Supplementary material

1. Results on USGS and ECOSTRESS spectral libraries

Table S1 – S16 present the number of spectra that were identified using different NDI with various threshold values on the USGS and ECOSTRESS spectral libraries.

Fig. S1 shows the scatter plot of all the vegetation and non-vegetation spectra in both USGS and ECOSTRESS. Fig. S2 and Fig. S3 show the non-vegetation spectra that were misidentified by NDVI. It was observed that almost all the vegetation spectra have a reflectance magnitude lower than 0.25 in blue band (except six spectra). Two of these are flower spectra, and the other four are not original real vegetation spectra but computationally shifted and ratioed spectra, which are actually aimed for the use of testing chlorophylll absorption band shifts. (See Fig. S4 and Fig. S5).

Because there is not sufficient number of various water types in both USGS and ECOSTRESS libraries, 35 typical water spectra were collected from the AVIRI-NG data (Chen et al., 2020). Fig. S6 shows the scatter plot of all the liquid water and non-water spectra. Almost all the water spectra have a reflectance magnitude lower than 0.07 in SWIR band (except four spectra). Two of these are heavily eutrophic water spectra, and the other two are water glint (Fig. S7).

Table S1. The number of spectra that are identified as vegetation using various threshold values on the ECOSTRESS spectral library.

Material	Number	Vegetation (NDVI>0)	Vegetation (NDVI>0.1)	Vegetation (NDVI>0.2)	Vegetation (NDVI>0.3)	Vegetation (NDVI>0.4)
Manmade	45	34	12	4	4	4
Mineral	857	571	94	32	9	4
NPV	52	52	52	44	26	7
Rock	380	249	35	6	2	0
Soil	41	41	32	18	7	1
Vegetation	544	544	544	544	537	529
Water	6	0	0	0	0	0
Recall		1.00	1.00	1.00	0.99	0.97
Precision		0.36	0.71	0.84	0.92	0.97

Table S2. The number of spectra that are identified as vegetation using various threshold values on the USGS spectral library (spectra convolved to ASD standard resolution).

Material	Number	Vegetation (NDVI>0)	Vegetation (NDVI>0.1)	Vegetation (NDVI>0.2)	Vegetation (NDVI>0.3)	Vegetation (NDVI>0.4)
Artificial	277	229	126	77	50	39
Coatings	11	9	3	1	0	0
Liquids	22	6	6	4	1	1
Minerals	885	604	85	26	16	7
Organic	142	74	25	11	7	7
Soils	173	143	22	7	4	1
Vegetation	284	282	277	262	212	161
Recall		0.99	0.98	0.92	0.75	0.57
Precision		0.21	0.51	0.68	0.73	0.75

Table S3. The number of spectra that are identified as vegetation using various threshold values on the USGS spectral library (spectra resampled to Landsat-8 characteristics).

Material	Number	Vegetation (NDVI>0)	Vegetation (NDVI>0.1)	Vegetation (NDVI>0.2)	Vegetation (NDVI>0.3)	Vegetation (NDVI>0.4)
Artificial	278	228	125	77	49	37
Coatings	12	9	3	1	0	0
Liquids	22	6	6	4	1	1
Minerals	886	606	85	26	16	7
Organic	142	72	25	11	7	6
Soils	175	144	22	7	3	1
Vegetation	285	282	277	262	212	159
Recall		0.99	0.97	0.92	0.74	0.56
Precision		0.21	0.51	0.68	0.74	0.75

Table S4. The number of spectra that are identified as vegetation using various threshold values on the USGS spectral library (spectra resampled to Sentinel-2 characteristics).

Material	Number	Vegetation (NDVI>0)	Vegetation (NDVI>0.1)	Vegetation (NDVI>0.2)	Vegetation (NDVI>0.3)	Vegetation (NDVI>0.4)
Artificial	278	225	115	73	47	39
Coatings	11	8	3	1	0	0
Liquids	22	6	6	4	1	1
Minerals	884	596	76	25	11	7
Organic	142	72	22	9	7	7
Soils	175	142	21	5	3	1
Vegetation	285	282	277	258	208	162
Recall		0.99	0.97	0.91	0.73	0.57
Precision		0.21	0.53	0.69	0.75	0.75

Table S5. The number of spectra that are identified as water using various threshold values on the ECOSTRESS spectral library.

Material	Number	Water (NDWI>0)	Water (NDWI>0.1)	Water (NDWI>0.2)	Water (NDWI>0.3)
Manmade	45	9	4	1	1
Mineral	857	243	83	42	31
NPV	52	0	0	0	0
Rock	380	106	11	1	0
Soil	41	0	0	0	0
Vegetation	544	0	0	0	0
Water	6	6	0	0	0
Recall		1.00	0.00	0.00	0.00
Precision		0.02	0.00	0.00	0.00

Table S6. The number of spectra that are identified as water using various threshold values on the USGS spectral library (spectra convolved to ASD standard resolution).

Material	Number	Water (NDWI>0)	Water (NDWI>0.1)	Water (NDWI>0.2)	Water (NDWI>0.3)
Artificial	277	40	9	4	1
Coatings	11	0	0	0	0
Liquids	22	15	11	7	3
Minerals	885	256	100	44	24
Organic	142	58	0	0	0
Soils	173	21	5	1	1
Vegetation	284	2	1	0	0
Recall		0.68	0.50	0.32	0.14
Precision		0.04	0.09	0.13	0.10

Table S7. The number of spectra that are identified as water using various threshold values on the USGS spectral library (spectra resampled to Landsat-8 characteristics).

Material	Number	Water (NDWI>0)	Water (NDWI>0.1)	Water (NDWI>0.2)	Water (NDWI>0.3)
Artificial	278	40	6	2	2
Coatings	12	0	0	0	0
Liquids	22	15	11	7	3
Minerals	886	250	98	43	23
Organic	142	56	0	0	0
Soils	175	21	5	1	1
Vegetation	285	2	1	0	0
Recall		0.68	0.50	0.32	0.14
Precision		0.04	0.09	0.13	0.10

Table S8. The number of spectra that are identified as water using various threshold values on the USGS spectral library (spectra resampled to Sentinel-2 characteristics).

Material	Number	Water (NDWI>0)	Water (NDWI>0.1)	Water (NDWI>0.2)	Water (NDWI>0.3)
Artificial	278	40	9	2	2
Coatings	11	0	0	0	0
Liquids	22	15	11	7	3
Minerals	884	252	98	43	23
Organic	142	57	0	0	0
Soils	175	21	5	1	1
Vegetation	285	2	1	0	0
Recall		0.68	0.50	0.32	0.14
Precision		0.04	0.09	0.13	0.10

Table S9. The number of spectra that are identified as soil using various threshold values on the ECOSTRESS spectral library.

Material	Number	Soil (NDSI>0)	Soil (NDSI>0.1)	Soil (NDSI>0.2)	Soil (NDSI>0.3)
Manmade	45	34	16	9	4
Mineral	857	557	240	160	115
NPV	52	37	30	20	8
Rock	380	252	126	55	25
Soil	41	40	37	16	3
Vegetation	544	5	3	3	1
Water	6	0	0	0	0
Recall		0.98	0.90	0.39	0.07
Precision		0.04	0.08	0.06	0.02

Table S10. The number of spectra that are identified as soil using various threshold values on the USGS spectral library (spectra convolved to ASD standard resolution).

Material	Number	Soil (NDSI>0)	Soil (NDSI>0.1)	Soil (NDSI>0.2)	Soil (NDSI>0.3)
Artificial	277	143	101	44	26
Coatings	11	11	10	8	7
Liquids	22	0	0	0	0
Minerals	885	621	338	222	126
Organic	142	19	5	3	3
Soils	173	119	60	32	18
Vegetation	284	123	62	13	4
Recall		0.69	0.35	0.18	0.10
Precision		0.11	0.10	0.10	0.10

Table S11. The number of spectra that are identified as soil using various threshold values on the USGS spectral library (spectra resampled to Landsat-8 characteristics).

Material	Number	Soil (NDSI>0)	Soil (NDSI>0.1)	Soil (NDSI>0.2)	Soil (NDSI>0.3)
Artificial	278	142	100	44	25
Coatings	12	12	10	8	7
Liquids	22	0	0	0	0
Minerals	886	615	336	215	125
Organic	142	15	5	3	3
Soils	175	118	61	33	19
Vegetation	285	123	61	14	4
Recall		0.67	0.35	0.19	0.11
Precision		0.12	0.11	0.10	0.10

Table S12. The number of spectra that are identified as soil using various threshold values on the USGS spectral library (spectra resampled to Sentinel-2 characteristics).

Material	Number	Soil (NDSI>0)	Soil (NDSI>0.1)	Soil (NDSI>0.2)	Soil (NDSI>0.3)
Artificial	278	142	102	43	26
Coatings	11	11	10	8	7
Liquids	22	0	0	0	0
Minerals	884	617	337	218	125
Organic	142	15	5	3	3
Soils	175	119	61	33	20
Vegetation	285	124	63	13	4
Recall		0.68	0.35	0.19	0.11
Precision		0.12	0.11	0.10	0.11

Table S13. The number of spectra that are identified with more than one NDI on the ECOSTRESS spectral library. The numbers in parenthesis in the first column are the numbers of spectra in the corresponding material group. In the first row, W, S, and V denote water, soil, and vegetation, respectively.

Material	Number	W&S	W&V	S&V	W&S&V
Manmade	45	8	0	3	0
Mineral	857	0	0	0	0
NPV	52	0	0	14	0
Rock	380	47	0	2	0
Soil	41	0	0	7	0
Vegetation	544	0	0	1	0
Water	6	0	0	0	0

Table S14. The number of spectra that are identified with more than one NDI on the USGS spectral library (spectra convolved to ASD standard resolution). The numbers in parenthesis in the first column are the numbers of spectra in the corresponding material group. In the first row, W, S, and V denote water, soil, and vegetation, respectively.

Material	Number	W&S	W&V	S&V	W&S&V
Artificial	277	14	0	12	0
Coatings	11	0	0	0	0
Liquids	22	0	0	0	0
Minerals	885	201	0	9	0
Organic	142	2	0	4	0
Soils	173	14	0	2	0
Vegetation	284	0	0	23	0

Table S15. The number of spectra that are identified with more than one NDI on the USGS spectral library (spectra resampled to Landsat-8 characteristics). The numbers in parenthesis in the first column are the numbers of spectra in the corresponding material group. In the first row, W, S, V and I denotes water, soil, vegetation, and impervious surface, respectively.

Material	Number	W&S	W&V	S&V	W&S&V
Artificial	278	14	0	10	0
Coatings	12	0	0	0	0
Liquids	22	0	0	0	0
Minerals	886	183	0	11	0
Organic	142	0	0	3	0
Soils	175	15	0	2	0
Vegetation	285	0	0	17	0

Table S16. The number of spectra that are identified with more than one NDI on the USGS spectral library (spectra resampled to Sentinel-2 characteristics). The numbers in parenthesis in the first column are the numbers of spectra in the corresponding material group. In the first row, W, S, V and I denotes water, soil, vegetation, and impervious surface, respectively.

Material	Number	W&S	W&V	S&V	W&S&V
Artificial	278	14	0	10	0
Coatings	11	0	0	0	0
Liquids	22	0	0	0	0
Minerals	884	186	0	6	0
Organic	142	1	0	3	0
Soils	175	15	0	2	0
Vegetation	285	0	0	15	0

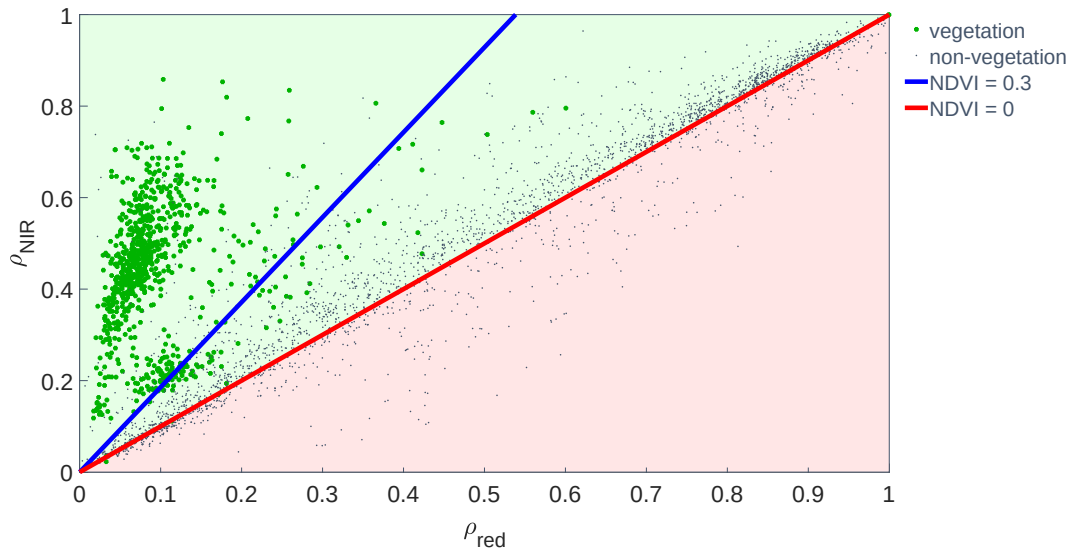


Fig. S1. Scatter plot of all the vegetation and non-vegetation spectra in the USGS and ECOSTRESS spectral libraries.

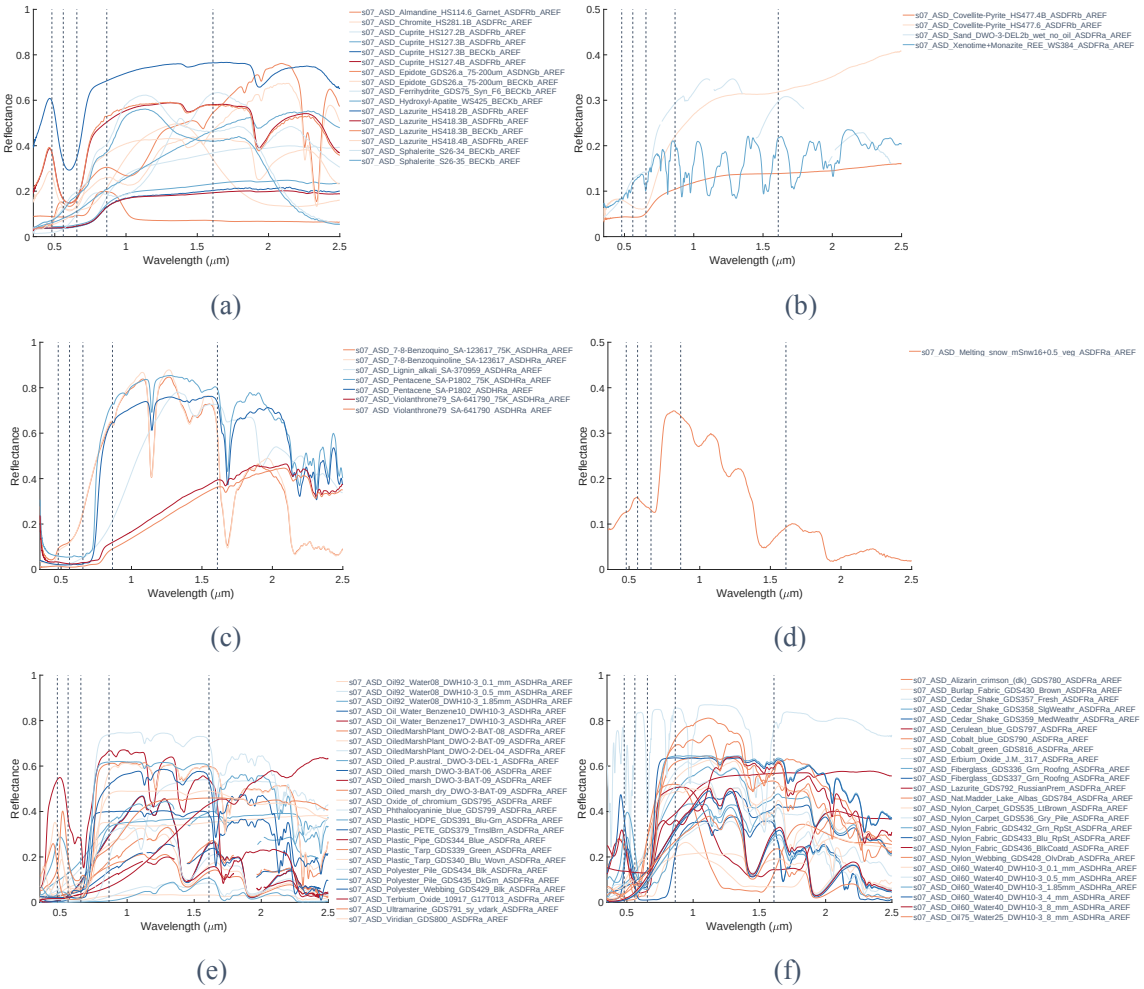


Fig. S2. Non-vegetation spectra in the USGS spectral library that are misidentified as vegetation. (a) Mineral spectra. (b) Soil spectra. (c) Organic. (d) Liquid. (e) Artificial (part 1). (f) Artificial (part 2)

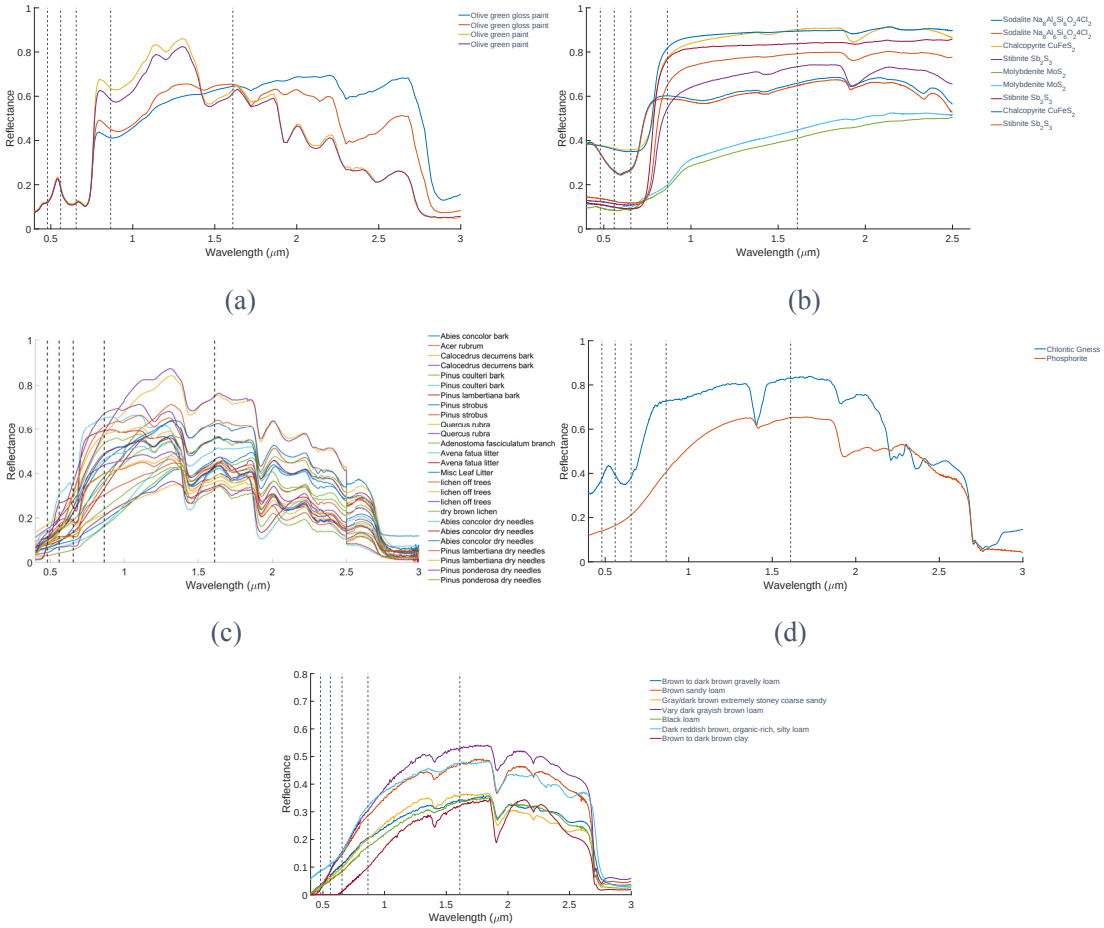


Fig. S3. Non-vegetation spectra in the ECOSTESS spectral library that are misidentified as vegetation. (a) Manmade. (b) Mineral. (c) NPV. (d) Rock. (e) Soil.

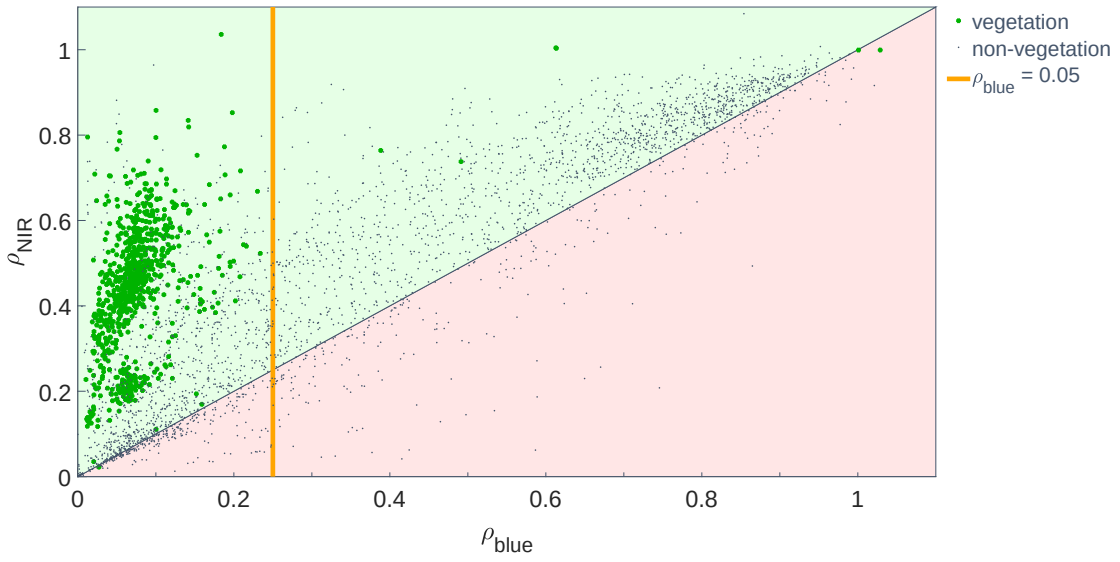


Fig. S4. Scatter plot of all the vegetation and non-vegetation spectra in the USGS and ECOSTRESS spectral libraries in the space spanned by the blue and NIR bands.

.

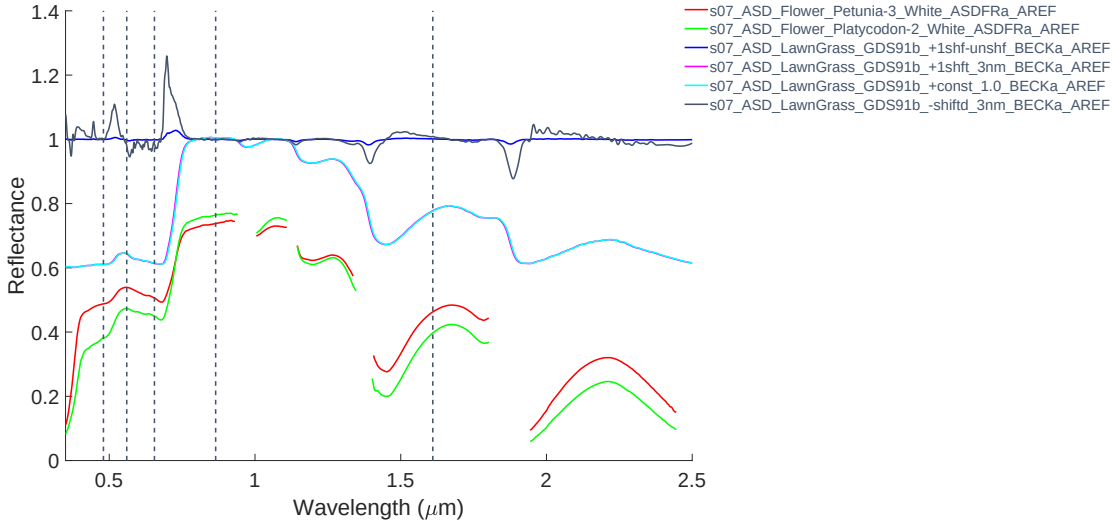


Fig. S5. Vegetation spectra that have reflectance magnitude larger than 0.25 on blue band.

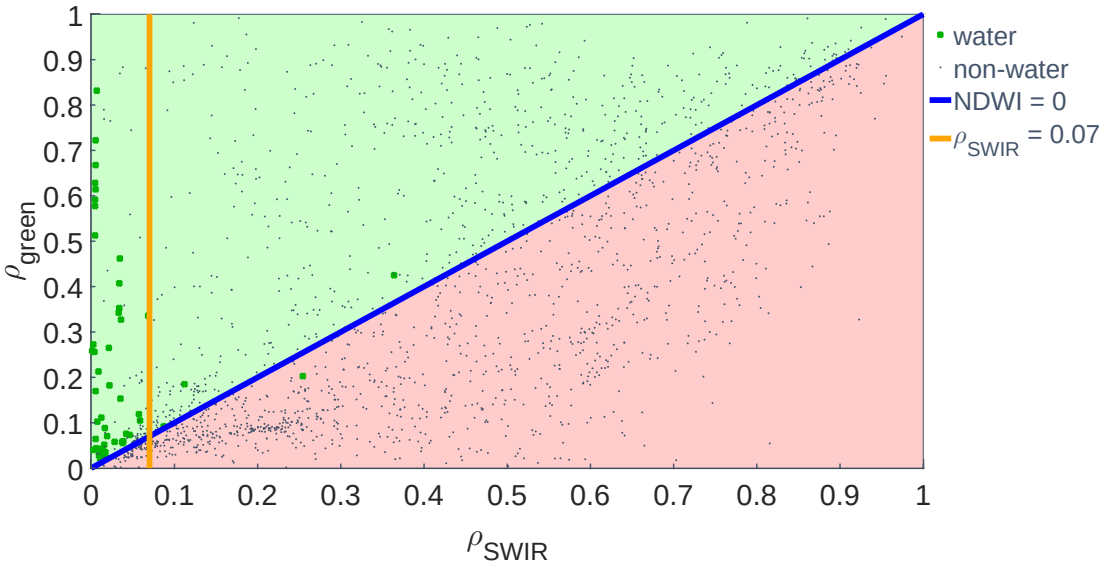


Fig. S6. Scatter plot of all the water and non-water spectra in the USGS spectral library and the collected typical water spectra dataset.

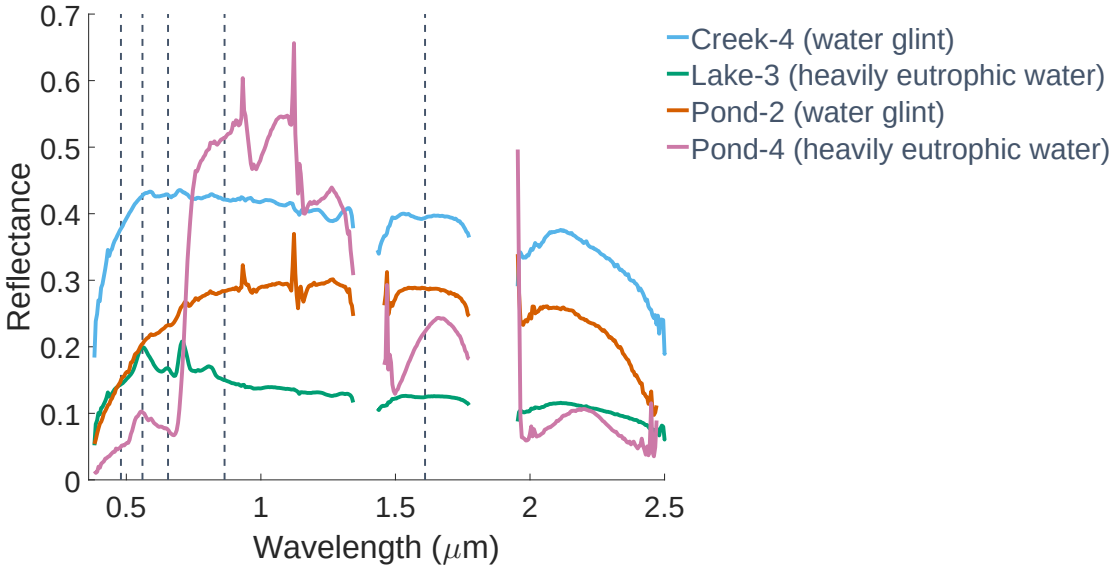


Fig. S7. Water spectra that have reflectance magnitude higher than 0.07 on SWIR band.

2. Results on real images

We validated the NDVI, NDWI and NDSI globally using Sentinel-2 data and Landsat-8 images. Some of the results are presented in the following.

Figure S8(a) shows a Sentinel-2 scene that covers the Beijing area, China. This Sentinel-2 image (level 2A BOA reflectance) was recorded on 2019-05-13. We observed that there are 1409927 pixels in the scene that were both identified by NDVI and NDSI (Figure S8(b)). Although some of them are soils with sparse vegetation cover, many impervious surface materials were also misidentified as both vegetation and soil. Figure S8(c) shows a Landsat-8 image that covers the same area. This image was recorded on 2019-09-18 and was atmospherically corrected to reflectance. There are 43039 pixels in the scene that were both identified by NDVI and NDSI (Figure S8(d)). The results of the zoomed area (marked in red frames) are presented in the paper.

Fig. S9-S16 show some results in other areas globally. Fig. S9, S10, S11, S12, S13, S14, S15, and S16 cover Bogota (Columbia), Sao Paulo (Brazil), Sydney (Australia), Melbourne (Australia), Johannesburg (South Africa), Port Louis (Mauritius), Berlin (German), and Tongliao (China), respectively. Note that in order for a clear demonstration, only zoomed images are shown in Fig. S9-S16.

Fig. S17 shows another image that covers the same area as Fig. 3 in the paper, but with more clouds.

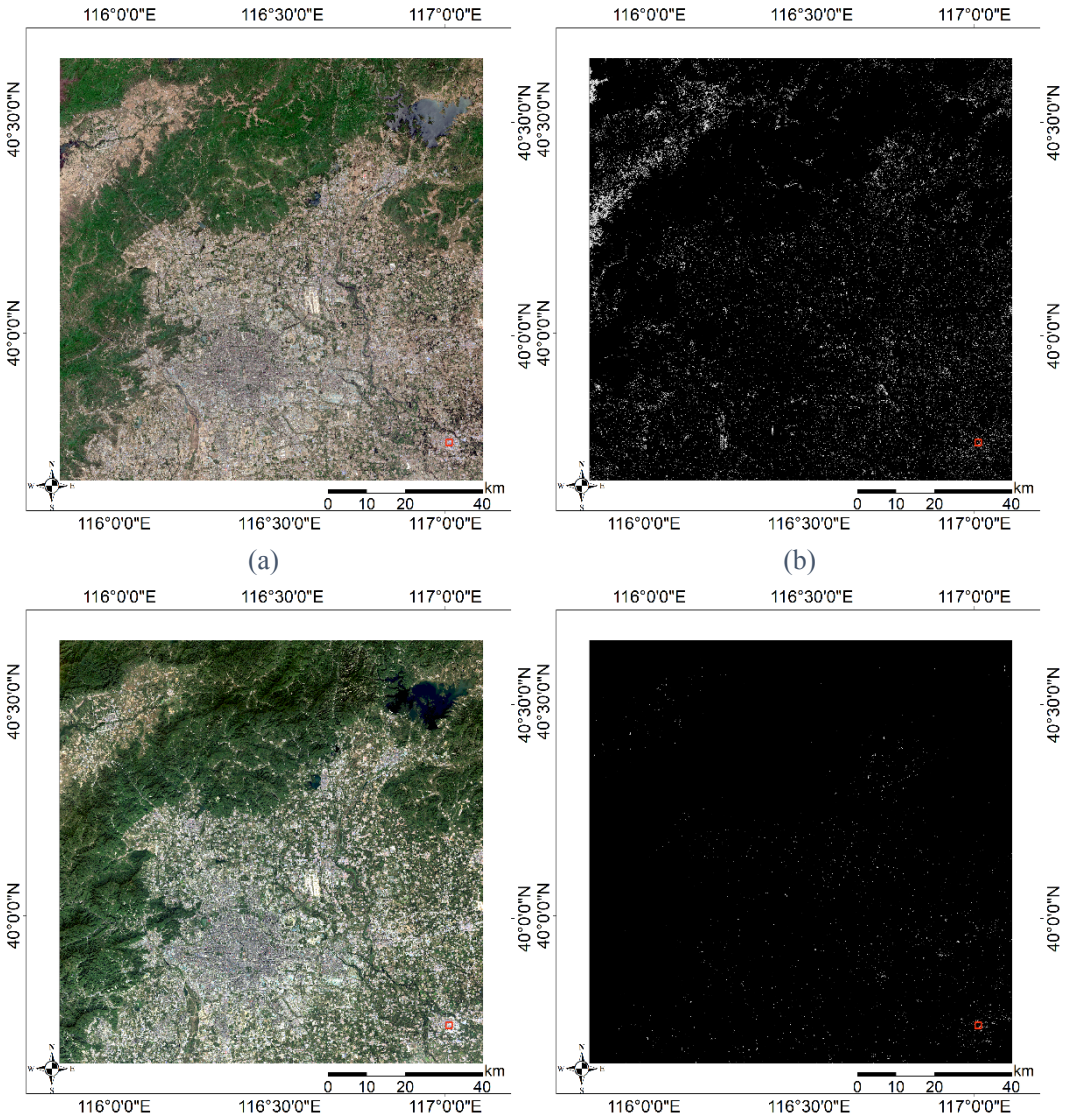
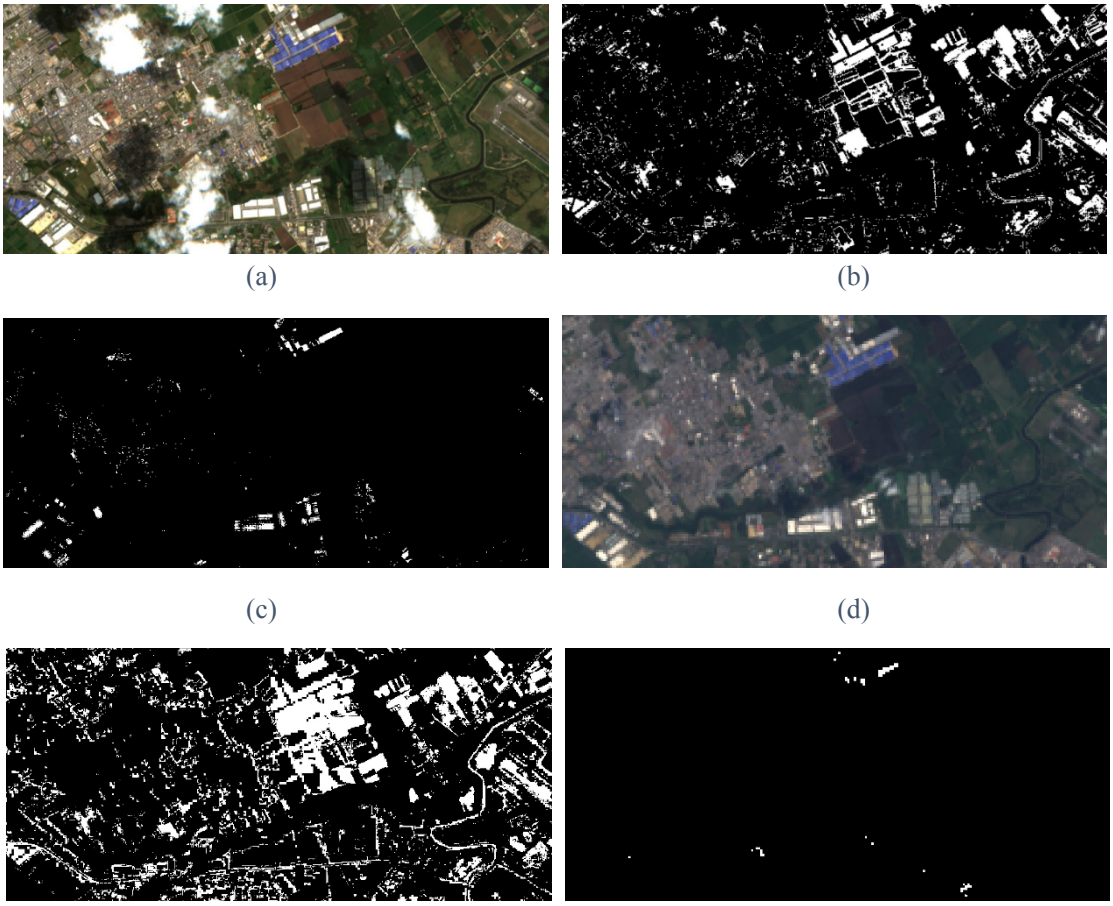


Figure S8. (a) True-color (red–green–blue) composite of Sentinel-2 scene that covers the Beijing area, China. (b) Pixels that were both identified as vegetation and soil in (a). (c) True-color (red–green–blue) composite of Landsat-8 image. (d) Pixels that were both identified as vegetation and soil in (c).

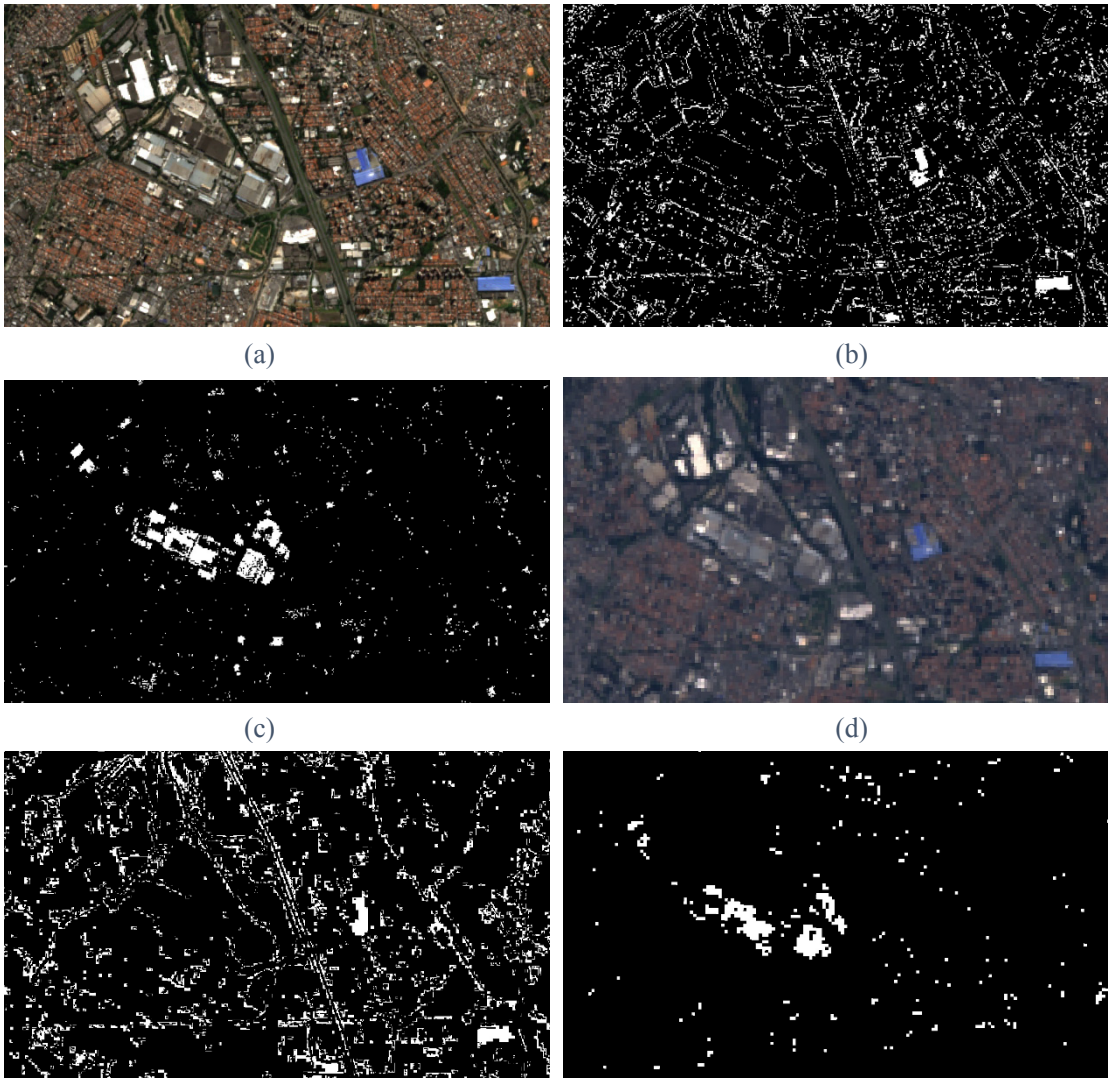


(a) (b)

(c) (d)

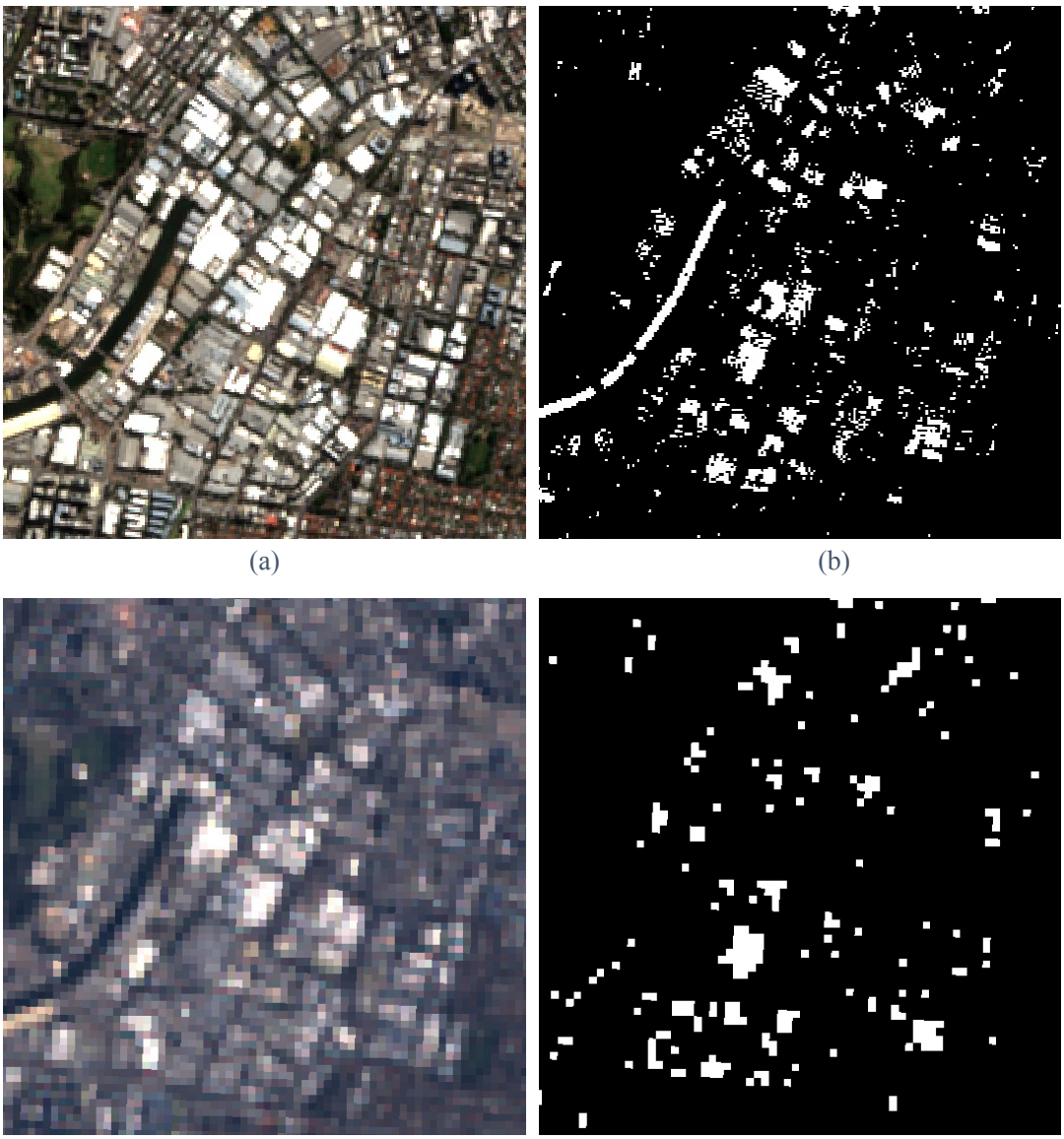
(e) (f)

Figure S9. (a) Sentinel-2 image that covers the Bogota area, Columbia. (b) pixels that were both identified as vegetation and soil in (a). (c) pixels that were both identified as water and soil in (a). (d) Landsat-8 image. (e) pixels that were both identified as vegetation and soil in (d). (f) pixels that were both identified as water and soil in (d).



(a) (b) (c) (d) (e) (f)

Figure S10. (a) Sentinel-2 image that covers Sao Paulo, Brazil. (b) pixels that were both identified as vegetation and soil in (a). (c) shows the pixels that were both identified as water and soil in (a). (d) Landsat-8 image. (e) pixels that were both identified as vegetation and soil in (d). (f) pixels that were both identified as water and soil in (d).



(a) (b)

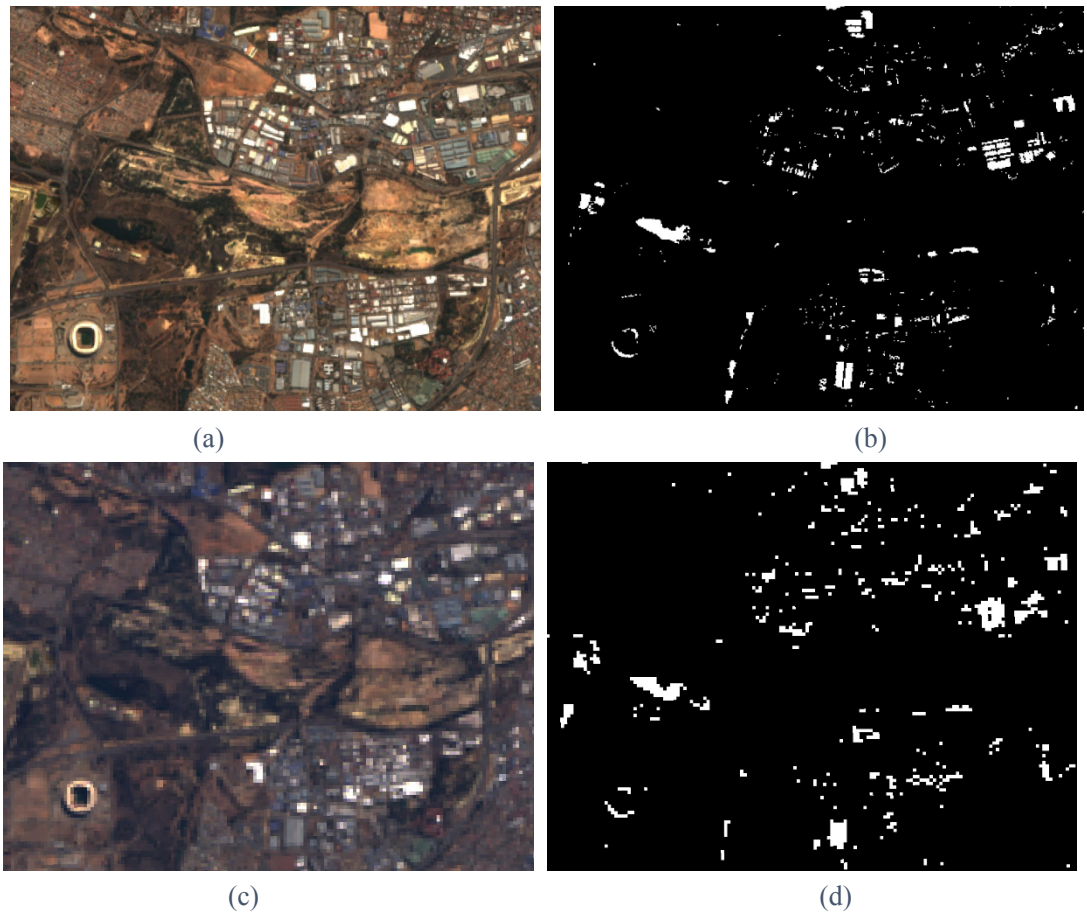
(c) (d)

Figure S11. (a) Sentinel-2 scene that covers Sydney , Australia. (b) pixels that were both identified as water and soil in (a). (c) Landsat-8 image. (d) pixels that were both identified as water and soil in (c).

(a) (b)

(c) (d)

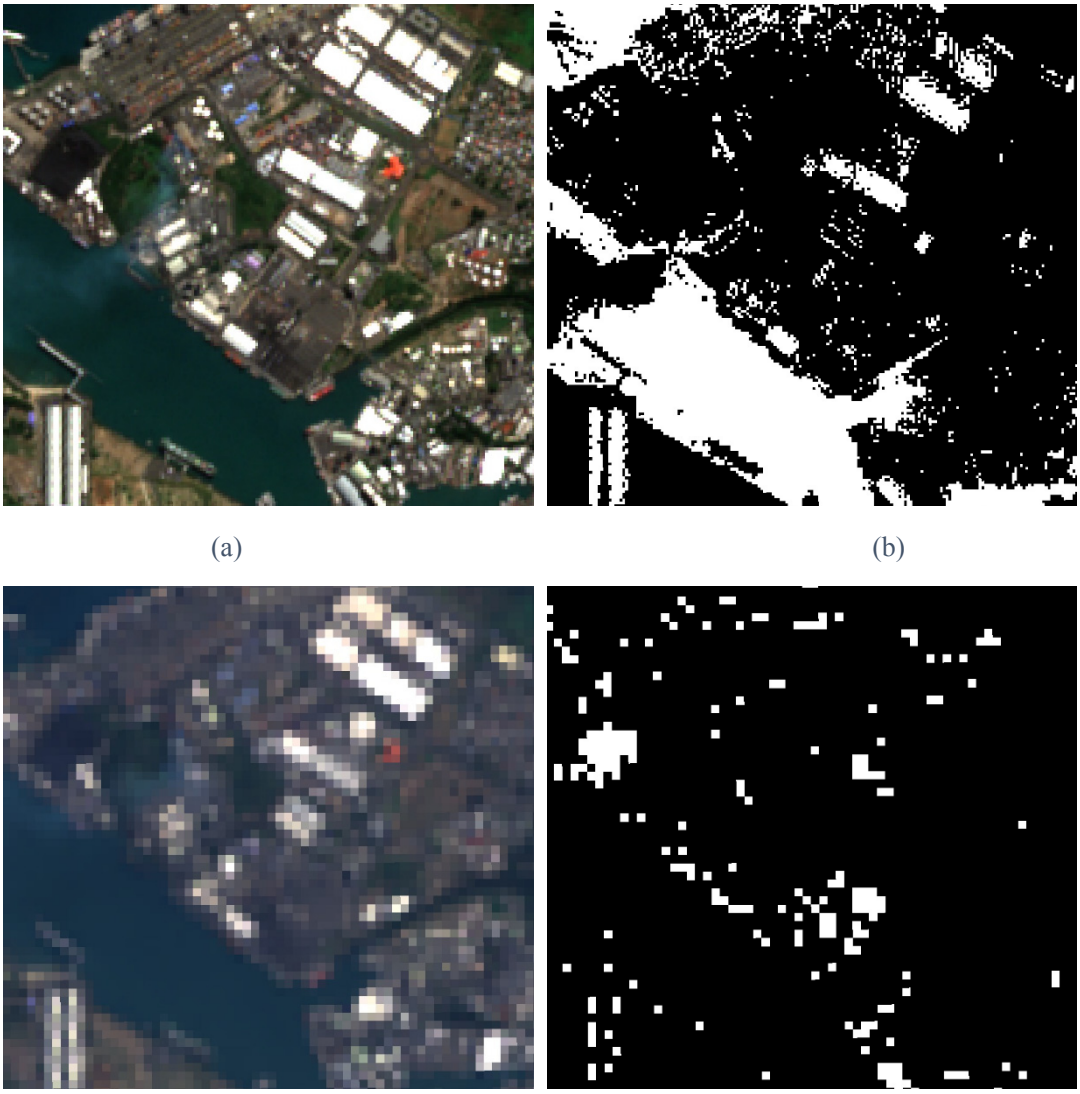
Figure S12. (a) Sentinel-2 scene that covers Melbourne, Australia. (b) pixels that were both identified as water and soil in (a). (c) Landsat-8 image. (d) pixels that were both identified as water and soil in (c).



(a) (b)

(c) (d)

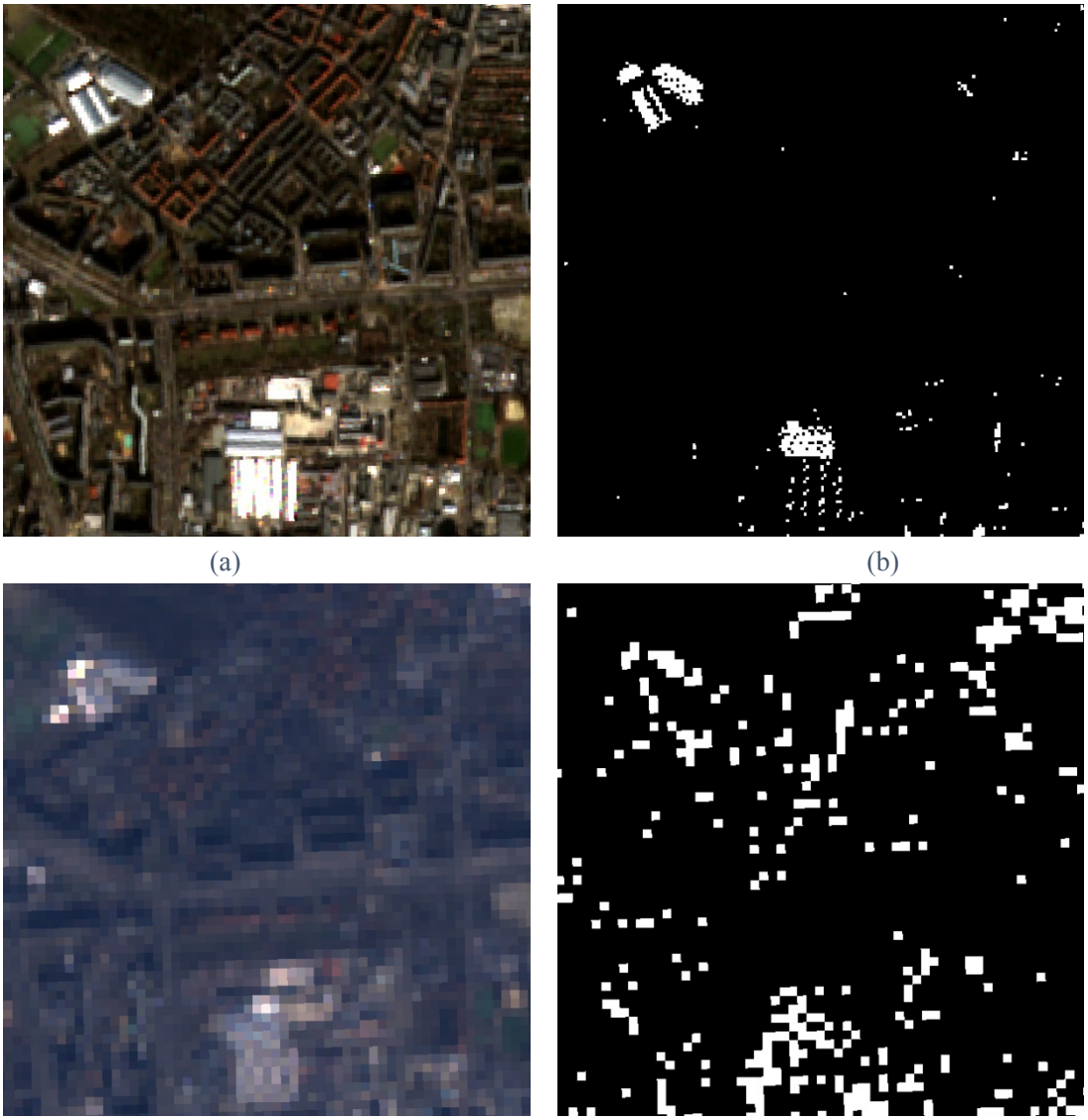
Figure S13. (a) Sentinel-2 image that covers Johannesburg, South Africa. (b) Pixels that were identified as water in (a). (c) Landsat-8 image. (d) Pixels that were identified as water in (c).



(a) (b)

(c) (d)

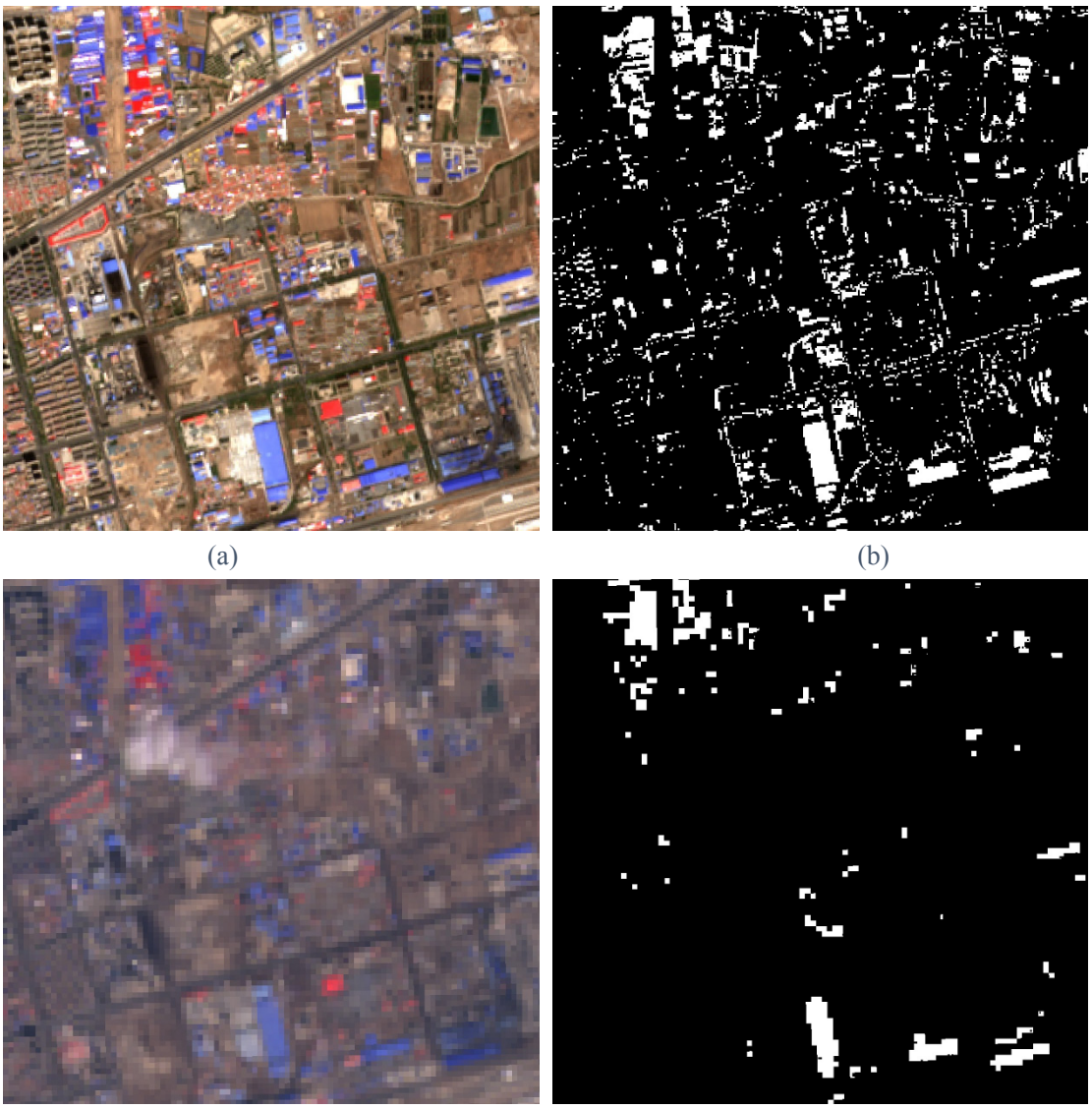
Figure S14. (a) Sentinel-2 scene that covers Port Louis, Mauritius. (b) pixels that were both identified as water and soil in (a). (c) Landsat-8 image. (d) pixels that were both identified as water and soil in (c).



(a) (b)

(c) (d)

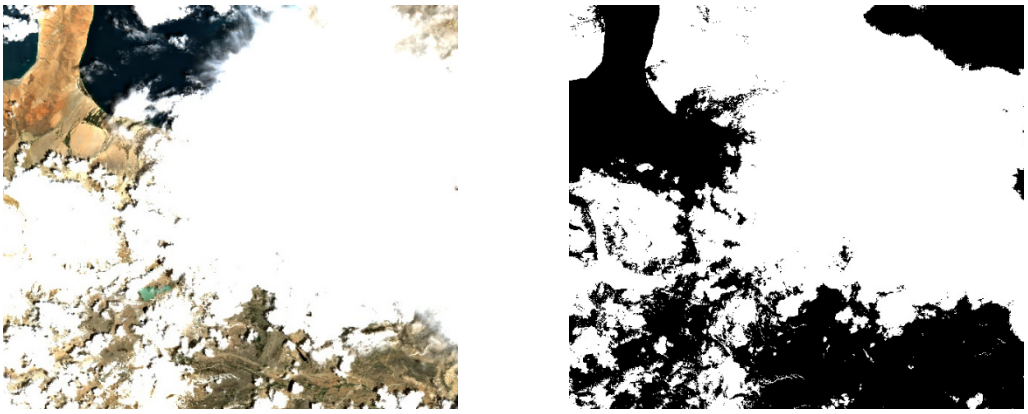
Figure S15. (a) Sentinel-2 scene that covers Berlin, Germany. (b) pixels that were both identified as water and soil in (a). (c) Landsat-8 image. (d) pixels that were both identified as water and soil in (c).



(a) (b)

(c) (d)

Figure S16. (a) Sentinel-2 scene that covers Tongliao, China. (b) pixels that were both identified as vegetation and soil in (a). (c) Landsat-8 image. (d) pixels that were both identified as vegetation and soil in (c).



(a) (b)

Fig. S17. Results of NDWI. (a) Sentinel-2 image. (b) Pixels that were identified as water.

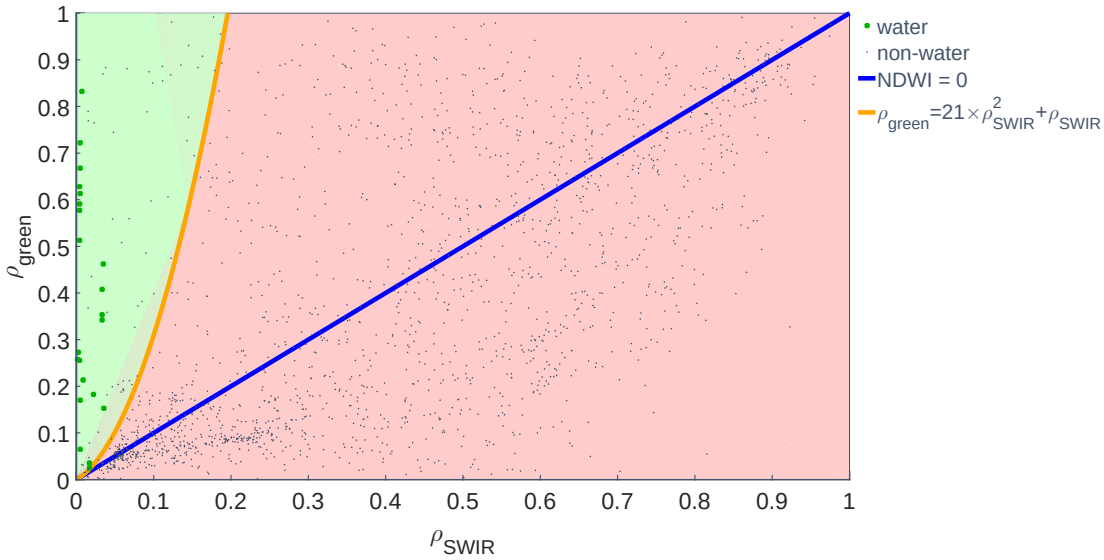


Fig. S18. Non-linear decision boundary for all the water and non-water spectra in the USGS spectral library.

3. Results of the normalized difference snow index

We validated the normalized difference snow index (NDSnI) with the USGS and ECOSTRESS spectral libraries (in order to make a difference with the normalized difference soil index, which is abbreviated above as NDSI, we used NDSnI to denote normalized difference snow index here). The results are presented in Table S17 - S20. Although NDSnI used a large suggested threshold value (0.4) to detect snow, there are still some other materials that are misidentified as snow.

Table S17. The number of spectra that are identified as snow using various threshold values on the ECOSTRESS spectral library.

Material	Number	Snow (NDSnI>0.2)	Snow (NDSnI>0.3)	Snow (NDSnI>0.4)	Snow (NDSnI>0.5)	Snow (NDSnI>0.6)
Manmade	45	0	0	0	0	0
Mineral	857	66	42	23	14	6
NPV	52	0	0	0	0	0
Rock	380	5	0	0	0	0
Soil	41	0	0	0	0	0
Vegetation	544	12	1	1	0	0
Water	6	4	4	4	4	3

Table S18. The number of spectra that are identified as snow using various threshold values on the USGS spectral library (spectra convolved to ASD standard resolution).

Material	Number	Snow (NDSnI>0.2)	Snow (NDSnI>0.3)	Snow (NDSnI>0.4)	Snow (NDSnI>0.5)	Snow (NDSnI>0.6)
Artificial	277	14	8	4	4	4
Coatings	11	0	0	0	0	0
Liquids	22	21	20	19	19	16
Minerals	885	45	19	11	8	5
Organic	142	33	15	8	4	4
Soils	173	2	0	0	0	0
Vegetation	284	3	3	3	0	0

Table S19. The number of spectra that are identified as snow using various threshold values on the USGS spectral library (spectra resampled to Landsat-8 characteristics).

Material	Number	Snow (NDSnI>0.2)	Snow (NDSnI>0.3)	Snow (NDSnI>0.4)	Snow (NDSnI>0.5)	Snow (NDSnI>0.6)
Artificial	278	15	8	4	4	4
Coatings	12	0	0	0	0	0
Liquids	22	21	20	19	19	16
Minerals	886	44	19	11	8	5
Organic	142	35	15	8	4	4
Soils	175	2	0	0	0	0
Vegetation	285	3	3	3	0	0

Table S20. The number of spectra that are identified as snow using various threshold values on the USGS spectral library (spectra resampled to Sentinel-2 characteristics).

Material	Number	Snow (NDSnI>0.2)	Snow (NDSnI>0.3)	Snow (NDSnI>0.4)	Snow (NDSnI>0.5)	Snow (NDSnI>0.6)
Artificial	278	16	7	4	4	4
Coatings	11	0	0	0	0	0
Liquids	22	21	20	19	19	16
Minerals	884	44	19	11	8	5
Organic	142	38	17	10	4	4
Soils	175	2	0	0	0	0
Vegetation	285	3	3	3	0	0

4. Results of VIBI for build-up

We validated the vegetation index built-up index (VIBI) with the USGS and ECOSTRESS spectral libraries. The results are presented in Table S21 –S24. Although built-up is a general term and it could be composed by various materials, in the USGS and ECOSTRESS spectral libraries, there are some natural material spectra, such as vegetation, NPV, liquid, and soil, which are certainly not in the built-up category, but that were misidentified as built-up nonetheless. This demonstrates that the risk of commission error of VIBI is high.

Table S21. The number of spectra that are identified as build-up using various threshold values on the ECOSTRESS spectral library.

Material	Number	Build-up (VIBI>-0.2)	Build-up (VIBI>-0.1)	Build-up (VIBI>0)	Build-up (VIBI>0.1)	Build-up (VIBI>0.2)
Manmade	45	10	11	14	20	22
Mineral	857	197	251	382	499	534
NPV	52	9	9	9	9	9
Rock	380	60	77	104	151	199
Soil	41	0	0	1	1	1
Vegetation	544	189	189	189	189	189
Water	6	0	0	1	5	6

Table S22. The number of spectra that are identified as build-up using various threshold values on the USGS spectral library (spectra convolved to ASD standard resolution).

Material	Number	Build-up (VIBI>-0.2)	Build-up (VIBI>-0.1)	Build-up (VIBI>0)	Build-up (VIBI>0.1)	Build-up (VIBI>0.2)
Artificial	277	39	49	60	75	86
Coatings	11	2	2	3	5	7
Liquids	22	6	6	6	12	17
Minerals	885	219	264	330	414	489
Organic	142	18	21	46	78	89
Soils	173	43	48	56	65	76
Vegetation	284	9	9	10	12	13

Table S23. The number of spectra that are identified as build-up using various threshold values on the USGS spectral library (spectra resampled to Landsat-8 characteristics).

Material	Number	Build-up (VIBI>-0.2)	Build-up (VIBI>-0.1)	Build-up (VIBI>0)	Build-up (VIBI>0.1)	Build-up (VIBI>0.2)
Artificial	278	38	45	58	75	87
Coatings	12	2	2	3	5	8
Liquids	22	6	6	6	12	17
Minerals	886	220	263	336	416	493
Organic	142	24	28	49	88	107
Soils	175	43	48	56	66	77
Vegetation	285	10	10	11	13	13

Table S24. The number of spectra that are identified as build-up using various threshold values on the USGS spectral library (spectra resampled to Sentinel-2 characteristics).

Material	Number	Build-up (VIBI>-0.2)	Build-up (VIBI>-0.1)	Build-up (VIBI>0)	Build-up (VIBI>0.1)	Build-up (VIBI>0.2)
Artificial	278	40	49	61	76	92
Coatings	11	2	3	3	6	7
Liquids	22	6	6	6	12	17
Minerals	884	219	255	331	416	497
Organic	142	24	26	48	92	110
Soils	175	43	47	58	66	78
Vegetation	285	9	9	10	13	13