

Assessing GAN Super-Resolution in Grasslands: The Role of Spatial Heterogeneity and Textural Complexity

Efrain Noa-Yarasca, Javier Osorio Leyton, Nada Jumaa, Haoyu Niu, and Lonesome Malambo

Supplementary Material

1. Landscape Structure Stratification (Cluster Analysis)

Elbow method to obtain the optimal number of clusters in structure stratification of tile images

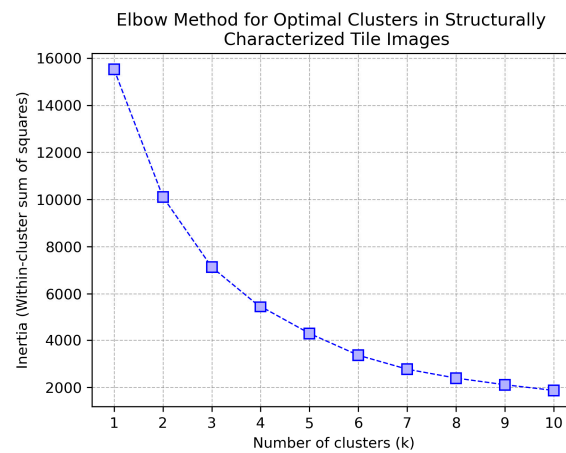


Figure S1. Elbow method for optimal clusters in landscape structure stratification

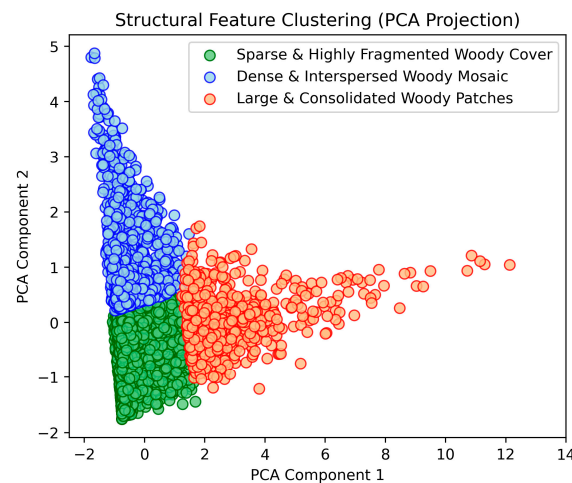


Figure S2. Structurally characterized tile images clustered into three groups and visualized on the first two PCA components

2. Hyperparameters of the SRGAN and ESRGAN models

Table S1. Hyperparameters of the SRGAN and ESRGAN models

Hyperparameter	SRGAN	ESRGAN
Optimizer (Generator)	Adam	Adam
Optimizer (Discriminator)	Adam	Adam
Generator Learning Rate	1.0E-04	1.0E-04
Discriminator Learning Rate	4.0E-04	4.0E-04
Adam β_1 (Generator)	0.5	0.5
Adam β_1 (Discriminator)	0.9	0.9
Gradient Clipping (clipnorm)	0.1	0.1
Batch Size	1	1
Epochs	30	30
Residual Blocks	16 (ResBlocks)	16 (RRDB blocks)
Discriminator Training Steps per Batch	5	5
Loss: Adversarial weight (λ_{adv})	1.0E-03	1.0E-03
Loss: Perceptual/VGG weight (λ_{vgg})	0.5	0.5
Loss: Pixel-wise weight (λ_{pixel})	1	1
Total Variation Loss weight	1.0E-06	1.0E-06
Perceptual Loss Network	VGG19 (layer 10)	
VGG19 Weights	ImageNet (frozen)	
Discriminator Base Filters	64	128
Label Smoothing (real)	[0.8, 1.0]	[0.8, 1.0]
Label Smoothing (fake)	[0.0, 0.2]	[0.0, 0.2]
LR Scheduler	ReduceLROnPlateau	
LR Decay Factor	0.1	0.1
LR Patience (epochs)	5	5
Min Learning Rate	1.0E-06	1.0E-06
Upscaling Factor	4×	4×

3. Mean, standard deviation, and coefficient of variation of PSNR and SSIM for the three types of segmentation

Table S2. Mean, standard deviation, and coefficient of variation of PSNR and SSIM values across **NDVI**-based quartiles, reported for each algorithm (SRGAN, ESRGAN, and Bicubic) and by downscaling strategy framework (intra-sensor, cross-sensor, and intra-to-cross generalization)

Metric	SR GAN model												ESR GAN model												BICUBIC model							
	Intra-Sensor				Cross-Sensor				Generalization				Intra-Sensor				Cross-Sensor				Generalization				Intra-Sensor				Cross-Sensor			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
PSNR Mean	34.74	33.64	27.45	27.92	28.43	28.30	27.86	25.94	21.07	4.45	9.41	3.26	34.93	35.26	35.26	36.46	29.02	28.97	29.01	30.07	17.39	18.06	20.21	20.78	36.56	36.58	36.62	37.94	17.52	20.08	20.01	19.95
PSNR SD	1.92	6.26	10.35	12.93	2.14	2.12	2.01	2.99	2.85	4.53	6.29	3.64	2.13	1.80	1.81	2.42	2.16	1.82	1.57	1.95	2.47	3.23	3.44	3.23	2.50	2.14	2.04	2.54	2.82	2.96	3.16	3.45
PSNR CV	5.53	18.59	37.69	46.31	7.51	7.50	7.22	11.52	13.54	101.8	66.81	111.4	6.10	5.10	5.14	6.63	7.45	6.28	5.41	6.47	14.19	17.86	17.01	15.55	6.85	5.86	5.58	6.70	16.11	14.76	15.79	17.29
SSIM Mean	0.83	0.84	0.81	0.81	0.77	0.77	0.76	0.71	0.71	0.29	0.43	0.27	0.82	0.83	0.84	0.86	0.76	0.74	0.76	0.79	0.51	0.59	0.61	0.58	0.86	0.87	0.87	0.89	0.60	0.63	0.62	0.64
SSIM SD	0.06	0.06	0.10	0.15	0.06	0.05	0.05	0.08	0.07	0.15	0.16	0.14	0.07	0.05	0.05	0.05	0.06	0.05	0.04	0.06	0.07	0.09	0.09	0.11	0.06	0.05	0.04	0.04	0.08	0.08	0.07	0.09
SSIM CV	7.75	7.63	11.86	18.72	7.62	6.55	5.91	10.89	9.80	49.69	36.79	52.45	8.35	6.34	5.65	6.21	8.46	6.96	5.33	7.44	14.55	15.07	14.72	18.23	7.49	5.85	4.94	4.80	13.46	12.47	11.97	14.10

Table S3. Mean, standard deviation, and coefficient of variation of PSNR and SSIM values across **Structured**-based clusters (C1-C3), reported for each algorithm (SRGAN, ESRGAN, and Bicubic) and by downscaling strategy framework (intra-sensor, cross-sensor, and intra-to-cross generalization)

Metric	SR GAN model									ESR GAN model									BICUBIC model					
	Intra-Sensor			Cross-Sensor			Generalization			Intra-Sensor			Cross-Sensor			Generalization			Intra-Sensor			Cross-Sensor		
	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3
PSNR Mean	32.63	33.39	30.04	27.55	26.86	26.57	16.81	22.26	14.89	32.80	32.66	32.39	27.43	27.70	26.79	18.18	21.02	20.08	33.97	34.72	35.19	17.69	22.31	21.54
PSNR SD	1.53	2.35	7.65	1.48	3.12	2.10	2.98	2.84	8.38	1.67	2.25	1.82	1.35	2.88	2.26	2.87	3.15	4.05	2.06	2.62	2.19	1.56	3.85	3.97
PSNR CV	4.7	7.0	25.5	5.4	11.6	7.9	17.7	12.7	56.3	5.1	6.9	5.6	4.9	10.4	8.4	15.8	15.0	20.1	6.1	7.6	6.2	8.8	17.3	18.4
SSIM Mean	0.75	0.80	0.79	0.68	0.73	0.72	0.60	0.69	0.57	0.74	0.75	0.76	0.67	0.70	0.68	0.54	0.60	0.56	0.80	0.82	0.85	0.55	0.65	0.60
SSIM SD	0.06	0.08	0.07	0.05	0.08	0.06	0.08	0.08	0.18	0.06	0.08	0.06	0.05	0.08	0.06	0.08	0.09	0.13	0.06	0.07	0.05	0.06	0.10	0.10
SSIM CV	7.8	9.5	9.3	7.1	10.9	7.8	13.4	11.7	32.1	8.3	11.1	8.2	7.8	11.5	9.3	14.7	14.9	22.7	8.0	8.0	6.0	11.6	14.9	16.4

C1: Cluster 1, C2: Cluster 2, C3: Cluster 3

Table S4. Mean, standard deviation, and coefficient of variation of PSNR and SSIM values across **Entropy**-based quartiles, reported for each algorithm (SRGAN, ESRGAN, and Bicubic) and by downscaling strategy framework (intra-sensor, cross-sensor, and intra-to-cross generalization)

Metric	SR GAN model												ESR GAN model												BICUBIC model							
	Intra-Sensor				Cross-Sensor				Generalization				Intra-Sensor				Cross-Sensor				Generalization				Intra-Sensor				Cross-Sensor			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
PSNR Mean	30.99	32.76	31.53	22.48	24.41	25.71	24.03	23.40	21.63	19.10	21.98	13.56	30.44	31.78	30.24	32.62	24.84	26.22	24.98	26.12	20.65	18.31	20.67	21.45	32.07	33.53	32.87	34.14	21.95	18.77	21.46	21.33
PSNR SD	2.07	2.09	1.96	11.85	2.46	1.91	2.34	3.52	3.00	1.93	3.48	8.53	2.18	1.92	1.81	2.51	2.45	1.65	1.91	2.24	2.80	2.29	3.41	3.51	2.41	2.25	2.19	2.60	2.59	2.47	3.38	3.57
PSNR CV	6.7	6.4	6.2	52.7	10.1	7.4	9.8	15.0	13.9	10.1	15.8	62.9	7.2	6.0	6.0	7.7	9.8	6.3	7.7	8.6	13.6	12.5	16.5	16.4	7.5	6.7	6.7	7.6	11.8	13.2	15.7	16.7
SSIM Mean	0.69	0.77	0.73	0.71	0.62	0.68	0.63	0.60	0.66	0.64	0.67	0.56	0.67	0.74	0.70	0.76	0.60	0.66	0.61	0.65	0.61	0.56	0.61	0.65	0.75	0.79	0.79	0.82	0.58	0.56	0.56	0.60
SSIM SD	0.08	0.07	0.07	0.15	0.07	0.06	0.07	0.11	0.08	0.07	0.08	0.17	0.09	0.07	0.07	0.08	0.08	0.06	0.06	0.07	0.08	0.07	0.08	0.09	0.08	0.07	0.06	0.06	0.10	0.07	0.09	0.10
SSIM CV	12.1	8.6	9.1	20.9	11.9	8.6	10.7	19.2	12.3	10.2	12.4	30.6	13.1	9.5	9.9	10.2	12.9	9.2	10.3	11.2	12.5	13.0	13.5	14.4	10.3	8.7	7.4	7.4	16.6	13.4	16.3	16.5

4. SSIM values for NDVI-, Structure-, and Entropy-based quartiles/clusters

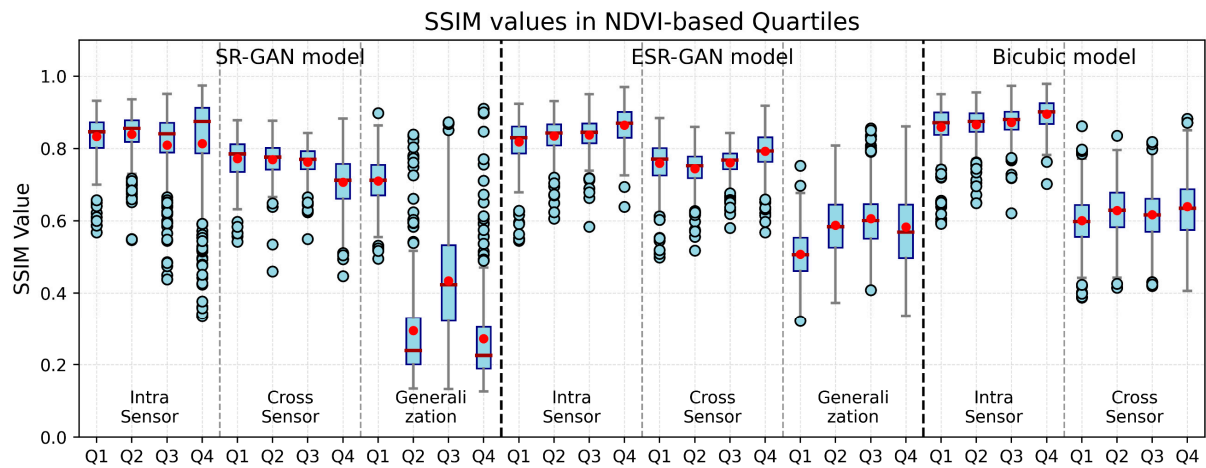


Figure S3. SSIM values across NDVI-based quartiles performed by the SRGAN, ESRGAN, and Bicubic model, grouped by downscaling strategy frameworks (intra-sensor, cross-sensor, intra-to-cross).

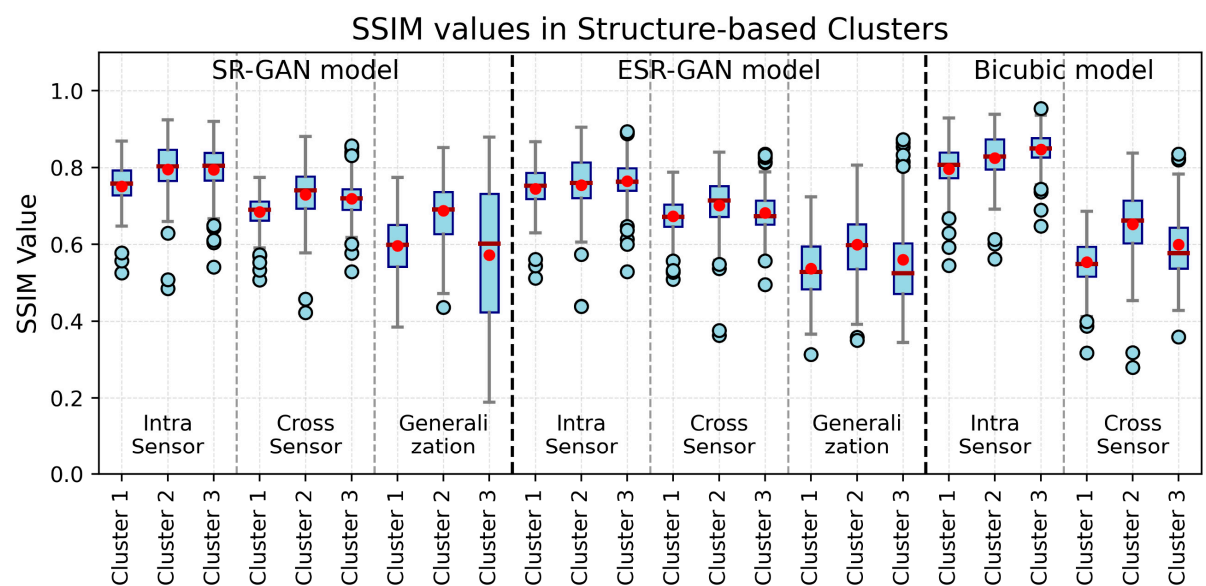


Figure S4. SSIM values across Structure-based clusters performed by the SRGAN, ESRGAN, and Bicubic model, grouped by downscaling strategy frameworks (intra-sensor, cross-sensor, intra-to-cross).

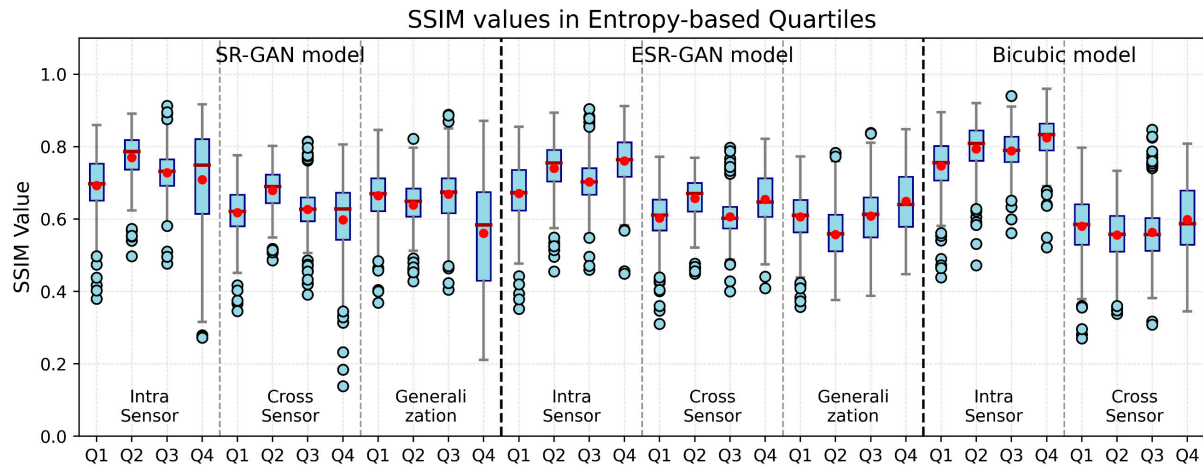


Figure S5. SSIM values across Entropy-based quartiles performed by the SRGAN, ESRGAN, and Bicubic model, grouped by downscaling strategy frameworks (intra-sensor, cross-sensor, intra-to-cross).

5. Normality and group comparison (ANOVA or Kruskal–Wallis) results for PSNR across NDVI-based quartiles for all models.

Table S5. Results of the Normality test and subsequent group comparisons of PSNR values across **NDVI-based** texture quartiles for the **SRGAN** model, using ANOVA for normally distributed data and Kruskal–Wallis tests for non-normal data.

Case	Variable	Shapiro_p	KS_p	DAgostino_p	Normality_OK	Levene_p	Test_Used	H_or_F	p_value
SR-GAN Intra-Sensor	Quartile 1	< 0.001	0.246	< 0.001	FALSE	< 0.001	Kruskal	38.12	< 0.001
SR-GAN Intra-Sensor	Quartile 2	< 0.001	< 0.001	< 0.001	FALSE	< 0.001	Kruskal		
SR-GAN Intra-Sensor	Quartile 3	< 0.001	< 0.001	< 0.001	FALSE	< 0.001	Kruskal		
SR-GAN Intra-Sensor	Quartile 4	< 0.001	< 0.001	< 0.001	FALSE	< 0.001	Kruskal		
SR-GAN Cross-Sensor	Quartile 1	0.032	0.409	0.095	TRUE	< 0.001	Kruskal	132.57	< 0.001
SR-GAN Cross-Sensor	Quartile 2	< 0.001	0.033	< 0.001	FALSE	< 0.001	Kruskal		
SR-GAN Cross-Sensor	Quartile 3	< 0.001	< 0.001	< 0.001	FALSE	< 0.001	Kruskal		
SR-GAN Cross-Sensor	Quartile 4	0.020	0.267	0.258	TRUE	< 0.001	Kruskal		
SR-GAN Generalization	Quartile 1	0.304	0.522	0.163	TRUE	< 0.001	Kruskal	651.05	< 0.001
SR-GAN Generalization	Quartile 2	< 0.001	< 0.001	< 0.001	FALSE	< 0.001	Kruskal		
SR-GAN Generalization	Quartile 3	< 0.001	0.002	< 0.001	FALSE	< 0.001	Kruskal		
SR-GAN Generalization	Quartile 4	< 0.001	< 0.001	< 0.001	FALSE	< 0.001	Kruskal		

Table S6. Results of the Normality test and subsequent group comparisons of PSNR values across **NDVI-based** texture quartiles for the **ESRGAN** model, using ANOVA for normally distributed data and Kruskal–Wallis tests for non-normal data.

Case	Variable	Shapiro_p	KS_p	DAgostino_p	Normality_OK	Levene_p	Test_Used	H_or_F	p_value
ESR-GAN Intra	Quartile 1	< 0.001	0.172	0.001	FALSE	< 0.001	Kruskal	62.84	< 0.001
ESR-GAN Intra	Quartile 2	< 0.001	0.133	< 0.001	FALSE	< 0.001	Kruskal		
ESR-GAN Intra	Quartile 3	< 0.001	0.065	< 0.001	FALSE	< 0.001	Kruskal		
ESR-GAN Intra	Quartile 4	0.422	0.189	0.553	TRUE	< 0.001	Kruskal		
ESR-GAN Cross	Quartile 1	0.225	0.432	0.478	TRUE	< 0.001	Kruskal	69.32	< 0.001
ESR-GAN Cross	Quartile 2	< 0.001	0.246	0.006	FALSE	< 0.001	Kruskal		
ESR-GAN Cross	Quartile 3	< 0.001	0.034	< 0.001	FALSE	< 0.001	Kruskal		
ESR-GAN Cross	Quartile 4	0.004	0.092	0.006	FALSE	< 0.001	Kruskal		
ESR-GAN Generalization	Quartile 1	0.171	0.680	0.186	TRUE	0.019	Kruskal	206.04	< 0.001
ESR-GAN Generalization	Quartile 2	< 0.001	0.063	< 0.001	FALSE	0.019	Kruskal		
ESR-GAN Generalization	Quartile 3	< 0.001	0.001	< 0.001	FALSE	0.019	Kruskal		
ESR-GAN Generalization	Quartile 4	< 0.001	0.005	< 0.001	FALSE	0.019	Kruskal		

Table S7. Results of the Normality test and subsequent group comparisons of PSNR values across **NDVI-based** texture quartiles for the **Bicubic** model, using ANOVA for normally distributed data and Kruskal–Wallis tests for non-normal data.

Case	Variable	Shapiro_p	KS_p	DAgostino_p	Normality_OK	Levene_p	Test_Used	H_or_F	p_value
BICUB Intra	Quartile 1	< 0.001	0.284	0.001	FALSE	0.001	Kruskal	51.99	< 0.001
BICUB Intra	Quartile 2	< 0.001	0.256	< 0.001	FALSE	0.001	Kruskal		
BICUB Intra	Quartile 3	< 0.001	0.077	< 0.001	FALSE	0.001	Kruskal		
BICUB Intra	Quartile 4	0.798	0.834	0.430	TRUE	0.001	Kruskal		
BICUB Cross	Quartile 1	0.268	0.912	0.175	TRUE	0.244	Kruskal	117.1	< 0.001
BICUB Cross	Quartile 2	0.029	0.481	0.313	TRUE	0.244	Kruskal		
BICUB Cross	Quartile 3	< 0.001	0.014	< 0.001	FALSE	0.244	Kruskal		
BICUB Cross	Quartile 4	< 0.001	0.003	< 0.001	FALSE	0.244	Kruskal		

Table S8. Normality + ANOVA/Kruskal test among Downscaling Strategy Frameworks

NDVI Inferential statistics			
Stat	SRGAN	ESRGAN	Bicubic
H	1879.69	2652.80	1543.56
p	< 0.001	< 0.001	< 0.001
df	2	2	1

6. Normality and group comparison (ANOVA or Kruskal–Wallis) results for PSNR across Structure-based clusters for all models.

Table S9. Results of the Normality test and subsequent group comparisons of PSNR values across **structure-based** clusters for the **SRGAN** model, using ANOVA for normally distributed data and Kruskal–Wallis tests for non-normal data.

Case	Variable	Shapiro_p	KS_p	DAgostino_p	Normality_OK	Levene_p	Test_Used	H_or_F	p_value
SR-GAN Intra-Sensor	Cluster 1	< 0.001	0.136	< 0.001	FALSE	< 0.001	Kruskal	8.29	0.016
SR-GAN Intra-Sensor	Cluster 2	0.087	0.552	0.023	TRUE	< 0.001	Kruskal		
SR-GAN Intra-Sensor	Cluster 3	< 0.001	< 0.001	< 0.001	FALSE	< 0.001	Kruskal		
SR-GAN Cross-Sensor	Cluster 1	0.001	0.196	< 0.001	FALSE	< 0.001	Kruskal	18.75	< 0.001
SR-GAN Cross-Sensor	Cluster 2	0.315	0.963	0.362	TRUE	< 0.001	Kruskal		
SR-GAN Cross-Sensor	Cluster 3	0.002	0.397	0.003	FALSE	< 0.001	Kruskal		
SR-GAN Generalization	Cluster 1	< 0.001	0.068	< 0.001	FALSE	< 0.001	Kruskal	85.61	< 0.001
SR-GAN Generalization	Cluster 2	0.022	0.094	0.727	TRUE	< 0.001	Kruskal		
SR-GAN Generalization	Cluster 3	< 0.001	0.066	< 0.001	FALSE	< 0.001	Kruskal		

Table S10. Results of the Normality test and subsequent group comparisons of PSNR values across **structure-based** texture quartiles for the **ESRGAN** model, using ANOVA for normally distributed data and Kruskal–Wallis tests for non-normal data.

Case	Variable	Shapiro_p	KS_p	DAgostino_p	Normality_OK	Levene_p	Test_Used	H_or_F	p_value
ESR-GAN Intra-Sensor	Cluster 1	0.002	0.266	0.001	FALSE	0.016	Kruskal	5.98	0.050
ESR-GAN Intra-Sensor	Cluster 2	0.079	0.314	0.019	TRUE	0.016	Kruskal		
ESR-GAN Intra-Sensor	Cluster 3	< 0.001	0.051	0.023	FALSE	0.016	Kruskal		
ESR-GAN Cross-Sensor	Cluster 1	0.026	0.406	0.008	FALSE	< 0.001	Kruskal	18.31	< 0.001
ESR-GAN Cross-Sensor	Cluster 2	< 0.001	0.276	0.005	FALSE	< 0.001	Kruskal		
ESR-GAN Cross-Sensor	Cluster 3	< 0.001	0.255	0.002	FALSE	< 0.001	Kruskal		
ESR-GAN Generalization	Cluster 1	0.001	0.050	0.005	FALSE	0.032	Kruskal	40.30	< 0.001
ESR-GAN Generalization	Cluster 2	0.493	0.890	0.949	TRUE	0.032	Kruskal		
ESR-GAN Generalization	Cluster 3	< 0.001	0.080	0.005	FALSE	0.032	Kruskal		

Table S11. Results of the Normality test and subsequent group comparisons of PSNR values across **structure-based** texture quartiles for the **Bicubic** model, using ANOVA for normally distributed data and Kruskal–Wallis tests for non-normal data.

Case	Variable	Shapiro_p	KS_p	DAgostino_p	Normality_OK	Levene_p	Test_Used	H_or_F	p_value
BICUB Intra-Sensor	Cluster 1	0.026	0.297	0.014	FALSE	0.027	Kruskal	15.27	< 0.001
BICUB Intra-Sensor	Cluster 2	0.233	0.936	0.130	TRUE	0.027	Kruskal		
BICUB Intra-Sensor	Cluster 3	0.003	0.159	0.045	FALSE	0.027	Kruskal		
BICUB Cross-Sensor	Cluster 1	0.131	0.642	0.508	TRUE	< 0.001	Kruskal	96.25	< 0.001
BICUB Cross-Sensor	Cluster 2	0.032	0.345	0.117	TRUE	< 0.001	Kruskal		
BICUB Cross-Sensor	Cluster 3	0.293	0.858	0.427	TRUE	< 0.001	Kruskal		

7. Normality and group comparison (ANOVA or Kruskal–Wallis) results for PSNR across Entropy-based quartiles for all models.

Table S12. Results of the Normality test and subsequent group comparisons of PSNR values across **entropy-based** texture quartiles for the **SRGAN** model, using ANOVA for normally distributed data and Kruskal–Wallis tests for non-normal data.

Case	Variable	Shapiro_p	KS_p	D'Agostino_p	Normality_OK	Levene_p	Test_Used	H_or_F	p_value
SR-GAN Intra-Sensor	Quartile 1	0.002	0.281	0.002	FALSE	< 0.001	Kruskal	124.11	< 0.001
SR-GAN Intra-Sensor	Quartile 2	< 0.001	0.014	< 0.001	FALSE	< 0.001	Kruskal		
SR-GAN Intra-Sensor	Quartile 3	< 0.001	0.096	0.004	FALSE	< 0.001	Kruskal		
SR-GAN Intra-Sensor	Quartile 4	< 0.001	< 0.001	< 0.001	FALSE	< 0.001	Kruskal		
SR-GAN Cross-Sensor	Quartile 1	< 0.001	0.120	< 0.001	FALSE	< 0.001	Kruskal	107.51	< 0.001
SR-GAN Cross-Sensor	Quartile 2	< 0.001	0.005	< 0.001	FALSE	< 0.001	Kruskal		
SR-GAN Cross-Sensor	Quartile 3	< 0.001	0.055	0.001	FALSE	< 0.001	Kruskal		
SR-GAN Cross-Sensor	Quartile 4	< 0.001	0.001	< 0.001	FALSE	< 0.001	Kruskal		
SR-GAN Generalization	Quartile 1	0.021	0.239	0.159	TRUE	< 0.001	Kruskal	244.84	< 0.001
SR-GAN Generalization	Quartile 2	< 0.001	0.526	< 0.001	FALSE	< 0.001	Kruskal		
SR-GAN Generalization	Quartile 3	0.003	0.061	0.255	TRUE	< 0.001	Kruskal		
SR-GAN Generalization	Quartile 4	< 0.001	< 0.001	< 0.001	FALSE	< 0.001	Kruskal		

Source: D:\work\research_t\downscaling\Results\Res\007_Norm_Kruskal_Table_SRGAN_TX.xlsx

Table S13. Results of the Normality test and subsequent group comparisons of PSNR values across **entropy-based** texture quartiles for the **ESRGAN** model, using ANOVA for normally distributed data and Kruskal–Wallis tests for non-normal data.

Case	Variable	Shapiro_p	KS_p	D'Agostino_p	Normality_OK	Levene_p	Test_Used	H_or_F	p_value
ESR-GAN Intra	Quartile 1	0.017	0.830	0.022	FALSE	< 0.001	Kruskal	192.59	< 0.001
ESR-GAN Intra	Quartile 2	< 0.001	0.143	< 0.001	FALSE	< 0.001	Kruskal		
ESR-GAN Intra	Quartile 3	< 0.001	0.082	< 0.001	FALSE	< 0.001	Kruskal		
ESR-GAN Intra	Quartile 4	0.046	0.384	0.334	TRUE	< 0.001	Kruskal		
ESR-GAN Cross	Quartile 1	< 0.001	0.736	< 0.001	FALSE	< 0.001	Kruskal	103.23	< 0.001
ESR-GAN Cross	Quartile 2	< 0.001	0.162	< 0.001	FALSE	< 0.001	Kruskal		
ESR-GAN Cross	Quartile 3	0.006	0.155	0.013	FALSE	< 0.001	Kruskal		
ESR-GAN Cross	Quartile 4	0.057	0.640	0.060	TRUE	< 0.001	Kruskal		
ESR-GAN Generalization	Quartile 1	0.405	0.487	0.492	TRUE	< 0.001	Kruskal	150.00	< 0.001
ESR-GAN Generalization	Quartile 2	< 0.001	0.060	< 0.001	FALSE	< 0.001	Kruskal		
ESR-GAN Generalization	Quartile 3	0.940	0.957	0.941	TRUE	< 0.001	Kruskal		
ESR-GAN Generalization	Quartile 4	< 0.001	0.005	0.003	FALSE	< 0.001	Kruskal		

Table S14. Results of the Normality test and subsequent group comparisons of PSNR values across **entropy-based** texture quartiles for the **Bicubic** model, using ANOVA for normally distributed data and Kruskal–Wallis tests for non-normal data.

Case	Variable	Shapiro_p	KS_p	DAgostino_p	Normality_OK	Levene_p	Test_Used	H_or_F	p_value
BICUB Intra	Quartile 1	0.064	0.644	0.038	TRUE	0.096	Kruskal	103.68	< 0.001
BICUB Intra	Quartile 2	< 0.001	0.050	< 0.001	FALSE	0.096	Kruskal		
BICUB Intra	Quartile 3	0.002	0.205	0.012	FALSE	0.096	Kruskal		
BICUB Intra	Quartile 4	0.053	0.564	0.034	TRUE	0.096	Kruskal		
BICUB Cross	Quartile 1	0.002	0.228	0.004	FALSE	< 0.001	Kruskal	174.13	< 0.001
BICUB Cross	Quartile 2	0.001	0.046	< 0.001	FALSE	< 0.001	Kruskal		
BICUB Cross	Quartile 3	0.029	0.287	0.491	TRUE	< 0.001	Kruskal		
BICUB Cross	Quartile 4	< 0.001	0.047	0.032	FALSE	< 0.001	Kruskal		

8. Visual comparison of downscaling results for NDVI-based quartiles (Q1, Q2, Q3, and Q4)

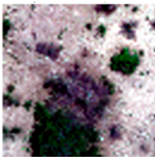
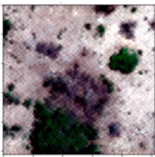
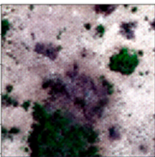
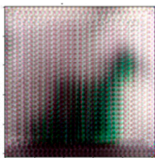
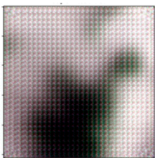
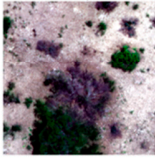
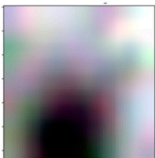
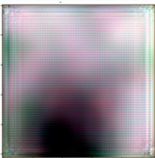
Strategy Framework	LR	Bicubic	SRGAN	ESRGAN	HR (Target)
intra-sensor					
cross-sensor					
intra-to-cross		NA			

Figure S6. Visual comparison of downscaling results for vegetation health **Quartile 1** (lowest NDVI) across three strategy frameworks: intra-sensor, cross-sensor, and intra-to-cross generalization.

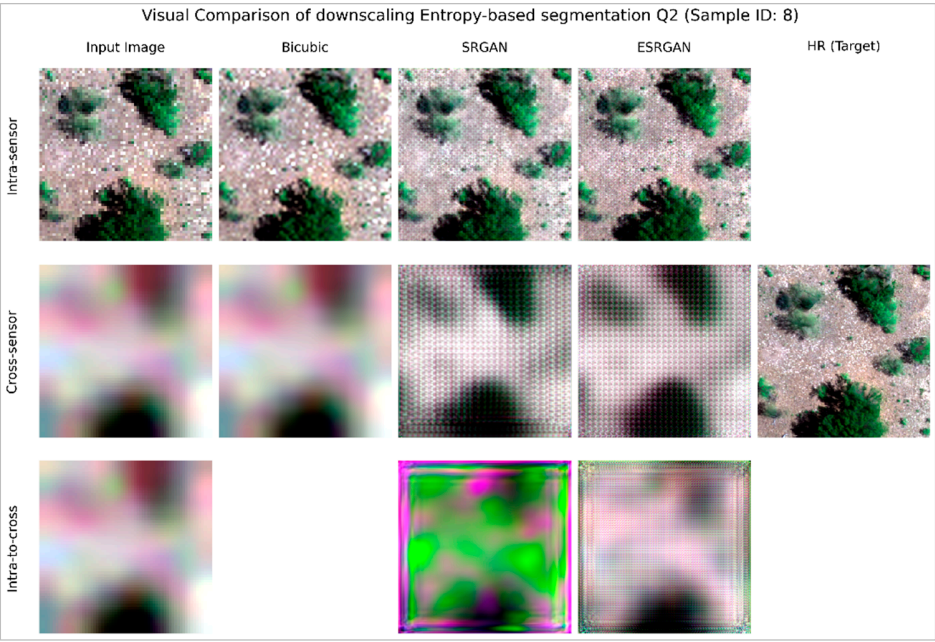


Figure S7. Visual comparison of downscaling results for vegetation health **Quartile 2** (low-to-moderate NDVI) across the intra-sensor, cross-sensor, and intra-to-cross generalization frameworks.

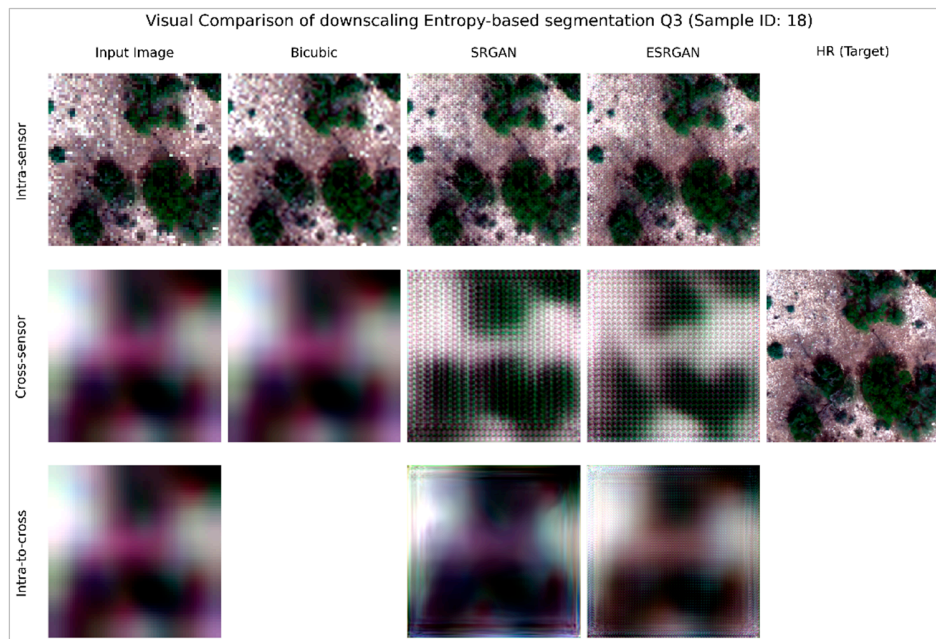


Figure S8. Visual comparison of downscaling results for vegetation health **Quartile 3** (moderate NDVI) across the intra-sensor, cross-sensor, and intra-to-cross generalization frameworks.

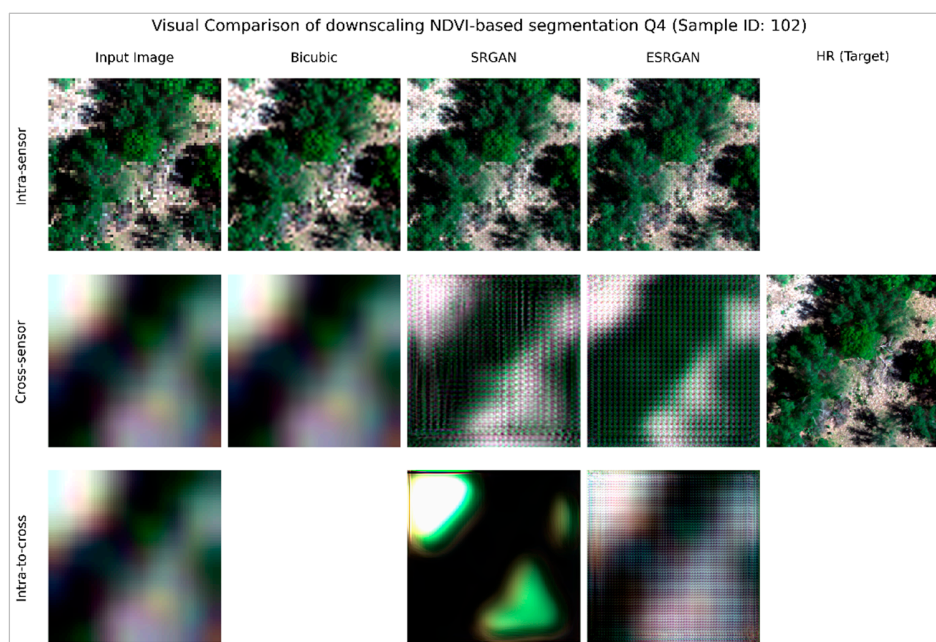


Figure S9. Visual comparison of downscaling results for vegetation health **Quartile 4** (High NDVI) across the intra-sensor, cross-sensor, and intra-to-cross generalization frameworks.

9. Visual comparison of downscaling results for Structure-based clusters (C1, C2, and C3)

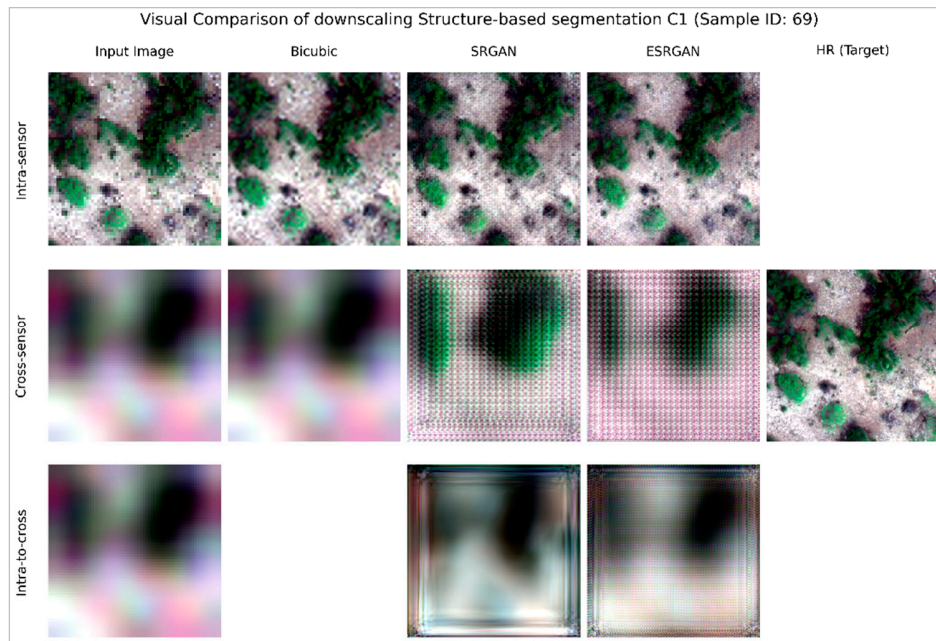


Figure S10. Visual comparison of downscaling for structure derived **Cluster 1** (Sparse & Fragmented Woody patches) across intra-sensor, cross-sensor, and intra-to-cross generalization frameworks.

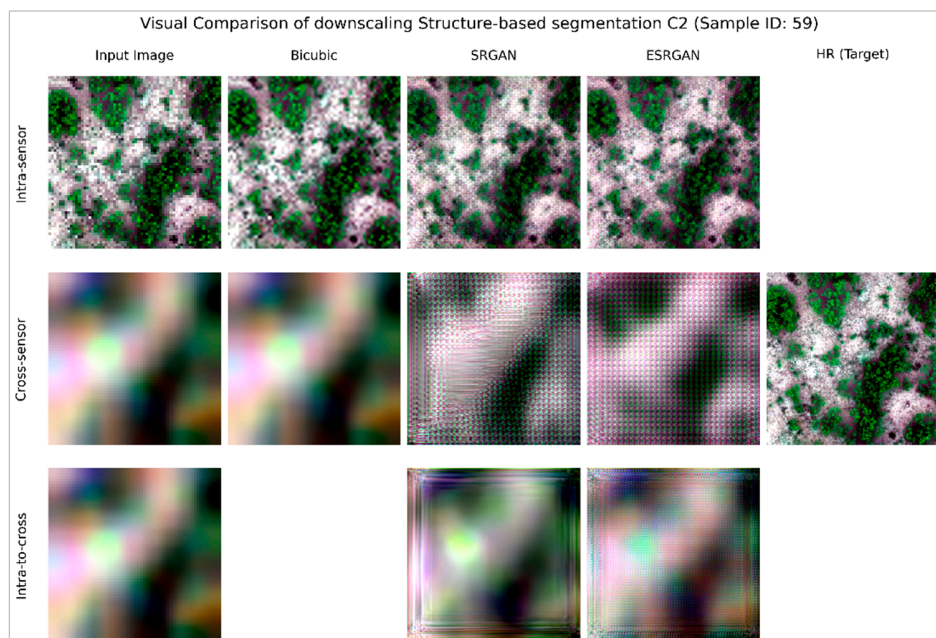


Figure S11. Visual comparison of downscaling for structure derived **Cluster 2** (Dispersed Woody Mosaics) across intra-sensor, cross-sensor, and intra-to-cross generalization frameworks.

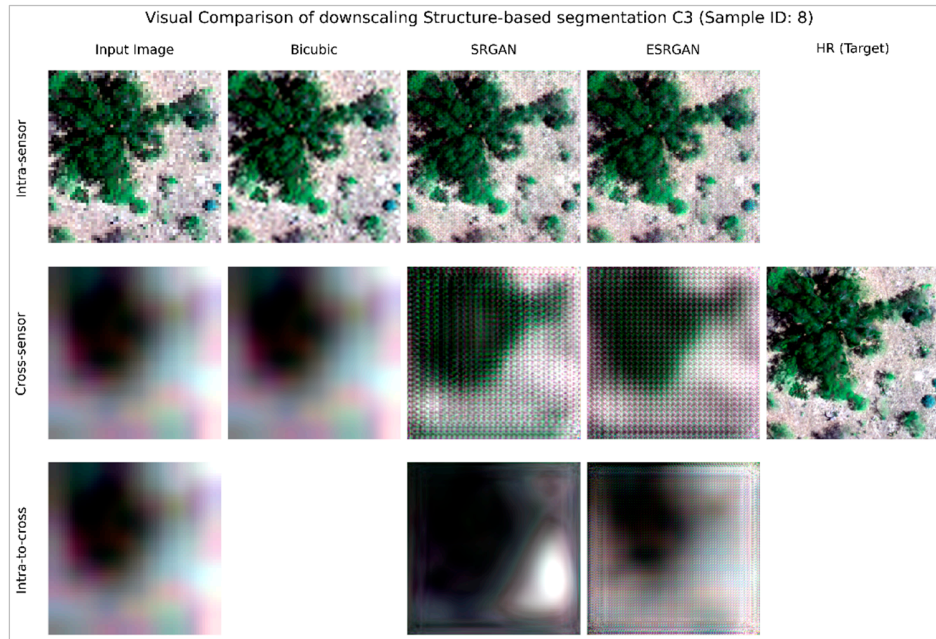


Figure S12. Visual comparison of downscaling for structure derived **Cluster 3** (Dense & Clumped Woody Dominance) across intra-sensor, cross-sensor, and intra-to-cross generalization frameworks.

10. Visual comparison of downscaling results for Entropy-based quartiles (Q1, Q2, Q3, and Q4)

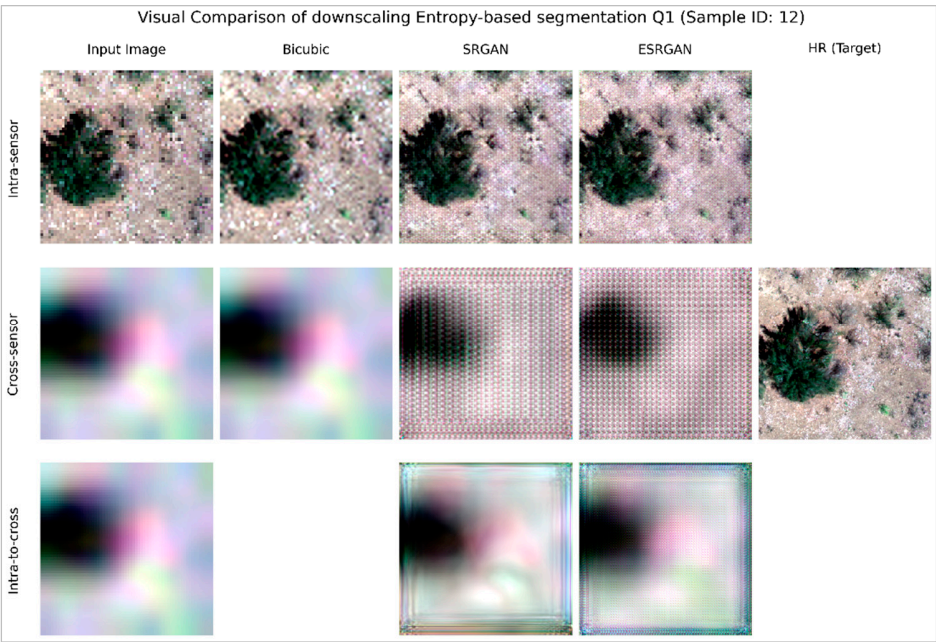


Figure S13. Visual comparison of downscaling for Entropy derived **Quartile 1** (Lowest Spatial Disorder) across three strategy frameworks: intra-sensor, cross-sensor, and intra-to-cross generalization.

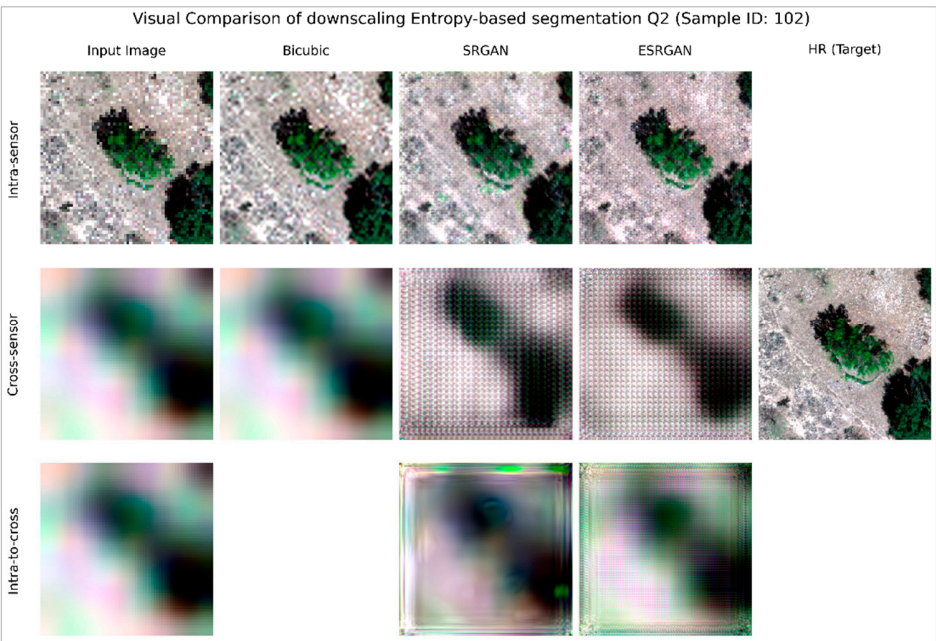


Figure S14. Visual comparison of downscaling for Entropy derived **Quartile 2** (Moderate Tonal Variability) across three strategy frameworks: intra-sensor, cross-sensor, and intra-to-cross generalization.

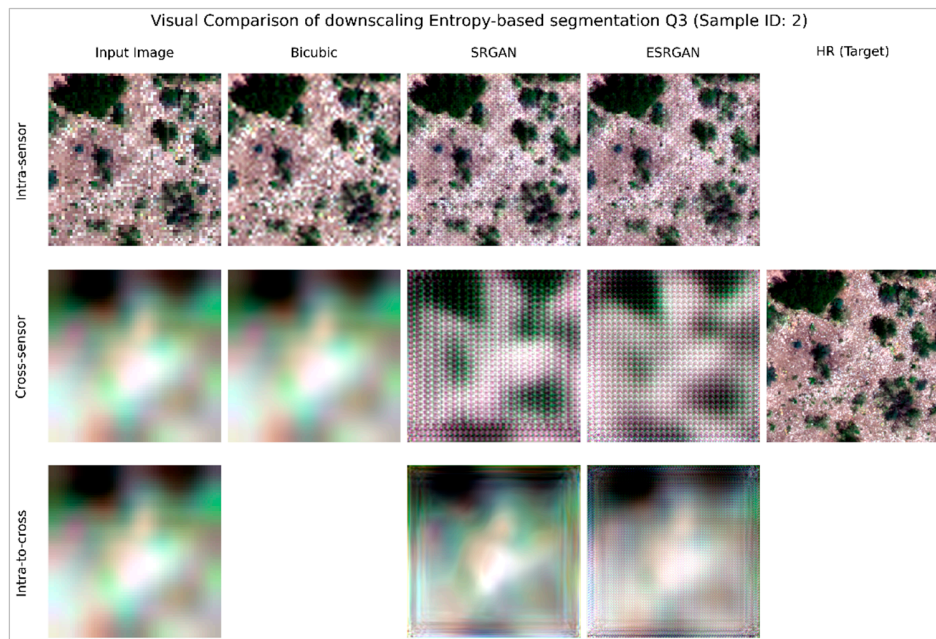


Figure S15. Visual comparison of downscaling for Entropy derived **Quartile 3** (High Pattern Complexity) across three strategy frameworks: intra-sensor, cross-sensor, and intra-to-cross generalization.

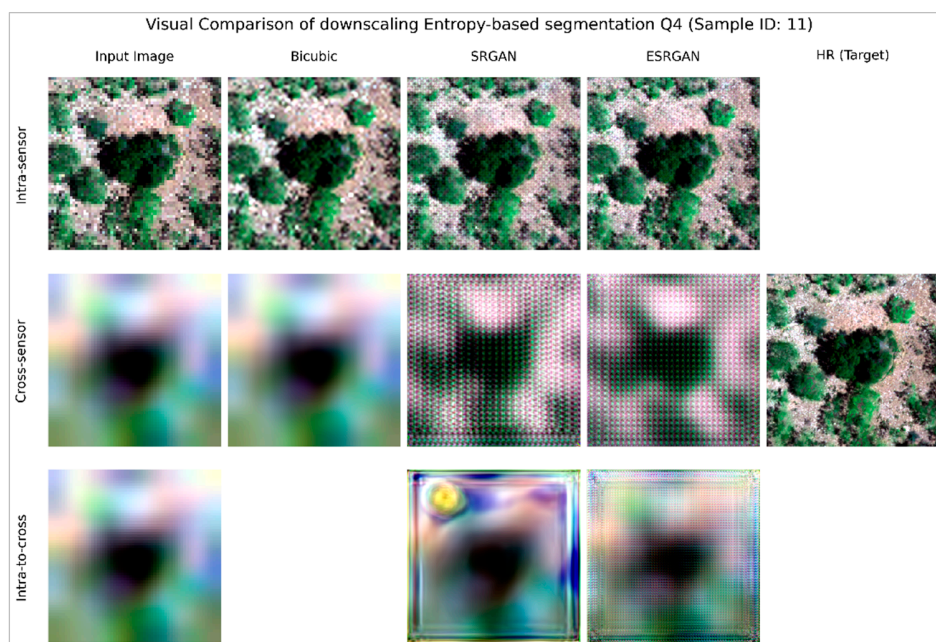


Figure S16. Visual comparison of downscaling for Entropy derived **Quartile 4** (Maximum Spatial Disorder) across three strategy frameworks: intra-sensor, cross-sensor, and intra-to-cross generalization.