# Monitoring Habitat Fragmentation and Biodiversity in Forest Ecosystems

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Aerial view of Bavarian Forest, Germany (Photo: Andrey Kuzmin/Adobe Stock)

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## Abstract

The current biodiversity crisis is primarily caused by habitat loss and fragmentation, which are exacerbated by global population expansion and land use intensification. The techniques applied to evaluate the impact of habitat loss and fragmentation in forest ecosystems tend to measure changes in landscape patterns induced by forest degradation. Earth observation techniques and remotely sensed imagery are crucial tools for the large-scale monitoring of forest habitat loss and fragmentation along with related changes in forest biodiversity characteristics. Recently, the relevance of remote sensing for monitoring forest fragmentation has been further amplified by new satellite missions providing up-to-date and high-resolution open-access data available on cloud computing platforms. However, while satellite programmes like Landsat that employ remote sensing techniques are suitable for large-scale monitoring of forest species distribution, they cannot capture micro-spatial variations, since their sensors cannot disentangle forest heterogeneity. Finally, remotely sensed canopy-level information alone cannot fully explain biodiversity patterns. Integration of remote sensing and ground survey activities may help to overcome the limitations of these techniques, providing solutions for designing and optimizing monitoring strategies to tackle forest fragmentation and biodiversity loss in forest ecosystems.

## Keywords

Remote sensing · Google earth engine · Habitat loss and fragmentation · Land use change · Landsat

## The Need to Monitor Forest Habitat Fragmentation

Human appropriation of the planet is restricting ecological connectivity for species and ecosystems and thus causing habitat loss and fragmentation, which are considered key drivers of the current biodiversity crisis together with pollution, overexploitation, and climate change (Bae et al. 2019; Muys et al. 2022). Habitat fragmentation (also known as habitat subdivision or patchiness) means the breaking apart of habitats into multiple patches (Fahrig 2003). It can compound habitat loss by reducing the size of the habitat area, increasing edge effects, and causing habitat isolation but it is also responsible for increasing habitat heterogeneity (but see the debate between Fletcher et al. 2018 and Fahrig et al. 2019). Smaller habitat patches can lead to population decline, as resources in smaller patches may be more limited. In addition, habitat fragmentation increases the isolation of remaining habitat areas, decreasing habitat connectivity which relates to the ability of species as well as ecological resources and processes to move through landscapes (Lindenmayer et al. 2008).

Habitat loss and fragmentation determine landscape degradation (Fahrig 2003), which Fischer and Lindenmayer (2007) define as the gradual deterioration of habitat quality. For example, logging is one of the main factors inducing degradation of intact forest habitats. Habitat degradation is a consequence of the impact of multiple anthropogenic stressors and transforms landscapes by reducing the size and connectivity of species' habitats. Its effects become visible at different scales, and its impact is not ubiquitous but rather species- and ecosystem-specific. The techniques and approaches commonly employed to evaluate the impact of habitat loss and fragmentation on biological systems tend to measure changes in landscape patterns induced by habitat degradation (Lindenmayer and Hobbs 2008).

Natural and anthropogenic disturbances affect habitat availability (amount) and configuration (connectivity) for biodiversity in forest landscapes (Thom et al. 2017). Timber harvesting as well as abiotic and biotic disturbances like windthrow, wildfires, insect outbreaks, diseases, pathogens, and drought may alter both the structural and functional connectivity of forest habitats, as well as the amount of habitat available for biodiversity. For example, windthrow events can quickly create large volumes of deadwood, while logging can isolate old-growth forest remnants. Forest management is an example of disturbance that can have positive as well as negative effects on the amount of connected habitat usable by forest species (Oettel and Lapin 2021). For example, intensive forest management conducted in the form of clear-cutting degrades the habitats of saproxylic species by reducing habitat amount through the removal of deadwood substrates on which they complete their life cycle as well as habitat connectivity through the creation of forest gaps impeding their dispersion (Mönkkönen et al. 2014; Mazziotta et al. 2023; Oettel et al. 2023). On the other hand, close-to-nature forest management (Bauhus et al. 2013)—for example, continuous cover forestry by means of selective logging (Peura et al. 2018)—improves habitat quality for species dwelling in semi-natural forests. The creation of forest gaps by selective logging increases habitat heterogeneity through the removal of large logs in the otherwise homogeneous mature forest, creating habitat for species developing in standing and lying deadwood associated with sunny microclimatic conditions. In doing so, selective logging also increases habitat connectivity by creating a heterogeneous forest matrix that facilitates the dispersion of saproxylic species associated with sunny microclimate. In both cases, forest management is changing the structure of the landscape by altering the amount of habitat available and the connectivity of suitable habitat patches for different species (Nordén et al. 2013; Undin et al. 2022). However, species that have declined due to forestry mostly require maintaining large living and dead trees, which cannot be preserved by continuous cover forestry alone. A mosaic of different management regimes may provide complementary ways to maintain valuable and connected habitats for forest species (Koivula et al. 2025; Rautio et al. 2025).

Since habitat loss and fragmentation induced by natural and anthropogenic disturbances take place on the level of the entire landscape rather than that of individual stands, tackling these changes requires earth observation techniques like remote sensing that can monitor variations in the characteristics of forests and their spatial patterns on a broad scale (Francini et al. 2022, 2023a) (Fig. 9.1).

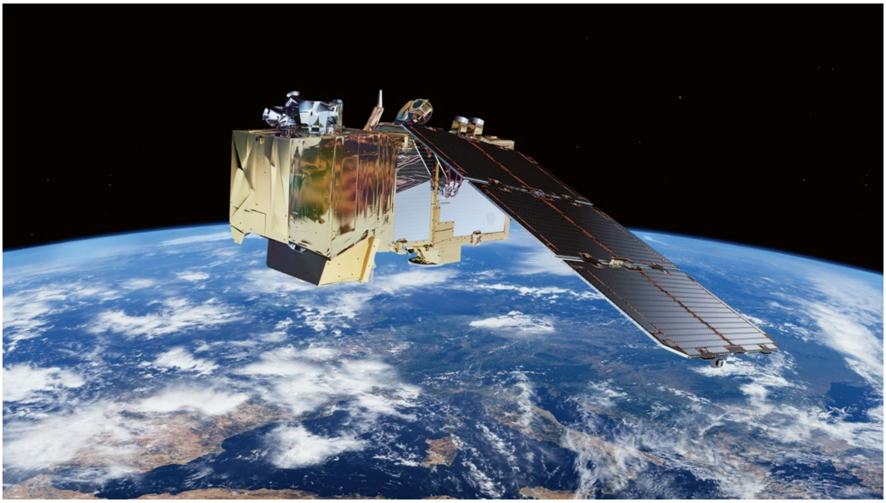


**Fig. 9.1** ESA Sentinel—2 (European Space Agency)

## The Role of Remote Sensing in Habitat Fragmentation Monitoring

Habitat loss and fragmentation are historically monitored by means of ground surveys. Field analysis and detailed information acquisition are effective strategies for collecting exhaustive and comprehensive information about these two drivers of landscape degradation. On the other hand, ground surveys are subject to several shortcomings. First, acquiring data on the ground is time-consuming and consequently expensive. As a result, such data is acquired with long remeasurement intervals and only from small areas, limiting its effectiveness for estimating forest changes quickly and precisely (Zald et al. 2016). This is a crucial issue with regard to monitoring the rapid forest changes induced by global warming and frequent anthropogenic disturbances. Second, ground data can be aggregated to provide estimates, but it cannot be employed alone to produce detailed, spatially explicit maps useful for habitat loss and fragmentation assessment.

Remote sensing offers an effective alternative to ground surveys for mapping the processes of habitat loss and fragmentation. For example, active and passive remote sensing data can be used to obtain land cover and forest disturbance maps and to track changes in forest cover and health status (Hao et al. 2019; Francini et al. 2022). Landscape metrics such as patch size, shape, and connectivity are numerical indices quantifying landscape patterns (McGarigal 2015) and can be calculated from these maps to quantify habitat fragmentation (Liu et al. 2021). In the meantime, photosynthetic activity indices (e.g., the Normalized Difference Vegetation Index, NDVI) can be calculated from remotely sensed optical imagery to monitor changes in vegetation status and assess habitat condition and degradation over space and time (Guo et al. 2019).

In addition, remote sensing provides valuable information for guiding conservation and land management efforts (Tayyebi et al. 2020). For example, remote sensing data can be used to identify areas where conservation efforts are most needed, track the effectiveness of conservation interventions, and prioritize areas for habitat restoration (Cord et al. 2018; Schwieder et al. 2019).

The relevance of remote sensing for monitoring habitat loss and fragmentation has been further amplified by three recent innovations and advancements. First, new satellite missions such as Sentinel, PlanetScope, and Pléiades Neo play a crucial role in this context by providing new high-resolution data with shorter revisitation times compared to previous missions. This is a key advantage in the context of highly fragmented regions where the pixel sizes of medium-resolution imagery may not be small enough to reveal subtle habitat changes. Second, several satellite missions have begun to provide data under free open-access licences (e.g., Sentinel-2, Landsat). The third factor is the development of cloud computing platforms including Sentinel Hub, Open Data Cube, SEPAL, JEODPP, pipsCloud, OpenEO, and Google Earth Engine (Gomes et al. 2020). Combining the high-resolution open-access data available from new satellite missions with cloud computing platforms enables the application of complex algorithms detecting changes across very large areas (Woodcock et al. 2008). Among the mentioned cloud computing platforms, Google Earth Engine (GEE) is particularly suitable for monitoring habitat fragmentation at large scales. GEE combines a catalogue of satellite imagery and geospatial datasets with planetary-scale analysis capabilities (Gorelick et al. 2017) for aspects including forest change assessment (Hansen et al. 2013) and surface water extent and dynamics (Pekel et al. 2016). GEE has three key strengths compared to the other mentioned cloud computing platforms: The first is its flexibility allowing users to apply different algorithms to the data and use high-level programming languages and high-performance computing. The second is scientific reproducibility together with storage and process scalability. The final advantage is its processing performance, which can be scaled by adding more resources without users needing to alter their approach or code.

GEE has already implemented several algorithms relating to forest disturbance detection and exploiting the analysis-ready satellite data: (i) LandTrendr (Kennedy et al. 2012, 2018), (ii) Continuous Change Detection and Classification (CCDC; Zhu and Woodcock 2014), (iii) Exponentially Weighted Moving Average Change Detection (Brooks et al. 2014), (iv) Vegetation Change Tracker (VCT; Huang et al. 2010), and (v) the Verdet forest change detection algorithm (Hughes et al. 2017). Although some of these algorithms can use imagery from different satellite missions, they were all originally designed to work with Landsat data. Zhu (2017) and Francini et al. (2020, 2021) provide comprehensive reviews of these temporal segmentation algorithms, and a brief overview of the most commonly used remote sensing approaches for monitoring forest disturbances is provided in Box 9.1.

### Box 9.1 Key Remote Sensing Approaches to Monitoring Changes in Forest Cover

During the past decade, the two most commonly used remote sensing techniques worldwide with the capability to monitor changes in forest cover have been LandTrendr (LT) (Kennedy et al. 2010) and the Global Forest Change (GFC) data set (Hansen et al. 2013).

LT consists of a temporal segmentation approach that predicts changes by identifying breakpoints in trajectories of a photosynthetic index (like NDVI) calculated over several consecutive years from a Landsat imagery time series. It requires calibration of input parameters for each ecosystem (Hudak et al. 2013; Fragal et al. 2016; Yang et al. 2018). Because LT is based on yearly time-series analyses, accuracy decreases for extremes of the time series and for near past detection applications.

By contrast, GFC data is constructed using more than 600,000 Landsat scenes and a hierarchic classifier based on recursive partitioning. The data consists of annual global maps of tree cover extent, loss, and gain. GFC was used together with aerial images to analyse harvested sites in mountainous boreal forests in Norway, but up to 30% omission errors were reported (Rossi et al. 2019). GFC has also been proven inaccurate in Mediterranean coppice forests in Italy, with an average precision of about 50% (Giannetti et al. 2020). Despite these shortcomings, GFC was recently used by Ceccherini et al. (2020) to assess the temporal trend of forest logging in Europe; however, several limitations were discovered by Palahí et al. (2021).

Further remote sensing algorithms include Continuous Change Detection and Classification (Zhu and Woodcock 2014), Breaks for Additive Season and Trend Monitor (Verbesselt et al. 2012), and Space-Time Extremes and Features (Hamunyela et al. 2017), most of which are likewise Landsat-based algorithms at 30-meter spatial resolution. Recently, new methods have been implemented for predicting forest disturbances at finer scales using Sentinel-2 and PlanetScope imagery (Francini et al. 2021, 2022).

Predictions of forest biomass loss due to disturbance have been possible through the combination of maps based on remote sensing with data from the Global Ecosystem Dynamics Investigation (GEDI) sensor (Francini et al. 2023a). Finally, remote sensing data has proven effective not just for forest disturbance monitoring but also for the detection and estimation of afforestation areas (Cavalli et al. 2022). Measuring afforestation rate is a key aspect considering that forest area is increasing in several world regions and that afforestation represents the main land cover change in Europe (Palmero-Iniesta et al. 2021).

## Remote Sensing to Monitor the Impact of Habitat Fragmentation on Biodiversity

The rapid pace at which habitat loss and fragmentation occur worldwide is one of the main causes for the fast decline in species populations. In the 2022 IUCN global Red List, 28% of all assessed species were classified as threatened with extinction, belonging to the critically endangered, endangered, or vulnerable categories (www.iucnredlist.org). Within this context, biodiversity monitoring is a major concern in forest ecosystems, as they cover a third of the world's total land area and host a high species diversity amounting to three quarters of all terrestrial plant, fungus, and animal species (Forest Europe 2020).

In order to guide policies and management strategies for biodiversity conservation, regular, reliable, and standardized data on the state of biodiversity is required. Since the term 'biodiversity' encompasses the biological diversity of organisms in terms of composition, structure, and functionality all the way from genes to ecosystems, hundreds of variables can be measured to study it (Muys et al. 2022). The best indicator to measure biodiversity within an ecosystem, for example, would be the measurement of species diversity. However, since it is impossible to record all species present in an area, the use of readily observable, measurable, and quantifiable proxies and indicators is essential (McElhinny et al. 2005; Ozdemir et al. 2018).

Historically, the most commonly used indicators for assessing biodiversity fall into two main groups: habitat-based and taxon-based indicators (Paillet et al. 2024). The former represent environmental and structural variables considered to be proxies of the richness, composition, or diversity of species, while the latter are linked to the presence or abundance of indicator species (Lindenmayer et al. 2014). Although biodiversity monitoring using taxon-based approaches is more reliable for describing local species patterns, these monitoring methods still rely on traditional sampling methods and plot-level ground surveys. This means that they remain costly and time-consuming, especially when applied to large areas. Moreover, they require a lot of human resources and can easily be biased by human error, even when experts are involved in species identification (Wang and Gamon 2019). Among the habitat-based indicators, the monitoring of forest attributes related to forest structural complexity is certainly pivotal (Ćosović et al. 2020). These attributes include variability in canopy cover, tree diameter, tree height, and understory vegetation, which support the occurrence of diverse ecological niches for wildlife (Zellweger et al. 2013). Multiple studies have highlighted the existence of a link between forest structure and several groups of species (see Zeller et al. 2023 for a review), including vascular plants (Burrascano et al. 2008), bryophytes (Madžule et al. 2012), lichens (Moning et al. 2009), and wood-inhabiting fungi (Mazziotta et al. 2016) (Ruokolainen et al. 2018), birds (Herniman et al. 2020), insects (e.g., Parisi et al. 2023, 2024), and bats (Vogeler et al. 2022). For example, using a database of forest stands in southern Sweden, Hedwall et al. (2019) have found that the cover and species richness of understory vascular plants increased with an increasing proportion of birch and decreased with increasing forest density, while the cover of bryophytes decreased with an increasing proportion of birch and increasing forest density.

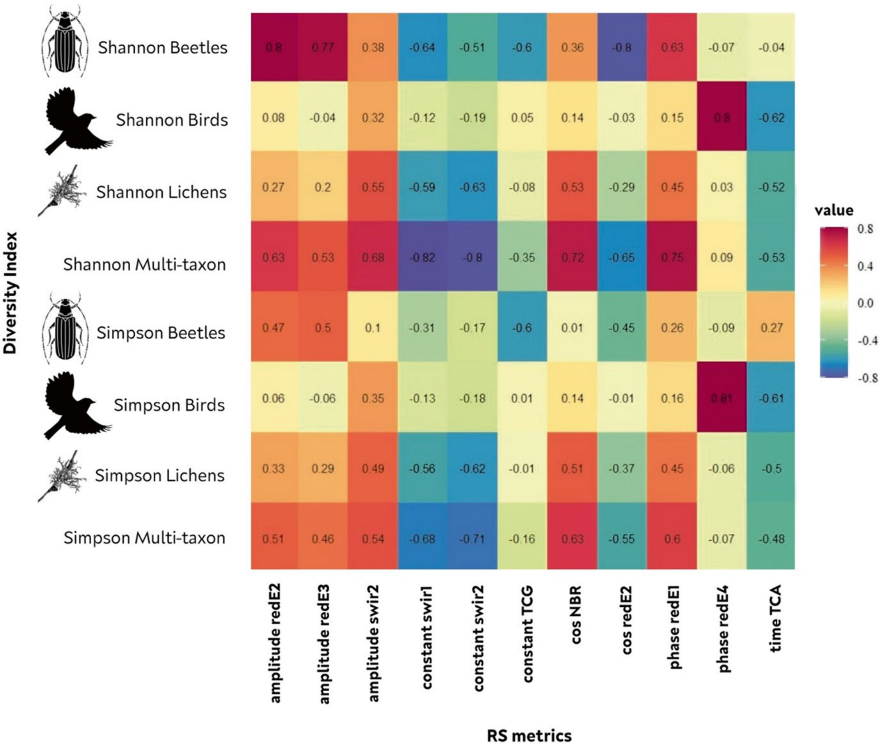
It is in this context that remote sensing can play a fundamental role in assessing habitat-based indicators of forest biodiversity at large scales (Fig. 9.2). Remote sensing represents a powerful and efficient instrument for monitoring forest characteristics and can efficiently support monitoring by providing open-access, up-to-date, and repeatable data that can be used to estimate and predict the abundance and diversity of different taxonomic groups at various scales of time and space (Parisi et al. 2022, 2024). One of the most important advantages of remotely sensed habitat-based indicators is that they are mapped 'wall-to-wall', meaning that they offer a continuous biodiversity assessment across the entire forest landscape (Ozdemir et al. 2018). The use of remote sensing techniques in biodiversity monitoring and mapping has only become more popular during the last three decades, with the first scientific studies regarding the topic emerging in the 1990s (Wang and Gamon 2019). Over this time, a variety of remote sensing sources ranging from passive—i.e. satellite imagery—to active methods like Light Detection And Ranging (LiDAR) have been developed and implemented.

Early uses of remote sensing in biodiversity assessment included landscape or habitat mapping through optical data (Wang and Gamon 2019). The sensors of the Sentinel-2 (ESA Copernicus programme) and Landsat (USGS/NASA) missions

**Fig. 9.2** Remote sensing facilitates biodiversity assessment by monitoring forest characteristics (Francesco Parisi)

allow the calculation of spectral indices (Kacic and Kuenzer 2022). In particular, vegetation indices such as NDVI offer information about canopy cover and tree species diversity (Arekhi et al. 2017). This data can be used for diversity monitoring following the spectral variation hypothesis, according to which greater spectral heterogeneity in an image corresponds to greater tree species richness on the ground (Ozdemir et al. 2018). For example, Parisi et al. (2023) have analysed time series for Sentinel-2 harmonic metrics to relate changes in NDVI remotely sensed via Landsat images with biodiversity indices for the taxonomic groups of beetles, birds, and lichens (Fig. 9.3). Graf et al. (2005) made use of LiDaR remote sensing to evaluate the availability of habitat of a forest grouse species (capercaillie) at multiple spatial scales.

Moreover, the implementation of LiDAR systems (Fig. 9.2) has expanded the range of data that can be remotely sensed (Wang and Gamon 2019). Especially in forest ecosystems, laser technology is a powerful tool for biodiversity monitoring as it can collect information and metrics regarding vegetation structure (Moudrý et al. 2023). Recently, Airborne Laser Scanning (ALS) (Fig. 9.4) performed using LiDAR sensors aboard aircraft has enabled simultaneous detection of both vegetation



| | amplitude redE2 | amplitude redE3 | amplitude swir2 | constant swir1 | constant swir2 | constant TCG | cos NBR | cos redE2 | phase redE1 | phase redE4 | time TCA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Shannon Beetles | 0.8 | 0.77 | 0.38 | -0.64 | -0.51 | -0.6 | 0.36 | -0.8 | 0.63 | -0.07 | -0.04 |
| Shannon Birds | 0.08 | -0.04 | 0.32 | -0.12 | -0.19 | 0.05 | 0.14 | -0.03 | 0.15 | 0.8 | -0.62 |
| Shannon Lichens | 0.27 | 0.2 | 0.55 | -0.59 | -0.63 | -0.08 | 0.53 | -0.29 | 0.45 | 0.03 | -0.52 |
| Shannon Multi-taxon | 0.63 | 0.53 | 0.68 | -0.82 | -0.8 | -0.35 | 0.72 | -0.65 | 0.75 | 0.09 | -0.53 |
| Simpson Beetles | 0.47 | 0.5 | 0.1 | -0.31 | -0.17 | -0.6 | 0.01 | -0.45 | 0.26 | -0.09 | 0.27 |
| Simpson Birds | 0.06 | -0.06 | 0.35 | -0.13 | -0.18 | 0.01 | 0.14 | -0.01 | 0.16 | 0.81 | -0.61 |
| Simpson Lichens | 0.33 | 0.29 | 0.49 | -0.56 | -0.62 | -0.01 | 0.51 | -0.37 | 0.45 | -0.06 | -0.5 |
| Simpson Multi-taxon | 0.51 | 0.46 | 0.54 | -0.68 | -0.71 | -0.16 | 0.63 | -0.55 | 0.6 | -0.07 | -0.48 |

**Fig. 9.3** Remote sensing supports detection of biodiversity patterns. Correlations between biodiversity indices of several taxa and the best Sentinel-2-derived temporal metrics (Parisi et al. 2023)

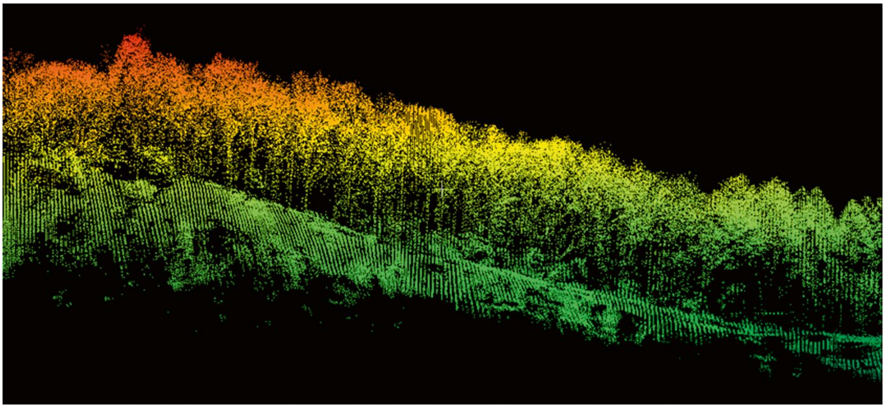


**Fig. 9.4** The term LiDAR is an acronym for Light Detection And Ranging and it refers to sensors used to capture point clouds from both static and mobile methods (https://geolabforest.com/)

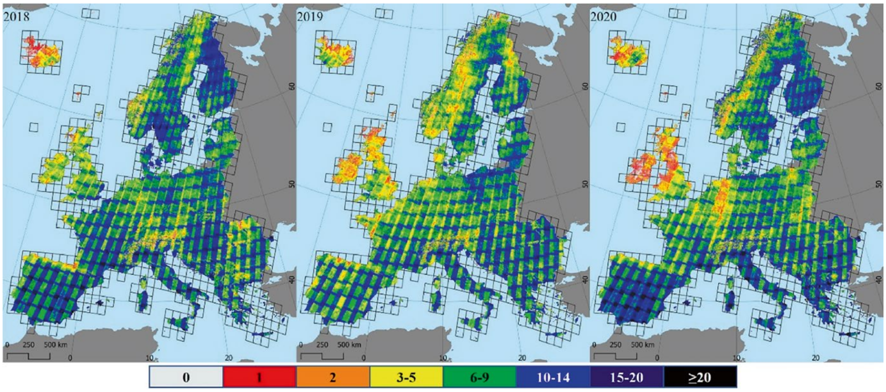


**Fig. 9.5** An example of temporal series from Remote sensing via Landsat-7. Number of per-pixel valid observations per analysis tile are reported (Francini et al. 2023)

biochemistry and structure, thus becoming the primary method for collecting accurate terrain and vegetation data across large areas (Moudrý et al. 2023).

Despite the important contribution of remote sensing to the habitat-based monitoring of biodiversity, Sabatini et al. (2016) found that indicators such as stand structural heterogeneity alone do not perform well for estimating overall landscape biodiversity. This is because different taxa respond to a particular set of structural variables in different ways due to their habitat requirements (Burrascano et al. 2023). Complementary use of habitat-based and taxon-based approaches is therefore necessary to enable comprehensive assessment of the status of biodiversity (Blasi et al. 2010; Burrascano et al. 2018) (Fig. 9.5).

In forest ecosystems, few existing studies have focused on combining measurements of habitat-based indicators based on remotely sensed vegetation indices with multi-taxon biodiversity assessments (Vogeler et al. 2022); instead, most research has been limited to individual taxonomic groups, such as vascular plants (Moudrý et al. 2023), birds (Alaniz et al. 2021), and butterflies (de Vries et al. 2021).

## Limitations of Monitoring via Remote Sensing and the Way Forward

To summarize, we have shown that remote sensing is an effective technique for detecting processes of landscape fragmentation as well as for evaluating changes in forest landscapes and consequent alterations to biodiversity patterns. It can be used at different spatial scales, is highly repeatable, and facilitates monitoring purposes as data can be easily compared over time. The recent advancements in terms of availability of high-resolution satellite images and global Landsat images (e.g., NASA Geocover dataset; Tucker et al. 2004) enable estimations of productivity using vegetation indices while simultaneously examining the relationships between these estimates and biodiversity indicators (Turner et al. 2015).

Despite the excellent opportunities offered by remote sensing and the long Landsat time-series data in particular, certain limitations should also be considered. First, the spatial resolution of Landsat is not adequate for capturing micro-spatial variations in the distribution of wood-dwelling species, which have poor dispersion capacity, making the Landsat data suitable only for monitoring biodiversity at large-scale resolution. Second, due to the well-known saturation effect of multispectral data, the Landsat sensor is not sensitive to multilayer canopy cover, dense forests, or complex topographic features (Chirici et al. 2020; Vangi et al. 2021; D'Amico et al. 2022) affecting NDVI values. Third, satellite data cannot fully explain biodiversity patterns since it only provides canopy-level information.

The integration of remote sensing approaches and ground monitoring activities within forest monitoring guidelines may overcome these limitations, helping to design and optimize monitoring strategies to tackle forest fragmentation and biodiversity loss in forest ecosystems. Although remote sensing data cannot replace fieldwork or identify individual species along with their rarity and composition, we assume that processing and analysing such data will become highly affordable in the future given the valuable insights provided by these images. In this regard, the availability of the GEE cloud platform allows an unprecedented view of forest areas worldwide.

In conclusion, despite the abovementioned limitations, the provided examples showcase that remote sensing data has great potential for supporting conservation planning and decision making in forest ecosystems. Remote sensing can help to identify hotspots for biodiversity and ecosystem services (de Araujo Barbosa et al. 2015) and even detect climate change refugia (Dubinin et al. 2018), thereby providing practical support for cost-effective biodiversity monitoring and nature-based forest management in complex silvicultural systems.

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