Received: 5 March 2021 | Revised: 16 July 2021 | Accepted: 30 July 2021

DOI: 10.1111/cobi.13820

Conservation Biology

CONTRIBUTED PAPER

Using historical spy satellite photographs and recent remote sensing data to identify high-conservation-value forests

Catalina Munteanu[1,2] | Cornelius Senf[3] | Mihai D. Nita[4] | Francesco Maria Sabatini[5,6] | Julian Oeser[1] | Rupert Seidl[3,7] | Tobias Kuemmerle[1,8]

[1] Geography Department, Humboldt University of Berlin, Berlin, Germany

[2] Wildlife Ecology and Management, Faculty of Environment and Natural Resources, University of Freiburg, Freiburg, Germany

[3] Ecosystem Dynamics and Forest Management Group, Technical University of Munich, Freising, Germany

[4] Department of Forest Engineering, Faculty of Silviculture and Forest Engineering, Transilvania University of Brasov, Brasov, Romania

[5] German Centre for Integrative Biodiversity Research (iDiv), Halle-Jena-Leipzig, Leipzig, Germany

[6] Institute of Biology/Geobotany and Botanical Garden, Martin Luther University Halle-Wittenberg, Halle, Germany

[7] Berchtesgaden National Park, Berchtesgaden, Germany

[8] Integrative Research Institute on Transformation in Human-Environment Systems (IRI THESys), Humboldt University of Berlin, Berlin

Correspondence
Catalina Munteanu, Geography Department, Humboldt University of Berlin, Unter den Linden 6, 10099 Berlin, Germany.
Email: catalina.munteanu@geo.hu-berlin.de

Article impact statement: Romania has over 700,000 ha of high-conservation-value forests, but as much as half of them are under high anthropogenic pressure.

Abstract

High-conservation-value forests (HCVFs) are critically important for biodiversity and ecosystem service provisioning, but they face many threats. Where systematic HCVF inventories are missing, such as in parts of Eastern Europe, these forests remain largely unacknowledged and therefore often unprotected. We devised a novel, transferable approach for detecting HCVFs based on integrating historical spy satellite images, contemporary remote sensing data (Landsat), and information on current potential anthropogenic pressures (e.g., road infrastructure, population density, demand for fire wood, terrain). We applied the method to the Romanian Carpathians, for which we mapped forest continuity (1955–2019), canopy structural complexity, and anthropogenic pressures. We identified 738,000 ha of HCVF. More than half of this area was identified as susceptible to current anthropogenic pressures and lacked formal protection. By providing a framework for broad-scale HCVF monitoring, our approach facilitates integration of HCVF into forest conservation and management. This is urgently needed to achieve the goals of the European Union's Biodiversity Strategy to maintain valuable forest ecosystems.

KEYWORDS

anthropogenic pressure, conservation value, distribution modeling, forest continuity, forest structure, spy satellite imagery, temperate forests

Uso de Fotografías Históricas de Satélites Espía y Datos Recientes de Telemetría para Identificar Bosques de Alto Valor para la Conservación

Resumen: Los bosques de alto valor para la conservación (BAVC) tienen una importancia crítica para el suministro de servicios ambientales y biodiversidad pero enfrentan muchas amenazas. En donde hacen falta inventarios sistemáticos de los BAVC, como en partes del este de Europa, estos bosques siguen siendo ignorados y por lo tanto carecen de protección. Diseñamos una estrategia novedosa y transferible para la detección de BAVC con base en la integración de imágenes de satélites espía, datos contemporáneos de telemetría (Landsat) e información sobre las presiones antropogénicas actuales (p. ej.: infraestructura vial, densidad poblacional, demanda de leña, terreno). Aplicamos el método en los Cárpatos rumanos, para los cuales mapeamos la continuidad forestal (1955 - 2019), la complejidad estructural del dosel y las presiones antropogénicas. Identificamos 738,000 ha de BAVC. Más de la mitad de esta área fue identificada como susceptible a las actuales presiones antropogénicas y además carecía de protección formal. Mediante la aportación de un marco de trabajo para el monitoreo a escala amplia de los BAVC, nuestra estrategia facilita la integración de los BAVC dentro de la gestión y conservación de los bosques. Lo último es una necesidad urgente para alcanzar las metas de la Estrategia de Biodiversidad de la Unión Europea para mantener los ecosistemas boscosos valiosos.

PALABRAS CLAVE:
bosques templados, continuidad forestal, estructura forestal, imágenes de satélites espía, modelado de la distribución, presión antropogénica, valor de conservación

INTRODUCTION

High-conservation-value forests (HCVFs) have a history of forest continuity and are typically composed of late-successional stands with structurally complex canopy and low levels of anthropogenic disturbance (Munteanu et al., 2015; Watson et al., 2018; Wirth et al., 2009). These forests provide valuable ecosystem services, such as carbon sequestration, and harbor high levels of biodiversity, including many endangered lichens, insects, and birds (Eckelt et al., 2018; Malíček et al., 2019; Mikoláš et al., 2019). Yet, increasing anthropogenic pressure accelerates the rate of HCVF loss (Curtis et al., 2018) and changes forest ecosystem dynamics (McDowell et al., 2020). Systematic identification is therefore an important prerequisite for ensuring persistence of HCVF and maintaining its natural and societal value (Angelstam et al., 2020; Kortmann et al., 2021; McDowell et al., 2020). Unfortunately, HCVFs in many regions remain undetected and unprotected due to the lack of systematic HCVF inventories.

The identification of candidate HCVFs requires information on forest continuity (i.e., continuous forest cover over an extended period), compositional and structural complexity (hereafter structural complexity), and anthropogenic pressures. Although some data are available for all 3 aspects in Europe (Potapov et al., 2017; Sabatini et al., 2018; Watson et al., 2018), existing approaches for identifying HCVFs rarely integrate across these dimensions. Maintaining forest continuity over time ensures that stands develop and preserve important ecological characteristics (e.g., accumulation of deadwood) and maintain species that are poor dispersers or highly sensitive to land use (McMullin & Wiersma, 2019; Munteanu et al., 2015). Forest structural complexity results from a history of stochastic natural disturbances with low to moderate severity (Donato et al., 2012; Senf et al., 2020) that lead to vertical layering, canopy gaps with natural regeneration, and downed and standing deadwood (Hilmers et al., 2018; Thom et al., 2017). Conversely, forest management can result in a loss of features associated with HCVF. This happens not only in the case of clear-cuts, but also in the case of thinning and salvage logging, all of which remove important biological legacies and alter natural disturbance regimes (Müller et al., 2019; Thorn et al., 2018). Quantifying forest continuity, structural complexity, and anthropogenic pressures consistently over large areas is challenging, yet a necessary, first step to detect HCVFs and to ensure their persistence over time.

Despite its longstanding history of human use, Europe still harbors important areas of continuous, old, and primary forests. This is particularly the case in the Carpathian and Balkan regions of Eastern Europe (Sabatini et al., 2018, 2020). There, large areas of HCVF remain unidentified and are increasingly threatened due to insufficient protection, weak policies, and rising economic pressure (Butsic et al., 2017; Knorn et al., 2012). Romania is a hotspot of HCVF in Eastern Europe (Sabatini et al., 2020; Veen et al., 2010), where large areas of valuable forests may remain underappreciated or be harvested, despite their unique conservation value from a European perspective (European Commission, 2020). The recent European Green Deal and the European Biodiversity Strategy for 2030 both highlight the importance of monitoring and protecting valuable forests at a continental level and propose increasing financial and legal support for their effective conservation (European Commission, 2020). However, such instruments can be applied only where HCVFs have been identified and mapped.

Our goals were to develop a transferable approach for identifying HCVFs, demonstrate the approaches' value by mapping the extent of potential HCVF in the Romanian Carpathians, and assess the current fragmentation and protection of these potential HCVFs. We define *high-conservation-value forest* as a continuously forested area (since 1955) where stands have similar structural complexity and are subject to anthropogenic pressure similar to primary and old-growth forests (i.e., low pressure) (Sabatini et al., 2018, 2020). To achieve these goals, we combined historical spy satellite images from the Cold War period, contemporary high-resolution remote sensing data, and accessibility data (i.e., road infrastructure, accessibility, population density, terrain, demand for fire wood) for characterizing forest continuity, structural complexity, and anthropogenic pressures in the Romanian Carpathians.

METHODS

Study area

We studied the entire Romanian Carpathians (Romanian portion of the Carpathian Ecoregion 135,000 km^2, 57% forested) dominated by deciduous and mixed forests (*Fagus sylvatica, Quercus* spp.). At higher elevations, the forest is primarily coniferous (*Picea abies, Abies alba*) (Nita et al., 2018) (Appendix S2). Forest ownership is shared between the state and private owners, and management is largely based on thinning, shelterwood cuts, and small clear-cuts (<1 ha), followed by natural regeneration (Schulze et al., 2014). At the end of the 19th century, Romania likely had up to 2 million ha of primary and old-growth forests, which by 2004 were one tenth of their former extent (Veen et al., 2010). Widespread harvests occurred particularly in the 1960s, to fulfil World War II reparation payments (Nita et al., 2018), and after 1990, during a phase of unclear ownership, weak law enforcement, and economic hardship (Griffiths et al., 2014; Knorn et al., 2012). Yet, Romania maintained a long forest rotation length (>100 years [Bouriaud et al., 2016]) and still has some of the largest areas of remaining primary forests in Europe. Forest conservation practice in Romania follows the system of protected areas and their International Union for Conservation of Nature (IUCN) categorization. Forest management and conservation are regulated through national legislation that established 6 classes of conservation and management regimes based on the environmental and ecological condition of each individual stand, irrespective of forest ownership (Carcea & Tudoran, 2012) (Appendix S9). In stands with a conservation function, only selected silvicultural interventions are allowed (e.g., low-intensity selective cuts) and management is geared toward continuous forest cover. Better knowledge of the extent, location, and threats to HCVFs is critical to ensuring their persistence.

Forest continuity

To map forest continuity across the Romania Carpathians, we used historical and modern remotely sensed images and topographic data. We defined *continuous forests* as forested areas that likely did not experience stand-replacing disturbance after 1955. To make this determination, we used Corona historical spy satellite imagery from 1955 to 1968 (Nita et al., 2018), military topographic maps (1:25,000) from 1968 to 1978 (Appendix S1), and Landsat TM/ETM+/OLI data (30-m resolution) (Senf & Seidl, 2021) from 1985 to 2019. First, we relied on a map of forest continuity from 1985 to 2019 from the Landsat time series by subtracting all areas that had stand-replacing disturbances since 1985 from a contemporary forest cover mask (Senf & Seidl, 2021). Second, we produced a historical forest-continuity map (1955–1979) by subtracting all areas previously classified as naturally disturbed or harvested in either historical remotely sensed images (Nita et al., 2018) or in subsequent military topographic maps (1:25,000) (Appendix S1) from a 1970 forest-cover layer (1:25,000 based on military topographic maps). All historical data were hand digitized and resampled to Landsat resolution (30 m). The resulting data sets were combined into a single map of forest continuity, which included forest areas classified as continuous in both steps. The historical spy satellite imagery allowed us to exclude areas of historical forest disturbance previously undocumented with modern data (530,000 ha from 1955 to 1965). The historical topographic maps provided us with estimates of forest extent and forest disturbance in the decades following Corona image collection and prior to modern Landsat data. All subsequent analyses for the identification of HCVF were limited to continuous forest areas as defined above (Appendices S1 & S2). Excluding historically disturbed area from our measure ensured that estimates of HCVF were conservative.

Structural complexity

To map canopy structural complexity, we used a machine-learning approach, namely, maximum entropy (Maxent) (Elith et al., 2011) as implemented in the dismo package (Hijmans et al., 2020) of the R programming environment. With our model, we aimed to identify areas with similar compositional and structural characteristics as the confirmed locations of primary and old-growth forests across the Romanian Carpathians. The model was based on a large data set (1853 points) of confirmed locations of primary and old-growth forests as training points and 10,000 random background points (Elith & Leathwick, 2009). Training points were obtained from 3 partially overlapping sources: officially designated UNESCO Ancient and Primeval Beech Forests of the Carpathians (https://whc.unesco.org/en/list/1133/; 23,982 ha), the Romanian National Catalogue of virgin and quasi-virgin forests (http://apepaduri.gov.ro/paduri-virgine/; 6665 ha of virgin and 23,396 ha of semivirgin forests), and the World Wildlife Fund areas submitte for inclusion in the national catalog (https://lemncontrolat.ro/useful-documents-and-links/downloads/; 29,239 ha, accessed October 2019) (Appendix S3). Training points were distributed randomly across all confirmed locations of primary and old-growth forests (minimum 10 points per forest stand at a minimum distance of 100 m).

We parametrized the structural complexity model with a series of spectral–temporal metrics derived from Landsat imagery that correlated well with important forest characteristics that can be indicative of old-growth forests, such as phenology, productivity, canopy structure, and canopy complexity (Oeser et al., 2020) (Appendix S4). We relied on continuous variables derived from satellite imagery as an alternative to categorical classifications (e.g., forest type) because they are reliable predictors in ecological models (Coops & Wulder, 2019; Leitão & Santos, 2019) and improve model performance relative to categorical classifications (Oeser et al., 2020). In addition to the Landsat metrics, we included 2 radar metrics derived from ALOS-2 PALSAR-2 because radar metrics may better capture vertical vegetation structure than optical remotely sensed data (Morin et al., 2019; Mulatu et al., 2019; Shimada et al., 2014) (Appendix S4). The resulting structural complexity index (i.e., complementary log-log output of the model [Phillips et al., 2017]) ranged from 0 to 1 and was a relative measure of similarity of a location to confirmed primary and old-growth forests in the study region, given the satellite-based structural characteristics of the forest. High index values indicated forests with high similarity in their structural complexity to sites at which the presence of primary and old-growth forests was confirmed (Figure 1).

Anthropogenic pressure

To assess anthropogenic pressure, we calculated a human pressure index. We assumed that known primary forests in the Romanian Carpathians persisted because human pressure on them has been low. To map anthropogenic pressure, we used a Maxent-based modeling strategy similar to the one employed for structural complexity (i.e., based on the same primary forest occurrence locations and background points described above for model training) (Appendix S3). As model predictors, we considered 6 variables that capture accessibility, road infrastructure, population density, local reliance on firewood, and 2 terrain variables (elevation and slope) (Appendix S4). This resulted

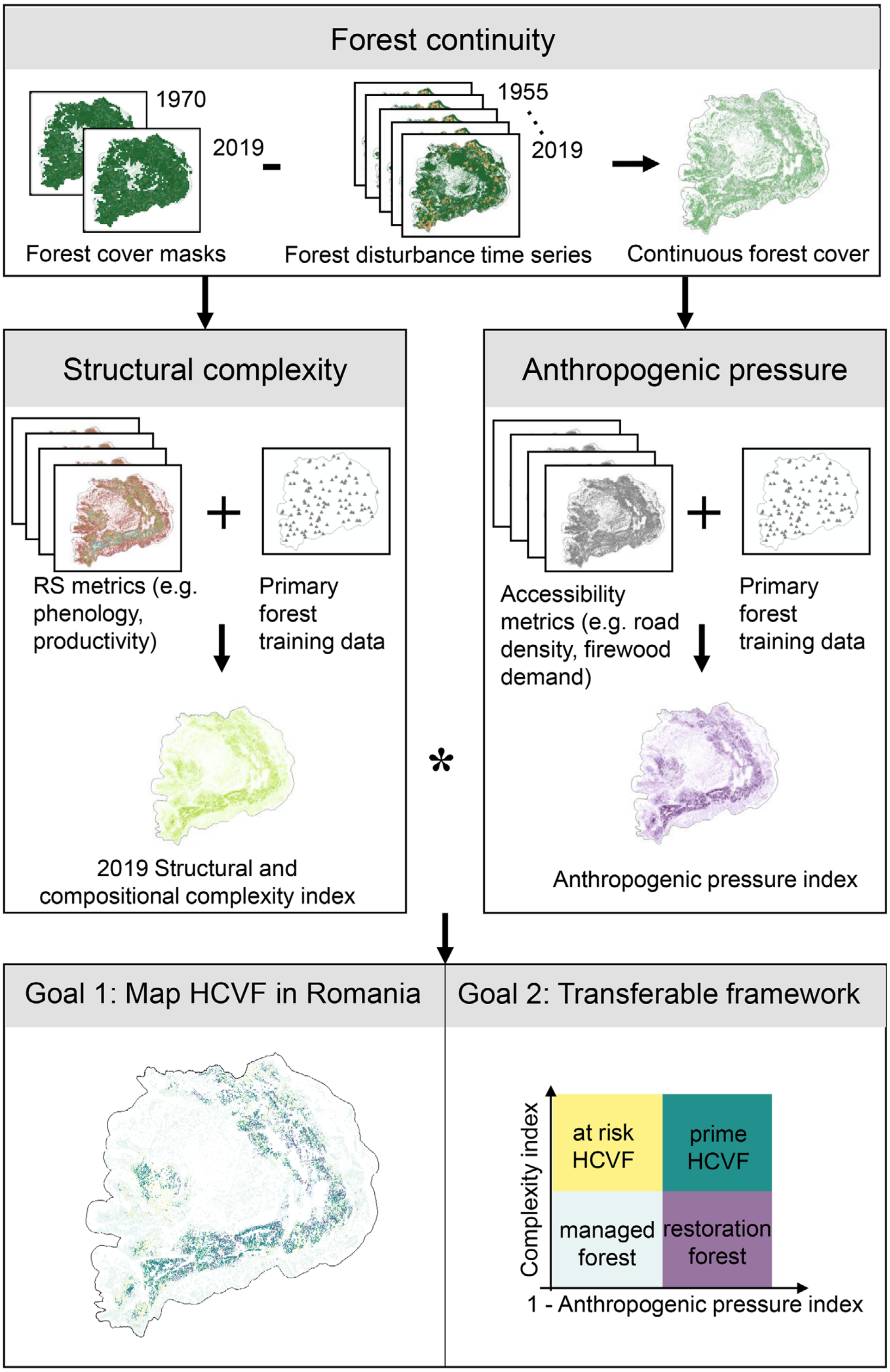

FIGURE 1 Framework for identifying high-conservation-value forests (HCVFs) based on historical spy satellite images, contemporary remote sensing (RS) data, and spatial layers of anthropogenic pressure

in an anthropogenic pressure index (i.e., complementary log–log output of the model) ranging from 0 to 1, which provided a relative measure of human impact on the forests. High index values indicated anthropogenic pressure on a forest pixel similar to sites with confirmed presence of primary or old-growth forest (Figure 1).

Model performance

We assessed model performance via 5-fold cross-validation to calculate area under the receiver operator curve (AUC). We used true-positive and true-negative rates to calculate the harmonic mean of model precision and recall (i.e., the F1 score) for different likelihood thresholds. Using the threshold for the maximum F1 value in each model, we first produced a binary map of each of the index components (Appendix S7), which we then combined in a bivariate map to identify 4 forest classes: *prime HCVF* (structural complexity similar to that of designated primary and old-growth forests and low anthropogenic pressure), *at-risk HCVF* (structural complexity similar to that of designated primary and old-growth forests and high anthropogenic pressure), *restoration forest* (structural complexity not resembling primary and old-growth forests and low anthropogenic pressure), and *managed forest* (structural complexity not resembling primary and old-growth forests and high anthropogenic pressure). These 4 final classes were defined along 2 separate and independent axes by comparing the ranks of the individual binary maps. Because the choice of thresholding can affect interpretation of results, we compared different methods, also using the maximum sensitivity-specificity thresholding approach (Liu et al., 2016). We report only the results of the more conservative estimate, but results of sensitivity analyses with different thresholds are reported in Appendix S8. To check model performance against ground-truth data, we used forest inventory data available for approximately 33% of the continuous forest area under study and verified the capacity of our method to distinguish differences in stand age, canopy structure, and forest management types among the 4 forest classes (Appendix S9).

Fragmentation and protection

To assess the fragmentation and protection of HCVF, we quantified the landscape-scale configuration of prime and at-risk HCVF based on landscape metrics that included total class area, patch size, and patch density. All metrics were calculated based on the categorical maps of the 4 forest classes with the landscape metrics (Landscape Metrics for Categorical Map Patterns 1.5.3) package in R. We determined protection status of *prime and at-risk HCVF* based on data in the World Database of Protected Areas (www.protectedplanet.net [accessed October 2019]). In overlapping protected areas, we assigned the highest protection category (e.g., IUCN I over V) to each pixel.

RESULTS

We identified 4 million ha (52% of the total forest area) of continuous forest in the Romanian Carpathians that had not experienced stand-replacing disturbance since the mid-20th century. Of these, 8.6% (approximately 351,000 ha) were prime HCVF with complexity levels and anthropogenic pressure similar to primary and old-growth forests. An additional 9.5% (approximately 387,000 ha) of continuous forests had canopy structures similar to primary and old-growth forests, but were under high anthropogenic pressures (at-risk HCVF). Approximately 73% of the continuously forested area was managed forest, with structural complexity index values that differed from primary and old-growth forests and with high anthropogenic pressure (Figure 2).

Model fits were good; AUC values were 0.86 (0.85–0.88) for the structural complexity model and 0.80 (0.78–0.81) for the anthropogenic pressure model. Elevation and population density contributed the most to the anthropogenic pressure model. For the structural complexity model, peak of the season (POS) Landsat metrics were the strongest predictors. The maximum F1 score corresponded to the 75th percentile with an index value of 0.60 for the model on forest complexity and 0.53 for the model on anthropogenic pressure (see Appendices S5, S6, & S7 for index values prior to applying thresholding). This threshold yielded a conservative estimate of the extent of HCVF forest. When we applied alternative thresholds to maximize specificity and sensitivity (0.47 and 0.34 index values, for the complexity and pressure models, respectively), an additional 582,000 ha of HCVF (1.3 million total, 63% of which was prime HCVF) were identified (Appendix S8).

When comparing our results with available forest inventory data, we found a higher average age for prime HCVF (110 years) compared with managed forests (85 years). Age structure of prime HCVFs was predominantly uneven (61%), and HCVF had a higher proportion of functional types T1 and T2, indicative of no or low-intensity silvicultural interventions (Figure 3 & Appendix S9). Of the HCVFs for which forest inventory data were available, 70% were in functional types T1 and T2 (Appendix S9).

We identified large tracts of *prime HCVF* in the southern Romanian Carpathians, whereas small, dispersed patches occurred in the eastern and western Romanian Carpathians. *At-risk HCVFs* were more fragmented than prime HCVFs, as indicated by patch size (0.82 vs. 2.09 ha) and patch density metrics (11.50 vs. 4.12 patches/100 ha). Patches of managed forests were generally large (7.55 ha). Hotspots of at-risk HCVFs were found in Apuseni, Banat, and the eastern Carpathians. Overall, 14% of the prime HCVF we identified was strictly protected (i.e., IUCN I-III, UNESCO reserves, or national protection), and this value dropped to 8.5% for at-risk HCVF (Figure 4). Furthermore, 37% of prime HCVF lacked formal protection, as did 52% of at-risk HCVF (Figure 4).

DISCUSSION

HCVFs are critical for biodiversity, ecosystem service provisioning, and climate regulation (Sabatini et al., 2020; Watson et al., 2018). In Europe, HCVFs are thought to be scarce and fragmented. Most remaining HCVFs are concentrated in Northern and Eastern Europe (Angelstam et al., 2020; Sabatini et al., 2018, 2020), where canopy turnover rates are still lower than in Central and Western Europe (Senf & Seidl, 2021; Senf et al., 2018). Effectively protecting HCVF in these areas is inhibited by a lack of spatial data on their distribution. Our work addresses this knowledge gap and showed that HCVF in Eastern Europe may be much more widespread than previously thought. Better protecting Europe's remaining old-growth and primary forests is an explicit goal of both the recent EU Biodiversity Strategy for 2030 and the European Green Deal (European Commission, 2020). Our work offers a framework for identifying and moni-

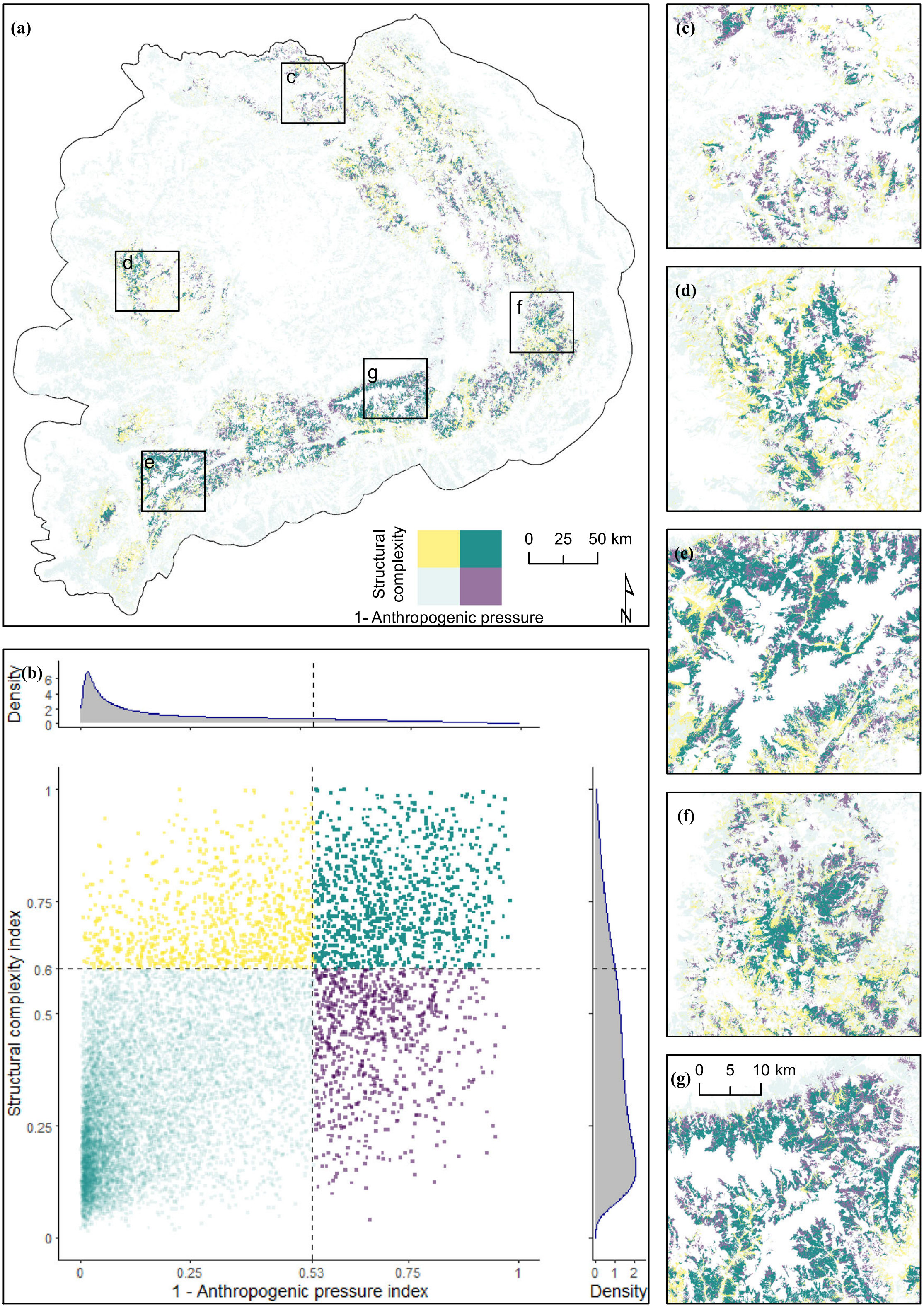

FIGURE 2 (a and b) Bivariate map of forest structural complexity and anthropogenic pressure in the Romanian Carpathians (yellow, at-risk high-conservation-value forests [*at-risk HCVF*] with high structural complexity similar to that of designated primary-growth forests and high anthropogenic pressure [387,000 ha]; green, *prime HCVF* with structural complexity similar to that of designated primary and old-growth forests and low anthropogenic pressure [352,000 ha]; light blue, *managed forest* [3 million ha] with structural complexity not resembling primary and old-growth forests and high anthropogenic pressure; purple, forests with restoration potential toward HCVF [*restoration HCVF*] with structural complexity not resembling primary and old-growth forests but low anthropogenic pressure [333,000 ha]; histograms, distributions of the 2 indices; dotted lines, thresholds identified based on the weighted average of precision and recall [F1 metric]). Insets: (c) Rodna Mountains, (d) Apuseni Mountains, (e) Cerna and Retezat, (f) Oituz, and (g) Fagaras Mountains

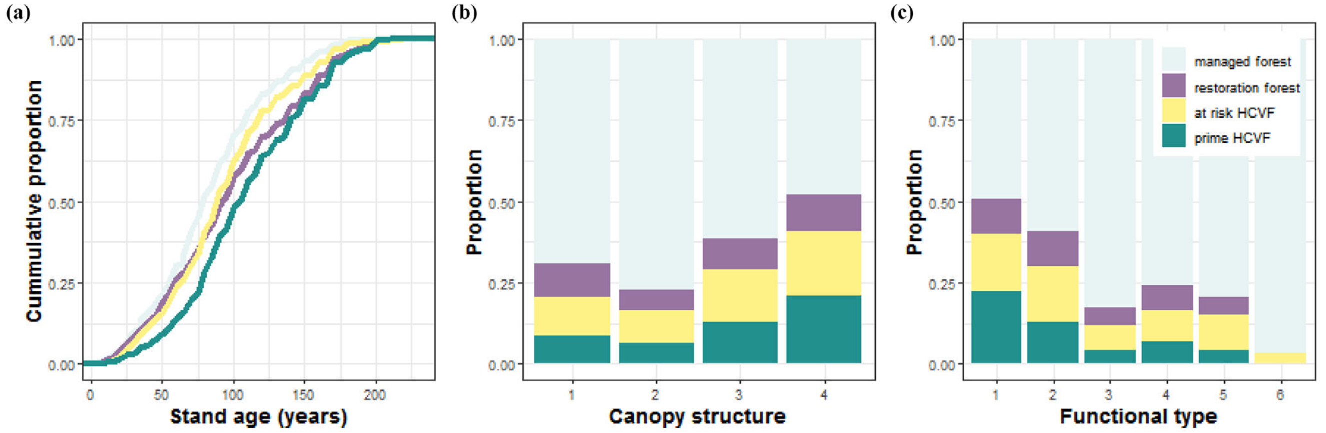

FIGURE 3 Summarized forest inventory data for ∼15,000 km^2 of Romanian state-owned forests across prime high-conservation-value forests (i.e., structural complexity similar to that of designated primary and old-growth forests and low anthropogenic pressure) (prime HCVF) (green); at-risk HCVF (i.e., structural complexity similar to that of designated primary and old-growth forests and high anthropogenic pressure, yellow); restoration forest (structural complexity not resembling primary and old-growth forests and low anthropogenic pressure, purple), and managed forest (structural complexity not resembling primary and old-growth forests and high anthropogenic pressure, light blue): (a) forest stand age, (b) canopy structure (1, even aged, to 4, uneven aged), and (c) functional forest type (1, no forest intervention, to 6, all silvicultural practices allowed)

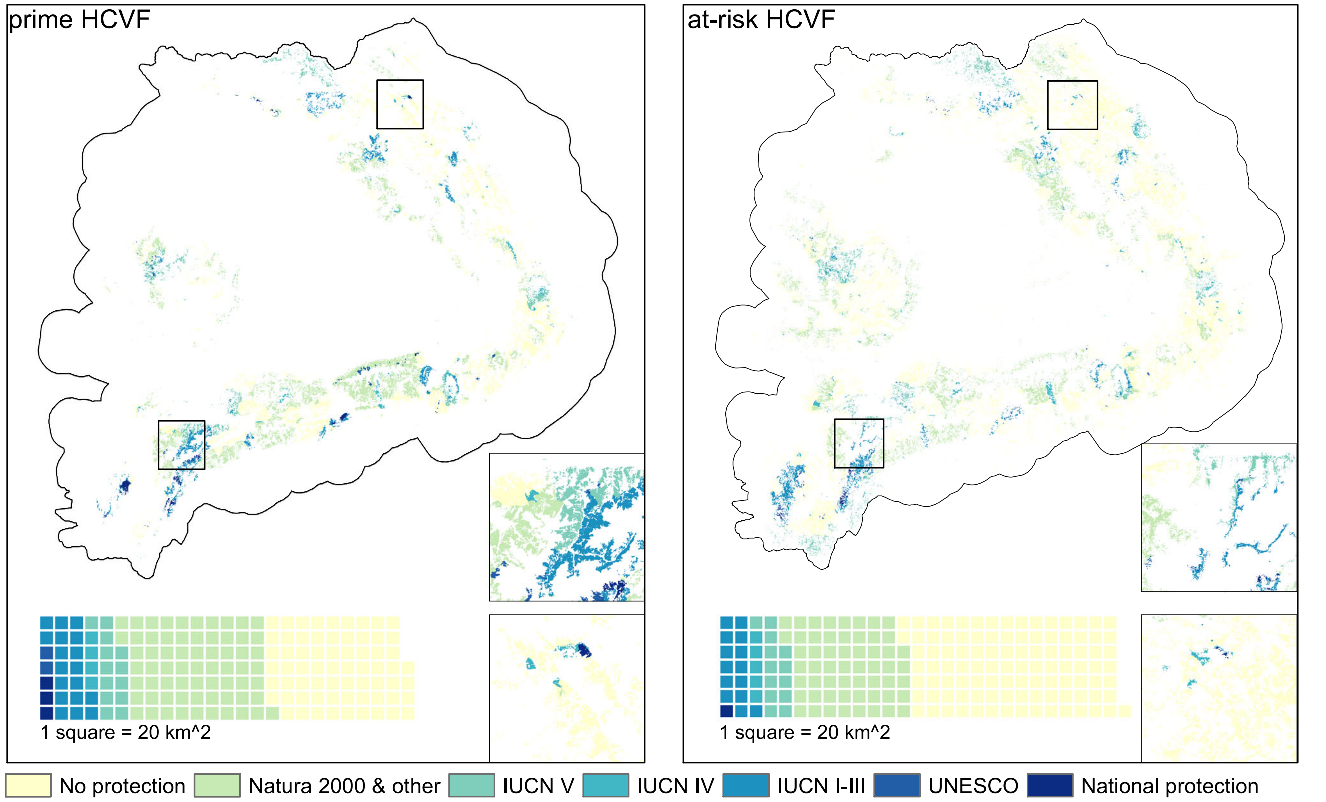

FIGURE 4 Distribution of protected areas in prime high-conservation-value forests (*prime HCVF*) (left) and *at-risk HCVF* (right). IUCN, International Union for Conservation of Nature; UNESCO, The United Nations Educational, Scientific and Cultural Organization

toring HCVFs and thus for operationalizing these policy commitments. Furthermore, given recent advancements in acquisition of remote sensing data, storage, and cloud processing, our approach is highly scalable and transferable to other regions, providing a model for temperate HCVF monitoring.

Within Europe, Romania harbors some of the largest remaining areas of primary forest (Sabatini et al., 2020) and represents an ideal case study for testing our framework for HCVF identification. Our results suggest the existence of substantially larger areas of potential HCVF compared with previously reported virgin forest areas (220,000 ha) (Veen et al., 2010]) and potential primary and old-growth forests in Romania (440,000 ha) (Schickhofer & Schwarz, 2019). This situation is likely indicative of other Eastern European countries as well. Our results are comparable in level and spatial distribution to previous model-based estimates of primary forest distribution in Romania (1.2 million ha) (Sabatini et al., 2018) (Appendix S12). Compared with these previous works, our approach has the benefit of accounting for a wider range of predictors, covering historical forest use, forest structure, and anthropogenic pressures at much finer spatial resolution and highlighting forests most at risk from anthropogenic disturbance. We caution, though, that comparisons across different estimates and maps are hampered by differences in methodologies, resolutions, and the only partially overlapping definitions of *primary*, *old-growth*, and *virgin forests* with HCVFs. Overall, our results highlight extensive opportunities to better safeguard HCVF in the Romanian Carpathians because more than half of the identified HCVF forests lack formal protection, although they may already be restricted in use by forest management measures (Appendix S9).

Although not all HCVFs we identified are primary or old-growth forests, none of them have been subject to large-scale disturbances since at least 1955 (average age 90–110 years) (Figure 3) and they have canopy structure similar to primary forests, making them great candidates for conservation or sustainable forest management that maintains their ecological value. Because many of these forests may be nearing the end of the sometimes very long rotation cycle in our study region (often exceeding 100 years) (Bouriaud et al., 2016), their conservation and sustainable management is particularly relevant at this time. Of the large area of HCVF in the Romanian Carpathians we identified, as much as half is under high anthropogenic pressures (at-risk HCVF). These at-risk HCVFs are primarily small, accessible forest patches that can be of outstanding value for conservation and provide important stepping stones for many species that depend on these ecosystems (Lindenmayer, 2019), despite possibly being overlooked in previous estimates of primary forest extent (Sabatini et al., 2018) (Appendix S12). Therefore, prioritizing the protection of at-risk HCVF would ensure that the most vulnerable stands are preserved. In addition to HCVF, both managed and restoration forests have large biodiversity potential if natural processes are maintained, diverse structures and compositions promoted, and salvage logging limited when natural disturbances occur. Although these management strategies are already regulated under Romanian legislation, they are poorly implemented in some areas.

We focused on forests that resemble primary forests in their structural complexity. We caution that our estimate of HCVF in highly accessible areas may be conservative due to the existing bias in primary forest distribution toward mountainous, remote areas, which are not entirely representative of the diversity of forest types occurring in the region (Butsic et al., 2017; Sabatini et al., 2020). We also note that areas recently affected by natural disturbances are of high value for biodiversity conservation (Hilmers et al., 2018; Swanson et al., 2011), and a comprehensive strategy to foster biodiversity should thus consider both old and recently disturbed forest ecosystems.

We excluded stand-replacing disturbances because many of the historical disturbances were large-scale clear-cuts and because natural disturbances are commonly followed by salvage logging, which affects natural regenerative processes (Leverkus et al., 2018). However, many of the HCVFs in our analyses likely experienced small-scale, natural disturbances or management that may have contributed to the diverse structures of these forests (Janda et al., 2017; Jõgiste et al., 2017; Senf et al., 2020). We further caution that certain characteristics of primary and old-growth forests (e.g., amount of standing and downed deadwood) cannot be estimated with the remotely sensed data we used. Our approach highlights HCVFs and restoration forests that are similar in their canopy structure and anthropogenic pressure to designated primary forests. Because existing designated primary forests are primarily spruce, beech, and fir forests in mountainous areas (Sabatini et al., 2020), we likely underestimated some of the lowland primary forests that are also good candidates for restoration. Our approach does not exclude the existence of other valuable forest systems, identified by different structural or management characteristics, that also play important roles in conservation practice (e.g., riparian forests as conservation corridors) (Kajtoch et al., 2016; Slezák et al., 2020).

Methodologically, our work highlights the value of combining historical and contemporary satellite data with spatial modeling for operationalizing the identification of potential HCVFs. Our model had good predictive performance (AUC 0.80 and 0.86). As expected, elevation and population density were large contributors in the anthropogenic pressure model. In the structural complexity model, Landsat spectral–temporal metrics characterizing vegetation conditions during the peak of season (i.e., summer) were the most important predictor variables, whereas radar backscatter metrics contributed little (Appendix S11). The relatively low importance of radar metrics may be related to the wide range of existing vertical structures among the different old-growth and primary forests used as training data and more generally among primary forests in the Romanian Carpathians (Albrich et al., 2021; Sabatini et al., 2020). Although we used pixel-wise annual composites of radar backscatter, more complex radar-based metrics incorporating seasonal or spatial variation in radar signals might lead to further improvements in the characterization of vertical forest structure (Bae et al., 2019; Morin et al., 2019). Although our approach is transferable and scalable, we caution that regionalized training and validation is needed and that the choice of spatiotemporal metrics and predictor variables might have to be adjusted for different bioclimatic conditions and forest management regimes. Still, our study lays the groundwork for expanding and extrapolating HCVF inventories on a European scale.

Our results can directly inform forest conservation and management by highlighting areas for specific conservation actions, such as increasing protection or introducing sustainable forestry practices. Based on our results, we recommend following conservation and management strategies for each forest class we identified. Protection of *prime HCVF* should be the first priority toward achieving the 10% protection goal set by the EU

Biodiversity Strategy for 2030 (European Commission, 2020). Currently, <15% of HCVFs in the Romanian Carpathians are strictly protected, but as much as 70% of the state-owned HCVFs are already under protection by no-silvicultural intervention plans (Appendix S9). Upgrading their existing protection status and developing new protected areas in prime HCVFs representative of all forest types (Sabatini et al., 2020) should therefore be a priority (see Appendix S10 for a comparison HCVF distribution by conservation targets in the Romanian Carpathians).

The conservation of *at-risk HCVF* is perhaps most urgent because of their vulnerability to human impact and their stepping-stone character (Lindenmayer, 2019). Establishment of new protected areas, upgrading protection status, including compensation measures for forest owners, and increasing public awareness of the value of HCVFs can ensure their persistence in the future. Where protection is not possible, prioritizing close-to-nature forestry and forest certification schemes (e.g., Forest Stewardship Council [FSC]) might contribute to maintaining HCVF character (Asbeck et al., 2021; Bauhus et al., 2009).

The *restoration forests* we identified are the best candidates for achieving long-term conservation and management outcomes, especially when these forests are already located in protected areas. In response to natural disturbances in these forests, natural regeneration should be prioritized and salvage logging should be limited because natural disturbances accelerate development toward complex and diverse forests (Thom et al., 2017; Thom & Seidl, 2016).

A large proportion of European forests have experienced intensive forest management in the past, and Romania is no exception (Brudvig et al., 2013; Munteanu et al., 2015). Land-use legacies are strongest in areas we identified as *managed forests*, and reversal of these areas to primary forest characteristics would take centuries (Albrich et al., 2021; Munteanu et al., 2015). Where restoration to HCVF characteristics is neither environmentally nor economically possible, adapted silvicultural approaches and forest certification schemes (FSC, 2.6 million ha certified in Romania) (Halalisan et al., 2018) would satisfy wood demands while maintaining ecosystem functioning and some forest biodiversity (European Commission, 2020).

We strongly encourage forest managers and conservationists to carefully consider HCVFs because the conservation returns from these areas will be the largest. Romania, with its disproportionally high levels of remaining HCVF in the Carpathian Mountains, could become a leading example of European conservation efforts if conservationists, forest managers, and the public focus their attention on these key ecosystems.

ACKNOWLEDGMENTS

C.M. acknowledges financial support by the European Commission under the Marie Sklodowska-Curie Program, Project EcoSpy (Grant Agreement 793554), and by the German Science Foundation (DFG), Research Training Group ConFoBi (GRK 2123/1 TPX). The authors are grateful to F. Buschke and 3 anonymous reviewers for their constructive comments on a previous version of this manuscript.

ORCID

Catalina Munteanu https://orcid.org/0000-0003-1616-9639
Cornelius Senf https://orcid.org/0000-0002-2389-2158
Mihai D. Nita https://orcid.org/0000-0002-6072-7784
Francesco Maria Sabatini https://orcid.org/0000-0002-7202-7697
Julian Oeser https://orcid.org/0000-0003-3216-6817
Rupert Seidl https://orcid.org/0000-0002-3338-3402
Tobias Kuemmerle https://orcid.org/0000-0002-9775-142X

LITERATURE CITED

Albrich, K., Thom, D., Rammer, W., & Seidl, R. (2021). The long way back: Development of Central European mountain forests towards old-growth conditions after the cessation of management. *Journal of Vegetation Science*, *32*(4), e13052

Angelstam, P., Manton, M., Green, M., Jonsson, B. G., Mikusiński, G., Svensson, J. M., & Sabatini, F. (2020). Sweden does not meet agreed national and international forest biodiversity targets: A call for adaptive landscape planning. *Landscape and Urban Planning*, *202*, 103838.

Asbeck, T., Sabatini, F., Augustynczik, A. L. D., Basile, M., Helbach, J., Jonker, M., Knuff, A., & Bauhus, J. (2021). Biodiversity response to forest management intensity, carbon stocks and net primary production in temperate montane forests. *Scientific Reports*, *11*, 1625.

Bae, S., Levick, S. R., Heidrich, L., Magdon, P., Leutner, B. F., Wöllauer, S., Serebryanyk, A., Nauss, T., Krzystek, P., Gossner, M. M., Schall, P., Heibl, C., Bässler, C., Doerfler, I., Schulze, E. D., Krah, F. S., Culmsee, H., Jung, K., Heurich, M., … Müller, J. (2019). Radar vision in the mapping of forest biodiversity from space. *Nature Communications*, *10*, 10.

Bauhus, J., Puettmann, K., & Messier, C. (2009). Silviculture for old-growth attributes. *Forest Ecology and Management*, *258*, 525–537.

Bouriaud, O., Marin, G., Bouriaud, L., Hessenmöller, D., & Schulze, E. D. (2016). Romanian legal management rules limit wood production in Norway spruce and beech forests. *Forest Ecosystems*, *3*, 20.

Brudvig, L. A., Grman, E., Habeck, C. W., Orrock, J. L., & Ledvina, J. A. (2013). Strong legacy of agricultural land use on soils and understory plant communities in longleaf pine woodlands. *Forest Ecology and Management*, *310*, 944–955.

Butsic, V., Munteanu, C., Griffiths, P., Knorn, J., Radeloff, V. C., Lieskovský, J., Mueller, D., & Kuemmerle, T. (2017). The effect of protected areas on forest disturbance in the Carpathian Mountains 1985–2010. *Conservation Biology*, *31*, 570–580.

Carcea, F., & Tudoran, G. (2012). Functional zoning of the forests included in protected natural areas. *Bulletin of the Transilvania University of Braşov*, *5*, 7–14.

Coops, N. C., & Wulder, M. A. (2019). Breaking the habit(at). *Trends in Ecology & Evolution*, *34*, 585–587.

Curtis, P. G., Slay, C. M., Harris, N. L., Tyukavina, A., & Hansen, M. C. (2018). Classifying drivers of global forest loss. *Science*, *361*, 1108–1111.

Donato, D. C., Campbell, J. L., & Franklin, J. F. (2012). Multiple successional pathways and precocity in forest development: Can some forests be born complex? *Journal of Vegetation Science*, *23*, 576–584.

Eckelt, A., Müller, J., Bense, U., Brustel, H., Bußler, H., Chittaro, Y., Cizek, L., Frei, A., Holzer, E., Kadej, M., Kahlen, M., Köhler, F., Möller, G., Mühle, H., Sanchez, A., Schaffrath, U., Schmidl, J., Smolis, A., Szallies, A., … Seibold, S. (2018). Primeval forest relict beetles" of Central Europe: A set of 168 umbrella species for the protection of primeval forest remnants. *Journal of Insect Conservation*, *22*, 15–28.

Elith, J., & Leathwick, J. R. (2009). Species distribution models: Ecological explanation and prediction across space and time. *Annual Review of Ecology, Evolution, and Systematics*, *40*, 677–697.

Elith, J., Phillips, S. J., Hastie, T., Dudík, M., Chee, Y. E., & Yates, C. J. (2011). A statistical explanation of MaxEnt for ecologists. *Diversity and Distributions*, *17*, 43–57.

European Commission. (2020). EU Biodiversity Strategy for 2030. Bringing nature back into our lives. Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions, Brussels, 20.5.2020, COM(2020) 380 final, Available from https://eur-lex.europa.eu/legalcontent/EN/TXT/?uri=CELEX:52020DC0380

Griffiths, P., Kuemmerle, T., Baumann, M., Radeloff, V. C., Abrudan, I. V., Lieskovsky, J., Munteanu, C., Ostapowicz, K., & Hostert, P. (2014). Forest disturbances, forest recovery, and changes in forest types across the Carpathian ecoregion from 1985 to 2010 based on Landsat image composites. *Remote Sensing of Environment*, *151*, 72–88.

Halalisan, A. F., Abrudan, I. V., & Popa, B. (2018). Forest management certification in Romania: Motivations and perceptions. *Forests*, *9*, 425.

Hijmans, A. R. J., Phillips, S., Leathwick, J., Elith, J., & Hijmans, M. R. J. (2020). *Package 'dismo.'* Cran R Project.

Hilmers, T., Friess, N., Bässler, C., Heurich, M., Brandl, R., Pretzsch, H., Seidl, R., & Müller, J. (2018). Biodiversity along temperate forest succession. *Journal of Applied Ecology*, *55*, 2756–2766.

Janda, P., Trotsiuk, V., Mikoláš, M., Bače, R., Nagel, T. A., Seidl, R., Seedre, M., Morrissey, R. C., Kucbel, S., Jaloviar, P., Jasík, M., Vysoký, J., Šamonil, P., Čada, V., Mrhalová, H., Lábusová, J., Nováková, M. H., Rydval, M., Matějů, L., & Svoboda, M. (2017). The historical disturbance regime of mountain Norway spruce forests in the Western Carpathians and its influence on current forest structure and composition. *Forest Ecology and Management*, *388*, 67–78.

Kajtoch, Ł., Wilk, T., Bobrek, R., & Matysek, M. (2016). The importance of forests along submontane stream valleys for bird conservation: The Carpathian example. *Bird Conservation International*, *26*, 350–365.

Knorn, J., Kuemmerle, T., Radeloff, V. C., Keeton, W. S., Gancz, V., Biriş, I.-A., Svoboda, M., Griffiths, P., Hagatis, A., & Hostert, P. (2012). Continued loss of temperate old-growth forests in the Romanian Carpathians despite an increasing protected area network. *Environmental Conservation*, *40*, 182–193.

Jõgiste, K., Korjus, H., Stanturf, J. A., Frelich, L. E., Baders, E., Donis, J., Jansons, A., Kangur, A., Köster, K., Laarmann, D., & Maaten, T., (2017). Hemiboreal forest: Natural disturbances and the importance of ecosystem legacies to management. *Ecosphere*, *8*(2), e01706.

Kortmann, M., Müller, J. C., Baier, R., Bässler, C., Buse, J., Cholewińska, O., Förschler, M. I., Georgiev, K. B., Hilszczański, J., Jaroszewicz, B., Jaworski, T., Kaufmann, S., Kuijper, D., Lorz, J., Lotz, A., Łubek, A., Mayer, M., Mayerhofer, S., Meyer, S., … Thorn, S., (2021). Ecology versus society: Impacts of bark beetle infestations on biodiversity and restorativeness in protected areas of Central Europe. *Biological Conservation*, *254*, 108931.

Leitão, P. J., & Santos, M. J. (2019). Improving models of species ecological niches: A remote sensing overview. *Frontiers in Ecology and Evolution*, *7*, 9.

Leverkus, A. B., Lindenmayer, D. B., Thorn, S., & Gustafsson, L. (2018). Salvage logging in the world's forests: Interactions between natural disturbance and logging need recognition. *Global Ecology and Biogeography*, *27*, 1140–1154.

Lindenmayer, D. (2019). Small patches make critical contributions to biodiversity conservation. *Proceedings of the National Academy of Sciences*, *116*, 717–719.

Liu, C., Newell, G., White, M., Correspondence, C., & Liu, A. (2016). On the selection of thresholds for predicting species occurrence with presence-only data. *Ecology and Evolution*, *6*, 337–348.

Malíček, J., Palice, Z., Vondrák, J., Kostovčík, M., Lenzová, V., & Hofmeister, J. (2019). Lichens in old-growth and managed mountain spruce forests in the Czech Republic: Assessment of biodiversity, functional traits and bioindicators. *Biodiversity and Conservation*, *28*, 3497–3528.

McDowell, N. G., Allen, C. D., Anderson-Teixeira, K., Aukema, B. H., Bond-Lamberty, B., Chini, L., Clark, J. S., Dietze, M., Grossiord, C., Hanbury-Brown, A., Hurtt, G. C., Jackson, R. B., Johnson, D. J., Kueppers, L., Lichstein, J. W., Ogle, K., Poulter, B., Pugh, T. A. M., Seidl, R., … Xu, C. (2020). Pervasive shifts in forest dynamics in a changing world. *Science*, *368*, eaaz9463.

McMullin, R. T., & Wiersma, Y. F. (2019). Out with OLD growth, in with ecological continNEWity: New perspectives on forest conservation. *Frontiers in Ecology and the Environment*, *17*, 176–181.

Mikoláš, M., Ujházy, K., Jasík, M., Wiezik, M., Gallay, I., Polák, P., Vysoký, J., Čiliak, M., Meigs, G. W., Svoboda, M., Trotsiuk, V., & Keeton, W. S. (2019). Primary forest distribution and representation in a Central European landscape: Results of a large-scale field-based census. *Forest Ecology and Management*, *449*, 117466.

Morin, D., Planells, M., Guyon, D., Villard, L., Mermoz, S., Bouvet, A., Thevenon, H., Dejoux, J. F., Le Toan, T., & Dedieu, G. (2019). Estimation and mapping of forest structure parameters from open access satellite images: Development of a generic method with a study case on coniferous plantation. *Remote Sensing*, *11*, 1275.

Mulatu, K. A., Decuyper, M., Brede, B., Kooistra, L., Reiche, J., Mora, B., & Herold, M. (2019). Linking terrestrial LiDAR scanner and conventional forest structure measurements with multi-modal satellite data. *Forests*, *10*, 291

Müller, J., Noss, R. F., Thorn, S., Bässler, C., Leverkus, A. B., & Lindenmayer, D. (2019). Increasing disturbance demands new policies to conserve intact forest. *Conservation Letters*, *12*, e12449.

Munteanu, C., Kuemmerle, T., Keuler, N. S., Müller, D., Balázs, P., Dobosz, M., Griffiths, P., Halada, L., Kaim, D., Király, G., Konkoly-Gyuró, E., Kozak, J., Lieskovsky, J., Ostafin, K., Ostapowicz, K., Shandra, O., & Radeloff, V. C., (2015). Legacies of 19th century land use shapes contemporary forest cover. *Global Environmental Change*, *34*, 83–94.

Nita, M. D., Munteanu, C., Gutman, G., Abrudan, I. V., & Radeloff, V. C. (2018). Widespread forest cutting in the aftermath of World War II captured by broad-scale historical Corona spy satellite photography. *Remote Sensing of Environment*, *204*, 322–332.

Oeser, J., Heurich, M., Senf, C., Pflugmacher, D., Belotti, E., & Kuemmerle, T. (2020). Habitat metrics based on multi-temporal Landsat imagery for mapping large mammal habitat. *Remote Sensing in Ecology and Conservation*, *6*, 52–69.

Phillips, S. J., Anderson, R. P., Dudík, M., Schapire, R. E., & Blair, M. E. (2017). Opening the black box: An open-source release of Maxent. *Ecography*, *40*, 887–893.

Potapov, P. Hansen, M. C., Laestadius, L., Turubanova, S., Yaroshenko, A., Thies, C., Smith, W., Zhuravleva, I., Komarova, A., Minnemeyer, S., & Esipova, E. (2017). The last frontiers of wilderness: Tracking loss of intact forest landscapes from 2000 to 2013. *Science Advances*, *3*, e1600821.

Sabatini, F. M., Burrascano, S., Keeton, W. S., Levers, C., Lindner, M., Pötzschner, F., Verkerk, P. J., Bauhus, J., Buchwald, E., Chaskovsky, O., Debaive, N., Horváth, F., Garbarino, M., Grigoriadis, N., Lombardi, F., Duarte, I. M., Meyer, P., Midteng, R., Mikac, S., … Kuemmerle, T. (2018). Where are Europe's last primary forests? *Diversity and Distributions*, *24*, 1426–1439.

Sabatini, F. M., Keeton, W. S., Lindner, M., Svoboda, M., Verkerk, P. J., Bauhus, J., Bruelheide, H., Burrascano, S., Debaive, N., Duarte, I., Garbarino, M., Grigoriadis, N., Lombardi, F., Mikoláš, M., Meyer, P., Motta, R., Mozgeris, G., Nunes, L., Ódor, P., … Kuemmerle, T. (2020). Protection gaps and restoration opportunities for primary forests in Europe. *Diversity and Distributions*, *26*, 1646–1662.

Schickhofer, M., & Schwarz, U. (2019). *PRIMOFARO - Inventory of potential primary and old-growth forest areas in Romania*. EuroNatur.

Schulze, E. D. et al. (2014). 'Forest management and biodiversity', *Web Ecology*, 14(1), 3–10. https://doi.org/10.5194/we-14-3-2014

Senf, C., Mori, A. S., Müller, J., & Seidl, R. (2020). The response of canopy height diversity to natural disturbances in two temperate forest landscapes. *Landscape Ecology*, *35*(9), 2101–2112.

Senf, C., Pflugmacher, D., Zhiqiang, Y., Sebald, J., Knorn, J., Neumann, M., Hostert, P., & Seidl, R. (2018). Canopy mortality has doubled in Europe's temperate forests over the last three decades. *Nature Communications*, *9*, 1–8.

Senf, C., & Seidl, R. (2021). Mapping the forest disturbance regimes of Europe. *Nature Sustainability*, *4*, 63–70.

Shimada, M., Itoh, T., Motooka, T., Watanabe, M., Shiraishi, T., Thapa, R., & Lucas, R. (2014). New global forest/non-forest maps from ALOS PALSAR data (2007-2010). *Remote Sensing of Environment*, *155*, 13–31.

Slezák, M., Jarolímek, I., Kochjarová, J., & Hrivnák, R. (2020). Floodplain forest vegetation in the northern part of the Western Carpathians. *Biologia*, *75*, 1789–1799.

Swanson, M. E., Franklin, J. F., Beschta, R. L., Crisafulli, C. M., DellaSala, D. A., Hutto, R. L., Lindenmayer, D. B., & Swanson, F. J. (2011). The forgotten stage of forest succession: Early-successional ecosystems on forest sites. *Frontiers in Ecology and the Environment*, *9*(2), 117–125.

Thom, D., Rammer, W., Dirnböck, T., Müller, J., Kobler, J., Katzensteiner, K., Helm, N., & Seidl, R. (2017). The impacts of climate change and disturbance on spatio-temporal trajectories of biodiversity in a temperate forest landscape. *Journal of Applied Ecology*, *54*, 28–38.

Thom, D., & Seidl, R. (2016). Natural disturbance impacts on ecosystem services and biodiversity in temperate and boreal forests. *Biological reviews of the Cambridge Philosophical Society*, *91*, 760–781.

Thorn, S., Bässler, C., Brandl, R., Burton, P. J., Cahall, R., Campbell, J. L., Castro, J., Choi, C. Y., Cobb, T., Donato, D. C., Durska, E., Fontaine, J. B., Gauthier, S., Hebert, C., Hothorn, T., Hutto, R. L., Lee, E. J., Leverkus, A. B., Lindenmayer, D. B., … Müller, J. (2018). Impacts of salvage logging on biodiversity: A meta-analysis. *Journal of Applied Ecology*, *55*, 279–289.

Veen, P., Fanta, J., Raev, I., Biriş, I.-A., Smidt, J., & Maes, B. (2010). Virgin forests in Romania and Bulgaria: Results of two national inventory projects and their implications for protection. *Biodiversity and Conservation*, *19*, 1805–1819.

Watson, J. E. M., Evans, T., Venter, O., Williams, B., Tulloch, A., Stewart, C., Thompson, I., Ray, J. C., Murray, K., Salazar, A., McAlpine, C., Potapov, P., Walston, J., Robinson, J. G., Painter, M., Wilkie, D., Filardi, C., Laurance, W. F., Houghton, R. A., … Lindenmayer, D. (2018). The exceptional value of intact forest ecosystems. *Nature Ecology & Evolution*, *2*, 599–610.

Wirth, C., Messier, C., Bergeron, Y., Frank, D., & Fankhänel, A. (2009). Old-growth forest definitions: A pragmatic view. In C. Wirth, G. Gleixner, & M. Heimann (Eds.), *Old-growth forests* (pp. 11–33). Springer.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Munteanu, C., Senf, C., Nita, M. D., Sabatini, F. M., Oeser, J., Seidl, R., & Kuemmerle, T. (2021). Using historical spy satellite photographs and recent remote sensing data to identify high-conservation-value forests. *Conservation Biology*, 1–11. https://doi.org/10.1111/cobi.13820