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Mountain Landscape Dynamics after Large Wind and Bark Beetle Disasters and Subsequent Logging—Case Studies from the Carpathians

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Abstract: High winds and the subsequent infestation of subcortical insect are considered to be the most extensive types of large natural disturbances in the Central European forests. In this paper, we focus on the landscape dynamics of two representative mountain areas of Slovakia, which have been affected by aforementioned natural disturbances during last two decades. For example, on 19 November 2004, the bora caused significant damage to more than 126 km^2 of spruce forests in the Tatra National Park (TANAP). Several wind-related events also affected sites in the National Park Low Tatras (NAPALT). Monitoring of related land cover changes during years 2000–2019 was based on CORINE Land Cover data and methodology set up on satellite and aerial images interpretation, on detailed land cover interpretation (1:10,000) for the local case studies, as well as on the results of field research and forestry databases. The dynamics of forest recovery are different in the clear-cuts (usually with subsequent tree planting) and in the naturally developing forest. The area in the vicinity of Tatranská Lonmnica encroaching on the Studená dolina National Nature Reserve in TANAP represents a trend of the gradual return of young forest. The area of Čertovica on the border between NAPALT and its buffer zone are characterized by an increase in clear-cut sites with potentially increasing soil erosion risk, due to repeated wind disasters and widening of bark beetle. Proposed detailed, large-scale approach is being barely used, when considering recent studies dealing with the natural disturbances.

Keywords: windstorm; bark beetle; disturbance; deforestation; satellite and air images; CORINE land cover; national parks; Slovakia

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1. Introduction

The increasing impact of climate change is becoming evident also in the forests of Central Europe [1]. Climate change also leads to more frequent storms and accompanying pest outbreaks, soil erosion and accelerated runoff. The disturbance of a forest ecosystem happens discretely over time, and disrupts the ecosystem's structure, composition and processes by altering its physical environment and resources, causing the destruction of plant biomass [2]. Natural disturbances cause a gradual increase of the land cover heterogeneity, the number of land cover types and fragmentation of landscape. The execution of human activities in forests disturbed by environmental factors affects the further functioning of these ecosystems. Research of spruce stands wind disturbances in Central Europe identified the age of stands, higher percentages of spruce, georelief and soils as the most important factors influencing the degree of forest damage [3]. A detailed evaluation of abiotic controls on windthrow disturbances in Tatras was carried out by Falťan et al. [4].

Synergic impact of numerous factors (e.g., recent windstorms, droughts) can induce bark beetle infestation and connected tree mortality, having significant effects on the ecology and value of both natural and commercial forests. Similar to the windstorm-driven deforestation analysis, susceptibility of the stand to bark beetle infestation can be evaluated using a set of independent variables connected to its abiotic and biotic conditions. The most frequently used abiotic variables are altitude, slope, aspect, slope position (distance from the slope footline and ridge), edaphic category or the amount of solar radiation [5–7]. As for the biotic variables, risk of infestation depends on the distance to the nearest infested forest, nearest clear-cut and the nearest unforested area, degree of naturalness and the species composition of the stand, its age, tree canopy, health condition and the presence of natural bark beetle enemies [6,8]. However, some of the aforementioned biotic driving forces are barely considered in the risk models.

Recognition of infestation phases and subsequent forest recovery phases from multispectral satellite imagery is also a common subject of interest connected to this issue. Landsat, Sentinel or Worldview missions nowadays provide data of sufficient temporal and spatial resolution to reliably capture bark beetle infestation dynamics, usually mapped by using visible spectrum or spectral indices. These indices are based on near infrared (NIR) and short-wave infrared (SWIR) reflectance. NIR decreases with increasing defoliation level, while SWIR increases with increasing defoliation level [9]. Commonly used indices are Normalized Difference Vegetation Index (NDVI), Normalized Difference Moisture Index (NDMI), Foliar Moisture Index (FMI), Simple Ration Index (SR), Transformed Vegetation Index (TVI) or several tasseled cap indices [10,11].

However, usage of these indices has its limitations. Their usage for analysis of small study areas is questionable. In addition, the aforementioned temporal and spatial resolution of imagery only grew in the last decade. Therefore, older disturbance events are not sufficiently covered. This is why we excluded them from our analysis.

Moreover, there are other approaches, such as using machine learning algorithms for modelling bark beetle spatial infestation [12], modelling future frequency of bark beetle outbreaks [13] or the barely used method of AHP (Analytical Hierarchy Process).

Windstorm significantly impacts and adjust the forest landscape structure and its physiognomy. Monitoring of land cover (LC) provides important information of actual land use and landscape dynamics. Land cover research results depend on the size of the area, the purpose of each study and the applied methodology. CORINE Land Cover (CLC) data is one of the most important sources of land use data for Europe [14]. The method for identifying and recording land cover based on satellite images [15,16] was applied throughout CLC projects and is usable at both national and regional levels. The CLC inventory was carried out by visual photo-interpretation, computer-assisted photo-interpretation and semi-automated satellite image methods [17]. The basic disadvantage of satellite data processing is that it is necessary to pre-prepare data focused mainly on atmospheric correction, but also to eliminate the effects of cloud cover. Aerial images can also be used in research with detailed legend and classification [18].

National parks are places where the landscape dynamics with varying degrees of human influence can be observed. In their core areas, respectively, nature reserves in Slovakia, nature protection is crucial. The Tatra National Park (TANAP) is the oldest national park in Slovakia. It was established in 1948 to protect Carpathian high mountain biotopes and their biodiversity. Together with the Polish Tatra National Park, the Tatras have been a UNESCO Biosphere Reserve since 1993. The Biosphere Reserves (BRs), established by the UNESCO Man and Biosphere (MaB) Programme, are areas in which "methods for managing natural resources are put to the test while simultaneously fostering economic development" [19]. The BRs are meant to function as "learning sites of excellence to explore and demonstrate approaches to conservation and sustainable development on a regional scale" [20] and have a history in preservation and conservation, which means that sustainability efforts lean towards the environmental dimensions of sustainable development [21]. The systematization of the scientific knowledge generated in each MaB Reserve allows defining conservation priorities from a systemic ecoregional approach [22]. Conservation and the sustainable use of biodiversity, ecosystems and their services are the key principles behind the establishment of "Biosphere Reserves" [23].

Designation of a Biosphere Reserve (BR) is does not guarantee the actual or complete implementation of the concept [24]. BRs are subjected to the intense human influence, especially in less-developed countries [25]. Similarly, agriculture has a negative impact on BRs, e.g., on the degradation of wetlands [26]. In the peripheral areas of MaB reservations in turn, land abandonment causes visual changes to the landscape [27–31]. Overall, BRs lack a certain legitimacy of importance because they lack broader social support. Clear objectives and distinctions to other conservation schemes, adequate human and financial resources, and political (local) support are important aspects to implement a conceptual shift [32]. In the Slovak Republic, national environmental legislation also takes precedence over the MaB document.

The National Park Low Tatras (NAPALT) was established back in 1978. With a total area of almost 2050 km^2, it is the largest national park in Slovakia. In TANAP, after the wind disaster, wood was processed outside the most strictly protected nature reserves, in NAPALT due to massive logging after several storms, and deforestation is significantly visible, especially in the vicinity of the Čertovica saddle. National Park of Low Tatras protects the eponymous mountains situated in the middle of Slovakia. The highest point of NAPALT—Ďumbier—reaches an altitude of 2043 m. Therefore, the Low Tatras are very heterogenous, when considering the variety of vertical vegetation zones. Submountain, mountain, subalpine and alpine zones are included. Even though the natural spruce stands occur only in a narrow belt with an altitude above 1100 m (and on the northern slopes in the forms of mixed fir-spruce forests, respectively), it was also intensively planted in the lower vegetation zones.

The aim of our study is to characterize the dynamics of the mountain landscape affected by wind events, bark beetle infestation and subsequent logging throughout the two national parks over the period 2000–2018. We use CORINE Land Cover data obtained by analysis of satellite images throughout national parks and the detailed interpretation of aerial images of representative areas, supplemented by field research and forestry databases.

For our detailed analyzes of the development of the land cover of the areas affected by the wind and bark-beetle calamity, we chose for comparison the part of TANAP in the vicinity of Tatranská Lomnica reaching the Studené doliny National Nature Reserve with the highest degree of protection [33] and the locality north of Čertovica saddle, on the border of NAPALT and its buffer zone.

2. Materials and Methods

2.1. Study Areas

TANAP covers the highest elevation of the Carpathian range, including its highest peak, Gerlachovský štít (2655 m a.s.l.). The total area of the park along with its buffer zone is more than 1045 km^2. It includes mainly montane spruce (*Picea abies*), dwarf-pine (*Pinus mugo*) and alpine ecosystems [34].

Windstorms periodically affect the spruce forest ecosystems of TANAP in the foothills of the Tatra Mts. The local winds and intensive, but rare, boras are conditioned by the orography of the highest mountains of the Carpathians. The exceptional situation in the forests belonging to TANAP, caused by the Elisabeth windstorm from 19 November 2004, was a result of its unusual dimension. The area of TANAP was affected by north-western winds with speeds reaching up to 200 km an hour. More than 126 km^2 of forests were damaged, with a wood volume of 2.3 million m^3 located at altitudes between 700 and 1350 m. The wind caused widespread damage, and it even contributed to the death of one person. 84,000 cubic meters of timber had to be removed from the intra-urban areas of various Tatra settlements [4].

Detailed research was realized in a 4 km^2 study area with disturbed spruce forests situated north-west of Tatranská Lomnica. The eastern part of the site represents habitats left for forest regeneration after the wind calamity and the western part was affected by the subsequent bark beetle expansion.

Spruce monocultures of NAPALT were prone to the several disturbances, which shaped the land cover during last two decades [35]. After the Elisabeth windstorm, large areas were deforested, mainly in the eastern part. The next windstorms, Kyrill and Phillip, hit the stands of the central and eastern north slopes during 2007. The most intense deforestation came after 2007, with the bark beetle infestation. The spread of subcortical insects was initiated by the recent windstorm, as well as by favorable climate conditions during the summer. The infestation culminated in 2009 [11]. During the subsequent few years, intense post calamity legal logging took place (Figure 1).

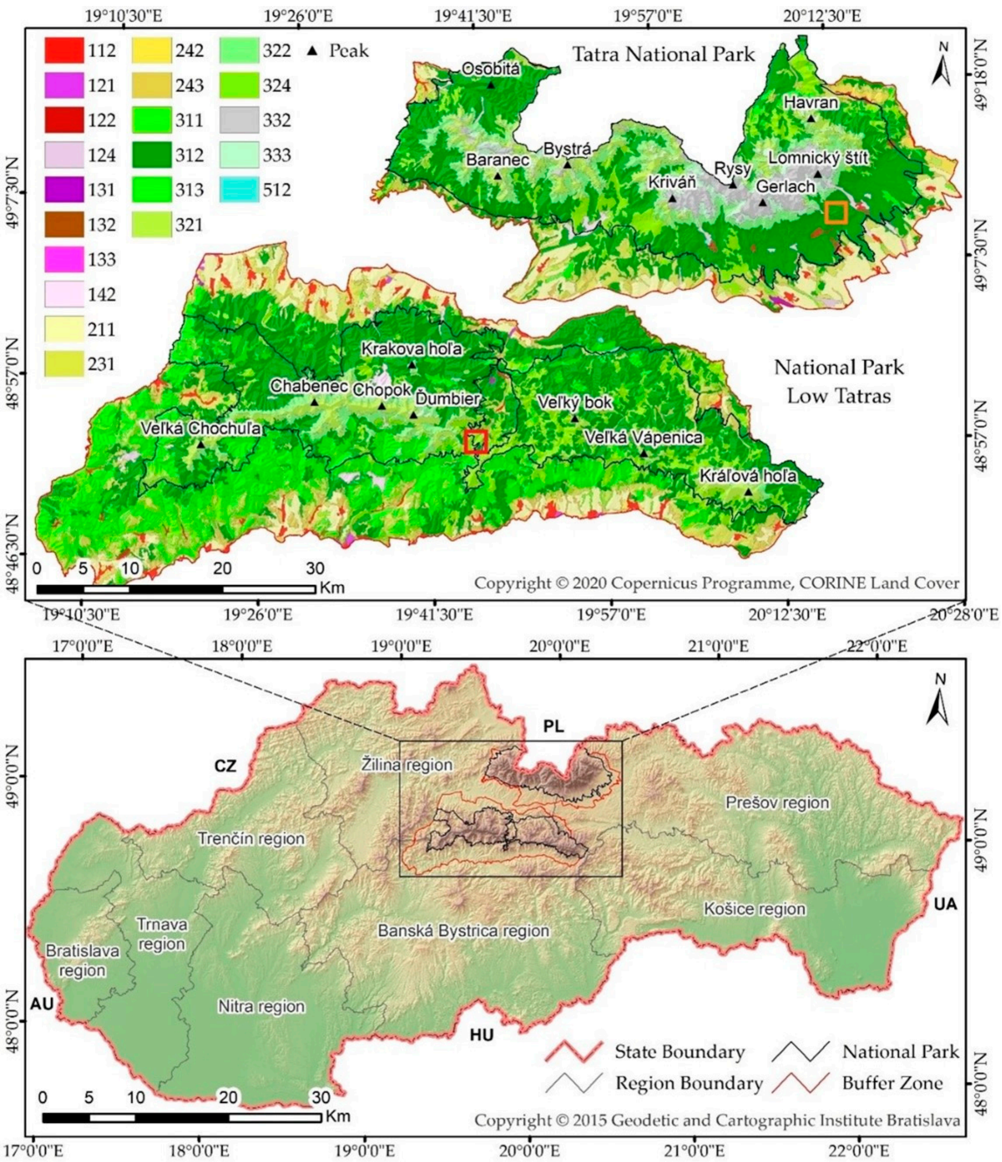

Figure 1. Localization of TANAP and NAPALT with the CORINE Land Cover 2018 inventory in Slovakia. Local studies: orange square—Vicinity of Tatranská Lomnica, red square—Surroundings of Čertovica. Description of the land cover classes (codes) in the legend is available at the following link: https://land.copernicus.eu/pan-european/corine-land-cover (accessed on 10 March 2019).

The study area in the Low Tatras (2 × 2 km) is situated north of the Čertovica saddle, near Vyšná Boca, on the border of the national park. It covers a small, closed, north-east orientated valley and its surroundings, including the short part of the Low Tatras central ridge.

2.2. Data

CLC project data based on satellite images interpretation was used to identify land cover at a scale 1:100,000 at the level of national parks. Land use/cover dynamics in chosen areas were evaluated between 2000 and 2018 (Table 1).

Table 1. Description of the source data for interpretation of land cover at a scale 1:100,000 (CORINE Land Cover).

Dataset	Year of Acquisition	Spatial Resolution	Source	Format
CLC2000	2000 +/− 1 year	≤25 m	Landsat-7 ETM	vector
CLC2006	2006 +/− 1 year	≤25 m	SPOT-4/5, IRS P6 LISS III	vector
CLC2012	2012 +/− 1 year	≤25 m	IRS P6 LISS III, RapidEye	vector
CLC2018	2018 +/− 1 year	≤10 m (Sentinel-2)	Sentinel-2, Landsat-8	vector

Source: https://land.copernicus.eu/pan-european/corine-land-cover (accessed on 27 May 2020).

For detailed large-scale mapping and analysis of land cover, digital vegetation ortophotomaps in RGB composite were used (Table 2). Aerial imagery was acquired, processed and provided by the Eurosense company. Spatial resolution of data is 20–50 cm. In the case of Čertovica, years 2002, 2006, 2009, 2012 and 2018 are covered. As for Tatranská Lomnica, acquisition dates are delayed by one year.

Table 2. Description of the source data for interpretation of land cover at a scale 1:10,000.

Dataset	Year of Acquisition	Spatial Resolution	Source	Format
Digital vegetation ortophotomap RGB	2002–2003	50 cm	Eurosense	TIFF
Digital vegetation ortophotomap RGB	2006–2007	50 cm	Eurosense	TIFF
Digital vegetation ortophotomap RGB	2009–2010	25 cm	Eurosense	TIFF
Digital vegetation ortophotomap RGB	2012–2013	25 cm	Eurosense	TIFF
Ortophoto mosaic of Slovakia	2018–2019	20 cm	NLC, GKÚ	TIFF

Sources: Eurosense, National Forestry Center (NLC), Geodetic and Cartographic Institute Bratislava (GKÚ).

2.3. Land Cover Interpretation

The land cover databases for years 2000, 2006, 2012 and 2018 at a scale of 1:100,000 were downloaded from the Copernicus programme (the CLC inventory). In the CLC, the size of the least identified area was set at 25 ha, minimum width of polygon was 100 m and minimum change polygon was 5 ha [14]. The layers were geoprocessed by clip tool to extract input features for the chosen national parks. The boundaries of the territorial and administrative arrangements of the Slovak Republic at a basic level (© Geodetic and Cartographic Institute Bratislava) were used as the clip feature.

The method for the detailed identification and inventorying of land cover classes [36] was used for the interpretation of air images of local study areas. It represents a modification of the CLC nomenclature on the 5th level at a scale of 1:10,000. The attributes of particularized nomenclature respect size of identified and recorded land cover objects by minimum area and spatial relationships, morphological and physiognomic attributes of objects and attributes of their function. Forest vegetation maps were used for the detailed specification of forest land cover classes.

The patterns of land cover were delimited after the interpretation of orthophoto mosaics in case studies using manual vectorization in ArcMap 10.7 (© ESRI). We adopted the minimum mapped area of 0.1 ha, minimum width of polygon 10 m and minimum recorded width of linear elements such a communication, accompanying vegetation and streams 2 m. [14]. The minimum change polygon was determined in an analogy to the generally applied CLC methodology of the third level as a fifth of the minimum identified area with the size of 0.02 ha [36]. The identification of patterns was verified according to the forest databases of the National Forest Centre and by own field research. General land cover flows were described according to Feranec et al. [37] and specified in detail for case studies.

In order to distinguish each type of disturbed forest, we used the following 5th level CLC classes: forest infested by bark beetle (32441) and forest damaged by windstorm (32442). Both categories have characteristic patterns, which were detected and interpreted during aforementioned process of manual vectorization. Bark beetle infestation was detected by pale, defoliated and dried clusters of coniferous trees. Consequences of windthrows were recognized by lying trees, usually in one direction. Inspection became more challenging several years after the disturbance. In that case, we used historical aerial imagery in order to detect initial or predominant disturbance driver.

3. Results

3.1. Land Cover Changes of the National Parks (1:100,000)

3.1.1. Land Cover Changes between 2000 and 2018 in TANAP

The windstorm in 2004 and the consequences associated with the expansion of bark beetle contributed most significantly to the change in land cover during the period, according to the CLC. In 2000, coniferous spruce forests (312) covered 55.89% of the national park area and 29.41% of the buffer zone area. In 2006, after harvesting most of the calamitous wood, coniferous forest areas grew to only 42.04% of the park and 26.30% of the buffer zone. Due to logging and bark beetle expansion, the smallest extent of the park's spruce forests (312) was recorded at 35.48% in satellite images in 2012. Due to the onset of succession 16 years after the storm, coniferous forests covered almost 48% of the national park and 28.53% of the buffer zone. Similarly, the area of young forest transition (324) in the park gradually increased, from 3.61% to 22.86% in 2012. At present, young forests occupy 10.50% of the park and 6.89% of the buffer zone. Other basic classes of land cover were minimally changed in the observed period (Figure 2, Table 3). The greatest dynamics of landscape changes were recorded in the southeastern part of the area at the boundary between the High Tatras and the Podtatranská kotlina Basin (Figure 3).

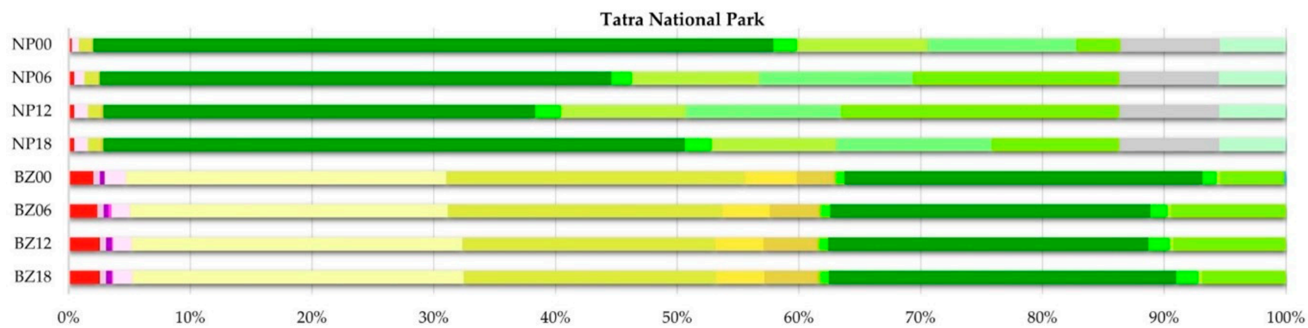

Figure 2. *Cont.*

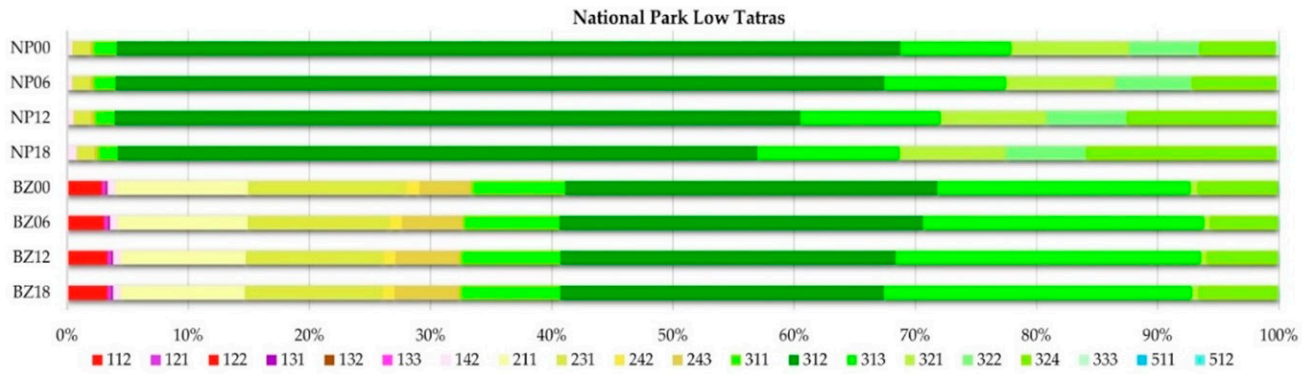

Figure 2. Development of Land Cover/LC values for TANAP and NAPALT according to recorded CLC3 data in 2000, 2006, 2012, 2018. NP—national park area, BZ—buffer zone. Description of the land cover classes (codes) in the legend is available at the following link: https://land.copernicus.eu/pan-european/corine-land-cover (accessed on 10 March 2019).

Table 3. Development of CLC-changes in TANAP (in the national park and its buffer zone separately).

CLC3-Change	Tatra National Park					
	National Park [ha]			Buffer Zone [ha]		
	2000–2006	2006–2012	2012–2018	2000–2006	2006–2012	2012–2018
142–324	10.71	-	-	-	-	-
231–324	1.01	-	-	248.96	25.76	-
312–324	10,334.66	5300.54	2906.25	1372.78	697.98	795.21
313–324	201.57	23.41	62.18	7.49	-	15.09
322–324	-	8.22	-	-	0.05	-
324–142	-	77.54	-	-	-	-
324–231	0.40	-	-	31.64	-	-
324–243	-	-	-	5.41	-	-
324–312	353.77	560.59	12,055.30	414.96	703.12	1467.16
324–313	28.37	272.49	96.44	0.24	84.91	27.03
324–321	41.63	-	-	-	-	-
324–322	215.27	-	-	0.06	-	-
Total change	11,187.38	6242.79	15,120.16	2081.53	1511.81	2304.49

3.1.2. Land Cover Changes between 2000 and 2018 in NAPALT

In contrast to TANAP, the impact of the storm in NAPALT in 2004 was dispersed throughout its territory, although its central and eastern parts were the most affected (Figure 3). The area of spruce forests (312) within the park decreased by only 1.26% from 2000 to 2006. During years 2006–2012, another decrease by 6.88% took place, as a consequence of logging, bark beetle infestation and another calamities. The moderate decrease continued also in the following period (2012–2018). During the entire monitored period, the proportion of coniferous forests in the park decreased from 64.69% to 52.78% and in the buffer zone from 30.70% to 26.67%, which represents a relative decrease of forest by 15%. Changes in land cover are illustrated in Figure 3 and Table 4. A more detailed resolution of landscape changes is provided by the interpretation of aerial photographs.

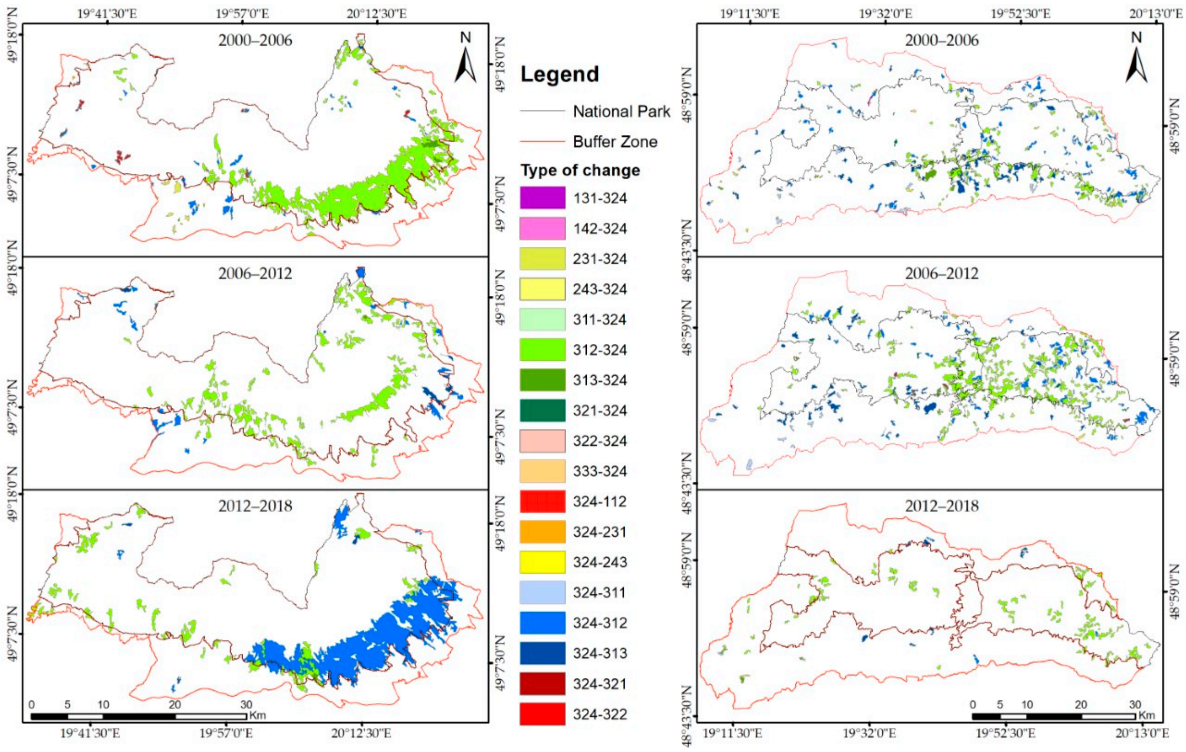

Figure 3. Development of CLC-Changes for TANAP and NAPALT between the two neighbor surveys. Description of the land cover classes (codes) in the legend is available at the following link: https://land.copernicus.eu/pan-european/corine-land-cover (accessed on 10 March 2019).

Table 4. Development of CLC-Changes in NAPALT (in the national park and its buffer zone separately).

CLC3-Change	National Park Low Tatras					
	National Park [ha]			Buffer Zone [ha]		
	2000–2006	2006–2012	2012–2018	2000–2006	2006–2012	2012–2018
131–324	-	-	-	37.81	-	-
231–324	82.14	-	-	151.54	89.42	42.44
243–324	-	-	-	-	35.49	-
311–324	5.37	-	-	6.51	-	18.06
312–324	1775.85	6141.76	2615.09	2073.20	2825.12	1057.97
313–324	89.16	175.68	-	594.81	195.41	85.69
321–324	80.09	195.85	-	-	0.58	-
333–324	28.88	-	-	-	-	-
324–112	-	-	-	10.69	-	-
324–231	-	-	-	82.92	-	-
324–243	-	-	-	107.49	-	-
324–311	-	14.50	-	456.42	398.65	27.,73
324–312	1332.55	1818.54	34.82	1485.83	941.10	105.17
324–313	258.31	463.78	39.66	1811.65	1503.47	329.58
324–322	-	126.93	-	-	-	-
Total change	3652.35	8937.04	2689.57	6818.87	5989.26	1666.63

3.2. Changes in the Land Cover of Selected Areas at a Scale of 1: 10,000

3.2.1. Vicinity of Tatranská Lomnica (TANAP)

For a representative area of the High Tatras, part of the Studená dolina Valley in the vicinity of Tatranská Lomnica, we can see (Figure 4) that in 2002 and 2006 the dominant class of land cover is spruce coniferous forest with a continuous canopy (31210). In addition, we see a large proportion of clear cuts (32411), areas after wind and subsequent bark beetle calamities, which grew exponentially from the east from 2002 to 2012. According to Table 5, we see due to logging a gradual increase in road categories and in the dominance of deforestation over afforestation processes. Greater reforestation and an increase in the area of forest have taken place since 2012 (Table 6, Figure 5). In addition, we can see from a detailed view that most of the bark beetle calamity (32441) binds to areas where calamity wood has not been harvested. We also see a significant increase in landscape fragmentation when comparing the years from 2002 to 2019, which was caused mainly by calamity events and their gradual removal, which is associated with the construction of unpaved forest roads and cuttings.

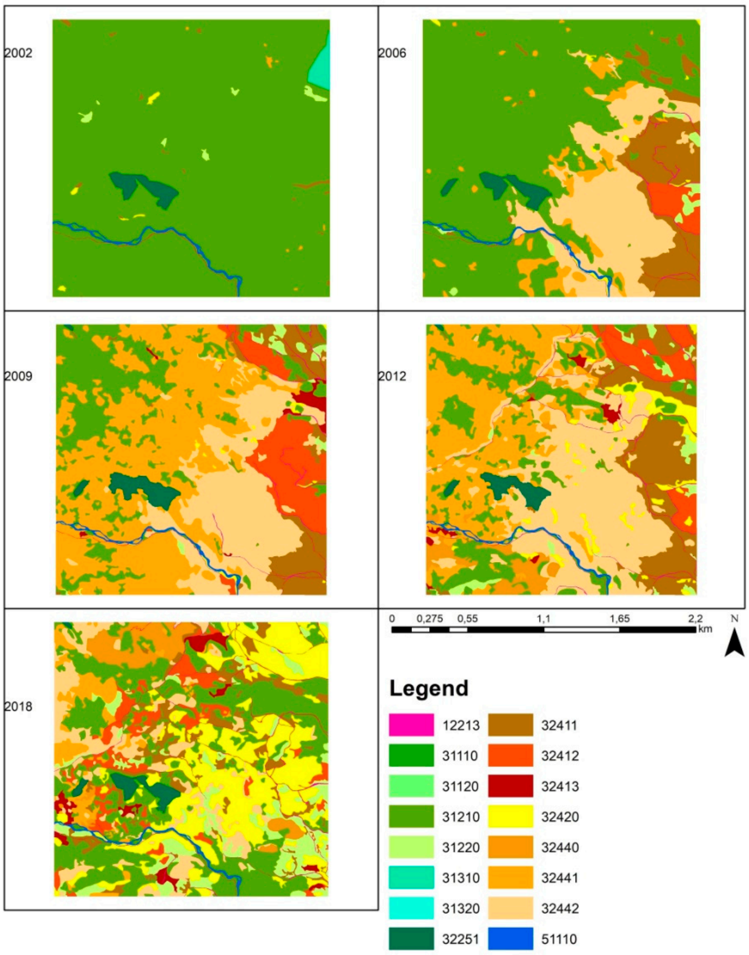

Figure 4. Detailed land cover maps of chosen TANAP area (NW from Tatranská Lomnica) in 2002–2019. Description of codes: 12213—Roads with an unpaved surface, 31110—Broad-leaved forests with a continuous canopy, 31120—Broad-leaved forests with a discontinuous canopy, 31210—Coniferous forests with a continuous canopy, 31220—Coniferous forests with a discontinuous canopy, 31310—Mixed forests with a continuous canopy, 32320—Mixed forests with discontinuous canopy, 32251—Prevailingly continuous dwarf pine stands, 32411—Clear-cut sites, 32412—Cut sites with individual trees, 32413—Cut sites with groups of trees, 32420 –Young forests succession, 32440 —Damaged forests, 32441—Forests damaged by biological pests, 32442—Forests damaged by natural disasters (windstorm), 51110—Rivers and brooks.

Table 5. Land cover development of area NW from Tatranská Lomnica (TANAP) in 2002–2019.

CLC5	Area (ha)				
	2002	2006	2009	2012	2018
12213	0.35	1.85	2.99	3.89	4.63
31210	383.34	238.18	73.25	61.92	121.08
31220	1.88	4.04	4.71	8.61	35.08
31310	3.56	0	0	0	0
32251	5.53	6.19	7.98	6.74	1.59
32411	1.29	42.79	28.55	52.79	25.56
32412	0	7.89	35.65	19.38	24.36
32413	0	0	3.74	3.22	7.87
32420	0.87	1.61	1.84	14.53	97.48
32440	0	0	0.31	14.63	19.26
32441	0.49	18.49	154.36	94.71	18.86
32442	0	76.29	83.96	116.89	41.51
51110	2.69	2.67	2.66	2.69	2.71
Total area	400	400	400	400	400

Table 6. Flows of land cover changes in the area NW from Tatranská Lomnica (TANAP).

Land Cover Flow	Area of Changes (ha)—NW Tatranská Lomnica					
	Detailed Description of Changes (CLC5 Codes)	2002–2006	2006–2009	2009–2012	2012–2019	2002–2019
no change		25,057	222.16	261.55	111.69	159.24
deforestation	all classes—>12213	1.52	1.42	2.51	1.62	4.31
	31210. 31220. 31310—>32411. 32412. 32413	49.93	17.74	4.47	2.91	57.43
	32440. 32441. 32442—>32411. 32412. 32413	0.29	1.29	10.70	41.68	0.02
	3xxxx—>32442	76.22	2.74	1.93	3.77	41.51
	3xxxx—>32441	18.49	144.10	24.89	4.31	19.18
	32441—>32442	0.08	7.89	43.51	14.55	0.004
	all classes—>32440	0	0.311	0	1.54	19.22
	32442—>32441	0	0.53	14.29	26.73	0.04
	312xx—>32420	1.35	0.23	0.42	3.95	96.96
	total deforestation	147.87	176.25	102.71	101.07	238.67
afforestation	12213—>all classes	0	0	0.69	0.65	0
	3241x—>32420. 31210. 31,220. 31330	1.56	0.95	8.62	72.86	1.68
	3244x—>32412. 32413. 31220	0	0.64	18.87	63.06	0.15
	3244x—>32420	0	0	7.57	50.67	0.25
	total afforestation	1.56	1.59	35.74	187.24	2.09

3.2.2. Surroundings of Čertovica (NAPALT)

From 2002 to 2018, 61.62% of the study area land cover has changed and 53.93% has been deforested. Between 2002 and 2006, the changes were relatively small (Figure 6, Table 7). The leading land cover flows were succession and deforestation.

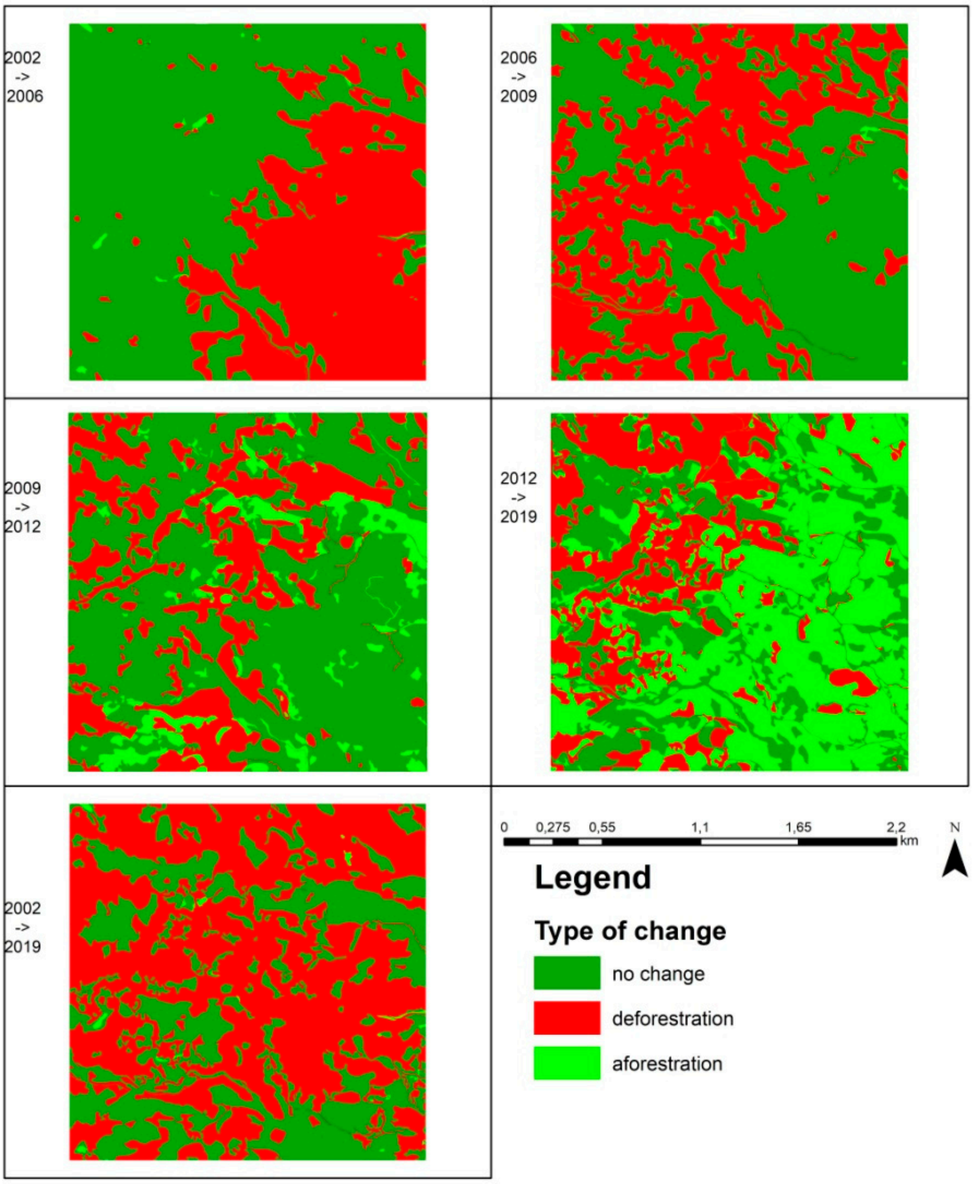

Figure 5. Land cover flows in area NW from Tatranská Lomnica (TANAP).

Elisabeth windstorm (November 2004) and subsequent post-calamity logging were detected as main deforestation drivers. During this period, 12% of the study area was deforested. Between 2006–2009, two other windstorms, Kyrill and Phillip, hit the study area, resulting in minor direct windthrows. As a consequence of these windstorms, massive bark beetle infestation (32441) and controlled logging took place (32411, 26% of the study area was deforested). During following years (2009–2012), ongoing infestation was stopped by the unprecedent logging (resulting in another 40% of the study area being deforested). From 2012, afforestation and connected landscape fragmentation took place, being a consequence of both natural succession and tree planting. Natural forest recovery processes couldn't be observed, because of anthropogenetic control above deforestation, as well as afforestation. The succession was considerably fast. It took only 6 years for clear-cuts to be covered by young shrubs (32420). On the contrary, there were large areas of clear cuts, which remained unforested (Figure 7, Table 8).

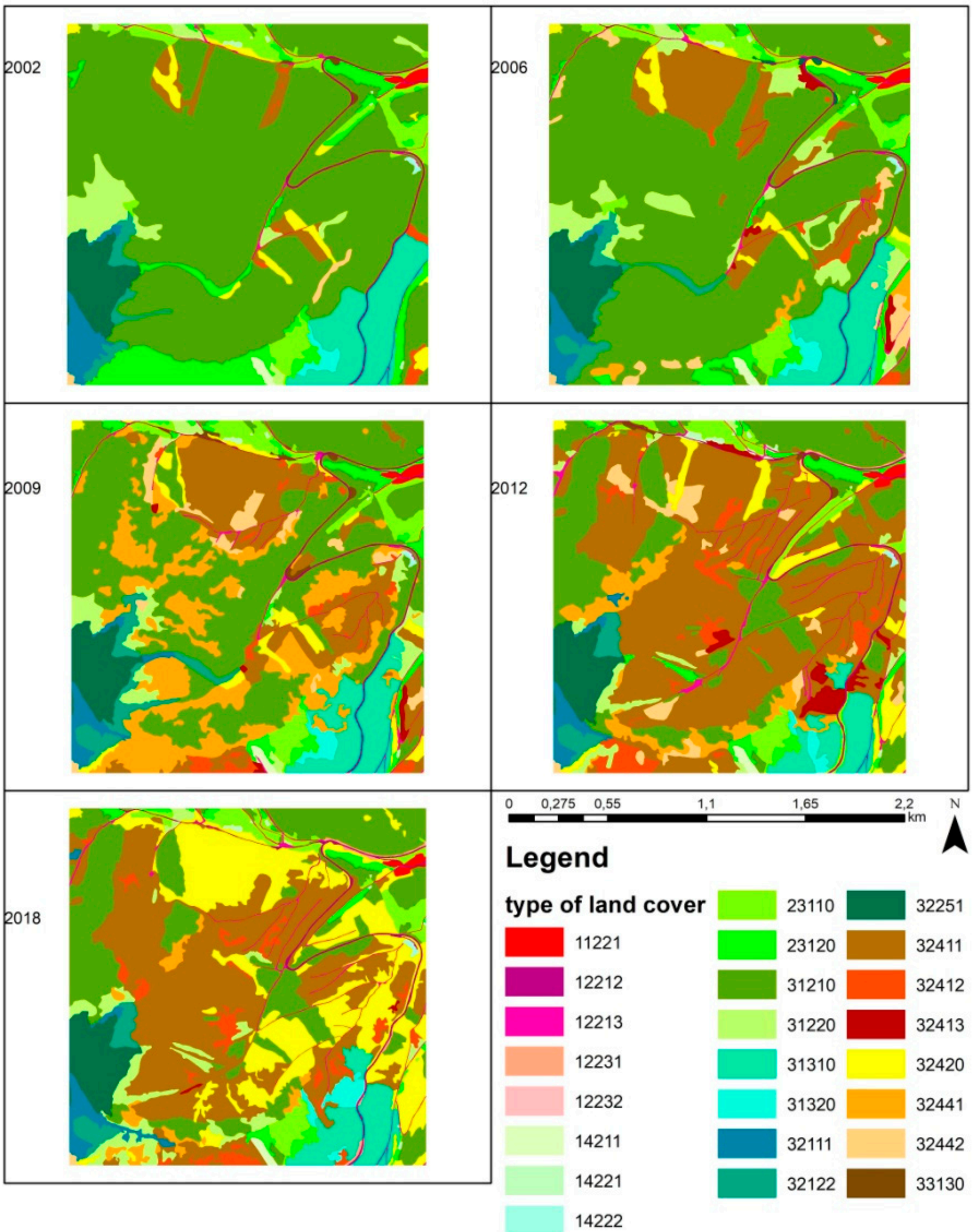

Figure 6. Detailed land cover maps of surroundings of Čertovica (NAPALT) in 2002–2018. Description of codes: 11221—Discontinuous built-up area with single-family houses, 12212—Roads with a paved surface, 12213—Roads with an unpaved surface, 12231—Accompanying prevailing grass vegetation, 12232—Accompanying prevailing shrub vegetation, 14211—Areas of sports with prevailing natural surfaces, 14221—Cottage colonies in tree (forest) areas, 14222—Mountain hotels and cottages, 23110—Grass stands prevailingly without trees and shrub, 23120—Grass stands with dispersed trees and shrubs, 31210—Coniferous forests with a continuous canopy, 31220—Coniferous forests with a discontinuous canopy, 31310—Mixed forests with a continuous canopy, 31320—Mixed forests with discontinuous canopy, 32111—Alpine meadows, 32122—Natural grass-herbaceous stands with dispersed woody vegetation, 32251—Prevailingly continuous dwarf pine stands, 32411—Clear-cut sites, 32412—Cut sites with individual trees, 32413—Cut sites with groups of trees, 32420 –Young forests succession, 32441—Forests damaged by biological pests, 32442—Forests damaged by natural disasters (windstorm), 33130—Bare soil, clay and loam.

Table 7. Detailed development of land cover-changes in surroundings of Čertovica (NAPALT).

CLC5	Area (ha)				
	2002	**2006**	**2009**	**2012**	**2018**
11221	1.31	1.31	1.31	1.49	1.30
12212	3.39	3.98	3.94	4.12	4.25
12213	2.04	3.05	3.96	6.01	5.04
12231	0	0	0	0.47	1.16
14211	0.91	0.96	0.89	1.01	0.83
14221	0.58	0.58	0.58	1.35	0.63
14222	0.33	0.33	0.33	0.33	0.33
23110	19.11	19.19	15.67	13.61	14.33
23120	26.86	13.16	9.72	8.88	6.53
31210	257.27	223.11	147.16	84.64	82.56
31220	14.25	22.41	14.30	7.29	16.37
31310	26.52	22.99	21.36	14.58	17.53
31320	1.99	2.49	2.49	2.01	3.93
32111	6.73	5.34	5.38	5.18	5.95
32122	5.28	7.79	10.62	5.61	5.45
32251	13.86	14.38	13.35	13.35	13.35
32411	8.38	35.51	55.05	167.64	123.32
32412	1.99	2.55	5.63	12.06	10.95
32413	0	2.29	1.59	6.73	0.36
32420	7.50	7.19	10.36	14.91	79.37
32441	0	3.32	65.64	16.94	6.18
32442	1.27	8.04	9.10	10.80	0.26
33130	0.41	0	1.55	0.98	0
Total area	4000	400	400	400	400

Table 8. Detailed development of land cover-changes in surroundings of Čertovica (NAPALT).

Land Cover Flow	Detailed Description of Changes (CLC5 Codes)	Area of Changes (ha)				
		2002–2006	**2006–2009**	**2009–2012**	**2012–2018**	**2002–2018**
no change		330.07	279.66	208.95	285.79	153.37
deforestation	all classes—>12213	1.69	1.25	4.91	1.13	4.47
	31210. 31220. 31310—>32411. 32412. 32413	31.29	21.52	81.42	4.48	124.52
	32440. 32441. 32442—>32411	0.32	3.95	45.01	8.23	0.75
	3xxxx—>32442	7.78	6.23	4.75	0	0
	3xxxx—>32441	3.07	60.91	4.79	1.19	6.18
	32441—>32442	0	0.55	3.92	0	0
	32442—>32441	0.25	3.11	0.29	0.27	0
	31210. 31220—>32420	0.02	2.21	1.41	2.51	69.03
	3xxxx—>231xx	2.46	2.79	5.13	5.53	1.87
	23120—>3241x	0.51	3.44	5.69	2.09	8.87
	total deforestation	47.41	105.94	157.32	25.42	215.68
afforestation	12213—>3xxxx	0.04	2.14	0.71	3.27	0.59
	3241x—>32420. 31210. 31220. 31330	22.04	11.01	22.52	71.25	30.16
	32442. 32441. 32440—>32412. 32413. 31220	0.44	1.25	8.24	8.91	0.18
	32442. 32441. 32440—>32420	0	0	2.26	5.36	0.02
	total afforestation	22.52	14.40	33.73	88.79	30.95

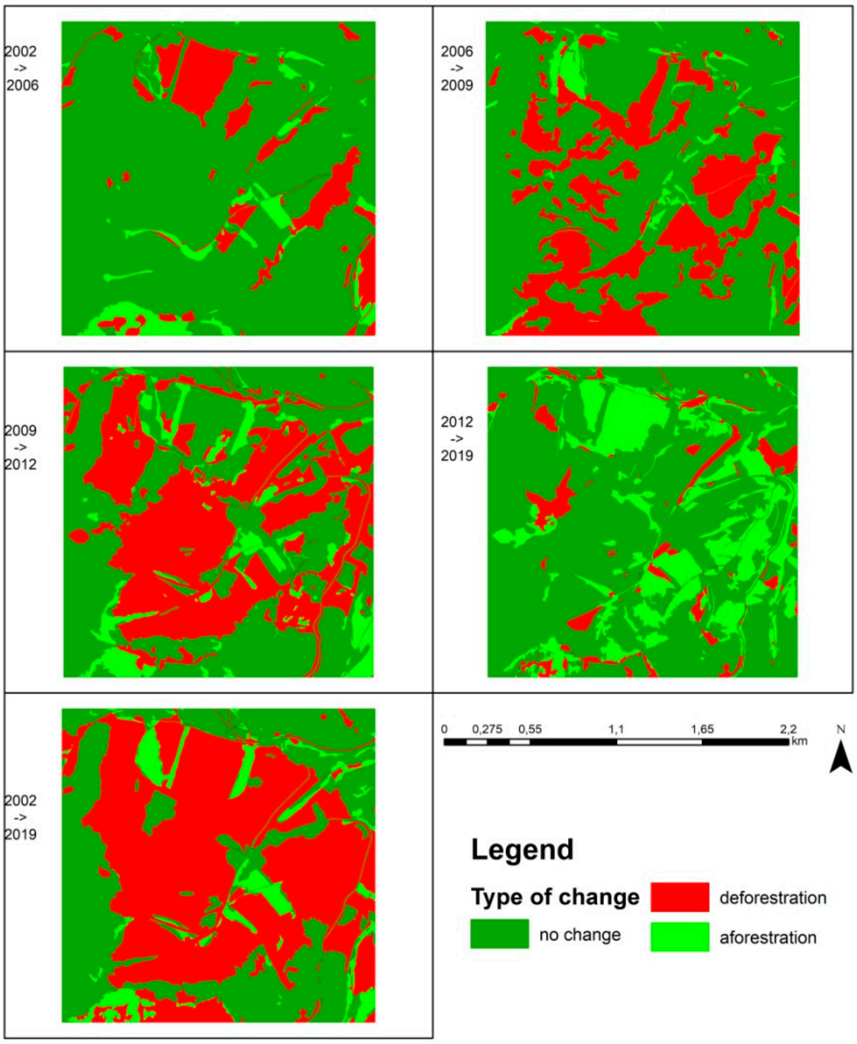

Figure 7. Land cover flows of surroundings of Čertovica (NAPALT).

4. Discussion

As a result of regular disturbance, a specific community of spruce forests has formed in the Tatra region at altitudes of up to 1200 m a. s. l., known as larch–spruce forests (*Lariceto-Piceetum*). Pine-spruce forests (*Pineto-Piceetum*) are occupying the higher altitudes. The species composition and quantity of the natural regeneration is reflected by the influence of both windthrow and tree extraction [38]. Falt'an et al. [4] concluded that the less-damaged stands were located farther from the slope foot lines on dryer and more-sloping localities with more and bigger skeletons in the topsoil, as well as deeper extremal skeleton properties (few and tiny, or many and big). Representative examples of these characteristics are the fault and erosional slope sites lying above the foot line with cambic podzols covered by natural spruce forests (especially communities of *Eu-Vaccinnio-Abietion* (Oberd. 1957)). Among the most wind damaged areas were wet sites containing glacifluvial forms, with waterlogged spruce forests located near the secondary slope foot line. In the local study area of Studené doliny, bark beetle had a greater impact on the overall deforestation.

Comparing the dynamics of deforestation due to bark beetle infestation and windstorms, bark beetle calamity is more complicated. Up to three generations of subcortical insect per year can occupy the territory. There is a general agreement on the leading triggers of bark beetle spread. In addition to worsened health conditions (e.g., as a consequence of recent windstorms), these triggers also include warm and dry summers [39,40].

Bark beetle outbreaks are a natural part of mountain forest dynamics. The frequency of maximum severity disturbances is approximately 130–260 years. In the Tatras, similar calamities of a smaller extent occurred, for example, in the early 20th century. Those areas influenced by stand replacing disturbances will be resistant to further disturbances for several decades, because of the more resilient forest structure (bark beetle usually attacks trees older than 60 years, when considering natural conditions) [5,6]. However, more frequent bark beetle outbreaks are expected in the future, as a consequence of climate change [41]. Once infestation has started, there are several main drivers, which influence the susceptibility of the stand. Apart from morphometric and edaphical variables, the distance to the nearest infested forest and distance to the nearest clear-cut seem to be the most important. However, the distance to the nearest clear cut is connected to the initial selective phase of infestation (trees on the clear cuts edges suffer from water stress and high amounts of radiation, while the natural forest edge represents a natural barrier). Once the threshold of bark beetle population size is overwhelmed, selective behavior becomes an unnecessary strategy and uncontrollable spreading takes place [6].

The initial phase of bark beetle infestation (green phase) cannot be observed on RGB composite imagery and multispectral information is needed. Most of the trees are infected in the first three years following the windstorm [39]. According to several studies from the Tatras and Šumava [10,11,39,41], bark beetle spreading cycles usually end in 5–6 years. These findings support our results in the Low Tatras, where the infestation reached its maximum in 2009, two years after the Kyrill windstorm. Subsequent dynamics could be observed only to a limited extent, due to massive logging in the disturbed areas. The wind-disturbed stands of the Tatras are also responsive to bark beetle invasions in the long term. Furthermore, an outbreak of *Ips typographus* was recorded before this event, from 1990 to 2000 [42].

According to Janík et al. [43], all the new infestations in one year are found in a 500 m buffer from the previous core of occurrence. Moreover, 65% of attacked trees stand in 100 m radius from the occurrence core. However, this cannot be understood as a linear trend. Other crucial variables must be considered, for instance whether the forest is natural or planted [44]. We were not able to perform similar analysis in our study areas, due to insufficient temporal resolution of the large-scale aerial imagery used.

The dynamics of forest recovery are different in the clear-cuts (usually with subsequent tree planting) and in the naturally developing forest. In the disturbed forest without logging and dead wood removal, regeneration lasts longer and results in stands with higher spatial and height heterogeneity, which are more resistant to potential upcoming disturbances. Moreover, *Picea abies* is proved to produce sufficient numbers of seedlings for further regeneration processes. From this point of view, the described disturbances pose no risk for mountain spruce forest existence, even without anthropogenetic interventions. On the contrary, clear cuts with planted trees are more homogenous and their recovery is faster [11,45], though large areas of clear cuts remain unforested. This can be a consequence of extreme exposure to sunlight, temperature and humidity conditions, factors that lead to higher seedling mortality [43].

During the recent years, the most common approach to study landscape dynamics disturbed areas was the interpretation of multispectral imagery and connected vegetation indices. Few studies focused on research based on large-scale RGB aerial imagery. Its advantages are high spatial resolution and the ability to map land cover changes with the highest accuracy. However, temporal resolution of accessible data is very limited. Natural disturbances (bark beetle infestation in particular) are very dynamic and analysis over several time horizons per year is needed to reliably capture its course. Moreover, the RGB spectrum is unable to detect all the phases of bark beetle infestation. Therefore, it is not suitable for predicting disturbance risk. As for the forest restoration process, the temporal resolution of available data seems to be sufficient. We recommend the use of this method in the case of small areas, where the highest spatial accuracy is needed, and where temporal resolution is less important. It can also be a valuable input layer, when building windthrow risk models.

Comparing large scale study areas, similar temporal patterns can be observed. Pre-disturbance land cover consisted of relatively homogenous coniferous forests (31210). First significant LC fragmentation took place after Elisabeth windstorm in 2004, resulting into decrease of forests (31XXX) and increase of clear-cuts (3241X) and naturally disturbed forests (32442). According to Koreň et al. [46], health condition of these forests was already declining decades before the windstorm. High Tatras were hit considerably stronger than Low Tatras. More detailed research of the post-disturbance LC changes in High Tatras was carried out by Falťan et al. [47]. Solár et al. [48] focuses on the longer time period and provides insight to historical LC changes connected to previous windstorms and national park establishment.

Another windstorms, Kyrill and Phillip (year 2007) barely changed LC of study areas. High proportion of *Picea abies* [49], drought [41] and previous windstorms created favorable conditions for spreading of subcortical insects. Increase of infested forest (32441) is characteristic for period 2006–2010. While bark beetle outbreak was stabilized in High Tatras after only small fragments of spruce forest remained, in Low Tatras started massive logging in order to stop infestation [50]. However, this approach was not applied in the whole territory of Low Tatras [51]. This resulted in significant increase of clear-cuts (3241X). After 2012, forest restoration (32420) and connected LC fragmentation took place in both study areas.

For High Tatras, aforementioned LC changes ran in linear, north-west direction. On the contrary, consequential processes of deforestation and afforestation were seemingly more spatially incoherent in Low Tatras. This is a consequence of more heterogenous and dissected relief of the second study area.

5. Conclusions

Remote sensing provides important sources of information for the assessment of calamity-affected forests. We use CORINE Land Cover data and methodology based on satellite images for the evaluation of forest logging and regeneration after windstorms and bark beetle infestation in 2 mountain national parks in Slovakia (TANAP and NAPALT) on the regional level form 2000–2018. For the detailed capture of landscape dynamics, manifestations of afforestation and deforestation of small areas, it is appropriate to use the methodology presented by us, due to its spatial accuracy and details of the legend. While the area in the vicinity of Tatranská Lomnnica encroaching on the Studená dolina National Nature Reserve in TANAP represents a trend of the gradual return of young forests, the Čertovica area on the NAPALT border is characterized by an increase in clear-cut sites with potentially increasing soil erosion risk, due to repeated wind disasters and widening of bark beetle. The use of the proposed methodology, with detailed inventorying of land cover classes of forests damaged by windstorm and biological pests, in larger areas is more time consuming, but it provides relevant data for the analysis of the relationships between the degree of forest damage and habitat conditions in large scale.

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