Accepted Article

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

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/cobi.13820.

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Running head: Romanian forests

Keywords:

Anthropogenic pressure, conservation value, forest continuity, forest structure, high conservation value forest, distribution modeling, spy satellite imagery

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 (HCVF) are critically important for biodiversity and ecosystem service provisioning, but face manifold threats. Where systematic HCVF inventories are missing, such as in parts of Eastern Europe, these forests remain largely unacknowledged and therefore often unprotected. Here, we propose a novel, transferable approach for detecting HCVF, based on integrating historical spy satellite images, contemporary remote sensing data and information on current anthropogenic pressures. Using Romania as a pilot-study, we mapped forest continuity (1955-2019) , canopy structural complexity, and anthropogenic pressures, and identified a large area (738,000 ha) of HCVF. More than half of this area is susceptible to current anthropogenic pressures

and lacks 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.

Introduction

High conservation value forests (HCVF) have a history of forest continuity, and are typically composed of late-successional stands with structurally complex canopy and low levels of anthropogenic disturbance (Wirth et al. 2009; Munteanu et al. 2015; Watson et al. 2018). 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; Mikoláš et al. 2019; Malíček 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). A systematic identification is therefore an important prerequisite for ensuring HCVF persistence, and maintaining their natural and societal value (McDowell et al. 2020; Angelstam et al. 2020; Kortmann et al. 2021). Unfortunately, HCVF in many regions remain undetected and unprotected due to the lack of systematic HCVF inventories.

The identification of candidate HCVF requires information on three aspects: (1) *forest continuity* (i.e., a continuous forest cover over an extended period of time), (2) composition and structural complexity (hereafter: *structural complexity*), and (3) *anthropogenic pressures*. Although some data is available for all three aspects in Europe (Potapov et al. 2017; Watson et al. 2018; Sabatini et al. 2018), existing approaches for identifying HCVF rarely integrate across these dimensions. 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 (Munteanu et al. 2015; McMullin & Wiersma 2019). Forest structural complexity results from a history of stochastic natural disturbances with low to moderate severity (Donato et al. 2012; Senf et al. 2020), leading to vertical layering, canopy gaps with natural regeneration, as well as downed and standing deadwood (Thom et al. 2017; Hilmers et al. 2018). Conversely, forest management can result in a loss of the features associated with high conservation value. This happens not only in the case of clearcuts, but also in the case of thinning or salvage logging, all of which remove important biological legacies and alter natural disturbance regimes (Thorn et al. 2018; Müller et al. 2019). Quantifying forest continuity, structural complexity, and anthropogenic pressures consistently over large areas is challenging, yet a necessary first step to detect HCVF 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 (Knorn et al. 2012; Butsic et al. 2017). Romania is a hotspot of HCVF in Eastern Europe (Veen et al. 2010; Sabatini et al. 2020) where large areas of valuable forests may remain underappreciated or get 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 only be applied where HCVF have been identified and mapped.

Our goals were to (1) develop a transferable approach for identifying HCVF (2) demonstrate its value by mapping the extent of potential HCVF in the Romanian Carpathians and (3) assess the current fragmentation and protection of these potential HCVF. We define HCVF as continuously forested area (since 1955) where stands have similar structural complexity and are subject to similar (low) anthropogenic pressure as primary and old-growth forests (as defined by Sabatini et al. 2018, 2020). To achieve these goals, we combine historical spy satellite images from the Cold War period, contemporary high-resolution remote sensing data and accessibility data for characterizing forest continuity, structural complexity and anthropogenic pressures in the Romanian Carpathians.

Methods

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 sp.*), with coniferous forest *(Picea abies, Abies alba)* at higher elevations (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 (<1ha), followed by natural regeneration (Schulze et al. 2014). At the end of the 19^{th} century, Romania likely harbored up to 2 million ha of primary and old-growth forests, which diminished to one tenth of their former extent by 2004 (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 (Knorn et al. 2012; Griffiths et al. 2014). Yet, Romania maintained a long forest rotation length (>100 years, Bouriaud et al. 2016) and still harbors some of the largest areas of remaining primary forests in Europe. Forest conservation practices in

Romania follow the system of protected areas and their IUCN categorization. In addition, forest management and conservation are regulated through national legislation that establishes six classes of conservation and management regimes depending 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 managed is geared towards continuous forest cover. Better knowing the extent, location, and threats to HCVF is a critical step for ensuring their persistence into the future.

To map *forest continuity* across the Romania Carpathians, we used historical and modern remote sensing imagery as well as topographic data. We defined continuous forests as forested areas that have likely not experienced stand-replacing disturbance after 1955 by corroborating three data sources: Corona historical spy satellite imagery between 1955 and 1968, (Nita et al. 2018), military topographic maps (1:25.000) between 1968 and 1978 *(Appendix S1)* and Landsat TM/ETM+/OLI data at 30m resolution (Senf & Seidl 2021) between 1985 and 2019. In a first step, we produced a map of forest continuity between 1985 and 2019 from the Landsat time series by subtracting (Senf & Seidl 2021) all areas that experienced stand-replacing disturbances since 1985 from a contemporary forest cover mask. In a second step, we produced a historical forest continuity map (1955 to 1979) by subtracting all areas that were previously classified as naturally disturbed or harvested either in historical remote sensing imagery (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 was hand-digitized and resampled to Landsat resolution (30m). The resulting datasets were finally combined into one single map of forest continuity, which includes forest areas classified as continuous in both steps *(see above)*. The historical spy satellite imagery allowed us to exclude areas of historical forest disturbance previously undocumented by modern data (530,000 ha between 1955-1965). 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 *(Text S1, Appendix S2*). Excluding historically disturbed area from our measure ensured that estimates of HCVF are conservative.

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. Our model aims at identifying areas with similar compositional and structural characteristics as the confirmed locations of primary and old-growth forests across the Romanian Carpathians, and is based on a large data set (1,853 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 three partially overlapping sources: (a) officially designated UNESCO Ancient and Primeval Beech Forests of the Carpathians (https://whc.unesco.org/en/list/1133/, 23982 ha), (b) the Romanian National Catalogue of virgin and cvasi-virgin forests (http://apepaduri.gov.ro/paduri-virgine/, 6.665 ha of virgin and 23.396 ha of semi-virgin forests) and (c) the WWF areas submitted for inclusion in the National Catalogue (https://lemncontrolat.ro/useful-documents-and-links/downloads/, 29.239 ha, accessed Oct 2019) (*Appendix S3*). Training points were distributed randomly across all confirmed locations of primary and old-growth forests (min 10 points per forest stand at a minimum distance of 100m).

We parametrized the structural complexity model using a series of spectral-temporal metrics derived from Landsat imagery that have been shown to correlate 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., 2019, *Appendix S4*). We relied on continuous variables directly 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 compared to categorical classifications (Oeser et al. 2019). In addition to the Landsat metrics, we included, two radar metrics derived from ALOS-2 PALSAR-2, because radar metrics may better capture vertical vegetation structure than optical remote sensing data (Shimada et al. 2014; Mulatu et al. 2019; Morin et al. 2019) (*Appendix S4)*. The resulting structural complexity index (i.e. the complementary log-log output of the model, Phillips et al. 2017) scales between 0 and 1 and is 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 indicate forests with high similarity in their structural complexity to sites at which the presence of primary and old-growth forests has been confirmed. *(Figure 1).*

To assess *anthropogenic pressure*, we calculated a human pressure index, assuming that known primary forests in the Romanian Carpathians have persisted because human pressure on them is low. To map anthropogenic pressure, we used a Maxent-based modelling 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 six variables capturing accessibility, transport networks, human population density and local reliance on firewood *(Appendix S4)*. This resulted in an anthropogenic pressure index (i.e. the complementary log-log output of the model) scaled between 0 and 1, which provides a relative measure of human impact on the forests. High index values indicate the anthropogenic pressure of a forest pixel is similar to sites at which the presence of primary and old-growth forests has been confirmed (*Figure 1*).

<<< Figure 1>>>

We assessed model performance using five-fold cross-validation to calculate Area Under the Receiver Operator Curve (AUC) scores. 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 that identified four forest classes: *prime HCVF* (i.e., structural complexity similar to that of designated primary and old-growth forests / low anthropogenic pressure), *at risk HCVF* (i.e., structural complexity similar to that of designated primary and old-growth forests / high anthropogenic pressure), *restoration forest* (i.e. structural complexity not resembling primary and old-growth forests /low anthropogenic pressure) and *managed forest* (i.e., structural complexity not resembling primary and old-growth forests / high anthropogenic pressure). These four final classes were defined along two separate and independent axes, by comparing the ranks of the individual binary maps. Because the choice of thresholding can affect the interpretation of the results, we compared different methods, also using the maximum sensitivity-specificity thresholding approach (Liu et al. 2016). Here we only report the results of the more conservative estimate, but a comparison of the sensitivity of our results to the specific thresholding chosen approach is presented in the *Appendix S8.* To check model performance against ground-true data, we used forest inventory data available for approximately 33% of the continuous forest area under study, and verified the capacity of our methodology to distinguish differences in stand age, canopy structure and forest management types among the four forest classes of our analysis (*Appendix S9*).

To assess the fragmentation and protection of HCVF, we quantified the landscape-scale configuration of *prime* and *at risk* HCVF considering landscape metrics that included total class area, patch size and patch density. All metrics were calculated on categorical maps of the four forest classes, using the landscape metrics (Landscape Metrics for Categorical Map Patterns 1.5.3) package in the R programming environment. We further assessed the protection status (WDPA, www.protectedplanet.net, accessed Oct 2019) of *prime* and *at risk* HCVF. 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, which have not experienced stand-replacing disturbance since the mid-20th century. Of these, 8.6% (approx. 351,000 ha) were identified as *prime HCVF*, with complexity levels and anthropogenic pressure similar to primary and old-growth forests. An additional 9.5% (approx. 387,000 ha) of continuous forests have canopy structures similar to primary and old-growth forests, but are under high anthropogenic pressures (*at risk HCVF*). Approximately 73% of the continuously forested area is *managed forest*, with structural complexity index values that differ from primary and old-growth forests and high anthropogenic pressure *(Figure 2).*

<<< Figure 2 >>>

Model fits were good, with AUC values of 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 had the largest contribution 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 (*Appendix S7*, *Appendix S5 and S6 for index values prior to thresholding)*. This threshold yielded a conservative estimate of the extent of HCVF forest. Using alternative thresholds maximizing specificity and sensitivity (0.47 and 0.34 index values, for the complexity and pressure models, respectively) would suggest an additional 582,000 ha of HCVF (1.3 Mil total, 63% of these being *prime* HCVF) (*Appendix S8).*

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

<<< *Figure 3*>>>

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

<<< *Figure 4*>>>

Discussion

High conservation value forests (HCVF) are critical for biodiversity, ecosystem service provisioning, and climate regulation (Watson et al. 2018; Sabatini et al. 2020). In Europe, HCVF are thought to be scarce and fragmented. Most remaining HCVF are concentrated in Northern and Eastern Europe (Sabatini et al. 2018, 2020; Angelstam et al. 2020) where canopy turnover rates are still lower than in Central and Western Europe (Senf et al. 2018; Senf & Seidl 2021). Effectively protecting HCVF in these areas is inhibited by a lack of spatial data on their distribution. Our work addresses this knowledge gap and shows 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 monitoring HCVF and thus for operationalizing these policy commitments. Furthermore, given recent advancements in remote sensing data acquisition, storage and cloud processing, our approach is highly scalable and transferable to other world 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 pilot study for testing our framework for HCVF identification. Our results suggest the existence of substantially larger areas of potential HCVF compared to previously reported virgin forest areas (220.000 ha, Veen et al. 2010) and potential primary and old-growth forests in Romania (440.000ha, 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 mil ha, Sabatini et al. 2018) (*Appendix S12*). Compared to 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 as well as highlighting forests most at risk from anthropogenic disturbance. We caution though that comparisons across different estimates and maps is hampered due to different methodologies, resolutions and the only partially overlapping definitions of primary, old-growth, and virgin forests with HCVF. Overall, our study highlights 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*).

While not all HCVF identified here are primary or old-growth forests, they have not experienced large-scale disturbances since at least 1955 (with average ages 90-110 years, *Figure 3*) and they have similar canopy structure 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 point in time. Of the large area of HCVF in the Romanian

Carpathians identified here, as much as half is under high anthropogenic pressures (*at risk* HCVF). These 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 do occur. Although these management strategies are already regulated under Romanian legislation, they are poorly implemented in some areas.

Our study 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 towards 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 (Swanson et al. 2011; Hilmers et al. 2018) and a comprehensive strategy to foster biodiversity should thus consider both old and recently disturbed forest ecosystems.

Our analyses 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 HCVF in our analyses have likely experienced small-scale, natural disturbances or management which might have contributed to the diverse structures of these forests (Korjus et al. 2017; Janda 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 from the remote-sensing data we used here. Our approach highlights both HCVF 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 are likely underestimating some of the lowland primary forest 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, which also play important roles for 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 data and satellite remote-sensing metrics from contemporary archives with spatial modelling for operationalizing the identification of potential HCVF. Our model showed high predictive performance (AUC 0.80 and 0.86). As expected, elevation and population density showed high contributions 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 period) were the most important predictor variables, while the radar backscatter metrics had only very small model contributions (*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 amongst primary forests in the Romanian Carpathians (Sabatini et al. 2020; Albrich et al. 2021). In addition, while we here 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 (Morin et al. 2019; Bae et al. 2019). While our approach is transferable and scalable, we caution that regionalized training and validation is needed and that the choice of spatio-temporal metrics and predictor variables might have to be adjusted for different bioclimatic conditions and forest management regimes. Still, our work lays the groundwork for expanding and extrapolating HCVF inventories to the European scale.

Conservation and management recommendations

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. Four broad conservation and management recommendations arise from our work:

1. *prime* HCVF should be the first target towards achieving the 10% protection goal set by the EU Biodiversity Strategy for 2030 (European Commission 2020). Currently, less than 15% of HCVF in the Romanian Carpathians are strictly protected, but as much as 70% of the state-owned HCVF are already under protection by no-silvicultural intervention plans *(Text S9).* Upgrading their existing protection status and developing new protected areas in *prime* HCVF 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).

2. The conservation of *at risk HCVF* is perhaps most urgent, due to 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 the public awareness about the value of HCVF 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 (Bauhus et al. 2009; Asbeck et al. 2021).

3. The *restoration forests* identified here are 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, as natural disturbances accelerate development towards complex and diverse forests (Thom & Seidl 2016; Thom et al. 2017).

4. 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 identified here as *managed forests*, and reversal of these areas to primary characteristics is unlikely for the near future (Munteanu et al. 2015), and would take many centuries (Albrich et al. 2021). Where the restoration towards HCVF is neither environmentally nor economically possible, adapted silvicultural approaches and forest certification schemes (FSC, 2.6 Mil ha certified in Romania (Halalisan et al. 2018)) would allow satisfying wood demands while maintaining ecosystem functioning and some forest biodiversity (European Commission 2020).

We strongly encourage forest management and conservation to carefully consider HCVF, because here conservation returns will be 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 general public focus their attention on these key ecosystems.

Acknowledgments

CM 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). We are grateful to Dr. Falko Buschke and three anonymous reviewers for the constructive comments on a previous version of this manuscript.

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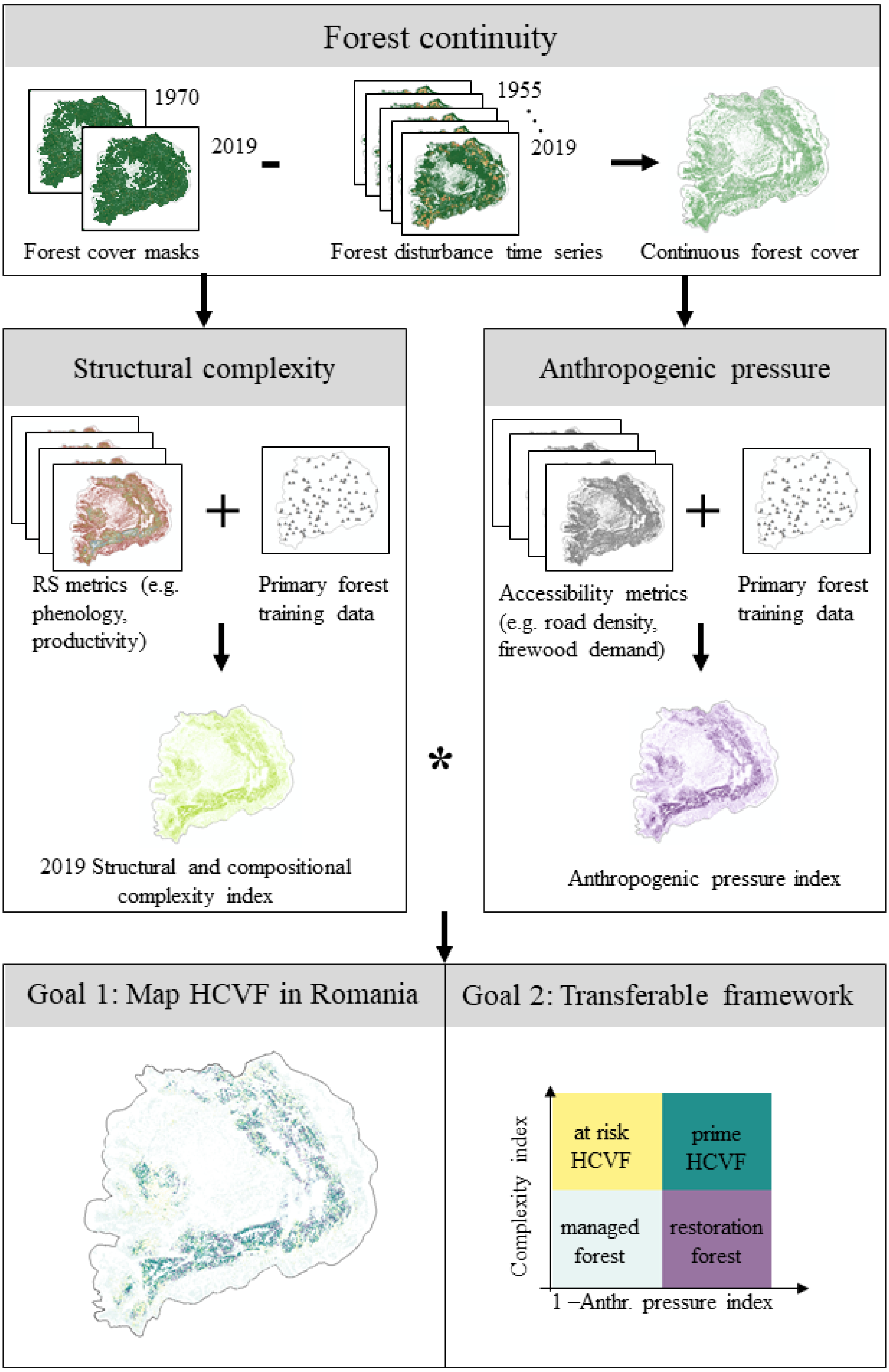
Figure captions

Figure 1. *Framework for identifying high conservation value forests (HCVF) based on historical spy satellite images, contemporary remote sensing data and spatial layers of anthropogenic pressure. In a first step, we identified forest areas that have not been disturbed since 1955. Next, we trained two separate models for detecting structural complexity and anthropogenic pressures on these continuity forests, using confirmed locations of primary forests as training data. The resulting predictions were overlayed to yield four forest categories:* at risk *HCVF,* prime *HCVF,* managed forest *and* restoration forest*. RS: Remote Sensing.*



Forest continuity
1970
2019
Forest cover masks
1955
2019
Forest disturbance time series
Continuous forest cover
Structural complexity
RS metrics (e.g. phenology, productivity)
Primary forest training data
2019 Structural and compositional complexity index
Anthropogenic pressure
Accessibility metrics (e.g. road density, firewood demand)
Primary forest training data
Anthropogenic pressure index
Goal 1: Map HCVF in Romania
Goal 2: Transferable framework
Complexity index
at risk HCVF
prime HCVF
managed forest
restoration forest
1 –Anthr. pressure index

F*igure 2. Bivariate map of structural complexity vs. anthropogenic pressure, yielding four forest classes across the Romanian Carpathians (A and B). Yellow tones indicate* at risk *HCVF with high anthropogenic pressure (387,000 ha). Green tones indicate* prime *HCVF in the Romanian Carpathians (352,000 ha). Light blue denotes* managed forests *(3 Mil ha) and purple denotes forests with restoration potential towards HCVF (333,000 ha). Histograms represent distributions of the two indices, the dotted lines indicate the thresholds identified based on the weighted average of precision and recall (F1 metric). Insets: C: Rodna Mountains; D: Apuseni Mountains; E: Cerna & Retezat; F: Oituz; and G: Fagaras Mountains.*

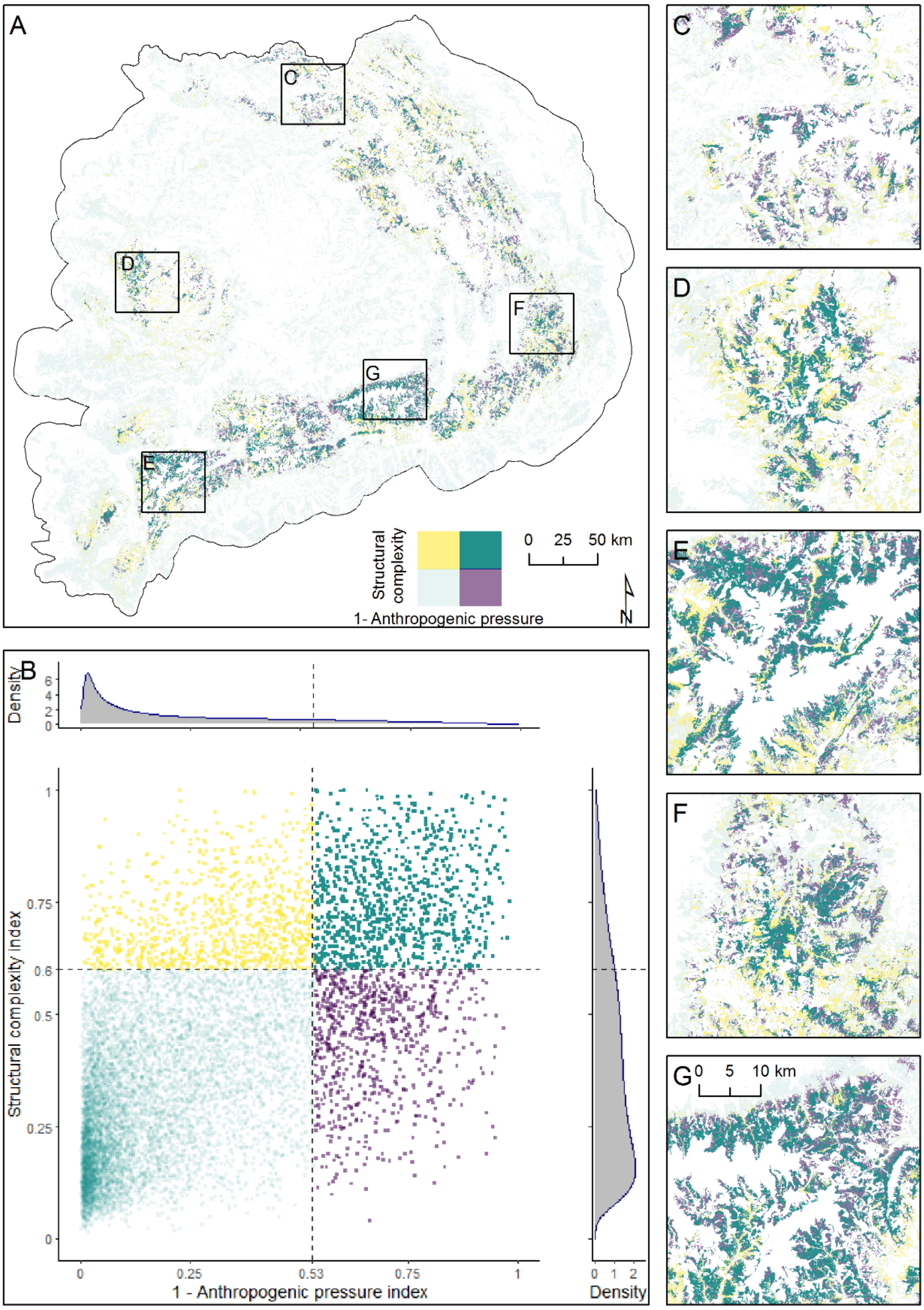

A
C
D
E
F
G
Structural complexity
1- Anthropogenic pressure
0 25 50 km
N
B
Density
6
4
2
0
Structural complexity index
1
0.75
0.6
0.5
0.25
0
0.25
0.53
0.75
1
1 - Anthropogenic pressure index
0 1 2
Density
0 5 10 km

Figure 3: Summarized forest inventory data for ~15,000 km² of state owned forests across our four forest classes: prime *HCVF (green),* at risk *HCVF (yellow),* restoration forest *(purple) and* managed forest *(grey). (A) Forest stand age: prime HCVF represent a higher proportion of older forests (>100 years), (B) Canopy structure (1: even aged - 4: uneven aged): Managed forests are mostly even aged, whereas* prime *HCVF and* at risk *HCVF occupy a larger proportion of the uneven aged classes (3 and 4). (C) Functional type (1: no forest intervention, 6: all silvicultural practices allowed). HCVF are primarily concentrated in functional types 1 and 2 (70%), indicating no management interventions.*

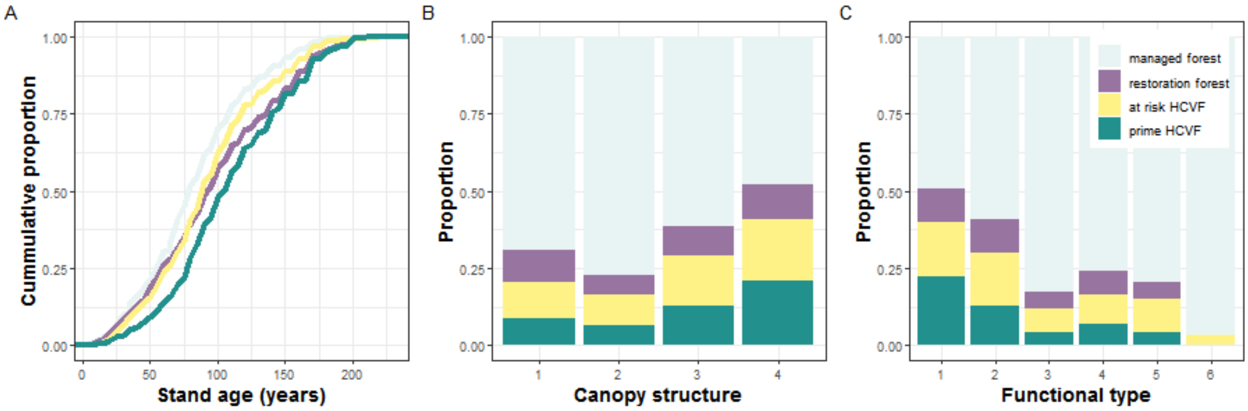


Figure 4. Distribution of protected areas in prime HCVF (left) and at risk HCVF (right). Overall, approximately half of these forests do not have formal protection, and at risk HCVF were, on

average, less protected than prime HCVF.