TREE STAND ASSESSMENT BEFORE AND AFTER WINDTHROW BASED ON OPEN-ACCESS BIODIVERSITY DATA AND AERIAL PHOTOGRAPHY

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Received: 31.12.2021. Revised: 16.03.2022. Accepted: 29.03.2022.

The ground-based surveys of areas affected by storms might be difficult or even impossible because of the limited ability to move within the damaged area. Therefore, this work was aimed to estimate storm damage based on aerial photography and open biodiversity data available via the Internet. The study was carried out in the old-growth hemiboreal forests of the Kologrivsky Forest State Nature Reserve (Kostroma Region, Russia), which was affected by a catastrophic windthrow caused by a storm on 15.05.2021. The sampling area was 100 000 m^2. We used our previous ground-survey studies and open-access biodiversity data available through the Global Biodiversity Information Facility for describing the forest stands composition before the catastrophic event. The aerial photography data were used for estimating tree stands damages after the windthrow. For remote data collecting, we used an unmanned aerial vehicle – quadrocopter DJI Phantom 4. Agisoft Metashape software was used for aerial photographs processing. The obtained photogrammetric digital elevation model (DEM) and orthophoto-mosaic were processed with QGIS software. Damaged areas were detected automatically based on the DEM. Individual fallen trees were visually detected using the orthophoto-mosaic. We found before the windthrow the study area was covered by old-growth stands developed naturally over a long time. The stand structure was multi-layered and uneven-aged. The ontogenetic spectra of late-successional tree species *Picea abies* (hereinafter – spruce) and *Tilia cordata* (hereinafter – linden) were normal. The old-growth stands were heterogeneous before the windthrow: the canopy closed multi-layered and uneven-aged stands, decaying spruce stands and areas where spruce completely fell out and the tree stand was absent. In addition, old-growth linden stands were present. According to the obtained results, the stand structure was critically changed caused by the windthrow. The DEM-processing results showed the windthrow strongly damaged 33.1% stands in the study area. Using the orthophoto-mosaic, we visually detected 759 fallen trees. Among them, 82.9% were associated with strongly-damaged areas. According to the DEM classification, the rest of the visually detected fallen trees were in non-damaged areas and canopy gaps established before the windthrow. The analysis showed that these were less damaged areas with survived stands or groups of trees after the storm. Thus, our results showed that it is necessary to use both the DEM and the orthophoto-mosaic for more accurate estimates. Our exploratory analysis of different tree stand damages found that apparently, spruce stands were more affected by the storm than linden stands. It is explained by the different wind resistance of spruce and linden and differences in regrowth density and species composition in these stands.

Key words: digital elevation model, GBIF, Kologrivsky Forest State Nature Reserve, orthophoto-mosaics, old-growth hemiboreal forests

Introduction

Wind disturbance is a significant phenomenon in forest spatial structure and succession dynamics (Ulanova, 2000; Gardiner, 2021). In recent years, extreme storm events have occurred regularly across Europe (Dorland et al., 1999; Usbeck et al., 2010). With climate change, such events are expected to occur more frequently in future (Seidl et al., 2011).

On 15.05.2021, a storm with wind estimated at up to 30–31 m/s affected approximately 155 km^2 in Ivanovo Region and Kostroma Region (Central Russia) (Lebedev & Chistyakov, 2021b), including the area of the Kologrivsky Forest State Nature Reserve. The storm damaged old-growth spruce forest stands of the Kologrivsky Forest State Nature Reserve (the Reserve Core). Determining the extent of damages in this area is crucial because the Reserve Core (the total area is 9.18 km^2) is the largest old-growth forest (Sokolov, 1986) saved after massive clear-cutting started in the Kostroma Region in the 1950s (Dudin, 2000).

Assessment of a wind disaster by ground-based methods is problematic. Remote sensing derived measurements are the most common for this task. Depending on the size of the area of interest, the detection of windthrows is mainly carried out using data either from optical sensors such as Landsat (Baumann et al., 2014), Sentinel (Rüetschi et al., 2019; Lazecky et al., 2021; Olmo et al., 2021), very-high-resolution imagery (Einzmann et al., 2017; Deigele et al., 2020; Kislov & Korznikov, 2020), as well as airborne laser scanning (Honkavaara et al., 2013; Mokroš et al., 2017; Polewski et al., 2017) or synthetic aperture radar (Tanase et al., 2018). The potential for increasing the efficiency of data collection could benefit unmanned aerial vehicles (UAV), which can provide more accurate, clear and detailed data compared to existing remote sensing techniques and allow the detection of individual windthrown trees (Inoue et al., 2014; Duan et al., 2017).

Reliable results require information about the territory before and after the storm. The available data on the forest vegetation of the Reserve Core before the windthrow are limited. The stands have been studied since the 1980s (Sokolov, 1986) and continue to the present (Ivanov et al., 2012; Khoroshev et al., 2013; Lebedev & Chistyakov, 2021b). However, most of these studies focus on permanent sampling plots monitoring, and georeferenced data of tree stand composition and structure in other parts of the Reserve Core are still lacking. Data on the ontogenetic structure of tree populations are almost wholly absent (Krinitsyn & Lebedev, 2019). The limitedness of these data makes it challenging to assess windthrown damages and predict the regeneration of stands.

In this case, open biodiversity data available via the Internet could be a valuable additional source for describing tree stands composition in the area before the catastrophic event. The amount of open biodiversity data is growing rapidly. The Global Biodiversity Information Facility (GBIF) is the most extensive international open data infrastructure with free and open access to biodiversity data (Heberling et al., 2021), aggregated more than 2 billion species occurrence records worldwide. GBIF open-access data are widely used for the assessment of the effect of global climate changes on species distribution (Dyderski et al., 2018; Ribeiro et al., 2018; Gallagher et al., 2019), for modelling the factors that contribute to the dispersal of invasive species (Jarnevich et al., 2018; Mally et al., 2021), and the risks of distribution of dangerous diseases (Cardador & Blackburn, 2019; Rai et al., 2021) and other macroregional studies. For local studies, GBIF data is rarely used but could be a crucial source for several tasks.

This study was aimed to detect windthrown areas in old-growth hemiboreal forests of the Reserve Core. For describing the forest stands before the catastrophic event, we used GBIF data and the results of our previous ground-survey studies. UAV data (a photogrammetric digital elevation model (DEM) and orthophoto-mosaic) were used for estimating tree stands damages caused by the storm.

Material and Methods

Study area

The Kologrivsky Forest State Nature Reserve is situated in the northeast of the Russian Plain, in the Kostroma Region, Russia (Fig. 1). The study area is characterised by a temperate continental climate with a strong seasonal cycle. The summer is relatively warm, and the winter has moderate to severe frosts and a moderate snow cover. According to the nearest weather station, Kologriv (RSM00027164, https://oscar.wmo.int/WIGOS ID 0-20000-0-27164), the average annual temperature is +2.9°C (1972–2020), minimum (+0.7°C) was in 1987, maximum (+4.7°C) in 2020. The average January temperature is -11.7°C; the average July temperature is +17.6°C. The average annual precipitation is 600 mm, minimum (417 mm) was in 2005, maximum (870 mm) in 1978 (Veselov et al., 2021). Kostroma Region is situated in the hemiboreal forest region, typically showing the joint natural occurrence and co-domination of dark-coniferous and broad-leaved trees (Isachenko, 2001).

The Kologrivsky Forest State Nature Reserve (https://www.protectedplanet.net/555711243) was established in 2006 and joined the International Man and Biosphere Reserve Network as a global conservation hotspot in 2020. The Protected Area consists of two clusters; the total area is 589 km^2. This study was carried out in the Reserve Core (https://www.geonames.org/, ID 12440508) of the Kologriv cluster. According to available data, mature *Picea abies* (L.) Karst. (also – spruce) forests is occupying 65% of the Reserve Core, and 35% is covered by *Betula* spp. (*Betula pubescens* Ehrh. with small participation of *Betula pendula* Roth.) (also – birch) stands, which developed after cutting performed in the 1928s and fires of 1938s (Fig. 2). The tree layer of spruce stands is dominated by spruce and *Tilia cordata* Mill. (also – linden), with *Abies sibirica* Ledeb. (also – fir) and *Betula* spp. In the second canopy layer, *Ulmus glabra* Huds. (also – elm) and *Acer platanoides* L. (also – maple) occur. Stands are uneven-aged (Sokolov, 1986).

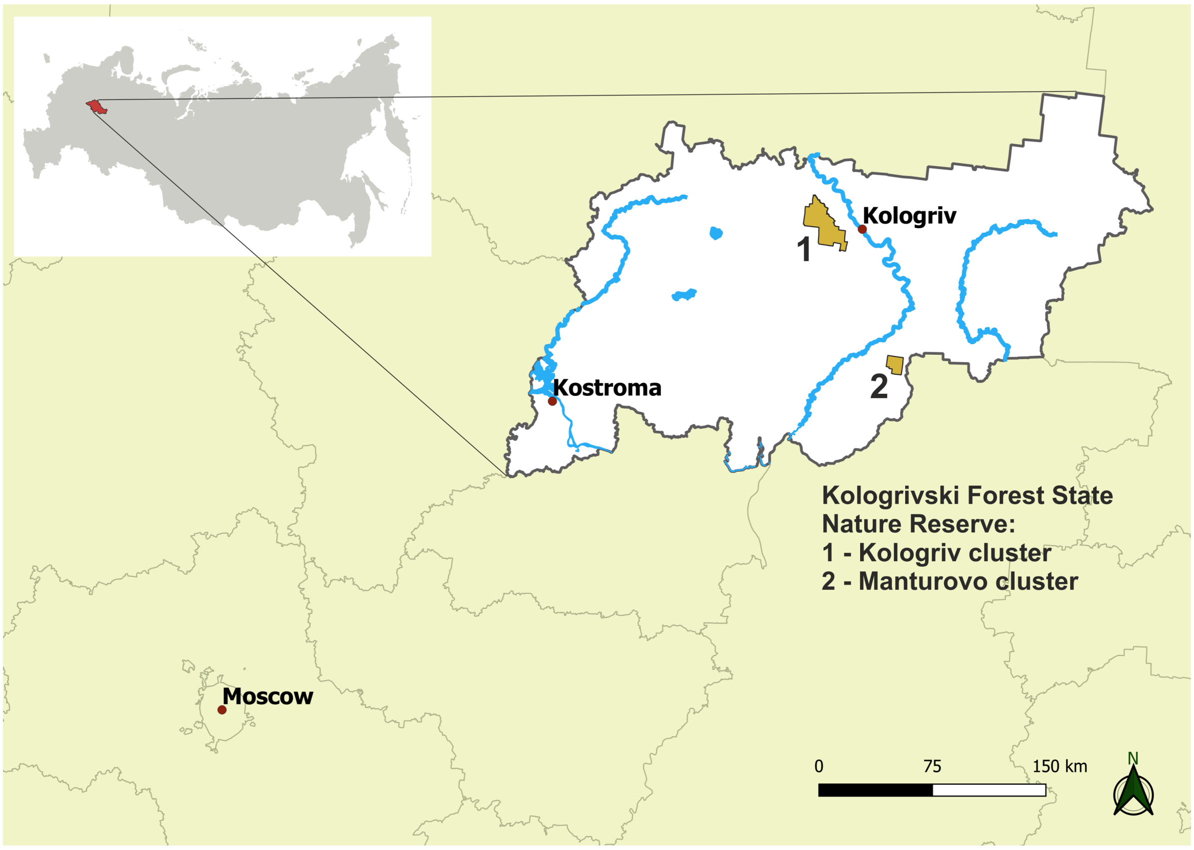

Fig. 1. The location of the Kologrivsky Forest State Nature Reserve, Russia.

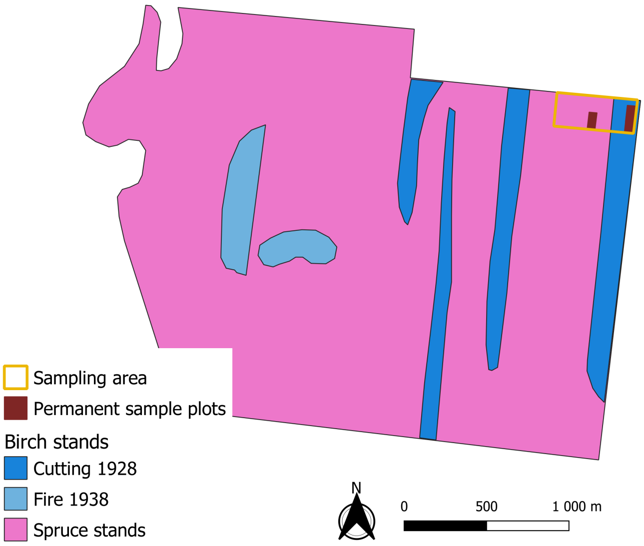

Fig. 2. The scheme of the old-growth tree stands in the Reserve Core of the Kologrivsky Forest State Nature Reserve (Russia) based on Sokolov (1986) with modifications.

The detection of windthrown areas was performed in the sampling area of 100 000 m^2, situated in the north-eastern part of the Reserve Core (Fig. 2). There are two permanent sample plots in the study area. The first one, 50 × 200 m, was established in the birch stand, and the second one, 50 × 100 m, in the spruce stand. Both plots were established in 1983 and re-measured in 2017 (Lebedev & Chistyakov, 2021b). According to the survey results, large spruce trees fell out on the spruce sampling plot, and the upper canopy layer consisted of birch (48 ind. / 10 000 m^2, 135 years old). Smaller surviving spruce trees dominated the second canopy layer (220 ind. / 10 000 m^2, 130 years old). The upper canopy layer of the birch sampling plot dominated birch (322 ind. / 10 000 m^2, 90 years old) with small participation of *Populus tremula* L. (2 ind. / 10 000 m^2). The second canopy layer consisted of spruce (344–386 ind. / 10 000 m^2, 90–95 years old) and linden (30 ind. / 10 000 m^2, 95 years old). Maple trees were also presented (2 ind. / 10 000 m^2, 20 years old).

Estimating of tree stands composition before the catastrophic event

We checked biodiversity data available for the study area through the GBIF repository (GBIF, 2021) for describing tree stands composition before the storm. The resulted dataset included 714 species occurrence records derived from four resources: «iNaturalist Research-grade observations» (Ueda, 2012), «Moscow University Herbarium (MW)» (Seregin, 2021), «Forest vegetation of the northeastern part of the Kostroma region (European Russia)» (Ivanova et al., 2018), and «Database of finds of rare lichen species *Lobaria* *pulmonaria* in Russia» (Shashkov & Ivanova, 2016). All data were collected from 2007 to 2021. Records with co-ordinate uncertainty > 100 m and duplicated co-ordinate points were excluded from the analysis. After this data cleaning, we extracted available data on the tree species composition or forest types. In addition, we checked all species occurrence-related photos in iNaturalist and found tree stand dominants if possible. In total, 39 records were obtained for further analysis (Table).

Moreover, we used our ground-survey tree stand measurements collected in 2013 during the study, which aimed to investigate factors limiting the distribution of rare lichen *Lobaria pulmonaria* (L.) Hoffm. in old-growth forests (Ivanova, 2015). During that study, we established 16 temporary sampling plots (20 × 20 m) located inside or near the sampling area. Diameters at breast height (DBH) were measured for all trees with DBH > 10 cm, and the number of trees with DBH < 10 cm was counted (these data are not presented in the article). The canopy height and tree age (for 2–6 trees per plot) were measured for each sampling plot. The ontogenetic structure of tree populations was counted. We distinguished juvenile (j), immature 1 (im1), immature 2 (im2), virginal 1 (v1), virginal 2 (v2), young generative (g1), middle-aged generative (g2), old generative (g3), and senile (s) individuals (Smirnova et al., 2017). Vegetation relevés were made on each plot in 100 m^2. Primary tree measurement data were published through GBIF (Ivanova & Shashkov, 2021b).

Estimating of storm damage based on UAV data

The DJI Phantom 4 (DJI-Innovations, Shenzhen, China) was used for remote sensing data collection. It is a widely available, consumer-grade quadcopter with a 12 Megapixel camera. UAV data were collected on 27.08.2021 and 28.08.2021 from an altitude of 336 m above ground level. The mosaic flight mode was used with 80% overlapping sides and front. The flight plan was designed with the DroneDeploy software and was drawn with a buffer around the sampling plot for avoiding data processing artefacts.

Stages of the UAV data processing are presented in Fig. 3. Photogrammetric imagery processing was performed in the Agisoft Metashape v. 1.5 software (Agisoft, 2019). The dense point cloud, DEM (40 cm/pixel) and orthophoto-mosaic (~10 cm/pixel) were generated. Then the DEM and orthophoto-mosaic were processed in QGIS v. 3.14 software (QGIS Development Team, 2021). The minimum height value was subtracted from the DEM for convenience processing because the sampling area surface was flat. After this transformation, the maximum DEM height model was well-matched with the ground-based tree height measurements, the latter reported by Ivanova & Shashkov (2021b).

We analysed the height distribution histogram derived from the normalised DEM (Fig. 4) to detect areas affected by windthrow. The distribution was bimodal. We assumed that the left maximum corresponds to windthrown areas, the middle part to canopy gaps established before the catastrophic event (due to naturally decaying spruce stands), and the right maximum to non-damaged stands. To achieve optimal windthrown areas detection, we tested different threshold values. The results were estimated visually using the orthophoto-mosaic. The best results were obtained using the threshold 0–12 m for strongly damaged areas, the threshold 12–22 m for canopy gaps established before the catastrophic event, and the threshold > 22 m for non-damaged stands. After automatic classification, we excluded from the damaged and non-damaged classes all polygons < 100 m^2 as classification artefacts. After that, the areas for each class were calculated.

Table. Biodiversity data available through GBIF for the sampling area in the Reserve Core of the Kologrivsky Forest State Nature Reserve, Russia

Dataset name	Total number of records for the sampling area	Number of records with habitat information	Number of records after the data cleaning
iNaturalist Research-grade Observations	61	19	19
Moscow University herbarium (MW)	1	1	0
Forest vegetation of the northeastern part of the Kostroma region (European Russia)	22 vegetation relevés (566 occurrences)	22 vegetation relevés	20
Database of finds of rare lichen species *Lobaria pulmonaria* in Russia	86	0	0

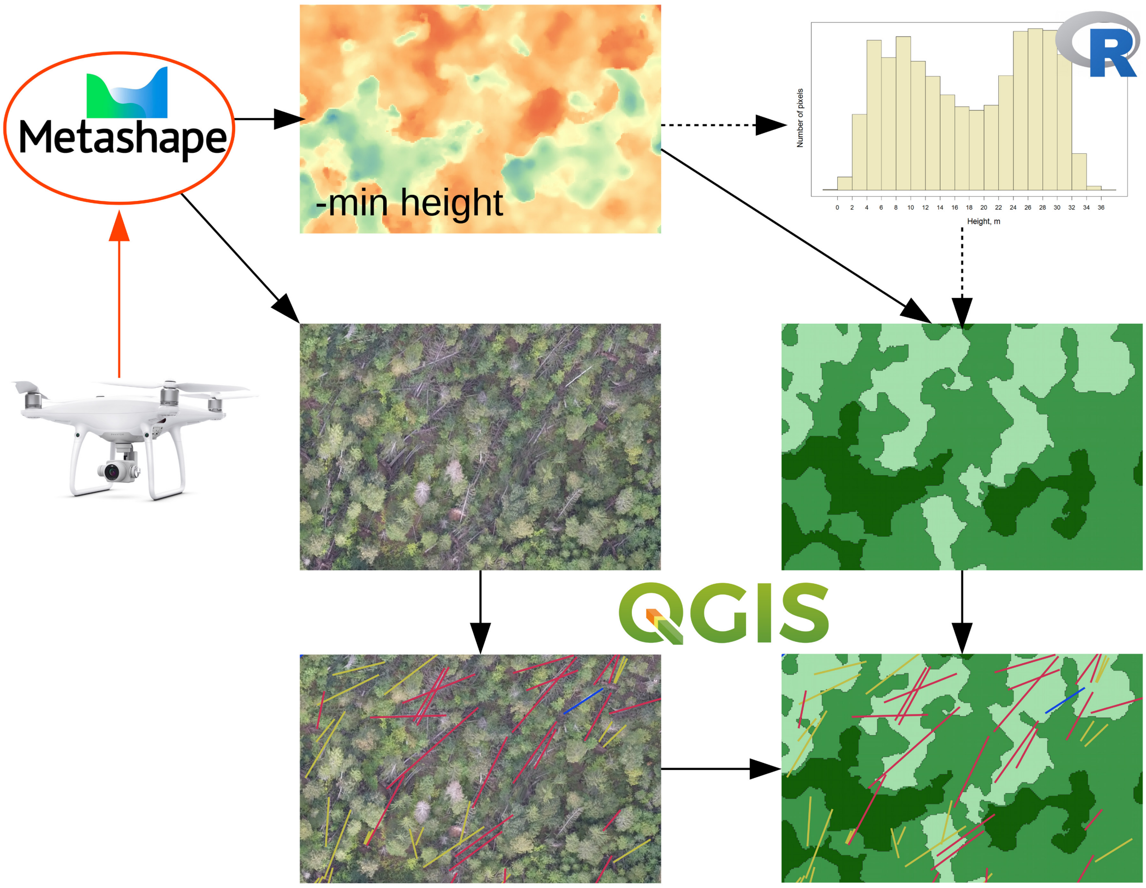

Fig. 3. The schema of UAV data processing for detecting of storm damaged areas in the Reserve Core of the Kologrivsky Forest State Nature Reserve, Russia.

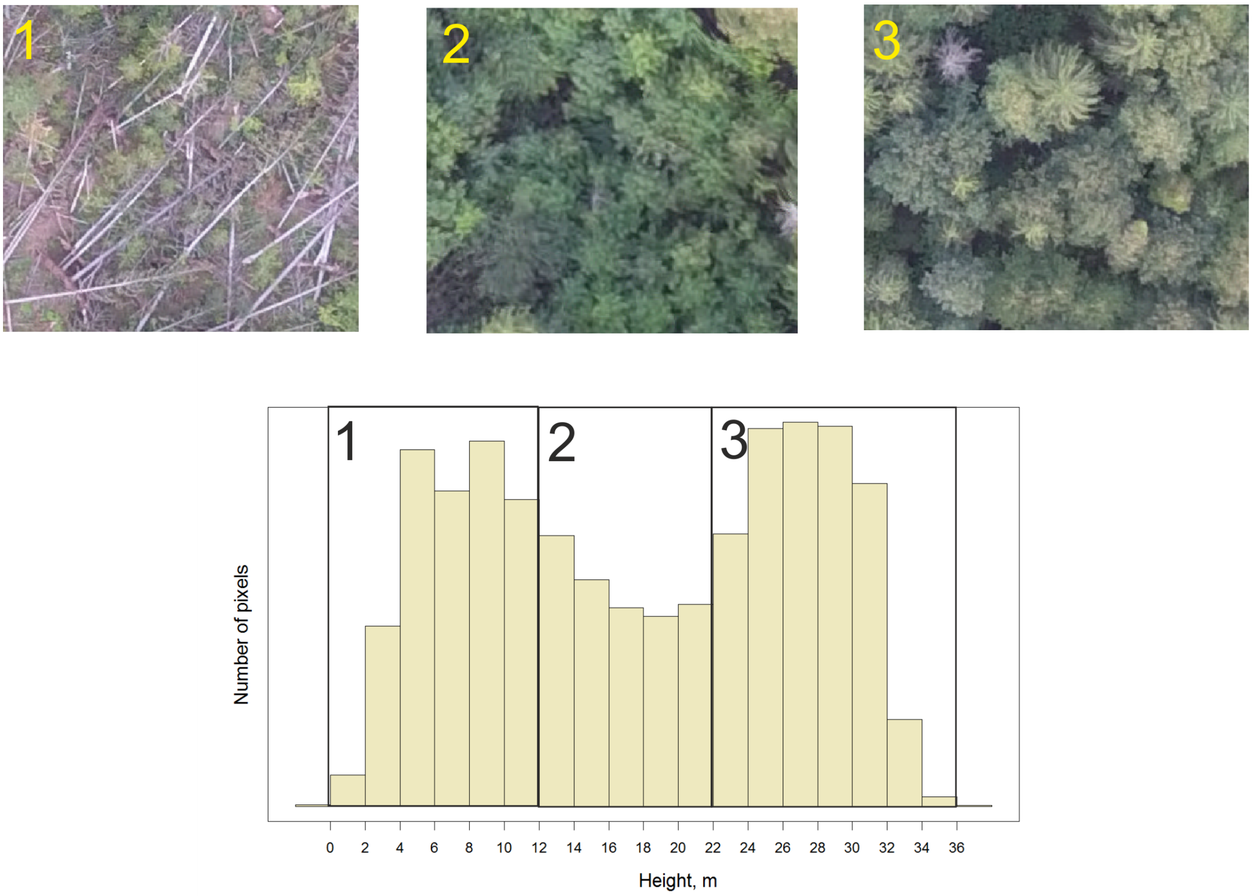

Fig. 4. Histogram of the pixel height's distribution derived from DEM and correspondence vegetation classes on the orthophotomosaic. Designations: 1 – strongly damaged areas, 2 – canopy gaps established before the storm, 3 – non-damaged areas.

Moreover, we visually detected and manually vectorised all fallen trees in the sampling area using the orthophoto-mosaic. The total number of such trees was counted, and tree species were identified if possible. The results were compared with DEM classification results.

Results

Tree stands structure and composition before the windthrow

We found that most of the sampling area was covered by heterogeneous old-growth linden-spruce stands before the catastrophic event. We identified 18 points with spruce-dominating stands, ten points with linden dominating stands, three canopy gap points (decaying spruce stands), and eight points with birch for this territory based on GBIF data (Fig. 5).

According to our ground-based measurements, the upper canopy layer of closed spruce stands (with tree height 26–36 m) was dominated by *Picea abies* with the participation of *Tilia cordata* and rarely *Betula* spp. and *Abies sibirica*. The second canopy layer (with tree height 18–25 m) was represented by *P. abies*, *A. sibirica*, *T. cordata*, *Acer platanoides*, *Sorbus aucuparia* L., and *Salix caprea* L. Regrowth was presented by *P. abies*, *A. sibirica*, *T. cordata*, *A. platanoides*, and *S. aucuparia*. The measured age of *P. abies* ranged from 70 to 215 years old, *T. cordata* from 70 to 120 years old, *Betula* spp. from 65 to 95 years old, *S. aucuparia* trees were 55–90 years old. The maximum measured age of *A. sibirica* was 65 years old. A virginal *A. platanoides* individual was 30 years old. A senile *S. caprea* individual was > 55 years old. We found normal ontogenetic spectra for *P. abies*, *T. cordata* and *S. aucuparia* populations, invasive spectra for the *A. sibirica* and *A. platanoides* populations. Generative individuals dominated the population of *Betula* spp. The *S. caprea* population was fragmented (Fig. 6).

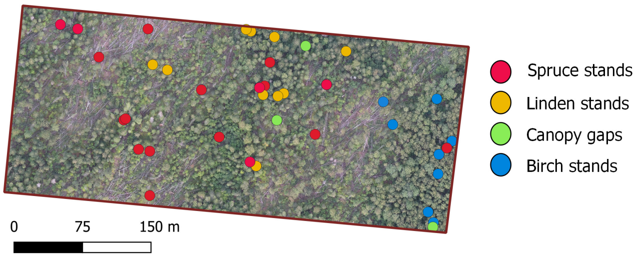

Fig. 5. GBIF-derived points for the sampling area in the Reserve Core of the Kologrivsky Forest State Nature Reserve (Russia) on the orthophoto-mosaics.

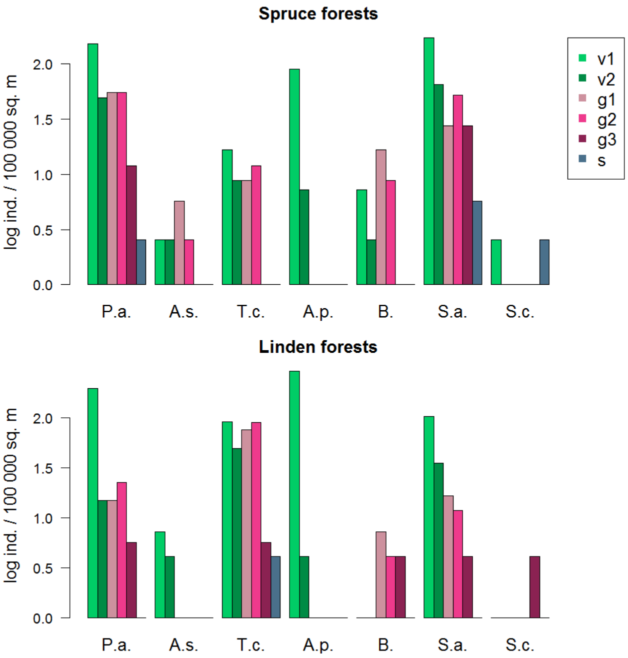

Fig. 6. Ontogenetic structure of tree populations in spruce (above) and linden (below) dominating stands in the Reserve Core of the Kologrivsky Forest State Nature Reserve, Russia. Designations: P.a. – *Picea abies*, A.s. – *Abies sibirica*, T.c. – *Tilia cordata*, A.p. – *Acer platanoides*, B. – *Betula* spp., S.a. – *Sorbus aucuparia*, S.c. – *Salix caprea*.

Linden stands were performed by *Tilia cordata*, *Picea abies* and *Betula* spp. The measured *T. cordata* age varied from 35 to 140 years old, *P. abies* 50 to 170 years old. The maximum age of *Betula* spp. was 80 years old. Regrowth was presented by *P. abies*, *Abies sibirica*, *T. cordata*, *Acer platanoides*, and *Sorbus aucuparia*, but the density and species composition were different from spruce stands. Regrowth in linden stands was more abundant than in spruce stands. The total number of immature and virginal individuals was 1984 in spruce stands, but 2713 in linden stands. According to the relevés data, the mean value of the shrub layer cover was significantly higher ($p < 0.05$) in linden stands rather than in spruce stands (65 ± 9.2% and 45 ± 14.3%, respectively). *Acer platanoides* was a more abundant tree in linden stands regrowth, while in spruce stands regrowth *P. abies* and *S. aucuparia* were dominated. We found normal ontogenetic spectra for *P. abies*, *T. cordata* and *S. aucuparia* populations, invasive spectra for *A. sibirica* and *A. platanoides* population. The population of *Betula* spp. was low-density and bimodal. The *Salix caprea* population was fragmented. Only old generative individuals were counted (Fig. 6).

Areas affected by the windthrow

Using the obtained thresholds, we found the strongly damaged area covered 33 156 m^2. The area of non-damaged stands was 39 349 m^2, and the area of canopy gaps established before the catastrophic events was 27 495 m^2 (Fig 7, Fig. 8A). We automatically detected 19 strongly damaged polygons from 114 m^2 to 13 091 m^2. We found large-scale damages; six strongly damaged areas were more than 1000 m^2 and contributed 89.0% to this class (Fig 8B).

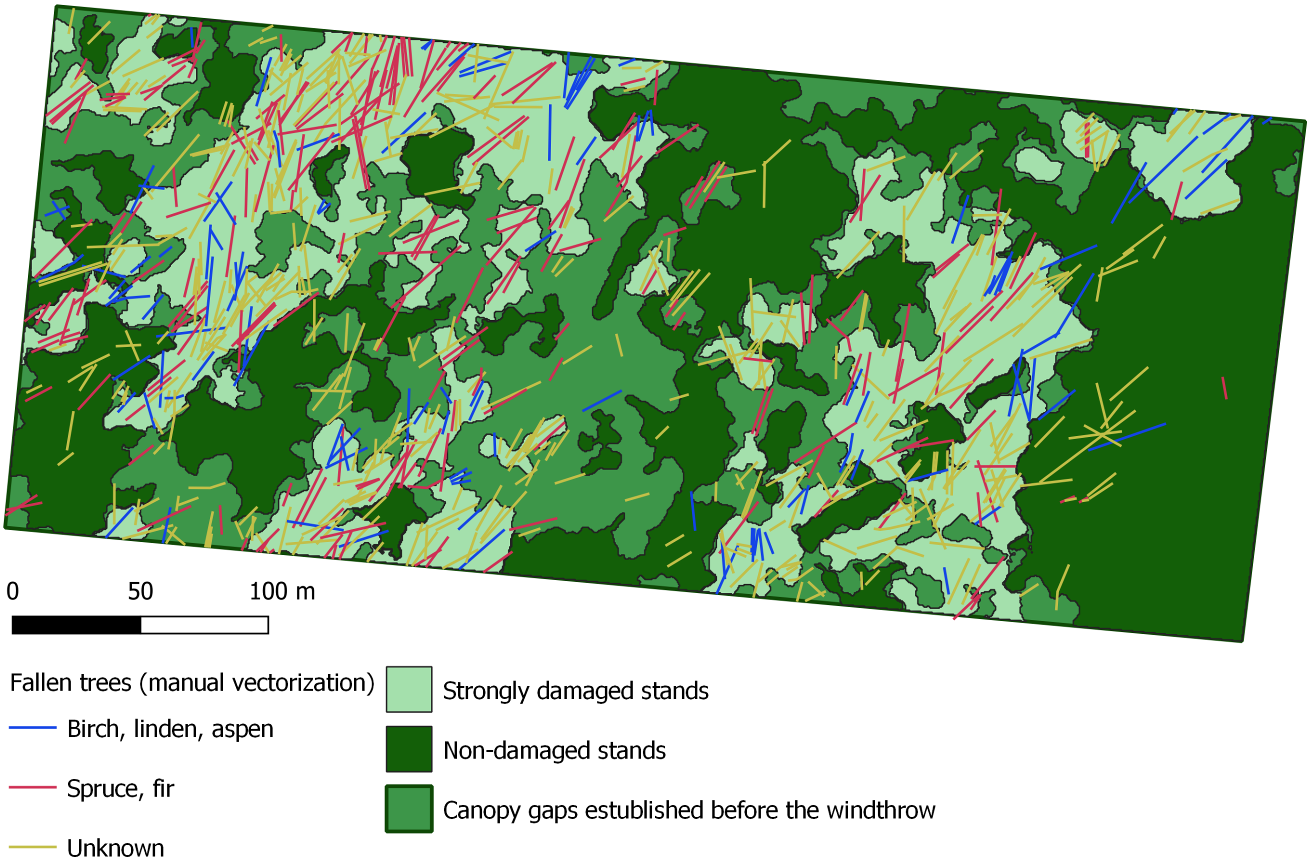

Fig. 7. Tree stands with different degrees of windthrow damage identified by DEM and manually detected fallen trees.

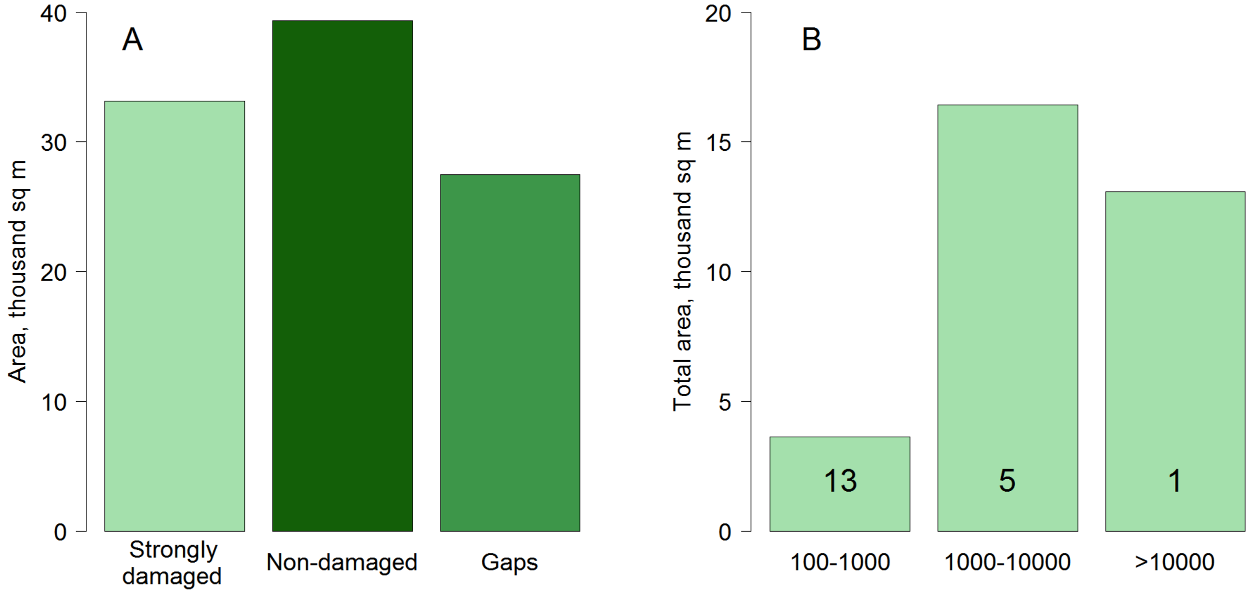

Fig. 8. Areas of tree stands with different degrees of windthrow damage (A) and distribution of damaged areas per different classes of areas (B). The numbers on the bars show the number of polygons in the class.

We visually detected 759 fallen trees using the orthophoto-mosaic. There were 215 coniferous trees (mainly spruce), 111 deciduous trees, and 433 trees that were not identified (Fig. 7). Fallen trees were distributed almost all over the sampling area. Among them, 82.9% were associated with strongly damaged areas. The remaining fallen trees were located in canopy gaps established before the storm and non-damaged areas. The analyses of the orthophoto-mosaic showed these trees indicated less damaged areas, where stands or groups of trees survived. Due to standing trees, less damaged areas could not be detected on the DEM.

We found that the uneven-aged birch stands were little affected by the windthrow. All GBIF-derived points with birch dominating were assigned to non-damaged areas (two points were located close to the damaged areas). Linden stands most likely were also less damaged. Only one GBIF-derived point from linden stands was located in the windthrown area, and nine in non-damaged areas. Old-growth spruce stands were highly fragmented. Among spruce stands, nine GBIF-derived points were signed to the damaged areas, five to canopy gaps established before the storm, and six to non-damaged stands.

Discussion

Ground-based surveys of areas affected by storms might be difficult or even impossible because of the limited ability to move in the area. Therefore, in this study, we performed an exploratory study to estimate storm damages based on aerial photography and open biodiversity data. We used the results of our previous ground-based tree measurements and open-access biodiversity data available through GBIF repository for describing tree stands composition before the storm. We found a low availability of information about habitat types in GBIF data. Only 5.4% of records (including iNaturalist-photos) provided it.

Although these data were incomplete, we found that old-growth stands were heterogeneous before the windthrow. Our results suggest that studied tree stands developed naturally over a long time. It is confirmed by multi-layered and uneven-aged stands structure and normal ontogenetic spectra of late-successional tree species *Picea abies* and *Tilia cordata* (Smirnova et al., 2017). The *Acer platanoides* population had an invasive ontogenetic spectrum due to a dramatic decrease after the extremely cold winter 1978–1979 with a minimal air temperature of -49.8°C (Sokolov, 1986; Veselov et al., 2021). The reasons for the invasive spectrum of the *Abies sibirica* population need additional studies. However, it is essential to point out that the northern limit of the distribution of *A. platanoides*, and the western limits of *A. sibirica* distribution pass through the study region (Sokolov et al., 1977). Therefore, environmental conditions are far from optimal for these tree species.

Based on UAV-derived products, we estimated storm-damaged areas. Results of DEM classification found the old-growth stands were strongly affected by the windthrow; 33.1% of the study area had fallen. Even-aged birch stands were affected less. The damaged area mainly represents large-scale polygons (> 1000 m^2), which indicates the destructive nature of the damages of the forest stands. The manually detected fallen trees were well-matched with fallen trees areas, which show the high accuracy detecting of the DEM estimate. About 20% detected trees were located in canopy gaps established before the storm and non-damaged areas. These trees indicated less damaged areas, where stands or groups of trees survived.

We infer that the storm has mainly affected spruce-dominated stands based on the obtained results. Linden stands were more wind-resistant than spruce stands. Several studies have shown high wind resistance of broadleaf trees (Ruel, 1995; Bobrovskiy & Stamenov, 2020), while spruce stands were most vulnerable (Taylor et al., 2019). Moreover, we found that the mean value of the cover shrub layer was significantly higher in linden stands compared to the spruce stands. *Acer platanoides* regrowth had a high density in linden stands. These features likely contributed to the mitigation of linden stands damage under high wind conditions.

In general, the aerial photography data allowed a more accurate estimate of the windthrown areas than preliminary data based on Landsat images (Lebedev & Chistyakov, 2021a), according to which the storm damaged the whole territory of the Reserve Core. Despite of this, our approach has some limitations.

Firstly, the representativeness of GBIF data remains low for most regions of Russia (Ivanova & Shashkov, 2021a). Therefore, these data were not enough to describe the territory before the disturbance event. This study has found heterogeneity in tree stand dominants based on GBIF data. However, a more detailed description of different tree stand structures required additional information. More common practice is based on comparisons of before and after event remote data (Honkavaara et al., 2013; Einzmann et al., 2017; Rüetschi et al., 2019; Lazecky et al., 2021). For example, in the study of Honkavaara et al. (2013), damaged areas were detected by comparing digital surface models before and after the storm. Nevertheless, the severe limitation of this approach is the availability of remote data before the windthrow. Another approach for detecting forest disturbances is to apply artificial intelligence and machine learning algorithms to remote sensing data (Hamdi et al., 2019; Deigele et al., 2020; Kislov & Korznikov, 2020). For example, Kislov & Korznikov (2020) used U-Net-like CNNs and very-high-resolution imagery (Pleiades-1A/B and Worldview-3) for recognising windthrow areas in the dark coniferous forests of Kunashir Island (Kuril Islands, Russia). This approach may be implemented based only on images after the storm. However, in this case, the problem of describing the territory before the storm remains unsolved.

Secondly, DEM classification allows detection of strongly damaged areas accurately. Nevertheless, we also found less damaged areas where tree stands were presented (as closed stands or individual tree groups). Such areas cannot be detected using the DEM and need the orthophoto-mosaic to identify. Other researchers obtained similar results. In the study of Honkavaara et al. (2013), storm-damaged areas in coniferous forests in Finland were identified by comparing two digital surface models (before and after a storm). Honkavaara et al. (2013) detected two classes of storm-damaged areas (great damages with less than half of the trees damaged and destroyed, and complete destruction with more than half of the trees damaged), but their method was too sensitive to detect minor damages. In some cases, only orthophoto-images are enough for damaged areas detection. For example, Hyvönen & Heinonen (2018) performed the estimating storm damage with the help of aerial photographs in managed forests of Finland. They used low-altitude (700 m) photos with 9 cm resolution to visually detect storm-damaged areas and individual fallen trees. Hyvönen & Heinonen (2018) concluded that this approach is applicable for monitoring storm damages. Nevertheless, according to our results, the orthophoto-mosaic is not enough for accurate classification in the case of old-growth multi-level stands.

Finally, an important limitation of the visual detection of fallen trees from the orthophoto-mosaic is the impossibility to identify whether the tree fell due to a storm or not. It could lead to overestimating the number of trees that fell due to the storm (Hyvönen & Heinonen, 2018). Thus, the accuracy of manual detection needs additional studies. Moreover, this study requires a considerable amount of time. Automatically detection algorithms working with RGB images or point clouds are more suitable for this task, especially in the case of large areas. According to the literature, their accuracy is about 75–80% (Mücke et al., 2013; Polewski et al., 2015; Duan et al., 2017), which is likely comparable to the results of manual detection.

Conclusions

The analysis based on available open biodiversity data and UAV-derived products allowed us to estimate the initial state of tree stands before the storm and stand damages due to a windthrow. We found a heterogeneous structure of old-growth tree stands before the catastrophic event in the study area. Based on the DEM, strongly damaged areas were detected. We found that the windthrow strongly affected the old-growth stands; 33.1% of the study area had fallen. Manual detection of fallen trees made it possible to assess the accuracy of the DEM classification and indicate less damaged areas where stands or groups of trees survived. Our results show that using both the orthophoto-mosaic and DEM is necessary for more accurate estimates. We also suppose spruce stands were more affected by the storm than linden stands due to the different wind resistance of spruce and linden and differences in regrowth density and species composition in these stands.

Acknowledgements

The work was supported by the Russian Science Foundation, project No. 18-14-00362-P (UAV data collection, processing and analysis). The work of Natalya Ivanova in GBIF data processing was done in the framework of the Basic Scientific Research theme of the Institute of Mathematical Problems of Biology, Russian Academy of Sciences – the Branch of Keldysh Institute of Applied Mathematics of the Russian Academy of Sciences.

References

Agisoft. 2019. *Agisoft Metashape (Version 1.5). Software.* Available from https://www.agisoft.com/

Baumann M., Ozdogan M., Wolter P.T., Krylov A., Vladimirova N., Radeloff V.C. 2014. Landsat remote sensing of forest windfall disturbance. *Remote Sensing of Environment* 143: 171–179. DOI: 10.1016/j.rse.2013.12.020

Bobrovskiy M.V., Stamenov M.N. 2020. An impact of the year 2006 catastrophic windfall on structure and composition of forest vegetation in «Kaluzhskiye Zaseki» Nature Reserve. *Russian Journal of Forest Science* 6: 523–526. DOI: 10.31857/S0024114820050022 [In Russian]

Cardador L., Blackburn T.M. 2019. Human-habitat associations in the native distributions of alien bird species. *Journal of Applied Ecology* 56(5): 1189–1199. DOI: 10.1111/1365-2664.13351

Deigele W., Brandmeier M., Straub C. 2020. A hierarchical deep-learning approach for rapid windthrow detection on PlanetScope and high-resolution aerial image data. *Remote Sensing* 12(13): 2121. DOI: 10.3390/rs12132121

Dorland C., Tol R.S.J., Palutikof J.P. 1999. Vulnerability of the Netherlands and Northwest Europe to Storm Damage under Climate Change. *Climatic Change* 43(3): 513–535. DOI: 10.1023/A:1005492126814

Duan F., Wan Y., Deng L. 2017. A novel approach for coarse-to-fine windthrown tree extraction based on unmanned aerial vehicle images. *Remote Sensing* 9(4): 306. DOI: 10.3390/rs9040306

Dudin V.A. 2000. *The history of forests of the Kostroma Region.* Kostroma: DiAr. 256 p. [In Russian]

Dyderski M.K., Paź S., Frelich L.E., Jagodziński A.M. 2018. How much does climate change threaten European forest tree species distributions? *Global Change Biology* 24(3): 1150–1163. DOI: 10.1111/gcb.13925

Einzmann K., Immitzer M., Böck S., Bauer O., Schmitt A., Atzberger C. 2017. Windthrow detection in European forests with very high-resolution optical data. *Forests* 8(1): 21. DOI: 10.3390/f8010021

Gallagher R.V., Allen S., Wright I.J. 2019. Safety margins and adaptive capacity of vegetation to climate change. *Scientific Reports* 9(1): 8241. DOI: 10.1038/s41598-019-44483-x

Gardiner B. 2021. Wind damage to forests and trees: a review with an emphasis on planted and managed forests. *Journal of Forest Research* 26(4): 248–266. DOI: 10.1080/13416979.2021.1940665

GBIF. 2021. *GBIF Occurrence Download.* Available from https://doi.org/10.15468/dl.fk42jj

Hamdi Z.M., Brandmeier M., Straub C. 2019. Forest damage assessment using deep learning on high resolution remote sensing data. *Remote Sensing* 11(17): 1976. DOI: 10.3390/rs11171976

Heberling J.M., Miller J.T., Noesgaard D., Weingart S.B., Schigel D. 2021. Data integration enables global biodiversity synthesis. *Proceedings of the National Academy of Sciences of the United States of America* 118(6): e2018093118. DOI: 10.1073/pnas.2018093118

Honkavaara E., Litkey P., Nurminen K. 2013. Automatic Storm Damage Detection in Forests Using High-Altitude Photogrammetric Imagery. *Remote Sensing* 5(3): 1405–1424. DOI: 10.3390/rs5031405

Hyvönen P., Heinonen J. 2018. Estimating storm damage with the help of low-altitude photographs and different sampling designs and estimators. *Silva Fennica* 52(3): 7710. DOI: 10.14214/sf.7710

Inoue T., Nagai S., Yamashita S., Fadaei H., Ishii R., Okabe K., Taki H., Honda Y., Kajiwara K., Suzuki R. 2014. Unmanned Aerial Survey of Fallen Trees in a Deciduous Broadleaved Forest in Eastern Japan. *PLoS ONE* 9(10): e109881. DOI: 10.1371/journal.pone.0109881

Isachenko A.G. 2001. *Russian Ecological Geography.* Saint-Petersburg: Saint-Petersburg State University. 328 p. [In Russian]

Ivanov A.N., Butorina E.A., Baldina E.A. 2012. Long-term dynamics of primary spruce forests (Southern taiga) in the Kologriv Forest Natural Reserve. *Vestnik Moskovskogo Universiteta, Seriya Geografiya* 3: 80–85. [In Russian]

Ivanova N.V. 2015. Factors limiting distribution of the rare lichen species Lobaria pulmonaria (in forests of the Kologriv Forest Nature Reserve). *Biology Bulletin* 42(2): 145–153. DOI: 10.1134/S1062359015020041

Ivanova N., Shanin V., Grozovskaya I., Khanina L. 2018. *Forest vegetation of the northeastern part of the Kostroma region (European Russia). Version 1.3*. Institute of Mathematical Problems of Biology RAS – the Branch of Keldysh Institute of Applied Mathematics of Russian Academy of Sciences. Sampling event dataset. Available from https://doi.org/10.15468/qemuyc

Ivanova N.V., Shashkov M.P. 2021a. The possibilities of GBIF data use in ecological research. *Russian Journal of Ecology* 52(1): 1–8. DOI: 10.1134/S1067413621010069

Ivanova N., Shashkov M. 2021b. *Tree stand investigations at the old-growth taiga forest (the Core of the Kologrivsky Forest Nature Reserve, Russia). Version 1.1*. Institute of Mathematical Problems of Biology RAS – the Branch of Keldysh Institute of Applied Mathematics of Russian Academy of Sciences. Sampling event dataset. Available from https://doi.org/10.15468/nd3wdv

Jarnevich C.S., Young N.E., Talbert M., Talbert C. 2018. Forecasting an invasive species' distribution with global distribution data, local data, and physiological information. *Ecosphere* 9(5): e02279. DOI: 10.1002/ecs2.2279

Khoroshev A.V., Nemchinova A.V., Koshcheeva A.S., Ivanova N.V., Petukhov I.N., Terentieva E.V. 2013. Landscape and succession factors determining the balance between nemoral and boreal features of the grass layer in the Kologriv Forest Reserve. *Vestnik Moskovskogo Universiteta, Seriya 5: Geografiya* 5: 11–18. [In Russian]

Kislov D.E., Korznikov K.A. 2020. Automatic windthrow detection using very-high-resolution satellite imagery and deep learning. *Remote Sensing* 12(7): 1145. DOI: 10.3390/rs12071145

Krinitsyn I.G., Lebedev A.V. 2019. Ecological characteristics of habitats of cenopopulations of linden heart-shaped and spruce fir in the Reserve «Kologrivsy Les». *Prirodoobustrojstvo* 3: 121–126. DOI: 10.34677/1997-6011/2019-3-121-126 [In Russian]

Lazecky M., Wadhwa S., Mlcousek M., Sousa J.J. 2021. Simple method for identification of forest windthrows from Sentinel-1 SAR data incorporating PCA. *Procedia Computer Science* 181: 1154–1161. DOI: 10.1016/j.procs.2021.01.312

Lebedev A.V., Chistyakov S.A. 2021a. Assessment of the impact of the wind 2021 on the Kologrvsky Forest Biosphere Reserve. In: A.V. Lebedev (Ed.): *The contribution of Protected Areas to the ecological sustainability of regions: current state and prospects*. Kologriv: Kologrivsky Forest State Nature Reserve. P. 71–77. [In Russian]

Lebedev A.V., Chistyakov S.A. 2021b. Long-term observations on permanent sample plots in stands of the Kologrivsky Forest Nature Reserve. In: A.V. Lebedev (Ed.): *The contribution of Protected Areas to the ecological sustainability of regions: current state and prospects*. Kologriv: Kologrivsky Forest State Nature Reserve. P. 31–43. [In Russian]

Mally R., Ward S.F., Trombik J., Buszko J., Medzihorský V., Liebhold A.M. 2021. Non-native plant drives the spatial dynamics of its herbivores: the case of black locust (*Robinia pseudoacacia*) in Europe. *NeoBiota* 69: 155–175. DOI: 10.3897/neobiota.69.71949

Mokroš M., Výbošťok J., Merganič J., Hollaus M., Barton I., Koreň M., Tomaštík J., Čerňava J. 2017. Early stage forest windthrow estimation based on unmanned aircraft system imagery. *Forests* 8(9): 306. DOI: 10.3390/f8090306

Mücke W., Deák B., Schroiff A., Hollaus M., Pfeifer N. 2013. Detection of fallen trees in forested areas using small footprint airborne laser scanning data. *Canadian Journal of Remote Sensing* 39(Sup.1): 32–40. DOI: 10.5589/m13-013

Olmo V., Tordoni E., Petruzzellis F., Bacaro G., Altobelli A. 2021. Use of Sentinel-2 Satellite Data for Windthrows Monitoring and Delimiting: The Case of «Vaia» Storm in Friuli Venezia Giulia Region (North-Eastern Italy). *Remote Sensing* 13(8): 1530. DOI: 10.3390/rs13081530

Polewski P., Yao W., Heurich M., Krzystek P., Stilla P. 2015. Detection of fallen trees in ALS point clouds using a Normalized Cut approach trained by simulation. *ISPRS Journal of Photogrammetry and Remote Sensing* 105: 252–271. DOI: 10.1016/j.isprsjprs.2015.01.010

Polewski P., Yao W., Heurich M., Krzystek P., Stilla P. 2017. Learning a constrained conditional random field for enhanced segmentation of fallen trees in ALS point clouds. *ISPRS Journal of Photogrammetry and Remote Sensing* 140: 33–44. DOI: 10.1016/j.isprsjprs.2017.04.001

QGIS Development Team. 2021. *QGIS Geographic Information System*. Open Source Geospatial Foundation Project. Available from http://qgis.osgeo.org

Rai A., Chettri M., Dewan S., Khandelwal B., Chettri B. 2021. Epidemiological study of snakebite cases in Sikkim: Risk modeling with regard to the habitat suitability of common venomous snakes. *PLoS Neglected Tropical Diseases* 15(11): e0009800. DOI: 10.1371/journal.pntd.0009800

Ribeiro B.R., Sales L.P., Loyola R. 2018. Strategies for mammal conservation under climate change in the Amazon. *Biodiversity and Conservation* 27(8): 1943–1959. DOI: 10.1007/s10531-018-1518-x

Ruel J.C. 1995. Understanding windthrow: Silvicultural implications. *Forestry Chronicle* 71(4): 434–445. DOI: 10.5558/tfc71434-4

Rüetschi M., Small D., Waser L.T. 2019. Rapid detection of windthrows using Sentinel-1 C-Band SAR data. *Remote Sensing* 11(2): 115. DOI: 10.3390/rs11020115

Seidl R., Schelhaas M.J., Lexer M.J. 2011. Unraveling the drivers of intensifying forest disturbance regimes in Europe. *Global Change Biology* 17(9): 2842–2852. DOI: 10.1111/j.1365-2486.2011.02452.x

Seregin A. 2021. *Moscow University Herbarium (MW). Version 1.206.* Lomonosov Moscow State University. Occurrence dataset. Available from https://doi.org/10.15468/cpnhcc

Shashkov M., Ivanova N. 2016. *Database of finds of rare lichen species Lobaria pulmonaria in Russia. Version 1.4*. Institute of Mathematical Problems of Biology RAS – the Branch of Keldysh Institute of Applied Mathematics of Russian Academy of Sciences. Occurrence dataset. Available from https://doi.org/10.15468/uennht

Smirnova O.V., Bobrovsky M.V., Khanina L.G., Zaugolnova L.B., Turubanova S.A., Potapov P.V., Yaroshenko A.Yu., Smirnov V.E. 2017. Methods of Investigation. In: O.V. Smirnova, M.V. Bobrovsky, L.G. Khanina (Eds.): *European Russian Forests. Their Current State and Features of Their History*. Dordrecht: Springer. P. 33–57. DOI: 10.1007/978-94-024-1172-0_2

Sokolov S.Ya., Svyazeva O.A., Kubli V.A. 1977. *Distribution areas of trees and shrubs in the USSR*. Vol. 1. Leningrad: Nauka. 164 p. [In Russian]

Sokolov V.E. (Ed.). 1986. *Kologrivsky Les (Ecological studies)*. Moscow: Nauka. 128 p. [In Russian]

Tanase M.A., Aponte C., Mermoz S., Bouvet A., Le Toan T., Heurich M. 2018. Detection of windthrows and insect outbreaks by L-band SAR: A case study in the Bavarian Forest National Park. *Remote Sensing of Environment* 209: 700–711. DOI: 10.1016/j.rse.2018.03.009

Taylor R.A., Dracup E., MacLean D.A., Boulanger Y., Endicott S. 2019. Forest structure more important than topography in determining windthrow during Hurricane Juan in Canada's Acadian Forest. *Forest Ecology and Management* 434: 255–263. DOI: 10.1016/j.foreco.2018.12.026

Ueda K. 2012. *iNaturalist Research-grade Observations. iNaturalist.org. Occurrence dataset.* Available from https://doi.org/10.15468/ab3s5x

Ulanova N.G. 2000. The effects of windthrow on forests at different spatial scales: a review. *Forest Ecology and Management* 135(1–3): 155–167. DOI: 10.1016/S0378-1127(00)00307-8

Usbeck T., Wohlgemuth T., Dobbertin M., Pfister C., Bürgi A., Rebetez M. 2010. Increasing storm damage to forests in Switzerland from 1858 to 2007. *Agricultural and Forest Meteorology* 150(1): 47–55. DOI: 10.1016/j.agrformet.2009.08.010

Veselov V.M., Pribylskaya I.R., Mirzeabasov O.A. 2021. *World Data Center (RIHMI-WDC). Roshydromet.* Available from http://aisori-m.meteo.ru/waisori

ОЦЕНКА СОСТОЯНИЯ ДРЕВОСТОЕВ ДО И ПОСЛЕ КАТАСТРОФИЧЕСКОГО ВЕТРОВАЛА НА ОСНОВЕ ОТКРЫТЫХ ДАННЫХ О БИОРАЗНООБРАЗИИ И АЭРОФОТОСЪЕМКИ

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Наземные исследования лесных территорий, пострадавших от ураганов, затруднительны или вовсе невозможны из-за их ограниченной доступности. Поэтому целью данной работы стала оценка поврежденных ураганом площадей на основе аэрофотосъемки и открытых данных о биоразнообразии. Исследования проводили в старовозрастных южнотаежных лесах заповедника «Кологривский лес» (Костромская область, Россия), пострадавших от катастрофического ветровала, вызванного ураганом 15.05.2021 г. Площадь исследованного участка составила 100 000 м^2. Для оценки состояния древостоев перед ветровалом использовали открытые данные, доступные через репозиторий Global Biodiversity Information Facility, а также результаты собственных предыдущих наземных исследований. Аэрофотосъемку проводили при помощи беспилотного летательного аппарата, квадрокоптера DJI Phantom 4. Для фотограмметрической обработки полученных материалов использовали программное обеспечение Agisoft Metashape, в котором строили цифровую модель высот (digital elevation model) и ортофотоплан. Для автоматического детектирования поврежденных ветровалом участков использовали цифровую модель высот. На основе анализа распределения значений высот пикселей выделено три класса древесной растительности: участки сплошного ветровала, неповрежденные ветровалом древостои и окна в пологе леса, образовавшиеся в результате естественного распада липо-ельников до катастрофического ветровала. Упавшие деревья также детектировали вручную по ортофотоплану, по возможности определяя их видовую принадлежность. Анализ данных о составе древостоев до ветровала показал, что на исследованной территории преобладали старовозрастные леса, которые развивались без антропогенных воздействий в течение длительного времени. Это подтверждается сложной многоярусной и разновозрастной структурой древостоев, а также нормальными онтогенетическими спектрами популяций позднесукцессионных деревьев *Picea abies* (ель) и *Tilia cordata* (липа), доминирующих в древостое. Лесной покров представлял собой мозаику участков с доминированием ели, реже – липы, а также фрагментов распадающихся ельников, где деревья ели почти или полностью выпали из состава древостоя. В результате ветровала лесной покров исследованного участка значительно изменился. Результаты обработки цифровой модели высот показали, что 33.1% площади древостоев изучаемой территории выпали. Вручную детектировано 759 поваленных ветром деревьев, из них 82.9% приходились на сильно поврежденные участки, выделенные по модели высот. Остальные поваленные деревья были приурочены к менее поврежденным участкам, где сохранился древостой или отдельные группы деревьев. Такие участки не были детектированы по модели высот. Полученные результаты показывают, что для более точных оценок поврежденных ветровалом площадей необходимо использовать как модель высот, так и ортофотоплан. Результаты предварительного анализа повреждений древостоев разного состава показали, что, по всей видимости, еловые насаждения пострадали от ветровала сильнее, чем липовые. Это объясняется разной ветроустойчивостью ели и липы, а также различиями в плотности и видовом составе подроста в этих древостоях.

Ключевые слова: GBIF, заповедник «Кологривский лес», ортофотоплан, старовозрастные южнотаежные леса, цифровая модель высот