Supplementary materials

Contents

1. Data integration

Table S1. *Whole system condition indicator set grouped by subsystem of the ecosystem as defined in Methodological Framework, 2017*

Ecosystem condition indicators and parameters as grouped in the Bulgarian adaptation of the Whole System approach	
Ecosystem structure	**Ecosystem processes**
Biotic Heterogeneity	**Energy budget**
Plant diversity	Energy balance (capture, storage)
Vegetation cover	Entropy production
Plant species richness	Metabolic efficiency
Animal diversity	Other energy budget indicators
Animal species richness	**Matter budget**
Fungal diversity	Matter balance (input, output)
Red list species	Matter storage
Red list animal species	Efficiency measures
Red list plant species	Element concentrations (other conditional variables)
Invasive species	Element concentrations (other state variables)
Invasive plant species	**Water budget**
Ecosystem presence	Water balance (input, output)
Habitat diversity	Water storage
Other biotic heterogeneity indicators (naturalness etc.)	Efficiency measures
Abiotic heterogeneity	Other conditional indicators
Air heterogeneity	Other state indicators
Hydrological heterogeneity	
Soil quality	
Soil heterogeneity	
Soil erosion risk	

Soil organic matter	
Concentration of pollutants in soil from surrounding areas	
Geomorphological heterogeneity	
Disturbance regime	
Other abiotic heterogeneity indicators	

Table S2. *Cross-reference of indicators between ecosystem types - Biodiversity subsystem*

Ecosystem condition indicators as grouped in the Methodological Framework (2017)	Indicator is used for ecosystem types				
	Grassland (Apostolova et al., 2017)	Heathland and Shrubs (Velev et al., 2017)	Sparsely Vegetated Areas (Sopotlieva et al., 2017)	Woodland and forest (Kostov et al., 2017)	Rivers and Lakes (Uzunov et al., 2017)
Ecosystem structure					
Biotic Heterogeneity					
Vegetation cover	Yes	Yes	Yes		
Habitat diversity				Yes	Yes
Plant diversity or plant species richness	Yes	Yes	Yes	Yes	Yes
Animal diversity or animal species richness	Yes	Yes	Yes	Yes	Yes
Fungal diversity	Yes				
Invasive species (not differentiated by kingdom or differentiated by plant and animal species)	Yes	Yes	Yes	Yes	Yes
Red list species (not differentiated by kingdom or differentiated by plant and animal species)	Yes	Yes	Yes	Yes	
Other biotic heterogeneity indicators (naturalness etc.)	Yes			Yes	Yes

Table S3. *Measurement methods for ecosystem parameters according to the Whole system approach as per the Bulgarian Methodological Framework for mapping and assessment of ecosystem condition and services (Methodological Framework, 2017). Preferred single methods are marked in **bold**; other methods are listed in order of increasing uncertainty (estimated basing on observation method and geolocation uncertainty). Models (in italic) are only applicable for areas with sufficient and consistent data[1].*

Ecosystem condition indicators as grouped in the Bulgarian adaptation of the Whole System approach	Data source(s)
Ecosystem structure	
Biotic Heterogeneity	**Field observations**
Plant diversity	Remote sensing (some
Vegetation cover	indicators only)
Plant species richness	eDNA
Animal diversity	Literature
Animal species richness	*Models and/or data*
Fungal diversity	*combinations between*

[1] Currently, in Bulgaria there are no systematic measurements of the indictors of the "Ecosystem process" group since the corresponding equipment is yet to be procured. Introducing flux measurements is planned as part of the upgrade of the Bulgarian Long-Term Ecosystem Research Infrastructure.

Red list species	*remote sensing and the other data sources*
Red list animal species	
Red list plant species	
Invasive species	
Invasive plant species	
Ecosystem presence	
Habitat diversity	
Other biotic heterogeneity indicators (naturalness etc.)	
Abiotic heterogeneity	**Field observations**
Air heterogeneity	Data from large scale air, water, soil monitoring and climate models
Hydrological heterogeneity	Remote sensing (some indicators only)
Soil quality	Literature
Soil heterogeneity	*Models and/or data combinations between remote sensing and the other data sources*
Soil erosion risk	
Soil organic matter	
Concentration of pollutants in soil from surrounding areas	
Geomorphological heterogeneity	
Disturbance regime	
Other abiotic heterogeneity indicators	
Ecosystem processes	
Energy budget	
Energy balance (capture, storage)	**Remote sensing**
Entropy production	Field data collected in suitably equipped observatories
Metabolic efficiency	*Models and/or data combinations between remote sensing and the other data sources, in particular field observations on fluxes*
Other energy budget indicators	
Matter budget	
Matter balance (input, output)	
Matter storage	
Efficiency measures	
Element concentrations (other conditional variables)	
Element concentrations (other state variables)	
Water budget	
Water balance (input, output)	
Water storage	
Efficiency measures	
Other conditional indicators	

Other state indicators	

2. Data collection

Table S4. *Satellite data sources. Note that Landsat images before Landsat 7 TM have a coarser grid*

№	Date	Sensor	NDWI availability
1	22/08/1977	Landsat	Not available
2	23/05/1984		Not available
3	26/07/1984		Not available
4	27/06/1985		Not available
5	22/05/1986		Available
6	04/10/1986		Not available
7	03/07/1987		Not available
8	11/07/1990		Not available
9	02/09/1992		Available but not calculated/ NDVI verified with NDGI for the period 1985 - 1994
10	29/06/1994		Not available
11	28/06/2000		Available
12	13/06/2009		Available
13	15/07/2009		Available
14	22/08/2011		Available
15	23/09/2011		Available
16	09/09/2012		Not available
17	02/08/2016	Sentinel 2	Available
18	02/05/2017	Landsat	Available
19	02/08/2017	Sentinel 2	Available
20	27/08/2017		Available
21	26/10/2017		Available
22	03/04/2018	Landsat	Available
23	06/10/2018	Sentinel 2	Available
24	16/10/2018		Available
25	26/10/2018		Available
26	24/04/2019		Available
27	13/06/2019		Available
28	23/06/2019		Available
29	03/07/2019		Available
30	12/08/2019	Landsat	Available

31	01/09/2019	Sentinel 2	Available
32	13/09/2019	Landsat	Available but not calculated/ NDVI verified with NDGI for the period 12.08.2019 – 13.09.2019
33	16/09/2019	Sentinel 2	Available

Table S5. *Data collection of the NDVI and climate parameter values used for Pearson Correlation analyses and correlation coefficients*

Date of image	NDVI value	t2m	tp	evpt	v10
22/08/1977	0.065607	no data	no data	no data	no data
23/05/1984	0.191586	6.513	2.684	-0.882	1.818
26/07/1984	0.381537	14.328	0.000	-1.480	-1.523
27/06/1985	0.503099	8.586	3.492	-0.932	-1.740
22/05/1986	0.283476	6.051	2.264	-0.755	-1.375
04/10/1986	0.358145	5.955	0.000	-0.433	-2.022
03/07/1987	0.45117	14.868	0.000	-1.761	-0.574
11/07/1990	0.46277	18.375	0.006	-1.313	2.079
02/09/1992	0.479891	17.145	0.004	-0.937	-2.583
29/06/1994	0.450397	9.065	0.000	-1.320	-1.703
28/06/2000	0.329287	9.379	0.978	-0.811	-2.672
13/06/2009	0.519486	12.299	0.982	-0.936	2.138
15/07/2009	0.582377	14.496	14.882	-0.733	-0.399
22/08/2011	0.464104	14.017	10.069	-1.170	-1.894
23/09/2011	0.5032	16.178	0.082	-0.731	-0.345
09/09/2012	0.479091	13.001	0.000	-0.901	0.040
02/08/2016	0.539184	17.056	1.412	-1.237	-1.918
02/05/2017	0.231385	8.555	1.074	-0.963	-0.042
02/08/2017	0.786584	15.066	0.000	-1.418	-1.332
27/08/2017	0.753507	15.066	0.000	-1.418	-1.332
26/10/2017	0.469508	6.433	0.005	-0.332	-0.277
03/04/2018	0.158468	1.345	2.308	-0.694	-1.040
06/10/2018	0.478677	8.481	0.134	-0.214	0.199
16/10/2018	0.537403	8.481	0.134	-0.214	0.199
26/10/2018	0.560783	8.481	0.134	-0.214	0.199
24/04/2019	0.289828	2.946	0.000	-0.701	-1.253
13/06/2019	0.618859	11.227	3.077	-1.042	-0.992
23/06/2019	0.548105	11.227	3.077	-1.042	-0.992
03/07/2019	0.689729	16.637	0.000	-1.693	-0.298

12/08/2019	0.383913	15.477	2.888	-1.188	-1.675
01/09/2019	0.664057	no data	no data	no data	no data
13/09/2019	0.305227	no data	no data	no data	no data
16/09/2019	0.63779	no data	no data	no data	no data
Correlation coefficient between NDVI and climate parameter:		**0.605**	**0.0228**	**-0.275**	**-0.0184**

Table S6. *Changes in t2m parameter values during the months May, June, July and August for the period 1979 – 2019 and 1979 – 2018 for September*

t2m values, ⁰ C	May 1979- 2019		June 1979- 2019		July 1979- 2019		August 1979- 2019		September 1979- 2018	
	1979-1999	1999-2019	1979-1999	1999-2019	1979-1999	1999-2019	1979-1999	1999-2019	1979-1999	1999-2019
Mean	6.3	8.5	10.4	11.5	13.8	14.7	15.9	15.3	12.5	13.7
Min.	2.3	3.8	4.9	7.5	8.8	10.2	12.8	12.7	7.6	8.3
Max.	13.8	14.6	14.8	16.2	18.4	23.6	19.9	18.9	17.2	17.7

3. Data analysis: single data sources
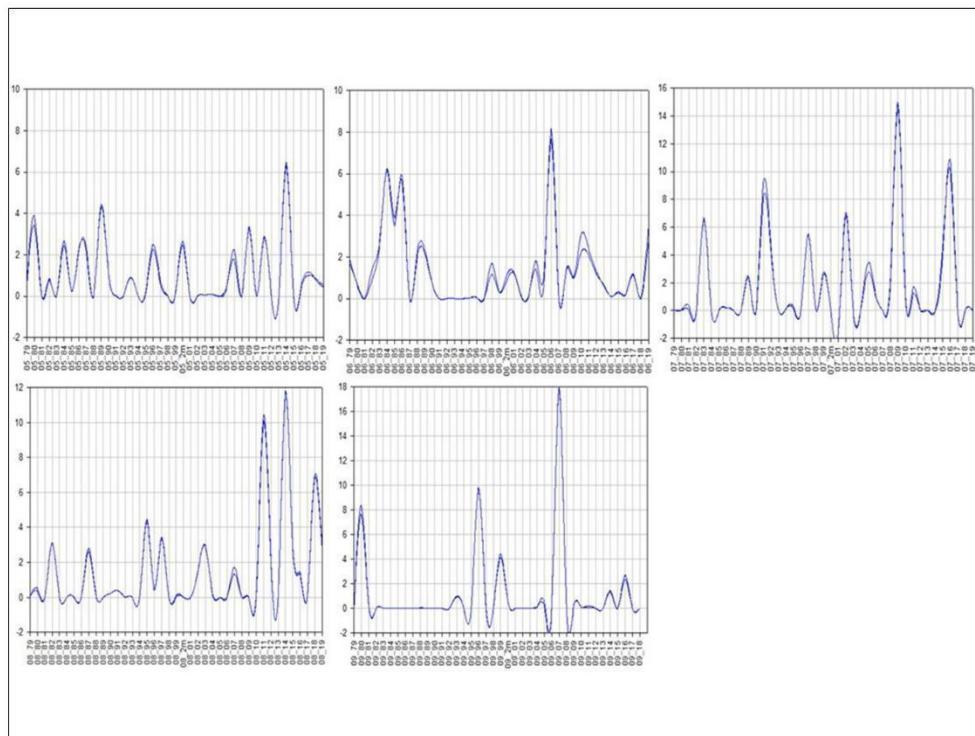
Figure S1. *Long-term trends in tp parameter during the vegetation season: a) May; b) June; c) July; d) August, and e) September*
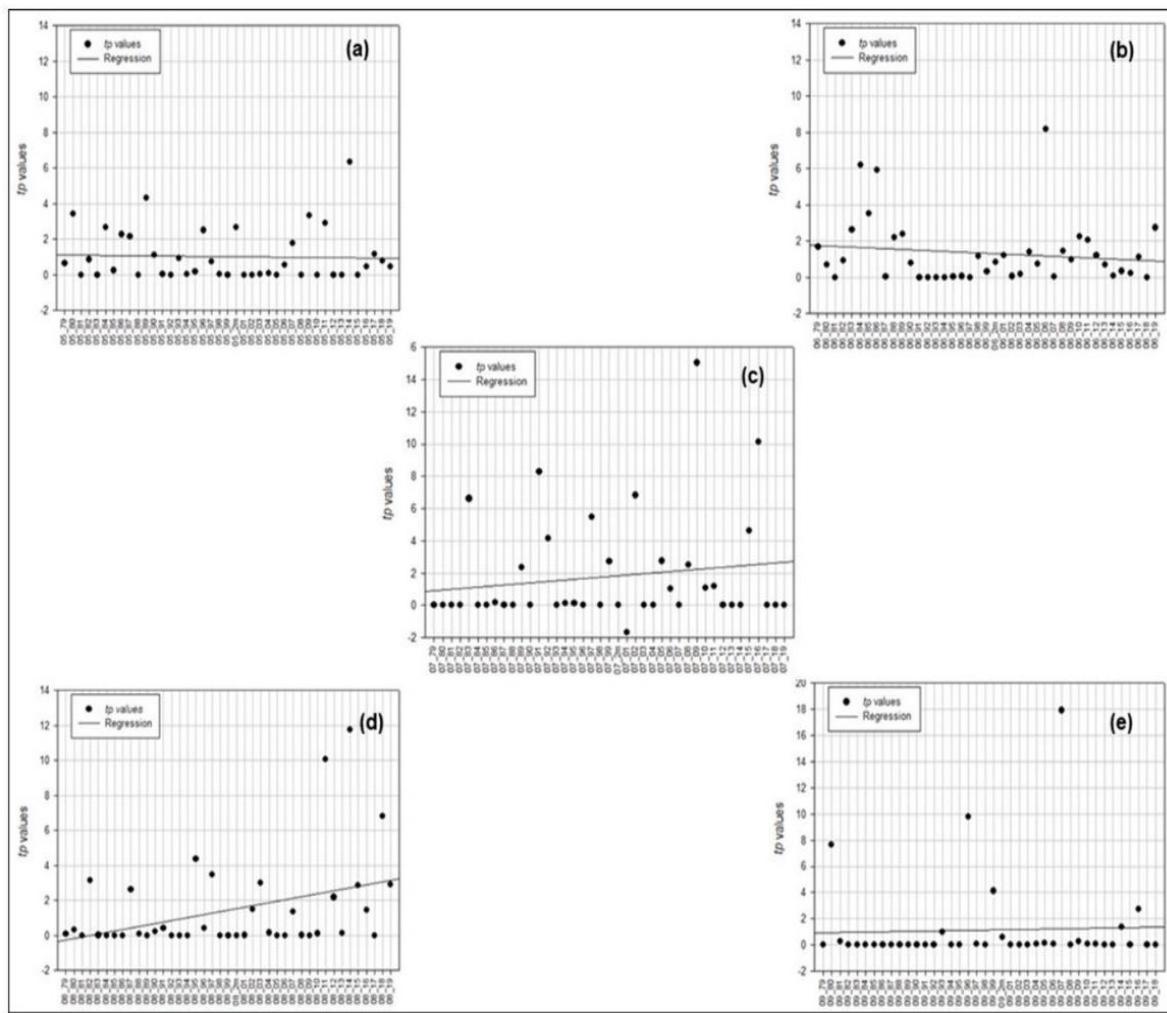
Figure S2. Long-term linear regression trends of tp by month: a) May; b) June; c) July; d) August, and e) September
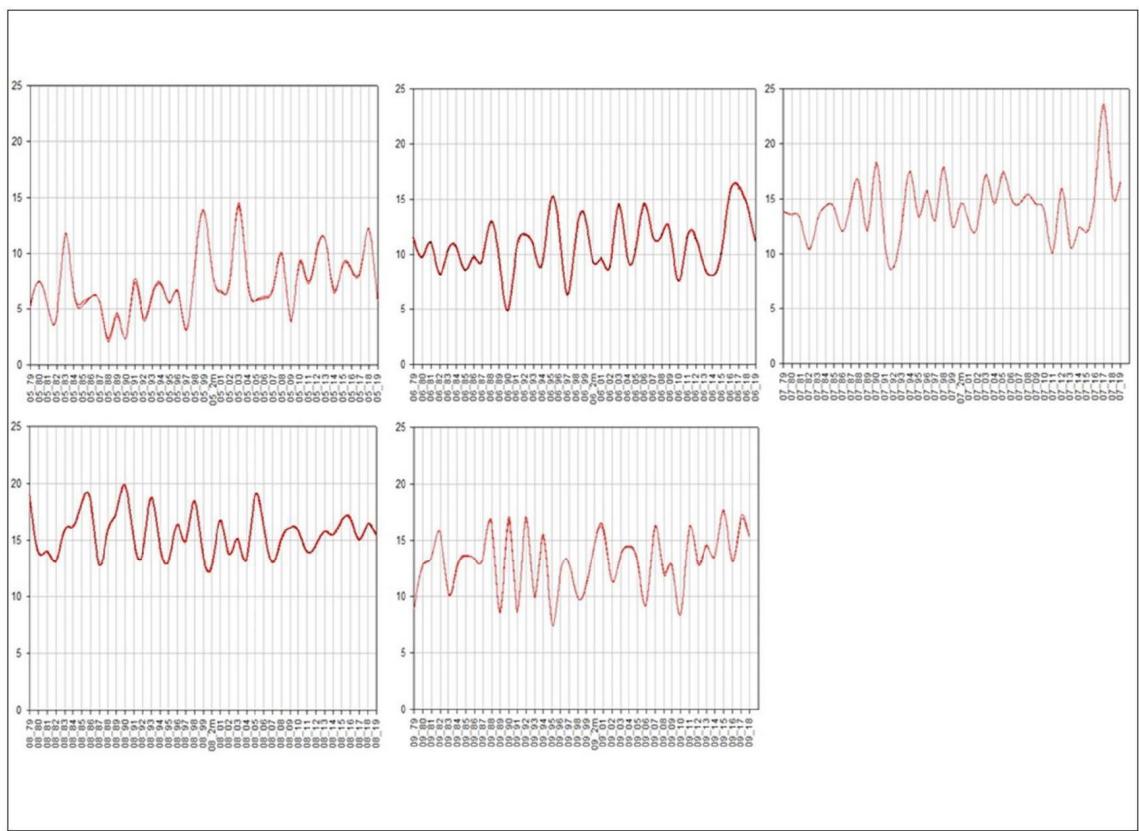
Figure S3. *Long-term trends in monthly temperatures in the active vegetation months (May to September)*
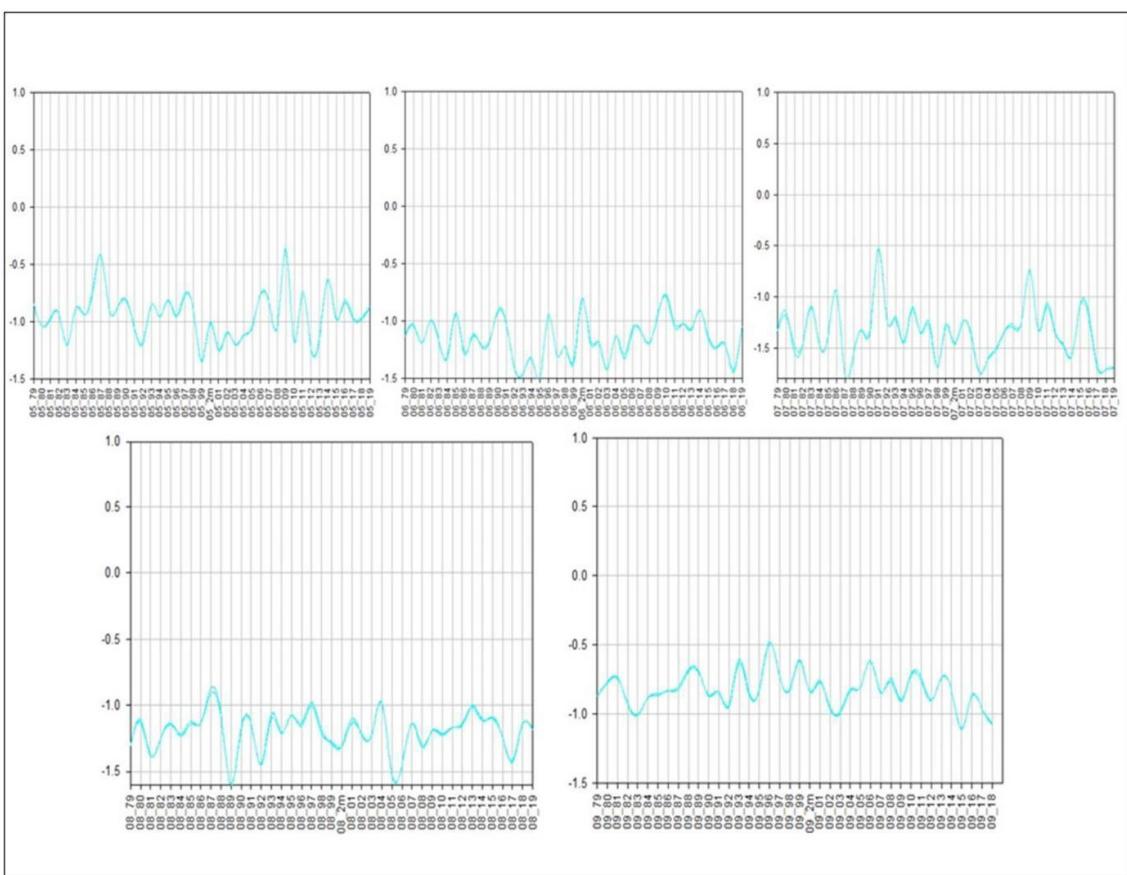
Figure S4. *Graph of evpt by month: a) May; b) June; c) July; d) August, and e) September*
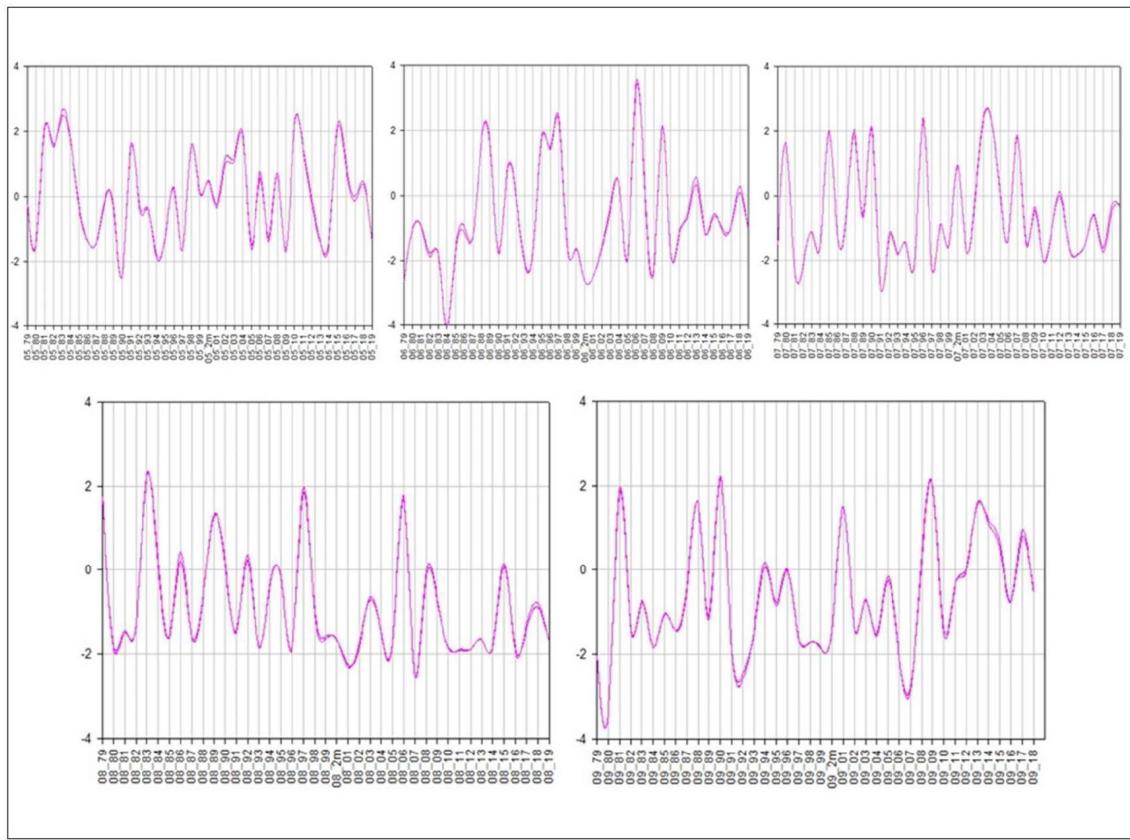
**Figure S5.** *Long-term graph of v10 by month: a) May; b) June; c) July; d) August, and e) September*
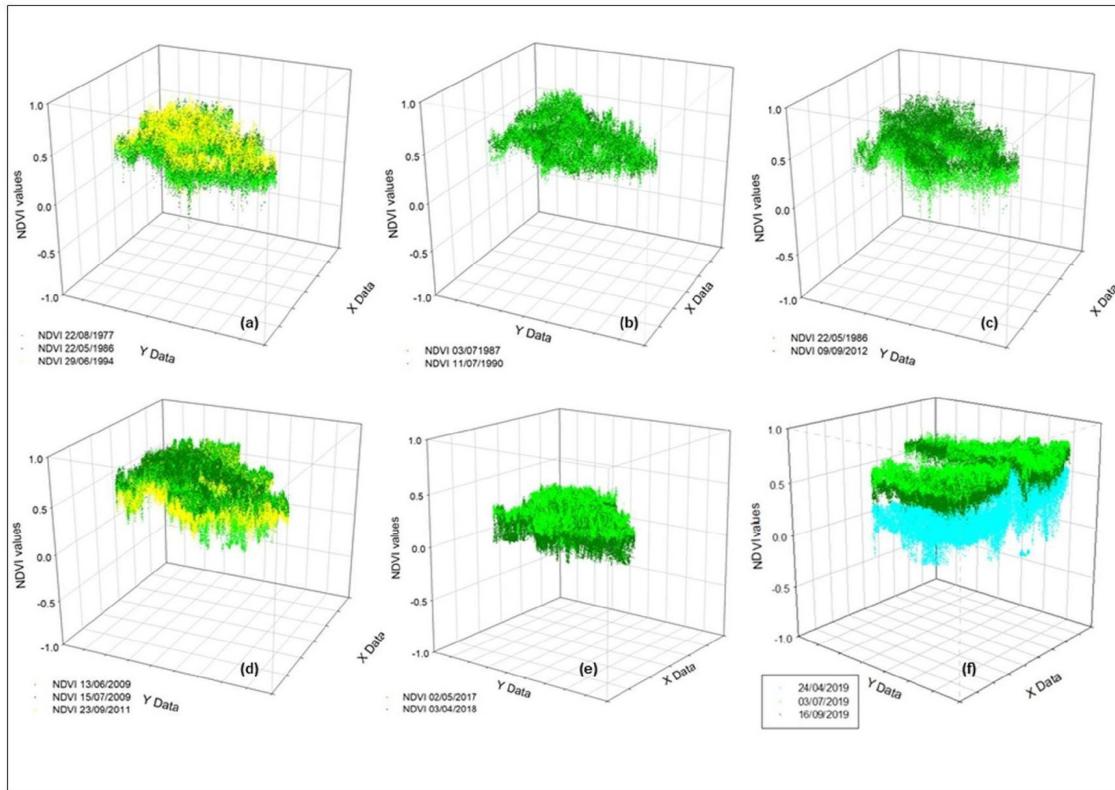
Figure S6. 3D graphics of the NDVI values for the period 1977 – 2019: a, b – in the beginning; c, d – in the middle; e, f – in the end of the period

4. Data analysis: combining satellite and climate data
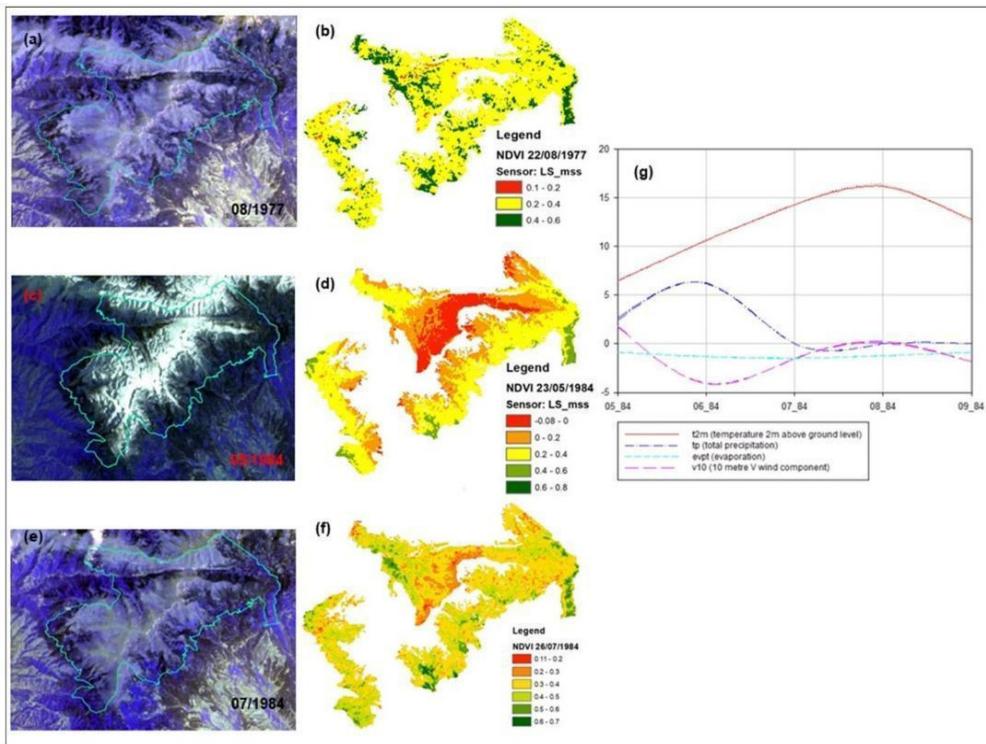
Figure S7. Data collection for vegetation periods in 1977 and 1984: (a, c, e) – satellite images; (b, d, f) – TM of NDVI: (b) The NDVI values were above 0 all over the study area and the advanced vegetation phase (i.e. leaf biomass production), which suggests overall good functionality of the HME; (g) – diagram of climate parameters dynamics. Due to the lack of t2m data, for 1977 we only show NDVI data
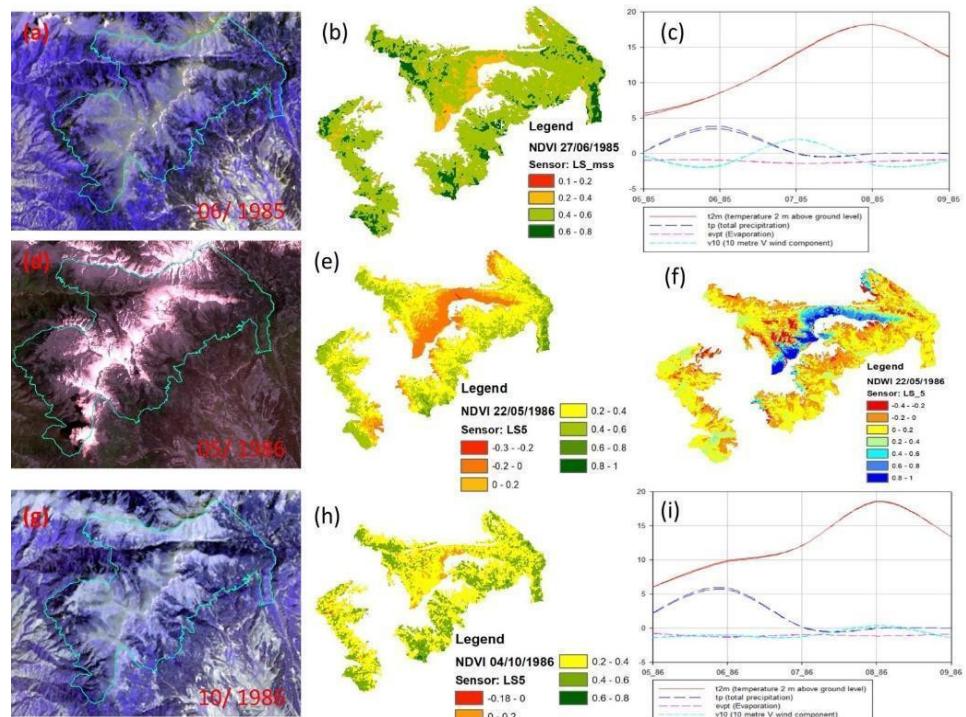
Figure S8. Data collection for vegetation period in 1985 and 1986: (a, d, g) – satellite images; (b, e, h) – TM of NDVI; (f) – TM of NDWI; (c,i) – diagrams of climate parameters dynamics
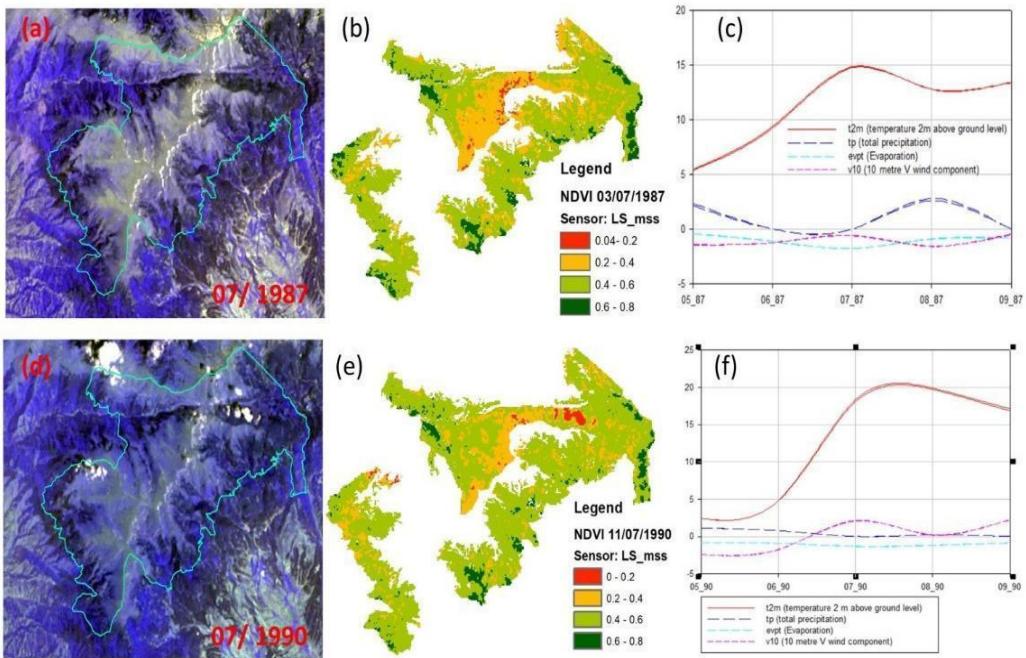
Figure S9. Data collection for vegetation periods in 1987 and 1990: (a, d) – satellite images; (b, e) – TM of NDVI; (c, f) – diagrams of climate parameters dynamics
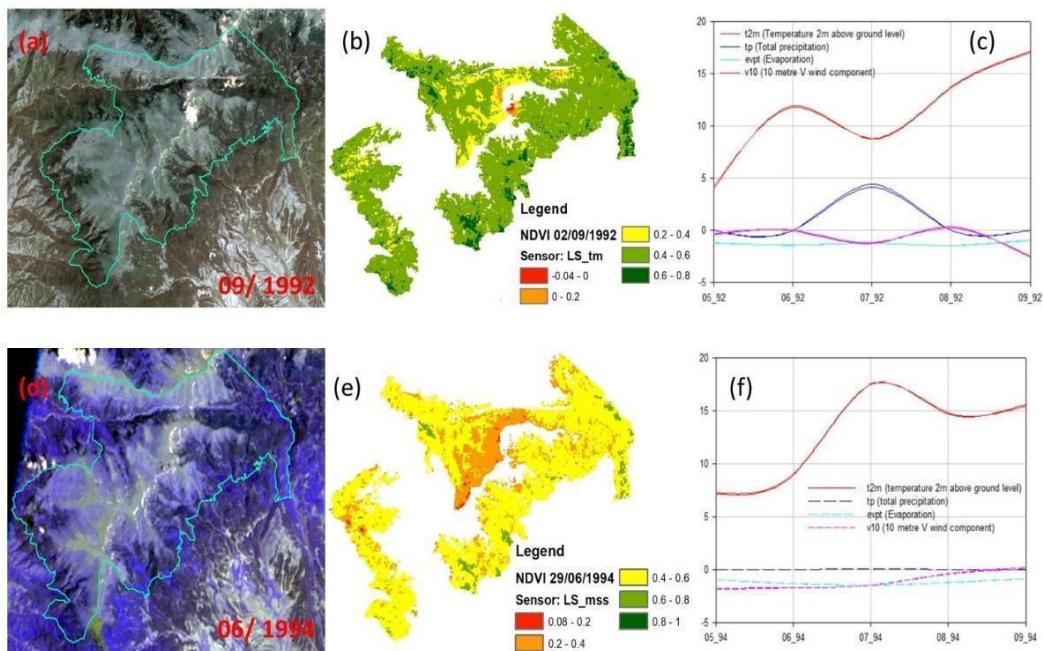
Figure S10. Data collection for vegetation periods in 1992 and 1994: (a, d) – satellite images; (b, e) – TM of NDVI; (c, f) – diagrams of climate parameters dynamics
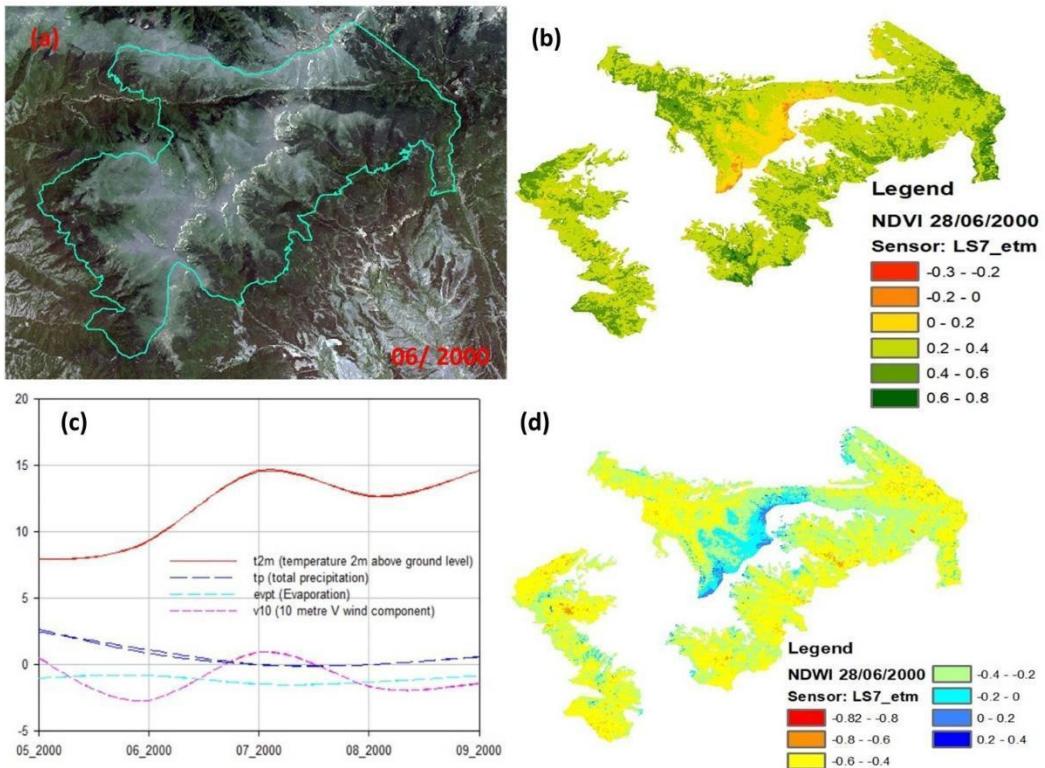
Figure S11. Data collection for vegetation period in 2000: (a) – satellite image; (b) – TM of NDVI; (c) – diagram of climate parameters dynamics; (d) – TM of NDWI
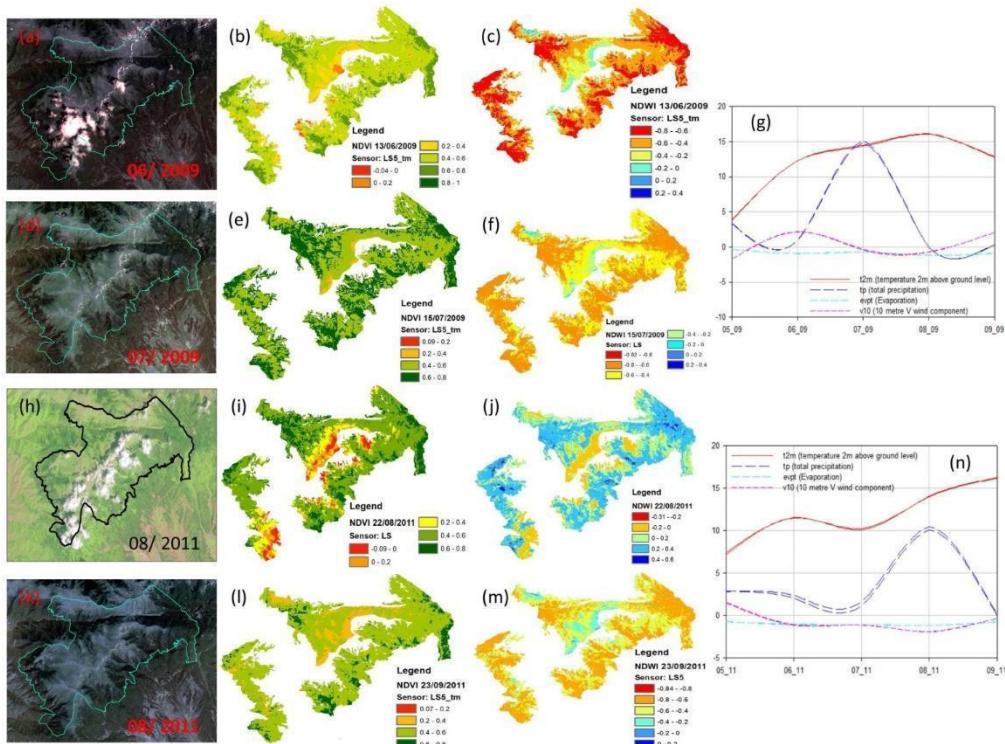
Figure S12. Data collection for vegetation periods in 2009 and 2011: (a, d, h, k) – satellite images; (b, e, i, l) – TM of NDVI; (c, f, j, m) - TM of NDWI; (g, n) – diagrams of climate parameters dynamics
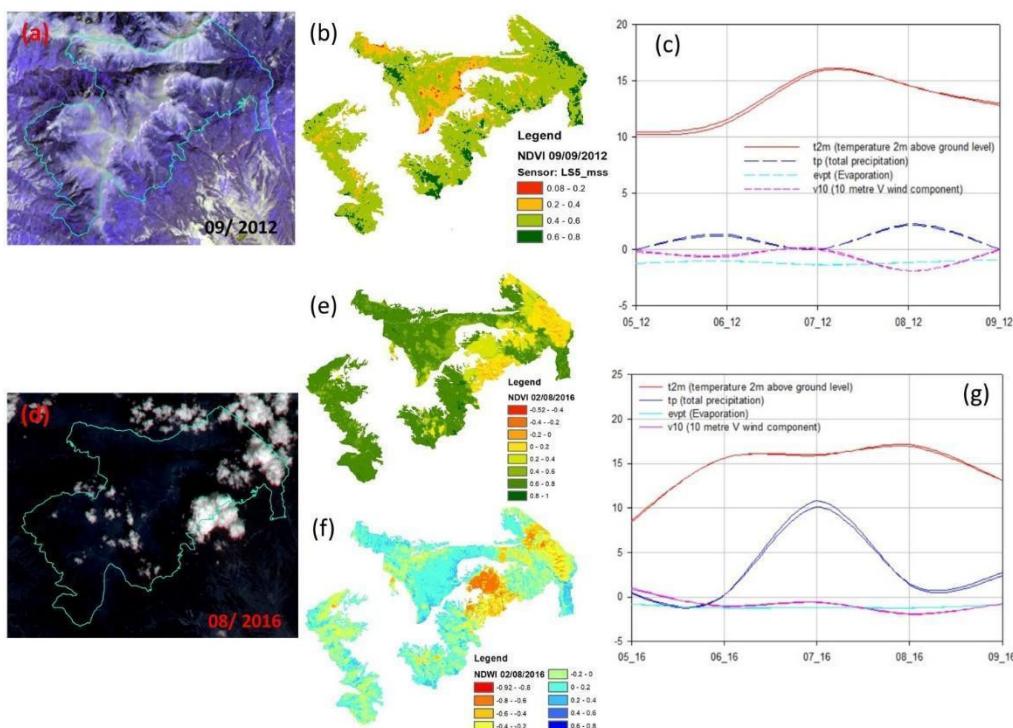
Figure S13. Data collection for vegetation periods in 2012 and 2016: (a, d) – satellite images; (b, e) – TM of NDVI; (f) - TM of NDWI; (c, g) - diagrams of climate parameters dynamics
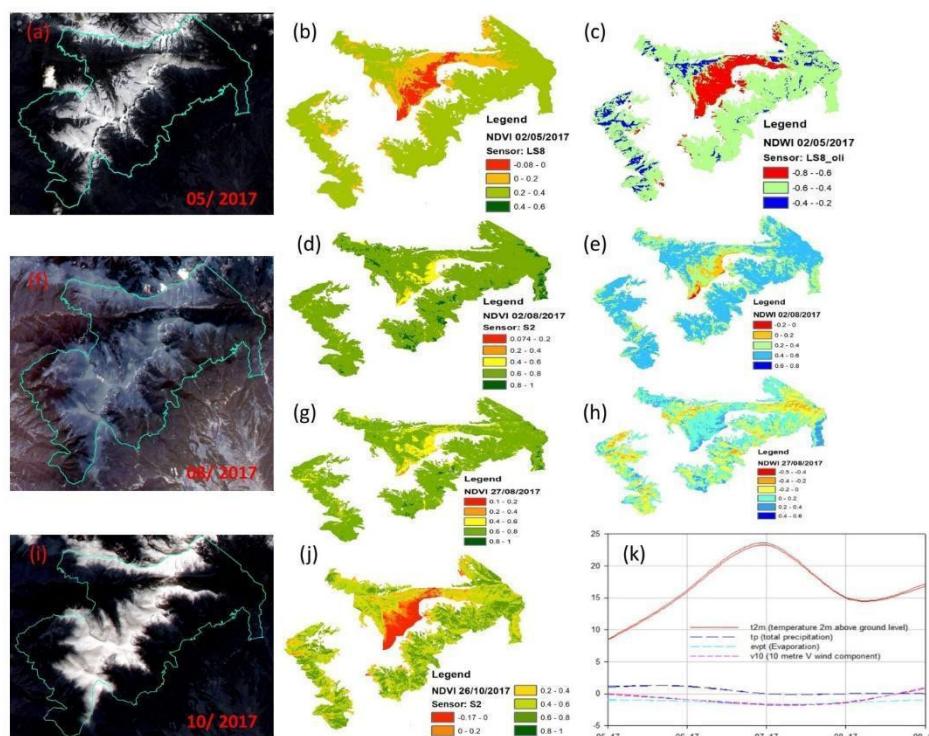

Figure S14. Data collection for vegetation period in 2017: (a, f. i) – satellite images; (b, d, g, j) – TM of NDVI; (c, e, h) - TM of NDWI; (k) – diagram of climate parameters dynamics
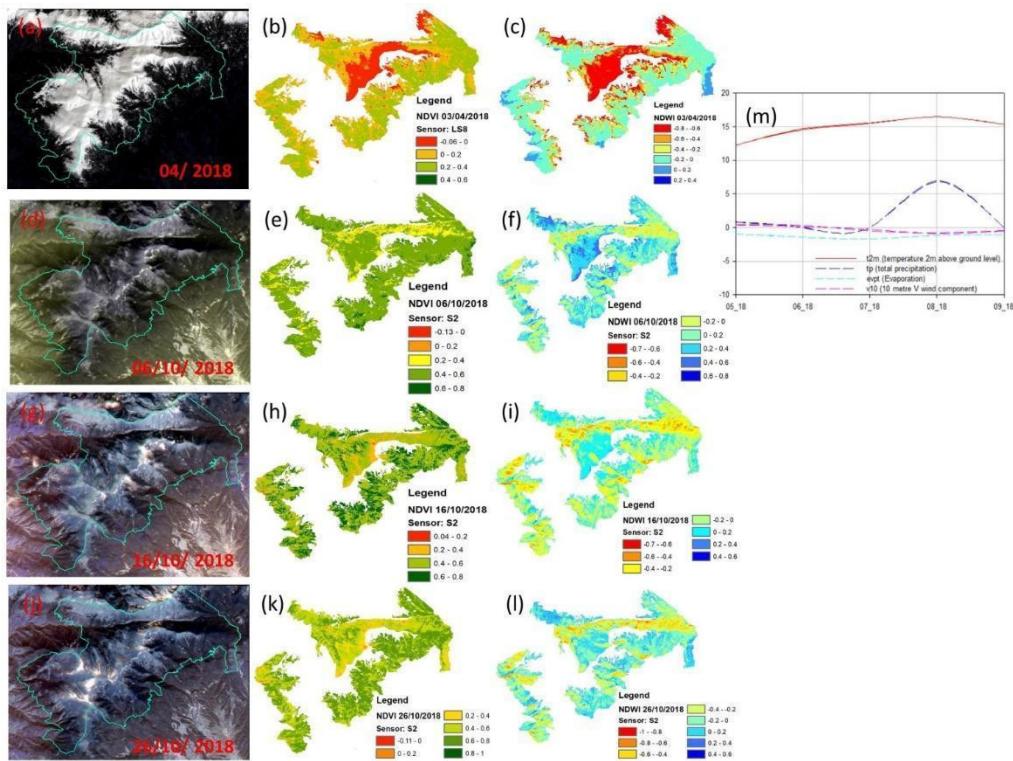
Figure S15. Data collection for vegetation period in 2018: (a, d, g, j) – satellite images; (b, e, h, k) – TM of NDVI; (c, f, i, l) – TM of NDWI; (m) - diagram of climate parameters dynamics
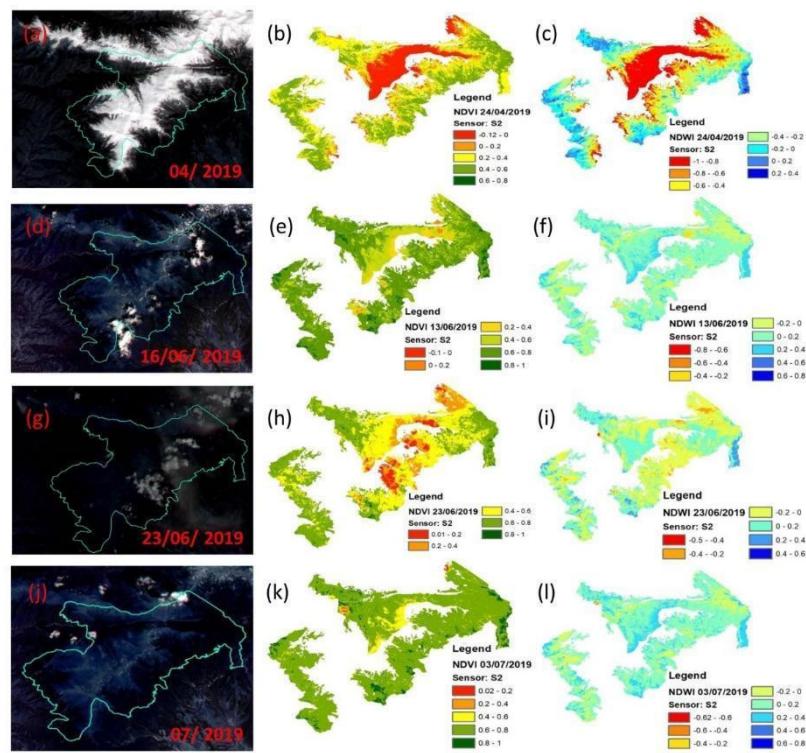

Figure S16. Data collection for vegetation period in 2019- part 1: (a, d, g, j) – satellite images; (b, e, h, k) – TM of NDVI; (c, f, i, l) – TM of NDWI
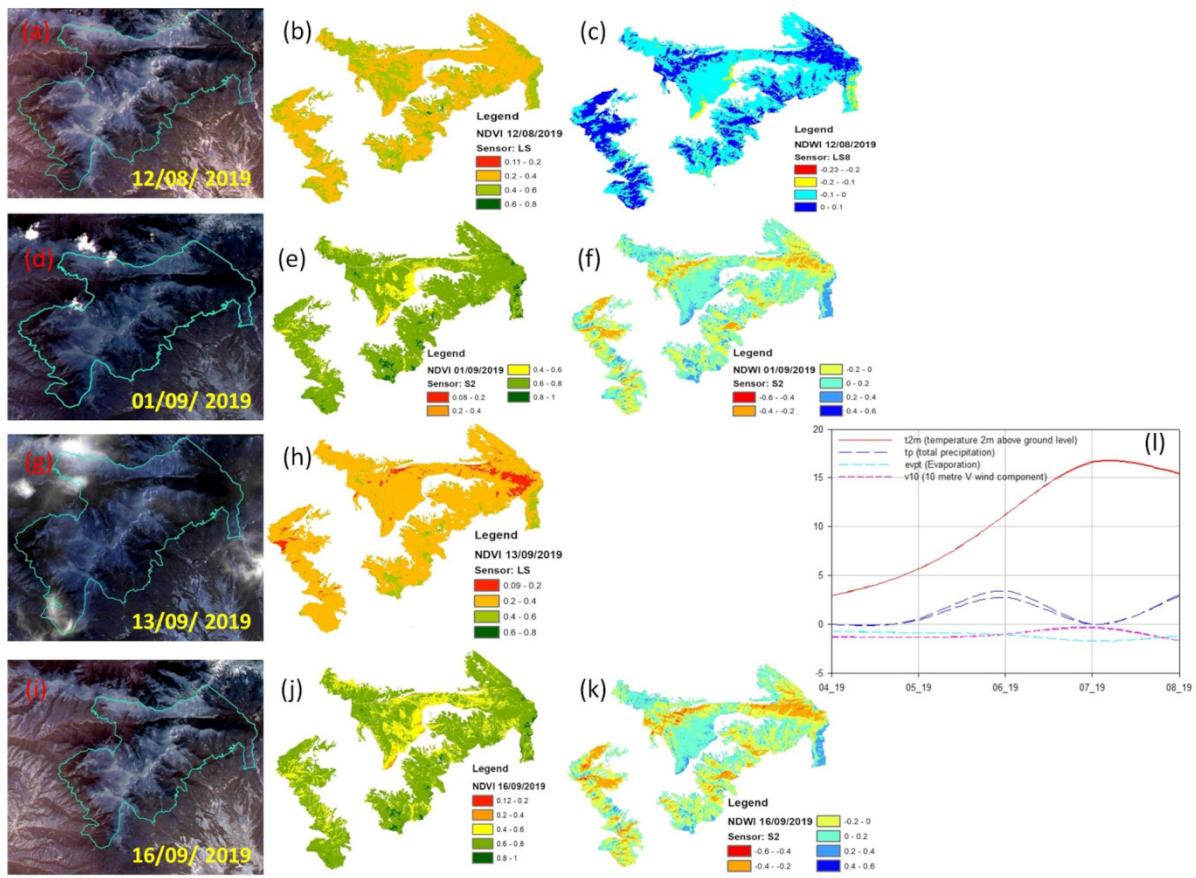
Figure S17. *Data collection for vegetation period in 2019- part 2: (a, d, g, i) – satellite images; (b, e, h, j)- TM of NDVI; (c, f, k) – TM of NDWI and diagram of climate parameters dynamics (l)*
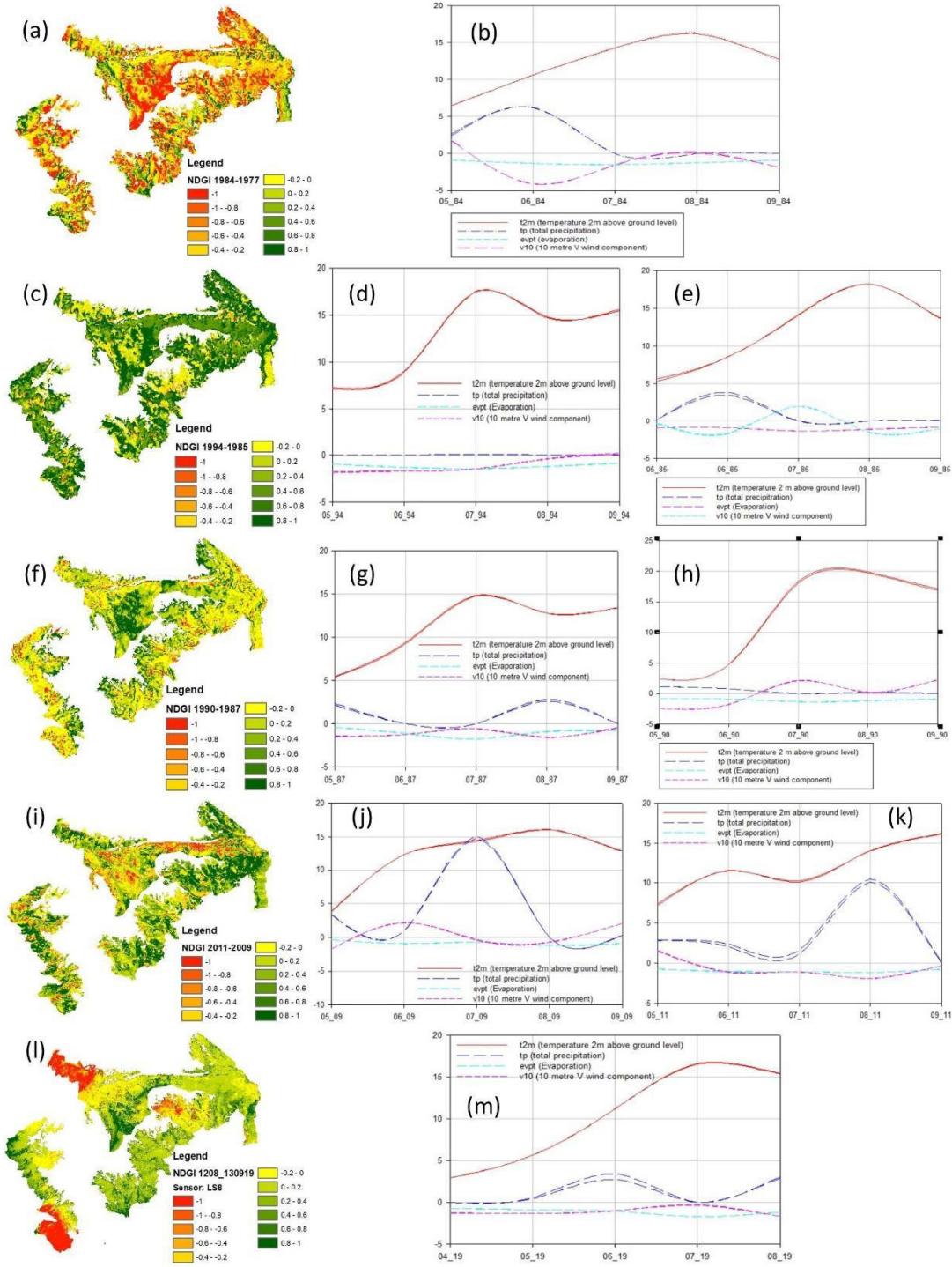
Figure S18. *Relation between NDGI and the respective climate conditions: (a) TM of NDGI between 22/08/1977 and 23/05/1984; (c) TM of NDGI between 03/07/1987 and 11/07/1990; (f) TM of NDGI between 27/06.1985 and 29/06.1994 (i) TM of NDGI between 13/06/2009 and 23/09/2011; (l) TM of NDGI between 12/08/2019 and 13/09/2019; (b, d, e, g, h, j, k, m) – diagrams of climate parameter dynamics for 1984, 1987, 1990, 1985, 1994, 2009, 2011 and 2019, respectively*

5. Data cross-validation: NDGI as means to identify outliers

This section describes the analytical steps for using a more sensitive vegetation index – NDGI – as a means to identify outliers.

As revealed in Figure S 17, there seems to be a double peak in vegetation growth in September 2019 – active growth indication on 01/09 and 16/09 while the growth seems to have stalled in the image taken

on 13/09. Considering there ought to be a time lag between rainfall and actual robust vegetation growth, this image sequence can be interpreted either as a sharp resurgence in growth after a dip in mid-September (caused by an earlier dip in rainfall in June), or as a flawed image, possibly due to mist whose extent was not correctly detected during cloud filtering. Since the NDWI for 11/09/2019 cannot be derived due to sensor limitations, we looked at NDGI to verify the possible extent of atmospheric distortion in the image quality. The NDGI image (Figure 8e) shows an even bigger extent of distortion in apparent growth patterns (indicated by anomalous values at or close to -1) than the visual inspection of cloud cover (Figure S 17g). In the NDGI, there's a much smoother transition from cloud covered areas to areas with apparent high vegetation growth than what would be manifest in case of single distinct cloud shadows. Thus, we found a strong indication of mist distorting the satellite scene taken on 13/09/2019, which causes a high uncertainty in its NDVI data. For this reason, we discarded the NDGI TM for the difference between 12/08 and 13/09/2019 from the further statistical analysis.