	TF1.3 Permanent marshes
Natural forests	*Fagus orientalis + Carpinus, Tilia, etc.*	T2.2 Deciduous temperate forests
	Quercus macranthera + Carpinus, Tilia, etc.	
	Quercus macranthera	
	Quercus iberica+ Carpinus, Tilia, etc.	
	Quercus iberica	
	Pinus kochiana (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
	Woody vegetation in human-modified landscapes	Closed forests recoded as T2.2 Deciduous temperate forests Open woodlands recoded as 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, screes and lava flows
	Sandy and clay habitats	Areas within the grassland zones were reclassified into the corresponding grassland FG
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 grassland zones were reclassified into the corresponding grassland FG

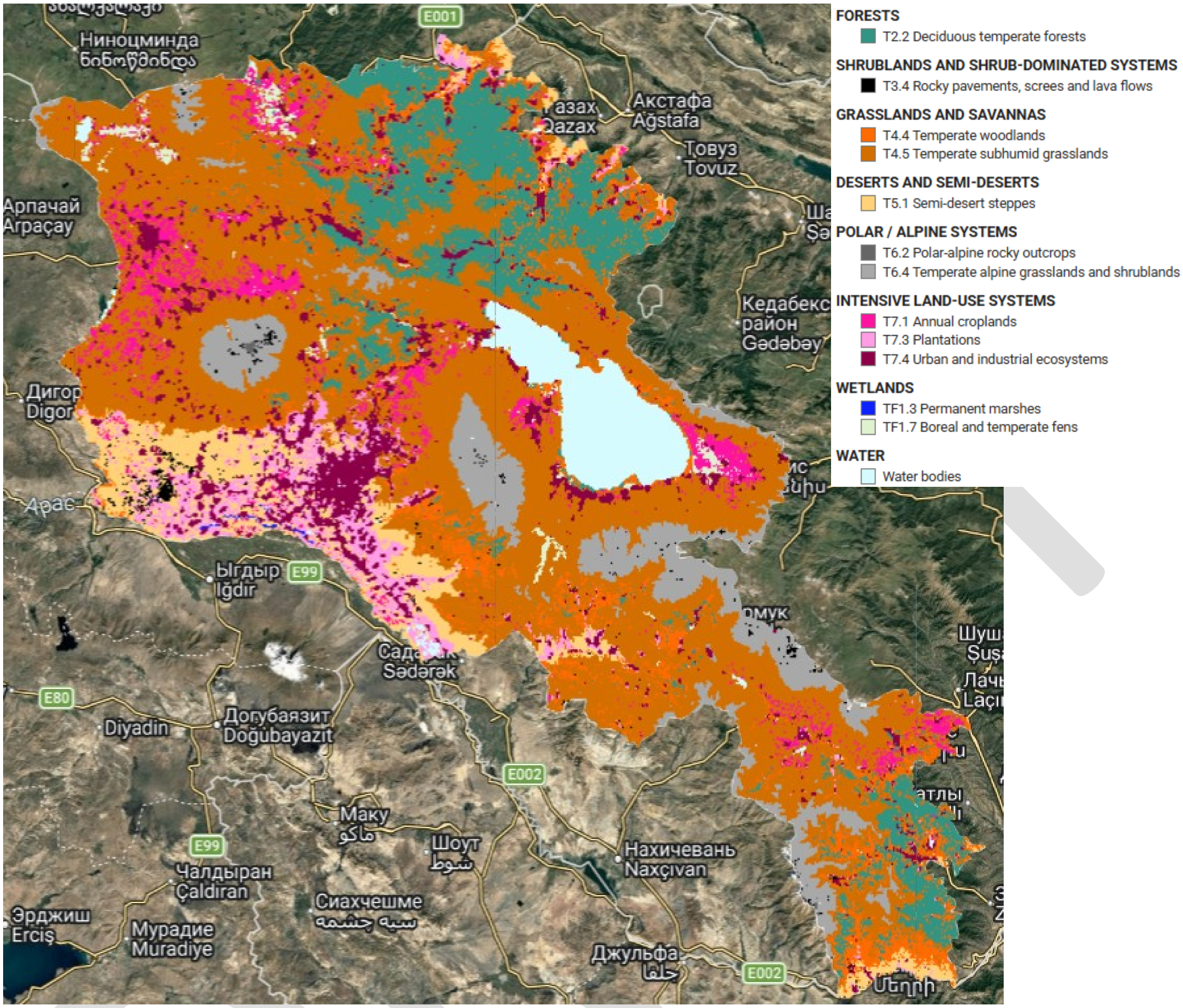


Figure 17. Ecosystem map of Armenia reclassified according to the IUCN Global Ecosystem Typology (GET).

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. Subalpine 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 natural 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.

2. Ecosystem extent and spatial distribution

2.1. 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 2, Fig. 18).

Table 2. Aggregated ecosystem extent statistics

Ecosystem groups	Area, km2	Share in Armenia, %
Grasslands	15,589.3	52.4
Wetlands	161.7	0.5
Sparse vegetation	249.0	0.8
Natural open woodlands	2,085.1	7.0
Natural closed forests	3,114.7	10.5
Forest plantations	135.4	0.5
Actively cultivated landscapes	3,550.9	11.9
Tree, vine and shrub crops	1,036.0	3.5
Urban and technogenically disturbed areas	3,466.9	11.7
Water	1,376.1	4.6

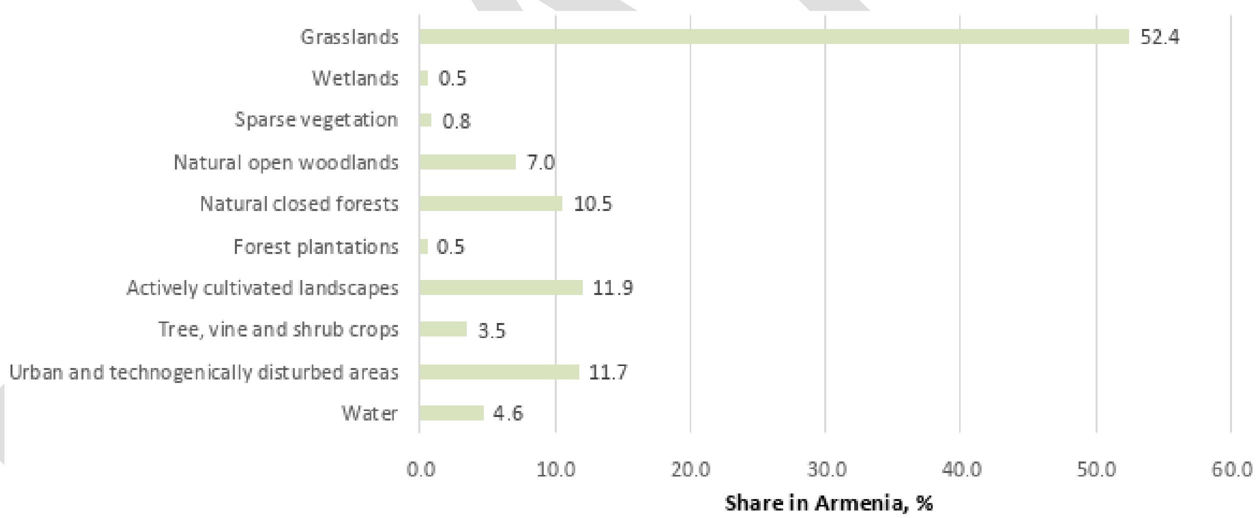


Figure 18. Aggregated ecosystem extent statistics

The area of all ecosystem types included in the Ecosystem Map of Armenia for the entire country is shown in Figure 19. 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.

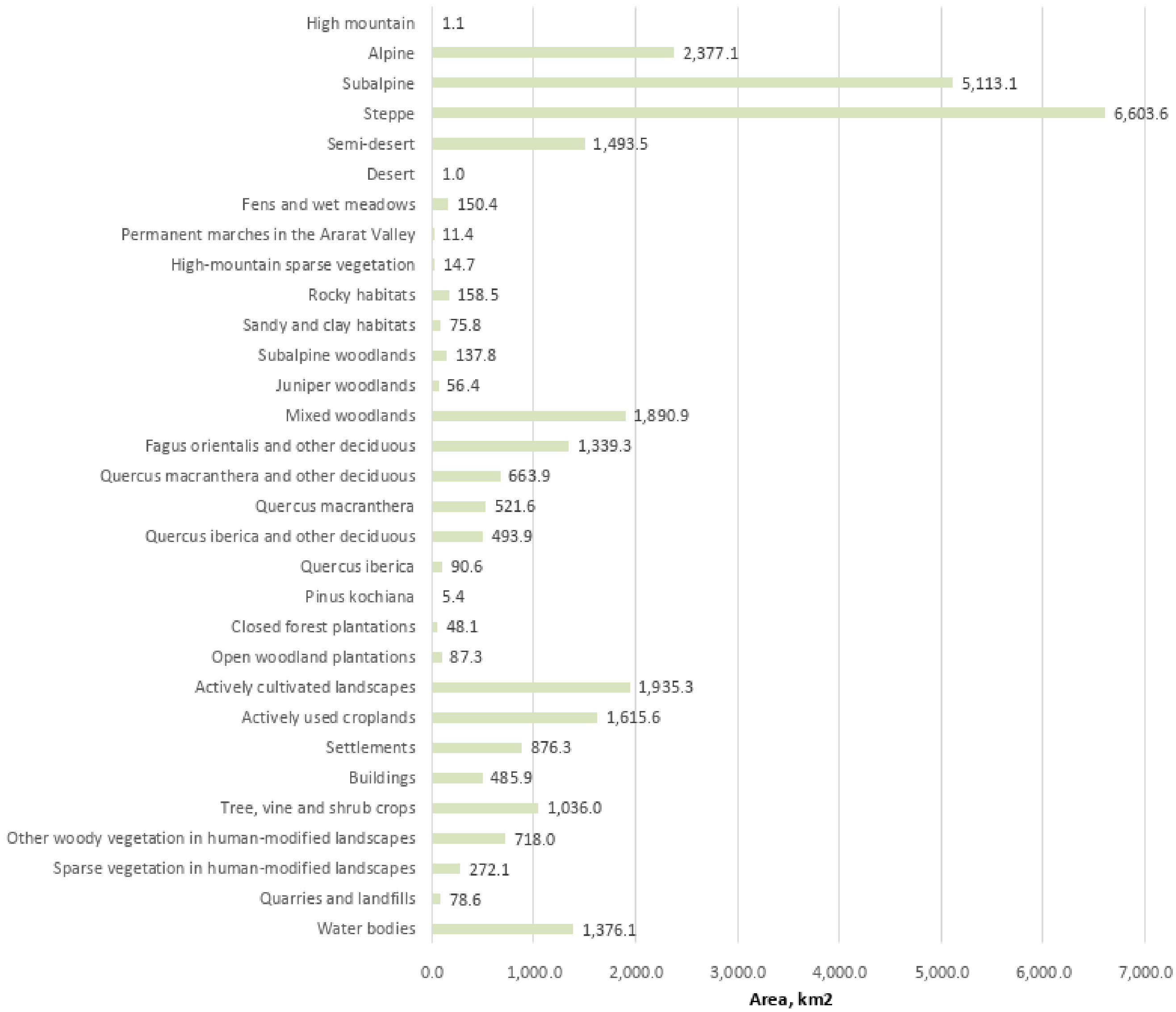


Figure 19. Extent of all ecosystem types in Armenia

Ecosystem extent varies considerably among marzes (Figure 20, Table 3). 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.

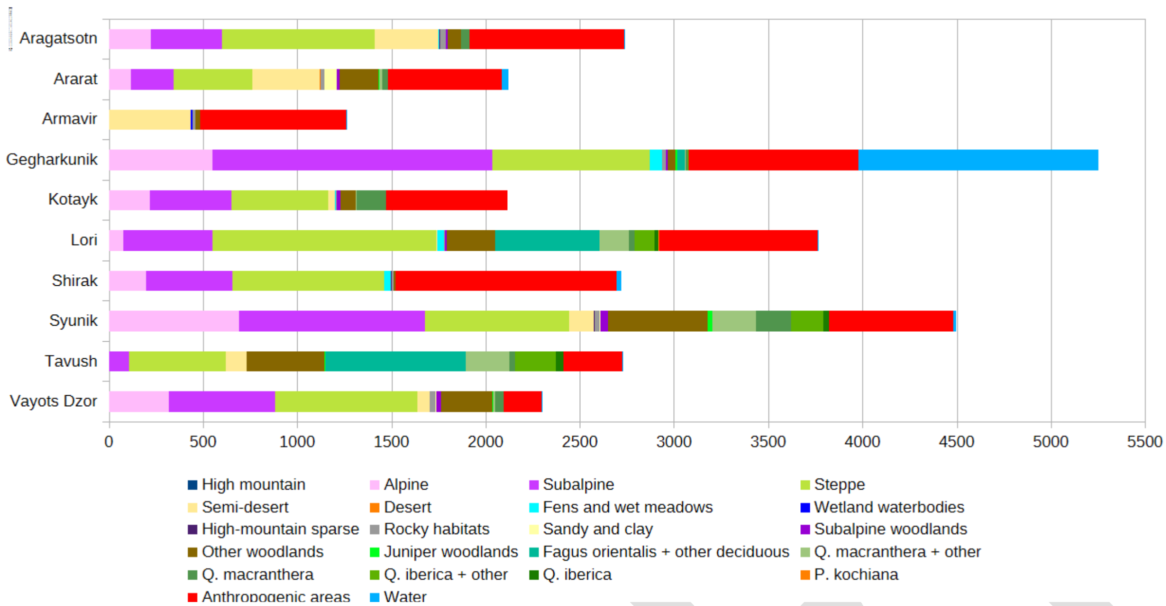


Figure 20. Ecosystem extent across marzes

Table 3. *Extent of all ecosystem types in Armenia and across marzes*

	ARMENIA	ARAGA-TSOTN	ARARAT	ARMAVIR	GEGHAR-KUNIK	KOTAYK	LORI	SHIRAK	SYUNIK	TAVUSH	VAYOTZ DZOR	YEREVAN
High mountain	1.1	0.6	0	0	0	0	0	0.2	0.3	0	0	0
Alpine	2377.1	219.5	116.3	0	550.3	214.2	73.6	195.9	688.3	2	316.9	0
Subalpine	5113.1	380.6	223.7	0	1484.7	437.2	472.9	456.6	987.4	104.2	565.9	0
Steppe	6603.6	809	420.7	0.5	831.7	513.6	1187.6	808.7	767	510.4	750.8	3.7
Semi-desert	1493.5	335.5	359	433.1	0	33.8	9.7	0	127.6	113.9	66.9	13.9
Desert	1	0	1	0	0	0	0	0	0	0	0	0
Fens and wet meadows	150.4	6.5	0	0	69.7	3.5	34.2	34.3	0	0	2.2	0
Permanent marshes in the Ararat Valley	11.4	0	1.2	10.1	0	0	0	0	0	0	0	0
High-mountain sparse vegetation	14.7	6.4	0	0	0.1	0.2	0	2.7	5.4	0	0	0
Rocky habitats	158.5	29.1	20.7	13.7	17.5	7.3	4.7	9.8	28.2	0.2	27.3	0
Sandy and clay habitats	75.8	0.3	63.1	2	1	0.2	0.2	0.2	0.9	0	7.9	0
Subalpine woodlands	137.8	11.5	15.3	0	11	20.7	9	1.3	43.3	0.3	25.3	0
Other woodlands	1890.9	69.4	206.9	22.8	39.9	75.8	257.9	10.8	526.2	411.6	269.5	0
Juniper woodlands	56.4	0	8	0	8.6	1.2	0.4	0	28.5	3.3	6.4	0
Fagus orientalis and other deciduous	1339.3	0	0	0	41.5	0	550.7	1.7	0	745.3	0	0
Quercus macranthera and other deciduous	663.9	1.1	12.5	0	6.7	8.1	158.6	0.1	232.1	235.2	9.3	0
Quercus macranthera	521.6	40.7	30.6	0	10	153.3	29.7	0.2	185.7	27.6	43.8	0
Quercus iberica and other deciduous	493.9	0.8	1.3	0.1	0.9	0.5	105.5	0	168.6	215.1	1.1	0
Quercus iberica	90.6	0	0	0.8	0	0	19	0	30.6	40.1	0	0
Pinus kochiana	5.4	0	0	0	0	0	3.8	0	0	1.6	0	0
Closed forest plantations	48.1	3.2	0	0	29.6	0.3	10.5	4.5	0	0	0.1	0
Open woodland plantations	87.3	5.4	0.1	0	54.7	2.9	13.2	10	0	0	1	0
Actively cultivated landscapes	1935.3	243.7	49.7	88.4	289.2	152.8	262.4	519.8	226.5	70.3	32.1	0.3
Actively used croplands	1615.6	208	34.6	57.5	266.4	133.4	230.4	435.7	196.9	37	15.4	0.4
Settlements	876.3	93.2	89.9	92.1	138.7	95	92.6	100.3	34.7	73.7	21.6	44.6
Buildings	485.9	34	60.5	74.8	53.8	44.4	42.7	56.8	12.7	29.2	5.9	71.2
Tree, vine and shrub crops	1036	122.4	305.9	324.9	0	99.5	6.6	0	32.5	59.6	61.6	23
Other woody veg. in human-modified landscapes	718	68	22.5	22.7	62.4	89.9	178.1	25.4	125.9	43.3	55.5	24.3
Sparse veg. in human-modified landscapes	272.1	28.5	38.7	110.3	5.3	17.1	1.8	6.6	10.5	0.3	4.6	48.4
Quarries and landfills	78.6	15.8	2.5	5.3	4.9	8.9	6.4	9.1	17.8	0.6	4.6	2.6
Water bodies	1376.1	4.9	31.9	5.3	1273.4	2.6	3.4	29.4	18.3	3.5	2.5	0.

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 21).

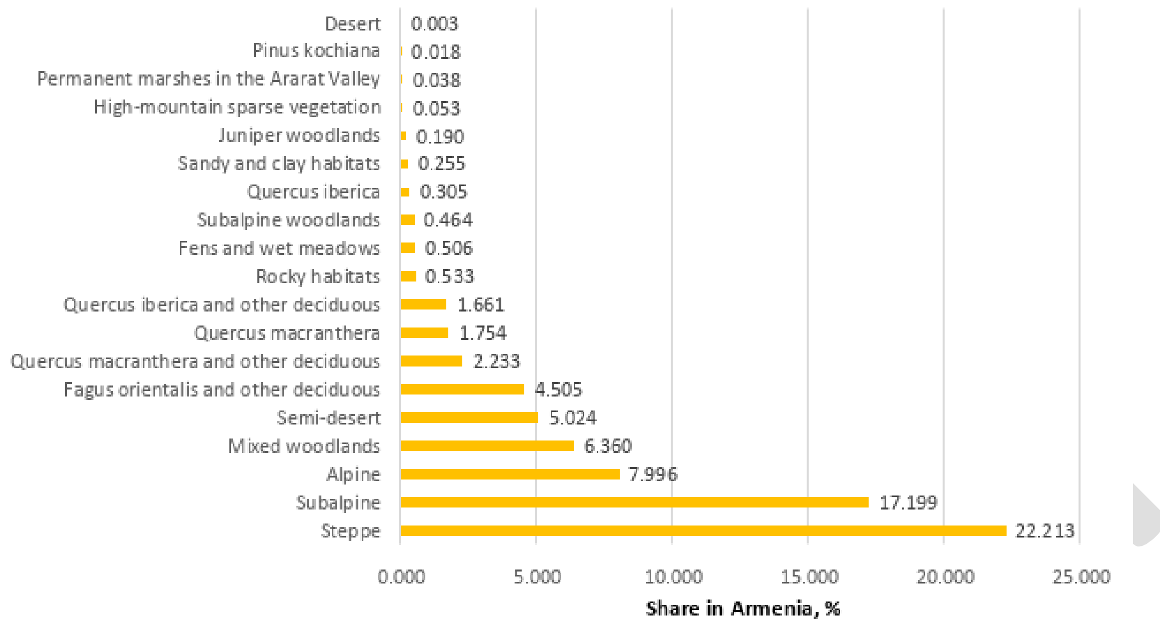


Figure 21. Ranking of natural ecosystem types by rarity

These rare ecosystem types are unevenly distributed among the marzes (Figure 22). Overall, the largest combined area of rare ecosystem types occurs in Syunik, while the smallest occurs in Armavir. 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. Permanent marshes of the Ararat Valley are concentrated in Armavir. 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.

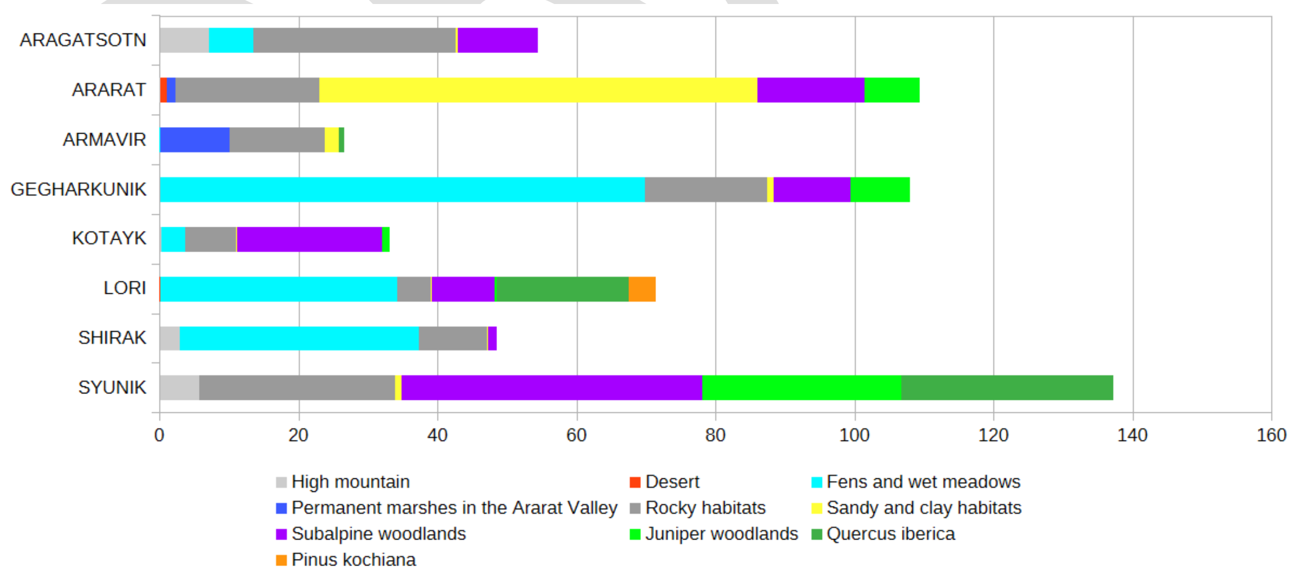


Figure 22. Extent of rare ecosystems across marzes

2.2. Degree of anthropogenic transformation of natural zones

The layer-based structure of the Ecosystem Map of Armenia preserves the underlying layers of zonal grassland types and wetlands separately from anthropogenic land-cover layers. Overlaying the latter on the former enables both visual and quantitative assessment of the degree of anthropogenic transformation of these ecosystem types (Fig. 23).

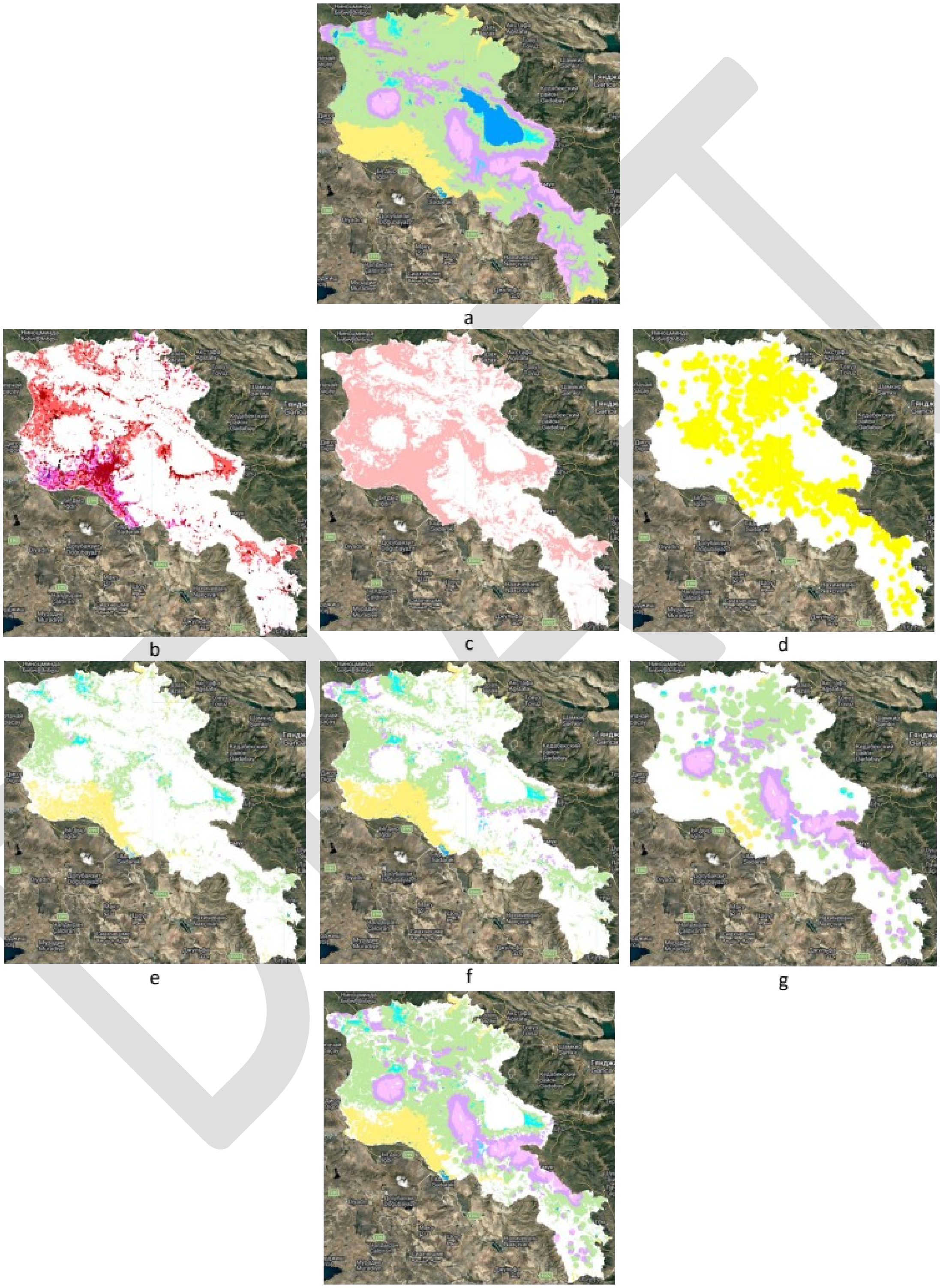


Figure 23. Mapping of anthropogenic transformation of ecosystems

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. To assess the degree of transformation of altitudinal grassland zones and fens, a separate underlying natural ecosystem layer was constructed to represent them irrespective of their current anthropogenic transformation. Water bodies were overlaid on this layer to exclude areas occupied by open water from the potential extent of terrestrial and wetland ecosystem types (Fig. 23a).

Anthropogenic transformation was assessed by overlaying three spatial layers on this underlying natural ecosystem layer. The first was a combined anthropogenic land-cover layer, constructed by sequentially overlaying actively cultivated landscapes, tree, vine and shrub crops, settlements, anthropogenic sparse-vegetation areas, and quarries and landfills (Fig. 23 b). The second comprised broad human-modified landscapes (Fig. 23 c). The third consisted of 3-km buffers around livestock camps, used as an indicator of potential grazing pressure (Fig. 23 d). For each grassland and wetland ecosystem type, the area and proportion overlapping each of these three layers were calculated.

Croplands, tree, vine and shrub crops, and settlements occupy the largest areas within the steppe and semi-desert zones (Fig. 23 e). The broader category of human-modified landscapes also extends partly into the subalpine zone (Fig. 23 f). Grazing zones are most extensive in the steppe zone, including areas currently occupied by forests and woodlands, as well as in the alpine and subalpine zones (Fig. 23 g). The combined footprint of land transformation associated with croplands and settlements and potential grazing pressure covers most of Armenia (Fig. 23 h). The largest areas remaining outside this combined footprint are located in the south of the country, particularly in Syunik and Vayots Dzor marzes.

According to our map, actively cultivated landscapes occupy 12.1% of Armenia, tree, vine and shrub crops 3.5%, settlements 5.7%, and anthropogenically degraded areas 1.2%. The remaining 77.5% of the country's territory lies outside these anthropogenic zones (Table 4, Figure 24). The degree of transformation varies markedly among the natural zones. The alpine, high-mountain, and desert zones are the least transformed; however, the very small extent of the latter two should be taken into account, and the desert ecosystem is delineated within the Goravan Sands protected area. The highest degree of transformation is observed within the potential distribution area of wetlands and wet meadows, indicating that these ecosystems may have formerly occupied substantially larger areas. More than 60% of their potential extent is currently occupied by croplands. The semi-desert zone is the next most 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.

Table 4. Share of natural-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	0.00	0.00	0.00	0.00	100.00
Alpine	0.00	0.00	0.06	0.18	99.76
Subalpine	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
Wetlands	63.11	0.00	1.36	0.09	35.43
Armenia	12.10	3.48	5.67	1.24	77.51

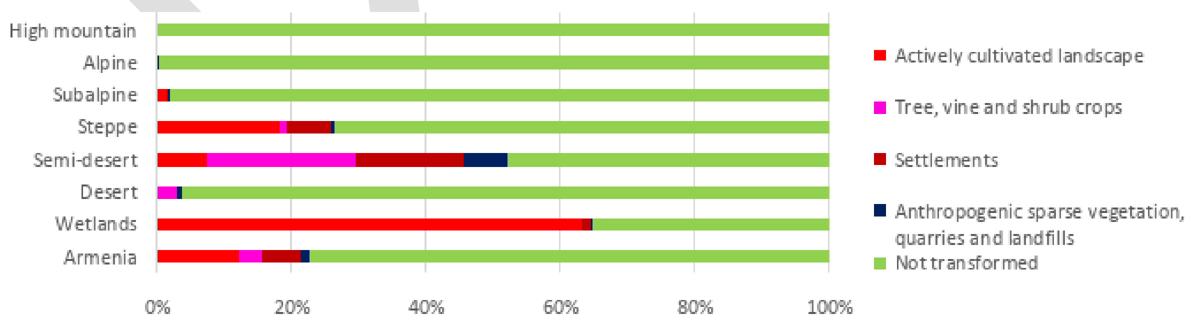


Figure 24. Share of natural-zone area transformed by different types of anthropogenic land use, %.

When the transformation of natural zones is assessed using the broader category of human-modified landscapes together with potential grazing-pressure zones, about 40% of Armenia's territory falls within human-modified landscapes and another 40% within potential grazing-pressure zones, with the two categories partially overlapping. About 32% of the territory lies outside both categories of anthropogenic influence (Figure 25 a). Similarly, in most zones, only around 30% of their potential extent remains outside areas of anthropogenic influence, while less than 10% of the potential wetland extent remains unaffected. More than 70% of the high-mountain and alpine zones fall within potential grazing-pressure areas. With decreasing elevation, the proportion occurring within human-modified landscapes increases, reaching 71% in the semi-desert zone and 88% within the potential distribution area of wetlands. Data by marz are presented in Appendix Table S5.

The area in which human activities affect natural ecosystems varies considerably among the marzes (Figure 25 b). Armavir is the most modified, with 87% of its area occurring within human-modified landscapes, while potential grazing pressure is minimal. Around half or more of the area of Shirak, Aragatsotn, and Kotayk lies within human-modified landscapes; in Kotayk, 68% of the area also falls within potential grazing-pressure zones. In most marzes, potential grazing-pressure zones cover a larger area than human-modified landscapes, whereas the opposite pattern is observed in Armavir and Shirak. Syunik, Vayots Dzor, and Gegharkunik are the least affected, with more than 40% of their area remaining outside the assessed zones of anthropogenic influence.

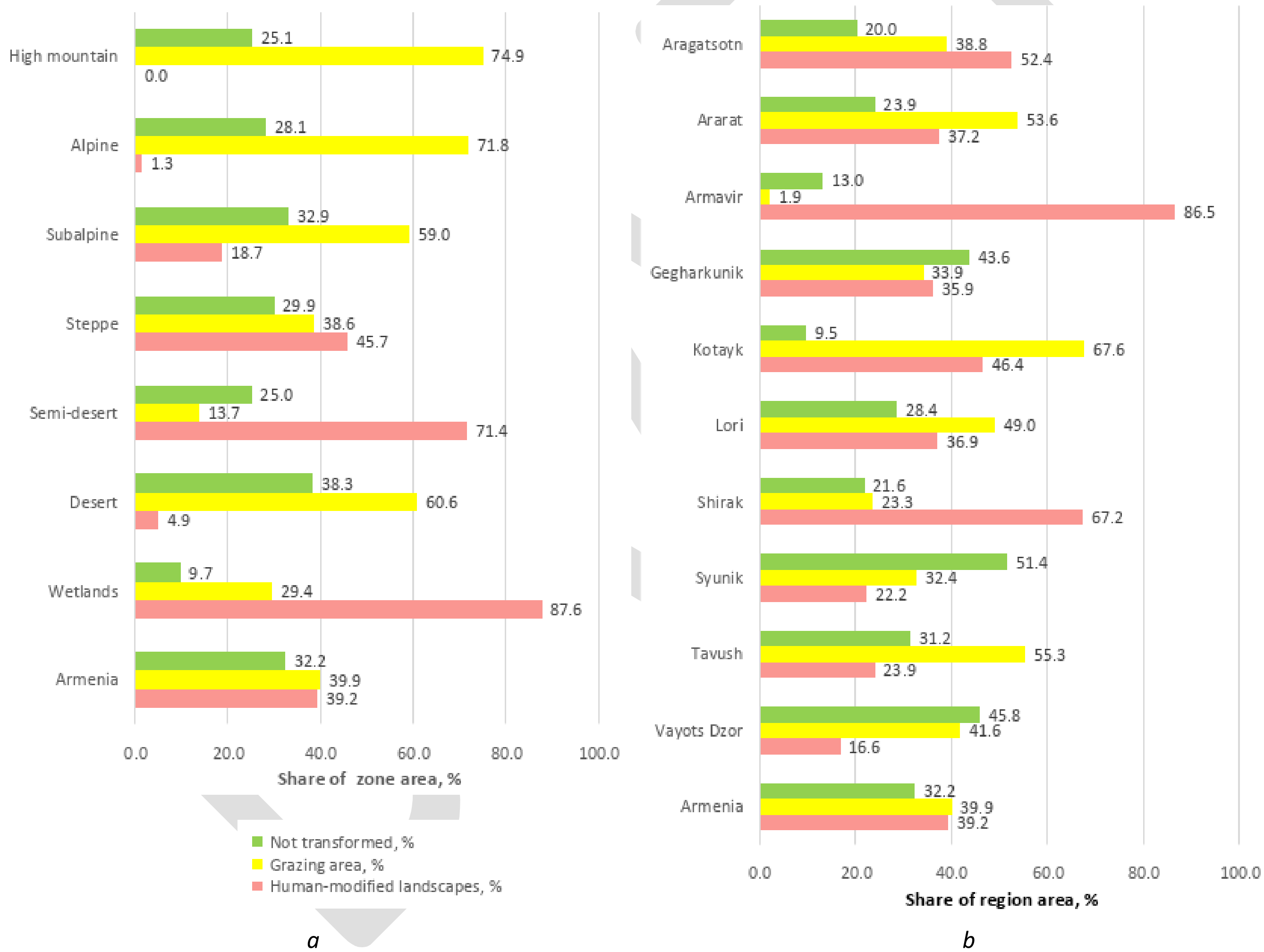


Figure 25. Share of natural zones in human-modified landscapes together with potential grazing-pressure zones: a) across natural zones; b) across marzes. The sum of the percentages exceeds 100% because the areas of anthropogenic influence partially overlap.

2.3. 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 national Ecosystem Map of Armenia, either directly reclassified or aggregated into GET Ecosystem Functional Groups according to the methodology described in Section 4 (Table 5, Figure 26).

Almost 40% of Armenia's territory is occupied by EFG T4.5 Temperate subhumid grasslands. Among natural ecosystems, this is followed by T2.2 Deciduous temperate forests, T6.4 Temperate alpine grasslands and shrublands, T4.4 Temperate woodlands, and T5.1 Semi-desert steppes, each occupying between approximately 6% and 11% of the country (Figure 26). The remaining natural ecosystem types — T3.4, T6.2, TF1.3, and TF1.7 — each occupy less than 1% of Armenia. The three anthropogenic ecosystem groups together account for 21.7% of the country, with T7.1 Annual croplands being the most extensive (11.9%).

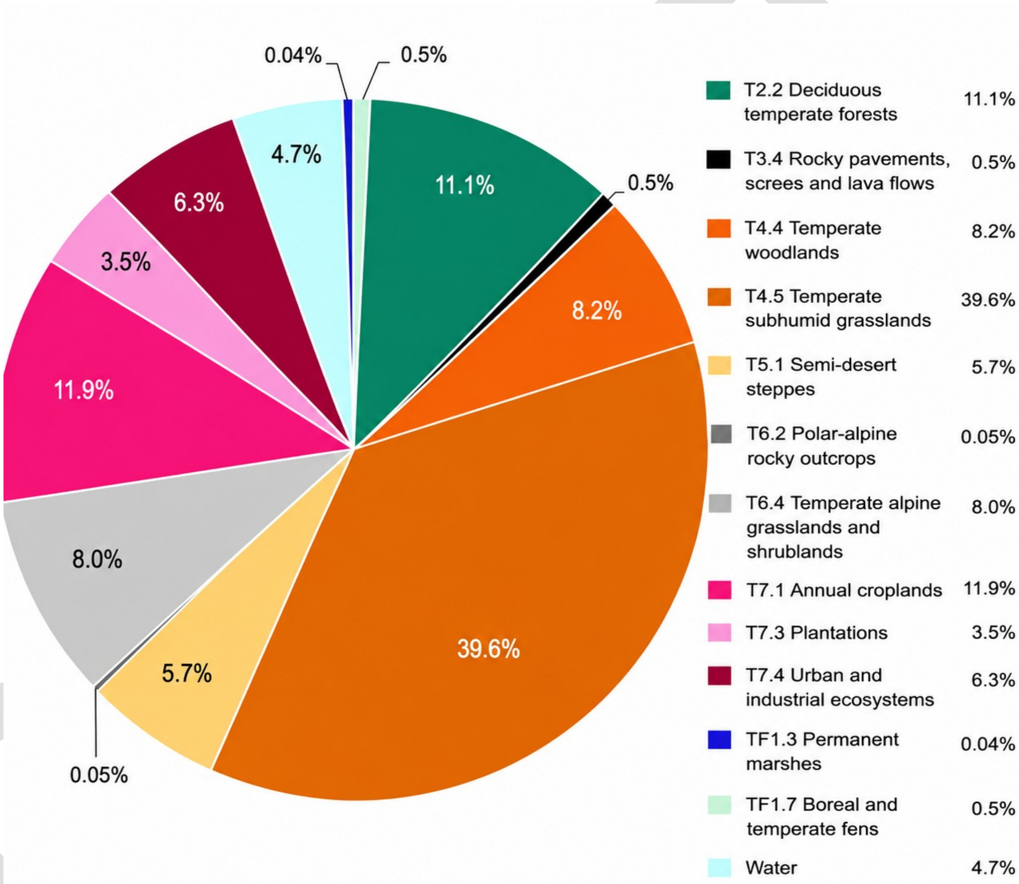


Figure 26. Proportional extent of ecosystem types in the GET-compatible Ecosystem Map of Armenia.

Table 5. Cross-referencing and extent of ecosystem types in the national Ecosystem Map of Armenia and the GET-compatible map.

	Ecosystem map of Armenia	*Area, km²*	*%*			*IUCN GET map*	*Area, km²*	*%*
High mountain	High mountain grasslands	1.1	0.0					
	Alpine grasslands	2377.1	8.0	2379.8	8.0	T6.4 Temperate alpine grasslands and shrublands	2379.8	8.0
Alpine	Sparse vegetation on sand and clay substrates	0.6	0.0					
	Human-modified sparse vegetation	1.1	0.0					
	Subalpine grasslands	5113.1	17.2					
Subalpine	Sparse vegetation on sand and clay substrates	0.5	0.0					
	Human-modified sparse vegetation	1.5	0.0	11760.5	39.6	T4.5 Temperate subhumid grasslands	11760.5	39.6
	Steppe grasslands	6603.6	22.2					
Steppe	Sparse vegetation on sand and clay substrates	25.8	0.1					
	Human-modified sparse vegetation	16.2	0.1					
Semi-desert	Semi-desert grasslands	1493.5	5.0					
	Sparse vegetation on sand and clay substrates	48.9	0.2					
	Human-modified sparse vegetation	140.4	0.5					
	Desert	1.0	0.0	1683.9	5.7	T5.1 Semi-desert steppes	1683.9	5.7
Desert	Sparse vegetation on sand and clay substrates	0.0	0.0					
	Human-modified sparse vegetation	0.0	0.0					
Wetlands	Fens and wet meadows	150.4	0.5	150.4	0.5	TF1.7 Boreal and temperate fens	150.4	0.5
	Wetland waterbodies in the Ararat Valley	11.4	0.04	11.4	0.04	TF1.3 Permanent marshes	11.4	0.04
Sparse vegetation	High-mountain sparse vegetation	14.7	0.05	14.7	0.05	T6.2 Polar-alpine rocky outcrops	14.7	0.05
	Rocky habitats	158.5	0.5	158.5	0.5	T3.4 Rocky pavements, screes and lava flows	158.5	0.5
Open woodlands	Subalpine	137.8	0.5					
	Juniper	56.4	0.2					
	Other woodlands	1890.9	6.4	2435.8	8.2	T4.4 Temperate woodlands	2435.8	8.2
	Open-canopy forest plantations	87.3	0.3					
	Woodland in human-modified landscapes	263.4	0.9					
Closed forests	Fagus orientalis and other deciduous	1339.3	4.5					
	Quercus macranthera and other deciduous	663.9	2.2					
	Quercus macranthera	521.6	1.8					
	Quercus iberica and other deciduous	493.9	1.7					
	Quercus iberica	90.6	0.3	3297.0	11.1	T2.2 Deciduous temperate forests	3297.0	11.1
	Pinus kochiana	5.5	0.0					
	Closed-canopy forest plantations	48.1	0.2					
	Forest-like woody veget. in human-modified landscapes	134.2	0.5					
Croplands	Actively cultivated landscapes	1935.3	6.5					
	Actively used croplands	1615.6	5.4	3550.9	11.9	T7.1 Annual croplands	3550.9	11.9
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	876.3	2.9					
	Buildings	485.9	1.6					
	Quarries and landfills	78.6	0.3					
	Sparse vegetation in Settlements	112.4	0.4	1873.9	6.3	T7.4 Urban and industrial ecosystems	1873.9	6.3
	Woodlands in settlements	278.9	0.9					
	Forest-like vegetation in settlements	41.8	0.1					
Water		1376.1	4.7			Water	1376.1	4.7
TOTAL		29729	100				29729	100

3. 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 https://www.e-draft.am/projects/7902/about

The total mapped area (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, while differences in the extent of individual land-cover classes reflect the different methodological approaches used. The Ecosystem Map represents spatially explicit land cover derived primarily from satellite observations and mapped ecosystem boundaries, whereas the government statistics are calculated from land-accounting categories and functional land-use designations. Consequently, the two datasets describe related but not fully equivalent characteristics of the territory, and the estimated extent of individual classes is not expected to coincide exactly.

The Ecosystem Map and government land-cover statistics serve different purposes. The Ecosystem Map was designed to represent the spatial distribution and extent of terrestrial ecosystem types, with a primary focus on natural ecosystems, whereas the government data are primarily intended for land-use statistics. Consequently, direct correspondence between their classification systems is neither expected nor required, and differences in the extent of individual classes should be interpreted in this context.

The Ecosystem Map does not include the detailed subcategories related to land designation and ownership represented in the government statistics. At the same time, the classification of natural ecosystems is substantially more detailed than that used in the government statistics. The Ecosystem 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 zonal types of natural grasslands, whereas grasslands in the government statistics are divided into 12 categories according to their use (hayfields and pastures) and the cadastral classification of the land.The Ecosystem 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. Therefore, at this stage, it is not possible to establish an exact correspondence between natural ecosystem types and cadastral categories for the purpose of comparing their areas. 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 approximately 1.2% of Armenia, was not included in the current version of the Ecosystem Map. Tree cover for the Ecosystem Map was identified using satellite imagery; however, shrub cover could not be reliably delineated using the available data and within the resources of the project. This task requires the development of a dedicated mapping methodology. The use of global land-cover datasets to map shrub distribution in Armenia was not considered sufficiently reliable, as their estimates differ several-fold from the government-reported data (Table 6).

The comparison of the Ecosystem Map with government-reported land-cover statistics is presented in Table 7.

Table 6. Comparison of shrub-cover area estimates from government statistics and global land-cover datasets by marz

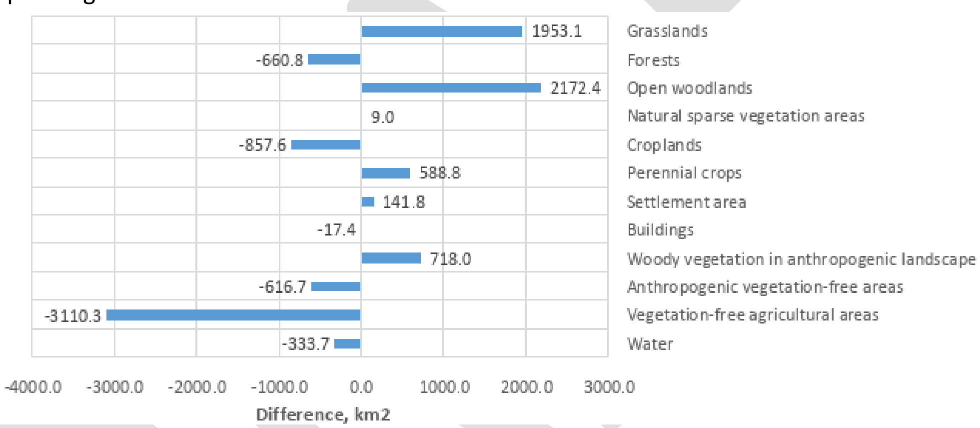
Marz	GOV 2022, km²	ESA 2021, km²	ESA difference, %	ESA / GOV	DW 2022, km²	DW difference, %	DW / GOV
Aragatsotn	3.925	0.000	−100.0%	0.000×	361.594	+9,112.6%	92.1×
Ararat	24.962	0.001	−100.0%	<0.001×	387.490	+1,452.3%	15.5×
Armavir	6.341	0.001	−100.0%	<0.001×	58.548	+823.3%	9.2×
Gegharkunik	36.351	0.000	−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×

Table 7. Comparison of the Ecosystem Map with government-reported land-cover statistics for 2024.

Major ecosystem and land-cover classes	Ecosystem map	Area km2		Government statistics	Area km2	
	High mountain grasslands	1.1		Shrubs	343.7	
	Alpine grasslands	2377.1		Agricultural lands — hayfields	1212.9	
	Subalpine grasslands	5113.1		Agricultural lands — pastures	10482.4	
	Steppe	6603.6		Agricultural lands — other grasslands	777.6	
Grasslands	Semi-desert	1493.5	15739.7	Grasslands on lands of PAs	608.4	13786.6
	Desert	1.0		Grasslands on special-purpose lands	149.0	
				Forest lands — hayfields	92.0	
	Fens and wet meadows	150.4		Forest lands — pastures	109.0	
				Forest lands — other frasslands	11.6	
	Forest - Fagus orientalis and other	1339.3				
	Forest - Quercus macranthera and other	663.9				
	Forest - Quercus macranthera	521.6				
Forests	Forest - Quercus iberica and other	493.9	3162.8	Tree-covered areas		3823.6
	Forest - Quercus iberica	90.6				
	Forest - Pinus kochiana	5.4				
	Closed forest plantations	48.1				
	Subalpine open woodlands	137.8				
Open woodlands	Mixed open woodlands	1890.9	2172.4	**Ambiguous assignment:** **- Tree-covered areas** **- Grasslands**		0
	Juniper woodlands	56.4				
	Open woodland plantations	87.3				
	High-mountain sparse vegetation	14.7		Vegetation-free areas — forest lands	46.3	
Natural sparse vegerta-tion	Rocky sparse vegetation	158.5	249.0	Vegetation-free areas — lands of PAs	167.7	240.0
	Sandy and clay sparse vegetation	75.8		Vegetation-free areas — water lands	26.0	
Croplands	Actively cultivated landscapes	1935.3		Arable land	4405.9	4408.5
	Actively used croplands	1615.6	3550.9	Arable forest lands	2.6	
Perennial crops	Tree, vine and shrub crops	1036.0	1036.0	Perennial crops	419.1	447.2
				Orchards	28.1	
				Grasslands on settlement lands, mixed develop-ment	5.0	
				Grasslands on public-use settlement lands	57.3	
Settlement area	Settlement area	876.3	876.3	Grasslands on settlement lands, public develop-ment	27.9	734.5
				Grasslands on other settlement lands	103.7	
				Grasslands on household plots	540.5	
				Settlement lands — residential development ex-cluding household plots	427.1	
Buildings	Buildings	485.9	485.9	Public development	53.7	503.3
				Mixed development	22.5	
Woody vegetation in human-modified landscapes	Woodland-like vegetation in human-modified landscapes	542.0		**Grasslands**		
	Forest-like vegetation in human-modified landscapes	176.0		**Ambiguous assignment:** **- Tree-covered areas** **- Perennial crops**		0
	Sparse vegetation in human-modified landscapes	272.1		Other anthropogenic vegetation-free lands	133.7	
				Public-use vegetation-free lands	127.2	
Sparse vegetation in human-modified landscapes			350.8	Vegetation-free lands for industry, subsoil use, and other production purposes	402.0	967.5
	Quarries and landfills	78.6		Vegetation-free lands for energy, communica-tions, 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 vegertation**		0	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**			**29743.7**

Because an exact correspondence between ecosystem types in the Ecosystem Map and land-cover subcategories in the government statistics cannot be established, different combinations of classes may be used for area comparisons.The combinations of classes used in our more detailed comparison are presented in Table 7. For example, shrub-covered areas reported in the government statistics are most likely represented primarily as grasslands in the Ecosystem Map and were therefore included in the grassland group for comparison. Open woodlands mapped in the Ecosystem Map may be classified partly as tree-covered areas and partly as grasslands in the government statistics; therefore, no correspondence was assigned to them in Table 7. Similarly, woody vegetation in human-modified landscapes may be represented in the government statistics either as tree-covered areas or as permanent crops and was therefore also left without a corresponding category. The government subcategory “vegetation-free agricultural lands” may correspond to areas mapped as grasslands, croplands, or anthropogenic sparsely vegetated areas in the Ecosystem Map and was likewise left without a corresponding class.

The largest differences in area were observed for grasslands, woodlands, and the government subcategory “vegetation-free agricultural lands” (Fig. 27a). No direct counterparts were identified for woodlands in the government statistics or for vegetation-free agricultural lands in the Ecosystem Map (Table 7). Grassland extent is larger in the Ecosystem Map, whereas vegetation-free areas are more extensive in the government statistics. This opposite pattern suggests that some areas classified as vegetation-free in the government data may be represented as grasslands in the Ecosystem Map. Forest extent is lower in the Ecosystem Map than in the government data, possibly because some tree-covered areas were classified as woody vegetation in human-modified landscapes. In relative terms, the largest difference was observed for permanent crops, whose mapped extent is 132% greater than that reported in the government statistics (Fig. 27b). A substantial difference (−64%) was also observed for anthropogenic sparsely vegetated areas. Differences of 100% occur for categories for which no corresponding class was identified in the other dataset.



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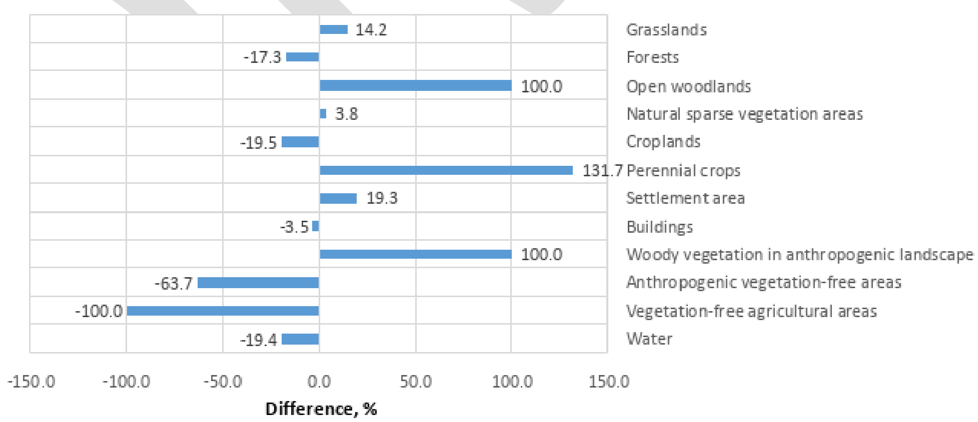

b

Figure 27. Differences between Ecosystem Map estimates and government-reported land-cover statistics: a) absolute difference, km2; b) difference relative to government data.

Table 8. Differences between Ecosystem Map estimates and government-reported land-cover statistics.

Major ecosystem and land-cover classes	*Ecosystem map, km2*	*Government data, km2*	*Difference, km2*	*Difference, % relative to government data*
Grasslands	15739.7	13786.6	1953.1	14.2
Forests	3162.8	3823.6	-660.8	-17.3
Open woodlands	2172.4	0.0	2172.4	100.0
Natural sparse vegetation areas	249.0	240.0	9.0	3.8
Croplands	3550.9	4408.5	-857.6	-19.5
Perennial crops	1036.0	447.2	588.8	131.7
Settlement area	876.3	734.5	141.8	19.3
Buildings	485.9	503.3	-17.4	-3.5
Woody vegetation in anthropogenic landscape	718.0	0.0	718.0	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
Total	**29729.3**	**29743.7**	**-14.4**	**0.0**

The main discrepancies occurred within the broad aggregated classes and largely reflect differences in the approaches used to classify their constituent subcategories. For example, the smaller extent of sparsely vegetated areas in the Ecosystem Map may reflect the use of more restrictive biomass and vegetation-cover thresholds than those applied in the government statistics, resulting in more extensive areas being assigned to this class in the government data. Similarly, the smaller forest extent in the Ecosystem Map may partly result from some tree-covered areas being classified as woodlands or as woody vegetation in human-modified landscapes. Another important source of discrepancy is the use of different criteria for assigning ecosystem types and land-cover subcategories to natural or anthropogenic classes.

Comparison of the generalized classes—Non-woody areas, Trees, Crops, and Built—shows substantially smaller discrepancies, ranging from 1.5% to 10% relative to the government-reported data for terrestrial classes (Table 9). 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 the government statistics revealed substantially larger discrepancies in the estimated areas of these generalized classes (Fig. 28).

Table 9. Differences between generalized classes of Ecosystem Map and government-reported land-cover statistics.

Generalized classes	*Major ecosystem and land-cover classes*	*Ecosystem map, km2*	*Governmen t data, km2*	*Difference, km2*	*Difference, % relative to government data*
Non-woody areas	Grasslands Natural sparse vegetation areas Anthropogenic vegetation-free areas Vegetation-free agricultural areas	18511.9	18104.4	407.5	2.3
Trees	Open woodlands Forests Woody vegetation in anthropogenic landscape	3880.8	3823.6	57.2	1.5
Crops	Croplands + Perennial crops	4586.9	4855.7	-268.8	-5.5
Built	Settlement area + Buildings	1362.2	1237.8	124.4	10.1
Water	Water	1387.5	1721.2	-333.7	-19.4

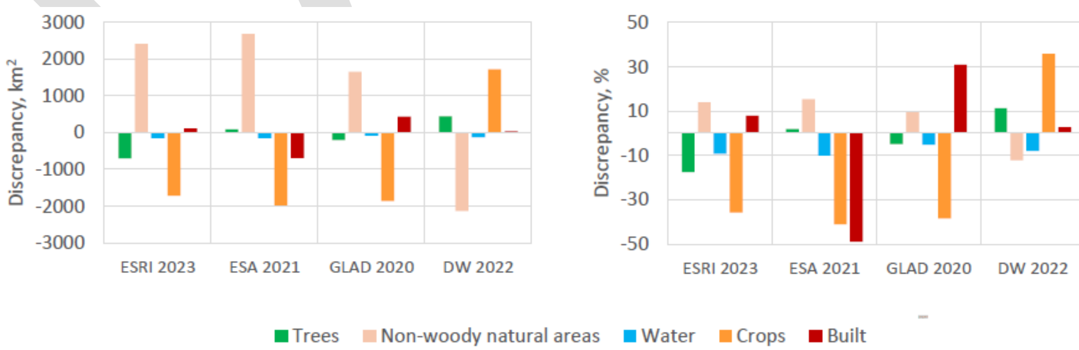

Figure 28. Differences between generalized land cover classes in four global datasets and government data: a) absolute discrepancy, km²; b) discrepancy relative to Government-reported data, %

The correspondence between ecosystem types in the National Ecosystem Map and the GET Map and land-cover subcategories in the government statistics is presented in Table 10. 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.

Table 10. 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.

UICN GET map			***Ecosystem map***			***Government statistics***		
FG	*Area km²*	*Area km²*	*Ecosystem types*		*Area km²*	*Land-cover categories*	*Area km²*	
T2.2 Deciduous temperate forests	3297.0	3162.8	Natural forests and forest plantations	3162.8	3297.0	Tree-covered areas	3823.6	3823.6
		134.2	Forest-like veg. in human-modified landscapes except settlements	134.2				
T6.2 Polar-alpine rocky outcrops	14.7	14.7	High-mountain sparse vegetation	14.7	249.0	Vegetation-free forest lands	46.3	240.0
T3.4 Rocky pavements, screes and lava flows	158.5	158.5	Rocky sparse vegetation	158.5		Vegetation-free lands of PAs	167.7	
Distributed between FG T4.5, T5.1, T6.6			Sandy/clay sparse vegetation in four grassland zones	0.6 0.5 25.8 48.9		Vegetation-free water lands	26.0	
T 6.4. Temperate alpine grasslands and shrublands	2379.8	1.1	High mountain grasslands	1.1	18175.6	Shrubs	343.7	16896.9
		2377.1	Alpine grasslands	2377.1		Agricultural lands — hayfields	1212.9	
		0.6	Sandy/clay sparse veget. -high mountain and alpine	Sandy/clay sparse veget.				
		1.1	Human-modified sparse veg.	Human-modified sparse veg.		Agricultural lands — pastures	10482.4	
T4.5. Subhumid grasslands	11760.5	5113.1	Subalpine grasslands	5113.1				
		6603.6	Steppe	6603.6		Agricultural lands — other grasslands	777.6	
		0.5 25.8	Sandy/clay sparse veget. In subalpine and steppe	Sandy/clay sparse veget.		Grasslands on lands of PAs	608.4	
		1.5 16.2	Human-modified sparse veg.	Human-modified sparse veg.		Grasslands on special-purpose lands	149.0	
T5.1.Semi-desert steppes	1683.9	1493.5	Semi-desert	1493.5		Forest lands — hayfields	92.0	
		1.0	Desert	1.0				
		48.9	Sandy/clay sparse veget. In desert and semi-desert	Sandy/clay sparse veget.		Forest lands — pastures	109.0	
		140.4	Human-modified sparse veg.	Human-modified sparse veg.		Forest lands — other grasslands	11.6	
TF1.7. Boreal and temperate fens	150.4	150.4	Fens and wet meadows	150.4				
T4.4 Temperate woodlands	2435.8	2172.4	Natural open woodlands and open woodland plantations	2172.4		Vegetation-free agricultural lands	3110.3	
		263.4	Woodland-like vegetation in human-modified landscapes except settlements	263.4				
T7.4. Urban and industrial ecosystems	1873.9	278.9	Woodland-like vegetation in settlementrs	278.9	1197	Grasslands on settlement lands, mixed development	5.0	734.5
		41.8	Forest-like vegetation in settlements	41.8		Grasslands on public-use settlement lands	57.3	
		876.3	Settlement area	876.3		Grasslands on settlement lands, public development	27.9	
						Grasslands on other settlement lands	103.7	
						Grasslands on household plots	540.5	

		485.9	Buildings	485.9	485.9	Settlement lands — residential development excluding house-hold plots	427.1	503.3
						Public development	53.7	
						Mixed development	22.5	
		112.4	Sparse vegetation in settlements	112.4	350.2	Vegetation-free - public-use	127.2	967.5
		78.6	Quarries and landfills	78.6		Vegetation-free - industry, subsoil and other production purposes	402.0	
			Human-modified sparse veg.	159.2		Vegetation-free - energy, communications, transport, and utility infrastructure	145.1	
						Special-purpose vegetation-free lands	153.3	
						Reserve vegetation-free lands	6.2	
						Other anthropogenic vegetation-free lands	133.7	
T7.1 Annual croplands	3550.9	3550.9	Actively cultivated landscapes	1935.3	3550.9	Arable lands	4405.9	4408.5
			Actively used croplands	1615.6		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	447.2
						Orchards	28.1	
TF1.3. Permanent marshes	11.4	11.4	Permanent marshes	11.4	1387.4	Water covered areas	1721.2	1721.2
Water	1376.1	1376.1	Water bodies	1376.1				
TOTAL		**29729**	**TOTAL**	**29729**	**29729**		**29743**	**29743**

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.

4. 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	S2C_NDRE2_p50	Five-year median of annual NDRE2 p50	

Predictor group	Predictor	Description	No.
	S2C_NDWI_GAO_p50	Five-year median of annual NDWI-Gao p50	
	S2C_NDWI_GAO_p90	Five-year median of annual NDWI-Gao p90	
	S2C_B11_iqr	Five-year median of annual B11 IQR	
metrics (S2C)	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 / 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. Ecosystem extent in Armenia and by marz

Ecosystem Accounting Areas	Ecosystem types		Area_km2	Share of EAA, %	EAA area, km2
Armenia	Grasslands	High mountain	1.1	0.0	29,729.2
		Alpine	2,377.1	8.0	
		Subalpine	5,113.1	17.2	
		Steppe	6,603.6	22.2	
		Semi-desert	1,493.5	5.0	
		Desert	1.0	0.0	
	Wetlands	Fens and wet meadows	150.4	0.5	
		Wetland waterbodies in the Ararat Valley	11.4	0.0	
	Sparse vegetation	High-mountain sparse vegetation	14.7	0.0	
		Rocky habitats	158.5	0.5	
		Sandy and clay habitats	75.8	0.3	
	Natural open woodlands	Subalpine woodlands	137.8	0.5	
		Other woodlands	1,890.9	6.4	
		Juniper woodlands	56.4	0.2	
	Natural closed forests	Fagus orientalis and other deciduous	1,339.3	4.5	
		Quercus macranthera and other deciduous	663.9	2.2	
		Quercus macranthera	521.6	1.8	
		Quercus iberica and other deciduous	493.9	1.7	
		Quercus iberica	90.6	0.3	
		Pinus kochiana	5.4	0.0	
	Forest plantations	Closed forest plantations	48.1	0.2	
		Open woodland plantations	87.3	0.3	
	Anthropogenic areas	Actively cultivated landscapes	1,935.3	6.5	
		Actively used croplands	1,615.6	5.4	
		Settlements	876.3	2.9	
		Buildings	485.9	1.6	
		Tree, vine and shrub crops	1,036.0	3.5	
		Other woody vegetation in human-modified landscapes	718.0	2.4	
		Sparse vegetation in human-modified landscapes	272.1	0.9	
		Quarries and landfills	78.6	0.3	
	Water	Water bodies	1,376.1	4.6	
YEREVAN	Grasslands	High mountain	0.0	0.0	233.4
		Alpine	0.0	0.0	
		Subalpine	0.0	0.0	
		Steppe	3.7	1.6	
		Semi-desert	13.9	6.0	
		Desert	0.0	0.0	
	Wetlands	Fens and wet meadows	0.0	0.0	
		Wetland waterbodies in the Ararat Valley	0.0	0.0	
	Sparse vegetation	High-mountain sparse vegetation	0.0	0.0	
		Rocky habitats	0.0	0.0	
		Sandy and clay habitats	0.0	0.0	
	Natural open woodlands	Subalpine woodlands	0.0	0.0	
		Other woodlands	0.0	0.0	
		Juniper woodlands	0.0	0.0	
	Natural closed forests	Fagus orientalis and other deciduous	0.0	0.0	
		Quercus macranthera and other deciduous	0.0	0.0	
		Quercus macranthera	0.0	0.0	
		Quercus iberica and other deciduous	0.0	0.0	
		Quercus iberica	0.0	0.0	
		Pinus kochiana	0.0	0.0	
	Forest plantations	Closed forest plantations	0.0	0.0	
		Open woodland plantations	0.0	0.0	
	Anthropogenic areas	Actively cultivated landscapes	0.3	0.1	
		Actively used croplands	0.4	0.2	
		Settlements	44.6	19.1	
		Buildings	71.2	30.5	
		Tree, vine and shrub crops	23.0	9.9	
		Other woody vegetation in human-modified landscapes	24.3	10.4	
		Sparse vegetation in human-modified landscapes	48.4	20.8	
		Quarries and landfills	2.6	1.1	
	Water	Water bodies	0.8	0.3	

LORI	Grasslands	High mountain	0.0	0.0	3,765.8
		Alpine	73.6	2.0	3,765.8
		Subalpine	472.9	12.6	3,765.8
		Steppe	1,187.6	31.5	3,765.8
		Semi-desert	9.7	0.3	3,765.8
		Desert	0.0	0.0	3,765.8
	Wetlands	Fens and wet meadows	34.2	0.9	3,765.8
		Wetland waterbodies in the Ararat Valley	0.0	0.0	3,765.8
	Sparse vegetation	High-mountain sparse vegetation	0.0	0.0	3,765.8
		Rocky habitats	4.7	0.1	3,765.8
		Sandy and clay habitats	0.2	0.0	3,765.8
	Natural open woodlands	Subalpine woodlands	9.0	0.2	3,765.8
		Other woodlands	257.9	6.8	3,765.8
		Juniper woodlands	0.4	0.0	3,765.8
	Natural closed forests	Fagus orientalis and other deciduous	550.7	14.6	3,765.8
		Quercus macranthera and other deciduous	158.6	4.2	3,765.8
		Quercus macranthera	29.7	0.8	3,765.8
		Quercus iberica and other deciduous	105.5	2.8	3,765.8
		Quercus iberica	19.0	0.5	3,765.8
	Forest plantations	Pinus kochiana	3.8	0.1	3,765.8
		Closed forest plantations	10.5	0.3	3,765.8
		Open woodland plantations	13.2	0.4	3,765.8
	Anthropogenic areas	Actively cultivated landscapes	262.4	7.0	3,765.8
		Actively used croplands	230.4	6.1	3,765.8
		Settlements	92.6	2.5	3,765.8
		Buildings	42.7	1.1	3,765.8
		Tree, vine and shrub crops	6.6	0.2	3,765.8
		Other woody vegetation in human-modified landscapes	178.1	4.7	3,765.8
		Sparse vegetation in human-modified landscapes	1.8	0.0	3,765.8
		Quarries and landfills	6.4	0.2	3,765.8
	Water	Water bodies	3.4	0.1	3,765.8
VAYOTZ DZOR	Grasslands	High mountain	0.0	0.0	2,298.3
		Alpine	316.9	13.8	2,298.3
		Subalpine	565.9	24.6	2,298.3
		Steppe	750.8	32.7	2,298.3
		Semi-desert	66.9	2.9	2,298.3
		Desert	0.0	0.0	2,298.3
	Wetlands	Fens and wet meadows	2.2	0.1	2,298.3
		Wetland waterbodies in the Ararat Valley	0.0	0.0	2,298.3
	Sparse vegetation	High-mountain sparse vegetation	0.0	0.0	2,298.3
		Rocky habitats	27.3	1.2	2,298.3
		Sandy and clay habitats	7.9	0.3	2,298.3
	Natural open woodlands	Subalpine woodlands	25.3	1.1	2,298.3
		Other woodlands	269.5	11.7	2,298.3
		Juniper woodlands	6.4	0.3	2,298.3
	Natural closed forests	Fagus orientalis and other deciduous	0.0	0.0	2,298.3
		Quercus macranthera and other deciduous	9.3	0.4	2,298.3
		Quercus macranthera	43.8	1.9	2,298.3
		Quercus iberica and other deciduous	1.1	0.0	2,298.3
		Quercus iberica	0.0	0.0	2,298.3
	Forest plantations	Pinus kochiana	0.0	0.0	2,298.3
		Closed forest plantations	0.1	0.0	2,298.3
		Open woodland plantations	1.0	0.0	2,298.3
	Anthropogenic areas	Actively cultivated landscapes	32.1	1.4	2,298.3
		Actively used croplands	15.4	0.7	2,298.3
		Settlements	21.6	0.9	2,298.3
		Buildings	5.9	0.3	2,298.3
		Tree, vine and shrub crops	61.6	2.7	2,298.3
		Other woody vegetation in human-modified landscapes	55.5	2.4	2,298.3
		Sparse vegetation in human-modified landscapes	4.6	0.2	2,298.3
		Quarries and landfills	4.6	0.2	2,298.3
	Water	Water bodies	2.5	0.1	2,298.3

SHIRAK	Grasslands	High mountain	0.2	0.0	2,720.2
		Alpine	195.9	7.2	2,720.2
		Subalpine	456.6	16.8	2,720.2
		Steppe	808.7	29.7	2,720.2
		Semi-desert	0.0	0.0	2,720.2
		Desert	0.0	0.0	2,720.2
	Wetlands	Fens and wet meadows	34.3	1.3	2,720.2
		Wetland waterbodies in the Ararat Valley	0.0	0.0	2,720.2
	Sparse vegetation	High-mountain sparse vegetation	2.7	0.1	2,720.2
		Rocky habitats	9.8	0.4	2,720.2
		Sandy and clay habitats	0.2	0.0	2,720.2
	Natural open woodlands	Subalpine woodlands	1.3	0.0	2,720.2
		Other woodlands	10.8	0.4	2,720.2
		Juniper woodlands	0.0	0.0	2,720.2
	Natural closed forests	Fagus orientalis and other deciduous	1.7	0.1	2,720.2
		Quercus macranthera and other deciduous	0.1	0.0	2,720.2
		Quercus macranthera	0.2	0.0	2,720.2
		Quercus iberica and other deciduous	0.0	0.0	2,720.2
		Quercus iberica	0.0	0.0	2,720.2
	Forest plantations	Pinus kochiana	0.0	0.0	2,720.2
		Closed forest plantations	4.5	0.2	2,720.2
		Open woodland plantations	10.0	0.4	2,720.2
	Anthropogenic areas	Actively cultivated landscapes	519.8	19.1	2,720.2
		Actively used croplands	435.7	16.0	2,720.2
		Settlements	100.3	3.7	2,720.2
		Buildings	56.8	2.1	2,720.2
		Tree, vine and shrub crops	0.0	0.0	2,720.2
		Other woody vegetation in human-modified landscapes	25.4	0.9	2,720.2
		Sparse vegetation in human-modified landscapes	6.6	0.2	2,720.2
		Quarries and landfills	9.1	0.3	2,720.2
	Water	Water bodies	29.4	1.1	2,720.2
ARARAT	Grasslands	High mountain	0.0	0.0	2,116.6
		Alpine	116.3	5.5	2,116.6
		Subalpine	223.7	10.6	2,116.6
		Steppe	420.7	19.9	2,116.6
		Semi-desert	359.0	17.0	2,116.6
		Desert	1.0	0.0	2,116.6
	Wetlands	Fens and wet meadows	0.0	0.0	2,116.6
		Wetland waterbodies in the Ararat Valley	1.2	0.1	2,116.6
	Sparse vegetation	High-mountain sparse vegetation	0.0	0.0	2,116.6
		Rocky habitats	20.7	1.0	2,116.6
		Sandy and clay habitats	63.1	3.0	2,116.6
	Natural open woodlands	Subalpine woodlands	15.3	0.7	2,116.6
		Other woodlands	206.9	9.8	2,116.6
		Juniper woodlands	8.0	0.4	2,116.6
	Natural closed forests	Fagus orientalis and other deciduous	0.0	0.0	2,116.6
		Quercus macranthera and other deciduous	12.5	0.6	2,116.6
		Quercus macranthera	30.6	1.4	2,116.6
		Quercus iberica and other deciduous	1.3	0.1	2,116.6
		Quercus iberica	0.0	0.0	2,116.6
	Forest plantations	Pinus kochiana	0.0	0.0	2,116.6
		Closed forest plantations	0.0	0.0	2,116.6
		Open woodland plantations	0.1	0.0	2,116.6
	Anthropogenic areas	Actively cultivated landscapes	49.7	2.3	2,116.6
		Actively used croplands	34.6	1.6	2,116.6
		Settlements	89.9	4.2	2,116.6
		Buildings	60.5	2.9	2,116.6
		Tree, vine and shrub crops	305.9	14.5	2,116.6
		Other woody vegetation in human-modified landscapes	22.5	1.1	2,116.6
		Sparse vegetation in human-modified landscapes	38.7	1.8	2,116.6
		Quarries and landfills	2.5	0.1	2,116.6
	Water	Water bodies	31.9	1.5	2,116.6

KOTAYK	Grasslands	High mountain	0.0	0.0	2,116.4
		Alpine	214.2	10.1	2,116.4
		Subalpine	437.2	20.7	2,116.4
		Steppe	513.6	24.3	2,116.4
		Semi-desert	33.8	1.6	2,116.4
		Desert	0.0	0.0	2,116.4
	Wetlands	Fens and wet meadows	3.5	0.2	2,116.4
		Wetland waterbodies in the Ararat Valley	0.0	0.0	2,116.4
	Sparse vegetation	High-mountain sparse vegetation	0.2	0.0	2,116.4
		Rocky habitats	7.3	0.3	2,116.4
		Sandy and clay habitats	0.2	0.0	2,116.4
	Natural open woodlands	Subalpine woodlands	20.7	1.0	2,116.4
		Other woodlands	75.8	3.6	2,116.4
		Juniper woodlands	1.2	0.1	2,116.4
	Natural closed forests	Fagus orientalis and other deciduous	0.0	0.0	2,116.4
		Quercus macranthera and other deciduous	8.1	0.4	2,116.4
		Quercus macranthera	153.3	7.2	2,116.4
		Quercus iberica and other deciduous	0.5	0.0	2,116.4
		Quercus iberica	0.0	0.0	2,116.4
	Forest plantations	Pinus kochiana	0.0	0.0	2,116.4
		Closed forest plantations	0.3	0.0	2,116.4
		Open woodland plantations	2.9	0.1	2,116.4
	Anthropogenic areas	Actively cultivated landscapes	152.8	7.2	2,116.4
		Actively used croplands	133.4	6.3	2,116.4
		Settlements	95.0	4.5	2,116.4
		Buildings	44.4	2.1	2,116.4
		Tree, vine and shrub crops	99.5	4.7	2,116.4
		Other woody vegetation in human-modified landscapes	89.9	4.2	2,116.4
		Sparse vegetation in human-modified landscapes	17.1	0.8	2,116.4
		Quarries and landfills	8.9	0.4	2,116.4
	Water	Water bodies	2.6	0.1	2,116.4
TAVUSH	Grasslands	High mountain	0.0	0.0	2,728.4
		Alpine	2.0	0.1	2,728.4
		Subalpine	104.2	3.8	2,728.4
		Steppe	510.4	18.7	2,728.4
		Semi-desert	113.9	4.2	2,728.4
		Desert	0.0	0.0	2,728.4
	Wetlands	Fens and wet meadows	0.0	0.0	2,728.4
		Wetland waterbodies in the Ararat Valley	0.0	0.0	2,728.4
	Sparse vegetation	High-mountain sparse vegetation	0.0	0.0	2,728.4
		Rocky habitats	0.2	0.0	2,728.4
		Sandy and clay habitats	0.0	0.0	2,728.4
	Natural open woodlands	Subalpine woodlands	0.3	0.0	2,728.4
		Other woodlands	411.6	15.1	2,728.4
		Juniper woodlands	3.3	0.1	2,728.4
	Natural closed forests	Fagus orientalis and other deciduous	745.3	27.3	2,728.4
		Quercus macranthera and other deciduous	235.2	8.6	2,728.4
		Quercus macranthera	27.6	1.0	2,728.4
		Quercus iberica and other deciduous	215.1	7.9	2,728.4
		Quercus iberica	40.1	1.5	2,728.4
	Forest plantations	Pinus kochiana	1.6	0.1	2,728.4
		Closed forest plantations	0.0	0.0	2,728.4
		Open woodland plantations	0.0	0.0	2,728.4
	Anthropogenic areas	Actively cultivated landscapes	70.3	2.6	2,728.4
		Actively used croplands	37.0	1.4	2,728.4
		Settlements	73.7	2.7	2,728.4
		Buildings	29.2	1.1	2,728.4
		Tree, vine and shrub crops	59.6	2.2	2,728.4
		Other woody vegetation in human-modified landscapes	43.3	1.6	2,728.4
		Sparse vegetation in human-modified landscapes	0.3	0.0	2,728.4
		Quarries and landfills	0.6	0.0	2,728.4
	Water	Water bodies	3.5	0.1	2,728.4

SYUNIK	Grasslands	High mountain	0.3	0.0	4,495.8
		Alpine	688.3	15.3	4,495.8
		Subalpine	987.4	22.0	4,495.8
		Steppe	767.0	17.1	4,495.8
		Semi-desert	127.6	2.8	4,495.8
		Desert	0.0	0.0	4,495.8
	Wetlands	Fens and wet meadows	0.0	0.0	4,495.8
		Wetland waterbodies in the Ararat Valley	0.0	0.0	4,495.8
	Sparse vegetation	High-mountain sparse vegetation	5.4	0.1	4,495.8
		Rocky habitats	28.2	0.6	4,495.8
		Sandy and clay habitats	0.9	0.0	4,495.8
	Natural open woodlands	Subalpine woodlands	43.3	1.0	4,495.8
		Other woodlands	526.2	11.7	4,495.8
		Juniper woodlands	28.5	0.6	4,495.8
	Natural closed forests	Fagus orientalis and other deciduous	0.0	0.0	4,495.8
		Quercus macranthera and other deciduous	232.1	5.2	4,495.8
		Quercus macranthera	185.7	4.1	4,495.8
		Quercus iberica and other deciduous	168.6	3.8	4,495.8
		Quercus iberica	30.6	0.7	4,495.8
	Forest plantations	Pinus kochiana	0.0	0.0	4,495.8
		Closed forest plantations	0.0	0.0	4,495.8
		Open woodland plantations	0.0	0.0	4,495.8
	Anthropogenic areas	Actively cultivated landscapes	226.5	5.0	4,495.8
		Actively used croplands	196.9	4.4	4,495.8
		Settlements	34.7	0.8	4,495.8
		Buildings	12.7	0.3	4,495.8
		Tree, vine and shrub crops	32.5	0.7	4,495.8
		Other woody vegetation in human-modified landscapes	125.9	2.8	4,495.8
		Sparse vegetation in human-modified landscapes	10.5	0.2	4,495.8
		Quarries and landfills	17.8	0.4	4,495.8
	Water	Water bodies	18.3	0.4	4,495.8
ARMAVIR	Grasslands	High mountain	0.0	0.0	1,264.5
		Alpine	0.0	0.0	1,264.5
		Subalpine	0.0	0.0	1,264.5
		Steppe	0.5	0.0	1,264.5
		Semi-desert	433.1	34.2	1,264.5
		Desert	0.0	0.0	1,264.5
	Wetlands	Fens and wet meadows	0.0	0.0	1,264.5
		Wetland waterbodies in the Ararat Valley	10.1	0.8	1,264.5
	Sparse vegetation	High-mountain sparse vegetation	0.0	0.0	1,264.5
		Rocky habitats	13.7	1.1	1,264.5
		Sandy and clay habitats	2.0	0.2	1,264.5
	Natural open woodlands	Subalpine woodlands	0.0	0.0	1,264.5
		Other woodlands	22.8	1.8	1,264.5
		Juniper woodlands	0.0	0.0	1,264.5
	Natural closed forests	Fagus orientalis and other deciduous	0.0	0.0	1,264.5
		Quercus macranthera and other deciduous	0.0	0.0	1,264.5
		Quercus macranthera	0.0	0.0	1,264.5
		Quercus iberica and other deciduous	0.1	0.0	1,264.5
		Quercus iberica	0.8	0.1	1,264.5
	Forest plantations	Pinus kochiana	0.0	0.0	1,264.5
		Closed forest plantations	0.0	0.0	1,264.5
		Open woodland plantations	0.0	0.0	1,264.5
	Anthropogenic areas	Actively cultivated landscapes	88.4	7.0	1,264.5
		Actively used croplands	57.5	4.5	1,264.5
		Settlements	92.1	7.3	1,264.5
		Buildings	74.8	5.9	1,264.5
		Tree, vine and shrub crops	324.9	25.7	1,264.5
		Other woody vegetation in human-modified landscapes	22.7	1.8	1,264.5
		Sparse vegetation in human-modified landscapes	110.3	8.7	1,264.5
		Quarries and landfills	5.3	0.4	1,264.5
	Water	Water bodies	5.3	0.4	1,264.5

ARAGATSOTN	Grasslands	High mountain	0.6	0.0	2,737.9
		Alpine	219.5	8.0	2,737.9
		Subalpine	380.6	13.9	2,737.9
		Steppe	809.0	29.5	2,737.9
		Semi-desert	335.5	12.3	2,737.9
		Desert	0.0	0.0	2,737.9
	Wetlands	Fens and wet meadows	6.5	0.2	2,737.9
		Wetland waterbodies in the Ararat Valley	0.0	0.0	2,737.9
	Sparse vegetation	High-mountain sparse vegetation	6.4	0.2	2,737.9
		Rocky habitats	29.1	1.1	2,737.9
		Sandy and clay habitats	0.3	0.0	2,737.9
	Natural open woodlands	Subalpine woodlands	11.5	0.4	2,737.9
		Other woodlands	69.4	2.5	2,737.9
		Juniper woodlands	0.0	0.0	2,737.9
	Natural closed forests	Fagus orientalis and other deciduous	0.0	0.0	2,737.9
		Quercus macranthera and other deciduous	1.1	0.0	2,737.9
		Quercus macranthera	40.7	1.5	2,737.9
		Quercus iberica and other deciduous	0.8	0.0	2,737.9
		Quercus iberica	0.0	0.0	2,737.9
	Forest plantations	Pinus kochiana	0.0	0.0	2,737.9
		Closed forest plantations	3.2	0.1	2,737.9
		Open woodland plantations	5.4	0.2	2,737.9
	Anthropogenic areas	Actively cultivated landscapes	243.7	8.9	2,737.9
		Actively used croplands	208.0	7.6	2,737.9
		Settlements	93.2	3.4	2,737.9
		Buildings	34.0	1.2	2,737.9
		Tree, vine and shrub crops	122.4	4.5	2,737.9
		Other woody vegetation in human-modified landscapes	68.0	2.5	2,737.9
		Sparse vegetation in human-modified landscapes	28.5	1.0	2,737.9
		Quarries and landfills	15.8	0.6	2,737.9
	Water	Water bodies	4.9	0.2	2,737.9
GEGHARKUNIK	Grasslands	High mountain	0.0	0.0	5,252.0
		Alpine	550.3	10.5	5,252.0
		Subalpine	1,484.7	28.3	5,252.0
		Steppe	831.7	15.8	5,252.0
		Semi-desert	0.0	0.0	5,252.0
		Desert	0.0	0.0	5,252.0
	Wetlands	Fens and wet meadows	69.7	1.3	5,252.0
		Wetland waterbodies in the Ararat Valley	0.0	0.0	5,252.0
	Sparse vegetation	High-mountain sparse vegetation	0.1	0.0	5,252.0
		Rocky habitats	17.5	0.3	5,252.0
		Sandy and clay habitats	1.0	0.0	5,252.0
	Natural open woodlands	Subalpine woodlands	11.0	0.2	5,252.0
		Other woodlands	39.9	0.8	5,252.0
		Juniper woodlands	8.6	0.2	5,252.0
	Natural closed forests	Fagus orientalis and other deciduous	41.5	0.8	5,252.0
		Quercus macranthera and other deciduous	6.7	0.1	5,252.0
		Quercus macranthera	10.0	0.2	5,252.0
		Quercus iberica and other deciduous	0.9	0.0	5,252.0
		Quercus iberica	0.0	0.0	5,252.0
	Forest plantations	Pinus kochiana	0.0	0.0	5,252.0
		Closed forest plantations	29.6	0.6	5,252.0
		Open woodland plantations	54.7	1.0	5,252.0
	Anthropogenic areas	Actively cultivated landscapes	289.2	5.5	5,252.0
		Actively used croplands	266.4	5.1	5,252.0
		Settlements	138.7	2.6	5,252.0
		Buildings	53.8	1.0	5,252.0
		Tree, vine and shrub crops	0.0	0.0	5,252.0
		Other woody vegetation in human-modified landscapes	62.4	1.2	5,252.0
		Sparse vegetation in human-modified landscapes	5.3	0.1	5,252.0
		Quarries and landfills	4.9	0.1	5,252.0
	Water	Water bodies	1,273.4	24.2	5,252.0

Table S5. Share of natural-zone area transformed by different types of anthropogenic land use, %

	Natural zone	*Human_modified landscapes*	*Grazing area*	*Not transformed*
Armenia	High mountain	0.00	74.91	25.09
	Alpine	1.26	71.75	28.13
	Subalpine	18.67	58.95	32.87
	Steppe	45.72	38.61	29.86
	Semi-desert	71.43	13.73	25.00
	Desert	4.85	60.62	38.25
	Wetlands	87.58	29.36	9.67
LORI	Alpine	0.00	24.47	75.53
	Subalpine	9.64	62.86	32.68
	Steppe	39.39	48.69	27.53
	Semi-desert	50.90	43.60	32.87
	Wetlands	96.15	21.35	1.98
VAYOTZ DZOR	Alpine	0.68	86.23	13.71
	Subalpine	7.44	56.92	39.52
	Steppe	21.17	26.87	57.38
	Semi-desert	50.85	1.14	48.77
	Wetlands	96.10	36.35	3.90
SHIRAK	High mountain	0.00	62.49	37.51
	Alpine	0.14	65.47	34.53
	Subalpine	46.97	36.39	31.27
	Steppe	79.16	16.05	17.64
	Semi-desert	0.36	0.11	99.57
	Wetlands	99.23	16.84	0.77
ARARAT	Alpine	0.28	99.66	0.34
	Subalpine	0.37	86.83	13.07
	Steppe	8.03	58.35	36.69
	Semi-desert	69.37	38.47	20.82
	Desert	4.85	60.62	38.25
KOTAYK	Alpine	0.11	89.89	10.11
	Subalpine	10.31	91.80	7.40
	Steppe	64.85	57.90	10.44
	Semi-desert	90.48	23.95	5.20
	Wetlands	77.85	19.76	21.37
TAVUSH	Alpine	0.00	59.02	40.98
	Subalpine	10.63	84.58	15.40
	Steppe	21.64	59.05	30.28
	Semi-desert	51.66	6.06	46.28
SYUNIK	High mountain	0.00	17.18	82.82
	Alpine	0.59	49.27	50.44
	Subalpine	7.83	40.71	55.73
	Steppe	35.06	26.98	46.93
	Semi-desert	19.04	6.44	76.73
ARMAVIR	Steppe	84.35	0.00	15.65
	Semi-desert	86.67	1.87	12.82
ARAGATSOTN	High mountain	0.00	92.74	7.26
	Alpine	0.11	95.79	4.21
	Subalpine	10.00	86.16	12.38
	Steppe	64.55	29.51	21.69
	Semi-desert	69.52	2.88	29.97
	Wetlands	98.22	56.93	1.51
GEGHARKUNIK	Alpine	4.20	77.48	22.43
	Subalpine	32.98	53.98	33.25
	Steppe	71.56	26.99	21.91
	Semi-desert	3.45	17.41	79.14
	Wetlands	74.77	30.14	19.99