

# Supplementary Material

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Paper Title: “HybridSN: Exploring 3D-2D CNN Feature Hierarchy for Hyperspectral Image Classification”

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## Experiment on Indian Pines dataset :

The Indian Pines dataset was gathered by AVIRIS (Airborne Visible/Infrared Imaging Spectrometer) sensor over the Indian Pines test site in North-western Indiana in 1992. The Indian Pines (IP) dataset has images with  $145 \times 145$  spatial dimension and 224 spectral bands and the ground truth available is designated into 16 classes of vegetation.

The experiments were conducted on the Indian Pines dataset with different numbers of training and testing samples. Some other experiments we performed involved observing the effects of different spatial window sizes and the effects of number of PCA components. The following Table 1 gives the distribution of train and test samples as well as the measurement of Overall Accuracy (OA), Kappa coefficient and Average Accuracy (AA) achieved by HybridSN and other methods on the Indian Pines dataset. We found 30 to be the optimal number of PCA components for this particular dataset. It is also observed from Table 1 that the proposed method outperforms most of the state-of-the-art methods.

Table 1: Number of training and test samples of the Indian Pines and classification accuracies (in percentages)

Classes	Train/Test	SVM	2D-CNN	3D-CNN	M3D-CNN	SSRN	HybridSN
Alfalfa	14/32	82.20	75.00	79.23	97.03	97.82	99.38
Corn-no till	428/1000	73.82	81.40	88.60	97.90	99.17	99.58
Corn-min till	249/581	82.15	87.60	85.81	92.41	99.53	99.66
Corn	71/166	77.12	62.04	90.53	93.25	97.79	99.88
Grass-pasture	145/338	73.66	92.30	96.11	95.00	99.24	99.53
Grass-trees	219/511	93.40	99.21	98.43	99.74	99.51	99.96
Grass-pasture-mowed	8/20	96.21	75.00	92.36	100	98.70	99.00
Hay-windrowed	143/335	85.72	100	98.51	99.99	99.85	100
Oats	6/14	97.38	64.28	88.90	96.61	98.50	100
Soybean-no till	292/680	71.01	82.79	87.72	96.32	98.74	99.56
Soybean-min till	736/1719	76.50	91.27	91.42	97.13	99.30	99.84
Soybean-clean	178/415	83.90	82.89	90.04	97.16	98.43	99.52
Wheat	62/143	83.56	99.30	99.00	99.60	100	99.86
Woods	379/886	98.63	98.87	97.95	98.42	99.31	100
Buildings-Grass-Trees-Drives	116/270	94.21	86.29	82.57	83.31	99.20	99.85
Stone-Steel-Towers	28/65	69.63	100	98.51	100	97.82	98.46
OA	3074/7175	$85.30 \pm 2.81$	$89.48 \pm 0.15$	$91.10 \pm 0.42$	$95.32 \pm 0.11$	$99.19 \pm 0.26$	$99.75 \pm 0.11$
Kappa		$83.10 \pm 3.15$	$87.96 \pm 0.51$	$89.98 \pm 0.50$	$94.7 \pm 0.20$	$99.07 \pm 0.30$	$99.71 \pm 0.13$
AA		$79.03 \pm 2.65$	$86.14 \pm 0.82$	$91.58 \pm 0.15$	$96.41 \pm 0.72$	$98.93 \pm 0.59$	$99.63 \pm 0.15$

## Experiment on University of Pavia dataset :

The University of Pavia dataset acquired by the ROSIS (Reflective Optics System Imaging Spectrometer) sensor during a flight campaign over Pavia, Northern Italy in 2001. The University of Pavia (UP) dataset consists of  $610 \times 340$  spatial dimension pixels with 103 spectral bands and the ground truth is divided

into 9 urban land-cover classes. Similar experiments like Indian Pines dataset were carried out on Pavia University dataset. The spatial size was kept same as before, however the optimal number of PCA components were chosen to be 15. The following Table 2 summarises the results of the experiments and provides the distribution of train and test samples in the experiment.

Table 2: Number of training and test samples of the University of Pavia and classification accuracies (in percentages)

Classes	Train/Test	SVM	2D-CNN	3D-CNN	M3D-CN	SSRN	HybridSN
Asphalt	1989/4642	94.72	98.51	98.40	98.31	100	100
Meadows	5594/13055	97.15	99.54	96.91	96.10	99.87	100
Gravel	630/1469	82.73	84.62	97.05	96.34	100	100
Trees	919/2145	96.82	98.04	98.84	98.82	100	99.84
Painted metal sheets	403/942	99.71	100	100	99.97	100	100
Bare Soil	1509/3520	90.48	97.10	99.32	99.83	100	100
Bitumen	399/931	87.73	95.05	98.92	99.66	100	100
Self-Blocking Bricks	1105/2577	88.29	96.39	98.33	99.23	99.34	99.98
Shadows	284/663	99.90	99.69	99.90	99.92	100	99.90
OA	12832/29944	94.34 $\pm$ 0.18	97.86 $\pm$ 0.20	96.53 $\pm$ 0.08	95.76 $\pm$ 0.20	99.90 $\pm$ 0.0	99.98 $\pm$ 0.01
Kappa		92.50 $\pm$ 0.70	97.16 $\pm$ 0.51	95.51 $\pm$ 0.21	94.50 $\pm$ 0.15	99.87 $\pm$ 0.0	99.98 $\pm$ 0.01
AA		92.98 $\pm$ 0.41	96.55 $\pm$ 0.03	97.57 $\pm$ 1.31	95.08 $\pm$ 1.21	99.91 $\pm$ 0.0	99.97 $\pm$ 0.01

### Experiment on Salinas Scene dataset :

The Salinas scene dataset was collected by the 224-band AVIRIS sensor over Salinas Valley, California in 1998. The Salinas Scene (SA) dataset contains the images with  $512 \times 217$  spatial dimension and 224 spectral bands, which also contains total 16 classes. The experimental set up was exactly same for Salinas dataset as used for Pavia University dataset. The following Table 3 illustrates the results of these experiments and the train and test samples distribution for the experiment.

Table 3: Number of training and test samples of the Salinas Scene and classification accuracies (in percentages)

Classes	Train/Test	SVM	2D-CNN	3D-CNN	M3D-CNN	SSRN	HybridSN
Brocoli_green_weeds_1	603/1406	99.60	100	98.41	97.50	100	100
Brocoli_green_weeds_2	1118/2608	99.82	99.96	100	100	100	100
Fallow	593/1383	99.26	99.63	99.23	99.43	100	100
Fallow_rough_plow	418/976	99.40	99.28	99.90	99.51	99.89	100
Fallow_smooth	803/1875	99.42	99.20	99.43	99.72	100	100
Stubble	1188/2771	100	100	99.55	99.23	100	100
Celery	1074/2505	99.83	100	99.72	99.45	100	100
Grapes_untrained	3381/7890	85.25	93.62	89.75	92.63	100	100
Soil_vinyard_develop	1861/4342	99.71	100	99.81	99.70	100	100
Corn_senesced_green_weeds	983/2295	97.03	98.82	98.36	97.31	99.91	100
Lettuce_roumaine_4wk	320/748	98.24	99.73	98.12	98.05	100	100
Lettuce_roumaine_5wk	578/1349	99.46	100	98.96	98.50	100	100
Lettuce_roumaine_6wk	275/641	98.77	100	98.93	98.70	100	100
Lettuce_roumaine_7wk	321/749	97.30	99.86	98.60	98.42	100	100
Vinyard_untrained	2180/5088	72.71	91.52	79.31	87.18	99.96	100
Vinyard_vertical_trellis	542/1265	99.41	99.92	94.51	91.11	100	100
OA	16238/37891	92.95 $\pm$ 0.34	97.38 $\pm$ 0.02	93.96 $\pm$ 0.15	94.79 $\pm$ 0.30	99.98 $\pm$ 0.1	100 $\pm$ 0.00
Kappa		92.11 $\pm$ 0.18	97.08 $\pm$ 0.10	93.32 $\pm$ 0.50	94.20 $\pm$ 0.22	99.97 $\pm$ 0.1	100 $\pm$ 0.00
AA		94.60 $\pm$ 2.28	98.84 $\pm$ 0.06	97.01 $\pm$ 0.63	96.25 $\pm$ 0.56	99.97 $\pm$ 0.0	100 $\pm$ 0.00

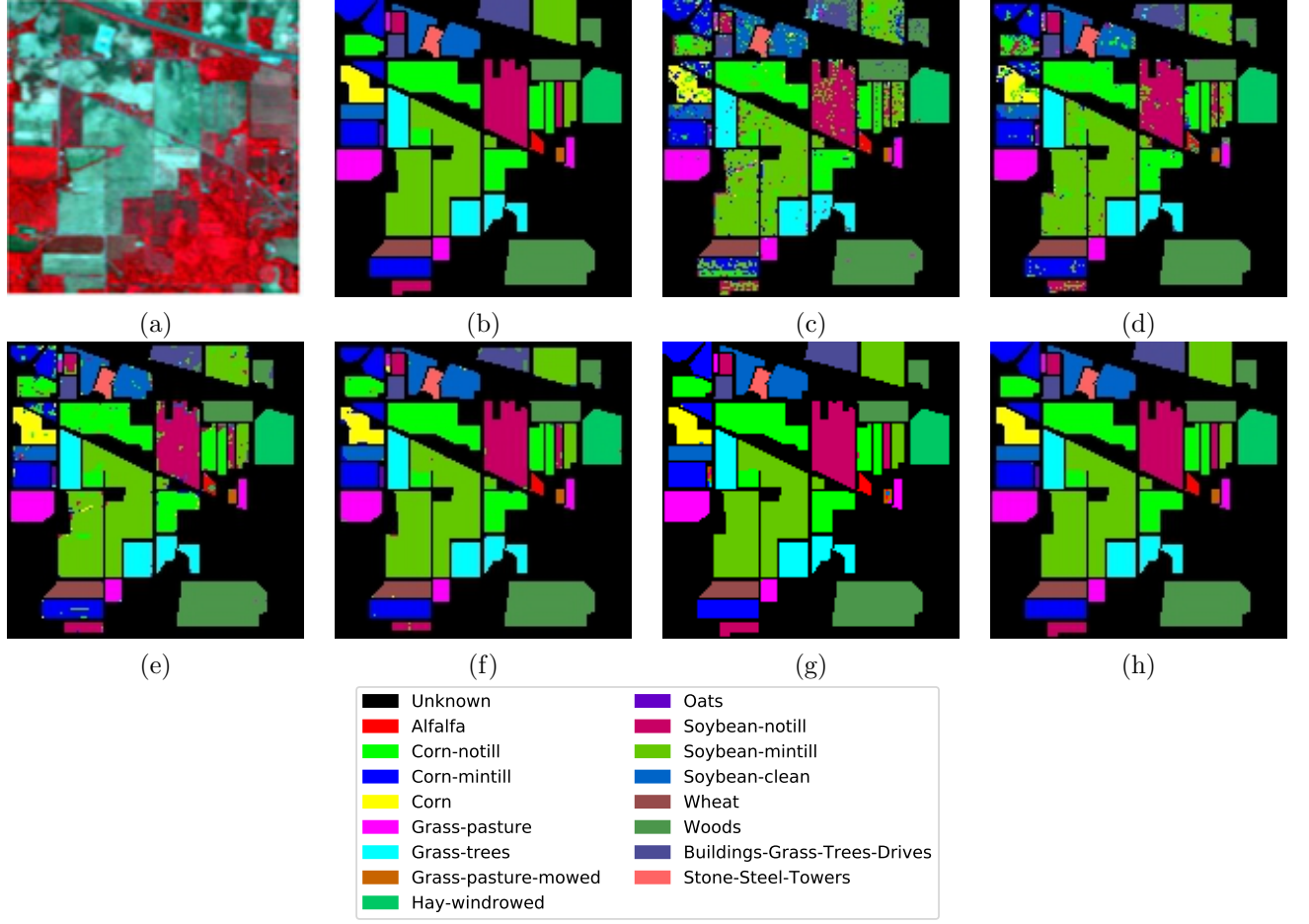


Figure 1: The Classification Map for Indian Pines (a) False color image (b) Ground Truth (c)-(h) Predicted Classification Maps for SVM, 2D-CNN, 3D-CNN, M3D-CNN, SSRN, and HybridSN

### Classification Maps:

The classification maps for Indian Pines, University of Pavia, and Salinas Scene hyperspectral images are illustrated in Fig. 1, 2 and 3 using SVM, 2D-CNN, 3D-CNN, M3D-CNN, SSRN and HybridSN methods.

### Class-wise Analysis of Precision, Recall, F1-score, and Support:

The class-wise analysis of Precision, Recall, F1-score, and Support are also shown in Table 4, 5, and 6 for Indian Pines, University of Pavia, and Salinas Scene hyperspectral datasets respectively.

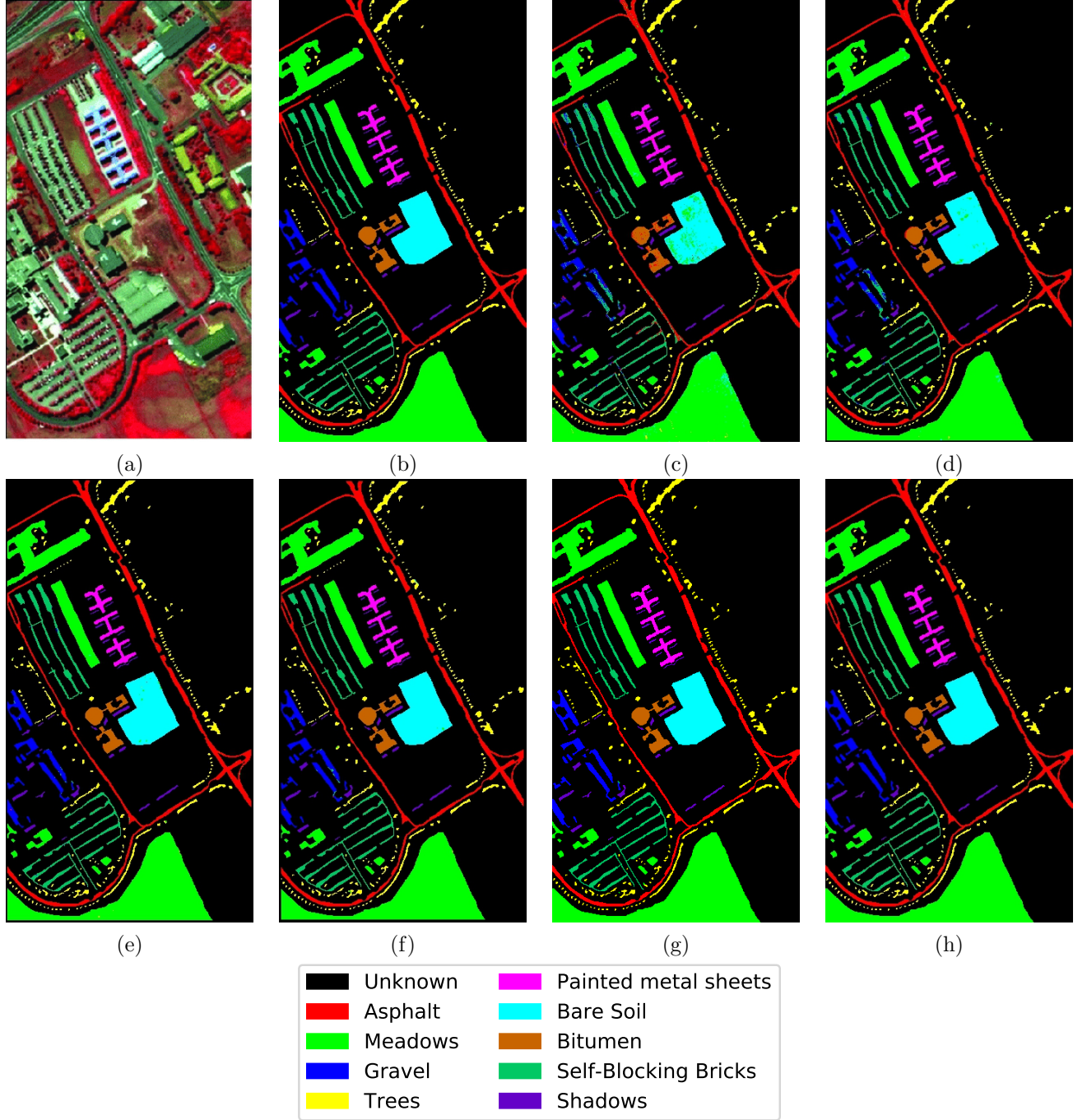


Figure 2: The Classification Map for Pavia University (a) False color image (b) Ground Truth (c)-(h) Predicted Classification Maps for SVM, 2D-CNN, 3D-CNN, M3D-CNN, SSRN, and HybridSN

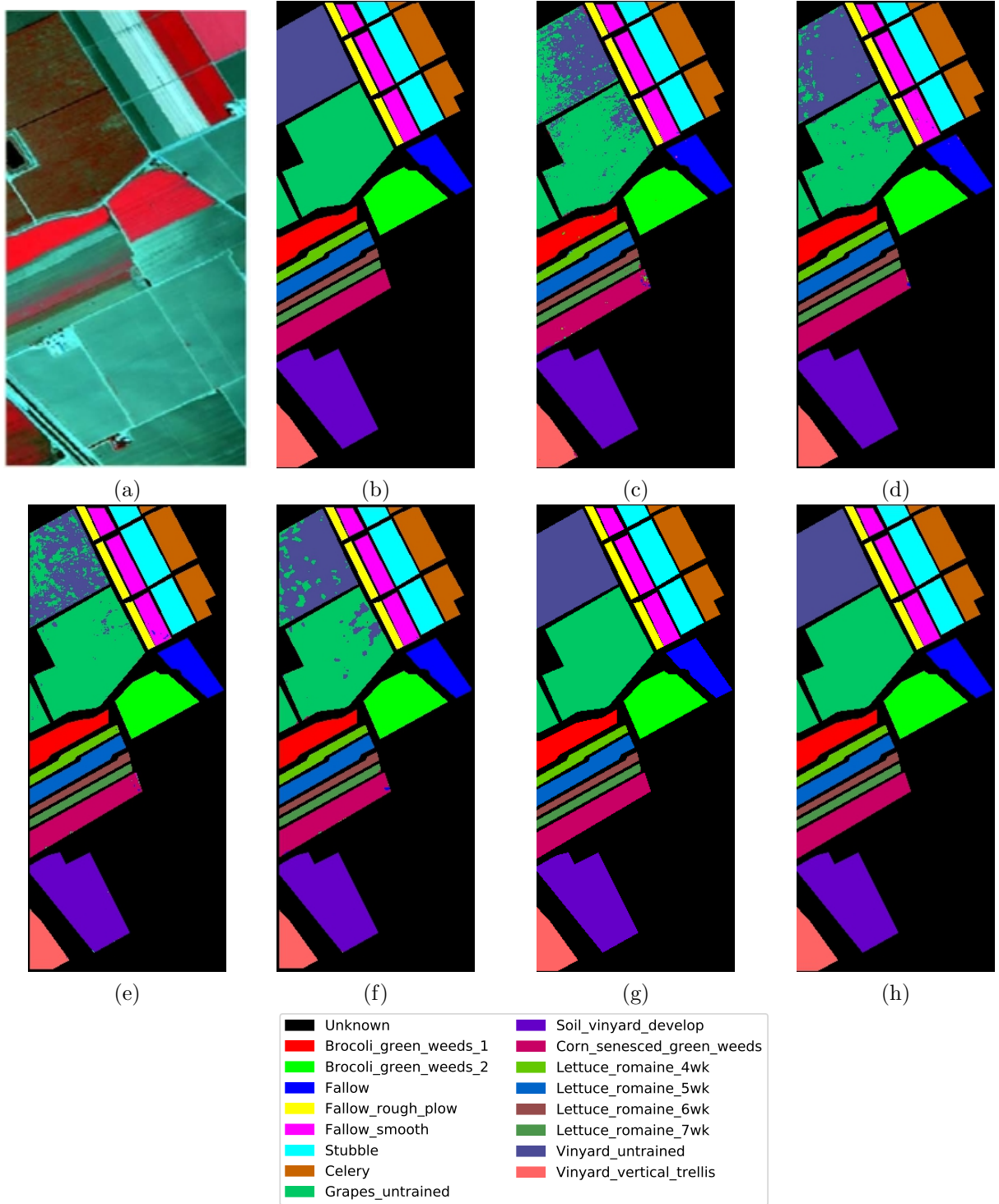


Figure 3: The Classification Map for Salinas Scene (a) False color image (b) Ground Truth (c)-(h) Predicted Classification Maps for SVM, 2D-CNN, 3D-CNN, M3D-CNN, SSRN, HybridSN

Table 4: Class-wise analysis of Precision, Recall, F1-score, and Support of India Pines data set.

Classes	Precision	Recall	F1-score	Support
Alfalfa	1.00	1.00	1.00	32
Corn-notill	1.00	1.00	1.00	1000
Corn-mintill	1.00	1.00	1.00	581
Corn	1.00	1.00	1.00	166
Grass-pasture	1.00	1.00	1.00	338
Grass-trees	1.00	1.00	1.00	511
Grass-pasture-mowed	1.00	0.95	0.97	20
Hay-windrowed	1.00	1.00	1.00	335
Oats	1.00	1.00	1.00	14
Soybean-notill	1.00	1.00	1.00	680
Soybean-mintill	1.00	1.00	1.00	1719
Soybean-clean	1.00	1.00	1.00	415
Wheat	1.00	1.00	1.00	143
Woods	1.00	1.00	1.00	886
Buildings-Grass-Trees-Drives	1.00	1.00	1.00	270
Stone-Steel-Towers	0.98	1.00	0.99	65
Micro avg	1.00	1.00	1.00	7175
Macro avg	1.00	1.00	1.00	7175
Weighted avg	1.00	1.00	1.00	7175

Table 5: Class-wise analysis of Precision, Recall, F1-score, and Support of University of Pavia data set.

Classes	Precision	Recall	F1-score	Support
Asphalt	1.00	1.00	1.00	4642
Meadows	1.00	1.00	1.00	13055
Gravel	1.00	1.00	1.00	1469
Trees	1.00	1.00	1.00	2145
Painted metal sheets	1.00	1.00	1.00	942
Bare Soil	1.00	1.00	1.00	3520
Bitumen	1.00	1.00	1.00	931
Self-Blocking Bricks	1.00	1.00	1.00	2577
Shadows	1.00	1.00	1.00	663
Micro avg	1.00	1.00	1.00	29944
Macro avg	1.00	1.00	1.00	29944
Weighted avg	1.00	1.00	1.00	29944

Table 6: Class-wise analysis of Precision, Recall, F1-score, and Support of Salinas dataset.

Classes	Precision	Recall	F1-score	Support
Brocoli_green_weeds_1	1.00	1.00	1.00	1406
Brocoli_green_weeds_2	1.00	1.00	1.00	2608
Fallow	1.00	1.00	1.00	1383
Fallow_rough_plow	1.00	1.00	1.00	976
Fallow_smooth	1.00	1.00	1.00	1875
Stubble	1.00	1.00	1.00	2771
Celery	1.00	1.00	1.00	2505
Grapes_untrained	1.00	1.00	1.00	7890
Soil_vinyard_develop	1.00	1.00	1.00	4342
Corn_senesced_green_weeds	1.00	1.00	1.00	2295
Lettuce_romaine_4wk	1.00	1.00	1.00	748
Lettuce_romaine_5wk	1.00	1.00	1.00	1349
Lettuce_romaine_6wk	1.00	1.00	1.00	641
Lettuce_romaine_7wk	1.00	1.00	1.00	749
Vinyard_untrained	1.00	1.00	1.00	5088
Vinyard_vertical_trellis	1.00	1.00	1.00	1265
Micro avg	1.00	1.00	1.00	37891
Macro avg	1.00	1.00	1.00	37891
Weighted avg	1.00	1.00	1.00	37891

Table 7: The classification accuracies (in percentages) using proposed and state-of-the-art methods on less amount of training data. (20 percent)

Methods	Indian Pines Dataset			University of Pavia Dataset			Salinas Scene Dataset		
	OA	Kappa	AA	OA	Kappa	AA	OA	Kappa	AA
2D-CNN	86.90 $\pm$ 1.3	85.01 $\pm$ 1.6	82.70 $\pm$ 1.0	96.02 $\pm$ 0.4	96.04 $\pm$ 0.3	95.10 $\pm$ 0.1	96.15 $\pm$ 0.6	95.71 $\pm$ 0.7	98.27 $\pm$ 0.2
3D-CNN	89.23 $\pm$ 0.2	87.70 $\pm$ 0.3	87.87 $\pm$ 0.1	97.30 $\pm$ 0.3	96.22 $\pm$ 0.1	97.02 $\pm$ 0.1	94.54 $\pm$ 0.5	93.81 $\pm$ 0.3	96.79 $\pm$ 0.6
M3D-CNN	93.67 $\pm$ 0.1	92.70 $\pm$ 0.3	93.60 $\pm$ 0.6	97.41 $\pm$ 0.2	96.05 $\pm$ 0.6	98.22 $\pm$ 0.1	94.92 $\pm$ 0.3	94.40 $\pm$ 0.1	97.28 $\pm$ 0.2
SSRN	99.23 $\pm$ 0.1	99.12 $\pm$ 0.1	92.52 $\pm$ 0.1	99.77 $\pm$ 0.1	99.69 $\pm$ 0.2	99.71 $\pm$ 0.1	99.88 $\pm$ 0.0	99.87 $\pm$ 0.0	99.84 $\pm$ 0.0
<b>HybridSN</b>	99.47 $\pm$ 0.1	99.40 $\pm$ 0.1	99.38 $\pm$ 0.1	99.86 $\pm$ 0.1	99.82 $\pm$ 0.0	99.71 $\pm$ 0.1	100 $\pm$ 0.0	100 $\pm$ 0.0	100 $\pm$ 0.0

Table 8: The classification accuracies (in percentages) using proposed and state-of-the-art methods on less amount of training data. (10 percent)

Methods	Indian Pines Dataset			University of Pavia Dataset			Salinas Scene Dataset		
	OA	Kappa	AA	OA	Kappa	AA	OA	Kappa	AA
2D-CNN	80.27 $\pm$ 1.2	78.26 $\pm$ 2.1	68.32 $\pm$ 4.1	96.63 $\pm$ 0.2	95.53 $\pm$ 1.0	94.84 $\pm$ 1.4	96.34 $\pm$ 0.3	95.93 $\pm$ 0.9	94.36 $\pm$ 0.5
3D-CNN	82.62 $\pm$ 0.1	79.25 $\pm$ 0.3	76.51 $\pm$ 0.1	96.34 $\pm$ 0.2	94.90 $\pm$ 1.2	97.03 $\pm$ 0.6	85.00 $\pm$ 0.1	83.20 $\pm$ 0.7	89.63 $\pm$ 0.2
M3D-CNN	81.39 $\pm$ 2.6	81.20 $\pm$ 2.0	75.22 $\pm$ 0.7	95.95 $\pm$ 0.6	93.40 $\pm$ 0.4	97.52 $\pm$ 1.0	94.20 $\pm$ 0.8	93.61 $\pm$ 0.3	96.66 $\pm$ 0.5
SSRN	98.45 $\pm$ 0.2	98.23 $\pm$ 0.3	86.19 $\pm$ 1.3	99.62 $\pm$ 0.0	99.50 $\pm$ 0.0	99.49 $\pm$ 0.0	99.64 $\pm$ 0.0	99.60 $\pm$ 0.0	99.76 $\pm$ 0.0
<b>HybridSN</b>	98.39 $\pm$ 0.4	98.16 $\pm$ 0.5	98.01 $\pm$ 0.5	99.72 $\pm$ 0.1	99.64 $\pm$ 0.2	99.20 $\pm$ 0.2	99.98 $\pm$ 0.0	99.98 $\pm$ 0.0	99.98 $\pm$ 0.0

Table 9: The classification accuracies (in percentages) using proposed and state-of-the-art methods on less amount of training data. (5 percent)

Methods	Indian Pines Dataset			University of Pavia Dataset			Salinas Scene Dataset		
	OA	Kappa	AA	OA	Kappa	AA	OA	Kappa	AA
2D-CNN	$72.83 \pm 0.5$	$68.58 \pm 0.2$	$69.23 \pm 3.1$	$93.82 \pm 0.2$	$90.10 \pm 0.6$	$92.09 \pm 0.4$	$95.26 \pm 0.5$	$94.73 \pm 0.4$	$97.70 \pm 1.5$
3D-CNN	$71.63 \pm 0.25$	$68.07 \pm 0.3$	$73.39 \pm 3.5$	$92.88 \pm 0.3$	$90.70 \pm 0.6$	$92.56 \pm 2.5$	$92.93 \pm 0.2$	$92.26 \pm 0.9$	$93.5 \pm 2.4$
M3D-CNN	$75.88 \pm 2.2$	$73.6 \pm 1.9$	$70.05 \pm 3.0$	$93.25 \pm 1.3$	$91.3 \pm 1.2$	$94.61 \pm 2.0$	$93.10 \pm 0.5$	$92.31 \pm 0.8$	$94.10 \pm 1.6$
SSRN	$94.39 \pm 0.1$	$93.58 \pm 0.6$	$83.33 \pm 0.9$	$99.10 \pm 0.2$	$99.00 \pm 0.6$	$98.15 \pm 0.0$	$99.53 \pm 0.2$	$99.70 \pm 0.0$	$99.73 \pm 0.0$
<b>HybridSN</b>	$94.90 \pm 1.7$	$93.73 \pm 2.1$	$86.81 \pm 2.5$	$99.35 \pm 1.1$	$98.86 \pm 1.4$	$98.65 \pm 0.8$	$99.95 \pm 0.0$	$99.95 \pm 0.0$	$99.94 \pm 0.0$