Supplementary Material for

Developing a phenology- and pixel-based algorithm for mapping rapeseed at 10-m spatial resolution using multi-source data

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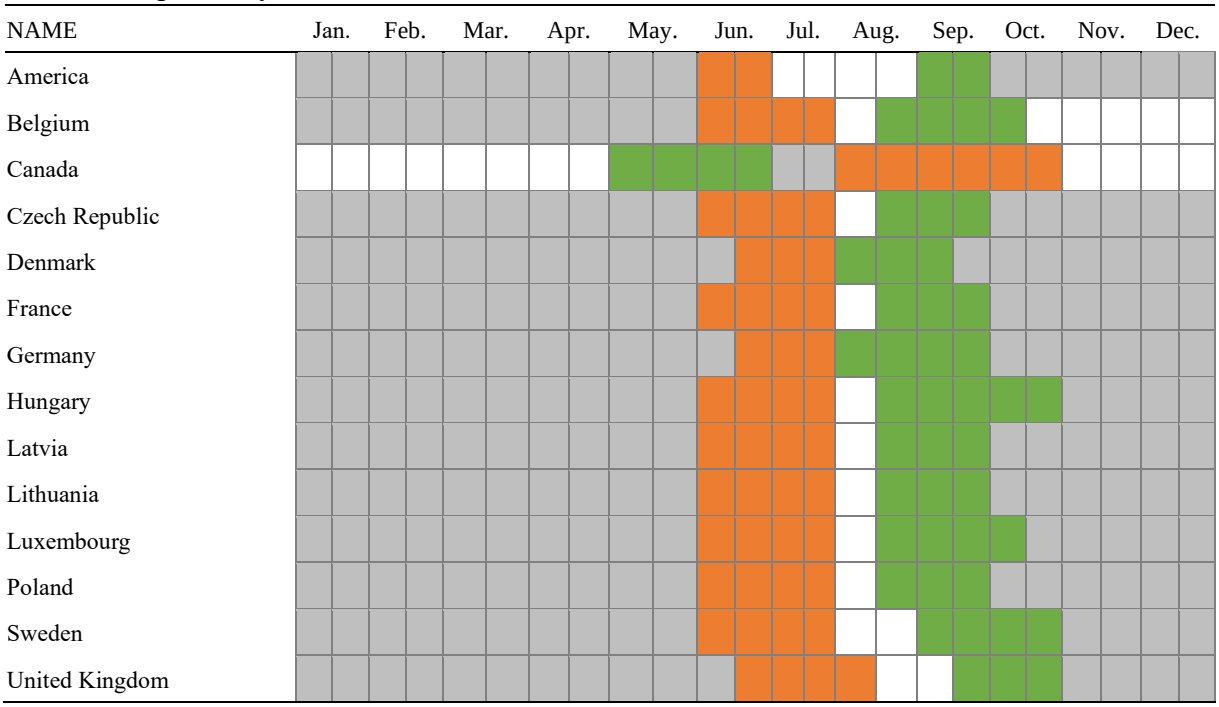
Table S1 Rapeseed planting and harvest times in different countries according to the United States Department of Agriculture. Green, gray, and yellow represent Planting, Mid-Season, Harvest, respectively.



15 Table S2 Confusion matrix table in this study

		Class	
		Non	Rapeseed
Reference	Non	X_{11}	X_{12}
	Rapeseed	X_{21}	X_{22}

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Table S3 Thresholds of different indicators in different regions

Country	Red	Green	VH	NDYI	NRGBI	Connected domain
North America	0.07	0.11	-11	0.05	-0.05	40
Republic of Chile	0.07	0.11	-12	0.05	-0.05	20
Europe	0.07	0.11	-12	0.05	-0.05	20

Table S4 Confusion matrix of rapeseed validation based on the random sampling points. Map categories are columns while reference categories are rows.

Methods	Class	Rapeseed	Non	Total	UA	PA	F1
North America	Rapeseed	1820	469	2289	0.89	0.80	0.84
	Non	235	2017	2252			
	Total	2055	2486				
Chile	Rapeseed	72	9	81	0.91	0.89	0.90
	Non	7	78	85			
	Total	79	87				
Europe	Rapeseed	5721	730	6541	0.95	0.88	0.91
	Non	302	6267	6569			
	Total	6023	6997				

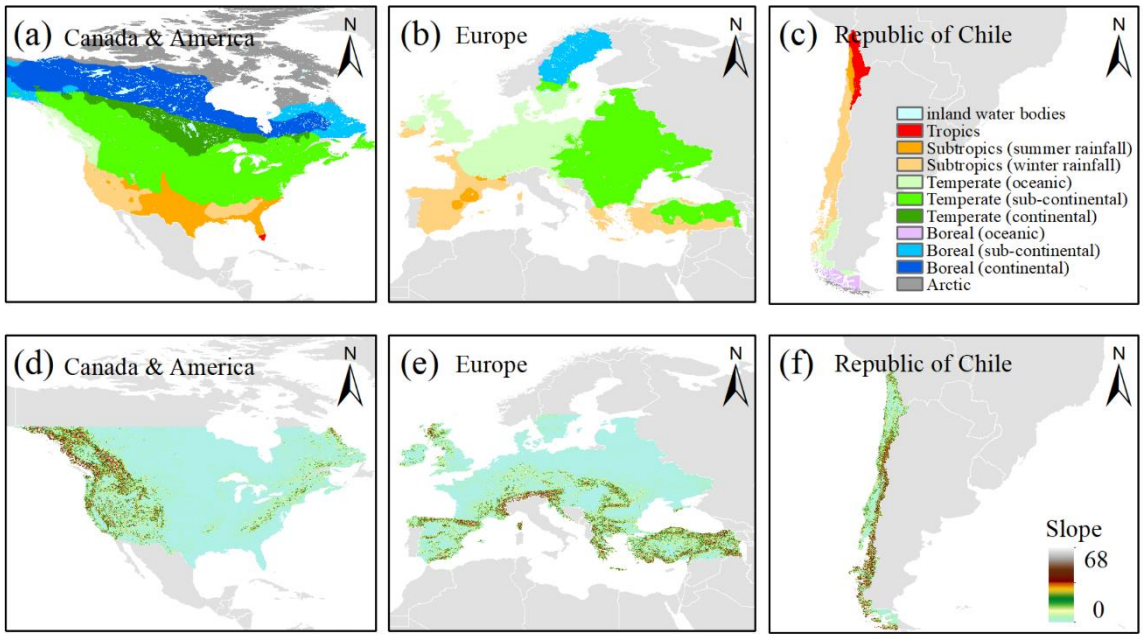


Figure S1. Spatial distribution of the climate zone (a-c) and slope (d-f) in the study area. The climate zone data is from the Food Insecurity, Poverty and Environment Global GIS Database (FGGD).

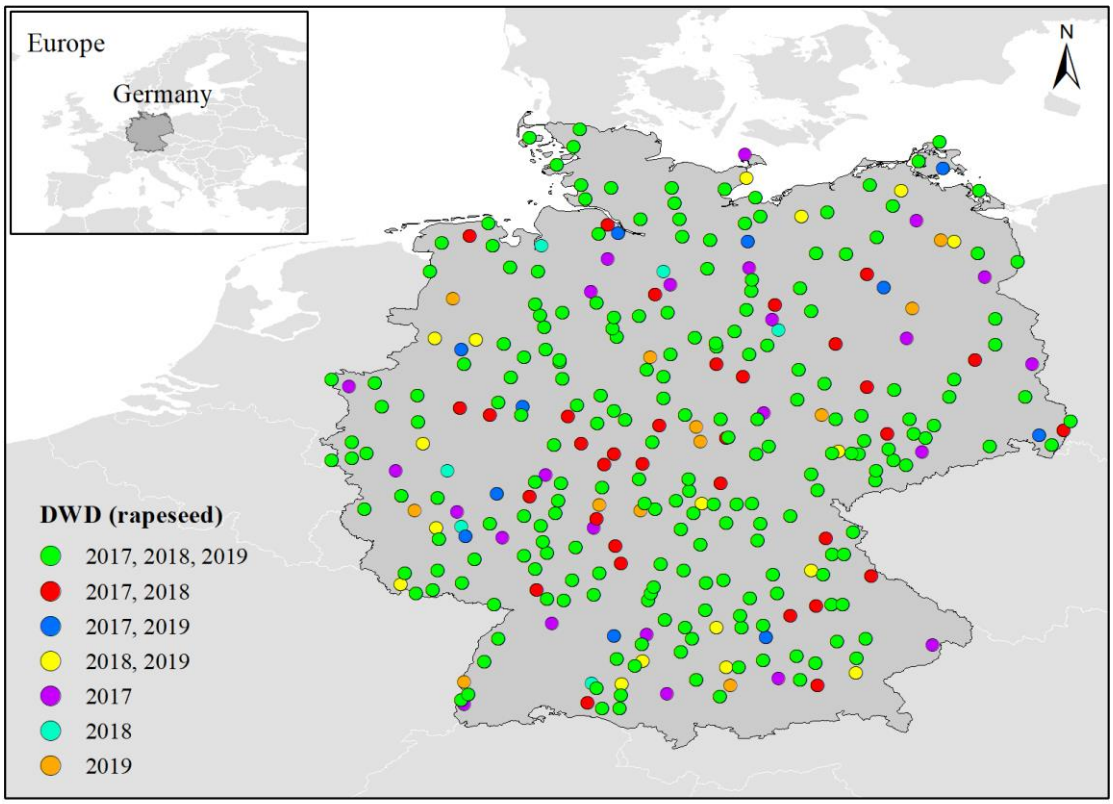


Figure S2. Locations of rapeseed phenological observation stations (DWD) and their time series. 281, 269, and 253 stations available in 2017, 2018, and 2019, respectively.

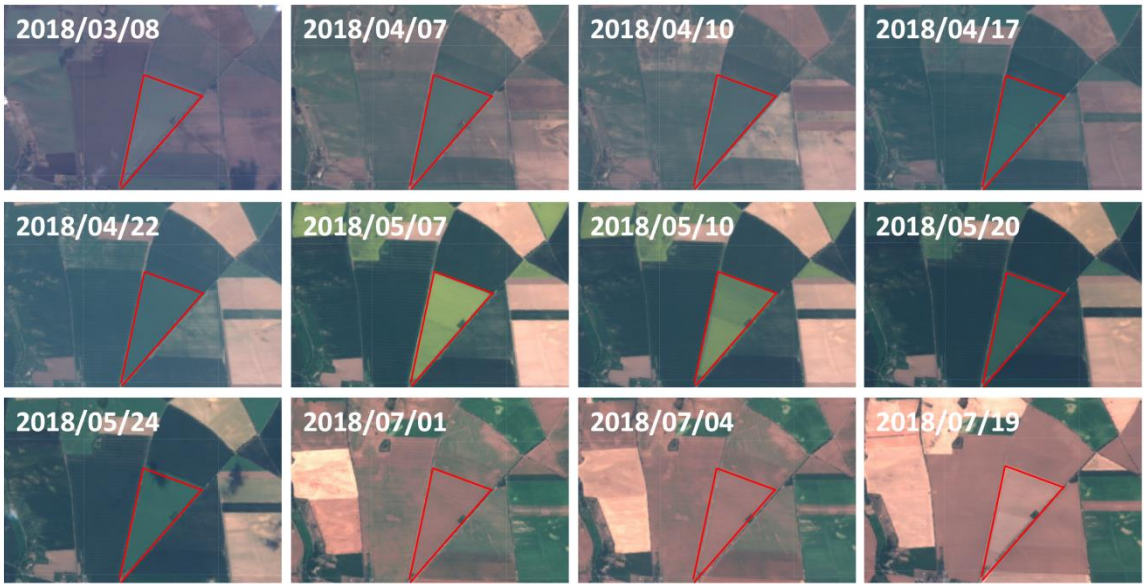


Figure S3. Sentinel-2 true-color images of rapeseed with different growth dates in typical planting areas. One rapeseed parcel around the DWD station with an id = 13126 in 2018 (Latitude: 52.22020729593276°, longitude: 11.346927901697747°). The parcel with red boundaries is rapeseed (image source: Copernicus Sentinel-2 data 2018).

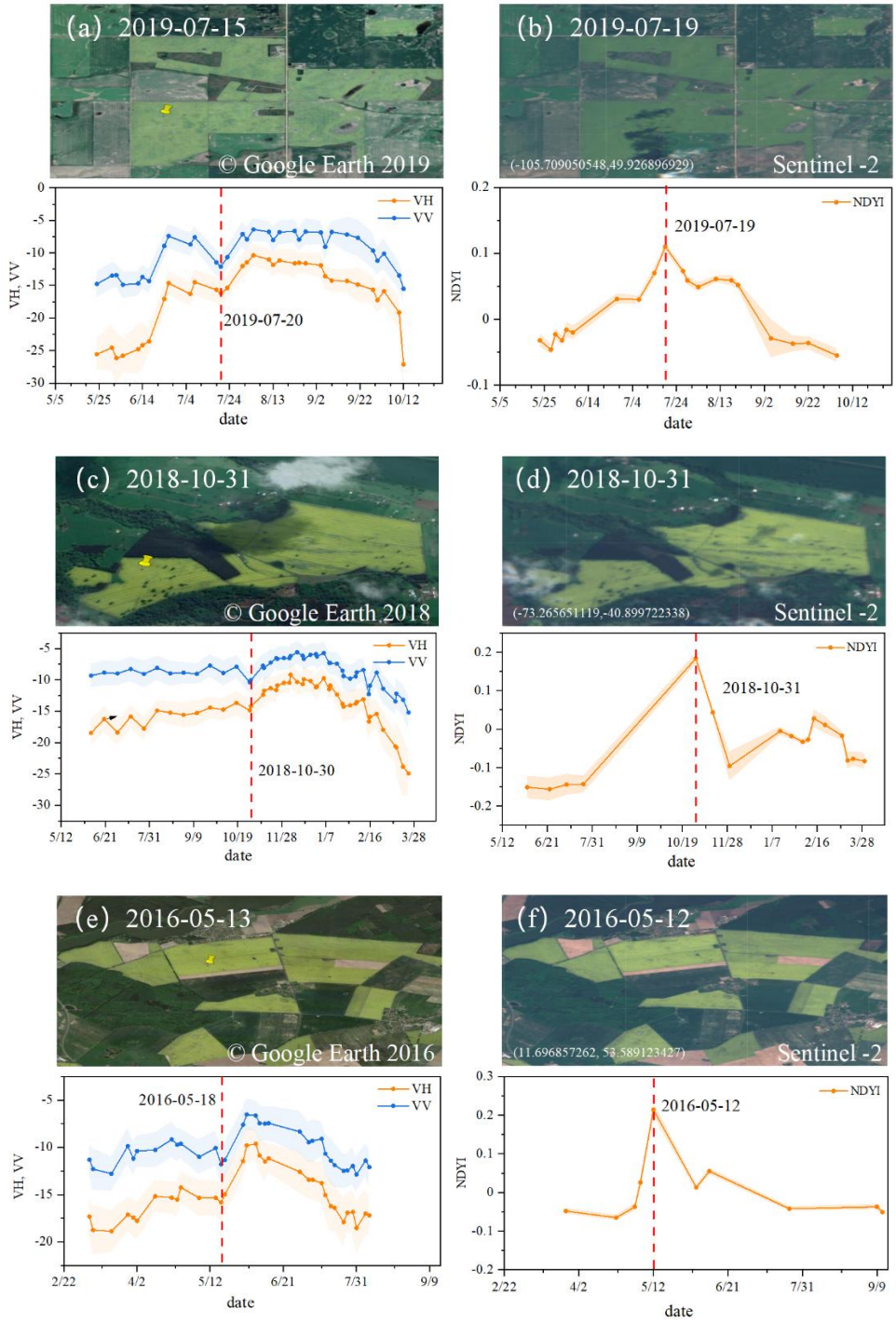


Figure S4. Sentinel-2 and Google Earth images at the flowering stage of rapeseed for visual comparison. The temporal profile of the spectral index (NDYI) and backscattering coefficient (VV, VH). The filled color areas with one positive/negative standard deviation were illustrated. We selected the rapeseed parcels in different climate types and years (a) Canada, (c) Chile, (e) Germany. For selecting the suitable images, we chose the Google Earth images according to the dates as close as possible to those of the Sentinel-2 images (images: Copernicus Sentinel-2 data).

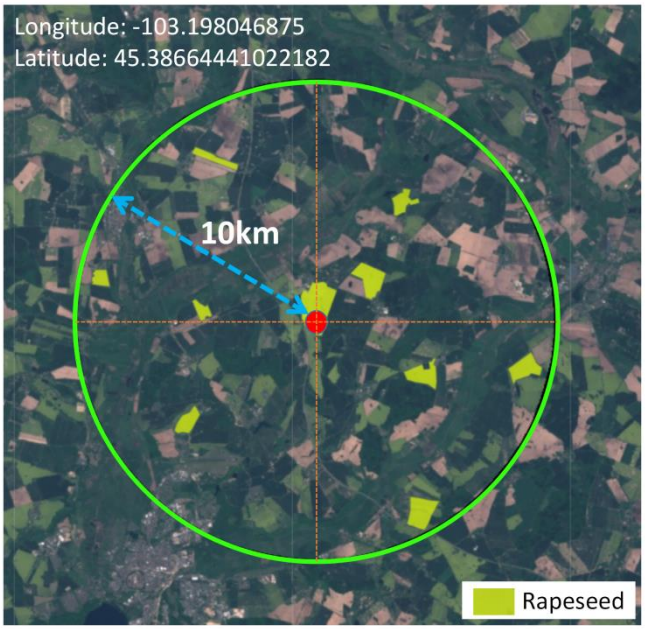


Figure S5. An example block collection for phenological monitoring. Visual interpretation of rapeseed parcels using Sentinel-2 images. The RGB images composite using bands from the red, green, and blue bands (image source: Copernicus Sentinel-2 data).

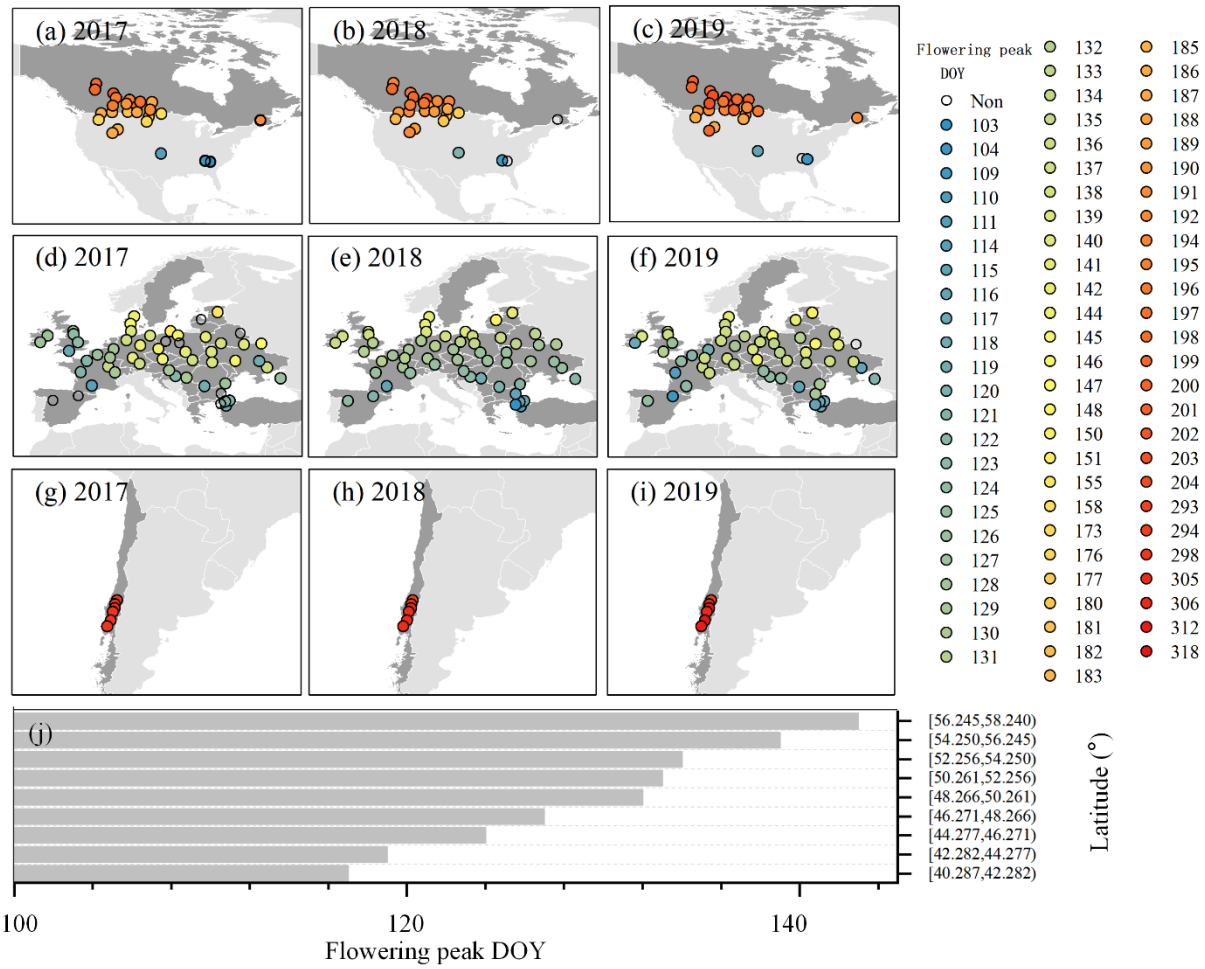


Figure S6. (a-i) Spatial distribution of flowering dates (Julian day) was monitored by different sample blocks in 2017, 2018, and 2019. (j) The latitude gradient characteristics in Europe (the date were calculated by the mean of the flowering date of all sample blocks in different latitudes intervals).

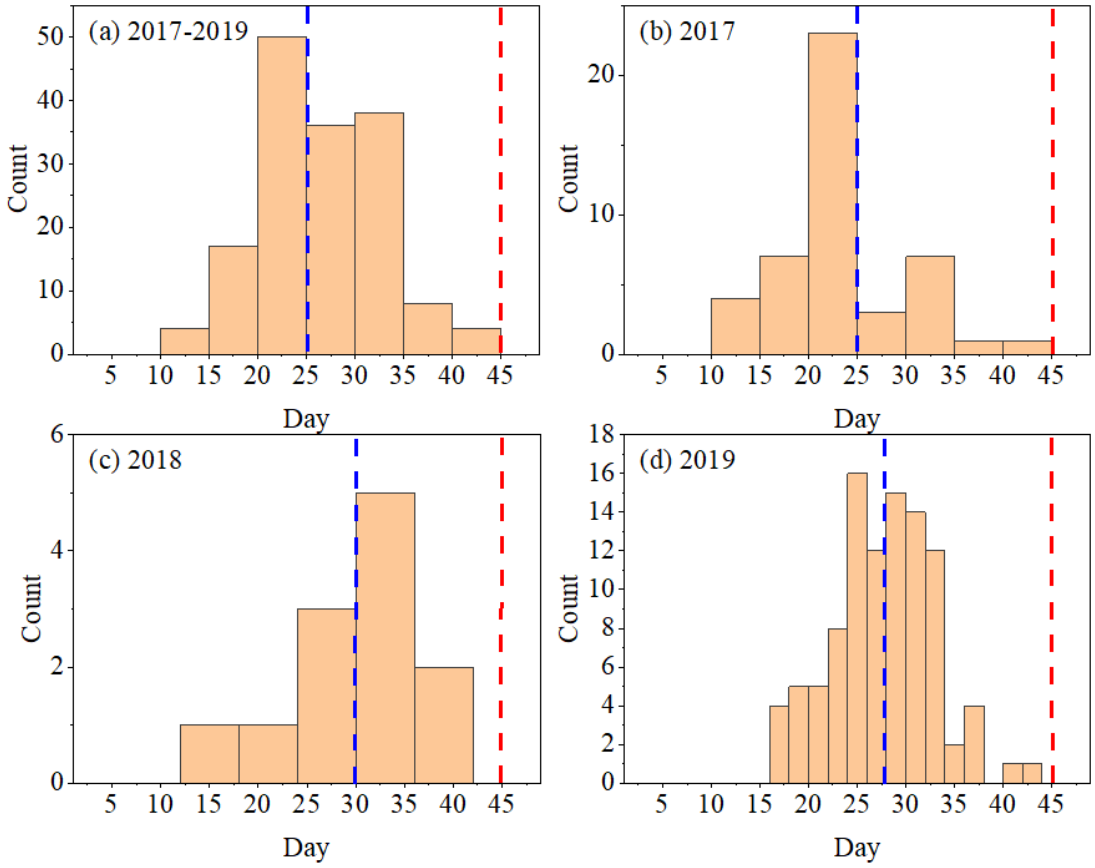


Figure S7. Histogram of the time interval between the date of the VH maximum value and the peak flowering date (the date of the local VH minimum value) of all sample blocks in different years: (a) 2017-2019, (b) 2017, (c) 2018, (d) 2019. The blue and red dotted lines are the median of days and 45 days, respectively.

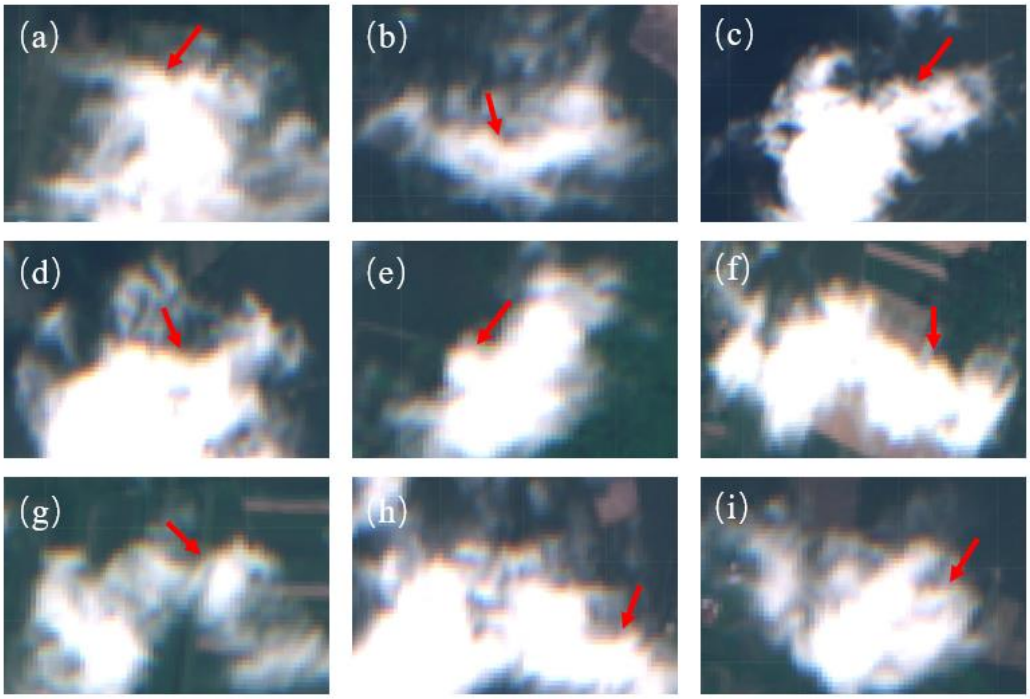


Figure S8. Examples of spectral misregistration effects and performance of cloud masking methods (quality assurance band (QA60)) for Sentinel-2 TOA images. The red arrow refers to the "rainbow" appearance of the cloud in the Sentinel-2 image. The RGB images composite using bands from the red, green, and blue bands (image source: Copernicus Sentinel-2 data).

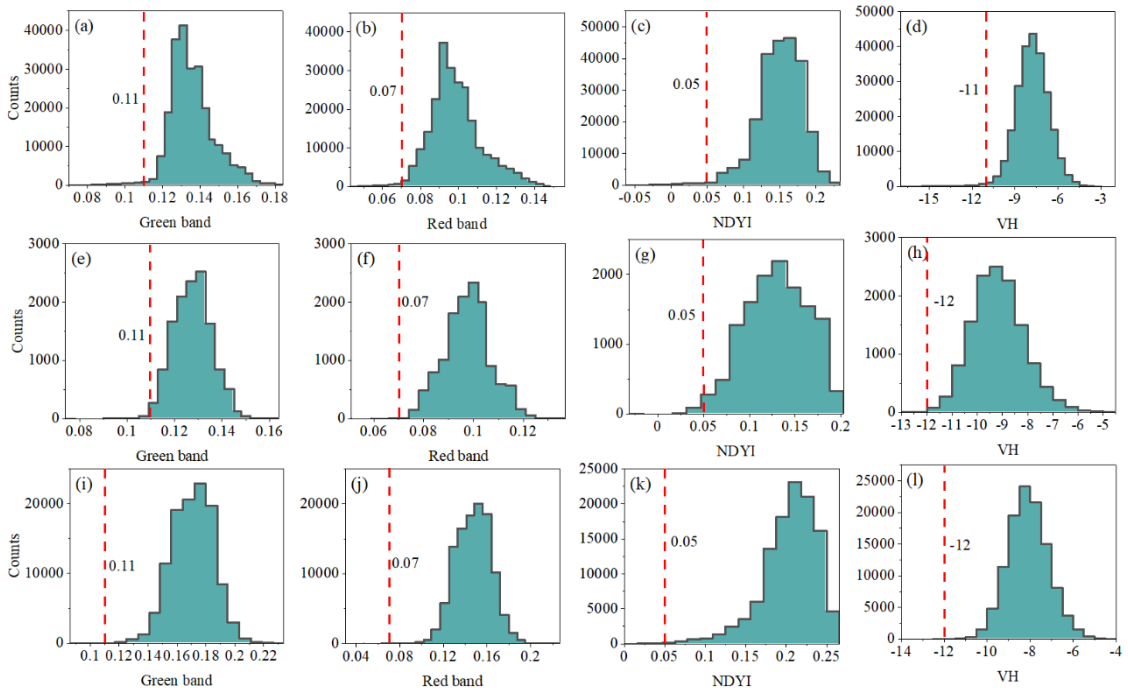


Figure S9. The histogram of green band, red band, NDYI, and VH based on sample rapeseed parcels in different regions: (a-d) North America, (e-h) Chile, (i-l) Europe. The red dashed line indicates the threshold of the corresponding indicator.

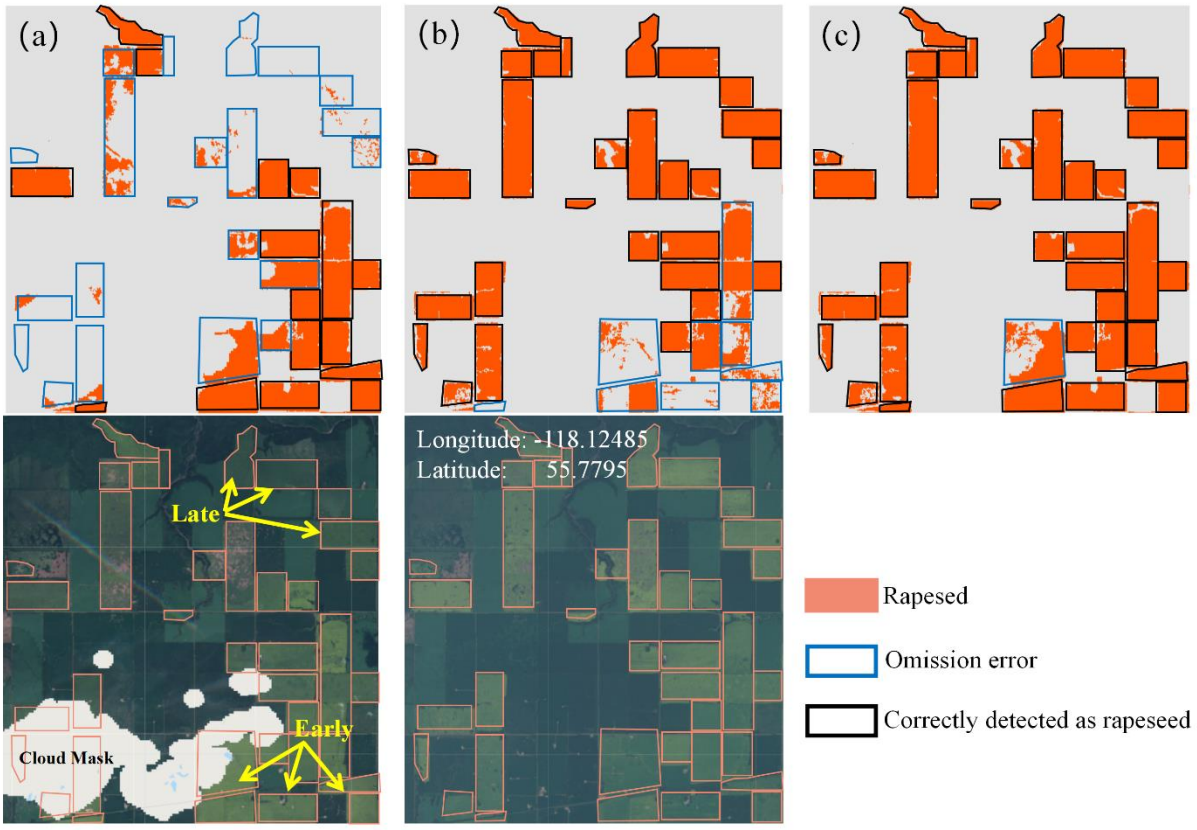


Figure S10. Rapeseed identification results based on pixel-based algorithm in different dates. (c) is the union of (a) and (b). We found that the cumulative the aggregate-based approach can reduce the misclassification from the effects of phenology and bad-quality observations (image source: Copernicus Sentinel-2 data 2018).

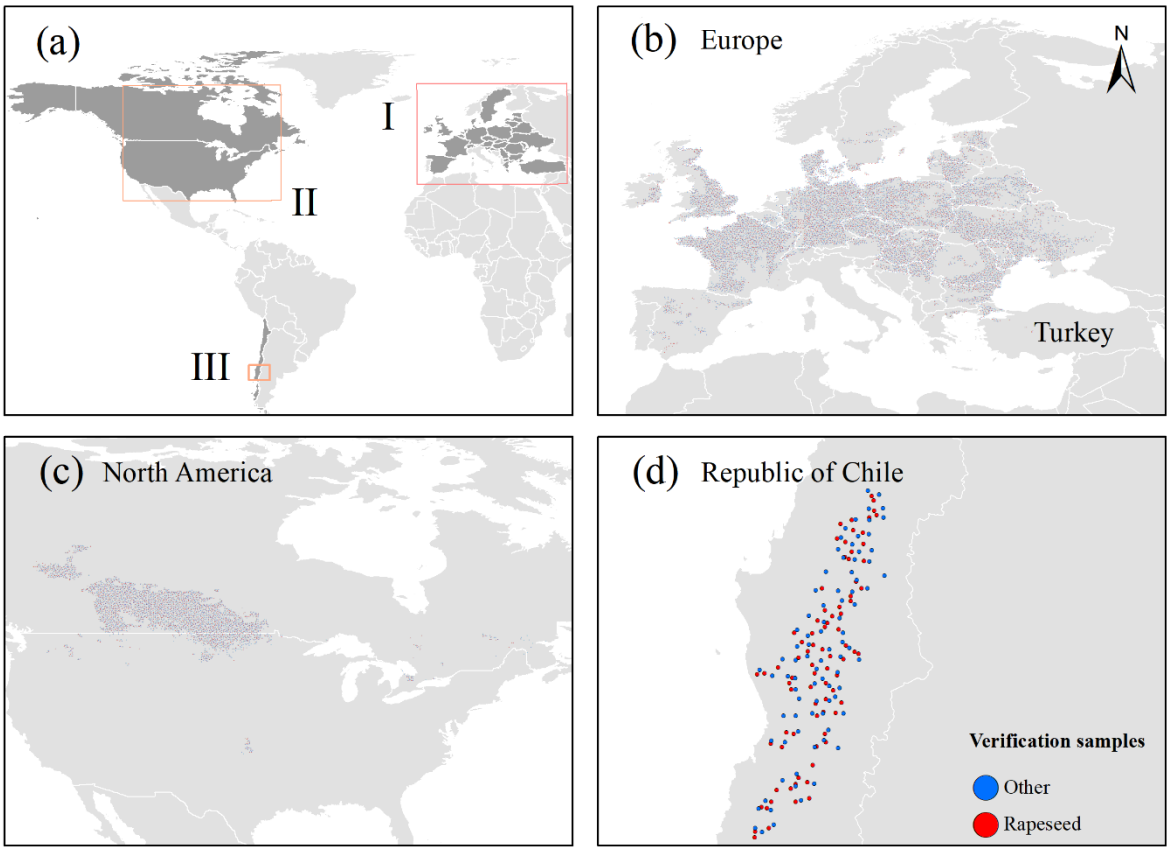


Figure S11. Geographic distribution of validation sample points at 0.2° ×0.2° grids

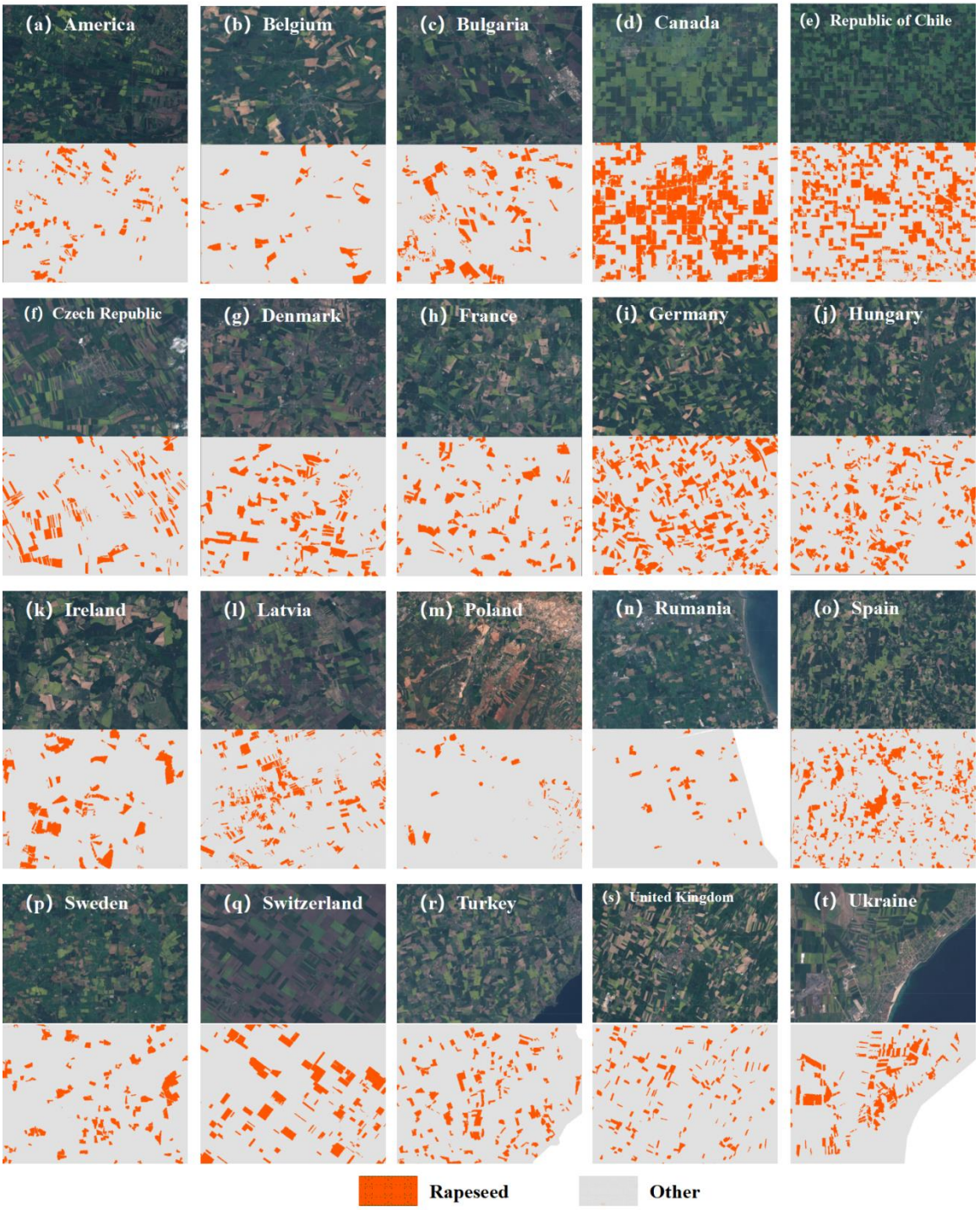


Figure S12. Spatially details of rapeseed maps in 20 countries with diverse crop structures in 2018. The base maps were RGB images composite using bands from the red, green, and blue bands of the Sentinel-2 images with good-quality observations in the flowering period of rapeseed (image source: Copernicus Sentinel-2 data).

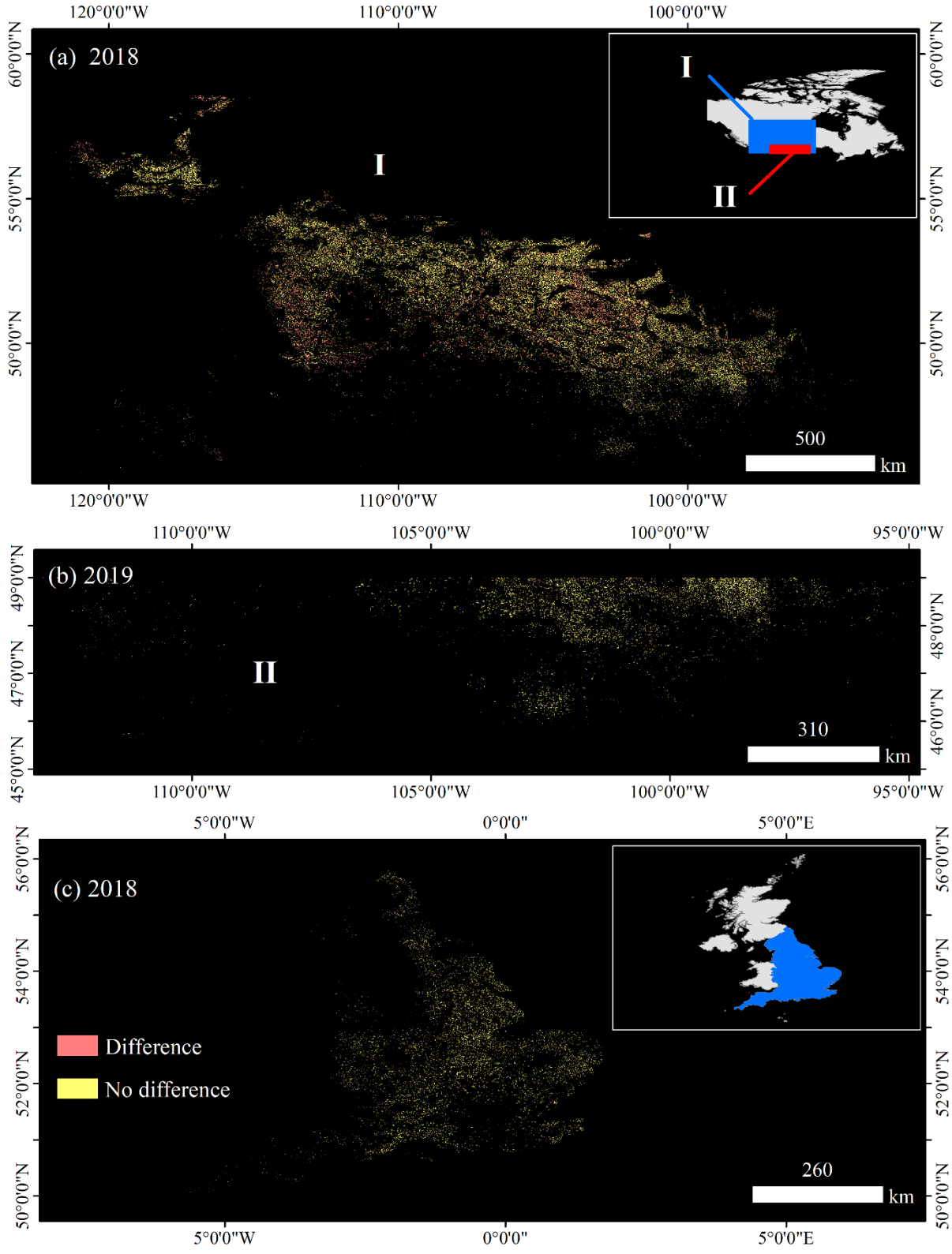


Figure S13. Spatial comparison between rapeseed classifications obtained by our pixel- and phenology-based method and other crop products in Canada (ACI, 2018), America (CDL, 2019), and England (CROME, 2018).

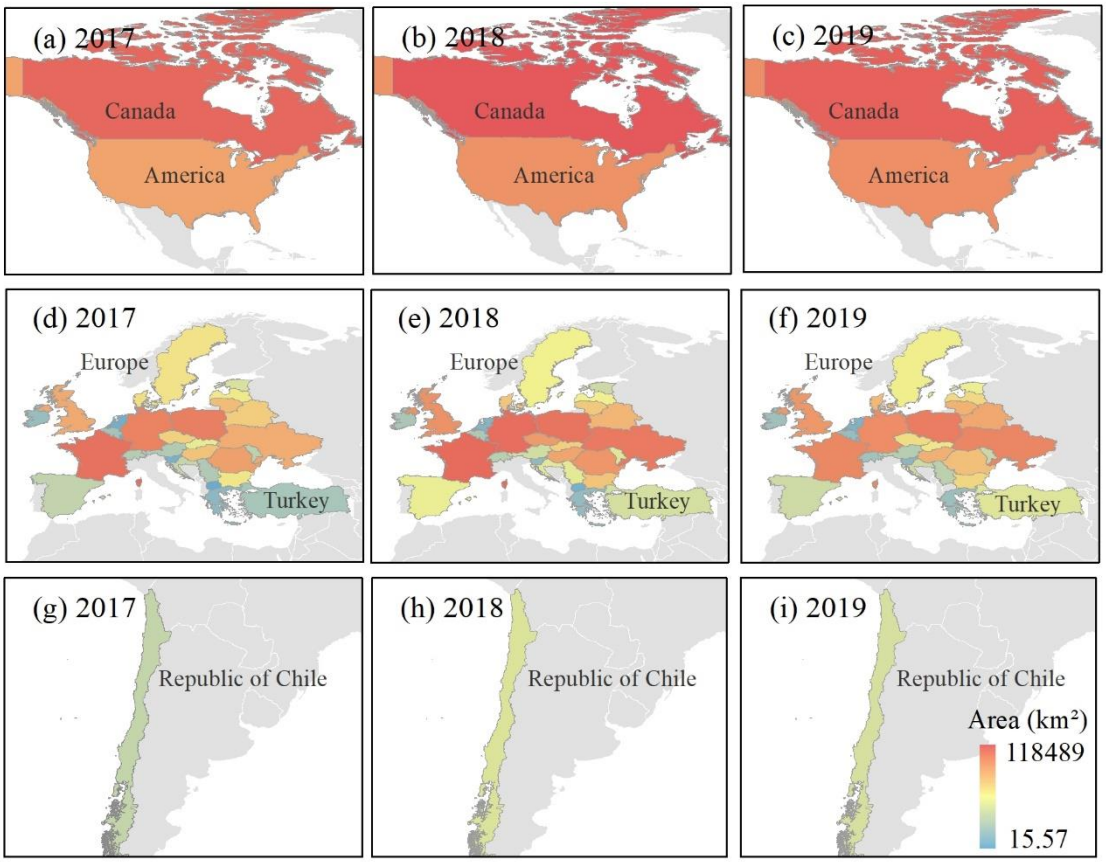


Figure S14. The normalized rapeseed planting areas derived from rapeseed maps in each country.

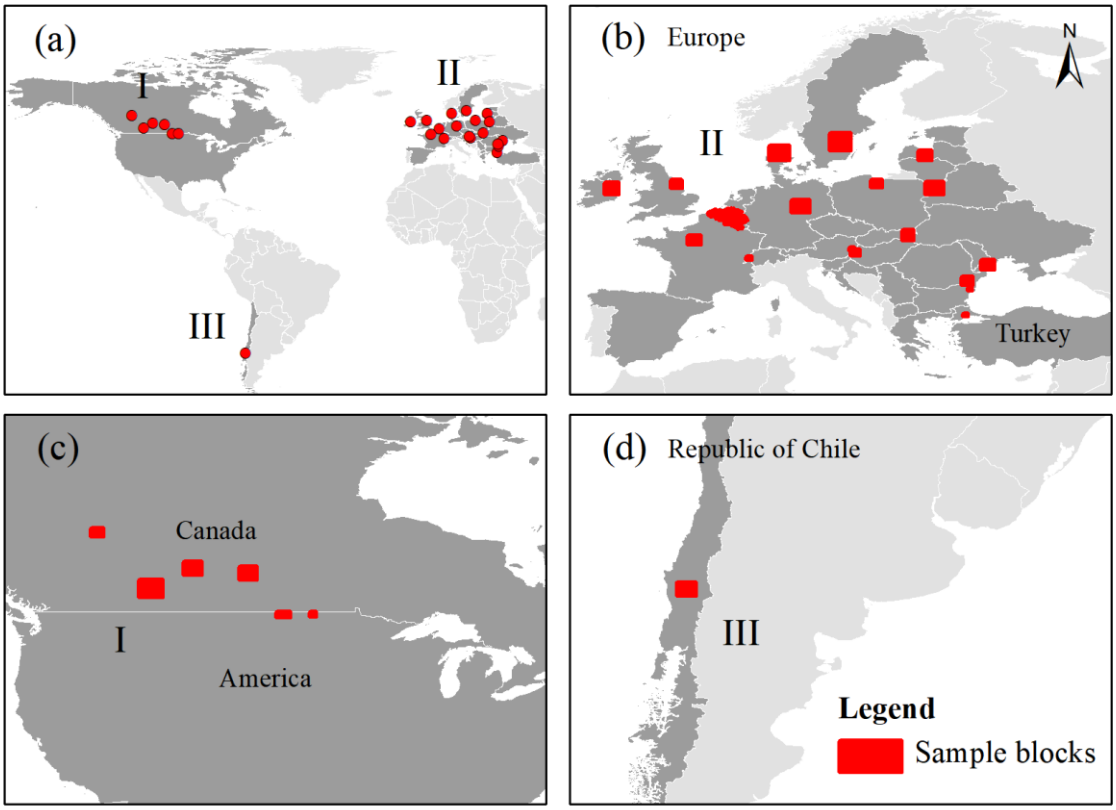
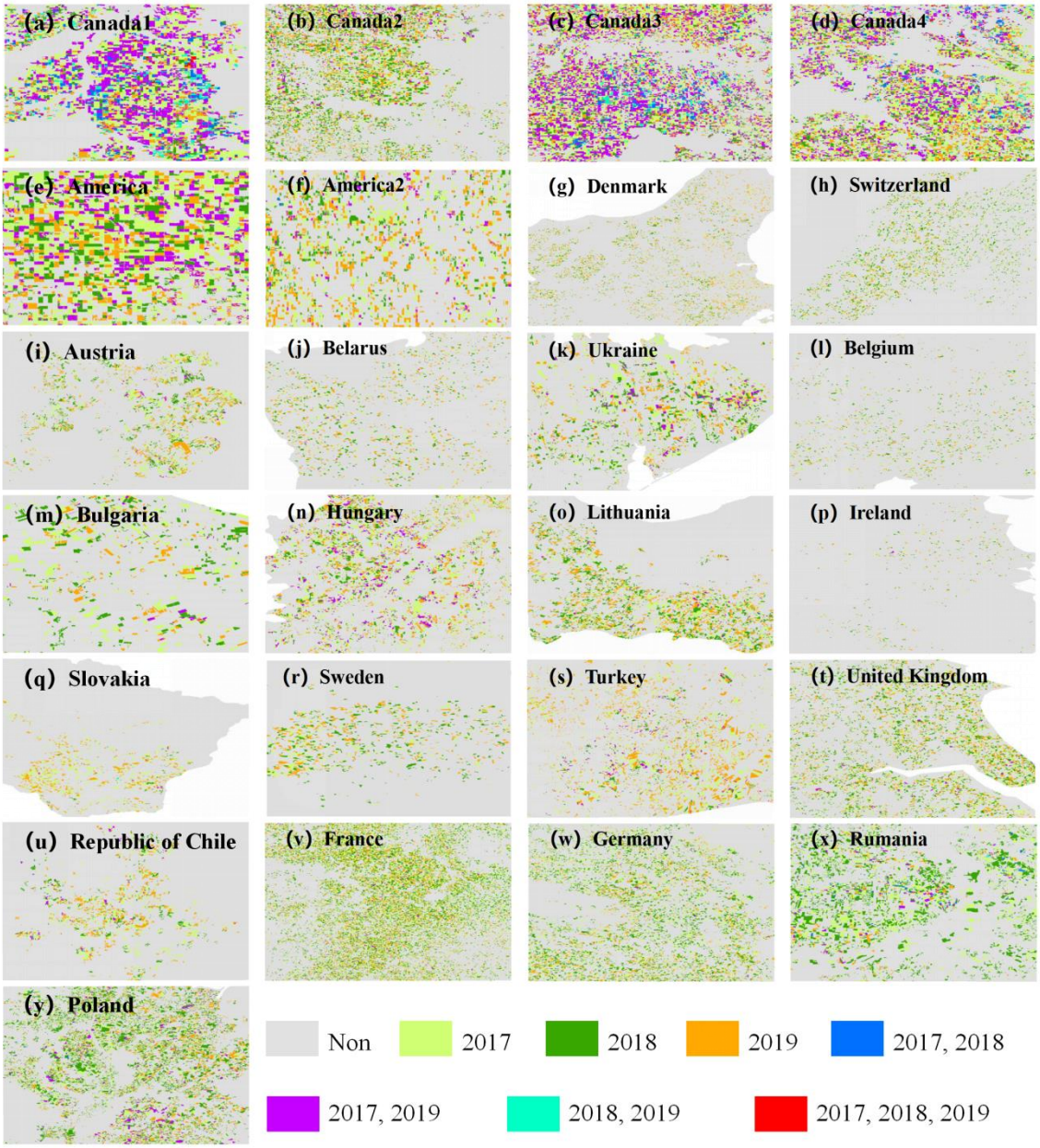


Figure S15. The 25 locations selected for investigating rotation information. Three criterions for selecting are: a) high-quality images available during the annual rapeseed flowering period from 2017~2019; b) high rapeseed classification accuracy; c) rapeseed is the main crop type and a large area is planted by rapeseed every year.



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94 Figure S16. Spatial distribution of rapeseed rotation patterns in different areas from 2017~2019.

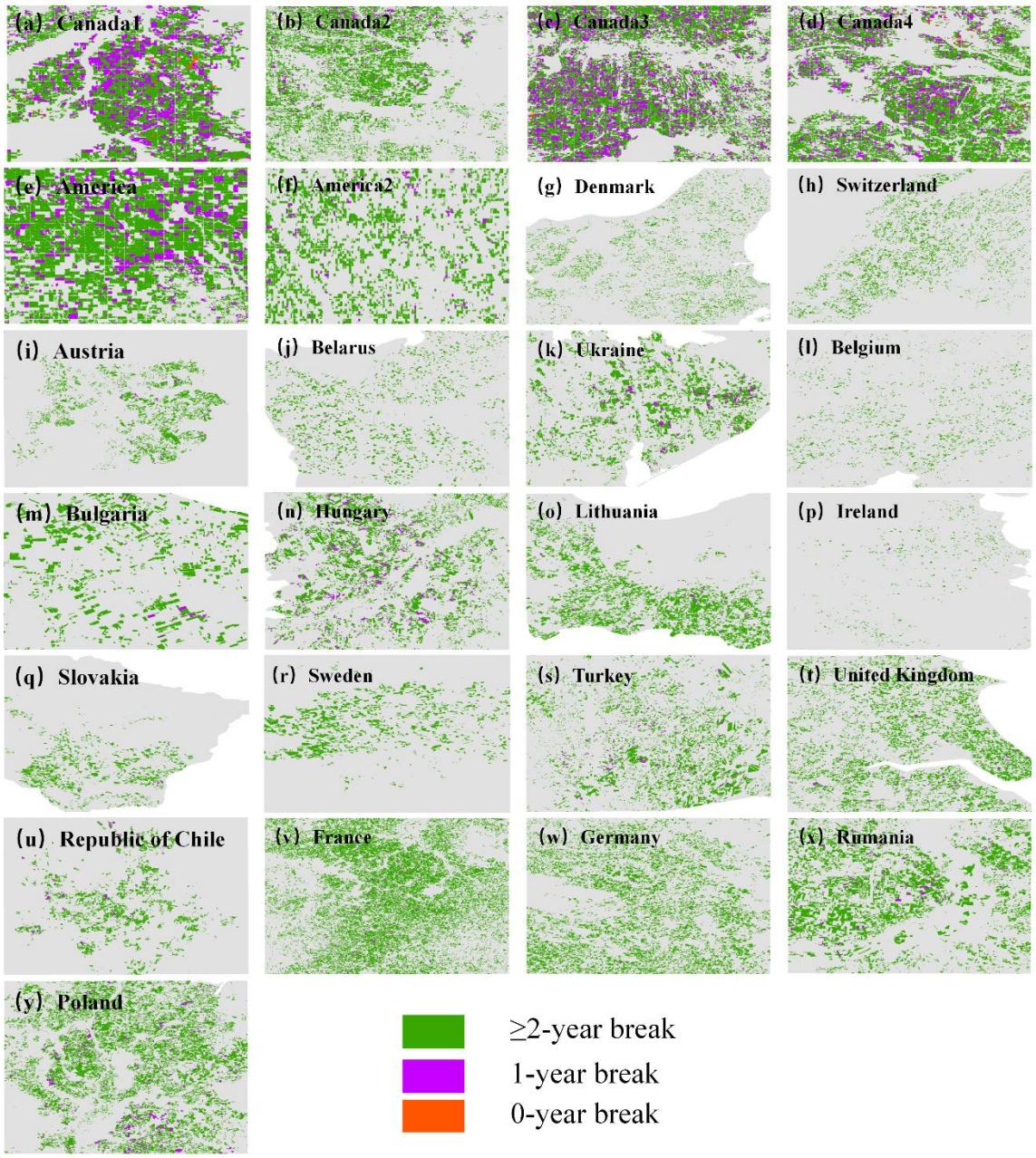
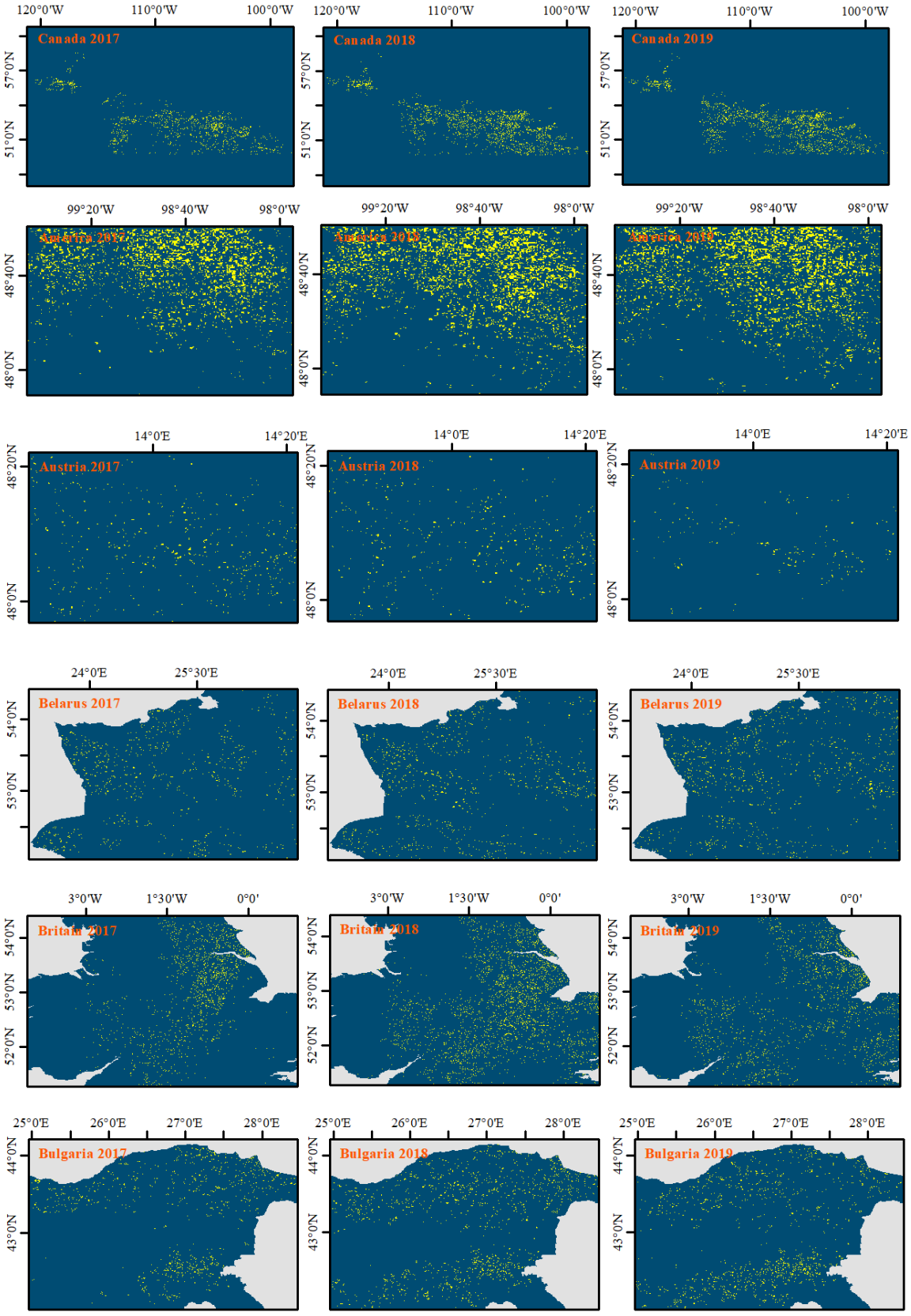
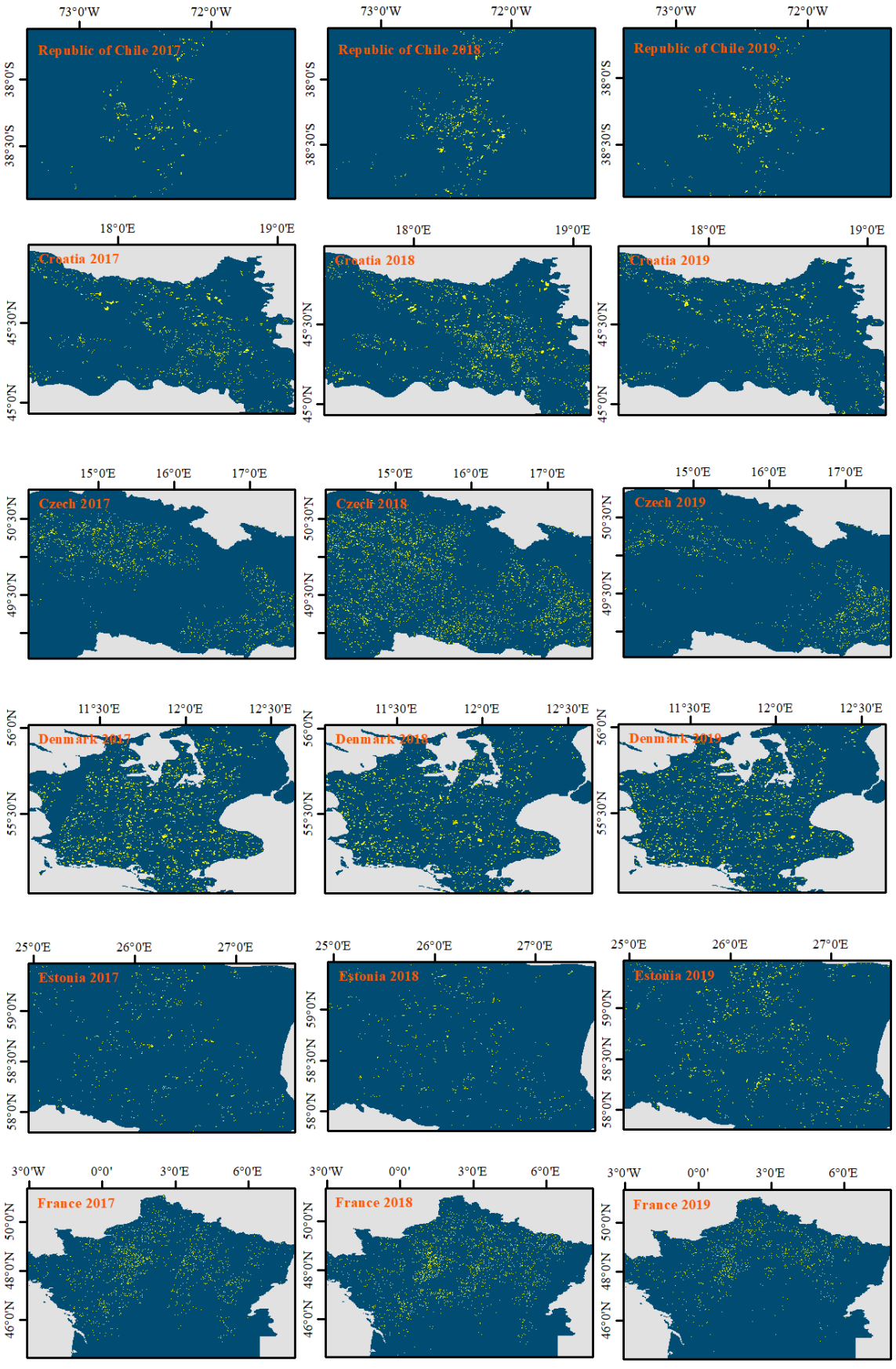
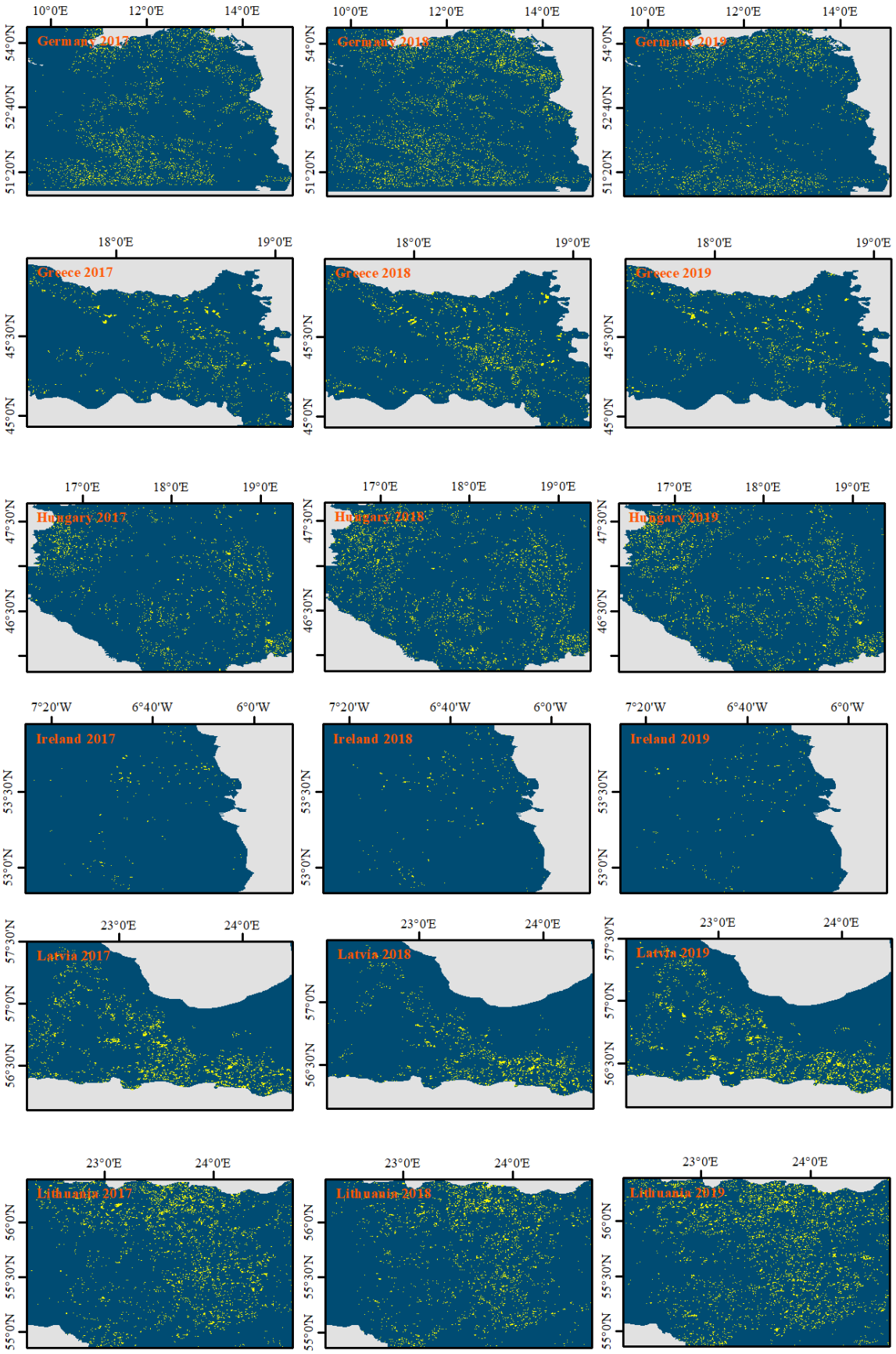
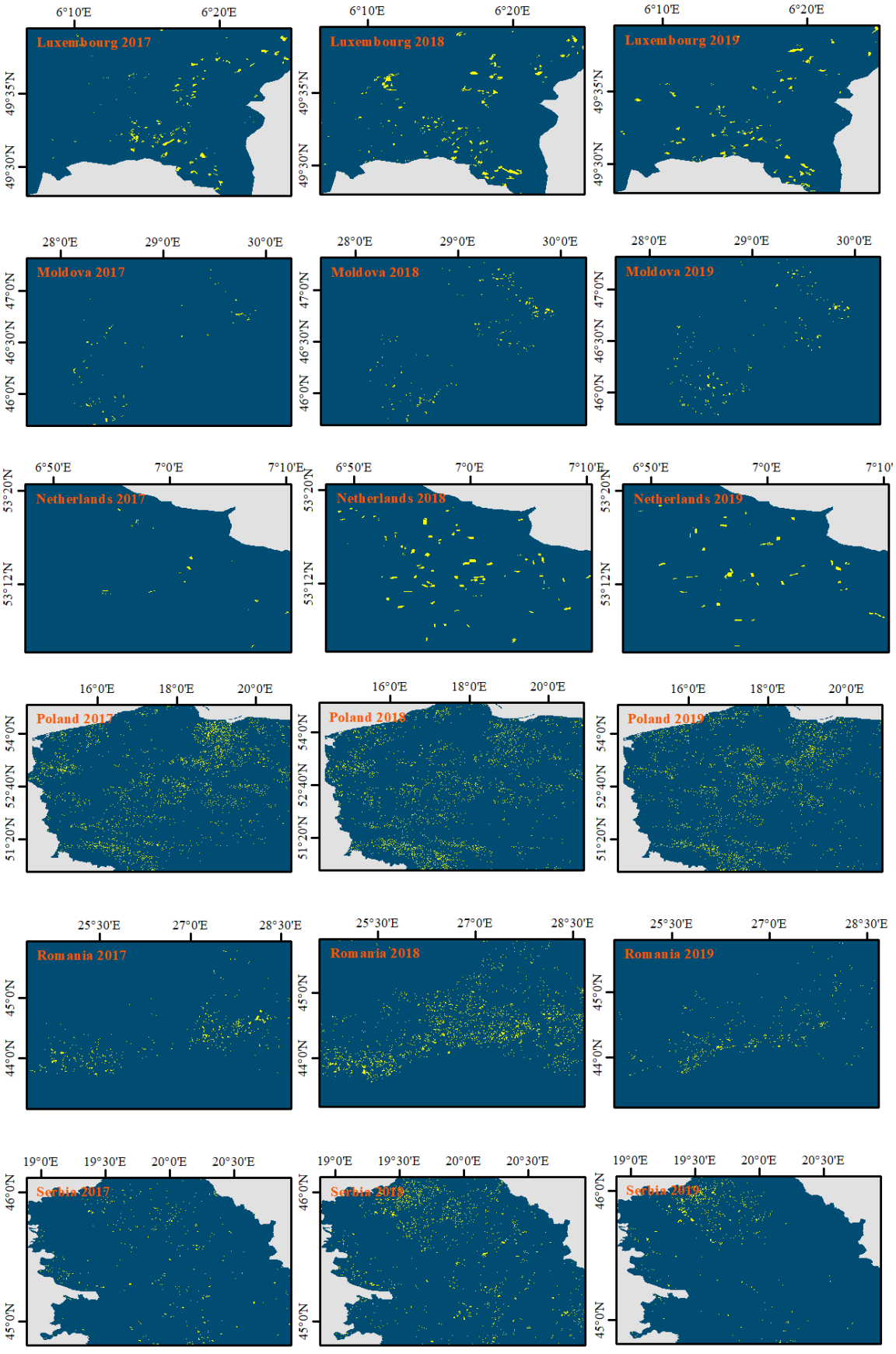


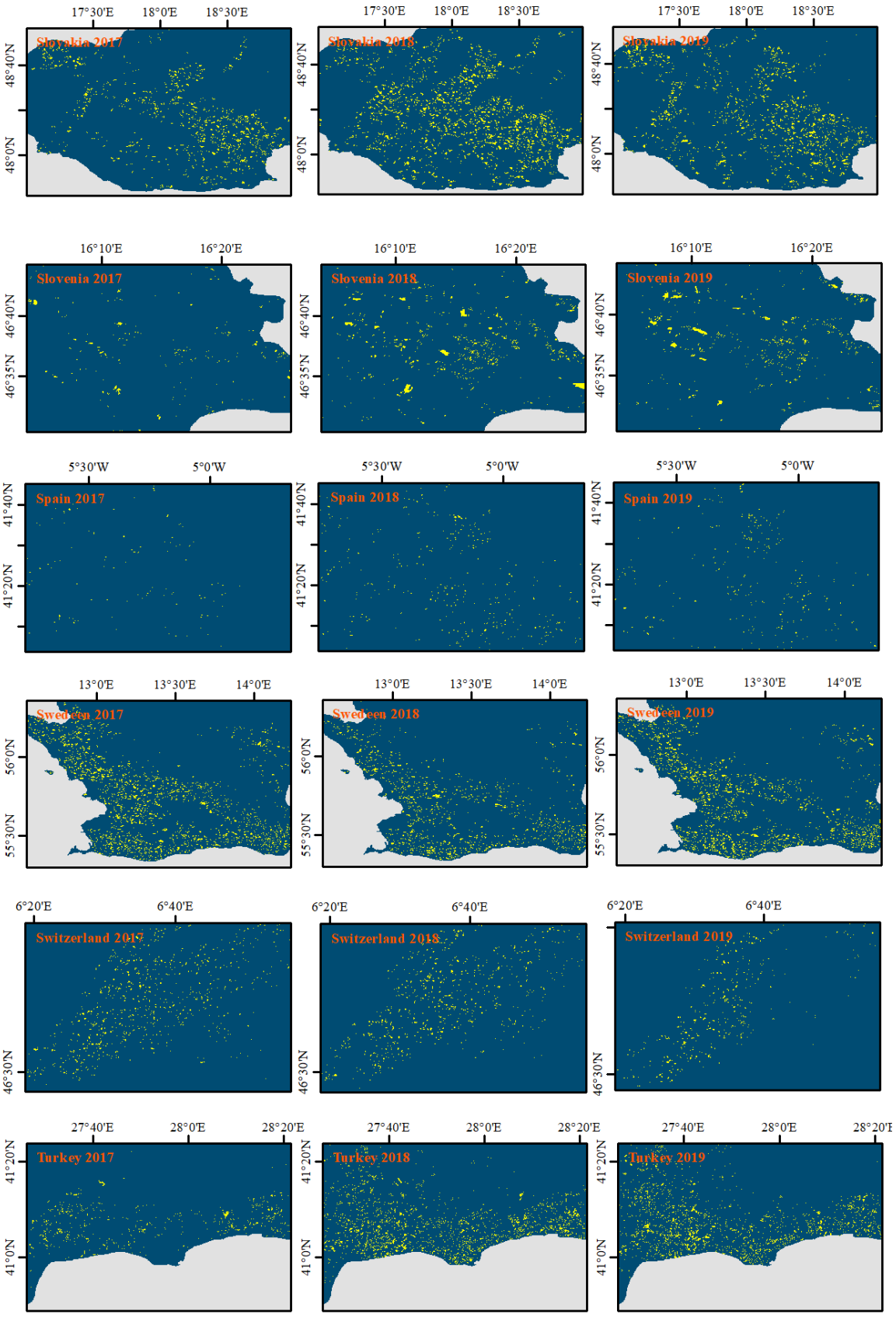
Figure S17. Spatial distribution of three types of rotations in different areas from 2017~2019.

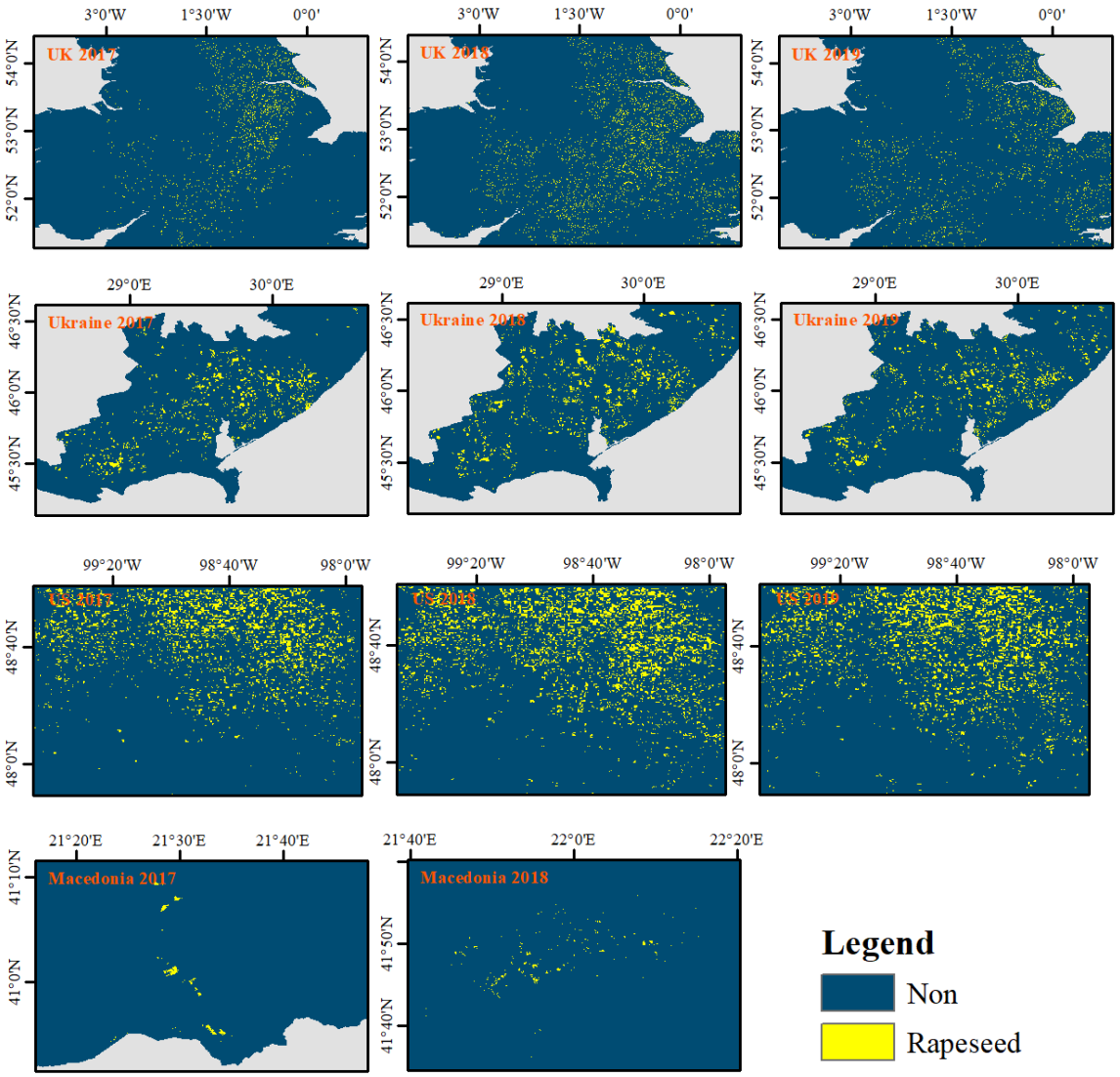

Canada 2017
Canada 2018
Canada 2019
120°0'W
110°0'W
100°0'W
57°0'N
51°0'N
99°20'W
98°40'W
98°0'W
48°40'N
48°0'N
Austria 2017
Austria 2018
Austria 2019
14°0'E
14°20'E
48°20'N
48°0'N
Belarus 2017
Belarus 2018
Belarus 2019
24°0'E
25°30'E
54°0'N
53°0'N
Britain 2017
Britain 2018
Britain 2019
3°0'W
1°30'W
0°0'
52°0'N
Bulgaria 2017
Bulgaria 2018
Bulgaria 2019
25°0'E
26°0'E
27°0'E
28°0'E
44°0'N
43°0'N


Republic of Chile 2017
Republic of Chile 2018
Republic of Chile 2019
73°0'W
72°0'W
38°0'S
38°30'S
Croatia 2017
Croatia 2018
Croatia 2019
18°0'E
19°0'E
45°30'N
45°0'N
Czech 2017
Czech 2018
Czech 2019
15°0'E
16°0'E
17°0'E
50°30'N
49°30'N
Denmark 2017
Denmark 2018
Denmark 2019
11°30'E
12°0'E
12°30'E
56°0'N
55°30'N
Estonia 2017
Estonia 2018
Estonia 2019
25°0'E
26°0'E
27°0'E
59°0'N
58°30'N
58°0'N
France 2017
France 2018
France 2019
3°0'W
0°0'
3°0'E
6°0'E
50°0'N
48°0'N
46°0'N


Germany 2017
Germany 2018
Germany 2019
Greece 2017
Greece 2018
Greece 2019
Hungary 2017
Hungary 2018
Hungary 2019
Ireland 2017
Ireland 2018
Ireland 2019
Latvia 2017
Latvia 2018
Latvia 2019
Lithuania 2017
Lithuania 2018
Lithuania 2019


Luxembourg 2017
Luxembourg 2018
Luxembourg 2019
6°10'E
6°20'E
49°35'N
49°30'N
Moldova 2017
Moldova 2018
Moldova 2019
28°0'E
29°0'E
30°0'E
47°0'N
46°30'N
46°0'N
Netherlands 2017
Netherlands 2018
Netherlands 2019
6°50'E
7°0'E
7°10'E
53°20'N
53°12'N
Poland 2017
Poland 2018
Poland 2019
16°0'E
18°0'E
20°0'E
54°0'N
52°40'N
51°20'N
Romania 2017
Romania 2018
Romania 2019
25°30'E
27°0'E
28°30'E
45°0'N
44°0'N
Serbia 2017
Serbia 2018
Serbia 2019
19°0'E
19°30'E
20°0'E
20°30'E
46°0'N
45°0'N


17°30'E
18°0'E
18°30'E
48°40'N
48°0'N
Slovakia 2017
Slovakia 2018
Slovakia 2019
16°10'E
16°20'E
46°40'N
46°35'N
Slovenia 2017
Slovenia 2018
Slovenia 2019
5°30'W
5°0'W
41°40'N
41°20'N
Spain 2017
Spain 2018
Spain 2019
13°0'E
13°30'E
14°0'E
56°0'N
55°30'N
Sweden 2017
Sweden 2018
Sweden 2019
6°20'E
6°40'E
46°30'N
Switzerland 2017
Switzerland 2018
Switzerland 2019
27°40'E
28°0'E
28°20'E
41°20'N
41°0'N
Turkey 2017
Turkey 2018
Turkey 2019



97 Figure S18. Spatial distributions of annual rapeseed fields in different countries in 2017~2019.