remote sensing

Review

Remote Sensing in Studies of the Growing Season: A Bibliometric Analysis

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Abstract: Analyses of climate change based on point observations indicate an extension of the plant growing season, which may have an impact on plant production and functioning of natural ecosystems. Analyses involving remote sensing methods, which have added more detail to results obtained in the traditional way, have been carried out only since the 1980s. The paper presents the results of a bibliometric analysis of papers related to the growing season published from 2000–2021 included in the Web of Science database. Through filtering, 285 publications were selected and subjected to statistical processing and analysis of their content. This resulted in the identification of author teams that mostly focused their research on vegetation growth and in the selection of the most common keywords describing the beginning, end, and duration of the growing season. It was found that most studies on the growing season were reported from Asia, Europe, and North America (i.e., 32%, 28%, and 28%, respectively). The analyzed articles show the advantage of satellite data over low-altitude and ground-based data in providing information on plant vegetation. Over three quarters of the analyzed publications focused on natural plant communities. In the case of crops, wheat and rice were the most frequently studied plants (i.e., they were analyzed in over 30% and over 20% of publications, respectively).

Keywords: phenology; end of season; start of season; season metrics; plant phenology; UAV; satellite data; earth observations

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1. Introduction

Phenology is a branch of science associating the events of the life cycle of organisms with their biotic and abiotic determinants [1]. Detailed knowledge of phenological phenomena and their mechanisms facilitates the identification of changes involved in plant growth and yield. The length of the growing season in a given area is the number of plant growing days. It determines the species of plants that can be grown in the area, as some plants require a longer growing season. Other species develop faster; hence, their growing season can be shorter. The length of the growing season is determined by multiple factors. Depending on the region, these include air temperature, frosty days, rainfall, and sunshine duration [2].

Changes in the length of the growing season may have both positive and negative effects on the yield of some crops [3–7]. A longer growing season may increase yields and improve plant living conditions on one hand, but may result in species modification on the other [8–11]. Changes taking place in plants are most often a result of climatic fluctuations; therefore, observations provide the basis for the formulation of conclusions about the consequences of contemporary climate changes [12–14]. In general, global warming is assumed to have a negative impact on the yield of staple crops; however, climate change may have a positive effect on crop yields in some regions [15–19]. A longer growing season may contribute to the diversification of crops or a possibility to harvest crops several times in one season. On the other hand, it may lead to the reduction in the number and types of cultivated plant species and varieties, unfavorable spread of invasive alien species, increased weed infestation, or higher irrigation requirements. A longer growing season may also disturb the function and structure of ecosystems in the region and indirectly affect the range and number of fauna species in the area [20–22].

Plant vegetation can be investigated with multidimensional temporal and spatial analyses. One of the most frequently used approaches in vegetation research is the method based on non-invasive and non-destructive remote sensing techniques [10,23–88]. As already mentioned, this method is based on the use of devices and techniques that allow measurements of plant characteristics and properties without direct contact with the analyzed object. In contrast to traditional methods, remote sensing facilitates a quick analysis and evaluation of plant growth and development conditions [89,90].

Plant analyses are mainly focused on the chlorophyll content [25] or substances contained in plants [91] and, consequently, the condition of plants [24,27]. Research on the growth and development of vegetation can be carried out in both strictly controlled laboratory conditions [29,79,92,93] and using satellite techniques [42,44,46,49–51,56,59,61,62,64–66,68,71,75–78,80,88,94–139] or other means of transporting remote sensing devices (UAV, airships, airplanes) [43,47,54,55,65,84,108–110,118,140–153]. Laboratory studies are usually carried out only on the scale of one plant or several specimens [22,29,85,92,154], while analyses carried out in larger areas (fields, provinces, continents, or global scale) require the use of remote sensing techniques based on spatial data acquisition [14,23,26,28,30–35,40,108–132,134–139,154–230].

The description of the growing season mainly consists in the determination of basic parameters (i.e., the start and end of the season). There are also attempts to define the peak season and its duration. The history of research on the temporal parameterization of the growing season is very long, as it dates back to the first decades of the 20th century [231]. For many years, measurements were based on traditional sources of information (i.e., direct phenological observations combined with meteorological data). The dynamic development of technology in recent decades has allowed for the use of remote sensing data, mainly properly processed satellite data with different temporal and spatial resolutions [10,14,23,26,28,30–35,40–56,58–72,94,95,108–132,134–139,151,152,154–230,232,233].

The start of season (SOS) (or often—the start of spring) is defined as a sharp increase in the green-up directly after a long period of photosynthetic dormancy [234]. At present, the beginning of the season is determined mainly with the use of remote sensing techniques, most often properly processed NDVI or EVI data. Growing season data are compiled as a smoothed curve, and season metrics are determined from the thresholds of seasonal amplitude. The term 'start of season' indicates the beginning of the growing season and usually refers to the date when there is a substantial increase in NDVI values. However, various SOS measures can be derived from the time-series (e.g., the time point with NDVI values exceeding a certain threshold) [235,236], breakpoints in the graph or the time point when the curve begins to rise [237], and the maximum development of the growing season (i.e., the time with the highest green-up increase rates) [238].

Another phenological parameter measured with the use of remote sensing techniques is the 'end of season' (EOS) [8,23,32–34,36,38,40,140,143,155,157,158,161,162,164–166,169,171,173,176,177,180,182–186,188,189,191,194,195,197–201,204,208,212,215,217,219,220,223,225,227,228,239–257]. It indicates the moment of a marked decrease in the values of certain plant indicators. The 'length of season' is most often defined as the duration from the start (SOS) to the end of the season (EOS). Some researchers have also defined the 'peak of season' as the date of maximum NDVI values [73,77,112,115,139,179,189,195,199,200,208–210,213,220,246,258–261].

Leaf greening is an important attribute of vegetation throughout the growing season and is a basis for quantifying the water, energy, and carbon exchange between the atmosphere and the biosphere [262–264]. A special case analyzed in terms of the growing season transition dates is the impact of urban complexes. The growing season in cities is generally longer than in non-urban areas [265].

Phenological phases can be established based on several types of observations (i.e., (1) direct visual observations by a human observer; (2) close-range near-surface measurements; and (3) satellite remote sensing) [71]. Direct visual observations of plant phenology have been carried out for over a century in many locations, and there are large observation networks in different regions of the world (e.g., the Pan European Phenology Network [266,267] and the National Phenology Network (NPN) [244] in the United States).

Growing season dates may differ in agricultural and urban areas [62]. This is related to the fact that, in autumn, leaves remain on urban trees for a longer time. Monitoring of vegetation may also be carried out with the use of the solar-induced fluorescence technique [268]. Radar is another relatively frequently used sensor for monitoring vegetation [151,269,270]. In combination with ground-based data, it can be a valuable source of information.

Special IT tools have even been devised for a better and faster analysis of vegetation data (e.g., the QGIS plugin developed by Duarte et al.) [195]. This plugin is intended for quick identification of various stages of vegetation growth based on multiyear MODIS observations.

One of the effects of changes in the length of the growing season may be the increased accumulation (sequestration) of carbon in forest [158,271,272] or grassland [152] areas.

The research on plant phenology is extremely important from the point of view of food production. Investigations of arable crops predict that, in the future, there may be changes in the possibility to cultivate species with specific requirements in climatic zones other than at present [273,274]. On the other hand, this research supports modifications of the requirements aimed at better adaptation of crops to climate change [275,276]. In the case of natural vegetation, analyses of the growing season may provide better understanding of species encroachment into areas previously occupied by less climate-demanding vegetation.

The aim of this study was to compile a comprehensive review of investigations based on remote sensing methods used for the determination of plant phenology in various aspects. In the scientific literature, there are reports summarizing this type of research, but they represent a merely fragmentary approach limited to a specific region, type of use, period of time, or data. There is no comprehensive study summarizing studies conducted with the use of specialized tools. This review is intended to fill this gap.

2. Materials and Methods

The most common approach in review papers consists of bibliometric analyses of available journal databases [8,9,11,22,24,71,79,89,90,93,142,207,272,277–281]. Publications included in the Web of Science Core Collection database were the basic material used in the present study; these were found using the following filters:

- abstract: "remote sensing" + "growing season", keyword plus: "phenology", "satellite", "ground";
- abstract: "remote sensing" + "growing season" + "airplane", "UAV", "ground-based", "flux", "crop monitoring", "forest", "optical", "radar", "thermal", "microwave"; and
- abstract: "remote sensing"; keywords: "start of season", "end of season".

The search yielded over 1295 publications. All search effects were combined into one database. Pre-2000 publications and duplicate entries were removed (Figure 1). In the subsequent stage, a manual selection of articles was carried out by analyzing the title, abstract, and content of the article with the use of the following questions (verification stage 1):

(a) Does the paper fall within the scope of phenological research?
(b) Does the paper address the issue of the plant growing season?
(c) Were the remote sensing data used in the study satellite, low-altitude, or ground-based?

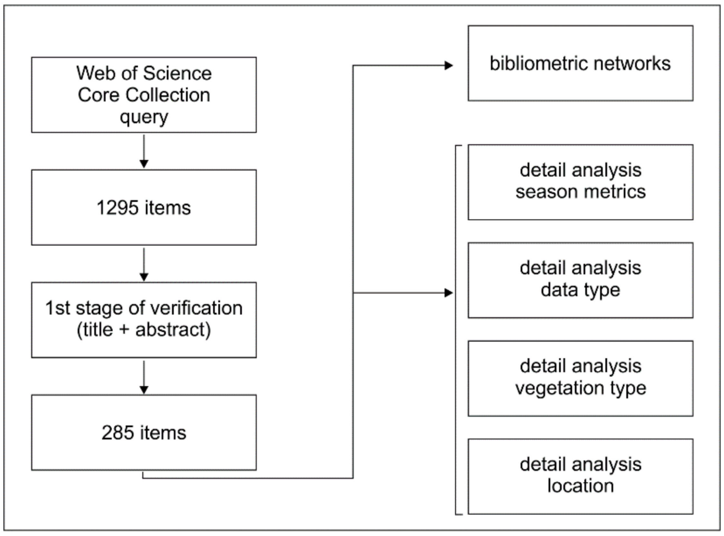

Figure 1. Procedure scheme—creation of a database and analysis of articles.

Finally, 285 publications [10,14,28,30–34,36–59,61–70,72–78,80–88,96–107,109–131, 133–141,143–148,150–157,159–179,181–206,208–230,232–234,240–243,245–247,249–261, 265,269,277,279,282–354] were compiled and analyzed using the VOSviewer software [355,356]. This software is applied for bibliometric analyses of the network of links and dependencies between the keywords contained in the publication. The aim of the analysis was to investigate the relationship between keywords related to vegetation in terms of the beginning, end, and duration of the growing season. From the available link types, a link based on partial calculation of the dependency strength was selected (Figure 2)—when an author is a co-author of a paper together with other authors (number n), the link has the strength of 1/n for each of the n coauthor links. There are similar differences between the two counting methods in the calculation of the strength of cooccurrence, bibliographic coupling, and co-citation links.

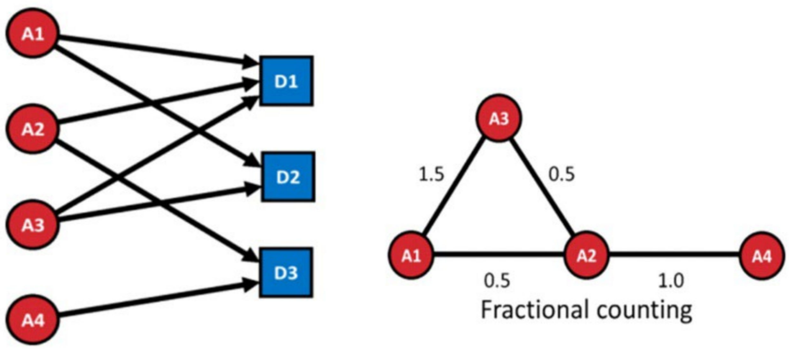

Figure 2. Scheme for the calculation of the strength of links between publications and authors based on the "fractional counting" function [Based on the VOSviewer manual].

Detailed query based on a detailed search for specific keywords was carried out. Publications with keywords related to season metrics (e.g., "start of season", "end of season", "length of season", and related phrases used by the authors were analyzed). The publications compiled in the database were analyzed using Zotero software, which searched for possible combinations of words defining the season metrics (i.e., "onset of season", "season end", and "duration of the growing season"). The Zotero lookup engines use article metadata, indexed content, and assigned tags. The results were summarized as the basic statistics.

The next stage of the detailed analysis was focused on:

(a) localization of the research taking into account climatic zones;
(b) scales of studies;
(c) types of input data used; and
(d) types of plant communities studied.

The analysis was based on the traditional verification of the substantive content of individual publications.

3. Results

3.1. Link Analysis

The clustering of information related to the keywords provides a certain view of the trends in the analyses performed in the publications (Figure 3). The publications analyzed in the literature review in terms of the keywords were organized into eleven clusters of various sizes. The largest cluster comprises the linking of 75 keywords (red color in Figure 3). Keywords such as "phenology", "spring phenology", "climate change", 'NDVI", or "MODIS" occur most frequently in the analyzed set of publications on the growing season (Figure 4). This is associated with the applied key of the search.

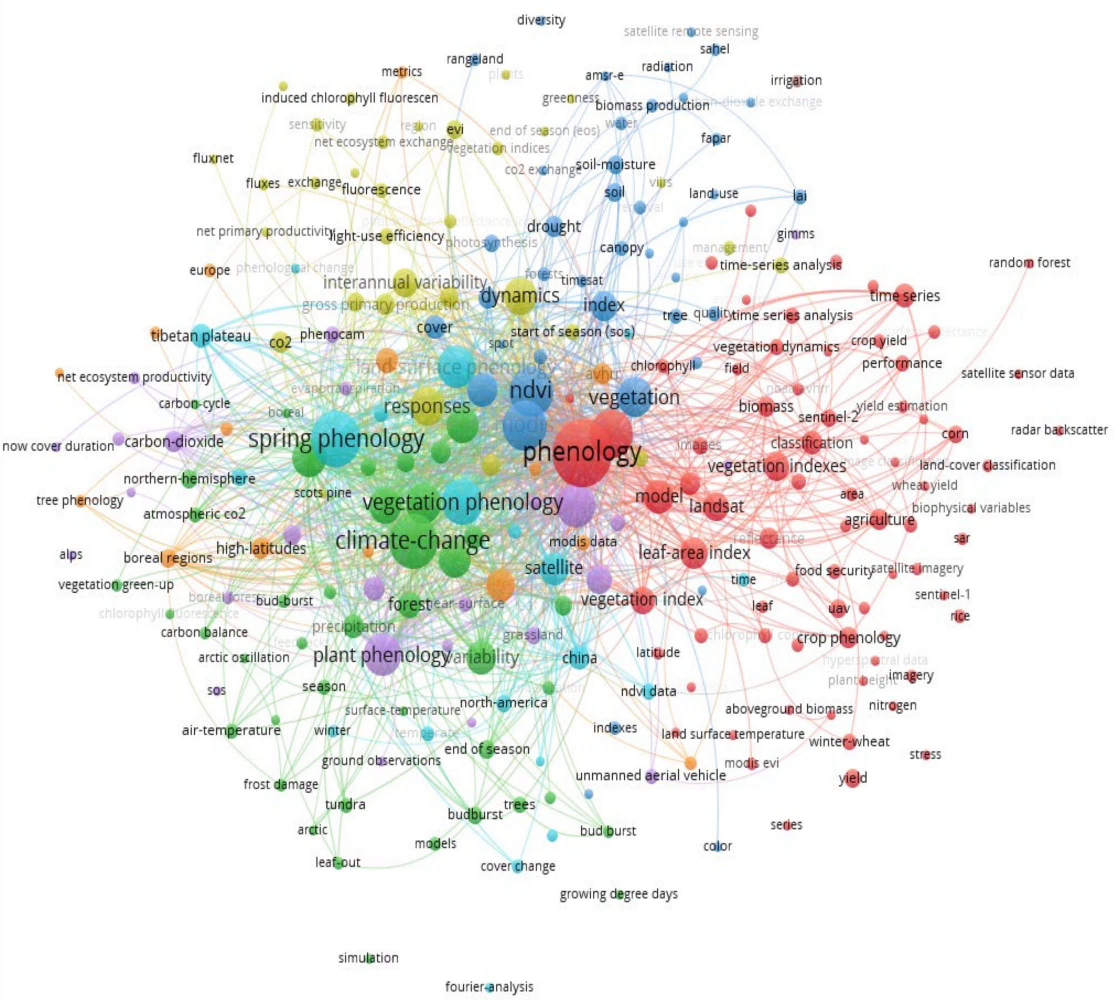

Figure 3. Link analysis of keywords.

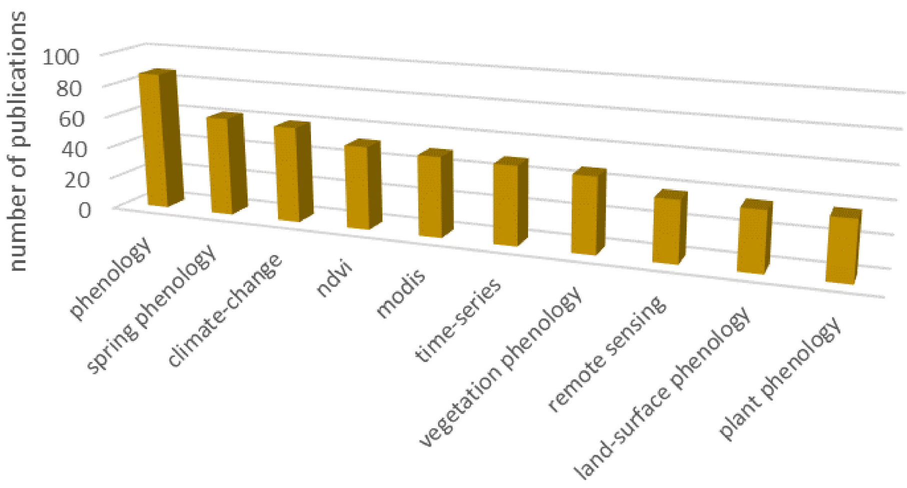

Figure 4. Most frequent keywords used in the analyzed articles.

The link between the term "start of season" and "phenology" is obvious due to the very close conceptual link between these words. There are also links (common use in keywords) between the words "start of season" and "snow cover duration", "precipitation", or "budburst". The analysis of keywords provides a basis for grouping terms into mutual cause-and-effect relationships without indicating the cause and the effect. In the case of the growing season, the analysis of keywords facilitates inference about the impact of various factors on its beginning, end, and duration.

Importantly, the analysis of keywords should take into account their spelling. Sometimes, several different keywords have the same meaning (budburst, bud burst, but-burst). This may have a negative impact on the search results in such cases.

The frequency of the "start of season" keyword showed a close link of this phrase with "phenology", "spring phenology", "climate-change", "vegetation phenology", "plant phenology", "trends", or "MODIS" (Figure 5a). Less frequently, the phrase "start of season" is linked with "snow cover duration", "carbon-dioxide", or "backscatter", which may imply negligible author interest in the analysis of the dates of the start of the growing season relative to the snow cover, CO_2 absorption, and backscattering.

Before 2015, "spatial resolution", "stress", "frost damage", "CO_2", and "different vegetation index" were the most frequently used keywords in publications. In turn, the most recent publications (after 2018) focused on keywords such as "crop phenology", "digital camera", and "unmanned aerial vehicle". Such a distribution of keywords may suggest rapid implementation of modern technologies in studies on the growing season.

The links between phrases related to the beginning, length, and end of the growing season exhibited high variability. The definition of phrases describing the phenophase events is not clear. The beginning of the growing season is defined in various ways by different authors; hence, various phrases are used as keywords. "Spring phenology" is much more frequently used than the "start of season" phrase. This may lead to a conclusion that, before formulation of the keywords, authors should analyze those used in similar publications, in order to provide a correct definition and increase the efficiency of searches.

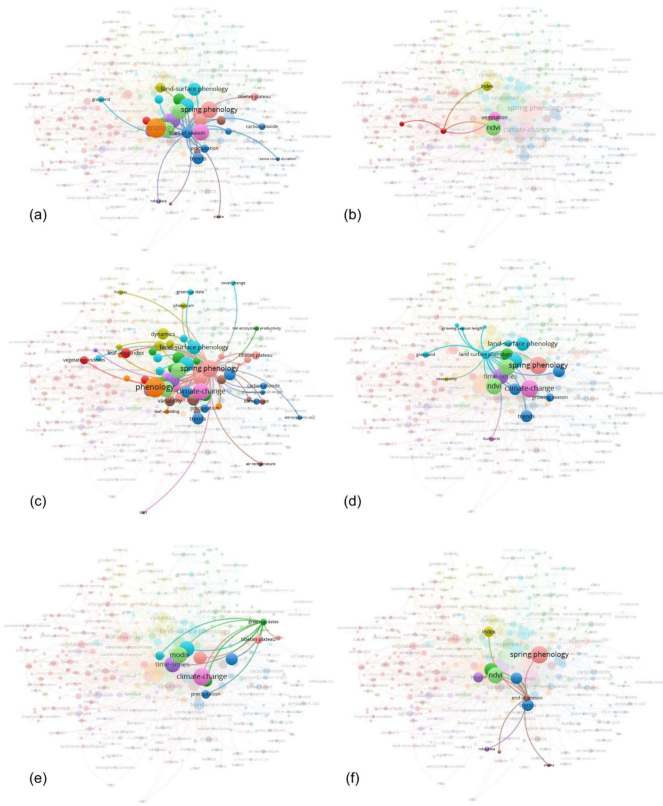

Figure 5. Links between the selected keywords in terms of their strength; (**a**) start of season; (**b**) soil; (**c**) spring phenology; (**d**) land-surface phenology; (**e**) green-up dates; (**f**) end of season.

The phrase "land-surface phenology" is most often used with the keywords "green up", "spring phenology", "phenology", and "climate-change" (Figure 5d). The greatest distance in the figure related to the low co-frequency of "land-surface phenology" was observed for the "reflectance", "net ecosystem productivity", "Sentinel-2", "cover change", and "green-up date" keywords. The phrase "green-up dates" is most often linked with "Tibetan Plateau" and "winter" (Figure 5e). In the case of the end of the growing season defined by the "end of season (EOS)" keyword, this phrase in the publications was accompanied by the "NDVI", "start of season", or "remote sensing", and "MODIS" keywords (Figure 5f).

3.2. Main Research Topics

3.2.1. Season Metrics

Remote sensing investigations have focused on various growing season parameters. The first of the metrics is the beginning of the season defined as "start of season" or, less frequently, "start of spring", "beginning of season", or "spring onset" (Figure 6). Authors have also described the beginning of the spring phenophase, directly referring to the vegetation cover as "green-up" or "spring vegetation green-up". A wide spectrum of metrics were presented by Baumann et al. [331]: "green-up (GU)", "start-of-season (SoS)", "maturity (Mat)", "senescence (Sen)", "end-of-season (EoS)", and "dormancy (Dorm)". These were determined based on MODIS/Landsat satellite data. Similarly, Berman et al. [329] analyzed the "start of season (SOS)", "peak instantaneous rate of green-up date (PIRGd)", "peak of season (POS)", and "end of season (EOS)". An example of another parameter is the "beginning of spring growth (BOSG)" described by Boyte et al. [340].

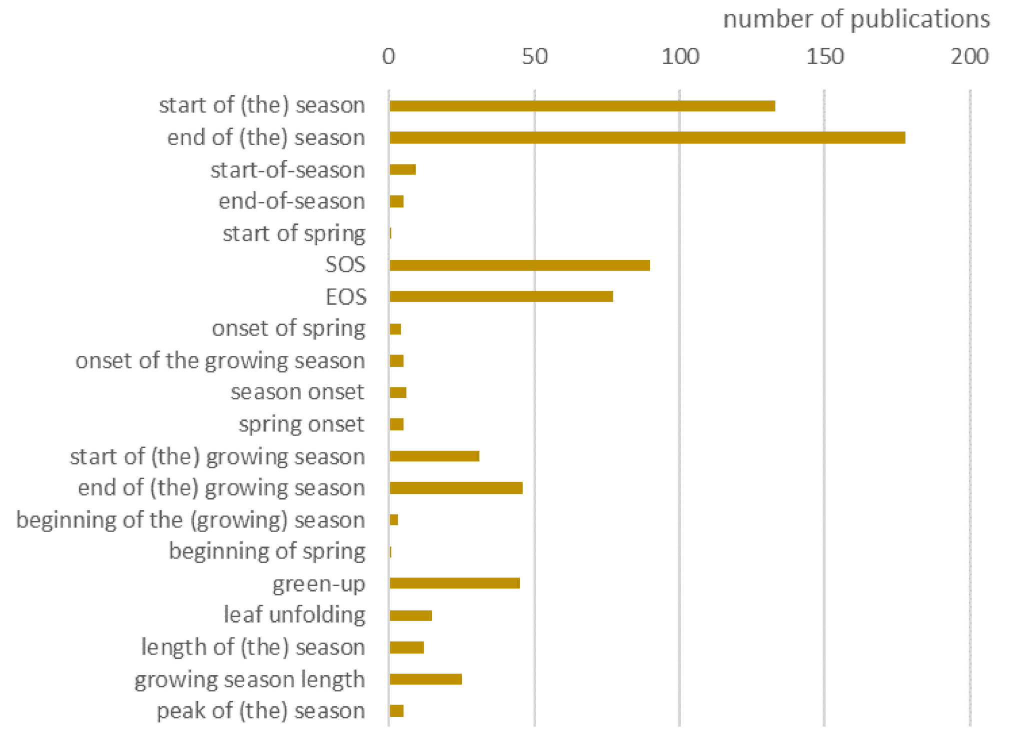

Figure 6. Frequency of phrases expressing season metrics in the analyzed publication database.

Analyses have been carried out for many years to verify/validate the methodology of determination of the growing season parameters based on remote sensing and a comparison with traditional methods [170]. Many studies, both those regarded as 'classic' and cited repeatedly [234] and the contemporary ones [341], present the problem of the methodology of determination of season metrics based on remote sensing data. There are also attempts to improve the existing algorithm models [49]. An interesting example of combining various data sources and their mutual validation is the use of low-budget photo-traps, which facilitate local analysis of plant development phases [64] and comparison of the indicators obtained with satellite data.

Some researchers have focused on a detailed analysis of factors influencing some parameters of the growing season, in particular, the impact of snow cover on the beginning of the growing season [59]. Spring frosts were also analyzed in relation to season metrics [204].

Research on the beginning and end of the growing season is often only a tool and a preliminary stage in far more advanced analyses (e.g., determination of the crop calendar for rice in [53], identification of forest habitat types [52], or analyses of the occurrence of fires [242]). Interesting investigations were conducted by [265], who studied the impact of the urban tissue on the differentiation of the beginning, end, and peak of the growing season. Researchers have used advanced digital tools to analyze the vegetation season metrics. A popular tool is TIMESAT, which was designed and developed at Lund University. The use of open-source GIS tools has also been described in the literature [195].

3.2.2. Location of Research

The distribution of the current research on the growing season with the use of remote sensing techniques is disproportionate. The majority of the analyzed studies have been conducted in Asia, Europe, and North America (i.e., 32%, 28%, and 28%, respectively) (Figure 7). Some studies analyzed data covering the entire area of a given continent (e.g., Europe [45,197]), or a large geographically homogeneous part of a continent (e.g., West Africa [58,210,323] or Southern Europe with the Maghreb [205]). Africa (5%

of the analyzed studies), Australia (4%), and South America (2%) are much less popular among the researchers. This was also found in the case of studies (2%) carried out in the Arctic area, which is particularly distinguishable from the other regions.

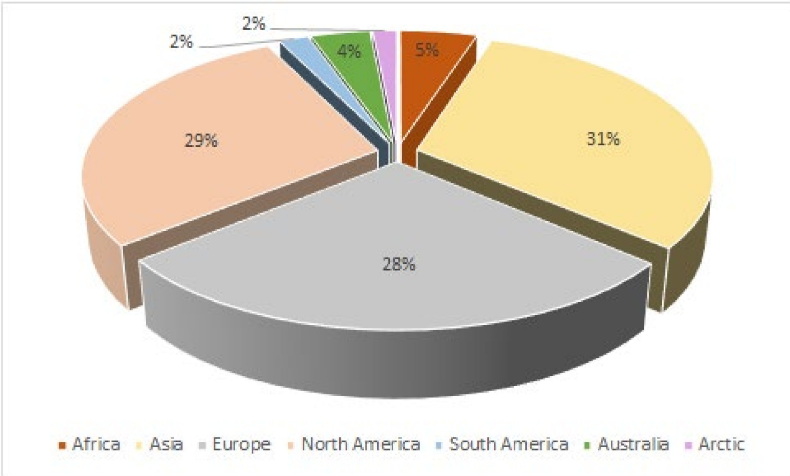

Figure 7. Percentage of research carried out on the continents. The sum does not coincide with the number of the analyzed publications, as studies performed on the global and hemisphere scale are not included in the analysis.

Some research has focused on large areas (e.g., the Northern Hemisphere [36,63,121,134,178,265]). Some researchers have used large datasets from the entire world and undertaken phenological investigations from a global perspective [37,218,325,345]. In most European countries, there were only single papers or no studies were recorded (Figure 8). The investigations were most frequently undertaken in Germany and France. In Asia, over two thirds of all publications (70%) were based on research conducted in China, and 10% were in India.

Figure 8. Remote sensing research conducted in Europe (number of publications shown by the query is indicated in the circles).

Precise determination of the climatic zone where the research was conducted would require a very thorough analysis of individual publications. This review paper presents the approximate location in relation to the physical regionalization. It should be noted that the reference to climatic conditions is difficult in many cases due to their high variability in the analyzed area. Europe, where the studies were carried out in a warm and dry climate [54,192,205], high mountain conditions (Swiss Alps—[170]), warm maritime climate (e.g., Ireland), or temperate climate (e.g., Germany) is one example. Similarly, in China, studies of the growing season were conducted in Tibet [353] and in loess uplands [259].

3.2.3. Research Scale

In terms of the scale of the research, the publications can be assigned to several groups. The first of these groups comprises research conducted on a global scale. For example, Ren et al. [325] analyzed the impact of climatic conditions on wheat phenophases from a global perspective; additionally, they analyzed the influence of haze on phenology in India and China.

Studies on a regional scale have been conducted in the USA [261,357,358], especially in the Corn Belt [329]. Similar studies have been carried out in Canada [194], where the analysis covered 26 areas in Wapusk National Park [32] and in northern Yukon [183]. Another relatively vast area was investigated in China [104] (i.e., North China Plains [359]). Zhu and Meng [219] analyzed the temporal variability of the phenology of grasslands in northern China from 1982 to 2010. In China, Wang et al. [126] analyzed the differences between the courses of phenological phases using different methods for the determination of the phenological transition dates. The data used in this study were provided by the MODIS sensor. As reported by the authors, the LAI (leaf area index) product is more suitable for analyses than the analogous phenological product in the area of evergreen forests and crop fields, whereas the phenological product provides better results than LAI in areas covered by low vegetation cover and meadows. Regional studies on plant phenology have also been conducted in East Africa [360], West Africa [58], and North and East Australia [42,327]. In Iran [354], researchers used data from the MODIS spectroradiometer to analyze the development phases in orchards surrounding Lake Urmia. Similarly, Rankine et al. [130] used MODIS data and ground-based data from observation stations to determine phenophases in the tropical zone. Baltzer et al. [242] investigated the influence of plant development phases on the occurrence of fires in the polar zone. An interesting study was carried out by Skakun et al. [129], who considered the middle states in the USA and Ukraine as research fields to develop a methodology for mapping winter crops based on phenology.

At the local scale, most often defined as the scale of a field [361] or several fields, researchers have performed a detailed analysis of crop development conditions [139,151,152,268,269,326,362,363].

3.2.4. Source Data

Remote sensing data used in the analyses of vegetation development stages can be divided into several groups. A clear advantage of the use of satellite data was observed (over half of the analyzed publications). In slightly over one quarter of the analyzed articles, the authors used ground-based data. Unmanned aerial platforms equipped with devices recording electromagnetic radiation in the range reflected and absorbed by plants are a relatively new source of spatial information about plant phenology [43,47,54,55,65,84,108–110,118,140–153]. Investigations conducted with such devices accounted for less than 10% of all the analyzed publications. The authors of papers on the stages of vegetation development also used indirect sources of remote sensing information (e.g., databases providing processed information from long-term satellite observations such as SPOT-VEGETATION or AVHRR) [28,177]. Such sources were mentioned in slightly more than 10% of the analyzed publications.

Due to the frequent use of satellite data, both alone and in combination with other data, the most frequently used information is provided by the MODIS sensor aboard the

EOS Terra and Aqua satellites (Figure 9). Satellite data from Landsat and AVHRR are also a frequent source of information about vegetation. In recent years, there has been an increase in the number of publications on the plant growing season analyzed with the use of satellite data (Figure 10), especially those from commonly available medium-resolution satellites such as Sentinel-2.

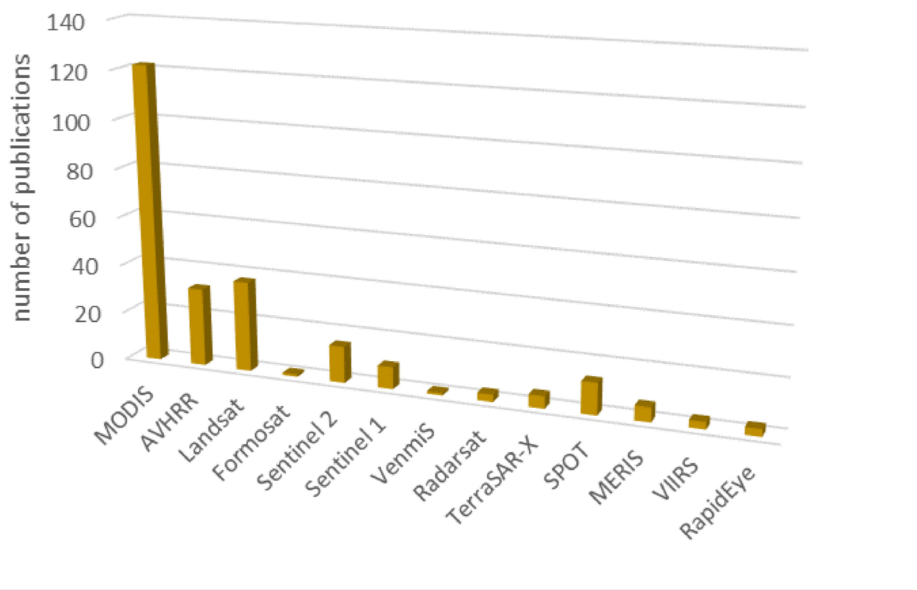

Figure 9. Number of publications with data provided by specific satellite sensors; most of the studies were based on more than one satellite dataset.

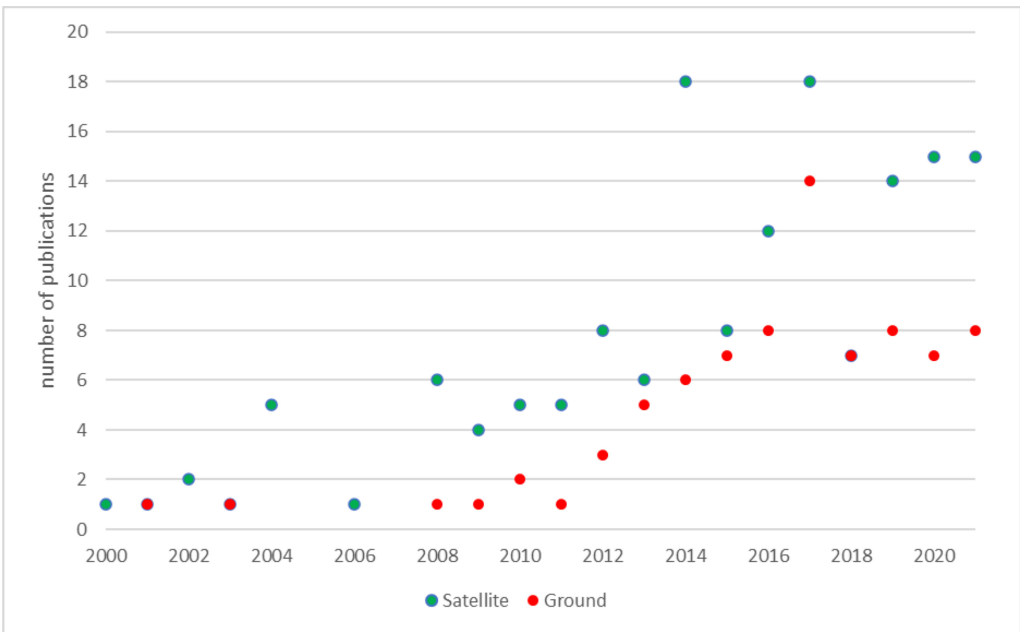

Figure 10. Variation in the number of publications based on satellite and ground-based data.

Since 2008, the number of publications based on ground-based data has increased, which may be associated with the development of the PhenoCam network for phenological observations [364] and processing of data from cameras directed at individual plants or groups of plants.

Satellite information combined with climate data and ground-based measurements are an invaluable source of information. Berma et al. [329] used satellite data and reanalysis data supported by information from the PhenoCam network to determine the variability of selected phenological dates in the U.S. Using ground-based data and MODIS satellite observations, Gao et al. [326] performed a net primary productivity analysis in the maximum plant growth phase in China. The authors used the NDVI index calculated from a hand-held spectroradiometer. To acquire high-resolution information about the development of vegetation, Gao et al. [97] used data from the commercial VENμS satellite and analyzed two growing seasons to determine corn phenological dates. Additionally, they used data from Sentinel 2 and Landsat 8 to obtain an operational product. Li et al. [365] used EVI data series provided by MODIS satellites to determine the beginning and end of the growing season in winter wheat. MODIS data and ground-based observations were used by Rankine et al. [130] to determine phenophases in the tropical forests of Brazil. Processed MODIS and SPOT data were used to monitor the functioning of pastures located in northern China [219]. Shen et al. [327] used LST and EVI data in combination with meteorological data to determine the relationship between crop phenology and climatic conditions. To determine the beginning and middle of the growing season, Younes et al. [42] used a combination of Sentinel 2 and Landsat data. Ren et al. [26] used 1981–2014 data from the AVHRR and MODIS satellites to analyze the vegetation from a long-time perspective. A very interesting trend in the phenology research is the application of knowledge provided by analyses of the time-series of vegetation indices to classify crop plants. To identify communities of crops such as corn, alfalfa, and wheat, Jakubauskas et al. [240] used the NDVI index time-series from AVHRR and constructed models for the identification of crops in Kansas. Ulsig et al. [128] used a MODIS data series from 2002 to 2014 to determine the annual variability of NDVI and PRI. MODIS data were also used by Ibrahim et al. [58] in their analyses of the variability of the growing season in Africa. Data from ground-based observations and MODIS data were used by Skakun et al. [129] to forecast the yield of winter crops. The authors also used a combination of various satellite data (Landsat and MODIS) [326] for the estimation of the plant growth rates in an arable field. MODIS and AVHRR, in combination with Landsat data (daily maximum, minimum, and mean temperature, and snow cover) and field measurements, were used to determine the onset and end of the growing season using the BLOSSOM methodology [194]. Processed data from the MODIS spectroradiometer were also used to determine the growth phases in orchards [354]. Various approaches were used by Shen et al. [48] to downscale the information from low-resolution satellite data (250 m) provided by the MODIS spectroradiometer to higher resolution (Landsat data) using various mathematical methods. Fraser et al. [183] used AVHRR data and available Landsat scenes to determine the temporal and spatial variation of vegetation in the northern Yukon area. A series of long-term AVHRR and SPOT-VEGETATION observations were used to determine the multi-seasonal variability of plant vegetation in East Africa [37]. The combination of satellite and ground-based data allowed the authors to determine the impact of various factors (mainly climatic) on the variability of vegetation growth in this part of the globe. In their study, Yang et al. [26] used a time-series based on the AVHRR sensor to analyze the influence of various meteorological factors on plant productivity. The results indicated the greatest effect of precipitation, potential evapotranspiration, and the number of growing days on the temporal and spatial variability of the vegetation season.

The rapid technological progress facilitating the use of unmanned aerial vehicles (UAVs) has resulted in an increase in the number of publications related to the acquisition and processing of phenological data provided by low-altitude measurements [43,84,132,146,152] (Figure 11). Publications presenting data from low-altitude flying platforms account for over 9% of all data used. Due to the costs, indicators based on RGB cameras attached to UAVs are relatively frequently used in studies [151]. The investigations conducted by Klosterman et al. [118] are an example of the use of the green chromatic coordinate (GCC) indicator based on the time-series of drone RGB images in forest phenology studies. Burkart et al. [269] adopted the method of time-series observation of RGB images provided by UAVs converted into GRVI (green-red vegetation index). Yang et al. [39] used RGB data collected from a UAV to determine the dates of the rice phenophases. For the same purpose (analysis of rice growth), Xue et al. [363] used a drone-mounted Tetracam camera and ground-based measurements to determine the relationship between GPP and the vegetation phase.

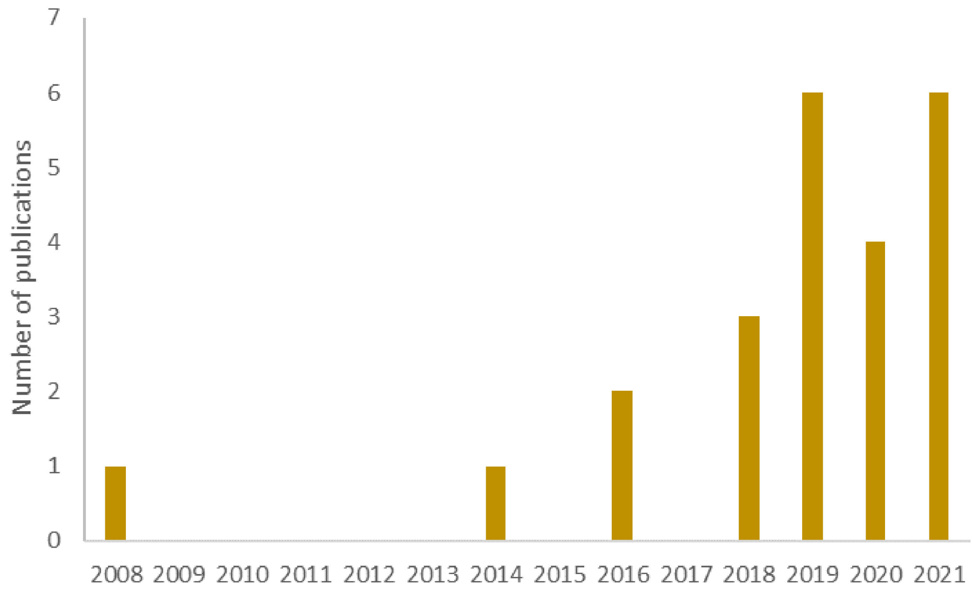

Figure 11. Number of publications based on UAV data in the analyzed multiyear period.

Given the fairly widespread use of UAVs, the airship seems to be quite an original research platform [366]. In addition to standard visible-light and near-infrared cameras, the authors of the study used a thermal imaging camera to determine the condition of vegetation at an early stage of development.

An equally important trend in the remote sensing phenology research consists of analyses based on ground-based observations. The most frequently employed methods include measurements at special stations with the use of stationary measurement devices at flux-stations [60,184,213,334,339,367]. PhenoCam stations are also a rapidly developing system for measurements of plant vegetation parameters [45,364]. Measurements at these stations are performed in a time sequence using RGB cameras directed at region-specific plants [106,364]. The literature also provides reports on observations dedicated to specific crops (e.g., where the measurement was performed by a mobile hyperspectral camera platform mounted above a rice field) [368]. Zhu et al. [268] used a hand-held spectroradiometer to determine phenophase parameters. In turn, Zhou et al. [21] used spectroradiometric measurements from a two-year period (2015–2017) performed by a camera mounted on a UAV to determine wheat phenophases. Researchers very often use a combination of various satellite and ground-based methods to monitor crops [38]. For instance, Zheng et al. [139] used two portable spectroradiometers to measure rice parameters every five days in order to determine the plant development conditions.

3.2.5. Vegetation Types

Most of the analyzed publications (over 70%) focused on natural or semi-natural areas, whereas almost 30% of publications presented studies on arable crops (Figure 12).

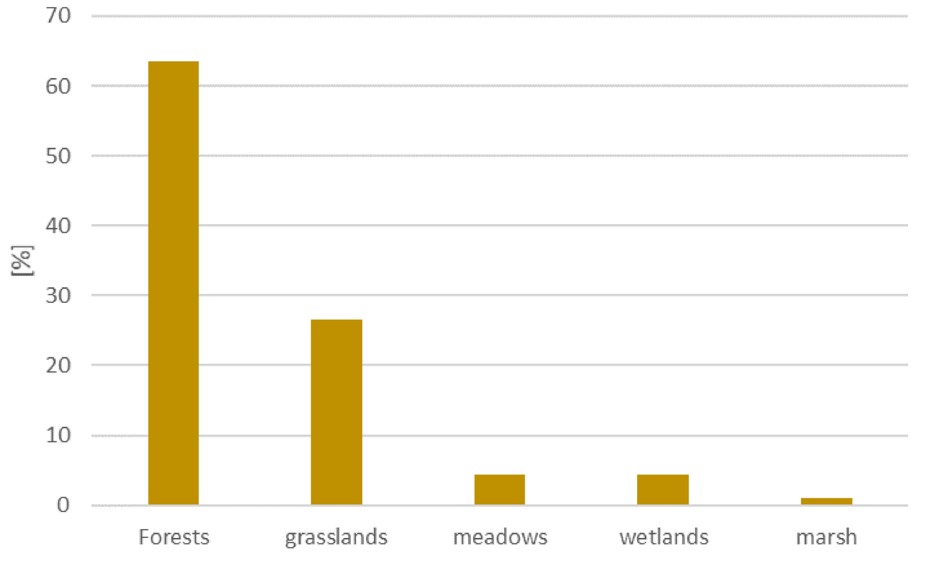

Figure 12. Percentage of the number of studies focused on different types of vegetation in the analyzed set of publications.

Forests account for over 50% of the analyzed plant communities (Figure 12) [31,51,56,63,72,173,177,179,181,182,209,221,227,245,250,256,261,338,344,348,351,369,370]. Meadows, grasslands, and wetlands mainly represent the other cases [10,26,60,63,72,120,147,162,187,213,225,295,313,336,350]. An example of this type of research is the study conducted by Ibarahim et al. [58], where satellite phenological data were used to monitor natural plant communities in West Africa.

Monitoring of crops for the determination of the seasonality of vegetation was mainly related to the major cereals [327,362]. The analyses of wheat and rice represented over 50% of all studies of arable crops [13,24,28,34,38,39,41]. Papers on maize accounted for 10% of the analyzed publications [3,5,65,292], whereas slightly less research has been carried out on vineyards and other crops such as soybean [98,101,132], oat [285], barley [269,301], and horticultural plants [30,212,354] (Figure 13).

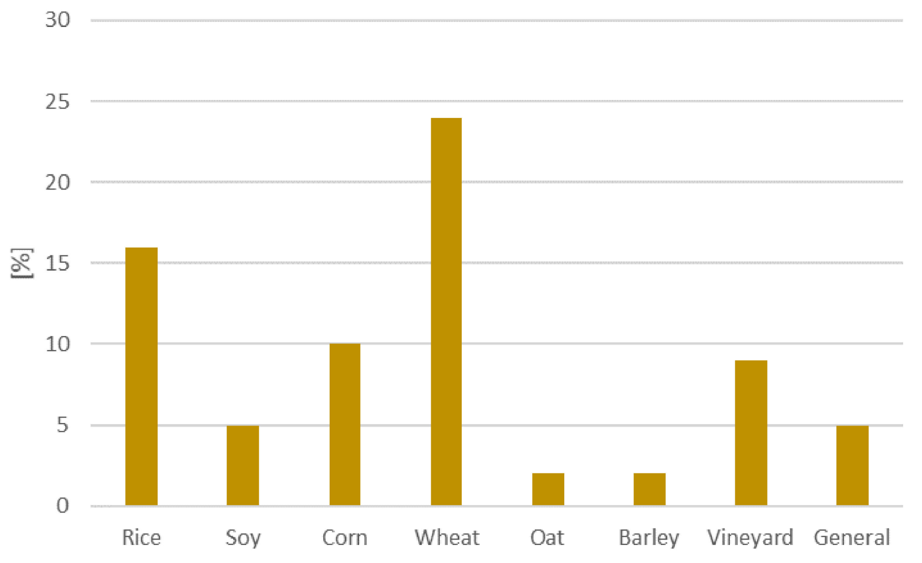

Figure 13. Percentage of the number of studies focused on different types of crops in the analyzed set of publications.

4. Discussion

An important problem in review studies on a specific issue may be the subjectivity of the selection of publications. Review studies are based on a set of publications selected arbitrarily by the authors in terms of the specific subject associated with remote sensing research on plant phenology [371–373]. Review articles may also be based on bibliometric data contained in their metadata, but manual verification with the use of subjective criteria and, additionally, the author's experience, is an indispensable element [374]. It seems that the available tools can be very helpful in searching for literature references, but they have serious limitations, as evidenced by the search path used in parallel to the basic search (i.e., based on keywords representing the basic season metrics: 'start of season' and 'end of season' (see the Methods section)). Consequently, the search did not yield a large number of articles on season metrics due to the absence of specific word combinations in the metadata; however, specific references could be found through a traditional literature query. A combined search path was used in the literature review presented in this article.

Noteworthy, the analysis of the set of publications in terms of the length of the research period revealed that individual data resources (data based on climatic indicators, data from direct observations of plants, remote sensing data) were not temporally consistent. The climate data used originate from the middle of the last century [36,330]; therefore, they represent the longest continuous data series available. Phenological data derived from direct observations have also been conducted for several decades at permanent research sites [343]. The beginning of remote sensing data acquisition dates back to the early 1970s when the Landsat satellite mission began, and this is the period of origin of the oldest remote sensing data obtainable [111]. AVHRR data acquisition started at the beginning of the 1980s [375], and the MODIS sensor was introduced a decade later [258]. However, there is still a clear difference in the length of data series acquired with the traditional method and with the use of remote sensing.

The large diversity of the currently available RS data should also be considered. The AVHRR and MODIS data series fall within the scope of satellite data. The multiyear automated acquisition is the premise of space missions. The research conducted with the use of unmanned aerial vehicles (e.g., [54,118,150]) consists of single measurements, most often performed during one growing season. The intensive development of the UAV technology used for environmental monitoring (Lee et al. 2018) will probably facilitate the acquisition of large amounts of data from sensors mounted on unmanned platforms in the future. However, the existing technological and legal solutions [376] do not allow regular, repetitive, fully automated, and autonomous flights over a given object to acquire spatial data, as is the case with sensors mounted on satellites. UAV-mounted sensors already ensure much higher spatial resolutions than satellite imagery and help to avoid problems posed by unfavorable weather conditions and the resulting gap in satellite data. However, they do not ensure the acquisition of long time-series data in a consistent and repeatable manner for a given area.

Due to the availability of a large amount of data in a wide spectrum, a substantial portion of publications did not analyze the growing season sensu stricto but focused on the issue of the validation of one research method using another approach (e.g., [137]).

High spatial resolution may have both positive and negative effects on phenological information. Insufficient spatial resolution may cause errors in the analyses of specific plants in the arable field scale. It may cause a problem of pixel heterogeneity [377], which may result in incorrect determination of the dates of individual phenological phases [35].

High-resolution data facilitate observations of single plants, which in a sense may cause problems associated with the inability to extrapolate information from one plant (often wrongly chosen) on the whole species. In such a case, there are also problems of the impact of habitat conditions, even within one field. Excessive amounts of data also pose difficulties with processing and correct inference. Appropriate balancing of the spatial and temporal scale helps to avoid errors in the interpretation of vegetation-related phenomena. The combination of the possibility of obtaining high-resolution data with fast communication over long distances and almost instant multithreaded analysis will allow future phenological observations to be carried out on each individual of a given species separately. Unfortunately, at present, authors are struggling with the problem of increasing the resolution in the context of the speed of the analyses performed and the possibility of extrapolating the results to larger areas.

Remote sensing input data on plant vegetation are usually acquired by the satellite in visible and near-infrared light [23,26,378]. The methods of data acquisition have aspects that limit their usefulness. The problems that may considerably affect the analysis and inference based on a multiyear observation series of the NDVI indicator are related to changes in the sensor observation angle, weather conditions (fog and cloud cover), and land cover (snow). These problems may lead to underestimation or overestimation of the index value, which impedes the determination of the growing season dates [23,248].

As shown by research, one data source may not be sufficient for correct assessment of the dates of individual phenophases [137,331]. Given the need for very precise determination of phenological events in temporal-spatial terms, it is necessary to combine several data sources with different resolutions for the most accurate analysis of phenology [127,137,311]. Very frequent ground-based observations (several times a day) non-validated by satellite data are also hardly useful [150].

Data on the growing season are analyzed on various spatial scales, starting with the global scale (e.g., [325]) through the regional scale (e.g., [63]) to the strictly local scale limited to the area of one field (e.g., [144]). The methods employed in these studies are characterized by a different spatial resolution and frequency of data acquisition and aggregation, starting from low-resolution AVHRR [165,167] or MODIS data aggregated to 8- or 16-day products [181,220] to high-resolution (centimeter-resolution) data from UAV [118,150] and RGB camera measurements [45,137] yielding continuous data covering the selected vegetation index. Such a range of possibilities facilitates the selection of appropriate data for the analyzed object. A much larger number of works based on low-resolution data (e.g., MODIS), facilitate analyses related to vegetation on a regional and local scale. The advantage of MODIS data over other data is the long period of observation, cost-free acquisition, and the large number of data processing tools. Satellite data with higher resolution (e.g., Sentinel-2), are used even less frequently due to the relatively short burst. In the following years, the number of publications is likely to increase in the importance of medium-resolution satellite data with a resolution of up to 10 m. This type of data will be used for regional and local analyses.

The use of combined data with different spatial and temporal resolutions allows the transition of low-resolution data to a higher resolution [180,379], which largely improves their interpretation and spatial adjustment.

The advantage of using UAVs for phenology monitoring is the substantially lower cost of data acquisition [132,149] and the higher time resolution than in the case of satellite- or aviation-derived data [108,142,380]. On the other hand, UAV monitoring has disadvantages. One of them is the small scale of the obtained data (i.e., an area of the field or a small farm). In the future, when the powering of unmanned aerial vehicles will be more efficient and the charging problem is solved, data acquisition will be possible continuously, and data will be able to be transmitted over long distances.

As already mentioned, it is impossible to link the publications with the climatic zone unambiguously due to the scope of the analyzed material. Undertaking a literature review in the context of specific climatic conditions and the related growing season dynamics can be an interesting challenge, which was beyond the scope of this study. There are reviews of the growing season of a specific type of plant communities [381], variability of phenology within a country, and studies based on data provided by a specific sensor. However, there is a gap in the type of studies conducted in different climate zones. This review confirms that advanced bibliometric tools can be used in such research by establishing links between a given parameter of the growing season (e.g., start of season) and a given climate zone indicated in thematic publications. The analyses carried out in this study showed that, in the analyzed set of publications, there were clear connections, for example, between the "start of season" and the region of Tibet or the "end of season" and Alaska. Performing a series of reverse analyses using climatic zones as the basis of the query may yield interesting results. A separate interesting issue is the lack or very few publications from selected areas of the world (e.g., South America, Central America, North Asia, etc.). The major part of the research was concentrated in Southeast Asia, Europe, and North America. Certainly, such inference may be burdened with an error related to the adoption of a specific methodology of the selection of the publications, but it indicates a large gap in the research on the growing season.

In the case of analyses carried out on a single-field scale [92,114,115,274,326], the differentiation of microhabitat conditions is of greater importance. The variability of phenology is certainly determined by climatic factors, which are, however, not responsible for spatial variability on the field scale [10,41,271,302].

A serious problem both in bibliometric analysis and in a traditional literature query may be posed by the non-uniform nomenclature of season metrics. The beginning of the growing season is described in the literature in 13 different ways. The grammatical structure of the phrase (e.g., end of season—end of the season) is also of great importance. As indicated by the bibliometric analyses, the authors more often focus on the end of the growing season in their research, in contrast to the previous conclusions [345]. Nevertheless, the beginning of the season is most frequently the subject of methodical publications [28,62,103,134,178,185,186,208,221,247,348], as its variability is regarded as a symptom of climate change [10,14,26,32,36,42,44,50,59,63,72,80,86,87,103,112,121,125,134,135,178,190,199,204,217,253,265,278,279,299,324,337,338,347,350,353].

It is significant that most researchers considered individual season metrics individually (i.e., focusing only on the start or end of season). Obviously, it is then impossible to refer to the length of the growing season, which requires that both parameters be defined jointly. It is also worth noting that in recent years, a few selected publications have referred to other phenophases such as the peak of season or middle season, which indicates the direction of research development in this area going beyond the most obvious indicators of the growing season.

During the analysis of the collected material, a clear differentiation of the methodology for determining season metrics can be observed, which is most often based, in the case of remote methods, on the analysis of the curve of a given vegetation index. Nevertheless, different thresholds are adopted, corresponding to the different phenophases. When comparing studies with each other, it is absolutely necessary to refer to the adopted methodology, otherwise conclusions may be drawn based on incorrect premises.

Bibliometric analyses revealed a greater number of co-authored than single-author publications. Phenology studies require the involvement of scientists with different expertise from different countries. For example, the International Long Term Ecological Research network (ILTER) is a scientific network of over 600 research stations located in various ecosystems [280]. Similar research networks: "PhenoCam" (http://phenocam.sr.unh.edu/webcam/, accessed on 17 December, 2021), "European Phenology Network (EPN)", and "Phenological Eyes Network (PEN)" (http://www.pheno-eye.org/, accessed on 17 December, 2021) were created for phenological observations in various types of vegetation: forests, meadows, or arable fields. Scientific networks involving scientists and non-scientists have been developed over the last several years [364]. Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

The conducted analysis, resulting in clustering of the keywords, allows determining the research ranges and the most important elements related to the growing season, which are of interest to researchers. It should be taken into account that in order to define trends in research in a proper way, a series of analyses should be carried out in an analogous way, in terms of time. This goes beyond the scope of this publication, but indicates the direction in the authors' further work in the next publication. A graphical way of presenting the strength of the relationships between the individual keywords, allowing easy distinction of clusters distinguished on the basis of the algorithm of the program, enables quick and easy identification and analysis of keywords in publications. This is of utmost importance because keywords in their own way constitute the core element of articles, summarizing the content of a given publication.

The analysis related to the estimation of the strength of connections and concentration around the selected keyword (start of season, soil, spring phenology, land-surface phenology, end of season) allows determining the weight and relationship of individual elements characterizing the growing season. Keywords are authoritative, and indicate how the authors of a given publication define the scope of the research and what their focal point is.

As above-mentioned, a challenge for future bibliometric research may be an in-depth analysis of the weight of a given keyword relative to other keywords over time. Due to the geographical conditions of the growing season, it might also be interesting to take into account the spatial differentiation of the research undertaken in this aspect.

5. Conclusions

The review of literature reports on the use of remote sensing techniques in phenological studies shows a very wide range of research conducted by scientific centers worldwide. The growing season analyses performed with the use of various techniques, in different climatic zones, and in different-length time-series were based on a variety of source data.

The analysis of the available literature allows for an attempt to define the trends in phenological research. At the beginning of this century, the investigations were based primarily on low-resolution data presented in long time-series. In recent years, there has been a significant change in terms of spatial resolution. At present, the commonly available satellite imagery offers an adequate resolution for the analysis of phenological parameters not only on a regional scale, but also on a single-field scale. A valuable supplement to satellite data could be data obtained using sensors mounted on mobile ground platforms, unmanned aerial systems, or airplanes. One should expect an increasing number of papers based on high-resolution data.

Currently, the intensive development of specialized analytical tools combined with the availability of spatial analysis software and high-resolution data facilitates advanced large-scale analyses. The observation of the present research trends allows for conclusions regarding the further development of remote techniques of observation of vegetation (i.e., an increase in the spatial and temporal resolution) and automation of data processing based on artificial intelligence. Relatively often, it is also used to combine data from different sources in order to improve their spatial accuracy. It seems that in the future, the methods of autonomous data acquisition and immediate analysis will be used in order to react quickly to the consequences of particular phases of plant development, especially in the case of cultivated crops.

The research differs in terms of its location. Europe, the United States, and China dominate in this respect, as areas where phenological investigations are applied in agricultural practice due to the need to intensify agricultural production. This type of research in other world regions is less extensive, hence the clear gap, which is worth filling in.

There is an apparent trend of a shift in the authors' interest from wide-spectrum research covering basic remote sensing issues (e.g., plant indices or spatial resolution) to smaller-scale problems and issues (e.g., the application of UAVs or the phenology of specific plants).

Due to the different nomenclature of individual parameters of the growing season and different definitions in the metadata of papers, it would be advisable to standardize the nomenclature, particularly including the season metrics. Given the significant increase in the availability of large amounts of spatial data with various parameters obtained with the use of various devices, the fusion of data from individual sources and compilation of a homogeneous multiyear series of phenological data will be a future challenge for researchers.

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