Supplementary Material

Detecting the Oak lace bug infestation in oak forests using MODIS and meteorological data

Anikó Kern [1,*], Hrvoje Marjanović [2,*], György Csóka [3], Norbert Móricz [4], Milan Pernek [5], Anikó Hirka [3], Dinka Matošević [5], Márton Paulin [3], Goran Kovač [6]

[1] Department of Geophysics and Space Sciences, Eötvös Loránd University, Pázmány P. st. 1/A, Budapest H-1117, Hungary

[2] Department of Forest Management and Forestry Economics, Croatian Forest Research Institute, Cvjetno naselje 41, Jastrebarsko HR-10450, Croatia

[3] Department of Forest Protection, NARIC Forest Research Institute, Hegyalja str. 18, Mátrafüred H-3232, Hungary

[4] Department of Ecology and Forest Management, NARIC Forest Research Institute, Várkerület 30/A., Sárvár H-9600, Hungary

[5] Department of Forest Protection and Game Management, Croatian Forest Research Institute, Cvjetno naselje 41, Jastrebarsko HR-10450, Croatia

[6] Forest Management Service, Sector for Planning, Analysis, Forest Management and Informatics, Croatian Forests Ltd., Ulica kneza Branimira 1, Zagreb HR-10000, Croatia

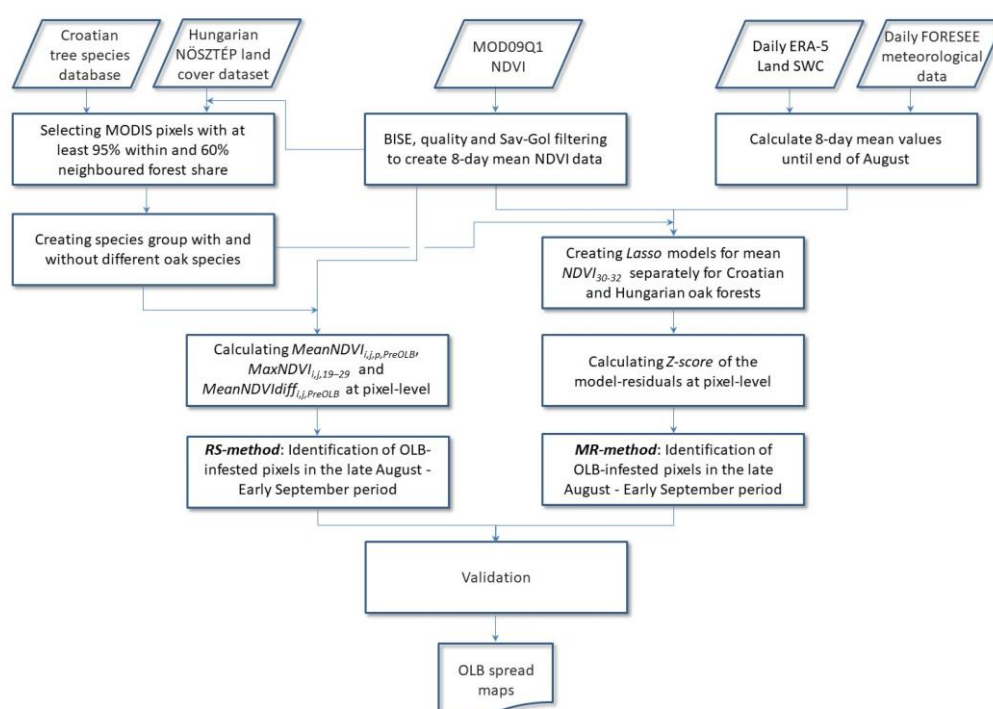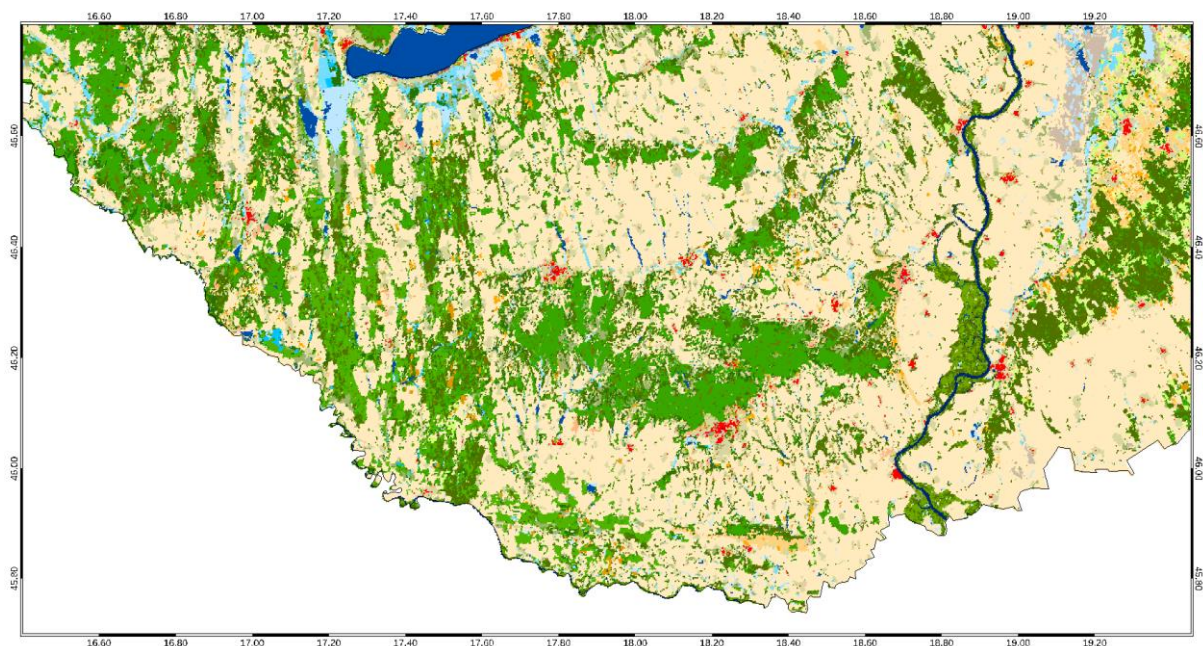* Correspondence: hrvojem@sumins.hr (H. Marjanović); anikoc@nimbus.elte.hu (A. Kern)
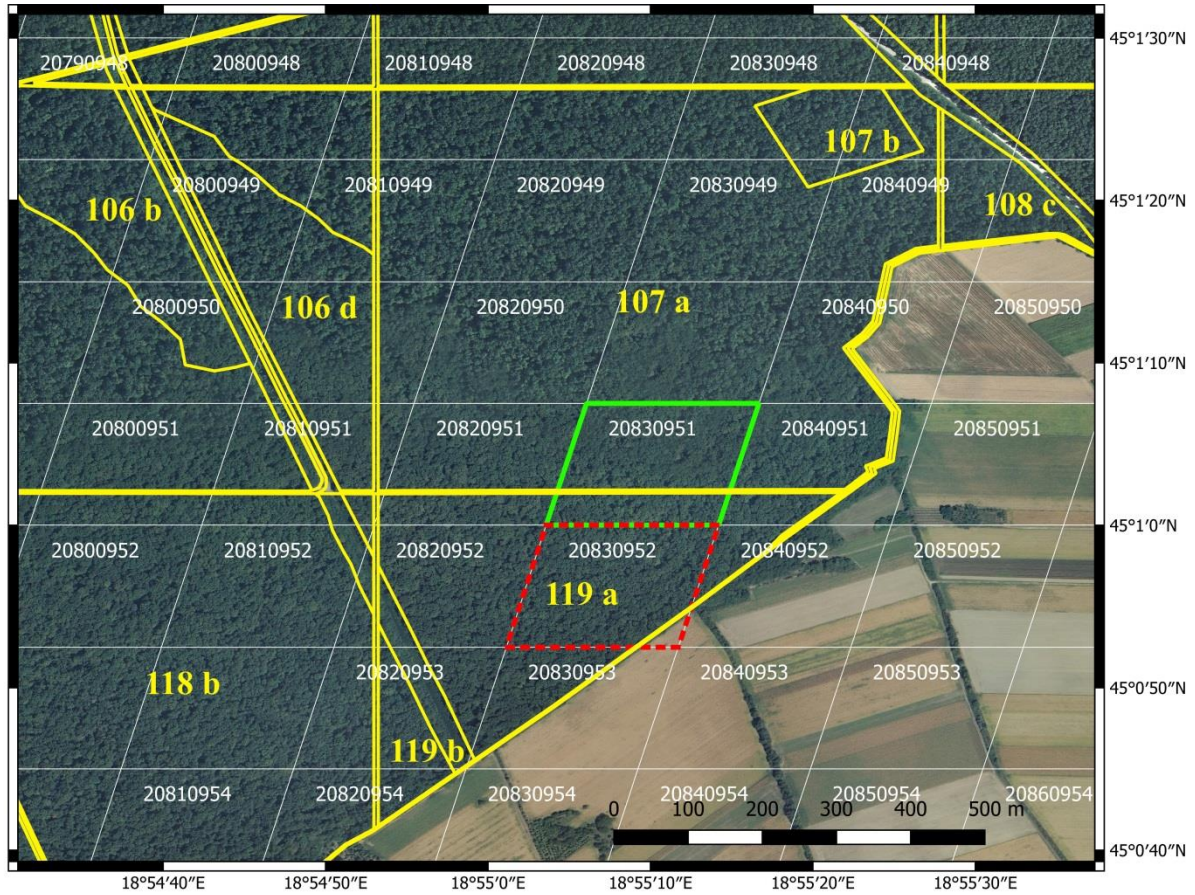
Figure S1. Flowchart of the applied methodologies.

Figure S2a. Land cover map of the Hungarian study area at MODIS QKM grid (250 × 250 m) with the dominant Level-3 NÖSZTÉP land cover category in the case of every pixel. For the detailed legend see Fig. S2b.

National Ecosystem Base Map land cover categories - Level-3

Urban
- 1100: Low buildings
- 1120: High buildings
- 1210: Solid roads
- 1220: Dirt roads
- 1230: Rails
- 1310: Other artificial roads
- 1410: Green areas in artificial environment with trees
- 1420: Green areas in artificial environment without trees

Cropland
- 2100: Arable lands
- 2210: Grape yards
- 2220: Fruit trees, berries
- 2230: Energy plantation
- 2310: Complex cultivation patterns with buildings
- 2320: Complex cultivation patterns without buildings

Grasslands and other herbaceous vegetation
- 3110: Open sandy grasslands
- 3120: Closed sandy grasslands
- 3200: Grasslands on saline soil
- 3310: Calciphile grasslands with rocks
- 3320: Other grasslands with rocks
- 3400: Closed grasslands on hard mountainous ground
- 3500: Other grasslands

Forests and woodlands
- 4101: Beeches
- 4102: Sessile oak with hornbeam
- 4103: European turkey oak
- 4104: Pubescent oaks
- 4105: Scots pine in Western Hungary
- 4106: Scots pine in Western Hungary mixed with broadleaf forests
- 4107: Poplars

Forests and woodlands
- 4108: Mountainous pionir forests
- 4109: Pedunculate oaks with hornbeams
- 4110: Only Pedunculate oaks, or, pedunculate oaks mixed with ashes
- 4111: Other native species without extra soil water effect
- 4112: Other mixed broadleaf forests
- 4201: Softwoods on floodplains
- 4202: Hardwoods on floodplains
- 4301: Only Pedunculate oak, or, pedunculate oak mixed with ashes
- 4302: Alders
- 4303: Pedunculate oak with hornbeam with extra soil water
- 4304: Willows outside of floodplains
- 4305: Poplars outside of floodplains, under extra soil water effect
- 4306: Birches
- 4307: European turkey oak under extra soil water effect
- 4308: Other native species under extra soil water effect
- 4309: Other mixed broadleaf forests under extra soil water effect
- 4401: Needle-leaf dominated plantations
- 4402: Robenia dominated plantations
- 4403: Populus x euramericana dominated plantations
- 4404: Other alien species dominated broadleaf forests
- 4501: Stemmed forests
- 4502: Forest under reconstruction
- 4600: Other, not classifiable woody plants

Wetlands
- 5110: Marshland plants standing in water
- 5120: Marshlands under temporary standing waters
- 5200: Marshlands forests

Rivers & lakes
- 6100: Dead-waters
- 6200: Rivers and streams

Figure S2b. Detailed legend of the NÖSZTÉP *National Ecosystem Base Map land cover* database Level-3 categories.

Figure S3. Intersection of the spatial data on forest sub-compartments from *HŠ Fond* database (yellow lines and letters mark borders and ID of the sub-compartment) and MODIS QKM grid (white lines and numbers). Polygon marked green is an example of the MODIS pixel in this study, while polygon marked with red dashed line was discarded from the study due to the fact that pixels to the south and to the west of it do not meet selection criteria (although the pixel is >95% forested and side-neighbouring pixels are not > 60% forested).
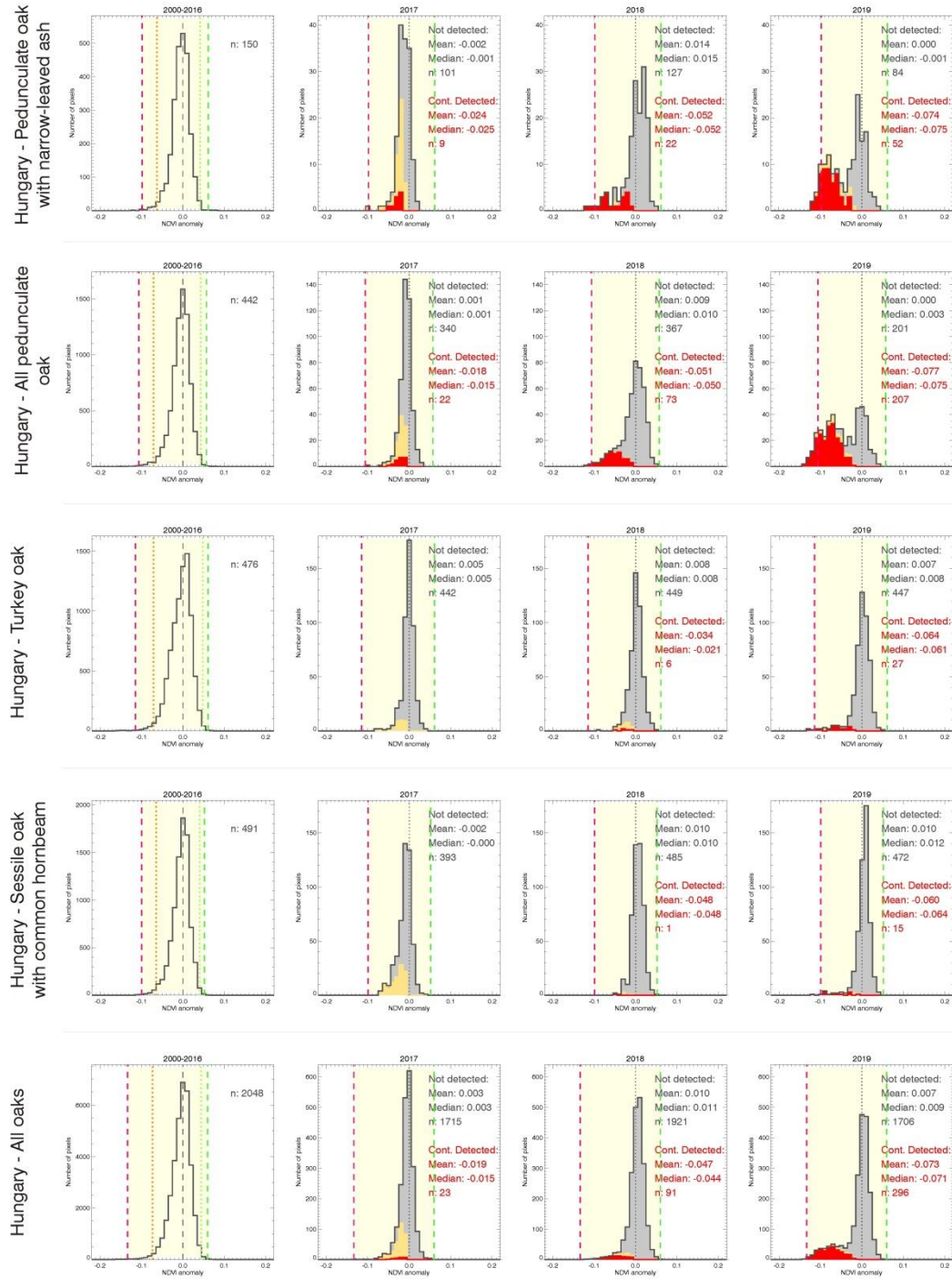
Figure S4. Distributions of the $NDVI_{30-32}$ anomaly showing the progression of the OLB infestation in the forest categories *Pedunculate oak with narrowed leaved ash* (top row), *All pedunculate oak* (second row), *Turkey oak* (third row), *Sessile oak with common hornbeam* (fourth row) and *All oaks* (bottom row) for the Hungarian part of the study area. The anomaly distributions for the infestation *not detected*, *not continuously detected*, and *continuously detected* pixels are indicated with grey, yellow and red colour, respectively.
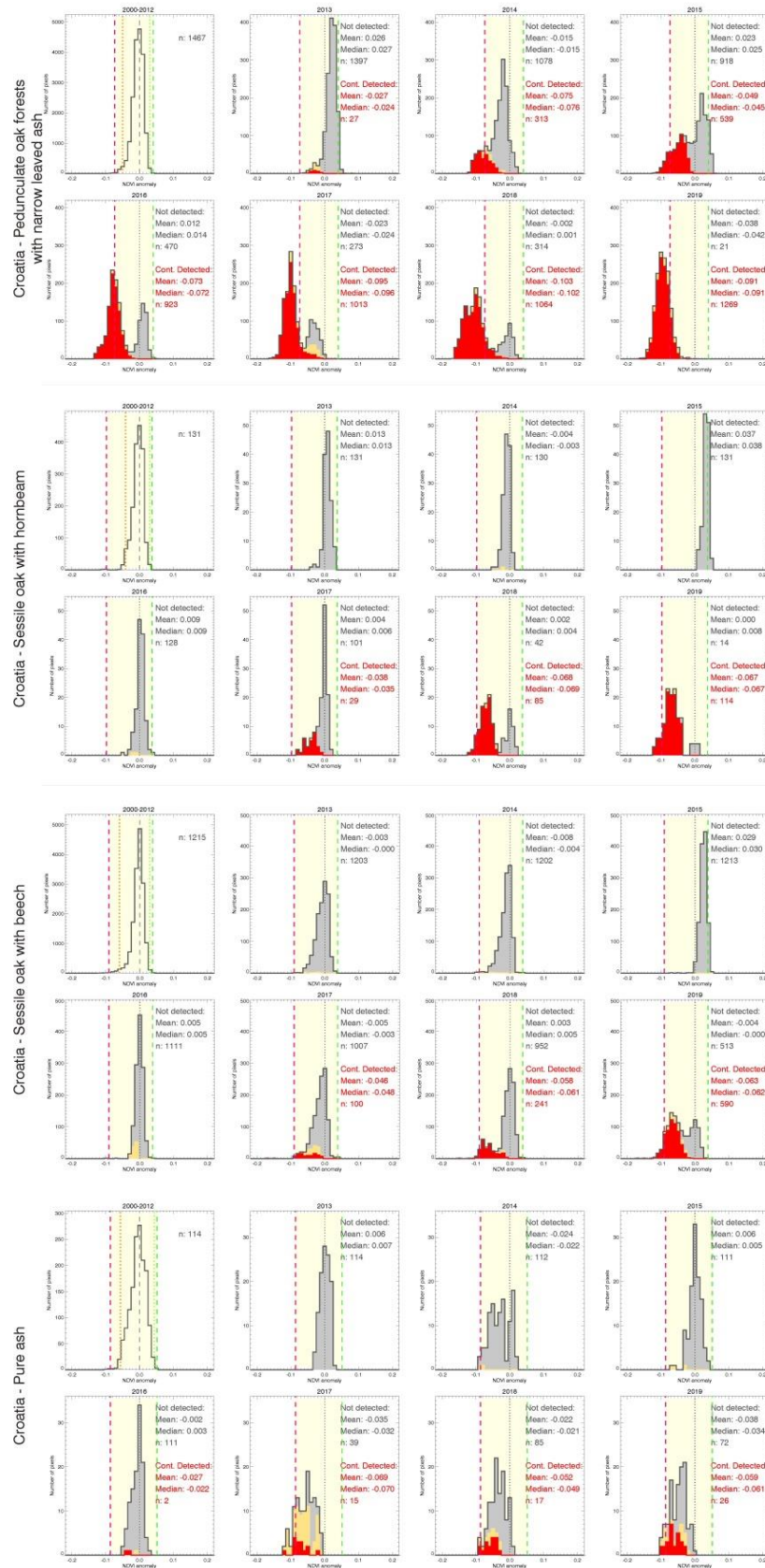
Figure S5. Distributions of the $NDVI_{30-32}$ anomaly showing the progression of the OLB infestation in the forest categories *Pedunculate oak with narrowed-leaved ash* (top row), *Sessile oak with common hornbeam* (second row), *Sessile oak with common beech* (third row) and *Pure ash* (bottom row) for the Croatian part of the study area. The NDVI anomaly distributions for the infestation *not detected*, *not continuously detected*, and *continuously detected* pixels are indicated with grey, yellow and red colour, respectively.

Table S1. The number of the so-called "pure category" QKM pixels (at 250 m) of the NÖSZTÉP National Ecosystem Base Map land cover database in each Level-3 category of the Forest and Woodlands Level-1 category in the study area. Data from the different Level-2 classifications (indicated with *,**,***) were merged to create unified categories for the given tree species.

Level 2	NÖSZTÉP category	Level 3	90-100%	91-100%	92-100%	93-100%	94-100%	95-100%	96-100%	97-100%	98-100%	99-100%
Without extra soil water effect	4101	Beech	2088	2005	1869	1731	1595	1449	1299	1110	953	777
	4102	Sessile oak (*Q. petraea*) with hornbeam ****	1052	985	914	844	769	693	599	525	437	355
	4103	Turkey oak (*Q. cerris*) ***	1629	1535	1413	1289	1160	1028	865	707	564	411
	4104	Pubescent oak (*Quercus pubescens*) *****	109	96	87	83	75	65	59	47	39	28
	4105	Scots pine (*Pinus silvestris*) in Western Hungary	380	353	317	285	254	227	200	148	108	80
	4106	Scots pine (*Pinus silvestris*) in Western Hungary mixed with broadleaf forests	27	24	24	22	19	14	13	10	6	5
	4107	Poplars	8	8	8	8	5	5	5	3	2	1
	4108	Mountainous pionir forests	0	0	0	0	0	0	0	0	0	0
	4109	Pedunculate oak (*Q. robur*) with hornbeam **	89	84	76	66	59	55	51	41	33	26
	4110	Only pedunculate oak (*Q. robur*), or, pedunculate oak mixed with narrow-leafed ashes *	17	16	14	14	13	9	9	8	7	7
	4111	Other native species without extra soil water effect	592	553	496	454	410	366	314	260	200	151
	4112	Other mixed broadleaf forests	422	399	372	344	311	279	242	200	155	119
Natural forests	4201	Softwoods on floodplains	144	134	120	109	96	91	74	60	51	34
	4202	Hardwoods on floodplains	258	232	197	171	145	128	103	74	58	36
Under extra soil water effect	4301	Only pedunculate oak (*Q. robur*), or, pedunculate oak mixed with narrow-leafed ashes *	869	789	690	608	533	433	340	247	180	132
	4302	Alders	408	364	320	274	232	202	167	121	92	64
	4303	Pedunculate oak (*Q. robur*) with common hornbeam **	343	314	282	253	217	185	151	106	67	42
	4304	Willows outside of floodplains	0	0	0	0	0	0	0	0	0	0
	4305	Poplars outside of floodplains	3	3	2	0	0	0	0	0	0	0
	4306	Birches	8	8	6	5	4	4	3	2	1	1
	4307	Turkey oak (*Q. cerris*) ***	20	18	16	14	10	8	7	4	3	1
	4308	Other native species	24	20	19	19	17	17	13	10	7	5
	4309	Other mixed broadleaf forests	9	8	7	6	2	2	1	1	1	1
Alien species dominated plantations	4401	Needle-leaf dominated plantations	289	266	235	214	177	146	120	90	62	44
	4402	Robenia dominated plantations	2159	1982	1807	1645	1469	1294	1140	939	738	550
	4403	*Populus* x *euramericana* dominated plantations	248	231	213	199	187	169	142	118	100	76
	4404	Other alien species dominated broadleaf forests	196	181	159	138	122	103	82	65	50	40
Registered as forests, but without stands	4501	Stemmed forests	26	25	22	20	18	15	13	9	7	5
	4502	Under reconstruction	312	289	270	242	214	195	171	148	131	106
Others	4600	Other, not classifiable woody plants	653	609	555	506	457	412	377	338	301	241

Table S2. The statistics of the constructed model coefficients (estimates, standard errors, *t*-statistics, *p*-values).

M1$_{2000–2016}$

independent variable	Intercept	Tmax $_{5-6}$	Tmax $_{21-22}$	Tmin $_{25-26}$	Tmin $_{27-28}$	Prec $_{29-30}$	SWC3 $_{1-2}$	NDVI $_{25-26}$	-	-
coefficient estimate	0.26899	0.00091	-0.00189	0.00427	-0.00273	0.00031	0.02975	0.67971	-	-
standard error	0.00240	0.00001	0.00003	0.00004	0.00005	0.000004	0.00088	0.00232	-	-
t-statistic	112.24	70.94	-73.86	103.10	-59.61	81.06	33.71	293.55	-	-
p-value	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-	-

M2$_{2000–2012}$

independent variable	Intercept	Tmin $_{1-2}$	Tmin $_{9-10}$	Prec $_{1-2}$	Prec $_{9-10}$	SWC3 $_{1-2}$	SWC3 $_{7-8}$	SWC3 $_{29-30}$	SWC4 $_{29-30}$	NDVI $_{25-26}$
coefficient estimate	0.19767	-0.00111	-0.00210	0.00020	0.00031	-0.09954	-0.24562	0.08909	0.26704	0.76656
standard error	0.00136	0.00001	0.00002	0.00000	0.00001	0.00120	0.00265	0.00117	0.00343	0.00147
t-statistic	145.06	-98.08	-129.86	59.17	58.03	-83.26	-92.74	75.84	77.89	523.02
p-value	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table S3. Ordinal numbers and dates of the regular 8-day periods in not leap-years.

| Number of the 8-day period	Julian day of the start	Date	Number of the 8-day period	Julian day of the start	Date
1	001	01–08 January	24	185	04–11 July
2	009	09–16 January	25	193	12–19 July
3	017	17–24 January	26	201	20–27 July
4	025	25 January – 01 February	27	209	28 of July – 4th of August
5	033	02–9 February	28	217	5–12 of August
6	041	10–17 February	29	225	13–20 of August
7	049	18–25 February	30	233	21–28 of August
8	057	26 February – 05 March	31	241	28 of August – 5th of September
9	065	06–13 March	32	249	6–13 of September
10	073	14–21 March	33	257	14–21 of September
11	081	22–29 March	34	265	22–29 of September
12	089	30 March – 06 April	35	273	30 September - 07 October
13	097	07–14 April	36	281	08-15 October
14	105	15–22 April	37	289	16-23 October
15	113	23–30 April	38	297	24-31 October
16	121	01–08 May	39	305	01-08 November
17	129	09–16 May	40	313	09-16 November
18	137	17–24 May	41	321	17-24 November
19	145	25 May – 01 June	42	329	25 November - 02 December
20	153	02–09 June	43	337	03-10 December
21	161	10–17 June	44	345	11-18 December
22	169	18–25 June	45	353	19-26 December
23	177	26 June – 03 July	46	361	27-31 December

Table S4. Comparison of *RS* and *MR* methods for detection of the OLB infestation and of the continuity in detection by year for Hungary. (0 – not infested; 1 – infested).

Case / Year	RS1 & MR1	RS0 & MR1	RS1 & MR0	RS0 & MR0	RS & MR in agreement
OLB infestation detection with RS and MR methods by year					
2017	13 (0.2%)	0 (0.0%)	1160 (15.5%)	6312 (84.3%)	84.5%
2018	57 (0.8%)	3 (0.0%)	312 (4.2%)	7113 (95.0%)	95.8%
2019	324 (4.3%)	6 (0.1%)	511 (6.8%)	6644 (88.8%)	93.1%
Total	394 (1.8%)	9 (0.0%)	1983 (8.8%)	20069 (89.4%)	91.1%
*CURRENT year status of pixels detected with **RS** as infested in the PREVIOUS year*					
2018	25 (2.1%)	0 (0.0%)	64 (5.5%)	1084 (92.4%)	94.5%
2019	96 (26.0%)	0 (0.0%)	79 (21.4%)	194 (52.6%)	78.6%
Total	121 (7.8%)	0 (0.0%)	143 (9.3%)	1278 (82.9%)	90.7%
*CURRENT year status of pixels detected with **MR** as infested in the PREVIOUS year*					
2018	1 (7.7%)	0 (0.0%)	0 (0.0%)	12 (92.3%)	100.0%
2019	41 (68.3%)	0 (0.0%)	12 (20.0%)	7 (11.7%)	80.0%
Total	42 (57.5%)	0 (0.0%)	12 (16.4%)	19 (26.0%)	83.6%

Table S5. Comparison of *RS* and *MR* methods for detection of the OLB infestation and of the continuity in detection by year for Croatia. (0 – not infested; 1 – infested).

Case / Year	RS1 & MR1	RS0 & MR1	RS1 & MR0	RS0 & MR0	RS & MR in agreement
OLB infestation detection with RS and MR methods by year					
2013	65 (0.4%)	7 (0.0%)	133 (0.8%)	16808 (98.8%)	99.2%
2014	612 (3.6%)	174 (1.0%)	237 (1.4%)	15990 (94.0%)	97.6%
2015	973 (5.7%)	51 (0.3%)	441 (2.6%)	15548 (91.4%)	97.1%
2016	2985 (17.5%)	108 (0.6%)	768 (4.5%)	13152 (77.3%)	94.9%
2017	4119 (24.2%)	21 (0.1%)	3095 (18.2%)	9778 (57.5%)	81.7%
2018	6107 (35.9%)	232 (1.4%)	1224 (7.2%)	9450 (55.5%)	91.4%
2019	9489 (55.8%)	823 (4.8%)	1114 (6.5%)	5587 (32.8%)	88.6%
Total	24350 (20.4%)	1416 (1.2%)	7012 (5.9%)	86313 (72.5%)	92.9%
*CURRENT year status of pixels detected with **RS** as infested in the PREVIOUS year*					
2014	89 (44.9%)	1 (0.5%)	15 (7.6%)	93 (47.0%)	91.9%
2015	406 (47.8%)	7 (0.8%)	122 (14.4%)	314 (37.0%)	84.8%
2016	1257 (88.9%)	9 (0.6%)	86 (6.1%)	62 (4.4%)	93.3%
2017	2941 (78.4%)	6 (0.2%)	356 (9.5%)	450 (12.0%)	90.4%
2018	5154 (71.4%)	87 (1.2%)	584 (8.1%)	1389 (19.3%)	90.7%
2019	6127 (83.6%)	130 (1.8%)	590 (8.0%)	484 (6.6%)	90.2%
Total	15974 (76.9%)	240 (1.2%)	1753 (8.4%)	2792 (13.4%)	90.4%
CURRENT year status of pixels detected with MR as infested in the PREVIOUS year					
2014	51 (70.8%)	1 (1.4%)	1 (1.4%)	19 (26.4%)	97.2%
2015	492 (62.6%)	9 (1.1%)	116 (14.8%)	169 (21.5%)	84.1%
2016	972 (94.9%)	7 (0.7%)	20 (2.0%)	25 (2.4%)	97.4%
2017	2872 (92.9%)	4 (0.1%)	146 (4.7%)	71 (2.3%)	95.2%
2018	3987 (96.3%)	35 (0.8%)	45 (1.1%)	73 (1.8%)	98.1%
2019	5684 (89.7%)	128 (2.0%)	350 (5.5%)	177 (2.8%)	92.5%
Total	14058 (91.0%)	184 (1.2%)	678 (4.4%)	534 (3.5%)	94.4%
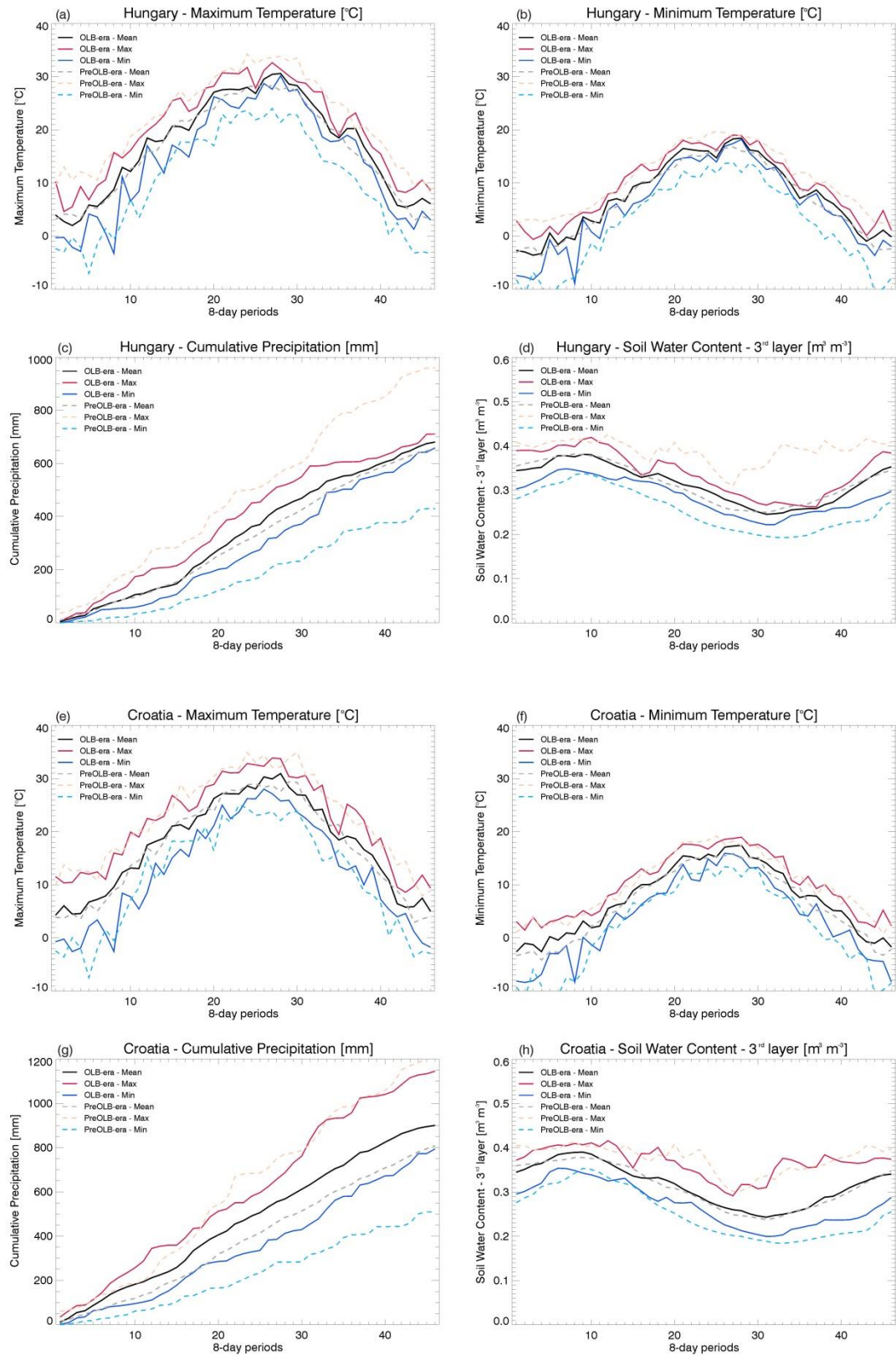
Figure S6. Meteorological conditions during the *PreOLB-* and the *OLB-era* of the Hungarian and Croatian part of the study domain for the *All oaks above 20% share* category (i.e. from 7,485 and 17,013 pixels, separately).