Project USAID "Economical support of Eastern Ukraine"

Methodology for mapping fire intensity and soil burn severity

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1. Research methodology

1.1. Remote sensing data

Three types of remote sensing (RS) data were incorporated in the study to determine fire burn severity and soil burn severity:

1) Suomi NPP VIIRS and MODIS MOD/MYD14 data on thermal anomalies – to determine the dates when fires started.
2) PlanetScope multispectral satellite images – to determine approximate perimeters of burned areas hereinafter referred to as areas of interest (AOI).
3) Sentinel 2 multispectral satellite images – to classify territories by fire burn severity, i.e., fire intensity imposed to vegetation, as well as soil burn severity.

1.1.1. Data on thermal anomalies

Data on thermal anomalies for the territory were interactively analyzed using web-interface https://worldview.earthdata.nasa.gov/ (Fig. 1). Based on this, two large fires were identified that occurred within the research territory in 2020. The start date of the first fire (July 6, 2020, Fig. 1b, sheet 1) as well as the end date of the fires, that occurred at the end of September and at the beginning of October (October 9, 2020, Fig. 1b, sheet 2) were used to determine a time interval to select satellite images and analyze changes in spectral characteristics of land cover.

1.1.2. PlanetScope satellite images

PlanetScope multispectral satellite images were used to determine approximate perimeters of burned areas, that allowed to focus on precise mapping of disturbance levels within AOI. Images were chosen according to start and end dates of fire period. PlanetScope satellite images, acquired during July 3–5, 2020, depicted the state of the territory before the fire, while those acquired on October 9, 2020 (Table 1) depicted the state of the territory after the fire. Considering that the analysis was done visually, there were no special requirements for the image mosaics regarding seasonality of images acquisition (e.g., summer or autumn images), but the dates were chosen based on availability of cloudless images. High spatial resolution (3 m) together with spectral bands combination (B3-B4-B2) allowed to outline perimeter of burned areas, that consisted of nine separate polygons (Fig. 3).

Table 1. Identifiers of scenes of PlanetScope satellite images

Summer mosaic (before the fire)	Autumn mosaic (after the fire)
20200704_053349_104b_3B_AnalyticMS_SR	20201009_073508_49_2277_3B_AnalyticMS_SR
20200704_053348_104b_3B_AnalyticMS_SR	20201009_051437_0f49_3B_AnalyticMS_SR
20200704_053347_104b_3B_AnalyticMS_SR	20201009_051438_0f49_3B_AnalyticMS_SR
20200703_073324_60_2271_3B_AnalyticMS_SR	20201009_051439_0f49_3B_AnalyticMS_SR
20200705_074409_0e20_3B_AnalyticMS_SR	20201009_051440_0f49_3B_AnalyticMS_SR
20200705_074408_0e20_3B_AnalyticMS_SR	20201009_080121_0f17_3B_AnalyticMS_SR
20200705_074407_0e20_3B_AnalyticMS_SR	20201009_080122_0f17_3B_AnalyticMS_SR
20200705_074406_0e20_3B_AnalyticMS_SR	20201009_080123_0f17_3B_AnalyticMS_SR
20200704_074635_64_1067_3B_AnalyticMS_SR	20201009_082836_77_2307_3B_AnalyticMS
20200704_074634_08_1067_3B_AnalyticMS_SR	20201009_082839_13_2307_3B_AnalyticMS
20200704_074632_52_1067_3B_AnalyticMS_SR	20201009_082926_63_2419_3B_AnalyticMS
20200705_081558_83_105c_3B_AnalyticMS_SR	20201009_082928_98_2419_3B_AnalyticMS
20200705_081556_96_105c_3B_AnalyticMS_SR	

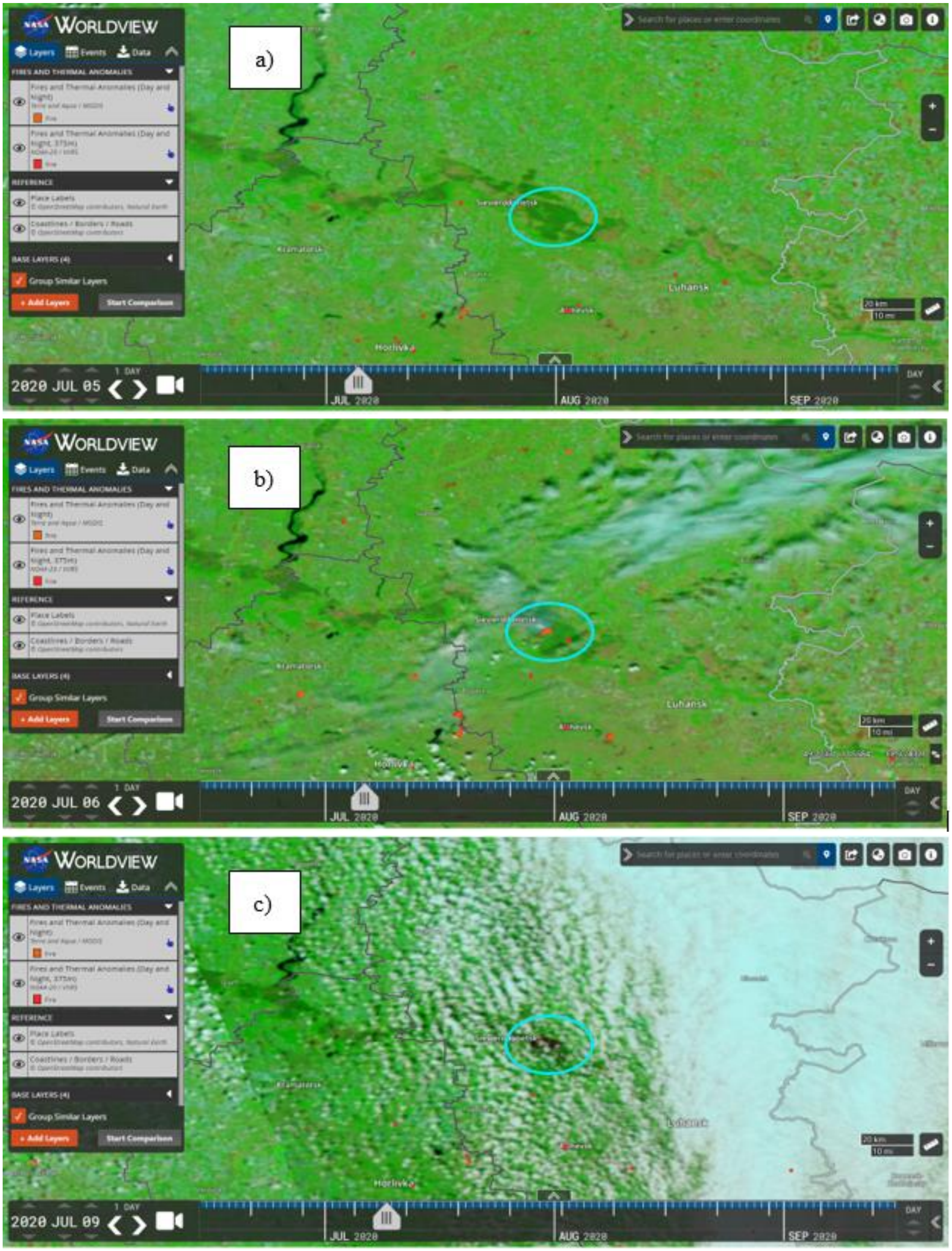


Fig. 1, sheet 1. Identification of fires on the research area (July 2020)

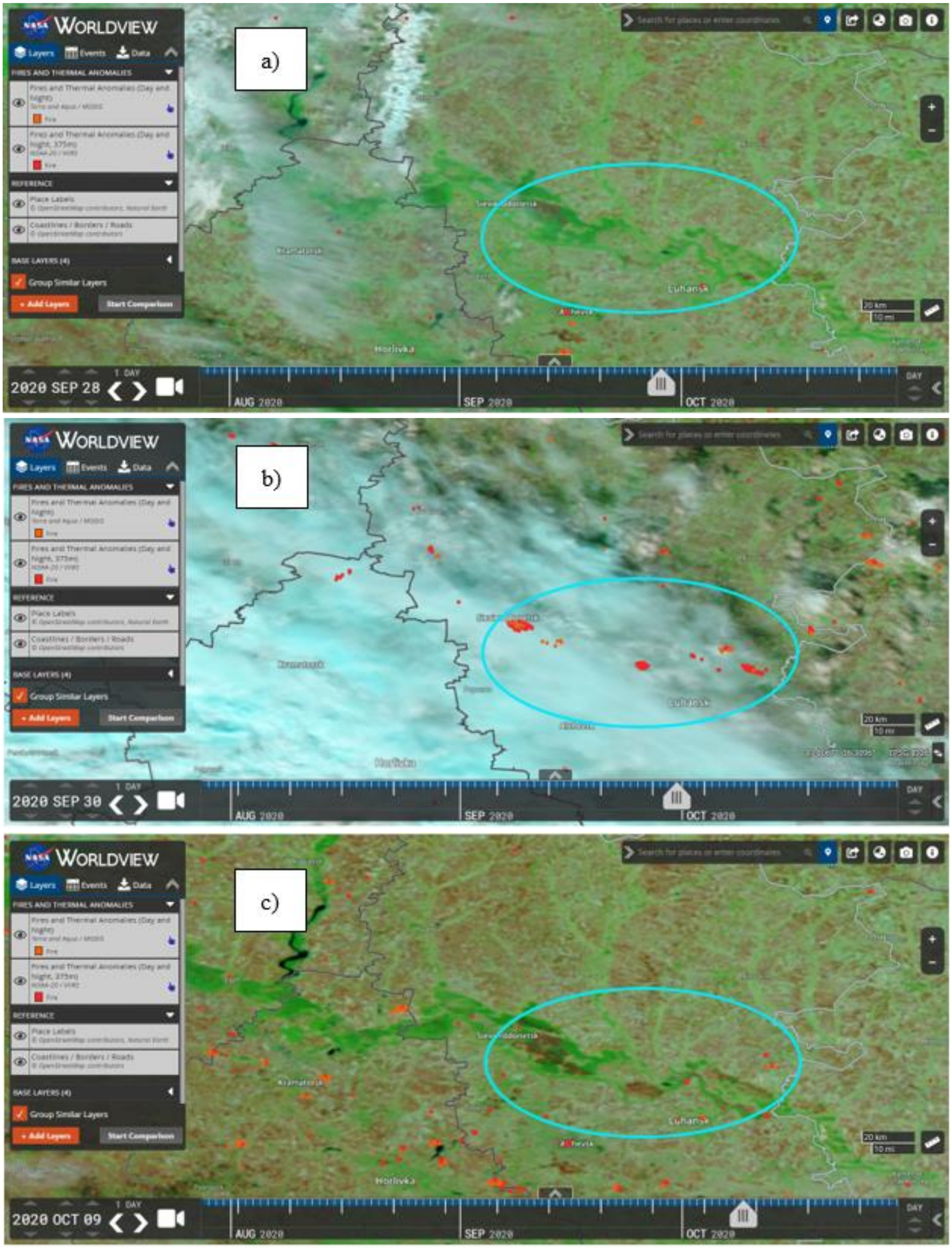


Fig. 1, sheet 2. Identification of fires on the research area (September – October 2020)

Fig. 2. Autumn mosaic from PlanetScope images (band combination 3–4–2): polygons depict perimeters of burned areas, which were outlined manually

1.1.3. Sentinel 2 satellite images

Fire burn severity levels were mapped based on Sentinel 2 multispectral satellite images. The images were collected to depict the state of the territory before and after the fire during the same phenological phase of vegetation. Within outlined fire contours (Fig. 2) two cloudless mosaics from Sentinel 2 images was created: before the fire using October 16, 2019 imagery, and after the fire using October 15, 2020 imagery (Fig. 3). In the study, we used the 2A level of satellite data processing. Spectral bands of those images characterize surface reflectance, which is a very important prerequisite for a bi-temporal data comparison. Besides, within the area of interest images were absolutely cloudless, which made it possible not to apply additional algorithms to improve the quality of mosaics.

Table 2. Scene identifiers of Sentinel 2 satellite images

Summer mosaic (before the fire)	Autumn mosaic (after the fire)
20191016T082929_20191016T083251_T37UDP	20201015T082931_20201015T083307_T37UEQ
20191016T082929_20191016T083251_T37UDQ	20201015T082931_20201015T083307_T37UEP
20191016T082929_20191016T083251_T37UEP	20201015T082931_20201015T083307_T37UDQ
20191016T082929_20191016T083251_T37UEQ	20201015T082931_20201015T083307_T37UDP

Classification of the territory by fire burn severity was performed based on $dNBR$ index (Key & Benson, 2006):

$$dNBR = NBR_{prefire} - NBR_{postfire}, \quad (1)$$

where $NBR_{prefire}$ та $NBR_{postfire}$– values of NBR index calculated accordingly before and after the fires.

Overall, NBR index is calculated for every pixel of the image based on data of NIR and SWIR 2 bands:

$$NBR = 1000 \cdot (NIR - SWIR\ 2)/(NIR + SWIR\ 2). \qquad (2)$$

Because Sentinel 2 band 8 (NIR – 0.83 micrometers) and band 12 (SWIR 2.0–2.2 micrometers) have different spatial resolution (10 m and 20 m accordingly), the fires were mapped at lower spatial resolution – 20m.

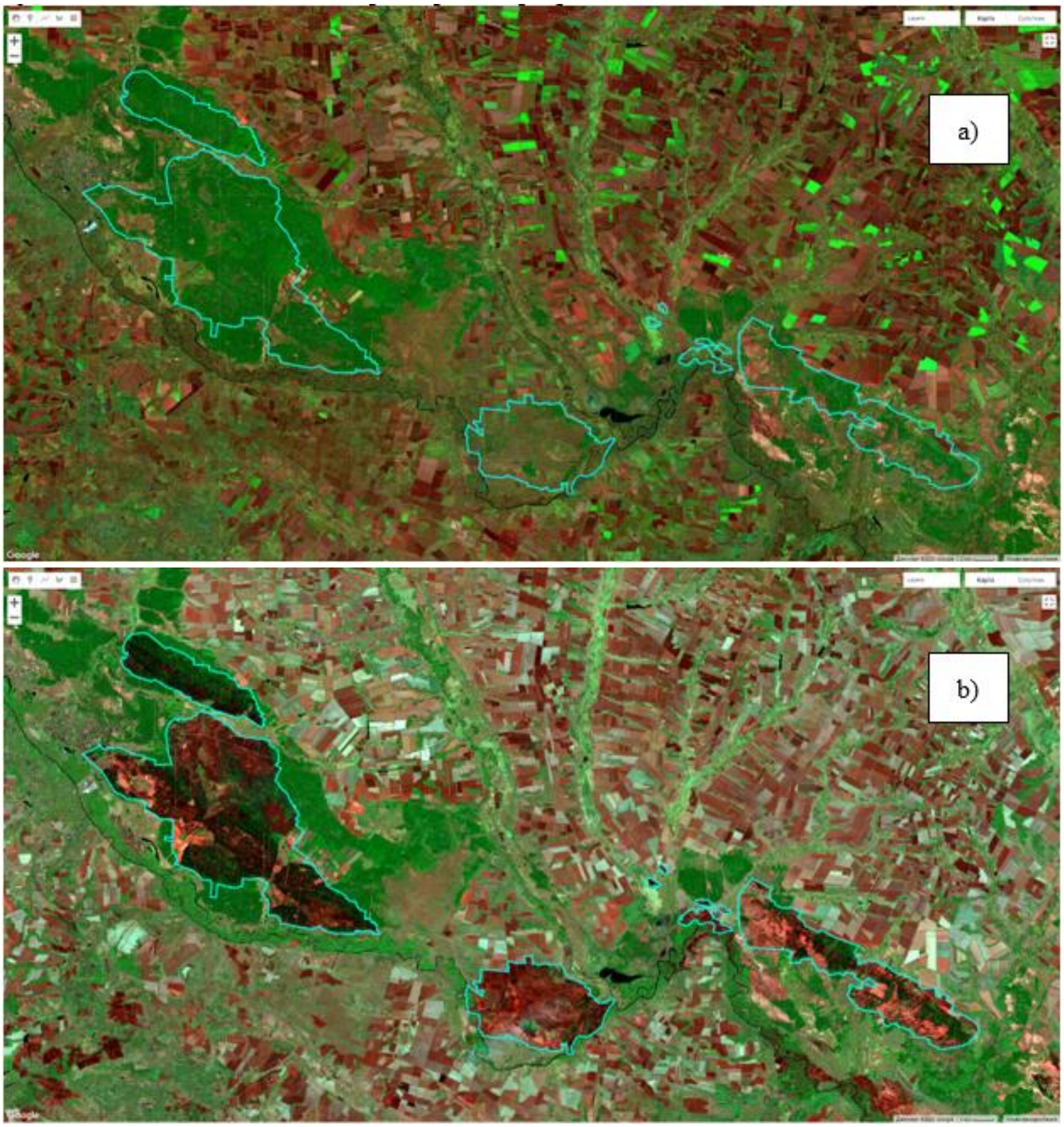


Fig. 3. Sentinel 2 mosaics before and after the fire (band combination 12–8–5): a) October 2019, b) October 2020; polygons depict perimeters of burned areas which were outlined manually

Preliminary, the territory was classified into three levels of fire burn severity using *dNBR* threshold values originally described by Key & Benson, 2006: high (≥ 0.660), moderate (0.270 ÷ 0.659), low (0.100 ÷ 0.269).

1.2. Stratification of the burned areas and field data

The forest inventory enterprise (PA Ukrderzhlisproject) database was used to assess the accuracy of the map of burned areas and further apply it in developing forest renewal strategy. Information on forested and unforested areas affected by fires was extracted from the database, then used to create an effective field sampling design. Thus, we focused on stratification approach that depicts the smallest number of homogeneous strata and could be used to prepare unified recommendation on forest renewal strategy. The applied scheme takes into account combinations of land categories, forest vegetation conditions, and predominant tree species (Table 3).

Table 3. The scheme of stratification of the study area

Code of the strata	Land cover class before fire	Site conditions	Main species	Percentage of the area, %
10	Forested areas	A_{2-3}	Scots pine	27
20	Forested areas	B_{2-3}	Scots pine	22
30	Forested areas	A_{0-1}; B_1; C_1; D_1	Deciduous species, Scots pine	10
40	Forested areas	A_{2-3}; B_{2-3} B_4; C_{2-5}; D_{2-5} C_{2-3}; D_{2-3}	Deciduous species Deciduous species Scots pine	8 5 1
50	Unforested areas	A_{0-1}; B_1; C_1; D_1	–	9
60	Other unforested areas and non-forest lands	A_{2-3}; B_{2-3} B_4; C_{2-5}; D_{2-5}	–	17 1

The adopted scheme implies an unified forest recovery strategy within the appropriate level of fire intensity and soil burn severity class. Its quality was assessed statistically using a stratified sampling design which relies on both land cover classes (Table 3) and three levels of fire burn severity. The field sampling was designed so that it proportionally (to the area of a strata) reflects different types of land cover and the fire burn severity (Olofsson et al., 2014). At least three samples were taken in the strata (land category – burn severity), while their maximum number reached 14–18 for each stratum. In total, 73 test plots were laid out including seven control plots outside the burned areas.

During field research, the actual level of fire burn severity was assessed at each sample site using determined on site the composite burn index (CBI) (Key & Benson, 2006) and its modified version, the GeoCBI index (De Santis & Chuvieco, 2009). Both indices are a comprehensive scoring of the fire burn severity expressed as the total value of disturbance level of various layers of vegetation: living aboveground soil, shrubs, stands. The GeoCBI additionally takes into account the fraction of cover (FCOV) of each strata, therefore is more efficient in terms of remote sensing-based estimation of the fire burn sevrity (Saulino et al., 2020). In addition, soil samples were taken from each site to determine the soil burn severity according to the BAER method (Parsons et al., 2010). The state of the territory was recorded using a series of images taken using the technique of creating 360-degrees panoramic photography of virtual reality VR360 (Myroniuk et al., 2020; See & Cheok, 2015).

2. Results of the research

2.1. Classification of fire burn severity and soil burn severity

The methodology of refining maps of fire intensity provides a selection of justified threshold of dNBR values, which are consistent with actual observed level of fire severity. Significant co-variation of the dNBR and CBI indices did not allow making a conclusion about applicability of CBI in the study (Fig. 4).

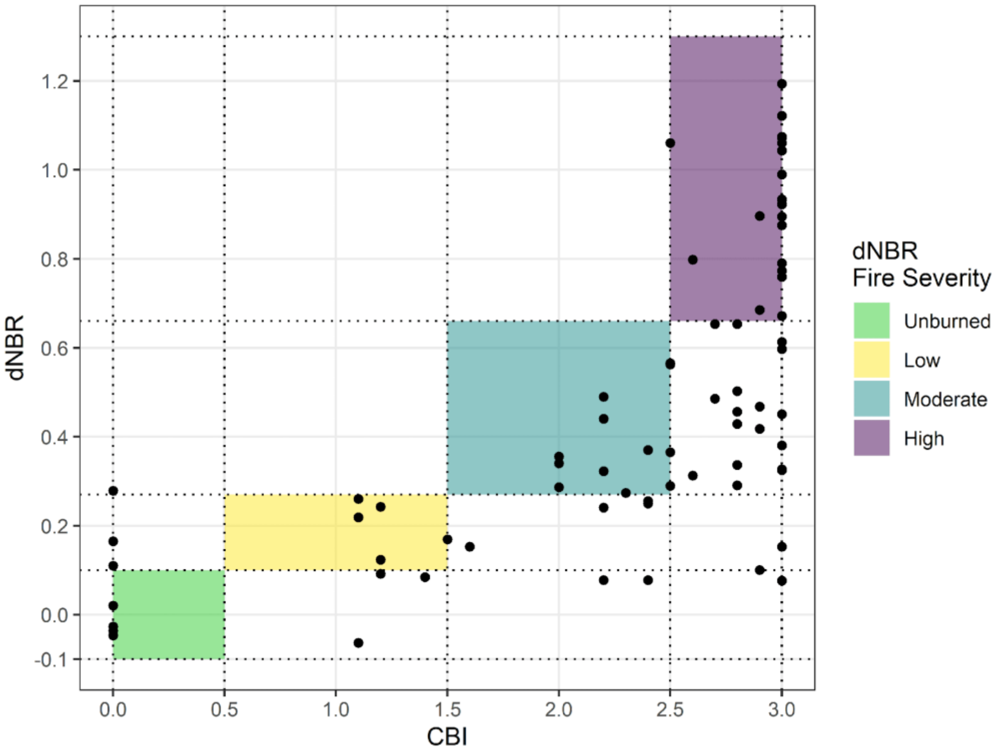


Fig. 4. Level of vegetation damage according to the CBI and Sentinel 2-derived dNBR index: points show the actual empirical data

Table 4. Error matrix between burn severity levels derived from Sentinel 2 satellite images and reference levels estimated on site using the CBI index

Map class ($dNBR$)	Reference class (CBI)				UA	PA
	Undamaged areas	Low	Moderate	High		
Undamaged areas	4	3	2	1	0.571	0.400
Low	2	4	5	2	0.571	0.308
Moderate	1	0	8	21	0.533	0.267
High	0	0	0	20	0.455	1.00

Overall accuracy of the classification is estimated to be within the range from 0.481 to 0.716. According to Fig. 4 and error matrix (Table 4) biased estimations for moderate and high classes of fire burn severity is observed, which caused the need to focus further on the GeoCBI index (Fig. 5). Equation (3) which has already been used in similar studies (Miller & Thode, 2007; Saulino et al., 2020), was used to adjust the threshold values of the dNBR index:

$$dNBR = a + b \cdot exp(c \cdot FBI), \tag{3}$$

where a, b, c – regression coefficients, FBI – fire burn index, determined by the CBI or GeoCBI indices.

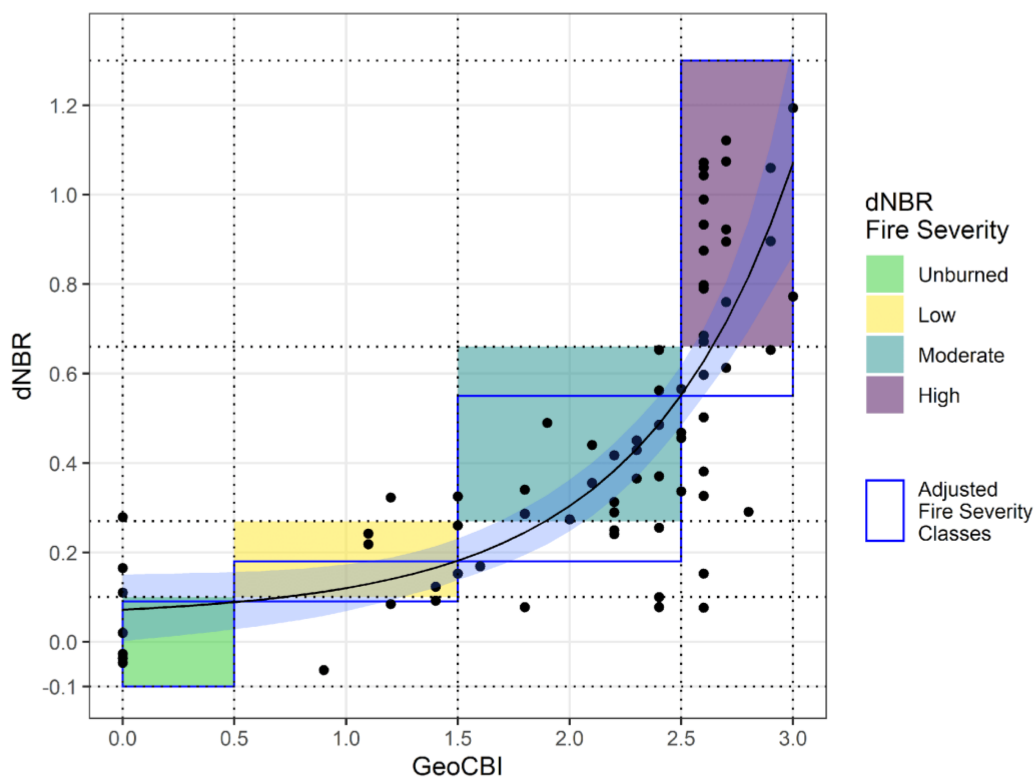


Fig. 5. Burn severity levels according to the GeoCBI and Sentinel 2-derived $dNBR$ index: points show the actual empirical data; line with ribbon plot on the background represent and average forecast with 95% confidence interval; blue rectangles depict the adjusted boundaries of burn severity classes

Parameters of the model were predicted in the R statistical software using nls function and bootstrap procedure (James et al., 2013). We used bootstrapping of 1000 random samples with replacement from the original data, refitting the model for each sample, evaluation of median, quantiles, and standard errors of the regression coefficients (Table 5), that allowed to derive 95 % confidence interval of fitted $dNBR$ values depending on the GeoCBI index.

Table 5. Parameter estimates of regression model (3)

Estimates	Regression coefficient		
	a	b	c
Parameter	0.05597	0.01513	1.400
Standard error	0.05128	0.01698	0.3191

As a result of the modeling, we adjusted the threshold values of the $dNBR$ index (blue rectangles), that were used to reclassify fire burn severity levels taking into account the results of field studies. As a result, the overall accuracy of the thematic map was 0.551–0.777 and the disaggregation of medium and high degrees of damage significantly improved (Table 6).

Table 6. Error matrix between adjusted burn severity levels of according to Sentinel 2-derived $dNBR$ and field validated GeoCBI indices

Map class ($dNBR$)	Reference class (GeoCBI)				UA	PA
	Undamaged areas	Low	Moderate	High		
Undamaged areas	4	2	2	1	0,571	0,444
Low	2	2	3	1	0,286	0,250
Moderate	1	3	19	7	0,730	0,633
High	0	0	2	24	0,727	0,923

Lower and upper intervals of the GeoCBI index were used to evaluate uncertainty of area estimates by burn severity levels which is important characteristic of any thematic map (Table 7).

Table 7. Threshold values (numerator) and area evaluations (denominator, thousand ha) of fire intensity classes

Fire burn severity	The $dNBR$ threshold values according to the method (Key & Benson, 2006)	Adjusted $dNBR$ threshold values based on the GeoCBI index		
		Lower bound of the confidence interval	**Average value**	Upper bound of the confidence interval
Low	0.10	0.16	**0.09**	0.02
	11475.9	4703.3	**5016.5**	2373.9
Moderate	0.27	0.23	**0.18**	0.14
	21162.7	22999.0	**24087.5**	23360.8
High	0.66	0.62	**0.55**	0.48
	6931.8	8002.9	**10466.4**	13835.7
Total	39570.4	35705.2	**39570.4**	39570.4

A map of the soil burn severity classyi was also prepared based on the correlation between the level of damage assessed during field sampling and the $dNBR$ values. It is important to note, the indirect relationship between the intensity of the fire and its impact on the soili is more relevant in this case. In general, during field studies, only two levels of damage were recorded, the $dNBR$ threshold values for which are shown in Fig. 6 and in Table. 8.

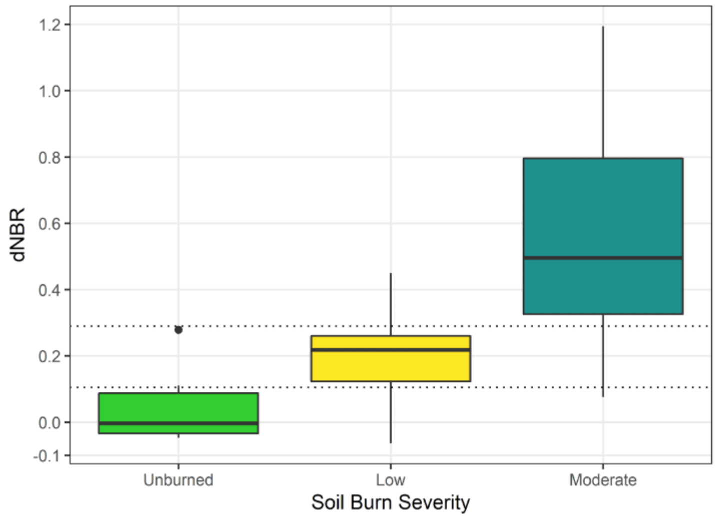


Fig. 6. Distribution of the *dNBR* values according to soil burn severity class: dotted line shows borders of soil burn severity classes

Table 8. Threshold values and area of soil burn severity

Parameter	Soil burn severity class		
	Low	Moderate	Total
$dNBR$	0,105	0,290	–
Area, thousand ha	12656,7	26604,7	39261,4

The distribution of the *dNBR* values (Fig. 7) allows to understand the specifics of redistribution of area between various options of classification of burned areas (Fig.8).

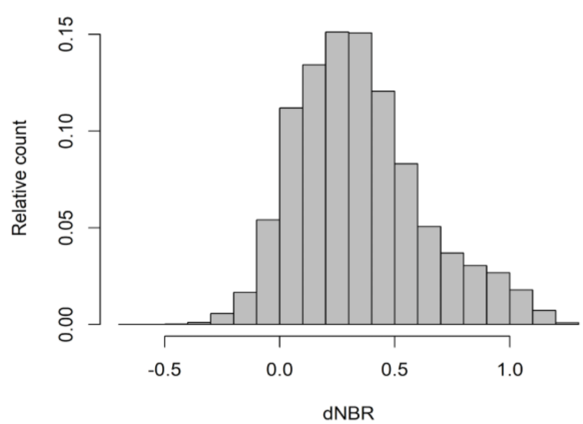


Fig. 7. Distribution of the *dNBR* values according to Sentinel 2 images

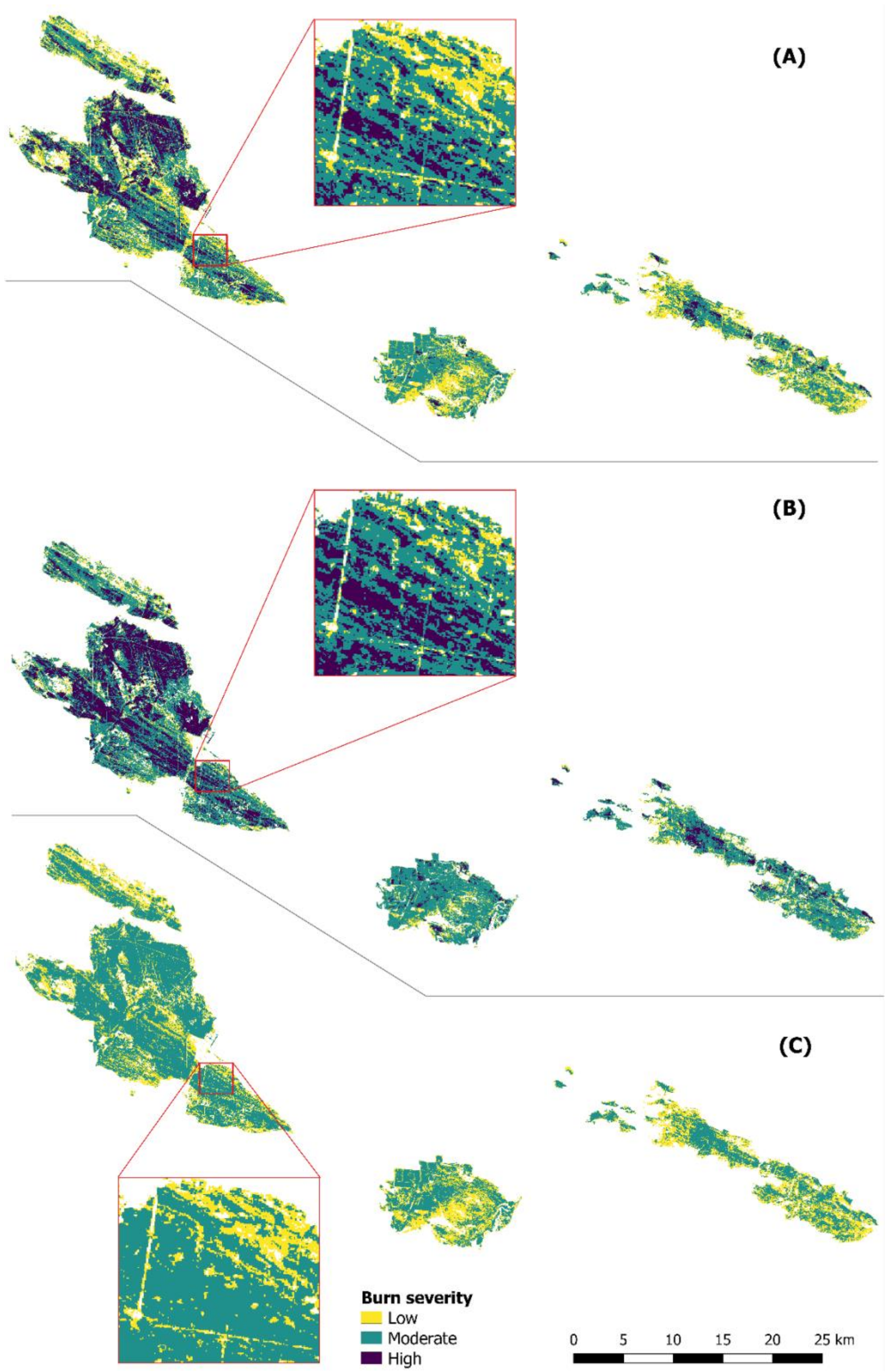


Fig. 8. Initial and refined maps of fire intensities and soil damage: (A) – fire burn severity, determined by Sentinel 2 satellite image (October 2020 and October 2019); (B) – adjusted fire burn severity based on field research data; (C) – soil burn severity

2.2. Vector maps of fire burn severity and soil burn severity

Predominant level of fire burn severity and soil burn severity within each forest polygon, as well as fraction of stands disturbance were calculated after intersection of GIS-layers of forest inventory database and adjusted maps of burn severity (Fig. 8). Derived vector maps of fire burn severity for all categories of areas, as well as by separate stratum are shown on the Fig. 9.

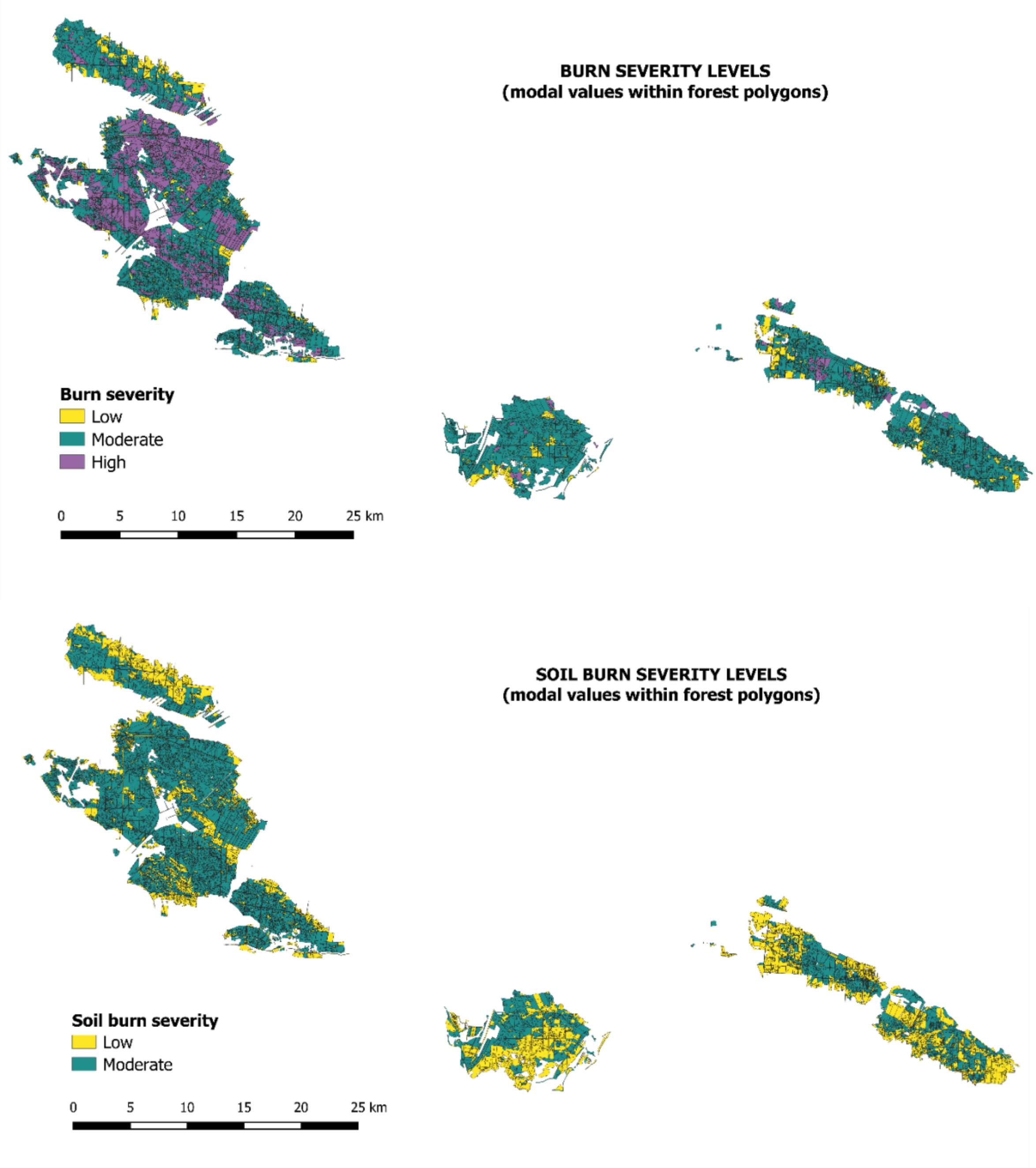


Fig. 9. Vector maps of the fire burn severity and soil burn severity classes derived within forest polygon using RS-based approach

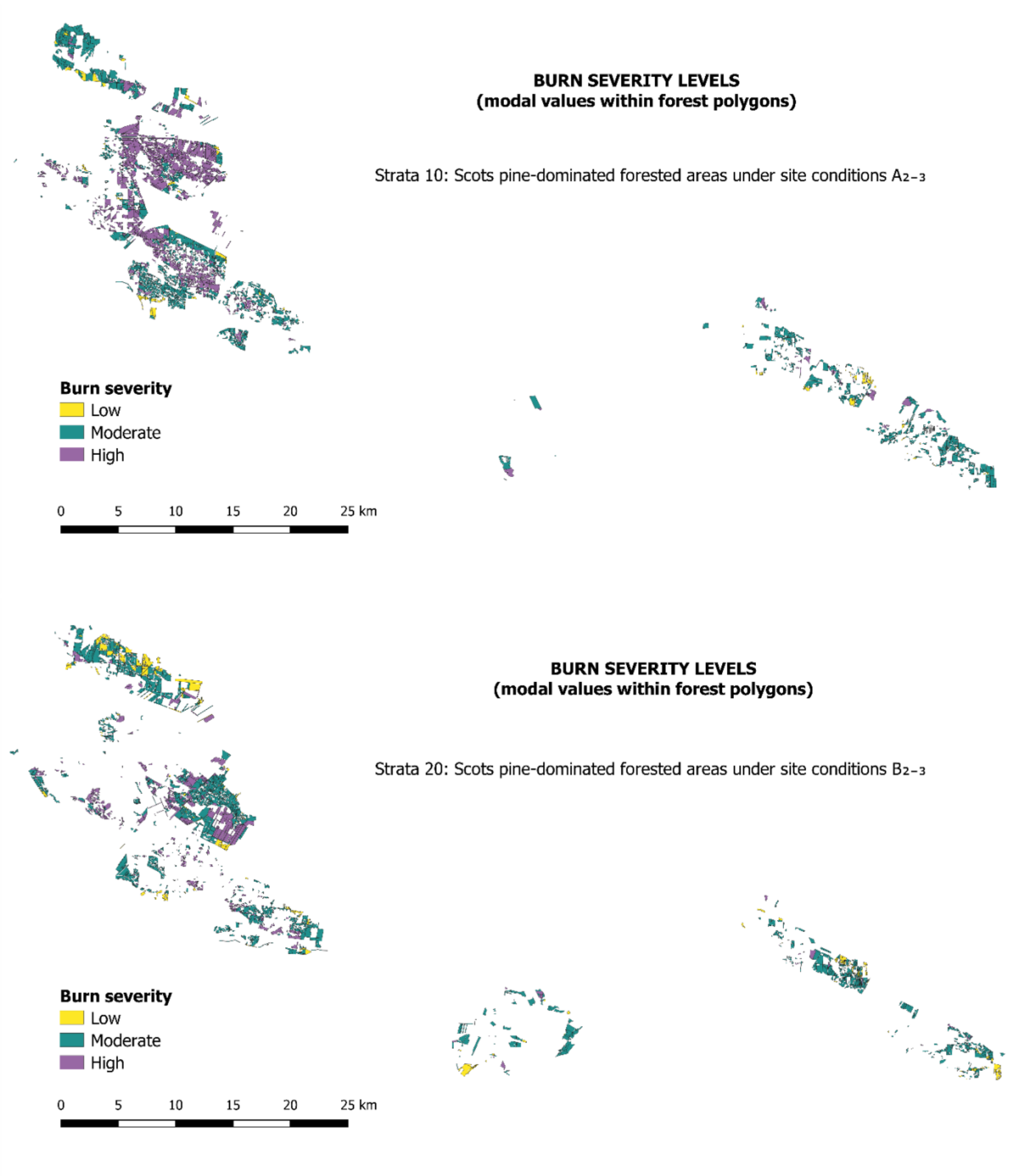
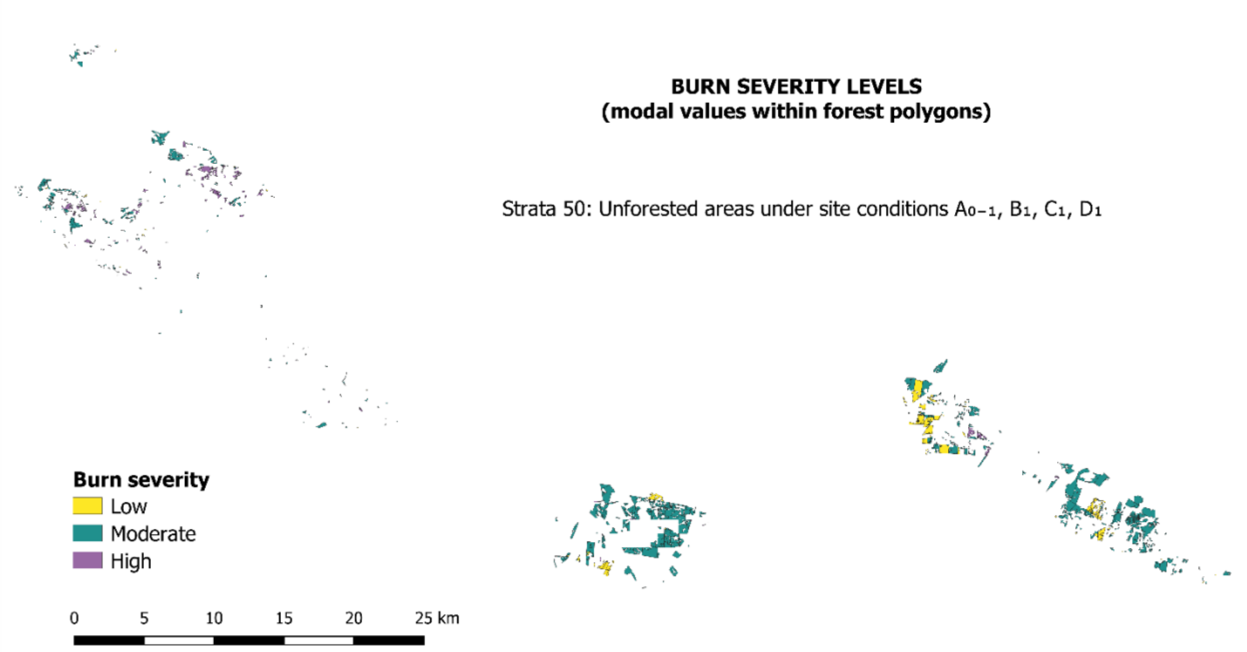


Fig. 10, sheet 1. Vector maps of the fire burn severity for selected strata: strata #10 and #20

Fig. 10, sheet 2. Vector maps of the fire burn severity for selected strata: strata #30 and #40



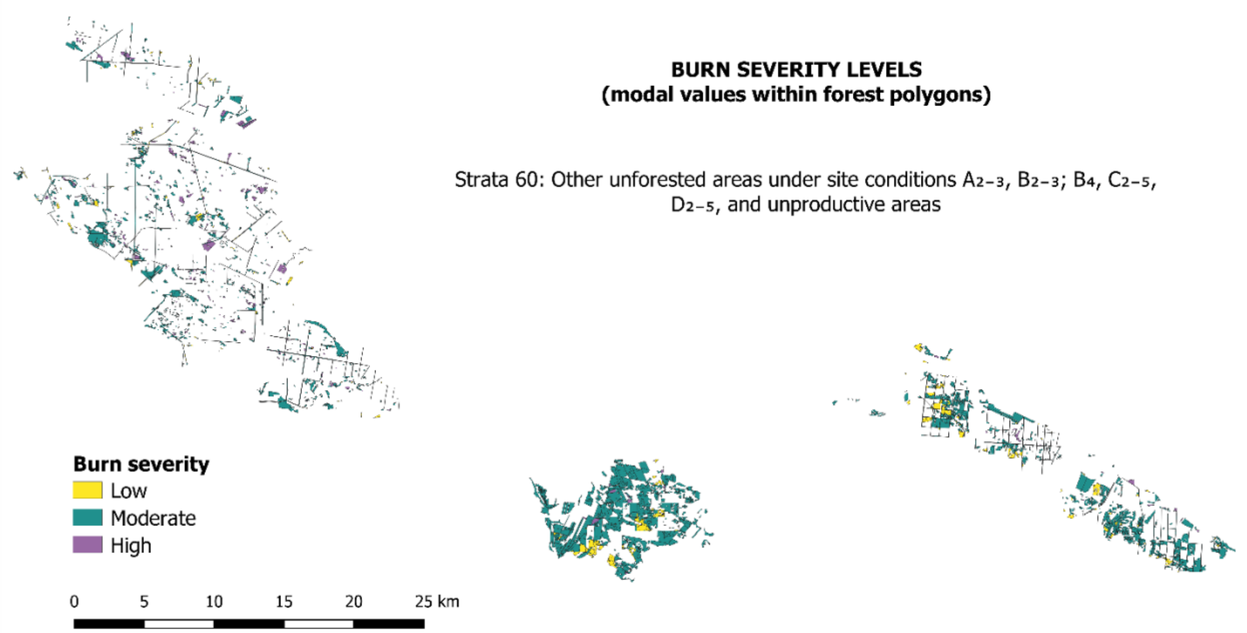


Fig. 10, sheet 3. Vector maps of the fire burn severity for selected strata: strata #50 and #60

Table 9 represents descriptions of fire burn severity and soil burn severity levels which were determined during field studies. The mapped levels are associated with provided descriptions given uncertainty of results of this study as it is shown on Fig. 5 and Fig. 6.

Table 9. Characteristic of fire burn severity and soil burn severity levels

Code of the strata	Level of fire intensity	Description	An example photo of the site and a link to the VR360 panoramic images
10	Low	Pine plantations that grow under site conditions A_2 – A_3. They are characterized by low level of damage. Average value of the CBI – 0.7, GeoCBI – 0.7. E.g.: test site ID-84. Characteristics: the area was impacted by low intensity ground fire; significant number of trees with green needle is present; bark char height – up to 2 m, CBI – 1.4, GeoCBI – 1.2; soil burn severity class – low.	 https://kuula.co/post/n1/collection/7Y2bq
	Moderate	Pine plantations that grow under site conditions A_2 – A_3. E.g.: test site ID-72. Characteristics: the area was impacted by high intensity ground fire; single trees with green needles are present, rest of the trees have brown colored needles; average bark char height – 6m, CBI – 2.4, GeoCBI – 2.4; soil burn severity class – average.	 https://kuula.co/post/7rPm7
	High	Pine plantations that grow under site conditions A_2 – A_3. E.g.: test site ID-2. Characteristics: middle-aged plantation; the area was impacted by high intensity ground fire; no trees with green needles are present, needles are brown or absent; 70% of needles fell off; average bark char height – 6 m, CBI – 2.9, GeoCBI –2.5; soil burn severity class – average.	 https://kuula.co/post/7rPXh

Code of the strata	Level of fire intensity	Description	An example photo of the site and a link to the VR360 panoramic images
20	Low	Pine plantations that grow under site conditions $B_2 – B_3$. E.g.: test site ID-70. Characteristics: pre-mature plantation; the area was impacted by low intensity ground fire; significant number of trees with green needles is present, rest of the trees have brown colored needles; average bark char height – 4 m, CBI – 1.5, GeoCBI – 1.6; soil burn severity class – low.	 https://kuula.co/edit/7rltG
	Moderate	Pine plantations that grow under site conditions $B_2 – B_3$. E.g.: test site ID-40. Characteristics: pre-mature plantation; the area was impacted by high intensity ground fire; insignificant number of trees with green needles is present, rest of the trees have brown colored needles or none; average bark char height – 5.5 m, CBI – 2.4, GeoCBI – 2.2; soil burn severity class – average.	 https://kuula.co/post/7rltG
	High	Pine plantations that grow under site conditions $B_2 – B_3$. E.g.: test site ID-69. Characteristics: middle-aged plantation; the area was impacted by high intensity ground fire; no trees with green needles are present, needles are brown or absent; 70 % of needles fell off; average bark char height – 7m, CBI – 2.8, GeoCBI – 2.6; soil burn severity class – average.	 https://kuula.co/post/7rP7y

Code of the strata	Level of fire intensity	Description	An example photo of the site and a link to the VR360 panoramic images
30	Low	Plantations that grow in very arid and arid conditions E.g.: test site ID-88. Characteristics: age group – young plantation, plants up to 40 years; the area was impacted by low intensity ground fire; significant number of trees with green needles and insignificant number of the trees with brown needles are present; average bark char height – 0.5 m, CBI – 1.2, GeoCBI – 1.4; soil burn severity class – low.	 https://kuula.co/post/7rPfX
	Moderate	Plantations that grow in very arid and arid conditions E.g.: test site ID-116. Characteristics: age group – young plantation (age up to 40 years), scattered overgrown trees present, mixed forest with predomination of deciduous species; the area was impacted by average intensity ground fire; significant number of trees survived; average bark char height – 1 m, CBI – 2.2, GeoCBI – 2.4; soil burn severity class – low.	
	High	Plantations that grow in very arid and arid conditions E.g.: test site ID-8. Characteristics: age group – young plantation, (age up to 40 years); the area was impacted by crown fire; trees have no needles; CBI – 3.0, GeoCBI – 2.8; soil burn severity class – average.	

Code of the strata	Level of fire intensity	Description	An example photo of the site and a link to the VR360 panoramic images
40	Low	Deciduous plantations that grow in all site conditions except of very arid and arid, pine plantations in fertile conditions (C_2-C_3, D_2-D_3) E.g.: test site ID-18 Characteristics: age group – young plantation, (age up to 40 years) deciduous plantation with scattered overgrown pine trees; the area was impacted by low intensity ground fire; CBI – 1.2, GeoCBI – 1.1; soil burn severity class – low.	
	Moderate	Deciduous plantations that grow in all site conditions except of very arid and arid, pine plantations in fertile conditions (C_2-C_3, D_2-D_3) E.g.: test site ID-78 Characteristics: age group – uneven-aged deciduous forest stands with scattered overgrown trees; the area was impacted by average intensity ground fire; young trees with thin bark died – rest survived; average bark char height – 1m, CBI – 1.2, GeoCBI – 1.1; soil burn severity class – low.	
	High	Deciduous plantations that grow in all site conditions except of very arid and arid, pine plantations in fertile conditions (C_2-C_3, D_2-D_3) E.g.: test site ID-57. Characteristics: middle-aged plantation (birch, aspen, alder); the area was impacted by high intensity ground fire; CBI – 3.0, GeoCBI – 2.6; soil burn severity class – average.	
50	Low	Non-forested areas in very arid and arid conditions (sands) E.g.: test site ID-108. Characteristics: non-forested area was impacted by low intensity ground fire; young oak trees that survived are present; CBI – 1.1, GeoCBI – 1.5; soil burn severity class – low.	

Code of the strata	Level of fire intensity	Description	An example photo of the site and a link to the VR360 panoramic images
	Moderate	Non-forested areas in very arid and arid conditions (sands) E.g.: test site ID-83. Characteristics: non-forested area (unstocked forest crops) was impacted by average intensity ground fire; young oak and birch trees that survived are present; CBI – 1.6, GeoCBI – 1.5; soil burn severity class – average.	
	High	Non-forested areas in very arid and arid conditions (sands) E.g.: test site ID-20. Characteristics: non-forested area with single pine trees and birch patches were impacted by ground fire; CBI – 3.0, GeoCBI – 2.6; soil burn severity class – low.	
60	Low	Other areas (non-forested areas) E.g.: test site ID-120. Characteristics: non-forested abandoned farmlands were impacted by low intensity ground fire; young fruit and shrub species that survived are present; CBI – 1.0, GeoCBI – 1.0; soil burn severity class – low.	
60	Moderate	Other areas (non-forested areas) E.g.: test site ID-92. Characteristics: non-forested abandoned farmlands were impacted by low intensity ground fire; young shrub species and pine trees are present, some share of trees died (approximately 40 %), rest – survived; CBI – 2.4, GeoCBI – 2.4; soil burn severity class – average.	

Code of the strata	Level of fire intensity	Description	An example photo of the site and a link to the VR360 panoramic images
	High	Other areas (non-forested areas) E.g.: test site ID-105. Characteristics: non-forested abandoned farmlands were impacted by average intensity ground fire; young pine and silver birch trees are present, most of the trees died; CBI – 2.8, GeoCBI – 2.8; soil burn severity class – average.	

3. Description of data sets provided in file

Luhansk_2020_fires_dnbr_continuous.tif

Continuous map of $dNBR$ index values estimated using Sentinel 2 satellite images:

- range of pixel values:-0.5÷1.4

Luhansk_2020_fires_dnbr_3cl.tif

Discrete map of burn severity levels developed using original $dNBR$ threshold values described in (Key & Benson, 2006):

- pixel values: 1 – low level; 2 – moderate level; 3 – high level

Luhansk_2020_fires_dnbr_3cl_GeoCBIadj.tif

Discrete map of burn severity levels according to adjusted thresholds in the study:

- pixel values: 1 – low level; 2 – moderate level; 3 – high level

Luhansk_2020_fires_dnbr_3cl_GeoCBIadj_LOW.tif
Luhansk_2020_fires_dnbr_3cl_GeoCBIadj_UP.tif

Lower and upper limits of 95 % confidence intervals of classes thresholds used in the burn severity map Luhansk_2020_fires_dnbr_3cl_GeoCBIadj.tif:

- pixel values: 1 – low level; 2 – moderate level; 3 – high level

Luhansk_2020_fires_dnbr_2cl_Soil.tif

Discrete map of soil burn severity derived using field validation data:

- pixel values: 1 – low level; 2 – moderate level

plot_level_burn_indices.shp

Vector map with aggregated within forest polygons levels of burn severity and soil burn severity:

- fields description:
    - strata – # of the strata
    - TotalBurned – share of forest polygon disturbed by fire (all levels)
    - FireIntens – fire burn severity
    - SoilBS – soil burn severity

field_smpl_dnbr.csv

The csv-file containing indices values estimated on field test sites:

- field description:
    - id – test site ID
    - X, Y – coordinates of test site center in WGS84 coordinate reference system
    - map_class – strata code (first digit) and burn severity (second digit) estimated using Luhansk_2020_fires_dnbr_3cl.tif map
    - CBI – CBI values estimated on test site
    - GeoCBI – GeoCBI values estimated on test site
    - SBSC – soil burn severity values estimated on test site

Literature cited

De Santis, A., & Chuvieco, E. (2009). GeoCBI: A modified version of the Composite Burn Index for the initial assessment of the short-term burn severity from remotely sensed data. *Remote Sensing of Environment*, *113*(3), 554–562. https://doi.org/10.1016/j.rse.2008.10.011

James, G., Witten, D., Hastie, T., & Tibshirani, R. (Eds.). (2013). *An introduction to statistical learning: With applications in R*. Springer.

Key, C. H., & Benson, N. C. (2006). *Landscape Assessment (LA): Sampling and Analysis Methods* (General Technical Report RMRS-GTR-164; FIREMON: Fire Effects Monitoring and Inventory System, p. LA-1-LA-51). Rocky Mountain Research Station, US Department of Agriculture, Forest Service.

Miller, J. D., & Thode, A. E. (2007). Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). *Remote Sensing of Environment*, *109*(1), 66–80. https://doi.org/10.1016/j.rse.2006.12.006

Myroniuk, V., Bilous, A., Khan, Y., Terentiev, A., Kravets, P., Kovalevskyi, S., & See, L. (2020). Tracking Rates of Forest Disturbance and Associated Carbon Loss in Areas of Illegal Amber Mining in Ukraine Using Landsat Time Series. *Remote Sensing*, *12*(14), 2235. https://doi.org/10.3390/rs12142235

Olofsson, P., Foody, G. M., Herold, M., Stehman, S. V., Woodcock, C. E., & Wulder, M. A. (2014). Good practices for estimating area and assessing accuracy of land change. *Remote Sensing of Environment*, *148*, 42–57. https://doi.org/10.1016/j.rse.2014.02.015

Parsons, A., Robichaud, P. R., Lewis, S. A., Napper, C., & Clark, J. T. (2010). *Field Guide for Mapping Post-Fire Soil Burn Severity* (General Technical Report RMRS-GTR-243; p. 49). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Saulino, L., Rita, A., Migliozzi, A., Maffei, C., Allevato, E., Garonna, A. P., & Saracino, A. (2020). Detecting Burn Severity across Mediterranean Forest Types by Coupling Medium-Spatial Resolution Satellite Imagery and Field Data. *Remote Sensing*, *12*(4), 741. https://doi.org/10.3390/rs12040741

See, Z. S., & Cheok, A. D. (2015). Virtual reality 360 interactive panorama reproduction obstacles and issues. *Virtual Reality*, *19*(2), 71–81. https://doi.org/10.1007/s10055-014-0258-9