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ORIGINAL PAPER

Dynamics of the condition of the Polish larch *Larix decidua* Mill. subsp. *polonica* (Racib.) Domin on Chełmowa Góra in the Świętokrzyski National Park in 2010-2020

Rafał Podlaski[(1)]✉, Monika Żelezik[(2)]

[(1)] Department of Environmental Biology, Institute of Biology, Jan Kochanowski University, Uniwersytecka 7, 25-406 Kielce, Poland

[(2)] Department of Geomorphology and Geoarchaeology, Institute of Geography and Environmental Sciences, Jan Kochanowski University, Uniwersytecka 7, 25-406 Kielce, Poland

ABSTRACT

The reserve on Chełmowa Góra in the Świętokrzyski National Park is the oldest in Poland where the Polish larch, *Larix decidua* subsp. *polonica*, is protected. In order to preserve forest stands that include the Polish larch, it is necessary to implement detailed and time-efficient monitoring of its condition. The objective of the study was to assess the dynamics of health (defoliation) and vitality of the Polish larch from 2010 to 2020 and to compare the results of these analyses obtained using both permanent sample trees (PST) and temporary sample trees (TST). The PST and TST larch trees were selected at random using a simple random sampling without replacement (SRSWOR) scheme for middle- and old-generation larches aged approximately from 70 to 150 years and older than 150 years, respectively, and according to a two-stage sampling scheme (with SRSWOR at both stages) (2SS: I-SRSWOR, II-SRSWOR) for the young-generation larches aged approximately from 20 to 30 years. The study noted a general improvement in health and vitality of the larch populations over the study period. In the years 2010-2015, the condition of larches was lower than in the years 2018-2020, which may be linked to environmental changes or conservation efforts. The estimation errors for the proportions of larches in the distinguished degrees of damage and vitality classes for middle- and old-generation ranged from 2.45% to 5.54% for PST and from 3.33% to 9.20% for TST, while for young-generation, they ranged from 2.58% to 7.12% for PST and from 3.20% to 7.58% for TST. The comparison between PST and TST revealed slightly lower error estimates for PST, suggesting its advantages in long-term ecological monitoring. However, the results showed no statistically significant differences between the two methodologies, demonstrating their effectiveness in assessing forest conditions in dynamic environments. These findings highlight the importance of continuous, adaptable monitoring strategies in forest management and conservation, especially under the impact of climate change and other ecological factors.

KEY WORDS

defoliation, forest monitoring, permanent sample trees, temporary sample trees, vitality

✉e-mail: r_podlaski@pro.onet.pl

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Introduction

The European larch, *Larix decidua* Mill. is one of the most valuable forest-forming species in Poland. It is distinguished by its high-quality timber, rapid growth, and relatively high resistance to European larch canker (*e.g.*, Andrzejczyk *et al.*, 2011). The Polish larch, *Larix decidua* Mill. subsp. *polonica* (Racib.) Domin was described from the Świętokrzyskie Mountains, it was introduced to cultivation in this region as early as the beginning of the 19th century (Bałut, 1962). A natural, isolated population of the Polish larch is located at Chełmowa Góra in the Świętokrzyski National Park, among other sites. In 1921, this area was designated as a strict nature reserve to protect the Polish larch, marking it as one of the first reserves in Poland. This site is of great value due to its contribution to pioneering research on the Polish larch, conducted by researchers such as Marian Raciborski and Władysław Szafer (Szafer, 1913). The research conducted demonstrated that the cones of the larches from Chełmowa Góra differ from those typical of larches from the Alps. Moreover, the larches of Chełmowa Góra are characterised by a distinctive deformation of the lower trunk, described as 'saber-shaped'. However, this anatomical feature is not considered a diagnostic element for differentiating the Polish larch (Szafer, 1913). These findings led to the initial classification of the Polish larch from the Świętokrzyskie Mountains as a separate species. The validity of this high systematic rank was questioned as early as the 1920s (*e.g.*, Ostenfeld and Syrach-Larsen, 1930). Currently, the Polish larch is recognised as a subspecies of the European larch (Boratyński, 1986).

As observed in numerous European locations, the 1970s and 1980s witnessed a pronounced decline in forest vitality and a reduction in the diversity of tree species (Jaworski, 1982; Spiecker *et al.*, 1997). In the case of Chełmowa Góra, the old-generation Polish larches (aged over 150 years) remained relatively healthy (Podlaski, 2001, 2003). The main challenge was achieving the regeneration of the Polish larch. To preserve forest stands involving the Polish larch, it is necessary to implement detailed and time-efficient monitoring of its condition.

The survey sampling method was employed to assess the condition of the Polish larch, allowing for the calculation of estimation errors for the trait under study based on a sample drawn from a finite population (Thompson, 2012). This method has been increasingly used in forestry. In Poland, it was introduced on a broader scale by Bruchwald (*e.g.*, Bruchwald, 2000a, b; Bruchwald and Zajączkowski, 2002; Bruchwald *et al.*, 2003). In the context of the contemporary environment, monitoring tree condition has become a pivotal aspect of forest resource management. While traditional methods, based on permanent sample trees (PST), are valuable, they can be time-consuming and less flexible in response to dynamic environmental changes. In this context, the use of temporary sample trees (TST) may offer significant benefits. This method, involving the periodic selection of trees for assessment, enables quicker and more precise adjustments to current conditions, especially critical in the face of swift climate change and ecological threats. Unfortunately, none of the manuscripts directly address the implications of permanent versus temporary sampling on the precision of forest monitoring.

The aim of the study is to assess the dynamics of health (defoliation) and vitality of the Polish larch growing on Chełmowa Góra, in the Świętokrzyski National Park, and to compare the results of these analyses obtained using permanent and temporary sample trees (PST and TST). The null hypothesis states that there are no significant differences between the classification results obtained using PST and TST in each of the years under consideration. In other words, it is assumed that both methods (PST and TST) yield comparable results in assessing the condition of the trees.

Materials and methods

Research area. Chełmowa Góra is a part of the Świętokrzyski National Park. It is a hill whose highest point is 350.8 m above sea level. In 1921, the Chełmowa Góra Reserve covered an area of 163.1 ha. (currently 183.44 ha). In 1951, the Chełmowa Góra Reserve's protection status was changed from strict to partial (except for a part of 13.36 ha), as ensuring the survival of the Polish larch, which is threatened by competition from beech *Fagus sylvatica* L., oaks *Quercus robur* L. and *Q. petraea* (Matt.) Liebl. and fir *Abies alba* Mill., required the application of active protection measures.

Data from short-term observations carried out between 1955 and 1958 and between 1960 and 1968 at the then meteorological station in Nowa Słupia, next to Chełmowa Góra (geographical position: 50°52'N, 21°05'E, altitude: 307 m above sea level), indicate that a precipitation minimum occurs around Chełmowa Góra (Dunikowski, 1985). During these periods, Chełmowa Góra received, on average, about 160 mm less precipitation per year than its neighbour, Św. Krzyż (the average annual precipitation in Św. Krzyż was 932.8 mm). The lower amount of precipitation is connected with the location of Chełmowa Góra, which is in the rain shadow of the main Łysogóry range. In the characterised area, the values of mean monthly, mean maximum and mean annual temperatures were about 2.5°C higher than in Św. Krzyż (Olszewski *et al*., 2000).

On Chełmowa Góra, soils have formed from aeolian deposits and Pleistocene periglacial covers over Silurian and Devonian formations. The predominant soil type, overwhelmingly, is *płowe typowe* PPt soils (PTG, 2019) [Albic Luvisols (Cutanic) (WRB, 2022)] covering 94.02% of the forest area. The soils of Chełmowa Góra are distinguished by their relatively high acidity, comparable to the acidity of the *brunatne kwaśne* BBkw soils (PTG, 2019) (Dystric Cambisols; WRB, 2022) in the main Łysogóry range, which were formed from Pleistocene glacial deposits. Moreover, the soils of Chełmowa Góra are relatively shallow and generally exhibit unfavourable water-air properties (Kowalkowski, 2000).

Selection of sample trees. In Chełmowa Góra, the sample trees were randomly selected using a simple random sampling without replacement (SRSWOR) scheme for middle- and old-generation larches aged approximately from 70 to 150 years and older than 150 years, respectively, and according to a two-stage sampling scheme, with SRSWOR at both stages (2SS: I-SRSWOR, II-SRSWOR) for the young-generation larches aged approximately from 20 to 30 years (Bracha, 1996). Due to the heavy shading of the forest floor and the lack of gaps, which only changed after thinning of the stands, there were no larche trees aged from 30 to 70 years in the whole area of Chełmowa Góra. From 2010 to 2020, the studied area of Chełmowa Góra contained a mixed forest with middle- and old-generation larches and gaps with the young-generation larches.

The sample trees (PST and TST) were randomly selected using research points chosen at random. After selecting and marking the research points on general management maps at a scale of 1:5000, they were traced out in the field. Coordinates from the SINUS system were used as a reference system during sampling (Ciołkosz, 1991; Podlaski, 2005).

In the case of the permanent sample and the SRSWOR scheme, 150 research points were randomly selected in 2010. Around each point (within a radius approximately equal to the height of the dominant tree layer), a middle- or old-generation larch was selected and permanently marked. A total of 80 larches were sampled in this manner and they were classified in 2010, 2012, 2015, 2018, and 2020. If no middle- and old-generation larches were present near a given point, no additional research points were sampled, resulting in only 80 trees being analysed instead of 150.

For the temporal sample and the SRSWOR scheme in 2010, 2012, 2015, 2018, and 2020, 100 research points were randomly drawn at each of these dates. In the vicinity of the first point drawn (within a radius of up to approximately one height of the dominant tree layer), a middle- or old-generation larch was selected and classified. This procedure was then repeated with the second and subsequent points until 30 trees were selected and classified. If there were no middle- and old-generation larches near a given research point, the next point was used. These steps were repeated in the years 2010, 2012, 2015, 2018, and 2020.

In the case of the permanent sample and the 2SS: I-SRSWOR, II-SRSWOR scheme in 2010, there were two stages. In the first stage, 5 out of the total 10 gaps on Chełmowa Góra were randomly selected. In the second stage, 15 research points were chosen within each selected gap, around which young-generation larches were individually marked for permanent monitoring. In total, 32 larches were selected in this manner and they were classified in 2010, 2012, 2015, 2018, and 2020. If no young-generation larches were present near a given point, no additional points were marked, resulting in the analysis of 32 trees instead of 75.

For the temporal sample and the 2SS: I-SRSWOR, II-SRSWOR scheme in 2010, 2012, 2015, 2018, and 2020, in the first stage 5 gaps were drawn from all 10 gaps, and in the second stage 15 research points were drawn on each gap, and then around each point a young-generation larch was selected and classified. This procedure was repeated in 2010, 2012, 2015, 2018, and 2020, with 25, 25, 22, 20, and 23 trees classified, respectively.

The sample trees were chosen from the second Kraft class in single-layered stands or from the upper layer (100 according to IUFRO) in complex-structured stands. In the gaps, the larches grew together with fir, beech, birch *Betula pendula* Roth and/or willow *Salix caprea* L. All young-generation larches were counted on each gap.

Assessment of the condition of the sample trees. The 'Atlas of the Assimilation Apparatus Loss of Trees' (Borecki and Keczyński, 1992) was used to assess health (defoliation), and then each tree was classified into one of the following degrees of damage:

0 – trees without damage (defoliation up to 10%),
1 – slightly damaged trees (defoliation from 11 to 25%),
2 – moderately damaged trees (defoliation from 26 to 60%),
3 – severely damaged trees (defoliation above 60%).

A modified classification proposed by Jaworski (Jaworski *et al.*, 1988) was used to assess vitality:

1. vigorously developed trees – trees with a strong tendency for height growth, having narrow, distinct tops, with long (above 2/3 of height) and fairly symmetrical crowns. Assimilative apparatus loss is up to about 10%;
2. normally developed trees – trees with an average tendency for height growth, characterised by conical or paraboloidal tops, with fairly long (from 1/2 to 2/3 of height) and slightly distorted crowns. Assimilative apparatus loss is up to about 25%;
3. slightly weakened trees – trees with a below-average tendency for height growth, marked by slightly flattened tops, with medium-length (from 1/3 to 1/2 of height) and moderately distorted crowns. Assimilative apparatus loss is up to about 25%;
4. severely weakened trees – trees with a weak tendency for height growth, characterised by moderately flattened tops, with short (up to 1/3 of height) and heavily distorted crowns. Assimilative apparatus loss is up to about 60%;
5. dying trees – trees that have stopped growing in height, characterised by severely flat-

tened tops, with short (up to 1/3 of height) and heavily distorted crowns, and assimilative apparatus loss above 60%. These trees display clearly visible withering and withered branches.

The classification presented was adjusted to the age generation of the tree. If the analysed tree 'fit' into two categories (*e.g.*, the top was classified in the second category while the crown was in the third), it was assigned to the 'lower' category (in this case, the third category).

Estimation of the proportion of trees in the degrees of damage and in the vitality classes. An unbiased estimator of the tree fraction and the estimation error were calculated for the studied Polish larch generations in the analysed degrees of damage and vitality classes. Formulas for the mean were used, assuming that the examined characteristic (defoliation or vitality) takes only two values (Bracha, 1996): '1' if a given tree belongs or '0' if a given tree does not belong to a certain degree of damage or vitality class k; k=1, 2, …, l. In this case l=4 (during the analysis of the degree of damage) or l=5 (during the assessment of the vitality).

For the simple random sampling without replacement (SRSWOR) scheme, we assume that the fraction ($\hat{\mu}_k \equiv \overline{y}_k$) and the standard square error of the estimate ($\hat{D}^2(\overline{y}_k) \equiv v\hat{a}r(\hat{\mu}_k) \equiv v\hat{a}r(\overline{y}_k)$) in the degree of damage or in the vitality class k are respectively (Bracha, 1996; Thompson, 2012):

$$\overline{y}_k = \frac{1}{n}\sum_{i=1}^{n} y_{ki} \tag{1}$$

where:

$\overline{y}_k$ – the sample mean being an unbiased estimator of the population mean μ_k; in the analysis of element share, this is the proportion of elements with a distinguished feature, *i.e.*, the proportion of trees belonging to a given degree of damage or vitality class k;

y_{ki} – the value of the examined characteristic in the sample which takes the value '1' or '0' depending on whether a given tree belongs or does not belong to a specific degree of damage or vitality class k;

n – the number of elements in the sample, *i.e.*, the number of investigated trees of a given Polish larch generation;

$$\hat{D}^2(\overline{y}_k) = \frac{N-n}{N} \cdot \frac{1}{n} s_k^2 \tag{2}$$

where:

$$s_k^2 = \frac{1}{n-1} \cdot \sum_{i=1}^{n} (y_{ki} - \overline{y}_k)^2$$

additionally in this case

$$\frac{N-n}{N} \approx 1$$

where:

$\hat{D}^2(\overline{y}_k)$ – the standard square error of the estimate during the analysis of element share, this is the standard square error of the estimate of the proportion of elements with a distinguished feature, *i.e.*, the proportion of trees belonging to a given degree of damage or vitality class k;

N – the total number of elements in the population, *i.e.*, the total number of trees of a given generation growing on Chełmowa Góra.

For the two-stage sampling, with SRSWOR scheme at both stages (2SS: I-SRSWOR, II-SRSWOR) we assume that the fraction $\hat{\mu}_{2SS,k}$ and the mean square error of the estimate ($MSE(\hat{\mu}_{2SS,k}) \equiv \hat{D}^2(\hat{\mu}_{2SS,k}) \equiv v\hat{a}r(\hat{\mu}_{2SS,k})$) are respectively (Bracha, 1996; Thompson, 2012):

$$\hat{\mu}_{2SS,k} = \frac{\sum_{i=1}^{n} \hat{y}_{ki}}{\sum_{i=1}^{n} M_i} \tag{3}$$

where:

$$\hat{y}_{ki} = \frac{M_i}{m_i} \cdot \sum_{j=1}^{m_i} y_{kij}$$

where:

$\hat{\mu}_{2SS,k}$ – an unbiased ratio estimator of the population mean $\mu_{2SS,k}$; during the analysis of element share, this is the proportion of elements with a distinguished feature, *i.e.*, the proportion of trees belonging to a given degree of damage or vitality class k;

y_{kij} – the value of the examined characteristic in the sample i which takes the value '1' or '0' depending on whether a given tree belongs or does not belong to a specific degree of damage or vitality class k;

n – the number of samples drawn in the first stage (the number of drawn primary units), *i.e.*, the number of drawn gaps;

M_i – the number of all elements in the sample i (the number of secondary units in the i^{th} primary unit), *i.e.*, the number of all trees of a given generation growing on the gap i;

m_i – the number of elements drawn in the second stage in sample i (the number of secondary units drawn in the i^{th} primary unit), *i.e.*, the number of investigated larches on the gap i;

$$MSE(\hat{\mu}_{2SS,k}) = \frac{1}{\hat{M}^2}\left[\frac{N(N-n)}{n(n-1)} \cdot \sum_{i=1}^{n}(\hat{y}_{ki} - M_i\hat{\mu}_{2SS,k})^2 + \frac{N}{n} \cdot \sum_{i=1}^{n} M_i(M_i - m_i)\frac{s_{ki}^2}{m_i}\right] \tag{4}$$

where:

$$\hat{M} = \frac{N}{n} \cdot \sum_{i=1}^{n} M_i$$

$$s_{ki}^2 = \frac{1}{m_i - 1} \cdot \sum_{j=1}^{m_i}(y_{kij} - \overline{y}_{ki})^2$$

$$\overline{y}_{ki} = \frac{1}{m_i} \cdot \sum_{j=1}^{m_i} y_{kij}$$

where:

$MSE(\hat{\mu}_{2SS,k})$ – the mean square error of the estimate during the analysis of element share, this is the mean square error of the estimate of the proportion of elements with a distinguished feature, *i.e.*, the proportion of trees belonging to a given degree of damage or vitality class k;

N – the total number of all elements in the population at the first stage (the number of primary units in the population), *i.e.*, the total number of all gaps on Chełmowa Góra.

In the case of two-stage sampling (2SS: I-SRSWOR, II-SRSWOR) a ratio estimator was used because when estimating the fraction the following condition must be met:

$$\sum_{k=1}^{l} \hat{\mu}_{2SS,k} = 1$$

To compare the proportions between PST and TST for the degrees of damage and vitality classes analysed, the Z-test for comparing two proportions was used for the 2010, 2012, 2015, 2018, and 2020 data (Agresti, 2013). Spatial autocorrelation was considered in the Z-test, as it can occur between sample trees. This indicates that the health and vitality of trees in the analysed datasets (PST and TST) may be interrelated due to their spatial location. In order to account for spatial autocorrelation in the *Z*-test, the Moran's *I* statistic was used to measure the degree of spatial autocorrelation in the datasets. The coordinates of each sampled tree were used to compute the spatial weights matrix, and subsequently, the Moran's *I* value was calculated. The effective sample size n_{eff} was adjusted to reflect the influence of spatial autocorrelation (Dormann *et al*., 2007):

$$n_{eff} = \frac{n}{1+(n-1)\cdot\rho} \quad (5)$$

where:

n – the original sample size and ρ is the Moran's *I* value.

For the dataset from 2020, the Moran's *I* value ranged between 0.143 and 0.387, indicating varying levels of spatial autocorrelation. To ensure the robustness of the results and to account for the potential maximum level of spatial autocorrelation, a conservative approach was taken by using a higher value of 0.5 for ρ in the calculations. This was done to simulate the worst-case scenario of spatial autocorrelation, ensuring that the analysis remains valid under higher levels of spatial dependency. These calculations were conducted using the R statistical environment (R Core Team, 2023), employing the *spdep* (Bivand *et al*., 2013) and *sf* (Pebesma, 2018) libraries for spatial data analysis.

Results

HEALTH (DEFOLIATION). On Chełmowa Góra, the proportion of larches without damage and slightly damaged from the middle- and old-generation varied from 43.8% in 2010 to 62.5% in 2020 for PST and from 43.3% in 2010 to 63.3% in 2020 for TST (Fig. 1). Similarly, for the young-generation, these proportions varied from 39.4% in 2010 to 64.8% in 2020 for PST and from 39.3% in 2010 to 63.1% in 2020 for TST (Fig. 2). The health of larches from these age generations was lower during 2010-2015 compared to the period 2018-2020 (Figs. 1, 2). A comparison of the share of

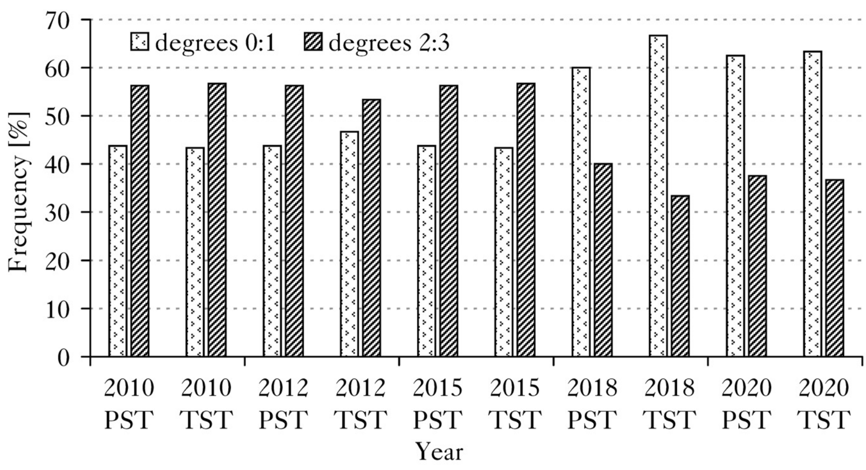

Fig. 1.

The proportions of middle- and old-generation Polish larches on Chełmowa Góra, classified as undamaged and slightly damaged (degrees 0 and 1) as well as moderately and severely damaged (degrees 2 and 3), based on data collected using permanent samples (PST) and temporary samples (TST)

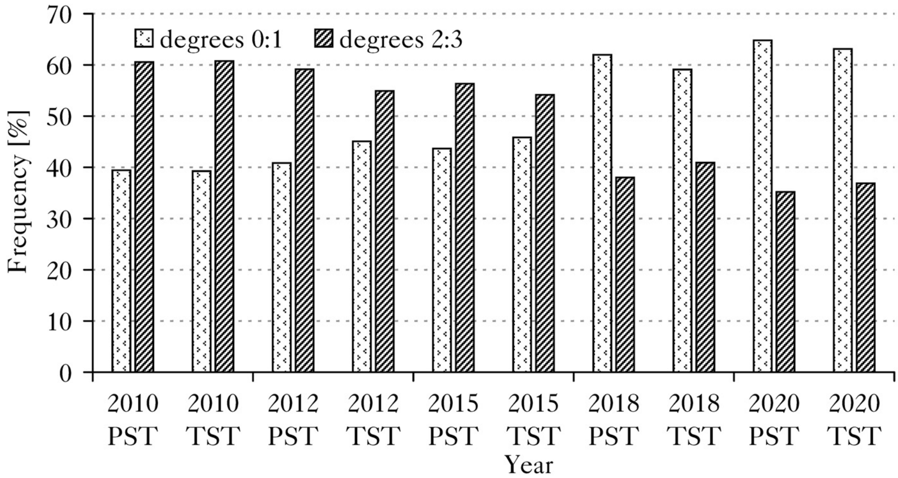

Fig. 2.

The proportions of young-generation Polish larches on Chełmowa Góra, classified as undamaged and slightly damaged (degrees 0 and 1) as well as moderately and severely damaged (degrees 2 and 3), based on data collected using permanent samples (PST) and temporary samples (TST)

larches in various degrees of damage indicates that the young-generation larches exhibited slightly worse conditions than the middle- and old-generation trees. The greatest discrepancies between these generations were observed during 2010-2015, while the smallest differences were noted during 2018-2020.

In the case of middle- and old-generation larches, the standard square error of the estimate for the degrees of damage ranged from 2.72% to 5.54% for PST and from 3.33% to 9.20% for TST. For young-generation larches, the mean square error of the estimate for the degrees of damage ranged from 2.58% to 6.70% for PST and from 4.15% to 5.53% for TST. Overall, the error rates associated with permanent samples (PST) are slightly lower than those observed with temporary samples (TST). This difference can be attributed to the more extensive data pool available from the permanent samples.

VITALITY. In the area under study, the proportion of vigorously and normally developed larches from the middle- and old-generation varied from 41.3% in 2010 to 55.0% in 2020 for PST and from 40.0% in 2010 to 60.0% in 2020 for TST (Fig. 3). For the young-generation, these proportions varied from 32.4% in 2010 to 53.5% in 2020 for PST and from 39.3% in 2010 to 57.3% in 2020 for TST (Fig. 4). The vitality of the larches was found to be lower during the period 2010-2015 than during 2018-2020 (Figs. 3, 4). A comparison of the share of larches in various vitality classes indicates that the young-generation larches exhibited slightly worse vitality than the middle- and old-generation trees. The greatest discrepancies between these generations were observed during 2010-2015, while the smallest differences were noted during 2018-2020.

For middle- and old-generation larches, the standard square error of the estimate for vitality classes ranged from 2.45% to 5.48% for PST and from 3.33% to 9.10% for TST. For young-generation larches, the mean square error of the estimate for vitality classes ranged from 2.58% to 7.12% for PST and from 3.20% to 7.58% for TST. In summary, permanent samples (PST) tend to yield more consistent data with lower error margins compared to temporary samples (TST), which is reflective of the higher quantity of trees chosen in permanent sampling.

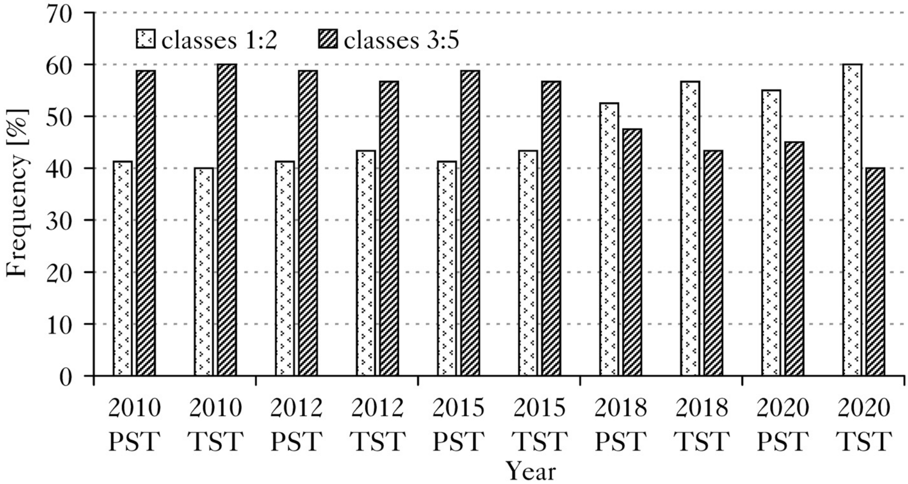

Fig. 3.

The proportions of middle- and old-generation Polish larches on Chełmowa Góra, classified as vigorously and normally developed (classes 1 and 2) as well as slightly weakened, severely weakened and dying (classes 3 to 5), based on data collected using permanent samples (PST) and temporary samples (TST)

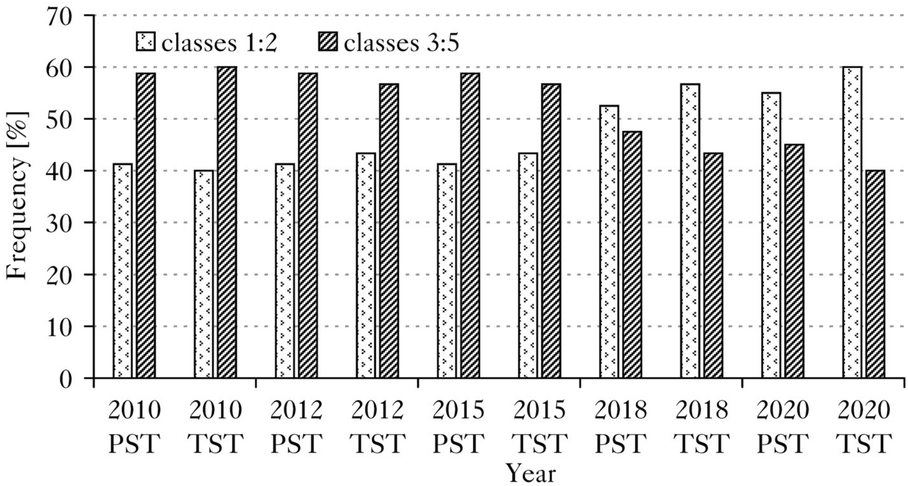

Fig. 4.

The proportions of young-generation Polish larches on Chełmowa Góra, classified as vigorously and normally developed (classes 1 and 2) as well as slightly weakened, severely weakened and dying (classes 3 to 5), based on data collected using permanent samples (PST) and temporary samples (TST)

Comparison of tree proportions for permanent and temporary samples (PST and TST). Following the application of the *Z*-test, the *p*-values for the proportions in the distinguished degrees of damage and vitality classes for PST and TST were noted. For middle- and old-generation larches, the *p*-values ranged from 0.650 to 0.978 for degrees of damage and from 0.739 to 0.933 for vitality classes. Similarly, for young-generation larches, the *p*-values were between 0.884 to 0.992 for degrees of damage and from 0.704 to 0.954 for vitality classes. Generally, the *p*-values for the years 2010, 2012, 2015, 2018, and 2020 are significantly higher than the typical significance threshold of 0.05. This indicates that there are no statistically significant differences between the proportions of trees belonging to PST and TST for the degrees of damage and vitality classes analysed. Consequently, the null hypothesis, which states that there are no differences between the classification results using PST and TST trees in each of the years under consideration, is not rejected.

Discussion

This decade-long study (2010-2020) at Chełmowa Góra has provided detailed insights into the health and vitality dynamics of different generations of Polish larch, using both PST and TST. The data revealed a general improvement in the health and vitality of the larch populations over time, particularly noticeable after 2015. This trend might be associated with environmental changes or enhanced conservation efforts, although further research is needed to confirm these potential causes.

The comparison between PST and TST methodologies revealed slightly lower error estimates for PST, suggesting that permanent monitoring sites may offer more stable data over time. However, the statistical analysis showed no significant differences between the outcomes of PST and TST, indicating that temporary sampling can be equally effective, especially in dynamic environmental conditions where rapid assessments are necessary. Permanent samples are utilised to study ecological succession and the stability of plant communities over relatively long periods, sometimes spanning several decades. In contrast, temporary samples are more frequently used for much shorter time intervals and often result in significant sampling errors and are generally less cost-efficient (Köhl *et al*., 2015; Sperandii *et al*., 2022). Both approaches have their advantages and limitations, and the choice between them depends on the specific research objectives and constraints. Sampling with partial replacement (SPR), which utilises both permanent and temporary plots, allows for change estimates comparable to those provided by permanent plots and offers flexibility in adjusting sample sizes over time (Köhl *et al*., 2015). Landsat time series (LTS) can improve the capacity to estimate forest condition, providing historical disturbance maps and improving the precision of disturbance estimates derived from permanent and temporary plots (Schroeder *et al*., 2014).

Furthermore, the study illustrated differences in health and vitality between generations, with younger larches generally exhibiting poorer conditions than their older counterparts. This variation could be due to multiple factors, including competitive dynamics, differential sensitivity to environmental stressors, or inherent vigor differences among generations. Addressing these disparities is crucial for the sustainability of the larch populations in the Chełmowa Góra Reserve.

The spatial distribution of the trees of the studied larch generations determined the suitability of the sampling schemes employed. Middle- and old-generation larches were distributed more or less evenly over almost the entire study area, while the young-generation larches were found in gaps. This spatial variation determined the choice of the SRSWOR sampling scheme for middle- and old-generation larches and the 2SS: I-SRSWOR, II-SRSWOR sampling scheme for young-generation larches. The relatively low estimation errors of less than 10% confirm the efficiency of the sampling schemes used. Particularly noteworthy is the high efficiency of the 2SS: I-SRSWOR, II-SRSWOR draw, for which the estimation errors are close to those obtained with the SRSWOR, with a smaller number of sample trees. The clustered distribution of population elements in space requires the use of more complex sampling schemes; in addition to the 2SS: I-SRSWOR, II-SRSWOR sampling, various variants of stratified sampling or multistage designs can be used, for example (*e.g.*, Thompson, 2012).

Conclusions

The research confirms the importance of continuous monitoring and demonstrates the effectiveness of both PST and TST approaches in tracking the health and vitality dynamics of forest species such as the Polish larch. While PST may be preferred for long-term data consistency in stable forest areas due to its slight advantage in error reduction, the flexibility of TST proves invaluable in rapidly changing environments or for shorter-term research projects.

The observed overall improvement in the Polish larch health and vitality towards the end of the study period provides support for the continuation of conservation efforts and underscores the need for a deeper investigation into the factors influencing these positive trends. Future studies should focus on identifying the specific environmental or biological factors that disproportionately impact younger generations and developing targeted management strategies to mitigate these effects.

In light of the ongoing silvicultural efforts aimed at promoting the regeneration of the Polish larch, it is imperative to conduct a systematic analysis of the condition of trees on Chełmowa Góra. The monitoring of tree condition can include the health and/or vitality of the trees, as both methods are useful and yield similar results. However, vitality is a more comprehensive characteristic. The optimal method would be to use TST and then assess the condition of the selected trees using a vitality classification.

In the context of collecting samples from tree populations that are growing in gaps or forming small patches, it is recommended to employ a two-stage sampling scheme. This method has proven to be more effective in such conditions than simple random sampling without replacement.

Authors' contribution

Conceptualisation – R.P.; methodology – R.P.; statistical analysis – R.P; fieldworks – R.P., M.Ż.; writing-original draft preparation – R.P.; writing-review and editing – R.P., M.Ż.

All authors have read and agreed to the published version of the manuscript.

Conflict of interest

Authors declare there is no conflict of interest.

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STRESZCZENIE

Dynamika kondycji modrzewia polskiego *Larix decidua* Mill. subsp. *polonica* (Racib.) Domin na Chełmowej Górze w Świętokrzyskim Parku Narodowym w latach 2010-2020

Modrzew polski *Larix decidua* Mill. subsp. *polonica* (Racib.) Domin, obecnie uznawany za podgatunek modrzewia europejskiego *Larix decidua* Mill., występuje m.in. w krainach Pasa Wyżyn Środkowych. Naturalne, wyspowe stanowisko tego podgatunku jest zlokalizowane na Chełmowej Górze w Górach Świętokrzyskich. Populacja ta została uznana za „przedstawiciela" modrzewia polskiego i dlatego wymaga m.in. szczegółowego monitorowania kondycji. Tradycyjne metody monitoringu, opierające się na stałych drzewach próbnych (PST), są na ogół bardziej pracochłonne w porównaniu do metod bazujących na czasowych drzewach próbnych (TST), ze względu m.in. na konieczność cyklicznego odnajdowania badanych drzew, odnawiania ich oznakowania oraz wykonywania prac związanych z ewentualnym dolosowaniem i oznakowaniem nowych drzew w przypadku wydzielenia się dotychczasowych z drzewostanu lub uszkodzenia ich przez różne czynniki. Celem pracy jest ocena dynamiki zdrowotności (defoliacji) i żywotności modrzewia polskiego rosnącego na Chełmowej Górze oraz porównanie wyników tych analiz uzyskanych z wykorzystaniem PST i TST.

Na Chełmowej Górze wybrano losowo drzewa próbne według schematu losowania prostego bez zwracania (SRSWOR) dla modrzewi średniej i starszej generacji w wieku odpowiednio od ok. 70 do ok. 150 lat i powyżej 150 lat oraz według schematu losowania 2-stopniowego, ze schematem SRSWOR na obu stopniach (2SS: I-SRSWOR, II-SRSWOR) w przypadku modrzewi młodszej generacji w wieku od ok. 20 do ok. 30 lat. Ze względu na silne zacienienie dna lasu i brak luk, co zmieniło się dopiero po wycięciu gniazd, na całym obszarze Chełmowej Góry brak było modrzewi w wieku 30-70 lat. Łącznie ze średniej i starszej generacji wyznaczono w 2010 r. 80 modrzewi PSP, które były klasyfikowane w latach 2010, 2012, 2015, 2018 i 2020 oraz po 30 modrzewi TST, które były za każdym razem wybierane i klasyfikowane w latach 2010, 2012, 2015, 2018 i 2020. Z młodszej generacji losowo wybrano w 2010 r. 32 modrzewie PSP, które były klasyfikowane w latach 2010, 2012, 2015, 2018 i 2020 oraz 25, 25, 22, 20 i 23 modrzewie TST, które były za każdym razem wybierane i klasyfikowane odpowiednio w latach 2010, 2012, 2015, 2018 i 2020. Do oceny zdrowotności wykorzystano 4-stopniową klasyfikację stopnia uszkodzenia bazującą na wielkości defoliacji (0 – drzewo „najlepsze", 3 – drzewo „najgorsze"), natomiast do oceny żywotności zastosowano 5-stopniową klasyfikację biorącą pod uwagę kształt wierzchołka, względną długość i zniekształcenie korony oraz stopień ubytku igieł (1 – drzewo „najlepsze", 5 – drzewo „najgorsze"). Dla badanych generacji drzew obliczono w wyznaczonych stopniach uszkodzenia i klasach żywotności nieobciążone estymatory proporcji drzew i błędy szacunku.

Aby porównać odpowiednie proporcje dla PST i TST, zastosowano test *Z* do porównania 2 proporcji dla danych z lat 2010, 2012, 2015, 2018 i 2020.

Większość modrzewi stanowiły drzewa słabo i średnio uszkodzone (stopień 1 i 2); powyżej 70% modrzewi dla wszystkich uwzględnionych generacji i terminów klasyfikacji, zarówno w przypadku PST, jak i TST, zostało zaklasyfikowanych do tych stopni. Podobne wyniki uzyskano w przypadku żywotności. Przeważającą liczbę modrzewi stanowiły drzewa normalnie rozwinięte i lekko osłabione (klasa 2 i 3); powyżej 70% modrzewi dla wszystkich uwzględnionych generacji i terminów klasyfikacji, zarówno w przypadku PST, jak i TST, zostało zaliczonych do tych klas. Porównanie udziału modrzewi badanych generacji w poszczególnych stopniach uszkodzenia i klasach żywotności świadczy o nieznacznie gorszej kondycji modrzewi młodszej generacji w porównaniu do modrzewi średniej i starszej generacji (ryc. 1-4). W badanym okresie zaobserwowano stopniową poprawę zdrowotności i żywotności populacji modrzewia. W latach 2010-2015 kondycja modrzewia była gorsza niż w latach 2018-2020 (ryc. 1-4). Błędy szacunku dla modrzewi średniej i starszej generacji wahały się w przedziale 2,45-5,54% dla PST oraz 3,33-9,20% dla TST, natomiast dla modrzewi młodszej generacji wynosiły 2,58-7,12% dla PST i 3,20-7,58% dla TST. Porównanie między PST a TST wykazało nieco niższe szacunki błędów dla PST, co potwierdza zalety wyboru stałych prób w długoterminowym monitoringu. Należy jednak podkreślić, że otrzymane wyniki nie wykazały statystycznie istotnych różnic między PST a TST, demonstrując ich zbliżoną skuteczność w ocenie stanu badanej populacji. Ze względu na prowadzone prace hodowlane promujące odnowienie modrzewia oraz mając na uwadze labilną kondycję badanych generacji, należy systematycznie analizować kondycję drzew na Chełmowej Górze. Monitoring ten może uwzględniać zdrowotność i/lub żywotność, ponieważ obie metody są przydatne i dają zbliżone wyniki, tym niemniej żywotność jest cechą bardziej wszechstronną. Optymalną metodą byłoby wykorzystanie TST i następnie przeprowadzenie oceny kondycji tak wybranych drzew z zastosowaniem klasyfikacji żywotności.