remote sensing

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Review

Remote Sensing of Forests in Bavaria: A Review

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Abstract: In recent decades, climatic pressures have altered the forested landscape of Bavaria. Widespread loss of trees has unevenly impacted the entire state, of which 37% is covered by forests (5% more than the national average). In 2018 and 2019—due in large part to drought and subsequent insect infestations—more tree-covered areas were lost in Bavaria than in any other German state. Moreover, the annual crown condition survey of Bavaria has revealed a decreasing trend in tree vitality since 1998. We conducted a systematic literature review regarding the remote sensing of forests in Bavaria. In total, 146 scientific articles were published between 2008 and 2023. While 88 studies took place in the Bavarian Forest National Park, only five publications covered the whole of Bavaria. Outside of the national park, the remaining 2.5 million hectares of forest in Bavaria are understudied. The most commonly studied topics were related to bark beetle infestations (24 papers); however, few papers focused on the drivers of infestations. The majority of studies utilized airborne data, while publications utilizing spaceborne data focused on multispectral; other data types were under-utilized- particularly thermal, lidar, and hyperspectral. We recommend future studies to both spatially broaden investigations to the state or national scale and to increase temporal data acquisitions together with contemporaneous in situ data. Especially in understudied topics regarding forest response to climate, catastrophic disturbances, regrowth and species composition, phenological timing, and in the sector of forest management. The utilization of remote sensing data in the forestry sector and the uptake of scientific results among stakeholders remains a challenge compared to other heavily forested European countries. An integral part of the Bavarian economy and the tourism sector, forests are also vital for climate regulation via atmospheric carbon reduction and land surface cooling. Therefore, forest monitoring remains centrally important to attaining more resilient and productive forests.

Keywords: remote sensing; earth observation; forest; Bavaria; bark beetle; Germany; review; climate change; drought; Bavarian Forest National Park

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1. Introduction

1.1. Forests in Bavaria

Bavaria, the largest state of Germany (Figure 1a), is characterized by temperate forests dispersed across the landscape. The southeasternmost state has an area of 70,550 km^2 and shares a border with the Czech Republic to the east and Austria to the south. The topography varies from rolling hills in the north, building into low-range mountains and the Bavarian Alps to the south, until reaching Zugspitze (2962 m), the highest peak in Germany (Figure 1b). Today, forests cover 37% of the land surface of Bavaria, the largest share of forest cover of all the federal states in Germany and greater than the national average overall [1]. Coniferous forests dominate the higher elevations (Figure 1e), particularly in the iconic Bavarian Forest National Park (BFNP) which lies on the eastern border (Figure 1d).

The annual climate of Bavaria follows a temperate continental pattern with cool, dry winters (−2 °C and less than 70 mm of precipitation on average) and warm, rainy summers (16 °C and more than 100 mm of precipitation on average) (Figure 1f) [2]. However, temperature and precipitation patterns fall along a gradient whereby conditions are warmer and drier in the northwest and wetter and cooler in the south toward the mountains [3]. Since the mid-1970s, there has been a notable climatic shift in Europe towards warmer, wetter winters, and hotter, drier summers [4], a trend which is predicted to continue [3]. This shift has been attributed to the consequences of increased atmospheric carbon dioxide from human activities [5].

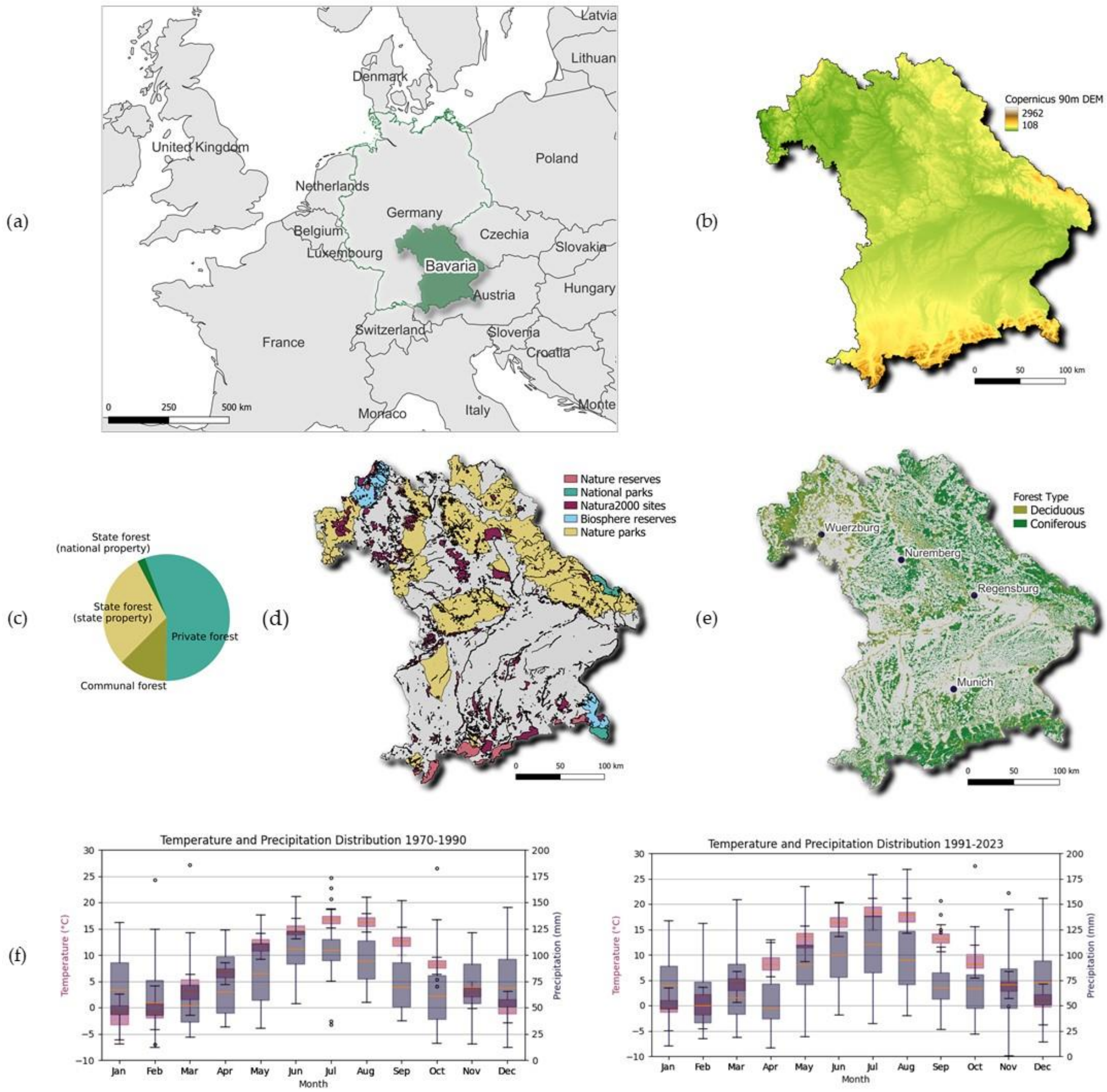

Figure 1. Bavaria is located in southeastern Germany, on the border with the Czech Republic and Austria (**a**). The elevation in Bavaria is highest in the south as low mountain ranges build into the Bavarian Alps (**b**). Slightly more than half of forests in Bavaria are privately owned (**c**). Bavaria has many protected nature parks and reserves, national parks, Natura2000 sites and Biosphere reserves (**d**) Reprinted/adapted with permission from Ref. [6] © Bayerisches Landesamt für Umwelt, www.lfu.bayern.de. Forests cover 37% of Bavaria (10 m 2018 Copernicus Forest Type) (**e**) [7]. The climate of Bavaria is shifting from cold and dry winters and warm, wet summers, towards warmer, wetter winters and hotter, drier summers (**f**) (temperatures in red, precipitation in blue) (source: Climate Data Center, Deutscher Wetterdienst, monthly averages 1970–1990, 1991–2023) [2].

Within Bavaria, forests are privately owned, communal, or state lands (Figure 1c) [8]. In either case a forest is defined by trees predominating an area of at least 0.1 hectares [9]. About half of private forests in Bavaria are smaller than 20 hectares; nevertheless, private forests make up more than half of the overall ownership types [10]. Among the state lands are two national parks (BFNP and Berchtesgaden National Park), many nature parks and reserves, a collection of 745 sites part of the Natura2000 habitat network (not all of which are forested or public), as well as two biosphere reserves (Figure 1d).

Four tree species dominate the forests; primarily the Norway spruce, followed by European beech (*Fagus sylvatica*), to a lesser extent, Scots pine (*Pinus sylvestris*), and oaks, namely sessile (*Quercus petraea*) and penduncluate (*Quercus robur*), among others. Species distribution typically follows an elevational pattern whereby coniferous species (particularly spruce) dominate in higher elevations, and deciduous species (beech and oak among others) dominate in the lowlands; meanwhile, in middle elevations, heterogeneously mixed forests of the two tree types are common. Non-forested areas comprise farmland, settlements, or transportation infrastructure with forests typically located on less productive soils or on steep terrain not suitable for agricultural activities [11]. Historically speaking, after the retreat of the last glacial maximum, it was initially pine and later oak which recolonized the landscape; finally, beech forests eventually dominated. However, in recent centuries, especially in the post-war years, spruce was selectively planted as it is fast-growing and economically valuable. This strategy was highly effective for the past 50–60 years, allowing Germany to recover its forest stock. However, a changing climate, particularly towards hotter and drier summer conditions, does not seem to favor the spruce [12,13].

The timber industry, largely based on spruce, is a sizeable part of the German economy [14]. In Bavaria, spruce accounts for about 40% of harvested wood [15]. Spruce was initially deliberately planted, while nowadays, spruce most often naturally regenerates year by year in large sections, especially throughout south and eastern Bavaria. However, forests are more than just economic assets. They are places of cultural and recreational significance which attract domestic and international tourists to Bavaria. The BFNP, for example, receives around 1.4 million visitors annually, while Berchtesgaden National Park receives around 1.6 million. The management strategy of the BFNP is largely without human intervention. Around 75% of the park area is deemed a 'natural zone', meaning the forest is left alone to recover from disturbances and regenerate naturally [16,17]. Management schemes typically vary across public forests and among private lands, depending on the owner and use intensity. Because of their careful management, Bavarian forests have continued to increase their biodiversity, ecosystem services, and economic functionality. Yet, there are still trade-offs amongst these services, which are also heterogeneously distributed across forests [18].

Forests are vital for climate regulation, and their preservation and enhancement are crucial for the mitigation of climate effects. Globally speaking, countries which have made climate pledges plan to utilize forests as a key strategy for reducing the levels of carbon dioxide from the atmosphere and cooling the land surface [19]. Furthermore, forests provide habitats and provisions like wood for building and food sources for people, as well as regulating our drinking water and lessening soil degradation. With the increase in atmospheric carbon dioxide and subsequent warming, forests are more important than ever. However, they are not a panacea. Healthy, intact, and biodiverse forests themselves can be resilient, but every living thing has its limitations.

1.2. Current Progress and Challenges in Bavarian Forests

The Federal Ministry of Food and Agriculture (BMEL) is tasked with monitoring German forests. Through the BMEL, the national inventory monitoring scheme is conducted every ten years, the outcome of which is compiled and reported. The most recent inventory in 2012 (the 2022 report is in preparation) revealed improvements to the forests of Germany as a whole. These improvements were measured in terms of 'naturalness', or the composition of tree species that more closely approximates the post-glacial condition (a higher proportion of deciduous species), and in terms of sustainability. The BMEL considers the ratio of the increment (how much biomass is grown) versus the harvest when approximating sustainable use. According to the last inventory, more wood was grown in German forests than was harvested, whilst the proportion of 'naturalness' has increased since the previous inventory was assessed [20]. Furthermore, tree species diversity, vertical structural diversity, deadwood area, the amount of land converted from especially unused agricultural areas into forests, and the size of minimum intervention areas have all increased under the strategy [21]. Updates to these results will be available upon the release of the 2022 national forest inventory.

The Bavarian State Ministry for Forests and Forestry (LWF) is responsible for monitoring the vitality of trees in Bavaria through an annual forest condition survey (*Waldzustandserhebung*, *WZE*). Crown condition and other visible tree damage is monitored using ground-based observations. In 2023, 25 foresters collected data on roughly 17,000 individual trees in the state of Bavaria. The results of the 2023 survey revealed that the thinning of crowns in both deciduous and coniferous tree types has increased since the previous report. These results follow a long-term trend (since 1998), whereby not only does the vitality of trees decrease year by year, but it also decreases more severely in summers following a drought in the previous year. This trend is more apparent in the northern parts of Bavaria, most notably in Franconia, than in the south. Although all of the major species were affected, beech and oaks were hit particularly hard. A common sign of drought stress is the increase in fruitification in beech trees. This process indicates an especially dry summer in the previous year, a trend which has been observed over many years [22].

In recent years, the forests of Bavaria have come under increasing pressure due to climate impacts. The result has been not only the thinning of crowns and decrease in vitality reported by the WZE, but the total loss of thousands of hectares. Bavaria was the most affected state in Germany in terms of area of canopy cover loss in 2018 and 2019 [23]. Although these losses affected many species, the hardest hit has been the Norway spruce (*Picea abies*). While drought-stressed trees are more susceptible to pest infestations, insects like the European spruce bark beetle (*Ips typographus*) prefer fallen dead trees (hereafter lying deadwood) until their population reaches a threshold whereby attack of live trees becomes possible [24]. Meanwhile strong winds during storm events can flatten parts of or entire stands, thus not only dramatically altering parts of the Bavarian landscape, but also providing new habitat for insects. This can become a feedback loop whereby lying deadwood can further support wood-burrowing pests like bark beetles [25]. These effects persist despite national efforts to enhance forests following a comprehensive and data-driven sustainable forest management scheme. Although this management strategy has brought about positive change in German forests [20], natural disturbances seem to outpace the efforts of the forestry sector.

1.3. Remote Sensing of Forests

Monitoring forests is crucial for understanding and taking advantage of their role in a changing climate. Traditional on-the-ground methods are highly accurate; however, these are extremely time- and personnel-intensive [26]. Parameters which can effectively approximate these in situ measures can be by comparison cheaply and quickly applied to very large spatial scales using space- or airborne remote sensing (RS). In terms of measurements, many effective proxies have been developed over time, e.g., spectral vegetation indices (SVIs). The use of these two strategies of measurement in combination is a concept often tested in RS forest applications. Thus, the supplementation of ground-based forest parameters tends to increase the effectiveness of RS [27]. Meanwhile, spatial and temporal resolution, especially from satellite-derived sensors, has markedly improved.

Forests were a key target of early RS. The capabilities of sensors to capture ground parameters has been tested experimentally for more than three decades [28]. In the case of Bavaria, RS has been applied to forests in scientific disciplines but less so in practical applications such as forest management [29]. Until the forthcoming 2022 inventory, RS has not been an integral part of the national inventory monitoring scheme of Germany as a whole [30]. However, airborne RS surveys have been integrated into forest inventories of the BFNP since 1988 [26]. In the case of the highest resolution freely available multispectral datasets, e.g., the 10 m Sentinel-2 series from the European Space Agency, wall-to-wall data can be captured over the entire state of Bavaria in less than one week, assuming cloud-free conditions [31].

Remotely sensed data can provide insights in terms of forest leaf emergence and senescence, species composition and regeneration, vitality and health of trees, forest structure and biodiversity, the impact of storms, drought, fire, and other disturbances such as insect infestations, among many other applications. Additionally, although the field is well established, RS is an under-utilized tool across the forests of Bavaria. The eight commonly established research areas of forest RS are summarized below [11,29]:

- Monitoring/Management (Figure 2A) aims to link ground-based national inventory data to remotely sensed data for large-scale mapping of parameters such as standing volume, mean and dominant height, and forest type. Field data can include metrics like stem position and diameter at breast height (DBH), a measurement used to approximate age classes.
- Disturbance (Figure 2B) includes both catastrophic events such as storms and the knock-on effects of for example drought. In this review, the drought topic is treated as a disturbance based on the catastrophic drought events of recent years. This research topic often also looks into quantifying the effects of forest disturbances over time.
- Leaf trait research (Figure 2C) aims to look at the small-scale traits of leaves, such as chlorophyll content, and link this to a remotely sensed parameter which can then be extrapolated to a stand or forest. This is especially useful for understanding the vegetation condition on a large scale.
- Biodiversity/Habitats (Figure 2D) is a field closely related to ecology, aiming to use data from RS of forests as a covariate for modelling a species- or taxa-specific habitat within a forest.
- Forest structure (Figure 2E) investigations take an interest in vertical or horizontal structure, meaning canopy heights and structural complexity, sometimes as a proxy for diversity or habitat. In this field, synthetic aperture radar (SAR) or lidar data are often employed.
- Phenology (Figure 2F) concerns the timing of leaf emergence and senescence at the start and end of the growing season, respectively.
- Forest type/Cover (Figure 2G) focuses on classifying tree species and the area forests cover, or changes therein.
- Biomass/Productivity (Figure 2H) concerns the growth, or increment, of forests which can be related to soil health and/or management schemes. This can also be used to inform practitioners about the biomass available for harvest.

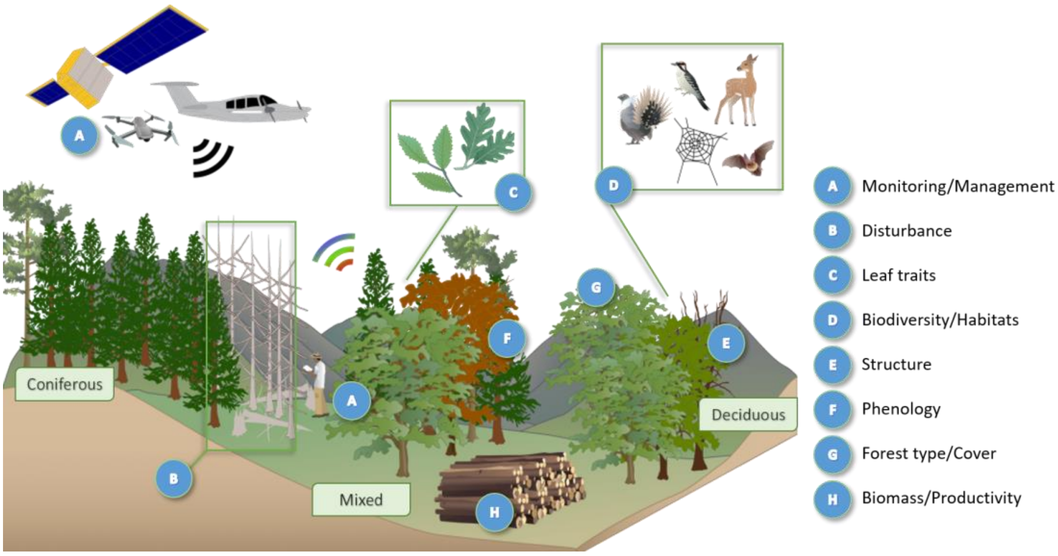

Figure 2. Common research areas for remote sensing of forests. Adapted graphic elements are courtesy of the University of Maryland (Center for Environmental Science, Integration and Application Network) Media Library, CC BY-SA [32].

It is worth noting that many of these topics overlap amongst themselves and with other emerging or experimental topics.

1.4. Aim

The aim of this investigation is to review the scientific literature concerning the RS of forests in Bavaria broadly. The need for this topic has emerged from the results of reviews conducted at a national scale [11,29]. Bavaria is a large and heavily forested state, with forests covering more area than the national average. An understanding of research gaps in this field in Bavaria will support future research at a time when large-scale understanding of forests and the impact and effectiveness of forest management schemes is increasingly crucial.

Scientific outputs are often unintentionally restricted to use within academic communities, thus partitioning the knowledge away from the potential end-user base of stakeholders. This effectively limits the potential applicability of RS knowledge towards real-world solutions for forest use and management. It is our hope that the intensification in applicable and broadly accessible work will foster the partnership and uptake of relevant scientific results in the community of end-users, including: forest owners, managers, and decision- or policymakers.

2. Materials and Methods

We conducted a literature search using the Web of Science (WoS) platform. Using the advanced search function, we constructed a conditional search string filtered by 'topic' with three primary categories: geographic location (Bavaria), topic (forest), and field of study (remote sensing) (Figure 3). Within each category, we used Booleans to specify our search conditions. We also restricted our search to journal articles written in English and the time period from 2000 to 2023. The last date of our article retrieval was 4 January 2024. Therefore, the search period considered all of the articles published within the final year of our review (2023). We utilized so-called 'wildcards' (* and ?) to allow for spelling variations. For example, 'fragment*' will return results related to 'fragment', 'fragments', and 'fragmentation', while 'Ha?berge' would return 'Hasberge' or 'Haßberge', which is useful for German spellings. Furthermore, some articles were identified from previous reviews and were not captured by our search string. This occurs when the search terms are not contained within the title, abstract, and keywords, but are nevertheless relevant for our review. These articles were added manually after the search results were filtered by abstract and exported from Web of Science. Our final paper selection, therefore, consists only of relevant papers which met our conditional criteria. In the following section, we summarize each parameter of the search string. For reference, the full search string is presented in Table S1 of the Supplementary Materials.

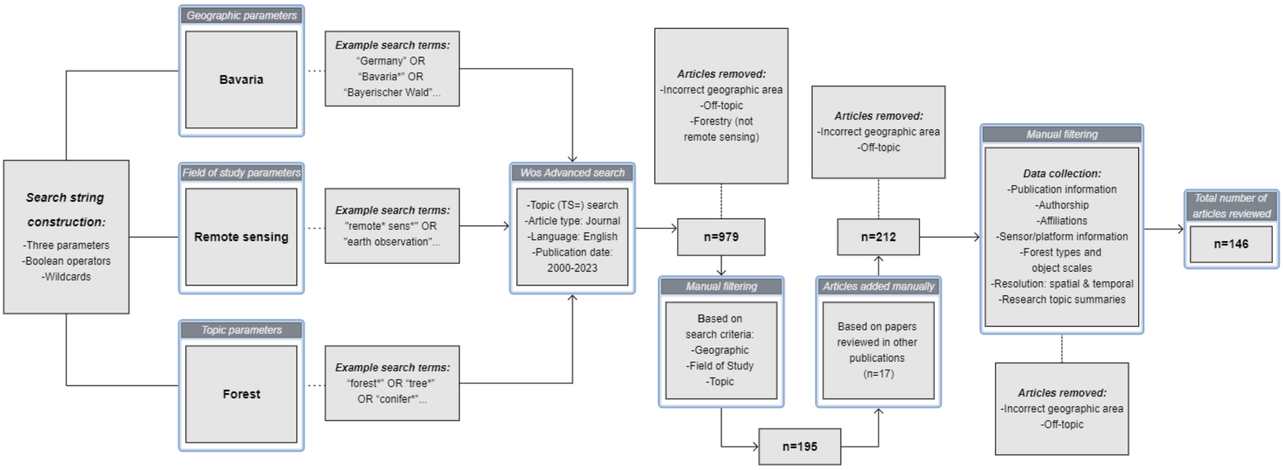

Figure 3. Web of Science search methodology. We utilized so-called 'wildcards' (* and ?) to allow for spelling variations of search terms.

Within the 'geographic location' category, the search terms included the German federal state of Bavaria. In order to capture as many relevant articles as possible, we also included increasing and decreasing spatial scales in case of studies conducted at the national or continental level which covered Bavaria, and by the same token, smaller-scale studies within Bavaria that might only include local geographic names such as parks or reserves. To ensure this, we included names of all national parks, biosphere reserves, nature reserves, and ForestGEO sites in Bavaria. The 'remote sensing' field of study category was constructed to capture any study utilizing satellite, airborne, or unmanned aerial vehicle (UAV) studies. We did not included studies which solely relied on terrestrial laser scanning (TLS) as a data source. Finally, the 'topic' category focused on forests. In order to capture more articles, we also included species-specific and forest type terms in our search.

The data collected in this review were based on other literature review publications in similar fields. A list of the data collected for this review can be found in Table S2 of the Supplementary Materials.

The WoS query captured a total of 979 articles containing the search terms outlined in our methodology from 2000 to 2023. We read each abstract and selected only those articles which matched our search parameters. However, many articles were irrelevant either because of the study area, the topic, or the field of research. For example, studies which took place in Baden-Wuerttemberg are located in southern Germany but not Bavaria. These papers were not included. We experimented with variations of the search string to reduce erroneous search results. Although many articles were deemed irrelevant, the broad search terms captured the highest number of appropriate articles for our investigation.

After a review of the relevant abstracts, 195 articles were found to be suitable (matching our topic, geographic region, and field of study) for the thorough review process and were exported. We added 17 additional papers which were identified through other previous reviews of similar topics [11,29]. Finally, we read each article and collected the data presented in this section. Overall, our literature search contained 146 total articles which covered the topic of remote sensing of forests in Bavaria. Because there were no remote sensing studies of forests in Bavaria prior to 2008, this review will present papers published from 2008 onwards. All figures were created using the matplotlib, numpy, pandas, and plotly packages in Jupyter Lab (version 4.0.6) with python (version 3.10.12).

3. Results

Here we present the sub-sectioned results below, beginning with the number of papers published over our study period together with the journal and author summaries (Section 3.1), followed by the study location (Section 3.2), and study area size (Section 3.3) summaries. With these background contexts established, we present the data platform and sensor usage (Section 3.4), the temporal resolution and in situ data summary (Section 3.5), followed by the forest type (Section 3.6). Furthermore, we present object scales investigated within the context of data resolution and trends (Section 3.7). Finally, the overarching research topics and sub-topics are then presented within the context of the aforementioned Section 3.8.

3.1. Number of Papers Published, Journal Summary, and Author Summary

RS investigations of forests in Bavaria began in 2008. Until 2014, there were fewer than ten papers published each year. Publications increased steadily until 2018, the year with the highest number of papers published (n = 21). After 2018, we saw a decreasing trend with a small increase in 2020 and a decreasing number of papers in the years afterwards (Figure 4). In 2023, eight papers were published.

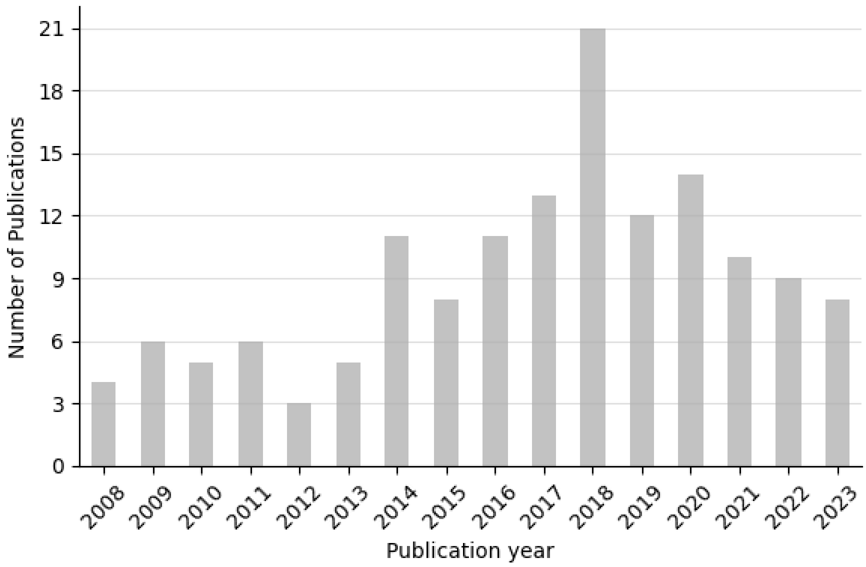

Figure 4. Number of publications per year.

There were 51 unique journals which published the articles examined within this review. Of these, 21 journals published two or more articles and are visualized together with the research topic in detail in Figure 5. The remaining 30 journals published only one article each and have been combined into the category 'Other'. The most common journals were *Remote Sensing* followed by *Remote Sensing of the Environment* and the *International Journal of Applied Earth Observation and Geoinformation*. Articles published by *Remote Sensing* covered all topics excluding 'Biomass/Productivity' while articles published by *Remote Sensing of the Environment* excluded this topic in addition to 'Monitoring/Management'. Articles published by the *International Journal of Applied Earth Observation and Geoinformation* also excluded 'Monitoring/Management' in addition to 'Biodiversity/Habitats' and 'Disturbance'. The remaining journals covered more specific topics. Research areas will be discussed in greater detail in Section 3.8.

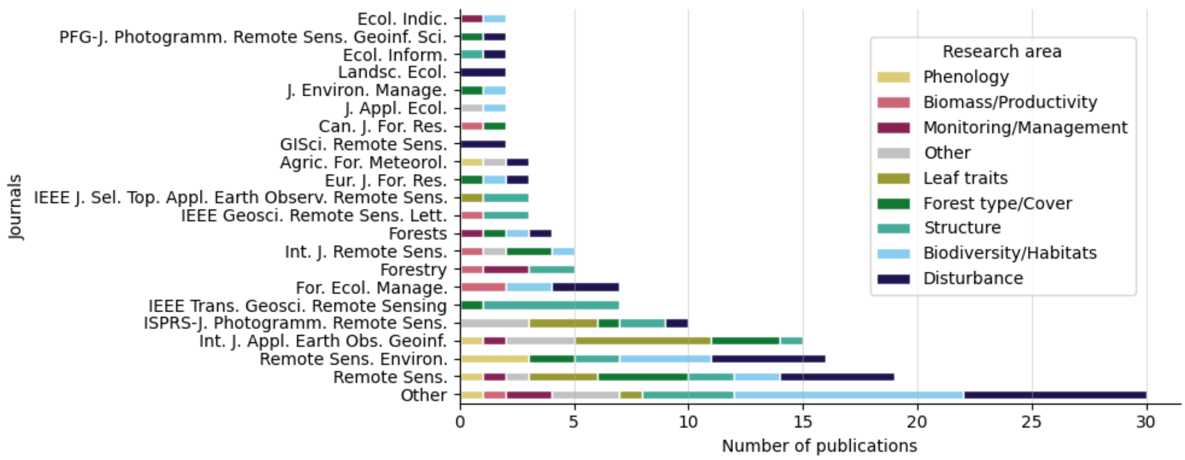

Figure 5. Journals which published two or more articles. Those journals which have published only one article are combined into the category 'Other'.

A total of 96 unique researchers had first authorship articles in our review. There were 28 authors who had one first authorship each. Sixteen researchers had two first authorships each, six researchers had three first authorships each, two authors had four first authorships each, and four were published as the first authors of five papers each (Table 1 (a)).

Table 1. First authors (a) and co-authors (b) showing the number of publications each.

	Number of Authors	First Authorships Each		Number of Authors	Co-Authorships Each
	28	1		253	1
	16	2		74	2–3
(a)	6	3	(b)	27	4–7
	2	4		8	8–13
	4	5		1	23
				1	52

In terms of co-authorships, 364 individual researchers co-authored articles in our review. There were 111 authors who had more than one co-authorship in the field. A total of 10 researchers had 4 co-authorships each, 8 researchers had 5 co-authorships each, 6 authors published 6 papers each, 3 published 7 papers each, with the remaining 10 researchers co-authoring 8, 9, 10, 11, 12, 13, 15, 19, 23, and 52 papers each, respectively (Table 1 (b)).

First authorships were affiliated with a global distribution of institutes in 21 countries (Figure 6). We summarized the publications from each country based on the number of papers an affiliated first author published. Germany had the highest number of affiliated publications at 86, followed by the Netherlands (17), Austria (8), China, (5), the Czech Republic, Switzerland, and Australia (3), and Italy (2). The remaining countries had one publication each from affiliated first authors; these are summarized in Table 2.

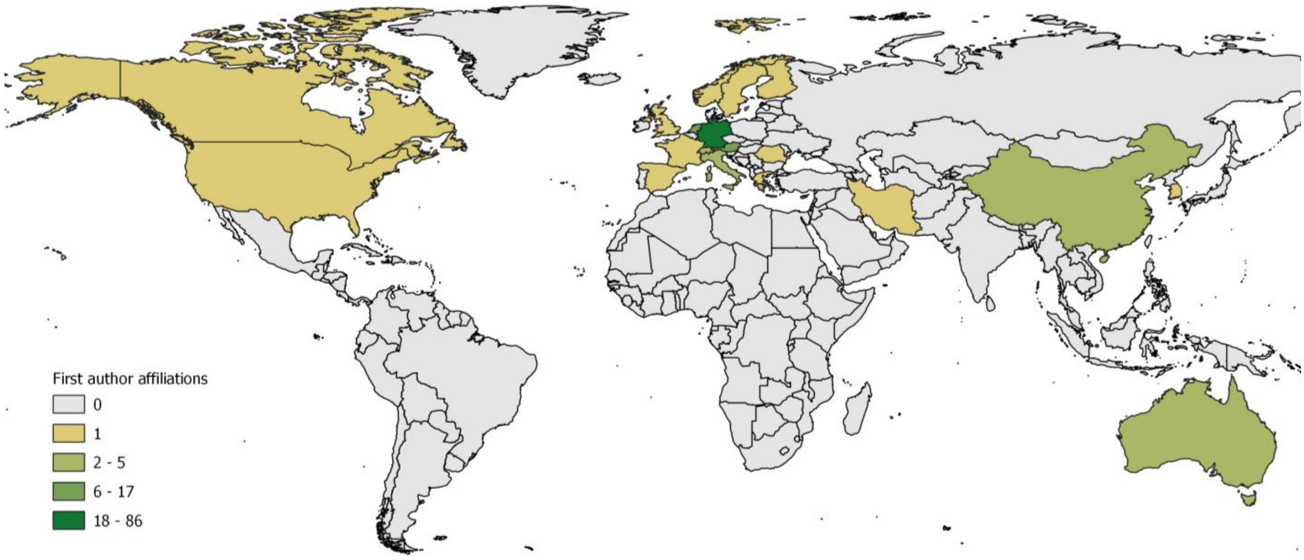

Figure 6. The distribution of first-authorship-affiliated institutes.

Table 2. Countries with publications at affiliated institutes.

Affiliated Institute Country	First Author Affiliations
Germany	86
Netherlands	17
Austria	8
China	5
Czech Republic, Switzerland, Australia	3
Italy	2
Iran, Sweden, South Korea, Hong Kong, Norway, United Kingdom, Canada, Finland, Romania, Greece, United States, Spain, France	1

3.2. Study Locations

There are seven administrative regions (*Regierungsbezirke*) in the free state of Bavaria. Forest cover, species composition, and management schemes differ in each region. There were 18 unique study sites within Bavaria (Figure 7). The most commonly studied area of interest (AOI) was the Bavarian Forest National Park (BFNP), which was the location of 88 studies in our review. The Traunstein forest, which is part of the global ForestGEO network, was the second most popular AOI with 19 studies, followed by Berchtesgaden National Park, which was the AOI for five papers in our review, while the Steigerwald forest was the AOI in four studies. The following AOIs were investigated in two or fewer papers: Rhon Biosphere Reserve (2), Frankenwald (2), Angelberger forest (2), Munich (2), Altoetting (2), Ebersberger (2), Coburg (1), Spessart (1), Nuremburg (1), Freisinger (1), Passau/Freyung-Grafenau (1), Landsberg (1), Kaufbeuren (1), Kranzberg forest (1), and Taubenberg (1). The entire state of Bavaria was covered by five studies, while the whole of Germany and Europe (where AOIs were located within Bavaria) were investigated in nine and two papers, respectively, with two studies not specifying an AOI. In terms of the overall number of studies and unique AOI locations, 89 studies within two AOIs were located in Lower Bavaria (Niederbayern), 34 studies among 9 AOIs were located in Upper Bavaria (Oberbayern), 5 studies within two AOIs were located in Middle Franconia (Mittelfranken), and 3 studies among two AOIs were located in Upper Franconia (Oberfranken), Lower Franconia (Unterfranken), and Swabia (Schwaben), while no studies were conducted in Upper Palatinate (Oberpfalz).

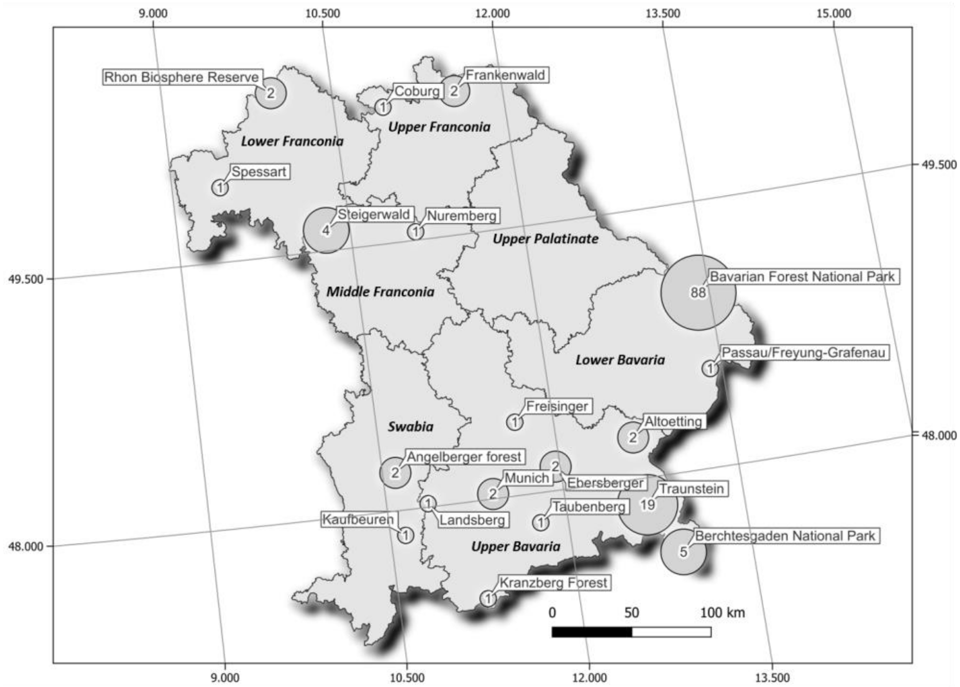

Figure 7. Study locations within Bavaria. Five studies covered the whole of Bavaria while nine studies covered Germany and two studies covered Europe with study sites in Bavaria (not pictured). Two study sites were not specified.

The distribution of research topics among the AOIs was varied. Because the BFNP was the site of the majority of investigations, it was covered by all of the topics identified in the review, however unequally. Topics investigated in each of the AOIs are visualized in Figure 8 and will be discussed in detail in sub-Section 3.8.

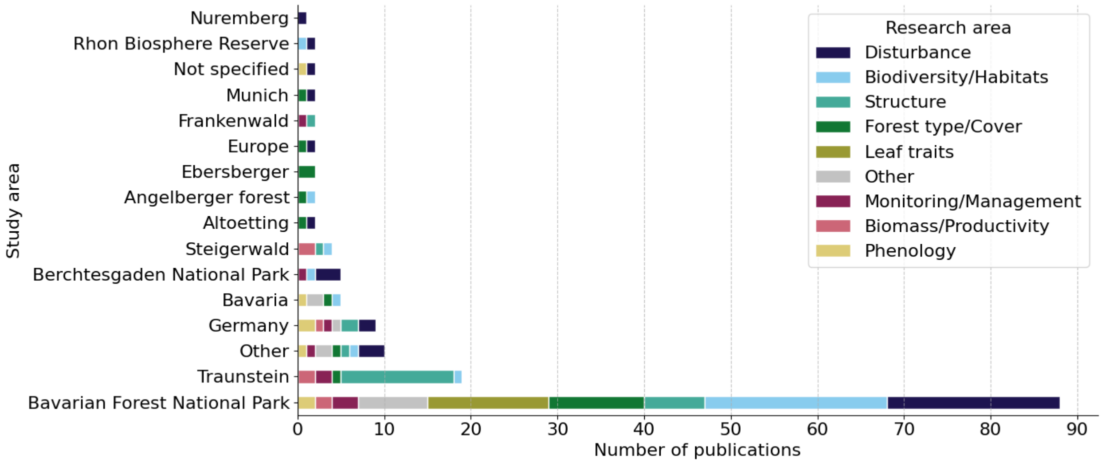

Figure 8. Area of interest (AOI) and the respective research topics investigated there.

3.3. Study Area Size

The BFNP covers approximately 25,000 hectares and is located on the border of Germany and the Czech Republic in southeastern Bavaria. About half of the studies in this review constituted AOIs smaller than the BFNP, with five papers focused on the entire state of Bavaria; nine and two studies covered Germany and Europe, respectively. Most of the studies which were smaller than the overall size of the BFNP nevertheless took place within the BFNP. Throughout the study period, many studies did not specify the AOI size, and while there is a slight increase in larger more regional study AOIs over time, more than half of studies in 2023 were in AOIs smaller than the BFNP (Figure 9).

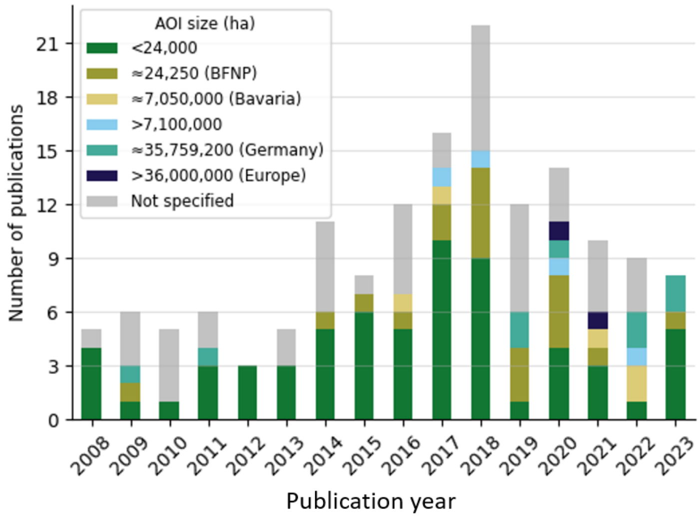

Figure 9. The trend of AOI sizes throughout the review period.

Among studies with known AOI sizes, the data platform selection tends to be related to the size of the study area (Figure 10). Airborne data tend to have a higher spatial resolution and lower temporal resolution and thus lends itself toward studies of a smaller spatial scale. For example, the BFNP in partnership with the German Aerospace Center (DLR) conducts flight campaigns to collect airborne high-spatial-resolution data, which are often used in RS studies of the park. Therefore, most of the AOIs which are smaller than the BFNP utilize airborne data. Studies which covered the whole of the BFNP utilized airborne and spaceborne data in nearly equal amounts. Conversely, spaceborne data, while less commonly used in smaller spatial scale studies, are used exclusively in studies investigating forests at the spatial scale of Bavaria or larger. Most of the studies which did not specify an AOI size used airborne data. There was one study which utilized UAV data and one study which created a dataset of simulated lidar points over the whole of Bavaria.

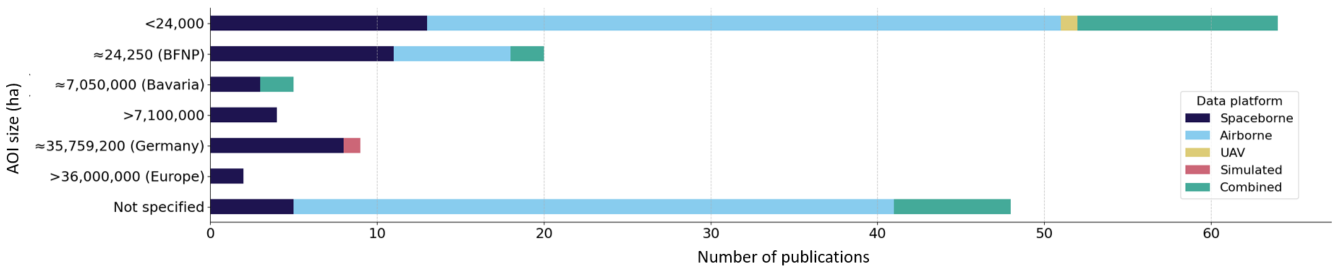

Figure 10. The size of the AOI in relation to the data platform.

3.4. Platforms and Sensors

We found that six AOIs were investigated using data both from spaceborne and airborne platforms, while one study utilized a simulated lidar dataset which covered the spatial extent of Germany and one study utilized UAV data for a study site outside of Nuremberg. (Figure 11a). Although airborne data have been predominantly used to investigate forests in Bavaria, particularly in the BFNP, over time more spaceborne data and studies which utilized data types used in combination tended to increase over time (Figure 11b). In the last two years (2022 and 2023), spaceborne data were used in more than half of these publications. The category of 'combined' data types refers to spaceborne and airborne used together within the same study. The highest number of publications utilizing combined data was in 2018.

(a)

(b)

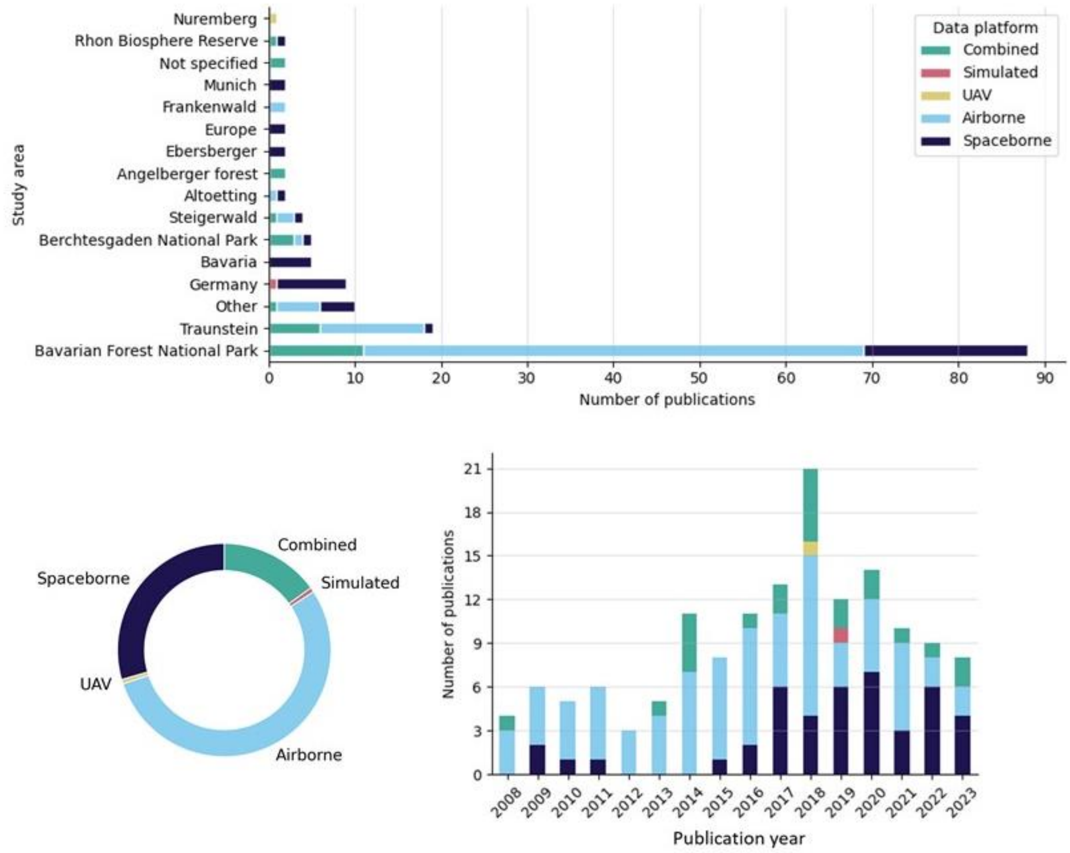

Figure 11. Data platform usage in terms of study area (**a**). The trend in data platform usage throughout the review period (**b**).

Sensor type varied by data platform. Among spaceborne sensors, multispectral data were predominantly used, specifically those from Landsat (22 studies) and Sentinel (20 studies) (Figure 12a). MODIS was utilized in 13 studies, while RapidEye, SPOT, WorldView-2, QuickBird, Planet, and AVHRR data were used by fewer studies. Synthetic Aperture Radar (SAR) data were used in 9 studies, mostly from TerraSAR-X and/or TanDEM-X. The remaining data types, namely stereo images, thermal infrared, lidar, and orthophotos, were used in three or fewer papers.

By contrast, among the airborne sensors, lidar was the most commonly used data type, utilized in 69 studies. (Figure 12b). Color infrared (CIR) images were used in 23 papers; however, the majority of studies did not specify the sensor. Hyperspectral data from the HySpex and HyMap sensors, a datatype not utilized by spaceborne platforms examined in this review, were used in 13 studies. SAR data were used in 10 publications; the sensor in these cases was the E-SAR or F-SAR from the DLR used primarily in tomographic applications over the Traunstein forest. Orthophotos, stereo and multispectral images, and other optical data were utilized in fewer than ten studies each. Two publications did not specify a sensor; however, they did specify the airborne platform.

Most studies used one sensor, independent of data platform, for their investigations. However, a growing share of papers utilized two or more different sensor types, e.g., multispectral and lidar. Two studies combined more than three sensors, but this was not the norm; instead, these two studies focused on the methodology of sensor comparison in the context of forests. Of the eleven studies which utilized three sensors, five were investigating topics related to forest disturbances. The use of more than two sensors appears to be increasing in recent years without a definite trend. The year with the most publications, 2018, also had the highest share of studies which used two or more sensors; however, in the most recent year examined (2023), just one study utilized two sensors. The majority of studies utilize data from one sensor.

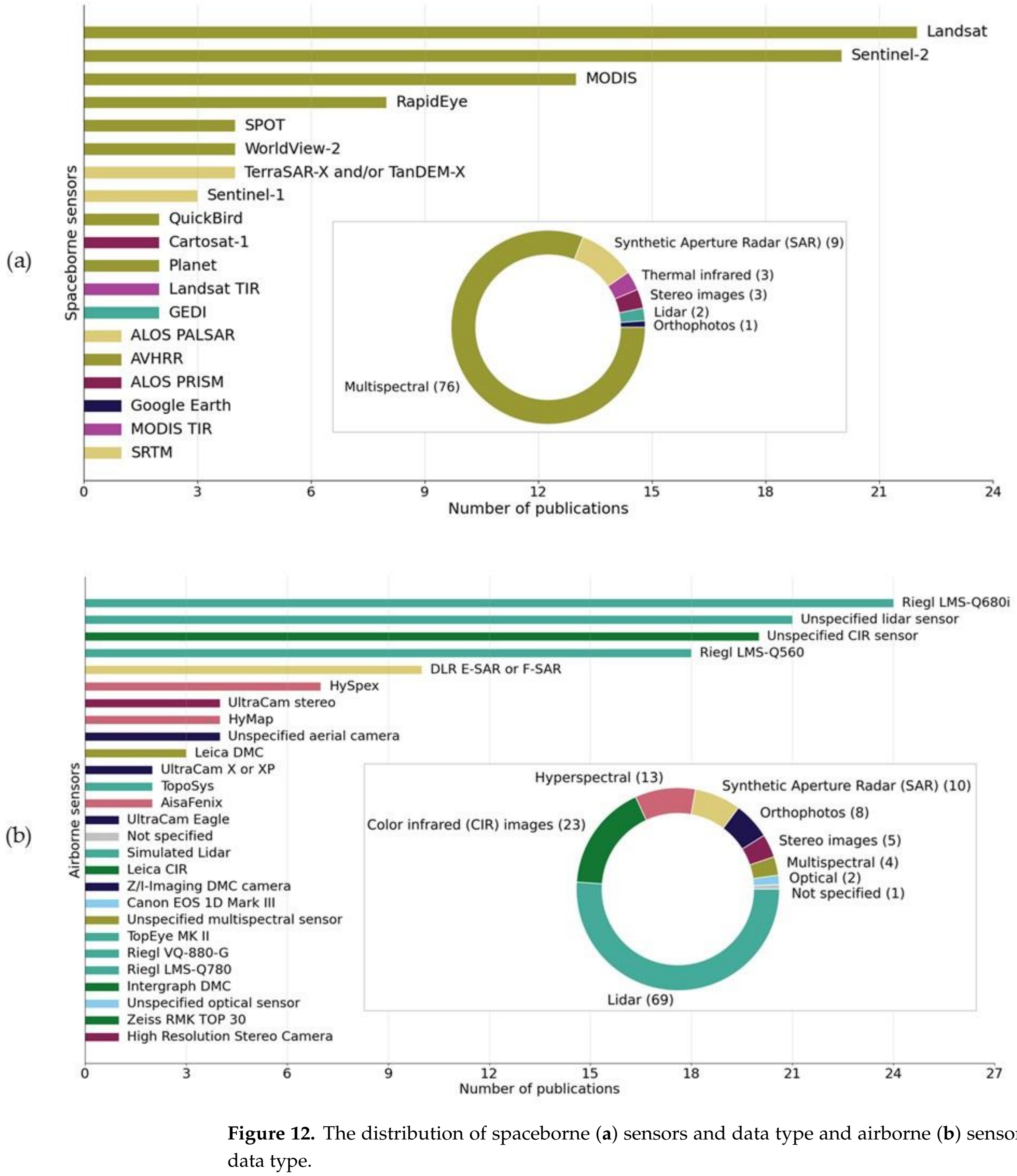

Figure 12. The distribution of spaceborne (**a**) sensors and data type and airborne (**b**) sensors and data type.

Data type and platform also varied according to the research area studied (Figure 13). Among the spaceborne sensors, the most common topic was ‘Disturbance’, which was investigated using multispectral, thermal, orthophotos, and SAR data. Among the studies which utilized spaceborne data, all of the topics were investigated at least three times using multispectral data, and three topics (‘Monitoring/Management’, ‘Phenology’, and ‘Leaf traits) were investigated solely using multispectral data.

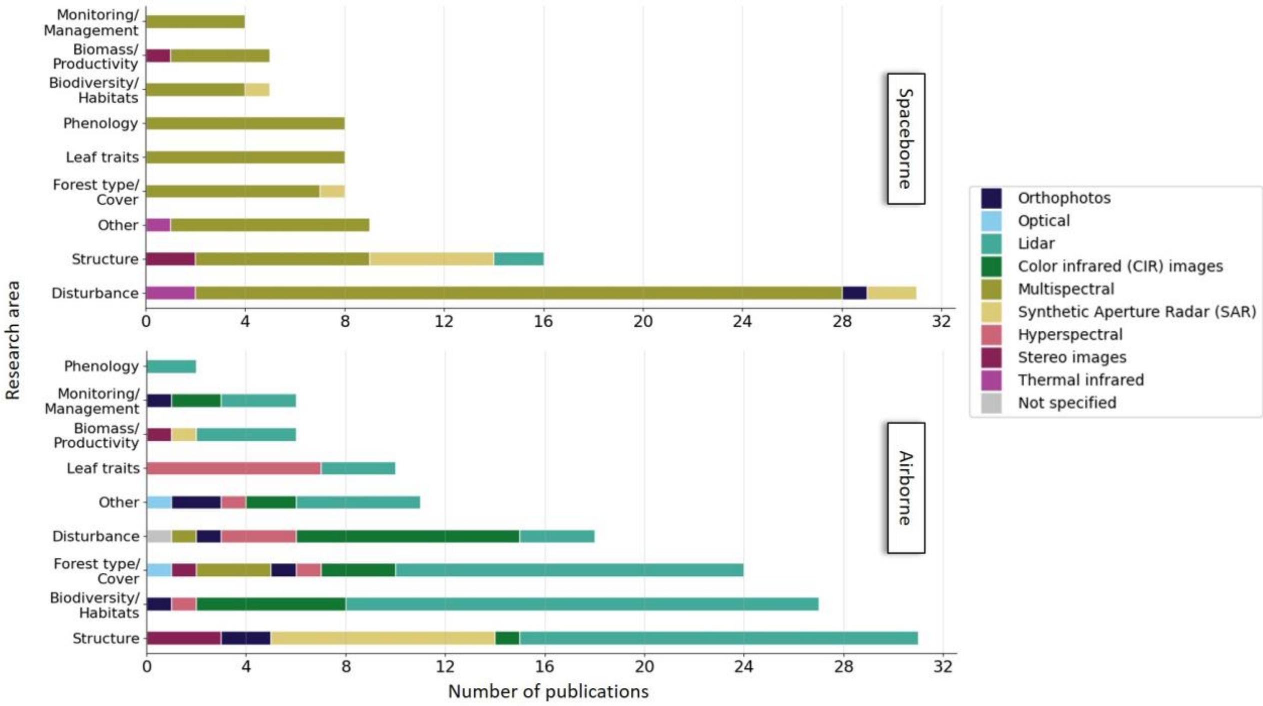

Figure 13. The type of data and platform used in each of the research topics.

Among the studies conducted using airborne data, the data type had a higher variation within the topic investigated. Three topics ('Disturbance', 'Forest type/Cover', and 'Structure') were investigated using six different types of data, while 'Phenology' was investigated using a combination of airborne lidar and spaceborne multispectral data in two publications. The topic of 'Leaf traits' was investigated mostly with hyperspectral data among users of airborne-derived data, while the same topic was investigated with multispectral data among studies conducted with spaceborne data. It is important to note that 18 publications utilized data from more than one spaceborne sensor and 26 publications utilized data from more than one airborne sensor in the same study. Figure 11 details the usage of combined sensors and platforms.

3.5. Temporal Resolution and In Situ Data

There were four temporal resolutions utilized by investigators in this review. Mono-temporal studies used data from a single acquisition, whereas multi-temporal studies utilized multiple acquisitions within the same year. Multi-annual studies acquired data once per year for more than one year, while multi-annual and multi-temporal studies utilized data which were acquired multiple times a year over the course of two or more years. The four resolutions were utilized relatively equally among spaceborne data types, while mono-temporal data acquisitions were used predominantly among airborne data users (Figure 14). There was a relatively even distribution of mono-temporal and multi-annual studies throughout the study period. However, the trend for studies which used data either multi-temporally or multi-annually and multi-temporally has increased in the years since 2017, with relatively few in the early part of the study period.

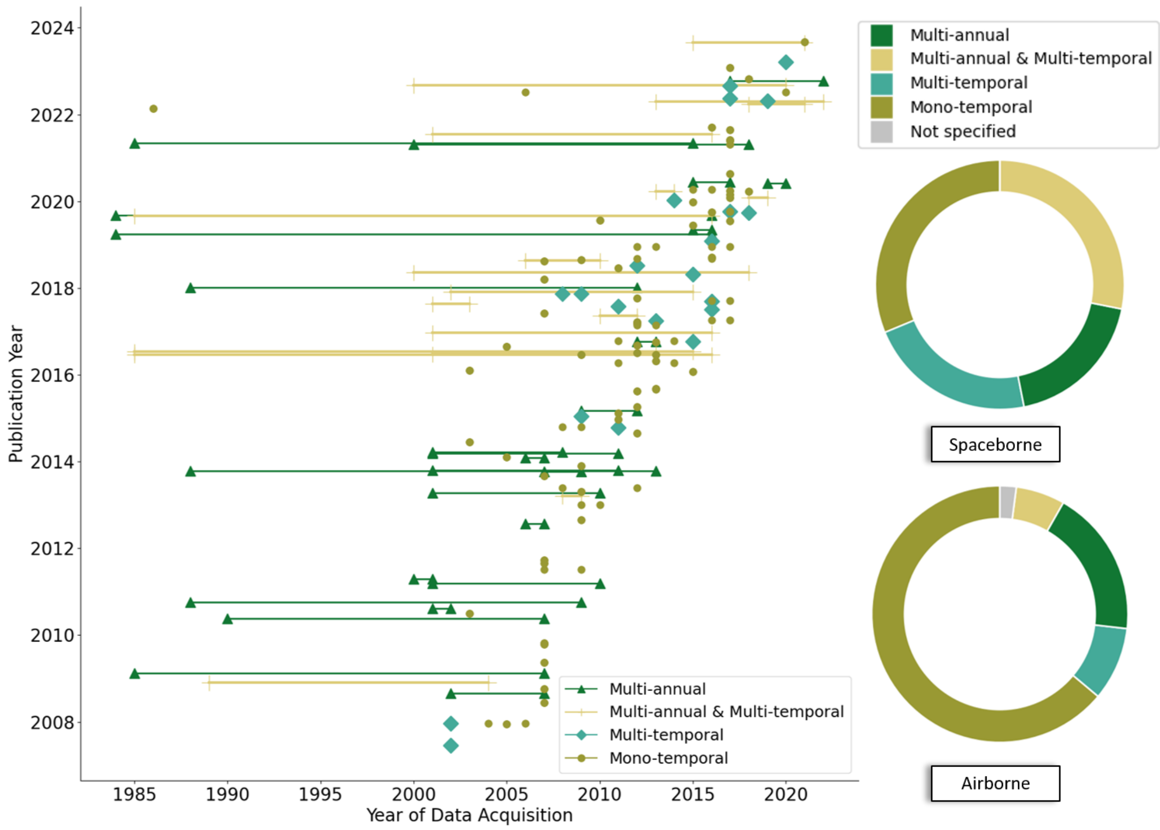

Figure 14. Temporal resolution and data platform.

In terms of monthly data acquisitions, investigators selected data within the growing season predominantly, i.e., May–August (Figure 15). However, studies which acquired data for multi-annual and multi-temporal studies also utilized more data relatively evenly throughout the leaf-off months as well (January–April and September–December). Although most studies accounted for temporal resolution within the Methodology section, 24 studies did not specify during which months the RS data were acquired.

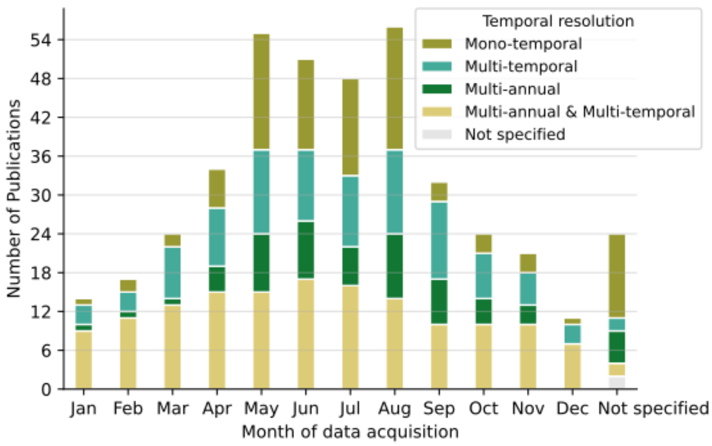

Figure 15. Data acquisition month and temporal resolution.

More than half of studies also utilized ground-based or in situ data in conjunction with remotely sensed data. Compared to the dates of air or spaceborne data acquisition, in situ data were often not gathered or not able to be gathered contemporaneously. Within this review, it was noted that a study would often identify a high-resolution airborne dataset as so-called in situ, field, or ground-based data. Over time, proportionally fewer studies utilized these types of data. Overall, 46 studies did not use any type of in situ data, whereas 100 publications integrated ground-based data into their studies.

Here, we present ground-based data based on temporal resolution and exclude all studies which either did not utilize in situ data or where the so-called in situ data were acquired from an airborne platform (Figure 16). Although many studies have utilized overlapping datasets, there are some which do not coincide temporally. This suggests a potential mismatch in the RS and in situ data. There is no clear trend as to which type of temporal resolution acquired more or less contemporaneous in situ data than others.

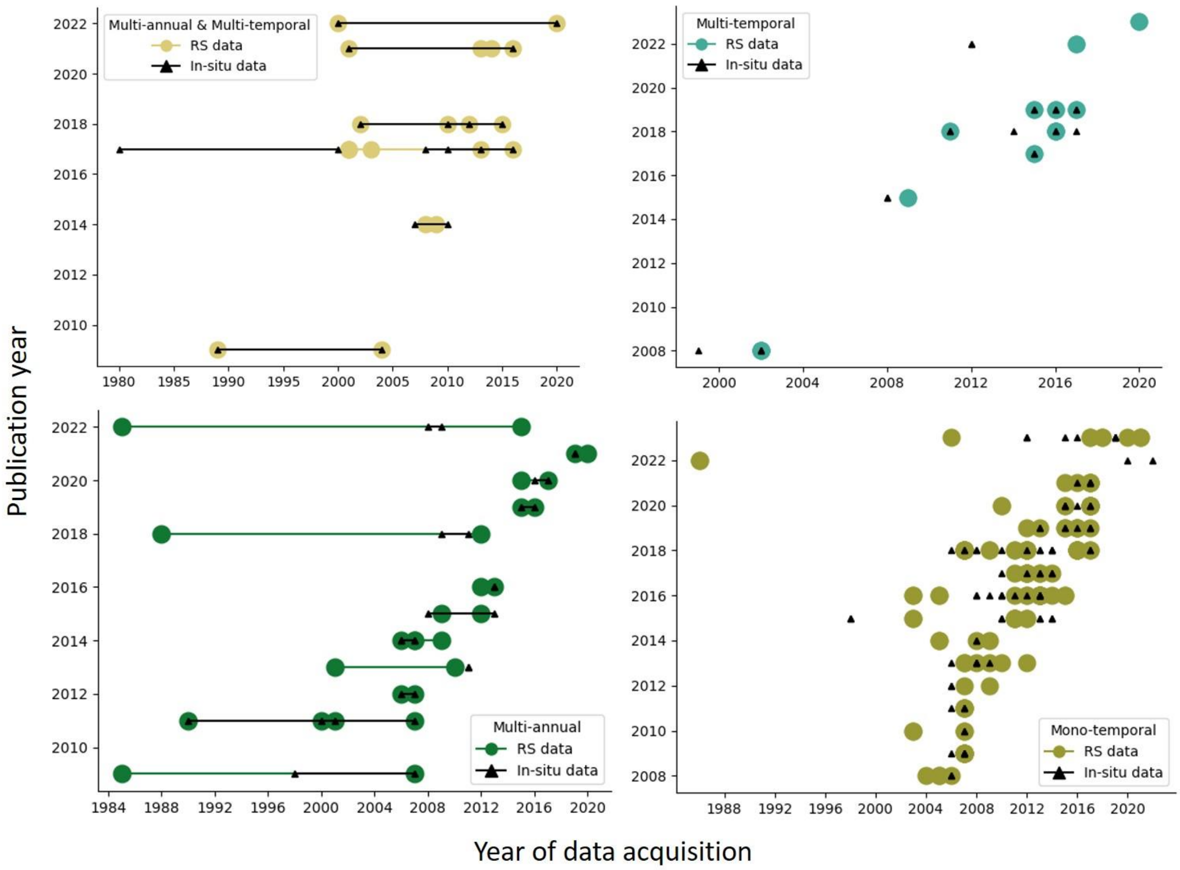

Figure 16. In situ and RS data acquisition dates by temporal resolution. Those publications which did not utilize any field data, or where the data source was an airborne dataset, have been excluded.

3.6. Forest Type

There are three forest types. In higher elevations, coniferous species, specifically the Norway spruce (*Picea abies*), dominate forested landscapes. Meanwhile, in lower elevations, deciduous trees are most common, especially the European beech (*Fagus sylvatica*). At middle elevations, these two types coincide in both heterogenous mixtures and clusters of pure stands. Because of their abundance, these two dominating species are the subject of the majority of RS forest investigations in Bavaria. Among them, we also find pine (*Pinus* sp.) and oak (*Quercus* sp.) species in smaller proportions. One study investigated Scots pine (*Pinus sylvestris*), specifically the effect of drought on the edge and forest interior [33]. While larch (*Larix* sp.) and fir (*Abies* sp.) trees make up a small proportion, the silver fir (*Abies* alba) was studied exclusively in one publication [34].

The forest types investigated (Figure 17) have not seen any major shifts over time, with each type of forest being investigated in relatively similar proportions during the study period. There were 34 publications which focused on all three types of forest, distinguishing or stratifying them within their scientific inquiry. This is often because the AOI size is large enough to cover all three types of forest. Six of these studies were part of the 'Other' topic category and further investigated the following sub-topics: land cover classification, carbon mitigation, fragmentation/climate change, succession, segmentation, and lying deadwood. Publications which investigated exclusively coniferous forests were predominantly investigating disturbances caused by bark beetles or bark beetle habitats such as standing or lying deadwood. Fewer studies were primarily interested in pure deciduous forests. These publications focused on either 'Biodiversity/Habitats' or 'Phenology', with sub-topics including structure, drought, and species distribution modeling. Finally, mixed forests were the most common forest type studied. The research areas were highly varied; however, the predominant topics were 'Biodiversity/Habitats', 'Forest type/Cover', and 'Structure'. In mixed forests, there were more methodological papers than other forest types, with deep learning as a commonly tested method. Research topics will be discussed in detail in Section 3.8.

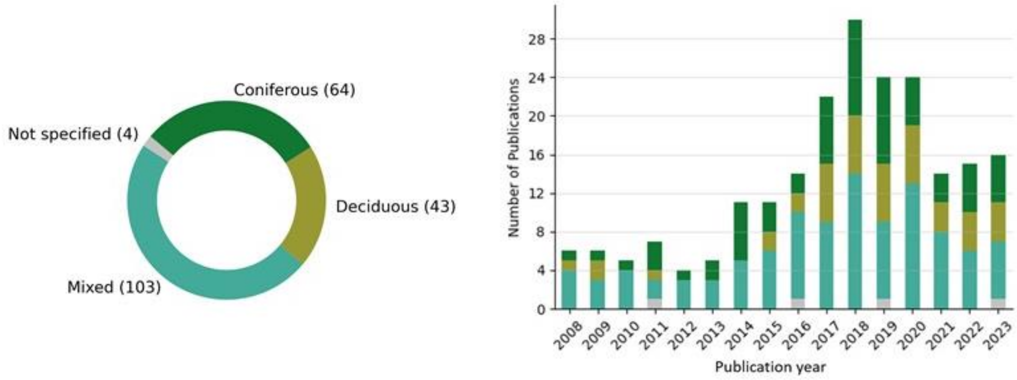

Figure 17. Forest types investigated over the study period.

3.7. Object Scales and Data Resolution

RS studies of forests utilized five object scales: 'Landscape', 'Forest', 'Stand', 'Tree', and 'Leaf' (Figure 18). The 'Landscape' scale refers to the largest spatial scale and typically focuses on a geographic area larger than a single forest or reserve. This could refer to the entire state of Bavaria, Germany, or Europe. The 'Forest' scale refers to a spatial investigation of a specific forest or reserve, such as the BFNP or the Steigerwald. 'Stand'-scale investigations typically refer to a forested area smaller than or within the boundaries of a forest or reserve. This often also refers to a pure cluster of conspecifics, notably spruce or beech stands. The 'Tree' scale refers to individual trees with their boundaries clearly defined either through object-based or pixel-based methods. Finally, the 'Leaf' scale is the smallest object scale. Studies investigating the 'Leaf' scale are often concerned with leaf traits and correlating in situ leaf data with RS data such as chlorophyll content.

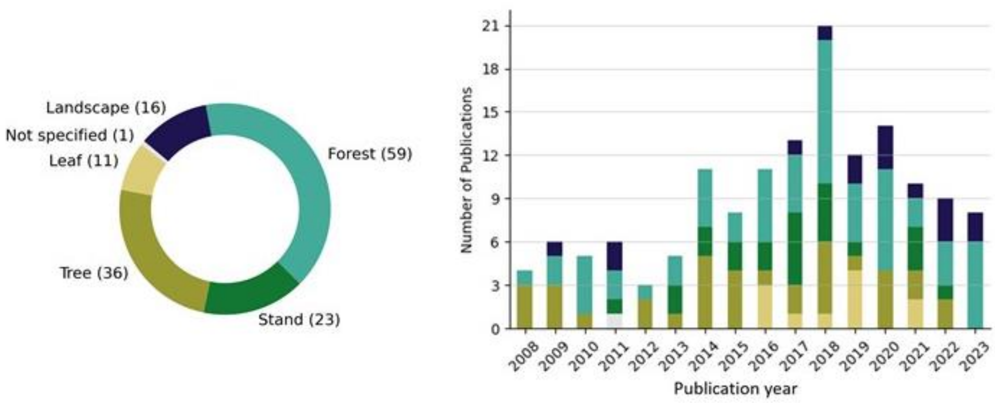

Figure 18. Object scales investigated over the study period.

'Forest' was the predominant object scale investigated and has been over the entire study period. 'Landscape' scale studies have increased in the years since 2017. 'Tree' and 'Leaf' scale studies have decreased in recent years, with the most recent year (2023) comprising studies at the 'Landscape' and 'Forest' scale only.

Data resolution varied by the platform and the object scale being investigated. Spaceborne data had the widest range in spatial resolution, from less than 4 m up to 1000 m. Since data resolution can vary by data type, and multiple data can be used in a single paper, we present the data resolution in terms of the number of sensors used. Sentinel data at 10 m resolution was utilized 18 times while Landsat data with 30 m resolution was used 25 times. Larger-scale studies tended to use lower-resolution data; however, all resolutions except the smallest and largest were used to investigate forests at all five object scales (Figure 19). Moreover, in many studies multiple sensors, and therefore resolutions, were often combined.

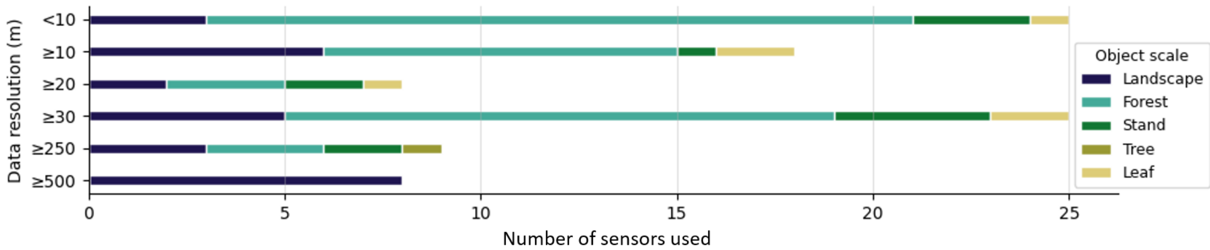

Figure 19. Spaceborne data resolution visualized with the object scale investigated.

Airborne data have much higher spatial resolutions due to the proximity of the sensor to the forest or other investigated objects. Here, we distinguish between the spatial resolution of lidar, which is commonly presented in points per square meter (pts/m^2) and that of optical data (which also refers to multispectral, hyperspectral, and color infrared (CIR) data). Among the publications utilizing lidar data, middle-resolution (<40 pts/m^2) data were most commonly used to investigate the 'Forest' and 'Tree' scale. Two studies investigated the 'Leaf' scale.

Within optical data types, the highest spatial resolution (<1 m) was the most commonly used data to investigate 'Forest', 'Tree', and, to a lesser extent, 'Stand' scale objects. It was also the preferred data type for 'Leaf' scale studies, likely due in part to the importance of reflectance values (and indices such as NDVI) for investigating topics such as phenology or bark beetle infestations. Airborne data were not used to investigate forests at the 'Landscape' scale (Figure 20a,b).

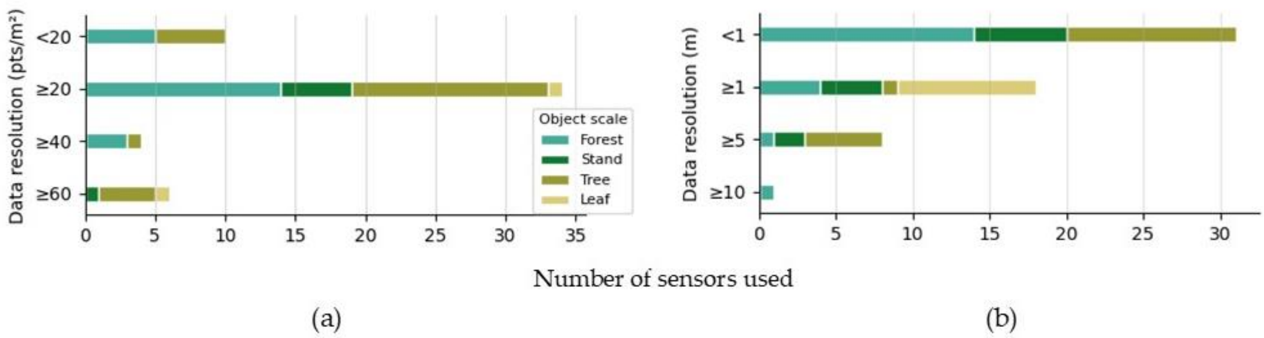

Figure 20. Airborne data resolutions distinguished between lidar (**a**) and optical sensors (**b**). The resolution is presented with the object scales investigated.

Finally, we present the trends in data resolution usage. Airborne lidar resolution has increased from less than 20 pts/m^2 to more than 60 pts/m^2 over the study period (Figure 21a). Researchers began to use the highest-resolution data in 2018 and the subsequent years aside from 2023. However, middle-resolution lidar data (between 20–60 pts/m^2) is still utilized. Most of the airborne lidar data studies were published in 2018.

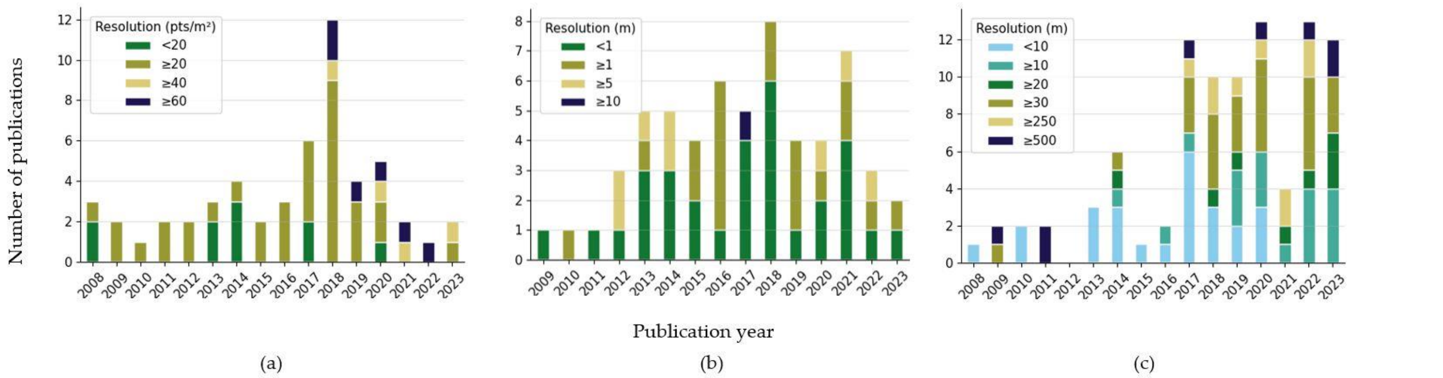

Figure 21. Resolution trends for airborne lidar (**a**), optical (**b**), and spaceborne (**c**) data.

Most of the airborne optical data had less than 5 m resolution, with the highest number of publications utilizing sub-meter resolution data (Figure 21b). However, middle-resolution data remains common even in recent years.

Overall, the usage of spaceborne data in general and of all resolutions has been increasing over the study period with a drop in sub-ten-meter resolution data usage in the most recent years (Figure 21c). Although the resolutions of Landsat (30 m) and Sentinel (10 m) data are the most commonly used overall, low-resolution sensors such as MODIS (250–1000 m) remain in steady use over the study period. Notably in 2012, there were no studies utilizing spaceborne data.

Several of the sub-ten-meter spaceborne studies also used airborne data in their analysis to investigate stand characteristics at the 'Forest' scale in Traunstein forest. Among these publications, RapidEye, Planet, WorldView, and QuickBird were the most popular of the high-resolution sensors. Among the 10 m resolution data, all of which were derived from Sentinel-1 or -2, all but five studies used them in combination with data from other sensors.

3.8. Research Topics

The articles contained in this review covered nine topical research areas, based on the findings of Holzwarth et al. [11,29], with the addition of the 'Monitoring/Management' topic as well as one topic entitled 'Other', which contained nine sub-topics and were represented by three or fewer papers each (Figure 22). The research area (or 'topic') refers to the overarching theme of the publication. We have further identified sub-topics which are presented in the subsequent section. The topic covered most often among the papers was 'Disturbance', which was investigated in 31 studies [23,26,33,35–61]. 'Structure' was the second most common topic, covered by 24 papers [62–85]. Twenty-three papers investigated the 'Biodiversity/Habitats' topic [86–109], while eighteen papers looked into 'Forest cover/Type' [34,110–126]. The topic of 'Leaf traits' was covered in 14 studies [127–140]. Thirteen papers were categorized in the aforementioned topic 'Other' [141–153]. The topic of 'Monitoring/Management' was investigated in eight studies [154–161], while seven papers each covered the topics of 'Biomass/Productivity' [162–168] and 'Phenology' [169–175]. 'Disturbance' and 'Structure' were the dominant research areas and have increased over time along with 'Forest type/Cover' and 'Leaf traits' (Figure 22). 'Monitoring/Management' has remained a steady but small research area; meanwhile studies investigating 'Biomass/Productivity' and 'Biodiversity/Habitats' have decreased over time.

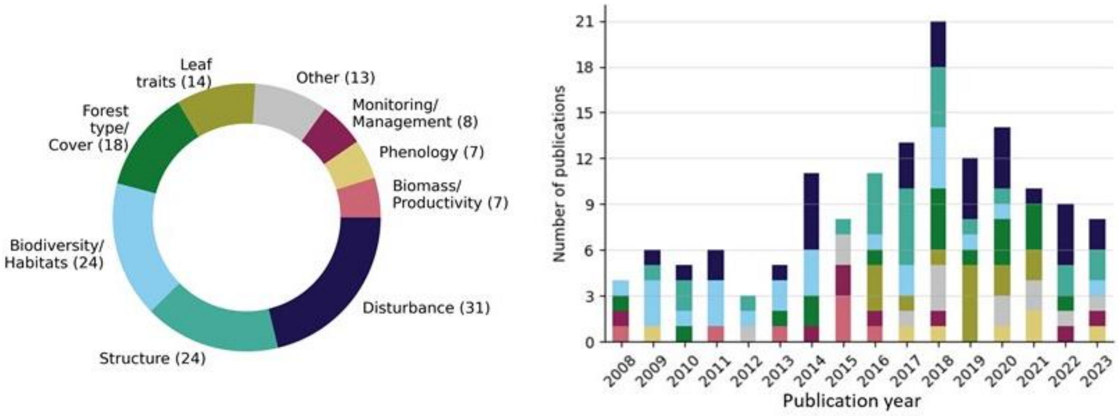

Figure 22. Research areas and publication trend.

3.8.1. Disturbance

The largest research topic was 'Disturbance'. These papers concerned an event or variation in biotic or abiotic conditions which lead to changes in the structural or phenological characteristics of the forest, individual trees, or leaf traits. Bark beetle (*Ips typographus*) infestations in spruce stands and the subsequent die-offs often followed by windthrow events are an example of the 'Disturbance' topic [26,35,36,38,41,42,44–56].

Beyond mapping windthrown [40,43,60] or structurally altered forests (for example, the occurrence of standing deadwood [26,41,56]), a particular aim of this research area was to identify earlier phases of bark beetle infestation (so-called green-attack [35,53,54]). Researchers tested various combinations of airborne and spaceborne data, in addition to new and well-established reflectance indices, together with higher temporal resolutions at varying object scales in order to land on the most effective methods for the earliest detection possible. Testing SVIs was a common approach, while thermal data were also used successfully for detecting early infestation stages [35,36,47–49]. Moreover, the location of follow-on infestations was tied to the distance to previously infested trees, particularly at forest edges where trees experienced more sun stress [46,52,93,94].

The motivation in these studies was to facilitate the mitigation of infestations in highly managed forests where the removal of trees (so-called sanitation or salvage logging) is used to avert the spread of insects. The BFNP is one exception where no management of this type occurs [176]; nevertheless, RS methods are often tested in the park due to the recent increases in infestations and the hands-off management scheme. Phenological changes, to a lesser extent, also comprised the 'Disturbance' topic. Researchers were also interested in the damage or lag-response of the forest in subsequent growing seasons following disturbance events [45,61].

3.8.2. Structure

Twenty-four papers studied the 'Structure' of forests in Bavaria using remote sensing. Investigations into canopy height [62,66,80,81,84] and SAR tomography [62,69,70,74,76–78,82] made up the majority of this topic; however, overall, the sub-topics remained a mixed bag of inquiries, with structure being a primary concern. In contrast to the other research areas of this review, the 'Structure' topic was comprised mostly of experimental methodology papers with smaller test study sites, mostly in the Traunstein forest (part of the global ForestGEO network). In terms of data, these methods tested the capabilities of typically lidar or SAR data or some combination of the two either from airborne, or to a lesser extent, spaceborne data. Overlapping sub-topics included productivity/biomass. Only two studies did not utilize some form of airborne data. Although slightly more than half of these studies included in situ data, of these, several did not specify the acquisition dates, while others were based on forest inventory data.

Using in situ data, some studies were concerned with the mapping of forest structure, especially height, biomass, and stem volume, in general, without regard to structural changes, whilst testing for the best-performing data sources [62,64–66,68,73,75,79,80,83–85]. Meanwhile, two studies developed structural products covering the spatial scale of Germany; a simulated lidar dataset based on forest inventory data was utilized in order to estimate structural parameters, especially in the context of biomass and productivity [71], and a product derived from Sentinel-1, -2, and GEDI spaceborne lidar was utilized for a better understanding of forest structure in the post-disturbance context [72].

3.8.3. Biodiversity/Habitats

Researchers in the 'Biodiversity/Habitats' topic were primarily interested in the habitat of a specific forest species, most commonly vertebrates. RS data provided structural metrics and were often derived from airborne lidar data. The spatial extent was typically based on in situ presence data vis à vis scat samples, acoustic monitors, telemetry, and GPS collars, in addition to other sources. Only one publication did not utilize any field data. Because RS data were primarily used as a co-variate for modeling species habitat by structural characteristics, the temporal resolution of these studies were either mono-temporal or multi-annual, suggesting that the topic did not explore habitat characteristics over time or in response to disturbance events.

A main finding of the papers in this topic was the link between forest structural complexity and biodiversity [86,95,97,98,106,108]. Furthermore, several studies demonstrated the effectiveness of remotely sensed structural metrics, particularly from lidar, for mapping habitats in particular [88,91,96,99,101–103].

3.8.4. Forest Type/Cover

The 'Forest type/Cover' topic primarily consisted of studies which classified tree species (67%). The remaining publications focused on other types of land cover in addition to forests, the segmentation of tree species, biomass, or, in two cases, the cover of forests in general. These studies took place in mixed forests (with one exception) where different species and tree types exist side by side. In highly mixed forests, where few dominant species (typically Norway spruce and European beech) approach an even mixture, their differentiation presents a challenge for classification.

Both data platforms were utilized in near equal number, and more than half did not integrate in situ data into their analyses. Where ground data were utilized, the type of data was uniform; species, stem position, and diameter at breast height (DBH) were the common parameters, while age class, height and soil type were collected for a few studies. To classify species, about half of studies employed machine learning algorithms; two papers each utilized convolutional neural networks and object segmentation, regressions, and the normalized cut algorithm. Moreover, 61% of studies were conducted in the BFNP, with one study each covering Traunstein forest, the state of Bavaria, and at the European landscape scale.

Most studies focused on the differentiation of deciduous and coniferous forest types [112,114,116,122]. Other studies included distinguishing standing deadwood [118,120,121], while two studies differentiated coniferous species [34,111]. One paper investigated the integration of lidar metrics [123], while another looked into the use of texture metrics derived from the CIR data [124].

3.8.5. Leaf Traits

There were 14 investigations into 'Leaf traits', which often tested the capabilities of high-resolution airborne data for monitoring leaf components or changes on the leaf-scale [133,134,137–140]. In 2019 it was the most-studied topic. In this category, all of the studies took place in the BFNP; however, only four studies covered the entire park, while five studies did not specify the AOI size. Although leaf chlorophyll content was the primary target of these papers, other traits of interest included the leaf area index and level of foliar nitrogen, among others. Less than half of the data were derived from spaceborne platforms, and in all cases, in situ leaf data were collected for the study.

The topic of bark beetles was also part of this category, whereby researchers aimed to distinguish between healthy and infested trees via in situ leaf trait measurements and high-resolution spectral reflectance data [128]. Additionally, three papers were related to structure [133,136,140]. In terms of analysis methods, the random forest algorithm was predominantly used among others, while in three papers, artificial neural networks were employed [129,132,139].

3.8.6. Monitoring/Management

Of the eight publications concerning the topic 'Monitoring/Management', seven utilized RS together with ground-based forest inventory data (part of a state or federal monitoring scheme) to assess various facets related to the status of the forest, or the forest condition following a disturbance event. Because of the temporal gap between inventory collections (once every 10 years), these studies are often motivated by the potential to use RS data to measure the same ground-based parameters collected during inventories in order to build a higher temporal resolution dataset. It is also argued that a remotely sensed forest inventory can cover larger spatial scales at reduced costs. In terms of data, 63% of studies utilized airborne data, 38% utilized spaceborne data, and one study utilized a combination of the two. In the case of satellite-based data, the resolutions were less than or equal to 10 m. Features examined from this data include predominantly NDVI, and to a lesser extent canopy height and the segmentation of individual trees. One study each covered the whole of Germany [154] and the BFNP [160], while the remaining publications were smaller in spatial extent.

Inherently, studies devoted to the monitoring and management of forests also rely on species classification; as such, there was overlap with this category and that of 'Forest type/Cover', 'Structure', and 'Disturbance'. In the case of Welle et al., the authors used Sentinel-2 data trained on national forest inventory in situ data to create a map of dominant tree species over the whole of Germany [154], while the team of Elatawneh and Wallner utilized RapidEye data for forest type mapping and post-storm forest damages [155–157].

3.8.7. Phenology

The spatial coverage of 'Phenology' studies was that of the BFNP, Bavaria, or Germany. Moreover, the forest type investigated was primarily deciduous forests or in two cases, a mixture of coniferous and deciduous with 86% of studies acquiring data either multi-temporally or multi-annually. Taken together, phenological studies looked at large-scale changes over time, particularly focusing on species where the greening up period could vary from year to year. In general, more than half of these studies used the CORINE landcover product in their analyses, and all but one paper utilized NDVI, EVI, or both. All of the studies relied on satellite-borne data, with two papers adding airborne-derived data and one additionally making use of UAV data [172]. Overall, the main findings concluded that the greening up period was occurring earlier in the year [171,175], and that there were growing mismatches in timing between different vertical layers and the canopy [170,171]. Additionally, preceding winter temperature and land cover class were found to have had an impact on phenological timing [173,174].

3.8.8. Biomass/Productivity

The 'Biomass/Productivity' research area was small and highly varied. The category contained seven papers, and few clear trends emerged in our analysis of these studies. Firstly, we note that the most recent paper was published in 2016, and that all but two studies analyzed airborne data with one paper integrating both airborne and satellite-derived data into their analysis on biomass. In situ data were used in all of the studies, which were either taken directly from forest inventory datasets, or, using the same parameters, were collected independently. As national inventory data are collected on a decadal basis, this may be an indication as to the sporadic and apparently declining trend of the publications in this topic.

Researchers used canopy height together with national inventory data to predict timber volume or growing stock estimations. In these cases, height was derived using stereo image data [162,164,167].

3.8.9. Other

The 'Other' topic was introduced in this review as a catch-all for papers which did not fall neatly into our pre-defined research area categories. There were three papers from the same first author investigating lying deadwood [149–151]. The aim of these publications was to detect fallen dead trees using aerial imagery and in one case, convolutional neural networks. Two papers looked into succession from the perspective of biodiversity and bark beetle infestations of windthrown areas [144,147]. Similarly, one paper investigated regeneration of spruce trees less than 10 m in height using a combination of aerial and UAV images and the triangular greenness index (TGI) [153]. Two papers studied forests for the whole of Bavaria, covering the topics of land cover classification [143] and carbon mitigation [142], both utilized CORINE land cover data. One paper used airborne lidar data together with in situ soil properties to investigate the quality of protective forests and their sensitivity to degradation [152]. Furthermore, we note one paper which focused on fragmentation and climate change [141]. This publication used land surface temperature together with forest fragmentation covering the whole of Germany. Their results suggest that areas of highly fragmented forest showed higher temperatures than unfragmented forested areas.

3.8.10. Sub-Topics

Within the aforementioned research areas, we have identified several sub-topics. We present them here for a more detailed inquiry of the breadth of topics within the field covered by this review (Figure 23). In cases where a sub-topic is the same as the primary research area, these papers were based solely on that topic and did not investigate any other sub-topics. The sub-topics below are ordered from most to least common within the overarching research area:

- 'Disturbance': Bark beetle, Drought, Windthrow, Structure, Disturbance, Standing deadwood, Vegetation condition, Cover.
- 'Structure': SAR Tomography, Canopy height, Structure, Leaf traits, Monitoring, Biomass, Disturbance, Segmentation, Habitats.
- 'Biodiversity/Habitats': Biodiversity, Habitats, Bark beetle, Species distribution modelling, Ecology, Spectral variability, Succession, Lying deadwood.
- 'Forest cover/Type': Tree species classification, Land cover classification, Cover, Segmentation, Biomass.
- 'Leaf traits': Leaf traits, Structure, Tree species classification, Bark beetle.
- 'Monitoring/Management': Forest inventory, Structure, Disturbance, Tree species classification.
- 'Phenology': Phenology, Structure, Habitats, Climate change.
- 'Biomass/Productivity': Forest inventory, Structure, Segmentation, Productivity, Biomass.
- 'Other': Lying deadwood, Succession, Vegetation indices, Carbon mitigation, Regeneration, Protective forests, Fragmentation/Climate change, Land cover classification, Segmentation, Land surface temperature.

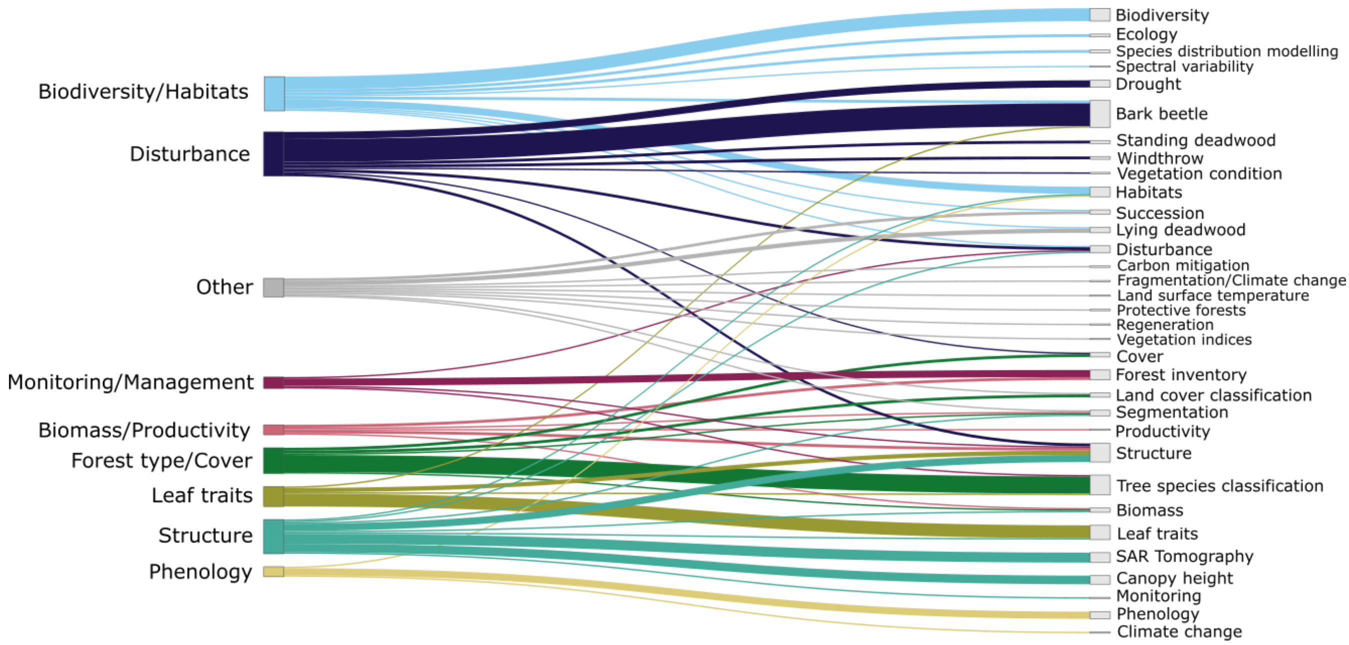

Figure 23. Sub-topics (**right**) presented with the respective overarching research area (**left**).

4. Discussion

4.1. Key Findings for RS of Bavarian Forests

In 2023, a review was published regarding RS of forests for Germany [29]. The authors highlighted the decline in the condition of German forests as a whole, the ecological and economic importance of heavily forests states such as Bavaria, and finally, the lack of studies covering individual states. Given that the state of Bavaria has more forest cover than the national average, we have undertaken this literature review to better understand and summarize the field of RS studies regarding forests in Bavaria. Notably, this review has highlighted a clear interest in the BFNP; 88 out of 146 papers focused on the park as an AOI. Within these inquiries, RS was utilized for investigating all of the eight forest topics in this review with particular regard towards animal habitats and biodiversity, and in response to disturbances. Indeed, the broad range of topics investigated within the park using remotely sensed data are an example of the potential for inquiries on a broader spatial scale. However, the number of studies conducted within the park versus the more than 2.5 million hectares of remaining forest in Bavaria is unbalanced. Interest in the park is understandable; it is the largest protected forest in central Europe.Furthermore, the management plan helps to maintain a near 'natural' environment. The breadth of studies conducted in the park exemplifies the depth of knowledge and expertise regarding RS of forests which could be applied in the broader Bavarian context. These 88 publications suggest the potential of Bavarian forests more generally in terms of ecological functionality, wildlife habitats, and contributions to ecosystem services. Thus, the thematic applications which have been outlined in this review warrant further investigation across the entire state.

In recent decades, climatic shifts in central Europe have tended to increase precipitation in winter along with increased winter and summer temperatures, while droughts have occurred more frequently in summer. The effects on the forests of Bavaria have been documented both by ground-based surveys of individual trees (the WZE) and in RS studies regarding phenological timing. Essentially, the findings of the WZE point to decreased vitality of individual trees, while the results of phenological RS studies revealed shifts—especially in response to drought—including early leaf senescence. Taken together, given the scale of the decline in forest health and tree cover due to droughts and insect disturbance, we emphasize the need for future investigations concerning all topics but especially forest decline covering the whole of Bavaria.

4.2. Disturbances by Bark Beetles—The Most Common Topic

In total, 24 papers dealt with some aspect of RS of forests disturbed by bark beetle infestations of the Norway spruce. This was the largest sub-topic across all of the main research areas of this review. Given the dominance of spruce in Bavaria, especially in the BFNP, the timely investigation of this topic was salient among forest researchers and managers. Bark beetles are not invasive in Germany; instead, they are a keystone forest species [177]. However, the spike in the scale and intensity of infestations is a relatively recent phenomenon. In fact, infestations are predicted to intensify due to climatic conditions if their habitat persists [178].

Over the past two decades, Bavaria has experienced two major droughts (2003 and 2018) [179]. Following drought events, spruce trees are weakened and more prone to bark beetle infestations, which take place in three phases: green-attack, red-attack, and grey-attack, whereby the tree visibly changes color with each phase and eventually dies [53]. The latter two phases can be effectively detected by remotely sensed spectral and structural changes; however, the green-attack phase remains a challenge [180].

It is the hope and goal of RS scientists and forest managers alike that the early detection of the green-attack phase could provide a window of opportunity to mitigate the spread of infestations by altogether removing trees in the green-attack phase. Moreover, beyond detection, communication of early attacks to forest managers continues to be a relevant issue. To that end, several papers proposed novel methods for such an endeavor [35,53,54]. However, this is not limited to Bavaria as the natural world rarely minds administrative borders. The increase in infestations is seen in neighboring states and countries, particularly in Šumava National Park, part of the Bohemian Forest Ecosystem, which includes the BFNP, separated by the Germany/Czech Republic border. This protected area is the largest in central Europe. Because the international border slices through the core area of the forest, management approaches and use intensity differ on either side. In both cases, the core interior of the park is left untouched after disturbances, in order to regenerate naturally. However, in the case of bark beetle infestations, salvage logging takes place in the peripheral management zones. The legacy of this duality has manifested over decades which has also affected changes to the forest. The net effect of these management practices is an increase in especially animal biodiversity, as windthrown trees open previously closed forest canopies and deadwood provides favorable habitats [181–183].

The occurrence of both standing and lying deadwood, which comprises bark beetle habitats, together with a persistent drought and earlier spring warming, contribute to pest infestation spikes. However, these sub-topics were seldom explored by RS scientists in Bavaria. The final piece of the bark beetle puzzle is the Norway spruce. Both the large-scale commercial planting and natural regeneration of the spruce is economically important in the forestry industry in Germany. However, the spruce is preferred by bark beetles and has suffered vast losses, particularly among mature trees. Therefore, forest management plans across the country now push for a more diverse species mixture. The 'German Forest Strategy 2020' aims for an increase in mixed forests with the follow-on expectation to further increase biodiversity and naturalness of forests, thereby increasing resilience and reducing the future impact of bark beetle infestations [21].

4.3. Topical and Spatial Scale Research Gaps

Put into the context of RS of forests in Bavaria, the topics stemming from the aforementioned 'German Forest Strategy 2020' strategy—species diversity in mixed forests, and the effect it could have on forest resilience, vitality, or productivity, for example—were understudied. Furthermore, topics related to the regeneration of stands lost to bark beetles (for example biomass and productivity), the monitoring and management of forest succession (in terms of species and cover for example), and the investigation of newly fragmented forests, are remain unresolved.

Although disturbance, forest structure, and tree species classification were well-covered topics in this review, these topics have not been explored at the landscape scale.

We also note that the region of Upper Palatinate (Oberpfalz) was not studied at all. There were nine papers covering the whole of Germany and five which investigated the entire state of Bavaria. These five papers focused on biodiversity, tree species classification, land cover classification, carbon mitigation, and habitats in coniferous, deciduous, and mixed forests. Of these studies, only two utilized in situ data. There is, therefore, a need for studies at the state scale which integrate contemporaneous in situ data in all research topics, but especially those which have not been covered, namely 'Disturbance', 'Structure, 'Leaf traits', 'Monitoring/Management', and 'Biomass/Productivity'.

Regardless of spatial scale, there are a handful of sub-topics that present interesting research gaps for remote sensing of forests in Bavaria. These sub-topics were categorized into the research area 'Other', and were thereby covered in three or fewer publications, namely succession/regeneration, climate change, protective forests, clear-cuts, carbon mitigation, and fragmentation. With the recent mass losses of spruce forest and the evidence of warming temperatures, changes in precipitation patterns and earlier green-up of vegetation, these understudied topics could reveal important insights for end-users like forest managers, policymakers, and decision makers.

4.4. Under-Utilized Data Platforms and Sensor Types

In terms of data usage, we note here not only the dominance of satellite-derived multispectral data, but by the same token a distinct lack in the use of other spaceborne sensors, e.g., hyperspectral, lidar, and thermal data. Among airborne sensors, lidar dominated; however, overall, there was a more even distribution in the use of other airborne data types.

Hyperspectral data were not at all utilized from spaceborne platforms in this review. These types of data provide a much higher number of narrow and continuous bands than multispectral data, and although this can provide more nuanced reflectance information, it also requires more pre-processing as the bands are inherently redundant. Hill et al. proposed tree species classification, forest structural and leaf traits, and the detection of stress in canopies (by bark beetle infestations, for example), among others, as potential applications of satellite-derived hyperspectral data [184].

Despite the high signal-to-noise ratio indicating good performance, the improved accuracies of hyperspectral versus multispectral data, and the applicability to the forest topic [185], the availability of this data type from free and open satellite-derived sources remains limited. Perhaps it is due to this inaccessibility together with the pre-processing workload that hyperspectral data were under-utilized by authors in this review.

Some of the available spaceborne hyperspectral data either require tasking (EnMAP), do not provide global coverage (DESIS), are of lower resolution (MODIS and CHRIS), or have been decommissioned (Hyperion). The EnMAP hyperspectral sensor has been in operation since 2022, while DESIS (onboard the ISS) has been collecting data since 2018. PRISMA (owned and operated by the Italian Space Agency, ASI) was launched in 2019, whereas NASA's Hyperion was in operation from 2000 to 2017. The CHRIS sensor onboard the PROBA-1 satellite was launched in 2001. The GLI sensor (onboard the ADEOS-2 platform) is similar to the MODIS sensor—each provides 36 spectral bands with 250 m resolution, and has been in operation since 2002. Yet, other hyperspectral systems are in less frequent use; meanwhile, the CHIME sensor from ESA is still in the planning phase with an expected launch date still several years away.

Conversely, hyperspectral data derived from airborne platforms were used in 13 publications. The topics investigated included 'Leaf traits' (seven papers) and 'Disturbance' (three papers) and to a lesser extent 'Biodiversity/Habitats', 'Forest type/Cover', and 'Other' (vegetation indices) in one paper each. Although hyperspectral data are less common overall, by utilizing satellite-derived sources, these topics could be broadened to larger spatial scales.

The spaceborne lidar sensor GEDI (onboard the ISS and operated jointly between NASA and the University of Maryland) is a full-waveform lidar instrument, which was utilized in just two papers investigating the research topic of 'Structure'. This topic closely aligns with the aim of the GEDI mission to map global forests in 3D, especially canopy height. The instrument was launched in December 2018 and is targeted for vegetation studies. However, it remains an under-utilized dataset for the topic of forests in Bavaria.

As GEDI is a relatively new and novel sensor, there are additional challenges for users which can act as potential barriers in the utilization of GEDI in forest applications in Bavaria. The accessibility of hierarchical data types and the lag in validation and user uptake may impede or delay working with GEDI. As this review has demonstrated, most practitioners working with spaceborne data are familiar mainly with multispectral data for forest monitoring. Furthermore, there is a limitation in spatial coverage for the whole of Germany, and while the state of Bavaria receives full coverage under this mission, this perceived spatial limitation, together with the distance between footprints, may also discourage its integration in RS forest research. Although the spatial coverage could be a limiting factor, the work of Kacic et al. presented a method for data fusion using GEDI lidar, multispectral, and SAR data [72]. Their product has been publicly available with wall-to-wall coverage of Germany since April 2023 (available on the DLR Geoservice, https://geoservice.dlr.de/ (accessed on 18 May 2024)).

Finally, the GEDI mission was under a limited two-year acquisition contract; therefore, temporal limitations might have prevented the investment in the usage of these data. However, the mission has been extended until 2030. In addition to GEDI, other spaceborne lidar sensors with the potential to investigate forests which were not utilized in this review include ICESat-2 and Gaofen and were summarized in a review by Aguilar et al. [186].

In terms of spaceborne thermal data, we reported that it was only applied in three papers related to the 'Disturbance' (bark beetles) and 'Other' (fragmentation/climate change) topics. In both topics, thermal data were well-correlated to the investigated variables. Taken together, solely multispectral data were utilized in three topics: 'Monitoring/Management', 'Phenology', and 'Leaf traits', while also being used in all but one paper in three additional topics: 'Biomass/Productivity', 'Biodiversity/Habitats', and 'Forest type/Cover'. Therefore, we see the potential for the introduction and investigation of additional data types within these research areas.

4.5. Potential for Densification of Time-Series and Integration of In Situ Data

Temporal resolution was presented on four distinct scales: mono-temporal, multi-annual, multi-temporal, and multi-annual & multi-temporal. The latter scales could also be referred to as a time-series. We found an evenly distributed number of publications of each resolution within the satellite-derived data with a trend towards a higher density of data acquisition. However, only 13 publications utilized data from 1990 or before. Essentially, these data are part of the Landsat archive. Of these studies, one covered the whole of Germany, while the remaining 12 covered the BFNP or smaller (yet all were within the BFNP). The topics covered did not include 'Leaf traits', 'Biomass/Productivity', or 'Monitoring/Management'. While older data are less commonly analyzed, we note a potential for more time-series studies for investigating long-term trends of forests in Bavaria.

Additionally, we discuss the use of in situ data. In all, 100 of the 146 papers did utilize some type of ground-based data. However, the contemporaneous collection of the data was not guaranteed. Furthermore, many studies equated very-high-resolution RS data with that of in situ data. We saw that in the most recent years, both the integration and the lack of in situ data were in near equal number of publications for forest RS in Bavaria. We therefore encourage investigations which aim to link remote and ground-based data in future applications. We found that because the majority of researchers investigating RS of Bavarian forests are based in Germany, collection of these data is, in theory, possible. Typically, the accuracy and precision of an RS study can be improved with the inclusion of some type of in situ data [27,28]. Moreover, Chave et al. suggest that the integration of ground-based measurements into RS applications related to forest biomass and carbon estimations is crucial not only for increasing model accuracies but also to legitimize the results of RS investigations for lay actors [187]. This lack in end-user uptake, despite the ubiquity of RS studies of forests globally, was also a key finding of Fassnacht et al. [28].

4.6. Considerations for the WoS Search String

After carefully constructing and testing iterations of our search string, we decided to retain the national park, national reserve, forest, and biosphere names in the geographic location block. However, the addition of these names did not precipitate additional results. The reasons behind this decision are twofold; firstly, we aimed to know how many studies investigated these areas specifically (and conversely how many did not), and secondly, to acknowledge the potential for RS studies in these locations, and the reproducibility of our search should there be publications on these parks in the future. The most obvious omission we report is the absence of publications from the Oberpfalz (Upper Palatinate) region and studies conducted specifically on the forests within nature reserves and parks.

4.7. Applicability and Outlook for RS in Bavaria

Although there is a high potential for the application of RS in Bavarian forests, the uptake by end-users is not generally the aim of scientific work. In order to make use of scientific RS studies, relevant results should be presented in context and at spatial scales utilized by decision makers and forest practitioners. This topic has been investigated by the forest RS scientists Fassnacht et al. in a recent paper which highlights not only key challenges with regard to end-user application, but also cites examples where user uptake has been successful, particularly in the Nordic countries [28]. The authors concluded that user uptake of, for example, aerial lidar surveys in Germany as a whole is low compared to Canada, Finland, Norway, and Sweden. In the context of this review, papers assigned to the research topic 'Monitoring/Management' would have the greatest relevance to end-users; however, the topic was only investigated in eight publications.

Bavaria is subdivided into spatially hierarchical administrative units; the largest are the administrative districts or *Regierungsbezirke*. These seven *Regierungsbezirke* are further subdivided into 71 counties or *Landkreis*, which are furthermore subdivided into 2056 municipalities or *Gemeinden*. Administrative units are governed by elected officials and managed by governmental bodies that oversee land-use policies like the forest management strategies implemented by the BMEL. Although there were five studies in this review covering the whole state of Bavaria, we note the potential for conducting studies at the level of *Regierungsbezirke*, *Landkreis*, or *Gemeinden*.

An exchange of scientific outputs at meaningful spatial scales can be carried out by using the aforementioned administrative units as AOI boundaries, which is an important step towards end-user uptake. This would facilitate a more rapid synthesis of RS study results and the implications for end-users. Moreover, such spatial layers on administrative boundaries are free and open for public use. This is in contrast to the commonly used practice of analyzing RS data by image tile boundaries, arbitrary polygons, or at the pixel-level. Furthermore, the translation of proxies used for modelling, such as SVIs, into meaningful information would encourage the application of scientific outputs. Although this can be a step beyond peer review and scientific publication, entering the realm of science communication, it is necessary to bridge gaps between academic, political, and forestry sectors. Finally, a more centralized approach whilst making state-collected data freely available to the public would improve RS application and thus end-user uptake in Bavaria [28].

User uptake is especially important as the crucial role forests play in climate regulation and the economy will be under pressure as global temperatures continue to increase in the coming years and decades. Therefore, collaborations with stakeholders (political actors, forest owners, and managers) are essential, and can also help guide the needs-based development of targeted RS investigations of forestry in Bavaria. As the body of scientific knowledge continues to grow, it is imperative this information is transferred to actors making decisions about forests which will impact carbon uptake, soil health, biodiversity, and a host of ecosystem services for future generations.

5. Conclusions

Today, forests cover 37% of the total area of Bavaria, the southeasternmost state of Germany. In Bavaria, there are two dominant tree species: the Norway spruce (*Picea abies*), a coniferous species, and the European beech (*Fagus sylvatica*), a deciduous species. Other less abundant but common species include sessile oak (*Quercus petraea*), and Scots pine (*Pinus sylvestris*), among others. In the higher elevations, especially in the southern- and easternmost mountains of Bavaria, spruce is the dominant species. In lower elevations, spruce give way to mixtures with pine and beech and towards primarily beech and other deciduous species. Forests in Bavaria are typically located in areas which are not favorable for settlements, farming, or transportation infrastructure, and as such may be situated on poor soils or in steep or inaccessible terrain.

The climate of Bavaria is changing from relatively dry and cool winters and warm, rainy summers towards wetter winters with hotter and drier summers. In recent years, central Europe has experienced several strong droughts which have led to measurable changes to the forests of Bavaria, particularly among mature spruce. These changes include increased susceptibility to the primary and knock-on effects of droughts and increased temperatures, particularly with regard to insect infestations, especially the bark beetle. These effects seem to be strongest in pure spruce stands, while mixed forests tend to have a greater resilience overall. Among deciduous species such as beech, early senescence and reduced greening in the year following drought have been observed.

The 'German Forest Strategy 2020', a comprehensive guideline for sustainable forest management, has been widely implemented across forestry sectors. However, forests continue to decline despite efforts to increase forest resilience by, for example, replanting a more diverse mix of species, particularly deciduous species. The national forest inventory is conducted by the Federal Ministry of Food and Agriculture (BMEL) and takes place every ten years. This report reveals the status of the forest in terms of biomass and several metrics approximating condition. The most recent inventory took place in 2022, and the public release of this report is expected in 2024. This will be the first national inventory to include assessments supplemented by remote sensing (RS). The results of the inventory will undoubtedly reveal how management practices of the last decade have impacted the forests of Bavaria.

In total, 146 papers regarding the RS of forests in Bavaria were reviewed. We identified nine topical research areas (ordered by number of papers) as follows: 'Disturbance', 'Structure', 'Biodiversity/Habitats', 'Forest type/Cover', 'Leaf traits', 'Other', 'Monitoring/Management', 'Biodiversity/Habitats', and 'Phenology'. Forest disturbances due to bark beetle infestations were the largest single topic in this review and took place largely within the BFNP. A likely reason for this could be the predominance of spruce overall, but especially in the well-studied BFNP. Investigations often aimed to detect the earliest onset of spectral changes to spruce crowns in the various phases of beetle infestations. Although we found a few publications related to the drivers of these infestations (drought, persistence of standing or lying deadwood, spring temperatures), these topics could be further investigated and at larger spatial scales whilst using under-utilized spaceborne data types, e.g., hyperspectral, lidar, and thermal data.

Overall, there was greater diversity in the data types utilized among the airborne sensors, while spaceborne data were altogether less commonly used. For example, airborne hyperspectral data were utilized in 13 studies, particularly in relation to phenology. However, spaceborne hyperspectral data were not utilized in any investigations examined in this review. Other data types were also under-utilized, including both spaceborne lidar and thermal data. In addition, few studies were conducted at the spatial scale of the state of Bavaria or larger. Therefore, we conclude that future studies could be conducted using a wider diversity of spaceborne sensors at a larger scale in all research topics.

To increase the user uptake of RS products, as well as the performance and accuracy of models, we recommend the integration of contemporaneous in situ data. The literature suggests that the use of in situ data helps to legitimize and contextualize RS studies for audiences in decision-making roles, such as managers. Furthermore, the integration of in situ data can increase model accuracy in some cases. However, we found that numerous studies utilized high-resolution airborne data in place of ground-based data. If data collection is not possible, we encourage data sharing through publication or collaborations among researchers and managers.

Finally, we identified topical research gaps among under-studied or novel topics for forests in Bavaria. This includes the regeneration of stands lost to disturbances, monitoring species composition after disturbance or in relation to the management schemes outlined in the 'German Forest Strategy 2020', and the investigation of newly fragmented forests. Furthermore, historical and dense time-series data were not well-utilized over the review period. Mid-resolution datasets with global coverage, such as Landsat, Sentinel-1, and Sentinel-2, have been freely and publicly available for data collection since 1972, 2014, and 2015, respectively. These data continue to have under-utilized potential with the identified topics for investigations into Bavarian forests using remote sensing.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs16101805/s1, Table S1: Detailed parameters of the Web of Science search string; Table S2: Data collected from each publication reviewed in this study.

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