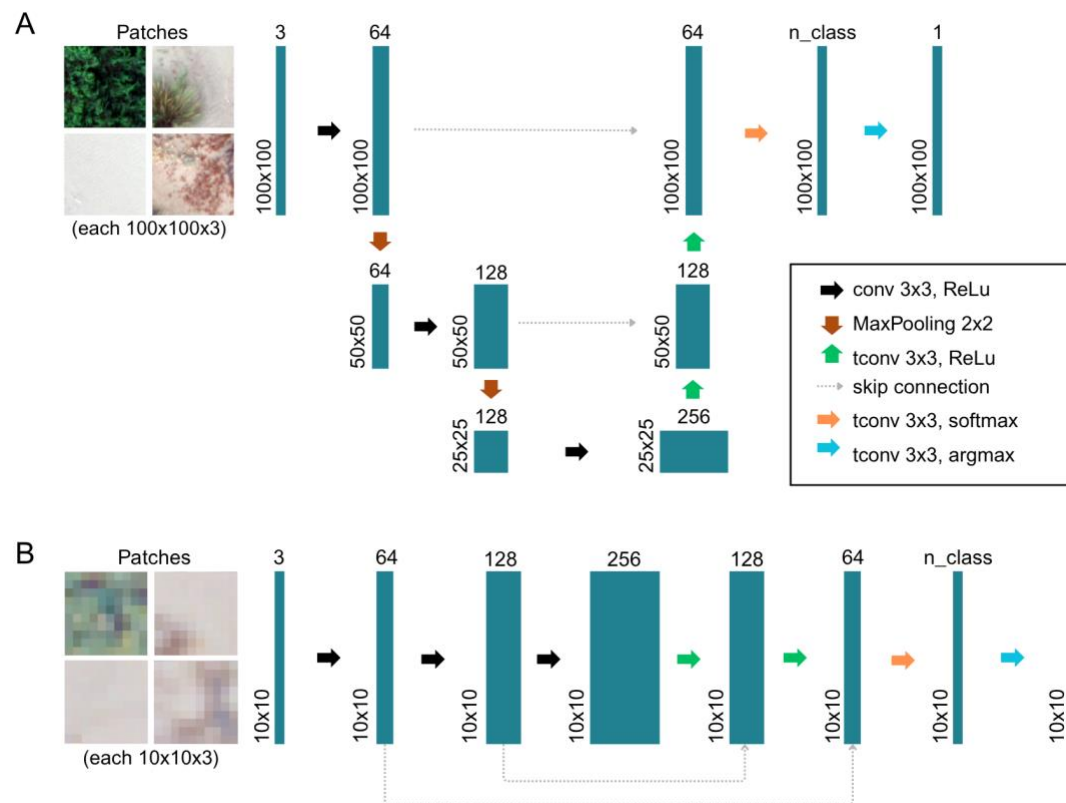
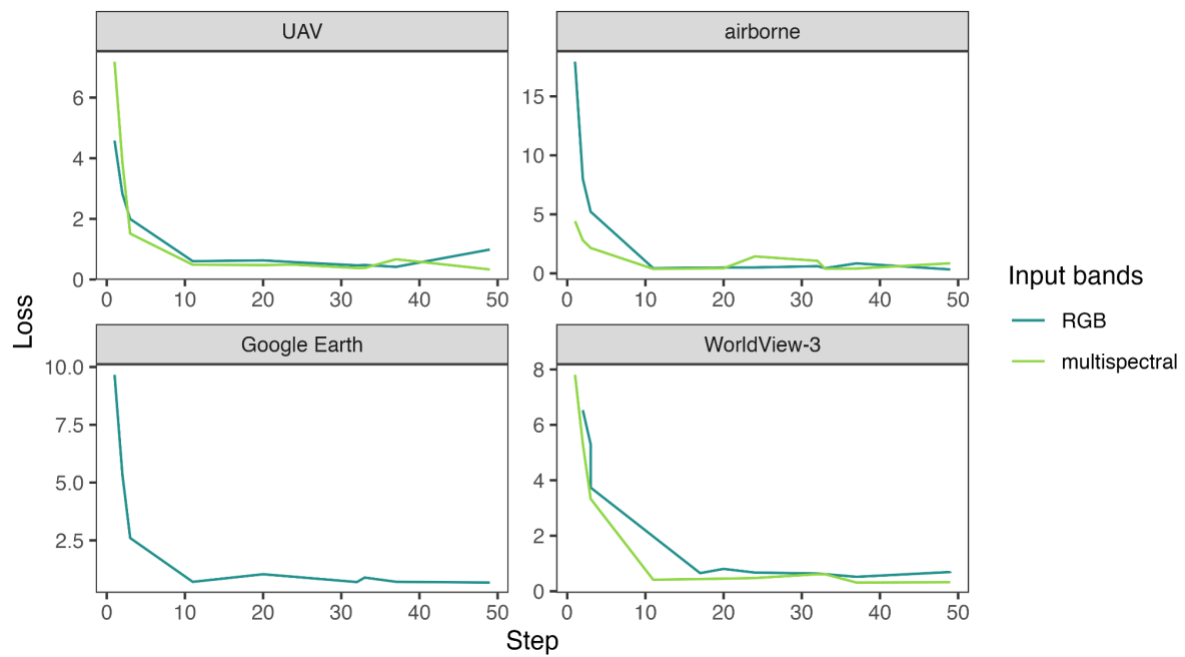


Supporting information to the paper

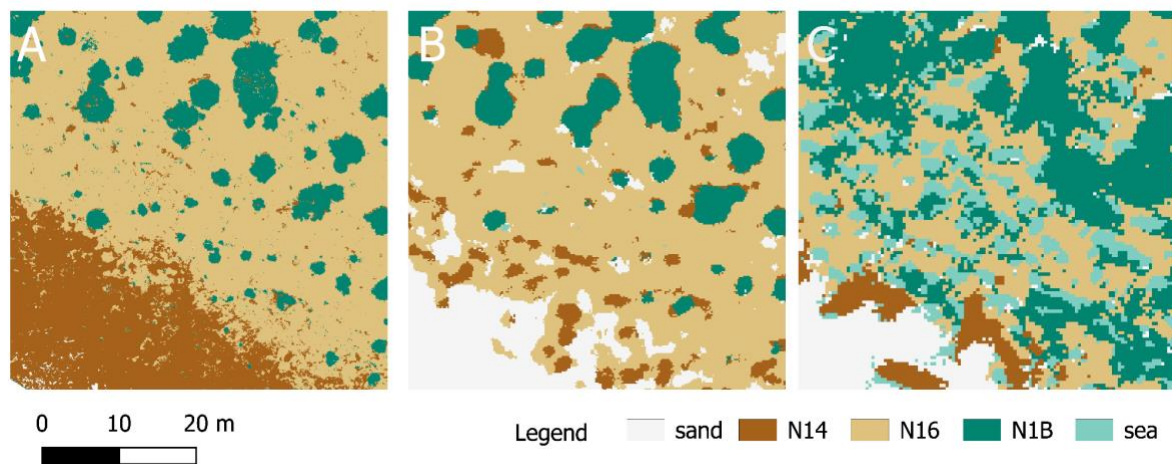
Pafumi, E. et al. Pixels and Patterns in the Sand: Decoding Coastal Dune Habitats With Multi-Resolution CNNs. *Journal of Vegetation Science*.



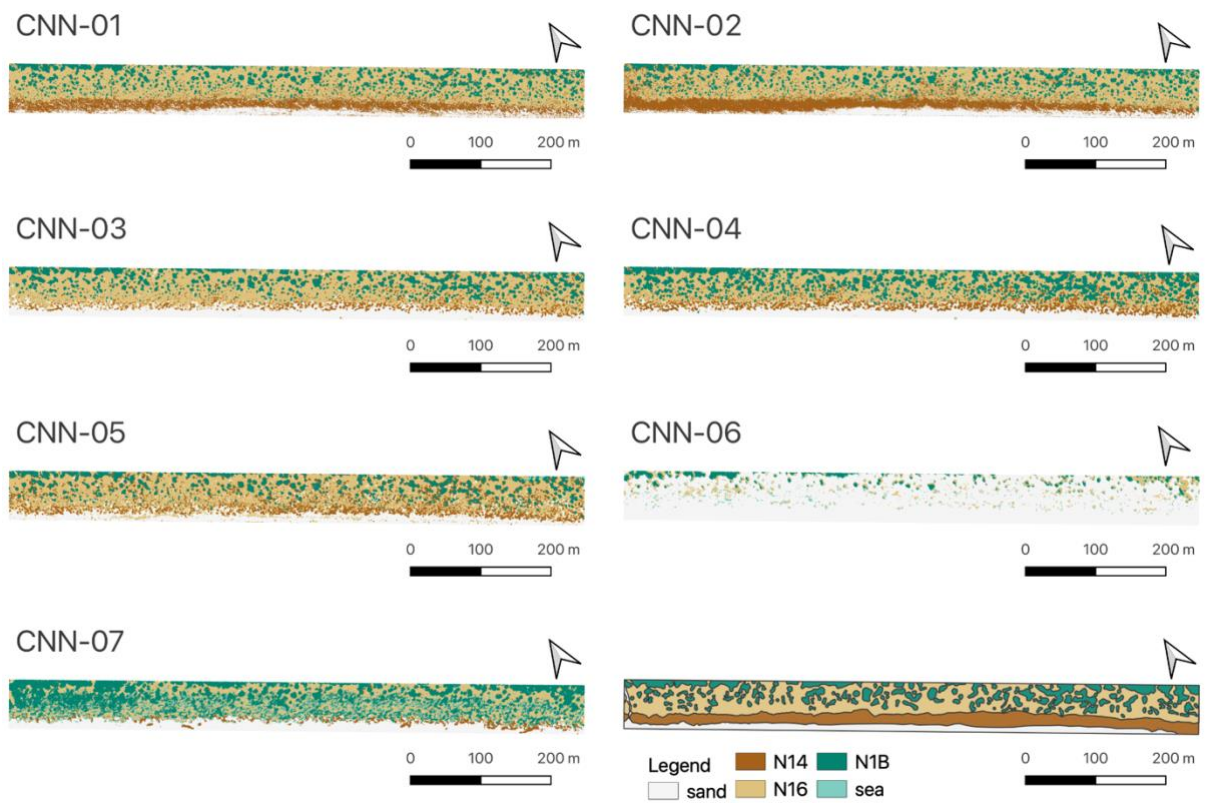
Appendix S1. Scheme of the CNN architecture used in this study for the UAV dataset (A) and for the other datasets (B). Reported patch sizes correspond to those used in CNN-01 (A) and CNN-03 (B).



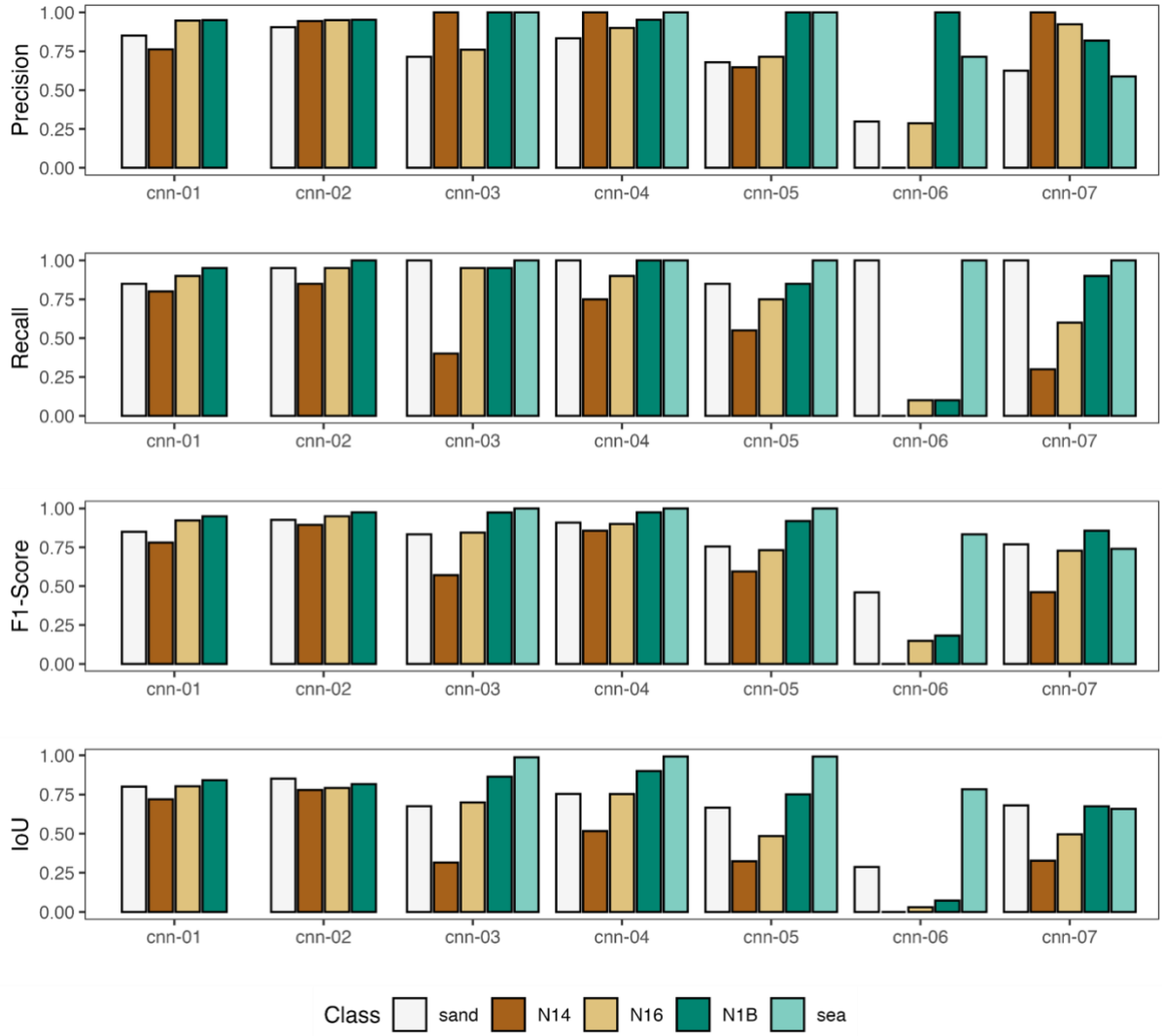
Appendix S2. Validation loss of CNN models trained on different datasets across learning epochs.



Appendix S3. Close-up views of the habitat maps produced through CNN segmentation of multispectral imagery from three datasets: UAV (A), airborne (B), and WorldView-3 (C).



Appendix S4. Habitat maps of the whole study area produced from CNN models trained on different datasets, and a ground truth map produced by visual interpretation of the highest-resolution imagery.



Appendix S5. Class-specific accuracy metrics for each CNN model: precision (i.e., proportion of true positives over all classified positives), recall (i.e., proportion of true positives over all actual positives), F1-score (i.e., harmonic mean of precision and recall), and IoU (Intersection over Union).

Appendix S6. Confusion matrices for CNN models. Real ground truth classes are reported on the rows, predicted values are reported on the columns. Values on the diagonal represent correct classifications.

CNN-01

	sand	N14	N16	N1B
sand	17	3	.	.
N14	3	16	1	.
N16	.	1	18	1
N1B	.	1	.	19

CNN-02

	sand	N14	N16	N1B
sand	17	1	.	.
N14	2	17	1	.
N16	.	.	19	1
N1B	.	.	.	20

CNN-03

	sand	N14	N16	N1B	sea
sand	20	.	.	.	.
N14	7	8	5	.	.
N16	1	.	19	.	.
N1B	.	.	1	19	.
sea	.	.	.	.	20

CNN-04

	sand	N14	N16	N1B	sea
sand	20	.	.	.	.
N14	3	15	2	.	.
N16	1	.	18	1	.
N1B	.	.	.	20	.
sea	.	.	.	.	20

CNN-05

	sand	N14	N16	N1B	sea
sand	17	.	3	.	.
N14	6	11	3	.	.
N16	2	3	15	.	.
N1B	.	3	.	17	.
sea	.	.	.	.	20

CNN-06

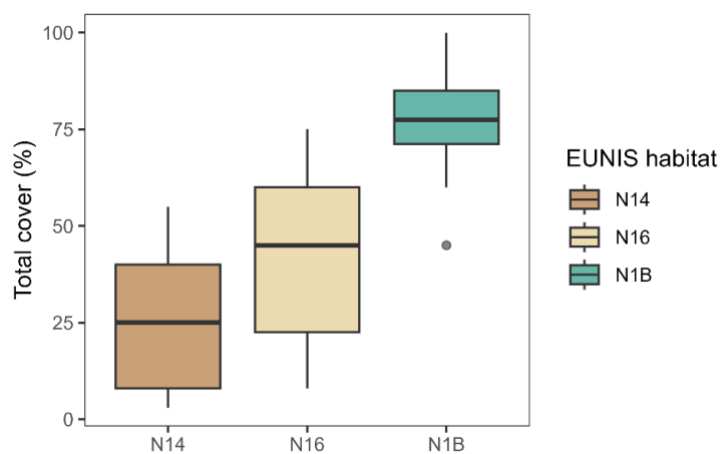
	sand	N14	N16	N1B	sea
sand	20	.	.	.	.
N14	20	.	.	.	.
N16	16	.	2	.	2
N1B	11	.	5	2	2
sea	.	.	.	.	10

CNN-07

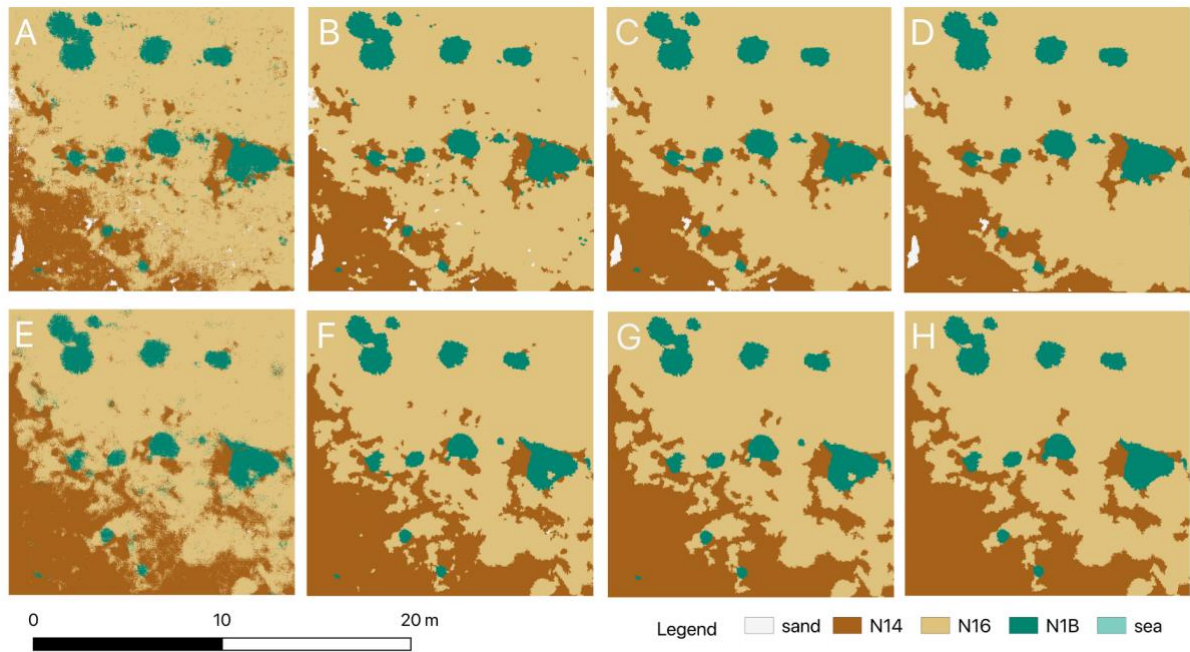
	sand	N14	N16	N1B	sea
sand	20	.	.	.	.
N14	10	6	1	.	3
N16	.	.	12	4	4
N1B	2	.	.	18	.
sea	.	.	.	.	10

Appendix S7. Percentage cover of each class in the habitat maps of the study area produced by the CNN models trained on different datasets, and in the ground truth map produced by visual interpretation.

map	sand (%)	N14 (%)	N16 (%)	N1B (%)	sea (%)
CNN-01	17.76	19.79	50.19	18.24	-
CNN-02	10.13	24.42	47.71	17.73	-
CNN-03	22.01	9.09	51.15	17.57	0.16
CNN-04	20.11	13.44	40.77	25.49	0.18
CNN-05	19.03	17.49	48.62	14.61	0.24
CNN-06	85.05	0.02	7.66	4.25	3.01
CNN-07	19.84	4.18	28.93	36.64	10.39
ground	12.51	22.00	44.74	20.74	-



Appendix S8. Boxplot of the total vegetation cover recorded in the field-surveyed plots, assigned to three EUNIS habitats: shifting dunes (N14), dune grasslands (N16), and dune scrub (N1B).



Appendix S9. Close-up views of the habitat maps produced from CNN-01 (A-D) and CNN-02 (E-H). The panels represent the output map before (A, E) and after (B-D, F-H) a post-processing step, consisting in the application of a sieve filter removing patches with < 25 pixels (B, F), < 100 pixels (C, G), and < 250 pixels (D, H).

Appendix S10. Accuracy metrics for habitat maps derived from UAV imagery, before and after applying post-processing sieve filters (25, 100, 250 pixels).

CNN	sieve	overall accurac	F1-Score			
			sand	N14	N16	N1B
CNN-01	no	0.88	0.85	0.78	0.92	0.95
	25	0.90	0.90	0.84	0.93	0.92
	100	0.90	0.90	0.84	0.93	0.92
	250	0.90	0.90	0.84	0.93	0.92
CNN-02	no	0.94	0.93	0.89	0.95	0.98
	25	0.94	0.93	0.90	0.97	0.95
	100	0.94	0.93	0.90	0.97	0.95
	250	0.94	0.93	0.92	0.95	0.95

Appendix S11. Description of the habitat classes considered in this study. Diagnostic species are derived from EUNIS habitat description (Chytrý et al., 2020), with species names updated according to the Portal to the Flora of Italy (2026).

Class	Description	Diagnostic species
N14	Mediterranean, Macaronesian and Black Sea shifting coastal dune	<i>Echinophora spinosa</i> , <i>Medicago marina</i> , <i>Eryngium maritimum</i> , <i>Thinopyrum junceum</i> , <i>Euphorbia paralias</i> , <i>Cyperus capitatus</i> , <i>Cutandia maritima</i> , <i>Achillea maritima</i> subsp. <i>maritima</i> , <i>Sporobolus pungens</i> , <i>Convolvulus soldanella</i> , <i>Pancratium maritimum</i> , <i>Calamagrostis arenaria</i> subsp. <i>arundinacea</i> , <i>Cakile maritima</i> subsp. <i>maritima</i> , <i>Anthemis maritima</i> subsp. <i>maritima</i>
N16	Mediterranean and Macaronesian coastal dune grassland (grey dune)	<i>Festuca fasciculata</i> , <i>Medicago marina</i> , <i>Daucus pumilus</i> , <i>Medicago littoralis</i> , <i>Cyperus capitatus</i> , <i>Marcus-kochia ramosissima</i> , <i>Pancratium maritimum</i> , <i>Erodium laciniatum</i> , <i>Silene niceensis</i> , <i>Lagurus ovatus</i> , <i>Thinopyrum junceum</i> , <i>Crucianella maritima</i> , <i>Euphorbia terracina</i> , <i>Silene colorata</i> , <i>Cutandia maritima</i> , <i>Eryngium maritimum</i> , <i>Ononis variegata</i> , <i>Echinophora spinosa</i> , <i>Lotus cytisoides</i> , <i>Lotus creticus</i> , <i>Centaurea sphaerocephala</i>
N1B	Mediterranean and Black Sea coastal dune scrub	<i>Juniperus oxycedrus</i> aggr., <i>Smilax aspera</i> , <i>Phillyrea angustifolia</i> , <i>Lonicera implexa</i>

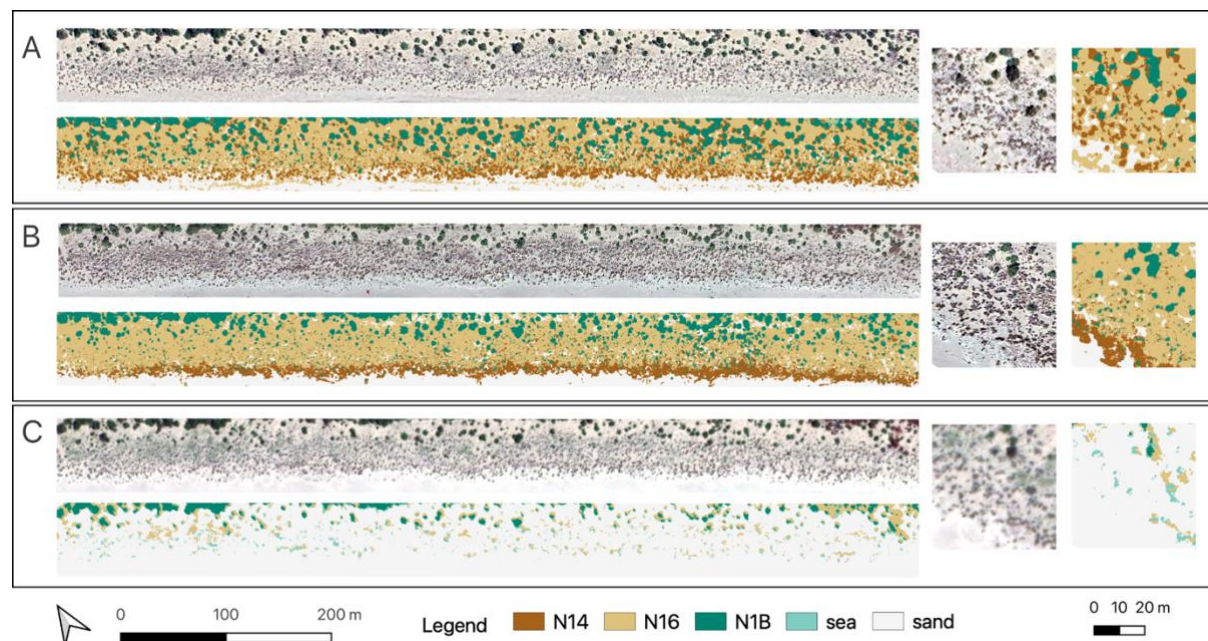
Appendix S12. Number of pixels for each class in the reference ground truth dataset derived from each remote sensing data source. For each class, 100 patches of 2 m x 2 m were considered as reference data.

Data	sand	N14	N16	N1B	sea
UAV	1,000,000	1,000,000	1,000,000	1,000,000	-
airborne	10,000	10,000	10,000	10,000	-
Google Earth	4,900	4,900	4,900	4,900	4,900
WorldView-3	2,500	2,500	2,500	2,500	2,500

Appendix S13. Location of the field-surveyed transects (coordinates are reported for the first and the last plot of each transect).

Transect	Start Latitude (°N)	Start Longitude (°E)	End Latitude (°N)	End Longitude (°E)
T1	42.636114	11.069541	42.636481	11.069831
T2	42.635367	11.071049	42.635727	11.071360
T3	42.634638	11.072587	42.634973	11.072928
T4	42.633879	11.074077	42.634171	11.074498
T5	42.633150	11.075635	42.633472	11.075971

Appendix S14. Comparison of remote sensing images and CNN-classified maps across different years and datasets to assess temporal vs. dataset-driven differences. Multiple datasets were compared: a Google Earth image from 2023 (A); a Google Earth image from 2019 (B); and a WorldView-3 image from 2019 (C). Close-up views (right panels) highlight local details. Maps derived from the same dataset (A, B) show high spatial consistency despite the 4-year gap, while maps from the same year but from different datasets (B, C) show a marked discrepancy. This pattern is also supported by the performance metrics summarized in the table below.



Performance metrics of the CNN models trained on different datasets for temporal and dataset consistency test. Models from the same dataset produce comparable performance values despite the 4-year gap, while a drop in performance is observed with the WorldView-3 dataset from 2019.

Dataset	Global metrics	Class	Precision	Recall	F-Score	IoU
Google Earth (2023)	OA = 0.80 mean IoU = 0.64	sand	0.68	0.85	0.76	0.67
		N14	0.65	0.55	0.59	0.32
		N16	0.71	0.75	0.73	0.48
		N1B	1.00	0.85	0.92	0.75
Google Earth (2019)	OA = 0.87 mean IoU = 0.73	sand	0.87	1.00	0.93	0.82
		N14	0.88	0.70	0.78	0.61
		N16	0.69	0.90	0.78	0.57
		N1B	1.00	0.75	0.86	0.67
WorldView-3 (2019)	OA = 0.38 mean IoU = 0.23	sand	0.30	1.00	0.46	0.29
		N14	0.00	0.00	0.00	0.00
		N16	0.29	0.10	0.15	0.03
		N1B	1.00	0.10	0.18	0.07

References

- Chytrý, M., L. Tichý, S. M. Hennekens, et al. 2020. EUNIS Habitat Classification: Expert system, characteristic species combinations and distribution maps of European habitats. *Applied Vegetation Science* 23: 648–675. <https://doi.org/10.1111/avsc.12519>
- Portal to the Flora of Italy, 2026. <https://dryades.units.it/floritaly> [Accessed: 15-05-2026].