JMBFS
Journal of Microbiology, Biotechnology and Food Sciences
International peer-reviewed scientific online journal

Published by
Faculty of
Biotechnology and
Food Sciences

QUANTITATIVE ASSESSMENT OF LEAF DAMAGE IN *AESCULUS HIPPOCASTANUM*: A COMPARISON OF VISUAL AND SOFTWARE-BASED METHODS FOR EVALUATING *CAMERARIA OHRID*ELLA INFESTATION

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https://doi.org/10.55251/jmbfs.12336

ARTICLE INFO

Received 3. 2. 2025
Revised 12. 1. 2026
Accepted 29. 1. 2026
Published 1. 2. 2026

Regular article

OPEN ACCESS

ABSTRACT

The invasive moth *Cameraria ohridella* significantly threatens *Aesculus hippocastanum* (horse chestnut) trees, causing extensive leaf damage that undermines urban aesthetics and tree health. Traditional visual evaluations of leaf damage are time-intensive and prone to subjectivity, resulting in variable accuracy. The aim of this study was (i) to test whether the accuracy of visual damage assessment depends on the level of biological expertise of evaluators, and (ii) to determine whether a software-based method provides faster and more reliable estimates than human assessment. This study compared visual assessments by laypeople and experts to a novel software-based method for evaluating leaf damage. Leaves were collected from multiple sites, scanned, and analyzed manually. In addition, a software algorithm based on digital image analysis was developed, which automatically segments leaf images and quantifies damaged areas using color-based pixel classification. Statistical analysis revealed significant differences between laypeople and expert assessments ($p < 0.05$) and between laypeople and the software ($p < 0.01$). No significant differences were found between software and expert evaluations ($p > 0.05$). The software method reduced evaluation time by 97.51%, with manual analysis of 105 leaves averaging 40.22 minutes per person, compared to under 3 minutes using the software. The software-based method offers a reliable, efficient, and scalable alternative to traditional visual assessments, particularly for large-scale monitoring. However, the study is limited to scanned leaf images collected under controlled conditions, and further validation under variable field conditions is needed. By providing faster and more consistent evaluations, it supports improved management of *Cameraria ohridella* infestations, aiding urban forestry efforts to preserve the health and aesthetics of horse chestnut trees.

Keywords: *Cameraria ohridella*, Leaf damage, Visual vs. software evaluation, *Aesculus hippocastanum*

INTRODUCTION

Horse chestnut (Aesculus hippocastanum) and the Cause of Leaf Browning

Horse Chestnut (*Aesculus hippocastanum*) belongs to the Sapindaceae family. The horse chestnut tree typically grows to a height of 30-35 meters **(Gilbert *et al.,* 2005; Shah *et al.,* 2024)**. *Aesculus hippocastanum* is one of the most widespread exotic tree species in Europe, with approximately 20,000 individuals aged 10 to 160 years recorded in Slovakia **(Hrubik and Juhasova 1998)**. The broad, conical to spreading crown of this tree can reach a width of up to 20 meters. Opposite leaves grow on stalks 20 cm long. The leaves are palmately compound, with each compound leaf consisting of 5 to 7 ovate leaflets. In autumn, the leaves turn orange-red and then fall. **Slight remains of dry leaves may occasionally remain on the tree until the following year (Straw and Tilbury 2006)**. Leaf browning and damage in *Aesculus hippocastanum* can be caused by various reasons. Leaves turn red-brown from the edges and along the main veins. Characteristic are spots bordered by leaf veins, making the spots more angular. In severe infestations, the entire leaf turns brown and curls. One cause can be the microfungus *Phyllosticta pavie*, known in Europe since the late last century and spreading epidemically in recent decades. It produces sexual spores in fallen leaves during winter and infects young leaves in May, causing leaf spot. During spring and summer, asexual spores (conidia) quickly infect additional leaves. After the leaves fall in autumn, sexual spore spread resumes. Another cause of leaf browning can be the mite *Eotetranychus aesculi*, which grows up to 0.5 mm and commonly appears in whitish, colorless, or orange-red forms. These mites suck the leaves, and their numerous generations and short developmental periods during the year cause leaf damage. Other causes of damage include wet and warm weather, as well as dry summers, which promote pest proliferation. Other causes of leaf browning include leaf edge necrosis, salt damage, frost damage, etc. **(Rogers 1994)**. One of the main causes of leaf damage in horse chestnuts in summer months is the invasive infestation by larvae of the moth *Cameraria ohridella*. This pest was discovered and described in Macedonia and has spread rapidly across Central and Western Europe over the past 19 years **(Sefrova and Lastuvka 2001)**. Damage caused by this leaf miner on its primary host plant, *Aesculus hippocastanum*, is particularly notable in cities where horse chestnuts are abundant and where the aesthetic impact of yellowing and browning trees in streets, parks, and gardens in June raises public concern **(Freise and Heitland, 2001)**. Over the last 20 years, *Cameraria ohridella* has gradually occupied a large part of Central and Western Europe at a rate of about 60 km per year **(Sefrova and Lastuvka 2001)**. This species has been reported from Spain **(Villalva and Del Estal 2003)**, the United Kingdom **(Straw and Bellett-Travers 2004)**, Denmark **(Karsholt and Kristensen 2003)**, Ukraine **(Akimov *et al.*, 2003, Gilbert *et al.* 2005)**, and the Czech and Slovak Republics **(Hrubik and Juhasova 1998)**. Some infestations have also been noted on *Acer platanoides* and *Acer pseudoplatanus*, but these appear to be opportunistic infestations near heavily infested *Aesculus hippocastanum* **(Gilbert *et al.*, 2005)**.

The significant success of settlement is related to the fact that *Cameraria ohridella* has very few natural enemies exerting pressure on its population (< 5% parasitism rate) **(Freise, Heitland and Tosevski 2002)** and has 3-5 generations per year **(Sefrova and Lastuvka 2001)**. Factors affecting mortality of *Cameraria ohridella* in all developmental stages are still poorly understood **(Girardoz *et al.*, 2007)**. On the other hand, many authors have focused on the parasites of this moth **(Hellrigl 2001; Freise *et al.*, 2002; Grabenweger 2003; Girardoz *et al.*, 2006; Volter and Kenis 2006)**. About 30 native generalist parasites have been recorded attacking this species. The parasitism rate is low, and the role of parasites in the natural regulation of *Cameraria ohridella* populations is negligible **(Girardoz *et al.*, 2007)**. In temperate zones, *Cameraria ohridella* usually has one or two generations per year **(Hering, 1951)**. In Europe, *Cameraria ohridella* can have three generations per year **(Hellrigl and Ambrosi 2000; Freise and Heitland, 2001)**. In southern Europe, four generations per year are observed, with non-wintering generations having a high growth rate **(Del Bene *et al.*, 2001)**. Many authors have shown that low winter temperatures cause mortality of approximately 50-90% of pupae in fallen leaves **(Girardoz *et al.*, 2007; Pottinger and Leroux 1971; Connor 1984)**. **Grabenweger *et al.* (2005b)** found that birds, specifically tits, have a measurable negative impact on *Cameraria ohridella* populations. Bird predation is estimated at 2-4% (i.e., a similar range to parasitism). **Laing et al. (1986)** determined that most of this mortality is caused by earthworms, which bury and consume leaves, thus destroying pupae or preventing emerged adults from reaching the surface. Removing leaves in autumn has a similarly significant impact on *Cameraria ohridella* populations in the following spring **(Pavan et al., 2003)**. When horse chestnuts are heavily infested with *Cameraria ohridella*, larvae may die due to intraspecific competition **(Pschorn-Walcher, 2001)**. Another method of reducing *Cameraria ohridella* populations is chemical spraying or insecticide application, for example, by injection or surface spraying. Many pesticides have been tested, most commonly systemic insecticides applied directly to tree trunks **(Gargani *et al*., 2002; Sánchez-Zamora and Fernández-Escobar 2004; Santi *et al*., 2004; Baraniak *et al*., 2005; Walczak, Giertych and Baraniak 2024)**. Pesticide application in urban and densely populated areas can pose significant public health risks. Another problem with application is the holes in the bark of treated plants. **Ferracini and Alma (2008)** report that most holes healed in the bark within 6-7 months of treatment. Only a few trees did not heal or developed cracks on the trunk.

Approaches to Leaf Damage Assessment

Understanding the spatial dynamics of invasive species is crucial in any attempt to predict their spread to new areas and represents a challenge in applying control methods **(Sakai *et al*., 2001)**. Assessing damage caused by herbivorous insects is a complex process. Accurate estimates require quantitative measurements, which are extremely time-consuming. Conversely, qualitative or semi-quantitative observations are faster and can provide results almost as accurate as more time-consuming quantitative techniques **(Gilbert and Grégoire, 2003)**. Monitoring population spread is important for appropriate control of invasive species. Assessing damage caused by herbivorous insects is challenging, especially over large areas. Accurate estimates require quantitative measurements, which are very time-consuming. Conversely, qualitative or semi-quantitative observations are faster, but their accuracy can be questioned. The compromise between accuracy and feasibility is, of course, difficult to establish. **Freise and Heitland (2001)** state that semi-quantitative visual assessments can provide almost as accurate results as more time-consuming quantitative techniques. Most proposed methods for assessing the occurrence of *Cameraria ohridella* are based on visual interpretation of the extent of damage on infested leaves. The basic assumption is visual evaluation of damage based on a damage scale. Many studies use this method to assess leaf damage of *Aesculus hippocastanum* **(Gilbert and Grégoire, 2003; Bacher 2005; Girardoz, Quicke and Kenis, 2007; Pocock and Evans, 2014; Anagnostis *et al*., 2020; Tzonev *et al*. 2024)** or by observing under a microscope and manually counting mines **(Ferracini and Alma, 2008; Percival, Banks and Keary, 2012)**. Leaf damage quantification can be performed either by software image processing or visual assessment **(Heitland *et al*., 2000)**. Software image processing has several disadvantages. It can tend to overestimate the damaged surface and image processing is time-consuming. Processing time could be improved by using devices specifically designed for scanning and analysis, which involves higher financial costs. The disadvantage of visual assessment is the time required for processing, personnel workload, assessor subjectivity, and others **(Gilbert and Grégoire, 2003)**. There are many software solutions for evaluating leaf damage, such as WinDIAS 3 leaf image analysis system, which can scan and analyze leaf damage, PlantEye F600 multispectral 3D scanner for plant phenotyping, or the WinFOLIA program specifically designed for leaf analysis (area, morphology, and disease analysis). Some studies use these software solutions to evaluate leaf damage **(Jagiełło, 2017; Pillajo, 2023; Li, Wang and Zhang, 2023; Eevera, Vanangamudi and Peske, 2009; Putniece, 2023)**. Applied machine learning has also become of interest in agricultural practice **(Dehnen-Schmutz *et al.* 2016)**. It has also started to be used in image recognition tasks **(Barbedo *et al.*, 2016; Fuentes *et al.* 2017; Barbedo *et al.*, 2018; Singh *et al.*, 2018; and others)**. The advantage of the software and instrumental evaluation method for horse chestnut leaves infested with *Cameraria ohridella* is still under-explored, which may be related to the cost and unavailability of this method among the scientific community. Despite extensive research on the biology and control of Cameraria ohridella, there is still limited methodological consensus on how to efficiently and reliably assess the severity of leaf damage, particularly under real urban monitoring conditions. Most existing approaches rely on visual scoring, which may be affected by observer bias and high personnel demands, highlighting the need for more objective and scalable assessment tools.

The aim of this study was to evaluate the reliability and efficiency of visual and software-based methods for assessing leaf damage caused by Cameraria ohridella. Specifically, we addressed the following research questions: (i) Does the accuracy of visual damage assessment depend on the biological expertise of the evaluator? and (ii) Can a software-based image analysis method provide comparable accuracy while significantly reducing evaluation time? We hypothesized that expert evaluators would achieve higher accuracy than laypersons, and that the software-based method would be faster and more consistent than human assessment.

MATERIAL AND METHODS

Material preparation and semi-quantitative evaluation

The study was conducted in the Slovak Republic in the city of Bratislava. Our research sample consisted of 7 locations, with 5 trees of the same age and no other damage signs other than damage caused by *Cameraria ohridella* being monitored at each location. Leaf collection was carried out with the help of a climber and telescopic scissors at the end of June 2021, when leaf damage due to *Cameraria ohridella* was most pronounced. During this time, damage from the pathogen *Guinardia aesculi*, salting, or frost is very low, so there is no confusion with very similar symptoms. Leaves were collected from approximately the same spots on each tree at each location. From the lower and middle branches of trees oriented east, west, north, and south, we collected 5 compound leaves, each consisting of 5-7 ovate leaflets. From one tree, we collected 40 compound leaves. From 7 locations, we collected 1400 compound leaves. From the total of 1 400 leaves, 105 were selected based on visual assessment for further analysis using software. From each of the 35 trees (7 locations × 5 trees), three compound leaves were randomly selected from different canopy positions to ensure spatial representativeness, resulting in a total of 105 leaves used for detailed software-based analysis. These leaves met the criteria for inclusion in the evaluation scale. The selection of 105 leaves was made to ensure the evaluation process remained manageable and feasible for human assessment. The collected leaves were placed in paper boxes and transferred to the laboratory. It is commonly observed that leaves from lower branches are more infested than leaves higher in the crowns **(Tomiczek and Krehan, 1998)**. Selecting only lower branch leaves for damage assessment can overestimate damage on a tree scale. This problem is difficult to consider because this model is highly variable (from trees where damage is homogeneously distributed to trees where upper leaves are almost untouched) and very hard to quantify. Therefore, we decided to take an even distribution of leaves from the lower and upper parts of the crown to avoid bias. The average damage allows for a more accurate idea of the overall damage to the tree. Leaves from each location were straightened using a sprayer, water, and cotton gloves, as some were curled due to severe damage. The leaves were weighted for 24 hours to straighten them. Leaves from each location were placed on a white area of 210-297 mm and scanned with a standard office device (HP DeskJet 3760 (T8X19B)) at a resolution of 1.200 × 1.200 dpi. Scanning the leaves in our study serves not only as an input for algorithmic evaluation but also as a method to ensure consistency and documentation of the leaves for visual assessment. The scanner allows for the acquisition of high-quality images that can be repeatedly analyzed by multiple evaluators, thereby minimizing subjectivity in the assessment. Since the compound leaves of horse chestnut (*Aesculus hippocastanum*) often exceed the dimensions of the scanner (210 × 297 mm), the leaves were divided into individual leaflets prior to scanning. Each leaflet was scanned separately to ensure high-quality and consistent imaging for subsequent analyses. From the set, we randomly selected 105 compound leaves (4-5 leaves per image), from which we prepared an evaluation questionnaire in Microsoft Excel. The questionnaire included a standardized key of eight standardized levels or classes of leaf damage used in similar studies **(Gilbert and Grégoire, 2002)**. The frequency of mines was estimated using the damage key (**Gilbert and Grégoire 2002)** based on visual assessment of the relative mined area per leaf. Each leaf was assigned one of eight levels defined by the authors: 0% damage, 2.5%, 10%, 25%, 50%, 75%, and 100% damage. **Gilbert and Grégoire (2003)** showed that their damage assessment system provides a good tool for estimating and comparing population density and is increasingly used in population studies of *Cameraria ohridella* **(Forbes and Korva, 1994; Rogers *et al.*, 1994; Gilbert *et al.*, 2005; Grabenweger *et al.*, 2005b; Kehrli *et al.*, 2005)**. These keys, however, are specific to individual damage and their effectiveness depends on their specific design tailored to leaf shape and damage pattern **(Duveiller, 1994)**. **Gilbert and Grégoire (2002)** used a similar assessment with 25 images (4-5 leaves per image). The images were presented sequentially in the questionnaire to 25 volunteers without botanical knowledge (laymen) and 25 volunteers working in research centers or universities (experts) to make a general estimate of the relative damage on each image.

Software image processing (algorithmic approach)

As we described in previous section, we have scanned the horse-chesnut leafs. We made sure that in every image there is one leaf as can be seen in Figure 1. Each image is represented by the grid (matrix) of pixels. Each pixel is a RGB-triplet of numbers from the interval <0, 255>. Any color, represented by it's RGB-triplet is a point in 3D Euclidean space. Therefore Euclidean distances between any two colors (each represented by it's RGB-triplet) can be calculated and understood as a distance between these colors.

In contrastu to Gilbert & Grégoire (2003), where humans needed to use Photoshop to correctly segment leaf, we developed an algorithm for automatic segmentation of green and brown parts of a leaf. The only algorithm parameters are the RGB base colors. Each of the base colors has it's RGB-triplet and class. Base color classes are three: green leaf part, brown leaf part or background.

The algorithm works pixel-wise, meaning that for every pixel it performs the following steps:

- calculates distance of a pixel RGB-triplet to each of the base colors
- select, to which of the base colors the pixel is closest
- asigns the class of the closest base color to the pixel

After assigning class to every image pixel, the algorithm produces an image mask. Example of such mask can be seen in Figure 1.

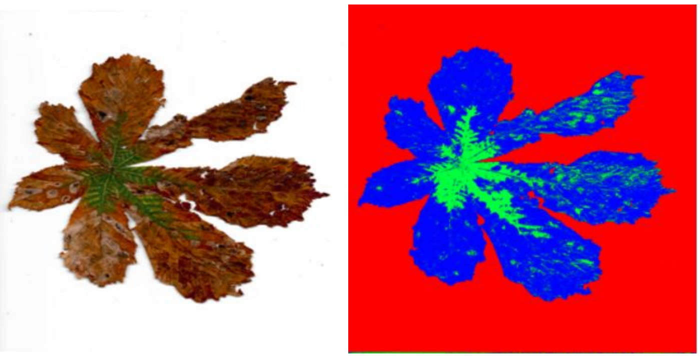

Figure 1 Principle of operation of the algorithm

In our case, the algorithm parameters included eight base colors, providing multiple base colors for each class. This multiplicity enables the algorithm to correctly assign classes to colors located near the green–brown boundary in RGB space. The appropriateness of the selected base colors was then validated by comparing the classes assigned by the algorithm with those assigned by a human assessor for each image pixel. Selecting too few base colors can introduce systematic errors, as the algorithm may incorrectly classify a large number of colors near class boundaries. Therefore, for any application of the algorithm, it is advisable to conduct a pixel-wise evaluation to verify its performance. The results of such an evaluation are presented in the Results section.
The time required for evaluation was recorded for both human assessors and the software. Each assessor noted the time needed to complete the evaluation process, while the software's processing time was measured using a timer. Both the assessors and the software were provided with the same set of 105 pre-scanned leaves to ensure consistency in the evaluation.

RESULTS

Distribution of data and statistical approach

Data were statistically processed using STATISTICA software (StatSoft Inc., 2011). Normality of the data was tested using the Shapiro–Wilk test, which indicated that the data were not normally distributed. Therefore, a non-parametric Kruskal–Wallis ANOVA was used to compare differences between groups. This test was selected because it is suitable for comparing median values among multiple independent groups when the assumption of normality is violated.

Comparison of visual and software-based assessments

We found a statistically significant difference in leaf damage evaluation between laypeople and experts ($p < 0.05$), and a highly significant difference between laypeople and the software-based method ($p < 0.01$). In contrast, no statistically significant difference was observed between expert evaluations and the software-based assessments ($p > 0.05$) (Figure 2). These results indicate that expert assessments are consistent with the software-based method, whereas laypeople tend to differ significantly from both.

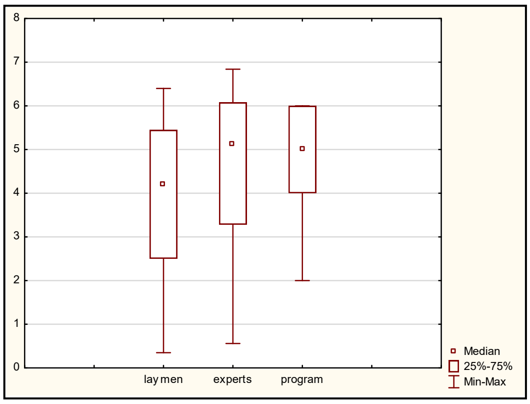

Figure 2 Comparison of average leaf damage scores between laypeople, experts, and the software

Comparison of semi-quantitative and algorithmic methods

When combining laypeople and expert assessments into a single semi-quantitative group and comparing it with the software-based evaluation, a statistically significant difference was observed ($p < 0.05$) (Figure 3).

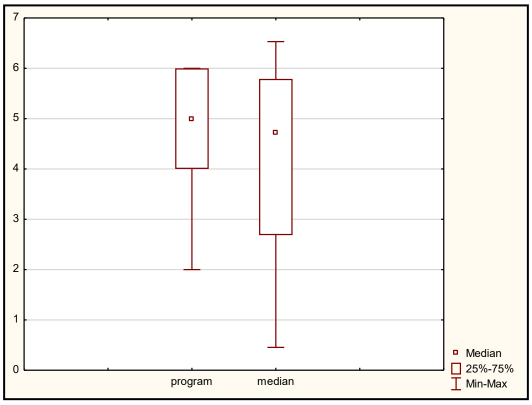

Figure 3 Comparison of semi-quantitative visual assessment and software-based evaluation.

Time efficiency of evaluation methods

We further compared the time required for semi-quantitative visual evaluation and software-based analysis of 105 leaves. The difference in processing time was statistically significant ($p < 0.05$). The software-based method reduced evaluation time by 97.51%. Using the developed software, 105 leaves were evaluated in under 3 minutes on a standard laptop. In contrast, manual evaluation required an average of 40.22 minutes per person. The cumulative time spent by 50 volunteers on visual assessment was 2011 minutes (approximately 33 hours and 51 minutes), whereas software-based evaluation required only 50 minutes by a single operator.

Accuracy of the algorithm

Algorithm performance was validated by comparison with expert evaluations. The software assigned the same damage class or differed by one class in 75% of cases, and differed by at most two classes in 93% of cases. In addition, pixel-level comparison between software segmentation and expert-defined leaf damage resulted in an average overlap of 89% ± 4% across 10 test images. This indicates high agreement between automated and expert-based assessments.

DISCUSSION

The assessors used a semi-quantitative damage scale **(Gilbert and Grégoire 2003)**, and leaf damage was additionally evaluated using a custom-written software program. These two evaluation approaches were compared in terms of accuracy, execution speed, and personnel requirements. Our first hypothesis, assuming that a higher level of biological education leads to more accurate visual damage assessment, was confirmed. Similarly, our second hypothesis, assuming that software-based evaluation would be faster than human assessment, was also confirmed. In this study, we estimated damage and infestation of horse chestnut (*Aesculus hippocastanum*) by the horse chestnut leaf miner (*Cameraria ohridella*) using image processing and compared the results with visual assessments performed by volunteers with and without specialized education using a semi-quantitative damage scale. These findings are consistent with broader trends in plant pathology and applied entomology, where remote sensing approaches (including visual inspection, digital photography, and automated image analysis) are increasingly used to quantify disease or pest severity at the level of individual leaves or plants **(Bock et al., 2010)**. Our results can be directly related to the seminal work of **Gilbert and Grégoire (2003)**, who used damaged areas of 411 horse chestnut leaves collected from 100 locations to estimate population size of herbivorous insects and demonstrated a close relationship between leaf damage and mine numbers. Based on this relationship, they compared digital image processing and visual assessment using a damage key reflecting the relative infested area on each leaf (0%, 0–2%, 2–5%, 5–10%, 10–25%, 25–50%, 50–75%, 75–100%), showing that both approaches provided similar estimates of damage. **Likewise, Gilbert and Grégoire (2002)** concluded that software image processing does not necessarily add value compared to visual assessments for estimating population density at the leaf level. However, visual assessments introduce additional variability due to subjective interpretation of damaged areas, a phenomenon widely reported in the literature (**O'Brien and Vanbruggen 1992; Rogers et al., 1994**). The presence of unavoidable rater-related variability is also emphasized by **Bock et al. (2010)**, who demonstrated that both inter-rater and intra-rater reliability can vary substantially, particularly when raters are not trained or when standardized assessment aids are not used. They further showed that human observers tend to systematically overestimate damage at low severity levels (<10%), and that lesion number relative to leaf area strongly influences visual accuracy. These mechanisms likely explain part of the variability observed in our volunteer-based visual assessments, especially among participants without formal biological training. In recent years, numerous studies have explored automated image-based approaches for plant disease and damage assessment using large datasets. The largest publicly available dataset, PlantVillage, contains over 54,000 leaf images across 38 classes **(Hughes and Salathe, 2015)**, and has been widely used in machine learning studies reporting classification accuracies exceeding 99% **(Mohanty et al., 2016; Too et al., 2019; Kaya et al., 2019)**. Other studies have developed crop-specific datasets and models, such as for tomato **(Fuentes et al., 2017)**, wheat **(Johannes et al., 2017)**, apple **(Liu et al., 2017)**, and cucumber **(Ma et al., 2018)**. Convolutional neural networks have also been applied to disease severity estimation **(Wang et al., 2017; Liang et al., 2019)**, with further related studies by **Ghosal et al. (2018), Manso et al. (2019), Barbedo (2019),** and **Esgario, Krohling and Ventura (2020)**. Nevertheless, several authors caution that extremely high classification accuracies reported in benchmark datasets such as PlantVillage may overestimate real-world performance, because images are typically acquired under controlled conditions and lack environmental noise, variable illumination, and heterogeneous backgrounds **(Bock et al., 2010; Barbedo, 2019)**. In contrast, our study operates under realistic field conditions and focuses not on disease classification but on quantitative severity estimation, which represents a more demanding task both for human observers and automated systems. Importantly, **Augustin et al. (2009)** demonstrated that semi-quantitative visual damage scales for *C. ohridella* are linearly related to log-transformed mine numbers and correlate significantly with pheromone trap data across multiple spatial scales. They concluded that visual damage assessment represents a cost-efficient and robust monitoring method for large-scale and long-term population studies, whereas pheromone traps are more suitable for fine-scale within-season dynamics. This directly supports our finding that visual assessment remains ecologically valid and operationally useful, but that automated image-based methods provide advantages in terms of objectivity, standardization, and processing speed. Taken together, our results align with the broader literature suggesting that visual assessment and digital image analysis often achieve comparable accuracy, but differ substantially in reliability, scalability, and susceptibility to observer bias. While visual methods remain cost-effective and practical for large monitoring campaigns, automated image analysis represents a more reproducible and future-proof solution, particularly in citizen science contexts and large datasets where assessor expertise cannot be guaranteed **(Bock et al., 2010; Augustin et al., 2009).**

Limitations and future research

Despite the promising results, several limitations of the present study should be acknowledged. First, the software-based method was validated primarily using scanned leaf images collected under relatively controlled conditions. Future studies should test the robustness of the algorithm under more heterogeneous field conditions, including variable illumination, leaf overlap, and different imaging devices. Second, the algorithm was developed and validated specifically for *C. ohridella* damage on *A. hippocastanum*, and its applicability to other host–pest systems remains to be explored. Finally, although expert assessments were used as a reference standard, future research could integrate additional validation approaches, such as independent ground-truth measurements or multi-site datasets, to further strengthen the generalizability of the method.

CONCLUSION

The developed algorithm is designed to be easily implementable in various environments and adaptable for the analysis of leaf damage in different plant species. Our results demonstrate that software-based assessment can substantially reduce evaluation time while maintaining accuracy comparable to expert visual scoring. The algorithm achieved an average pixel segmentation accuracy of 89%, showing high agreement with expert-defined damage areas. In contrast to earlier segmentation approaches (e.g. **Bakr, 2005**), which are difficult to implement on modern systems, our method was developed in the Python programming language and is fully compatible with current computing environments. The complete source code and installation instructions are publicly available via a GitHub repository (https://github.com/trunibio/leafs_color_segmentation), allowing transparent reuse and further development by other researchers. Importantly, the proposed method is lightweight and does not require large training datasets, unlike neural network-based approaches. This makes it particularly suitable for practical applications in ecological monitoring and urban forestry, where data availability and technical resources are often limited. Overall, the presented approach provides a simple, efficient, and reproducible tool for large-scale assessment of leaf damage, with potential relevance for pest monitoring, citizen science projects, and evidence-based management of urban green spaces.

Acknowledgments: This research was supported by the VEGA project 1/0535/24 STRO:ViD - Cultural Ecosystem Services of Trees in Public Open Spaces of the Slovak Countryside.

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