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REVIEW ARTICLE

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Site index research: a literature review

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Abstract. The purpose of this paper was to review literature covering the topic of site index with particular emphasis on Scots pine, the most important forest-forming species in Poland. We discuss the history of the site index, research on various tree species, statistical modelling methods, the spatial application of site index and age impact assessment.

The history of research on the site index of forest species is long and dates back to the 18th century. Many researchers thought that determining the quality of the habitat is very important from the point of view of rational forest management. The site index, as a measure of the potential of the habitat on which the forest grows, is one of the most important characteristics of forest stands. The site index depends on the selected model, but is most often expressed as the average or top height of trees of a given species at a certain age.

In our review, we point out several insufficiencies of studies on the site index, external influences and the connection of the site index with spatial conditions. Furthermore, research conducted so far has not explicitly confirmed that there is a relationship between the site index of pine stands and their geographical location in Poland. More research on the site index, especially in regard with climate change, is needed.

Keywords: Forest site index, tree growth, forest site quality, forest site productivity

1. Introduction

The dynamic changes taking place in the availability of information enable research to be conducted at an increasingly wider scale. Modern methods of collecting field data from a large number of sample plots has allowed many problems, which until recently were unanswered, to be solved. One of such important scientific problems for forestry is the more complete characterization of the site index and the attempt to spatially characterize forest growth based on this feature.

All tree species are equally important in the biocenosis, but from an economic point of view, some are given priority. In Poland, among all forest-forming species, the Scots pine *Pinus sylvestris* L. deserved and deserves special recognition. Due to the existing soils and climate forming the habitat, pine is the most common species in Polish forests. Its value to Polish forestry is increased by the few problems it poses in its management, its high productivity and economic utility.

A better understanding of the factors influencing the growth of pine will contribute to enriching the basic knowledge about this species, and thus, allow for more effective management. The site index of a stand, which characterizes the growth potential of the species, is a good measure of the impact of the surrounding environment on the life of trees. A constant site index value over time expresses the consistency of environmental conditions, while its fluctuations indicate that some features of the surrounding ecosystem are changing. Knowing the variability and dependence of the site index on external factors can help in understanding the preferences of pine. This is particularly relevant and important in the current dynamics of climate change associated with its warming.

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The aim of this paper is to review the literature on the site index of important forest species, with particular emphasis on pine, the most important forest-forming species in Poland. The current state of knowledge about the site index of pine in Poland seems to be insufficient, and the current possibilities of continuing this research may significantly broaden this knowledge.

2. The evolution of measures of the production potential of the forest

Research on the site index was conducted as early as in the 18th century by Oettelt (1764), who defined the height of the trees as an indicator of 'soil goodness'. The 19th century brought the development of forestry science, which changed the approach to the problem of the site index. Heyer was the first to observe the link between height increment and volume growth (Heyer 1841). He believed that determining the quality of a habitat is important in terms of its productivity (Heyer 1845). Franz von Baur described average height as the most accurate and only proper indicator, not only for assessing normal stand growth, but also for appraising its site index (Baur 1881). In this method, the site index was categorized into classes, with each class assigned to an equal interval of average height. These intervals increased proportionally with the age of the stand. The graphical interpretation resembled the increasing height of ranges, hence its name – the range method. It assumed that the height of a stand increases in accordance with the determined height change curve, and that stands at a certain age have similar productivity. Since then, despite initial scepticism (e.g., Hartig 1892), the height site index started to be identified with productivity. This method, called the 'phytocentric method', consists of measuring the vegetation growing in a given area (Skovsgaard, Vanclay 2008). Unlike the 'geocentric method', which is based on the properties of the soil and climate, it is often easier to apply. The phytocentric method usually involves measuring plant yields. This is often practiced in farming, but given the differences between the types of farming and forestry, it is difficult to apply. Annual crop harvests in agriculture makes it possible to make long-term analyses of productivity changes. Such a way of experimenting in stands would require many centuries of research. In forestry, an attempt to solve this problem was to measure yield expressed as volume (Assmann 1968) or the average total production increment calculated for the age of 100 years (Philipp 1893). At a time when silviculture practice included light thinning, allowing some of the dominated trees in Kraft's classes 4–5 (Kraft 1884) to remain in the stand, this method worked well in reflecting the production capacity of the habitat. However, since the use of moderate and strong thinning, there have been instances where the stock levels were lower in a habitat with potentially higher productivity than in one with a lower potential. It turned out that the abundance does not precisely determine the productive potential of a habitat, because the intensity of the treatment had a significant impact on the growth of wood resources – after strong thinning, the potential was often underestimated, whereas with light thinning, it was overestimated (Magin 1958). As a result of searching for a more convenient measure for the site index, average stand height was chosen as a measure that is less affected by external factors.

The measurement of the site index using volume is based on the Eichhorn's Rule (formulated for fir), which states that a certain average stand height for all habitat classes corresponds to the same stand volume (Eichhorn 1902). In later years, Gerhardt extended this to spruce and pine (Gehrhardt 1909, 1921) and reformulated it into the 'Extended Eichhorn's Rule', stating that there is a relationship between productivity and habitat-dependent stand height, which was proven by Assmann (1955, 1959).

3. Height site index

Site index, understood as the height of a stand at a particular age, is today the most common way to assess the quality of a forest habitat. Currently, there are two approaches to measuring it and both use an indicator method – you have to measure the sample trees and check which discount they belong to.

The first approach involves measuring the average height and assigning it to a specific grade. However, this has some consequences. During natural tree growth, the weakest trees lose the competition and are separated from the stand. These processes are simulated during the tending process. With severe lower thinning, this can lead to a sudden and significant increase in the average height. For example, strong bottom thinning in a 65-year-old stand changes the average height from 24.5 m to 25.9 m, which increases the discount by ½ class (Assmann 1968).

The second way is based on the determination of the height of the upper stand, understood as the average height of a certain number of the thickest trees on an area of 1 ha. In this case, as a result of thinning or natural processes of tree secretion, there will be only slight shifts in the results of the discount. In the study from the experimental plots in Sachsenried 2, it was found that the difference in height between the upper and the average height, with an appropriate intensity of cultivation, may decrease from 2.1 m to 1.0 m

(Assmann 1968). Further studies on the application of average and upper altitude showed that for different thinning treatments, differences of up to 3.2 m can be obtained.

In both methods, individual variation in height may be a problem. The growth rate deviating from the accepted 'fan' of the discount results in its change, usually a decrease of even 0.7 degree of quality. In addition, deterioration of water conditions during stand growth, for example, may cause a reduction of the discount (Assmann 1968).

It is not only changes in the level of the water table that can affect the amount of the discount. It turns out that the increase in height varies from one climate to another. Two types of abundance tables from different regions were compared: Hummel and Christie (1953) for conifers in Great Britain and Wiedemann (1936) for spruce in Germany and it turned out that their growth rate is different (Magin 1957).

It is also problematic that different tables used different number of discount classes as well as different width of compartments characterizing the classes. Schober (after: Assmann 1968) proposed that the distances between the different discount classes should be 4 m at the age of 100 (4.5 m for spruce). Another proposal was absolute site index (as opposed to class ones), which determined the height of the stand at the felling age. A problem proved to be the assessment of the site index at a possible change of the felling age. Difficulties were also encountered when comparing the absolute tree stand and stand height between the species. An attempt to unify the various proposals was made by Weck's postulate that the absolute site index should be measured as the average stand height at the age of 100 years (Weck 1948). However, this created the problems discussed earlier. Therefore, the Assmann proposal is currently the most common form of determining the stand's site index. This proposal assumes that the site index is the upper height (the height of the 100 thickest trees per 1 ha) at the age of 100 years (Assmann 1959).

The absolute site index can be adopted for height discounting (Assmann 1959; Skovsgaard, Vanclay 2008) and at the same time is unambiguous in designation and easy to measure, it can be compared without additional conversions. It should be noted that in forestry, the desired feature to be determined is the habitat classification, determined by means of the stand classification. The latter is burdened with a certain error, for example, inadequate species composition to the habitat or disturbed growth conditions in previous periods (Gieruszyński 1959). From these studies, it results that the stand site index is not adapted to different species of stands, the afforestation coefficient is not taken into account, the site index is not constant and may change over time, the site index for different species cannot be directly compared. It should be remembered that the problem is the precise determination of the stand age.

Aside from these limitations, the site index is a useful measure to use a simple numerical value that is easy to measure and understand by the practitioner. It will remain in use until it is replaced by a meter without these limitations, the calculation of which will be equally easy (Avery et al. 2019). Therefore, the site index is most often expressed as the upper height of trees of a given species at a specific age (Bruchwald, Kliczkowska 1997; Bruchwald et al. 1999; Sharma et al. 2012; Socha et al. 2017).

As mentioned earlier, research on the class and absolute site index has been conducted at least since the 18th century. The main effect of these studies is the construction of models of the coefficient of variation (coefficient curves) for different species, for example, Douglas fir *Pseudotsuga menziesii* (Mirb.) Franco (Monserud 1984; Means, Helm 1985; Milner 1992), yellow pine *Pinus ponderosa* Dougl. ex C. Lawson (Milner 1992), West Larch *Larix occidentalis* Nutt. (Milner 1992), dune pine *Pinus contorta* Douglas (Milner 1992), taeda pine *Pinus taeda* L. (Popham et al. 1979; Cao et al. 1997), the long-needle pine *Pinus palustris* Mill. (Cao 1997), California *Pinus radiata* D. Don (Burkhart, Tennent 1977), *Pinus sylvestris* L. (Bruchwald, 1979; Elfving, Kiviste 1997; Socha, Eagle 2013), *Fagus sylvatica* L. beech (Nord-Larsen 2006), spruce of common *Picea abies* L. H. Karst (Kliczkowska, Bruchwald 2000; Socha et al. 2015) or black alder *Alnus glutinosa* L. (Socha, Ochał 2017).

In the work by Cieszewski and Zasada (2002), a transformation of the Bruchwald's (2000a) anamorphous site index model was carried out to a dynamic form, which allows to obtain the value of the discount rate for any measured pair 'age-height' in a less labour-intensive way. The tables of Szymkiewicz's affluence were successfully transformed by Cieszewski and Zasada (2003a) into a voucher model. The work by Cieszewski and Zasada (2003b) proposed the use of a universal method of algebraic differences to derive general dynamic discount equations.

Research on the variability of characteristics of pine trees and stands in Poland, also taking into account the site index, has been conducted for a relatively long time, which determines the potentially large amount of comparative material (Bruchwald 1977; Keller 1991; Bruchwald, Kliczkowska 2000; Socha, Orzeł 2011). The literature clearly shows the trend of research on the pine voucher models themselves, both locally (Sewerniak 2008; Beker, Andrzejewski 2013) and nationally (e.g., Cieszewski, Zasada 2003a).

From similar studies, only those limited to the selected regions can be found in the literature (Sewerniak, Piernik 2012; Socha, Orzeł 2013). The previous research on the variability of pine stand site index on the national scale has indicated the necessity to include additional environmental and stand parameters that may potentially affect the variability of pine stand site index (Bruchwald et al. 2000a).

The top stand height was studied by Bruchwald (1979), Socha (2005) and Beker (2007). The latter proposed the upper biological height – of the top and dominating trees according to Kraft (1884) – as the most accurate in the entire life of the stand, but difficult to measure due to the high labour intensity.

Socha and colleagues (2015) in their research developed discount models for basic forest-forming species in Poland (pines, firs *Abies alba* Mill., ash *Fraxinus excelsior* L., aspen *Populus tremula* L., birches *Betula* L., black alder, oak *Quercus* L., beech, larch *Larix decidua* Mill., spruce, acacia *Robinia pseudoacacia* L., red oak *Quercus rubra* L., Douglas fir *Pseudotsuga* Carriere, hornbeam *Carpinus betulus* L., lime trees *Tilia* L. and maple *Acer* L.). They have managed to build a mathematical model of the coefficient of discount based on data from the abundance tables used in Poland. For most species, they used a modified model of Cieszewski (Cieszewski, Zasada 2003b), which gave the best results. They also developed discount models for the main forest-forming species in Poland, based on the latest empirical material (Socha et al. 2017).

In the research carried out in the stands of the southern part of Poland (Socha, Orzeł 2013), a set of dynamic discount curves for pine was developed. What is more, it was noted that the Schwappach's table model (1943) shows a lower growth rate in youth and a higher growth rate in older stands. The mathematical model of Bruchwald (Bruchwald et al. 2000a,b), built according to different principles, shows significant discrepancies between the predicted and actual growth rate.

In the research carried out in the Niepolomice Forest (Socha, Orzeł 2011), a local, dynamic system of site index curves was developed. The research was extended in subsequent years to include stands from southern Poland (Socha, Orzeł 2013), as well as to

The work on the inclusion of an increase in altitude or discount in the mathematical framework was carried out by Stępień (1979), who, using electronic calculation techniques, determined the coefficients of the equation for calculating discount depending on age for pine, fir, spruce, beech and oak. Similar studies were also conducted by Socha (1997) and Jarosz and Kłapeć (2002).

4. Statistical modeling of site index

The analysis of the site index was also carried out in methodological works, focusing on the evaluation of the usefulness of various statistical methods in modelling the value of this feature. In Subedi and Fox's work (2016) focusing on the influence of soil traits on the site index of *P. taeda* pine, the use of multiple and partial regression of the smallest squares was compared. Wang and colleagues (2005) investigated the spatial dependence of the site index on environmental factors in Canada using various statistical techniques. In their case, the best technique, also dealing with unusual data values, was the technique of generalized additive models (GAM). Similar conclusions have been reached by researchers dealing with site index in Turkey's mountains (Aertsen et al. 2010). In the Czech Republic and Slovakia, neural networks were used with prediction of the site index based on climatic data for spruce, beech and fir (Hlásny et al. 2017). In a study from the Western United States (Latta et al. 2009), data from the Large-Area Forest Inventory were used to model the impact of climate variables on potential stand productivity. Wang (2005) compared four modelling methods (non-linear regression, decision tree, generalised additive models and neural networks) of spatial variability of the site index of *Pinus contorta* Dougl dune pine. ex Loud. in Canada's mixed boreal forest. The possibility of using remote sensing to determine the site index for California *P. radiata* pine in New Zealand (Watt et al. 2015) was also investigated. In addition, a model was developed to determine the productivity of the two variants: with age data and with the variant assuming no such data (Watt et al. 2016).

5. Spatial investigation of site index

Despite many studies carried out so far, there is still little knowledge of the relationship between environmental factors and their impact on tree growth in spatial terms. In a study on *Populus tremuloides* Michx., Chen et al. (2002) analysed the impact of the environment on the site index in a wider spatial dimension, yielding 61% of the explained variability. Some factors had a different impact on the feature studied in different zones. This shows that the results may vary depending on the spatial scale in which they are analysed. In the study on the Douglas firing rate, *P. menziesii* compared the use of linear and Geographically -Weighted Regression in central Idaho, USA (Kimsey et al. 2008). It was shown that the use of the spatial method allowed to explain by 29% more variability in the site index and reduced the error by about 53%. The studies conducted so far have not confirmed unequivocally that there is a dependence of the pine stands' site index on their geographical location in Poland. These studies also do not definitively explain whether the dependence observed locally is reflected on a nationwide scale (Bruchwald et al. 2000a).

6. Age impact on site index

The problem of larger than expected tree growth was addressed in a paper by Elfving and Tegnhammar (1996), which showed that management can have a significant impact on tree growth. At the same time, it is known that the growth at height is inhibited by breeding work, that is, cleaning and thinning, which can disturb the discount model (Hynynen 1995). Research conducted on spruce in Germany and Austria showed a statistically significant change in the stand height increment pattern related to the age of the examined object (Schadauel 1996; Wenk, Vogel 1996). Similar studies on beech confirm the same relationships (Untheim 1996). At the same time, studies from southern Germany show that the abundance tables used today do not reflect well the growth dynamics of trees, most often overestimating the results obtained empirically (Pretzsch 1996). Extensive research on the growth dynamics of spruce and beech stands in Europe since 1870 shows that they continue to follow the previously determined trends, although the stands are increasing their growth more rapidly (Pretzsch et al. 2014). At the same time, the lengthening of the growing season and temperature increase accelerate physiological processes (Crafts-Brandner, Salvucci 2004), especially in more fertile habitats. Studies on the site index of the Baden-Württemberg spruce (Yue et al. 2014) have shown that in the mid-20th century, the growth pattern of the species under investigation changed. Similar studies in Finland on pine, spruce and larch showed a difference in the growth pattern of the studied species compared to Central Europe (Mäkinen et al. 2017). In-depth analyses of nitrogen immissions in the study area proved that the most probable cause of doubling of tree growth during the last century was the forest management.

7. Summary

The history of research on the site indexof forest species is long and goes back to the 18th century. Many pioneers of this research rightly believed that determining the quality of a habitat is very important for rational forest management. Tree site index, as a measure of the potential of a habitat on which a forest grows, is one of the most important characteristics of economic stands. Site index, depending on the chosen model, is usually expressed as the average height of trees of a given species at a certain age (Bruchwald 1997, 1999; Sharma et al. 2002; Socha et al. 2017). However, it is not possible to compare the site index between species due to the ecology of individual species. Determination of the density of the species in the stand allows to unambiguously characterize the growth potential of the habitat (Chen, Klinka 2000; Kliczkowska, Bruchwald 2000; Socha 2005). Modelling of this potential is most often performed for one tree species. Summarizing the literature review concerning this problem, it should be stated that for the basic forest-forming species in Poland, that is, pine, there are no current studies covering the stand site index on the national scale. This concerns both the statistical characteristics, as well as the influence of external factors and the connection of the discount with the conditions prevailing in the spatial system.

Conflicts of interest

The authors declare no potential conflicts of interest.

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W.K., R.T., T.B. – conceptualization, W.K., R.T. – literature review, W.K. – manuscript preparation

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