Journal of Artificial Intelligence and Computing Applications (2024) 2(2): 7–17

Critical perspective

The Role of AI in Combating Mistletoe Infestation in Mexican Forests: A Call for Interdisciplinary Action

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Este artículo ha sido publicado tanto en inglés como en español para garantizar la accesibilidad a una audiencia más amplia. Se puede acceder a la versión en español de este artículo en el siguiente DOI: https://doi.org/10.5281/zenodo.14720118.

Keywords: mistletoe detection, artificial intelligence in conservation, ecological management tools

PERSPECTIVE

Mistletoe is a hemiparasitic plant that attaches to host trees, extracting water and nutrients, which weakens the trees, reduces biodiversity, and disrupts critical ecosystem services. While often romanticized in cultural contexts, mistletoe poses a serious ecological threat, particularly in urban and forested ecosystems where infestations can spread unchecked. This article examines the role of artificial intelligence (AI) and remote sensing in addressing the detection and management challenges posed by mistletoe. Through a critical evaluation of methodologies ranging from texture-based machine learning to advanced deep learning models such as ResNet-34, this paper reflects on the successes, limitations, and implications of these approaches. Our interdisciplinary research highlights the transformative potential of combining AI with ecological expertise to develop scalable and efficient tools for conservation. However, we also identify key challenges, including the need for equitable access, ethical considerations, and scalability across diverse ecological contexts. Moreover, we emphasize the importance of engaging the broader community, as misconceptions about mistletoe hinder conservation efforts. By integrating public awareness with technological advancements, we advocate for a balanced and sustainable approach to ecological management. This paper aims to provoke critical dialogue and inspire actionable strategies for leveraging AI in addressing global conservation challenges.

Introduction

Mistletoe infestations represent a localized instance of a broader global issue: the ecological and socioeconomic challenges posed by invasive plant species. These species, characterized by their ability to rapidly establish and proliferate in non-native ecosystems, have significant and far-reaching impacts. Globally, invasive plants contribute to biodiversity loss by outcompeting native species, disrupting food webs, and altering ecosystem services [1, 2]. In this sense, their spread can compromise carbon sequestration, temperature regulation, and habitat support for native wildlife, while simultaneously creating socioeconomic burdens by affecting agriculture, forestry, and public health.

Mistletoe is a hemiparasitic plant that requires a host tree to extract water, minerals, and other nutrients by inserting a specialized root called haustoria. This parasitic relationship weakens host trees over time, reducing their structural stability, decreasing biodiversity, and threatening critical ecosystem services [3, 4]. In Mexico City, three mistletoe species—*Cladocolea loniceroides*, *Phoradendron velutinum*, and *Struthanthus interruptus*—have been identified as significant contributors to ecological disruption and one of the main problems of urban green spaces[5].

Among these species, *S. interruptus* and *P. velutinum* stand out due to their extensive impact on urban ecosystems and forested areas. For example, *S. interruptus* is prevalent in 9 of the 16 boroughs of Mexico City [5], while *P. velutinum* is particularly noted for its ability to blend seamlessly with host vegetation in conservation forests [6]. Both species form dense clusters in advanced infestation stages, dominating tree crowns and disrupting natural tree structures [7]. These infestations compromise forest health, reduce biodiversity, and hinder essential ecosystem services, including carbon sequestration and habitat support for native species [3, 4]. The widespread ecological and economic impacts of these mistletoe species underscore the urgency of developing effective and scalable detection and management strategies.

Detecting and managing mistletoe infestations presents significant challenges due to the plant's ability to visually blend with host vegeta-

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https://doi.org/10.5281/zenodo.14699764

tion, particularly in its early stages [6]. As shown in Figure 1, mistletoe clusters closely resemble the healthy foliage of their host trees, making manual identification difficult, especially in dense vegetation. This challenge is further compounded by environmental variability, including changes in lighting, viewing angles, and seasonal foliage density, which reduce the reliability of traditional methods [7]. Manual surveys, conducted by trained experts, remain the main approach for mistletoe detection, but they are labor intensive, time consuming, and resource demanding, rendering them impractical for large-scale implementation [6]. Additionally, the physical inaccessibility of certain forested areas exacerbates these inefficiencies, allowing infestations to spread undetected. Together, these limitations underscore the significant difficulties faced in managing mistletoe infestations and highlight the pressing need for improved methods to enhance the efficiency and scalability of detection efforts.

The urgent need for innovative and scalable solutions to address the mistletoe infestation problem in Mexico catalyzed the formation of an interdisciplinary research initiative. This collaborative effort brought together experts from Centro de Investigación en Ciencias de Información Geoespacial, A.C. (CentroGeo), Tecnológico Nacional de México/Instituto Tecnológico de Mérida (ITM), Instituto Tecnológico de Pabellón de Arteaga (ITPA), and included support from Secretaría de Educación, Ciencia, Tecnología e Innovación de la Ciudad de México (SECTEI), Secretaría del Medio Ambiente de la Ciudad de México (SEDEMA), and the UNAM-Huawei Innovation Space. By combining expertise in artificial intelligence (AI), remote sensing, ecological management, and field operations, the team seeks to tackle the multifaceted challenges posed by mistletoe infestations in both urban and forested ecosystems.

Central to the team strategy is the integration of advanced technologies with ecological knowledge. In particular, remote sensing technologies, such as high-resolution multispectral imagery collected via unmanned aerial vehicles (UAVs), have provided the ability to monitor large areas efficiently and capture detailed information related to vegetation health, phenology, among others. These data, combined with cutting-edge AI techniques, have enabled the development of scalable detection tools. Hence, by leveraging machine learning algorithms and deep learning models, the team aims to create methodologies capable of distinguishing mistletoe clusters from surrounding healthy vegetation with high precision, even under challenging environmental conditions.

The overarching goal of the initiative is to develop innovative, technology-driven methodologies for the automated detection and management of mistletoe infestations. Designed to address the limitations of traditional approaches, these methodologies prioritize scalability, precision, and efficiency while ensuring interpretability and actionable insights for ecological practitioners. By focusing on scalability, the tools aim to support diverse ecological contexts, from urban parks to forestry conservation areas, contributing to biodiversity preservation and ecosystem health.

To address the challenges of mistletoe detection, comprehensive datasets have been collected from diverse study sites, including the *San Bartolo Ameyalco* ecological conservation area, the *Ramón López Velarde Garden*, and Xochimilco pier, in Mexico City. These locations were chosen in conjunction with SEDEMA due to their high prevalence of mistletoe infestations and their diverse environmental conditions, which provide a robust foundation for developing robust detection models.

The datasets were built using a P4 multispectral drone, which provides detailed spatial and spectral information critical for distinguishing mistletoe from host vegetation. This device allowed to capture high-resolution imagery, preserving the fine-grained details of mistletoe clusters, such as their broad, velvety leaves and distinct coloration. These characteristics are essential for accurate identification, particularly in early infestation stages where mistletoe blends seamlessly with its host trees. The original aerial image on the left of Figure 2 highlights this visual similarity, demonstrating the challenge of differentiating mistletoe from healthy vegetation. To address this, preprocessing steps such as multispectral band co-registration and normalization were applied to ensure consistency across the dataset.

The identification and segmentation of mistletoe clusters in each set of images were performed manually by an ecological specialist. These labeled maps served as the foundation for supervised learning, providing accurate ground-truth data to train machine learning models. The left image of Figure 2 shows an example of segmentation map overlaid (in red) to the original corresponding image. This combination of high-resolution imagery and expert segmentation created a robust dataset for advancing automated detection methodologies.

The integration of AI and remote sensing holds promise not only for addressing the immediate challenge of mistletoe infestations, but also for broader ecological applications. These tools enable conservationists to monitor biodiversity, assess the health of ecosystems, and develop targeted management strategies for invasive species. As highlighted in this research, the use of these technologies requires a multidisciplinary approach that combines ecological expertise with computational advancements, ensuring that solutions are both scientifically robust and practically actionable.

The objectives of this paper are threefold. First, to reflect on the insights gained from the ongoing collaborative efforts of our interdisciplinary research team, emphasizing both successes and challenges encountered in applying AI and remote sensing to ecological conservation. Second, to encourage dialogue within the scientific and conservation communities, fostering interdisciplinary collaboration and inspiring innovation. Finally, to outline po-

Figure 1. Visual representation of mistletoe clusters (*S. interruptus*) highlighted in blue, captured in the Ramón López Velarde Garden, Mexico City in November 2024. The hemiparasitic mistletoe blends seamlessly with its host vegetation, complicating manual detection and emphasizing the need for automated identification methods.

tential directions for future research, emphasizing the importance of sustainable and equitable deployment of AI technologies in addressing pressing environmental challenges.

Current Advances

The initial phase of our research explored the potential of evolutionary computating approaches, specifically Genetic Programming (GP), to address the challenge of mistletoe detection. GP was employed to develop a spectral index method capable of distinguishing mistletoe infestations in UAV-acquired multispectral imagery [6]. By simulating natural evolutionary processes, GP iteratively optimized combinations of spectral bands to create a highly effective index for detecting *Phoradendron Velutinum* species during its flowering stage.

This methodology demonstrated remarkable accuracy, exceeding 96% in controlled conditions, and provided a foundational proof of concept for automated detection. The focus on the flowering stage of *P. velutinum* leveraged the unique spectral characteristics of the parasitic plant, enabling precise differentiation from host trees and surrounding vegetation. This achievement evidenced the potential of computational approaches to complement traditional ecological methods, particularly in addressing labor-intensive tasks such as manual field inspections.

The success of GP not only validated the feasibility of using automated spectral analysis for mistletoe detection, but also highlighted the complexity of scaling such methods to broader ecological contexts and the monitoring of different mistletoe species. These insights set the stage for subsequent explorations into more adaptable techniques capable of handling environmental variability and addressing a wider range of species. Hence, our research expanded to explore the use of texture descriptors and machine learning techniques for mistletoe detection.

Recognizing the importance of spatial patterns in differentiating mistletoe from host trees, we employed descriptors such as Gray Level Co-occurrence Matrices (GLCM) and Gabor filters, along with color transformations and vegetation indices, to capture the unique

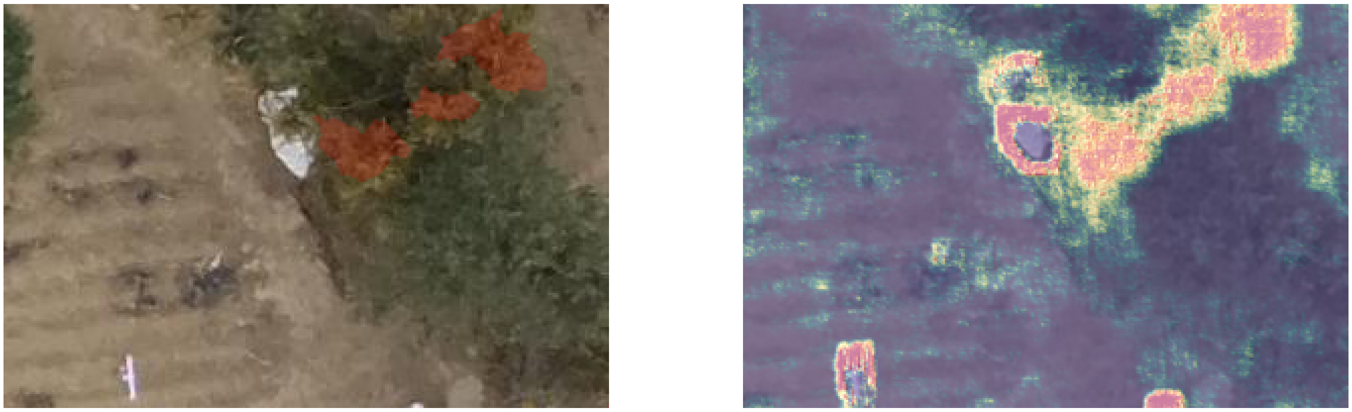

Figure 2. Visualization of the ResNet-34 CNN model's processing for the identification of mistletoe species known as *P. Velutinum.* On the left, the original high-resolution RGB image with an overlaid binary segmentation mask (red) highlighting mistletoe regions (expert-labeled), and on the right, the CNN-generated heatmap emphasizing areas identified as mistletoe.

textural and spectral characteristics of mistletoe clusters [8]. These features were selected with the aim of improving the classification performance of *S. Interruptus* species carried out by Support Vector Machines (SVMs), which achieved an accuracy close to 60% in controlled environments [8]. These results demonstrated the potential of combining texture and spectral descriptors with machine learning models for the current application. However, the performance of these methods was significantly affected by the close similarity between the mistletoe and host tree foliage. Moreover, the lack of other spectral features limited the adaptability of our approach to more complex and heterogeneous settings, such as large forested areas with various mistletoe species.

The results of SVM revealed the potential of using computational techniques to classify mistletoe infestations, but also evidenced their limitations in adapting to environmental variability and capturing the complexity of texture patterns. These challenges highlighted the need for methodologies capable of learning intricate features directly from the data, without relying on predefined handcrafted descriptors. This realization led us to explore deep learning approache, which offered a more dynamic and adaptive framework for handling complex ecological tasks.

Among deep learning techniques, Convolutional Neural Networks (CNNs) emerged as a natural and highly suitable choice. CNNs are specifically designed to extract spatial hierarchies of features from images, making them particularly effective for texture-rich tasks, like mistletoe detection. By learning patterns directly from UAV-acquired imagery, CNNs provided the flexibility needed to account for variability in environmental conditions, such as changes in lighting, foliage density, and tree structure. This adaptability made CNNs an ideal next step in our research, bridging the gap between earlier efforts and the need for robust and scalable solutions.

With the purpose of testing the feasibility of advanced image-based classification techniques, we began by the development of a simpler application oriented to the detection of dead trees in urban parks [9]. This task allowed us to focus on well-defined visual features, such as the absence of foliage or grenness, while making use of UAV-acquired data to establish baseline models. To do so, we implemented ResNet-34, a convolutional neural network (CNN) architecture known for its balance between computational efficiency and representational power [10, 11, 12]. ResNet-34 utilizes residual blocks with shortcut connections, which mitigate the vanishing gradient problem and enable effective training in deep networks [13]. This architecture excels in extracting fine-grained features, making it particularly suitable for ecological monitoring tasks where subtle distinctions, such as identifying invasive species or degraded vegetation, are critical.

This phase of our research not only confirmed the potential of CNNs for ecological and vegetation monitoring, but also laid the groundwork for subsequent efforts to capture more subtle texture patterns associated with mistletoe infestations. By successfully applying CNNs to the detection of dead trees, we were able to refine our methodologies and build confidence in the scalability and adaptability of deep learning models for broader ecological challenges, such as mistletoe species classification.

Our research then progressed to implement ResNet-34 for the more intricate task of mistletoe classification in urban green spaces. To deepen our understanding of the visual features and characteristics associated with such parasitic plant, we conducted experiments that perturbed the input images with changes in brightness, noise, and resolution. These perturbations were designed to explore how variations in environmental conditions affected the model's ability to identify mistletoe clusters. This approach provided valuable insights into the specific visual features that ResNet-

34 prioritized during classification, such as color, texture, and spatial patterns, enhancing our ecological understanding of mistletoe and its distinct visual signatures.

In addition, we integrated explainability tools, such as class activation maps (also known as heatmaps), to further validate the model predictions. These visualizations highlighted the regions of the images that the model relied on for its classifications, allowing us to ensure that its decisions aligned with ecological expectations. This combination of perturbation analysis and explainability not only strengthens the model interpretability, but also intends to provide end-users, such as forestry experts and conservation practitioners, with actionable insights into the visual characteristics of mistletoe, facilitating more informed ecological management.

The implementation of convolutional neural network models significantly improved our ability to identify mistletoe clusters; however, these models also introduced substantial computational demands. Training and deploying CNNs at scale requires considerable processing power, particularly when handling high-resolution UAV imagery. This challenge was addressed through our collaboration with the UNAM-Huawei Innovation Space, which provided access to high-performance computational infrastructure, enabling the optimization and efficient training of our models. Nevertheless, certain experiments required an evaluation on diverse hardware configurations and computational environments to assess performance and adaptability across different scenarios. For instance, the optimal combination of hardware setups, resource allocation strategies, and system configurations to minimize training times remains inadequately understood, highlighting the need for further exploration into hardware-performance trade-offs for ecological deep learning applications.

To address the previous exploration, we conducted a comparative analysis of hardware platforms, evaluating configurations ranging from consumer-grade laptops to high-performance servers. The study revealed critical insights into the trade-offs between computational efficiency, cost, and model performance. High-performance workstations and specialized hardware provided significant reductions in training time and improved the scalability of our models. By optimizing hardware performance, we not only increased the feasibility of deploying deep learning models for mistletoe detection, but also set the stage for broader applications in ecological conservation. This phase of research reinforced the need for interdisciplinary collaborations and resource-sharing initiatives to overcome computational barriers, paving the way for more robust and scalable solutions to complex environmental challenges.

A primary goal of our research has been to develop scalable and practical tools for ecological conservation, transitioning from experimental methodologies to real-world applications. Our detection systems, ranging from infestation maps to automated classification models, are designed with usability in mind, addressing the needs of forestry personnel, urban park managers, and policymakers. These tools have the potential to automate labor-intensive tasks, provide actionable insights for resource allocation, and monitor the effectiveness of management strategies. Additionally, explainability tools, such as class activation maps, ensure interpretability and trust in the models' outputs, bridging the gap between advanced computational methods and practical conservation efforts.

Discussion

The advancements achieved so far in this initiative represent significant progress toward addressing the ecological challenges posed by mistletoe infestations. However, as with any innovative approach, the journey has revealed not only successes but also limitations that warrant critical reflection. Beyond the technical achievements, this work raises broader questions about the role of AI in ecological conservation, the ethical and practical implications of deploying such technologies, and the challenges of ensuring scalability and accessibility. This section aims to provide an analysis of these aspects, exploring the lessons learned, the unresolved challenges, and the opportunities for future innovation. By reflecting on these dimensions, we hope to inspire continued dialogue and interdisciplinary collaboration in the pursuit of sustainable and impactful conservation solutions.

The methodologies explored reflect an evolving response to the complex challenges posed by mistletoe infestations. GP demonstrated significant potential by automating the design of a spectral index that achieved an overall accuracy of 96.6% in detecting mistletoe infestations during the flowering stage of *P. velutinum*. This precision was achieved in controlled conditions with multispectral UAV imagery, underscoring GP's ability to derive tailored solutions for specific ecological challenges. However, its dependency on flowering-stage spectral characteristics highlights limitations in generalizing across variable conditions and phenological stages.

This success was juxtaposed with challenges in scalability and adaptability. While GP excelled in specific scenarios, its reliance on spectral indices limited its robustness in heterogeneous settings. The detailed analysis of GP solutions revealed a strong reliance on visible spectrum bands, particularly the R and B channels, aligning with the characteristic pigmentation of mistletoe. This specificity, while effective in the targeted study area, raises questions about the adaptability of the GP-based algorithms to other environments and mistletoe species.

Subsequent exploration of texture descriptors and machine learning classifiers represented an important step in addressing the spatial complexity of mistletoe infestations. Techniques such as Gray Level Co-occurrence Matrices (GLCM), Gabor filters, and Local Binary Patterns (LBPs) were employed to capture the distinct textural characteristics of mistletoe regions, complemented by vegetation indices derived from UAV-acquired multispectral imagery. These approaches showed the critical role of texture in differentiating mistletoe from healthy vegetation, particularly in controlled scenarios. However, classification experiments conducted with SVMs, revealed notable challenges. These included sensitivity to environmental variability, such as lighting and seasonal changes, as well as the inherent limitations of handcrafted features, which restricted scalability and generalization to heterogeneous ecosystems. While the methodology offered valuable insights, the results highlighted the necessity of more adaptable techniques capable of learning features directly from data, setting the stage for deep learning approaches.

Deep learning techniques, while offering greater adaptability, require large, annotated datasets to fully exploit their potential. Our dataset, however, was of limited size, posing significant constraints for training CNNs to perform tasks like semantic segmentation, which demand pixel-level annotations. To address this limitation, we adopted an image classification approach by dividing larger aerial images into smaller tiles for analysis. This method maximized the utility of the available data and leveraged the robust feature extraction capabilities of CNN architectures such as ResNet-34. Rather than immediately addressing the complex task of distinguishing mistletoe from green vegetation, we opted for a more incremental approach. By focusing initially on the classification of dead trees versus green vegetation, we refined our methodologies, built a solid foundation for model training, and validated the feasibility of our approach. This stepwise progression balanced the technical challenges of deep learning implementation with the practical constraints of limited data availability and ecological complexity.

Our research achieved a significant milestone with the classification of dead trees using UAV-acquired multispectral imagery. The comparative study of ResNet-34 and DenseNet-121 provided insights into the applicability of these architectures for detecting vegetation anomalies indicative of ecological disturbances. Both models demonstrated robust performance, with DenseNet-121 slightly outperforming ResNet-34 in metrics such as accuracy and F1-score, achieving values of approximately 97% [9]. This high level of precision was complemented by the integration of heatmaps, which illuminated the areas within input images most relevant to the classification process. These visual tools enhanced the interpretability of the models' decisions, bridging the gap between computational outputs and actionable ecological insights. While these results validated the feasibility of using CNNs for tree health monitoring, they also set a precedent for tackling more complex classification tasks, such as distinguishing mistletoe infestations from healthy vegetation.

Building on the success of dead tree classification, we transitioned to the more intricate task of identifying mistletoe infestations. Confident in our approach, we extracted tiles in the same manner as before, this time focusing specifically on mistletoe. These tiles, derived from UAV-acquired multispectral imagery, formed the basis for training the model to distinguish mistletoe (*S. interruptus*) from the surrounding vegetation. Figure 3 showcases representative tiles of mistletoe, capturing the distinct visual features necessary for classification.

The ResNet-34 model achieved notable accuracy, with baseline performance metrics consistently exceeding 83% across both holdout and k-fold validation strategies. Heatmap visualizations effectively highlighted biologically relevant features, aligning with annotated mistletoe regions and validating the ecological relevance of the model's classifications.

However, the study also highlighted specific limitations. The model exhibited sensitivity to environmental perturbations, such as changes in color channels and the introduction of noise, particularly Salt-and-Pepper noise at higher intensities. While this sensitivity underscores areas for further refinement—such as enhancing robustness through noise-tolerant training methodologies or adaptive preprocessing strategies—it also offers a unique opportunity to better understand the visual characteristics of mistletoe. By analyzing the model's responses under varying conditions, we gain deeper insights into the defining features of mistletoe, such as its texture, color, and spatial patterns. This enhanced understanding can inform both manual identification by ecological practitioners and the development of more sophisticated automated detection methods. Additionally, the reliance on tile-based classification, while practical given the dataset constraints, presents challenges in capturing the broader spatial context necessary for large-scale ecological monitoring.

Looking forward, these results highlight the potential for integrating semantic segmentation techniques to overcome the spatial limitations of tile-based classification. By advancing the model's capacity to identify mistletoe at a pixel level, future efforts could significantly enhance detection precision and scalability. However, the computational demands of such refined methodologies remark the importance of efficient hardware solutions. As deep learning models grow in complexity, addressing the trade-offs between computational efficiency and performance becomes essential to ensuring their feasibility for large-scale ecological applications.

Our results provide valuable insights into optimizing the computational demands of deep learning models for mistletoe detection. Multiple configurations were evaluated, including Intel and AMD processors, consumer-grade GPUs, and high-performance workstations, to assess their suitability for training ResNet-34. Notably, AMD processors consistently outperformed their Intel counterparts in training efficiency, with mid-range AMD setups striking a balance between cost and performance. Additionally, disabling hy-

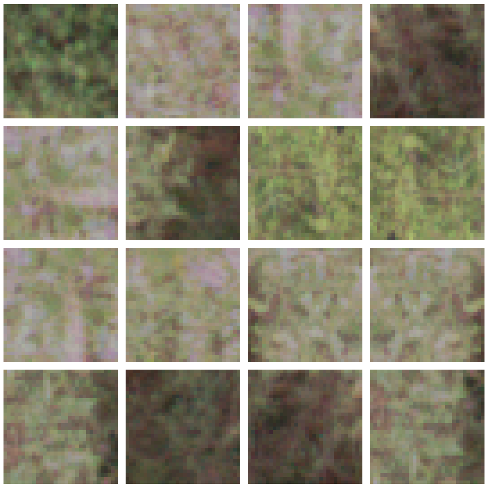

Figure 3. Sample tiles used in the training dataset for mistletoe (*S. interruptus*). Each tile measures 32 × 32 pixels and corresponds to a segment extracted from the original aerial imagery. These tiles were used to train and validate the ResNet-34 model.

perthreading (HT) on CPUs accelerated training times across most platforms, highlighting the importance of carefully tuning hardware settings for deep learning tasks.

Consumer-grade GPUs demonstrated effectiveness for short-term training tasks, delivering competitive performance relative to high-performance workstations in scenarios with moderate computational demands. However, high-performance servers exhibited unparalleled scalability and reduced training times, making them indispensable for extensive datasets or long-term workloads. These findings highlight the trade-offs between computational efficiency and cost, emphasizing the need to select hardware configurations that align with the scale and scope of ecological applications.

These outcomes reinforce the feasibility of deploying advanced models for ecological monitoring, provided that hardware choices are optimized for specific operational constraints. They naturally transition to broader considerations of deployment, such as addressing accessibility challenges in under-resourced regions and balancing computational performance with environmental sustainability.

While our methodologies have demonstrated significant potential, they are not without limitations, many of which present critical challenges for broader implementation and scalability. A key constraint lies in the reliance on high-resolution UAV-acquired imagery, which, while enabling precise detection, demands substantial resources for data collection and processing. This dependence raises questions about the feasibility of deploying such methods in resource-limited regions or over large-scale ecosystems where UAV coverage and computational capacity may be restricted.

Another limitation is the challenge of generalizing our models to diverse ecological contexts. The high accuracy achieved in controlled or semi-controlled environments does not guarantee equivalent performance in more complex and heterogeneous landscapes. Variations in vegetation types, mistletoe species, and environmental conditions, such as lighting or seasonal changes, can significantly affect model robustness. This highlights the need for extensive field validation and the development of models capable of adapting to the dynamic nature of ecological systems.

Scaling these approaches to larger areas also introduces unresolved challenges, including the computational demands of processing expansive datasets and the need for automation in UAV flight planning and data annotation. Moreover, biases in the training data—stemming from an overrepresentation of specific ecological conditions or geographic areas—may inadvertently limit the models' applicability. Addressing these biases will require careful dataset curation, with a focus on improving representativeness and diversity in training samples.

These gaps invite further exploration and innovation within the scientific and conservation communities. How can we balance the need for high-resolution data with the goal of creating scalable and accessible solutions? Are there hybrid approaches, such as integrating satellite imagery for broader coverage with UAV data for fine-tuning, that could bridge this gap? Additionally, adaptive learning techniques, where models are continuously updated with new data from diverse environments, could offer a path toward greater generalizability and resilience.

By acknowledging these limitations, we aim to stimulate debate and collaboration on how to address them. While the challenges are significant, they also present opportunities to refine and expand the applicability of AI-driven conservation tools, paving the way for more inclusive and impactful ecological solutions.

The methodologies and insights developed in this research hold significant potential for advancing AI applications beyond the detection of mistletoe infestations. The integration of UAV-acquired imagery, machine learning, and deep learning techniques establishes a scalable framework that can be adapted for a variety of ecological challenges. For example, these approaches could be utilized to monitor biodiversity in threatened habitats, assess the spread of other invasive species, or evaluate the health of forests affected by climate change. The ability of AI models to process and analyze large volumes of high-resolution imagery positions them as transformative tools in ecological conservation.

However, the broader application of these technologies raises important ethical and practical questions. Data ownership and privacy concerns are particularly relevant when UAVs are deployed in areas with human activity, potentially capturing unintended information. Establishing clear protocols for data governance and ensuring compliance with privacy regulations will be essential to maintain public trust and ethical integrity. Similarly, the accessibility of advanced AI tools in under-resourced areas remains a pressing challenge. High-performance computing and UAV infrastructure are often limited to well-funded institutions, creating disparities in who can benefit from these innovations. Addressing these inequities will require collaborative efforts to design cost-effective solutions and share resources more equitably.

Environmental sustainability is another critical consideration. UAV flights, particularly those involving multiple missions, contribute to carbon emissions, while the energy-intensive nature of high-performance computing adds to the environmental footprint of AI applications. These factors remark the importance of optimizing resource use and exploring greener alternatives, such as edge computing or more energy-efficient hardware, to align technological progress with conservation principles.

Looking forward, this research invites critical reflection on the sustainability and inclusivity of AI in ecological applications. How can we ensure that these tools are accessible to under-resourced regions and adaptable to diverse ecological contexts? Are there ways to integrate traditional ecological knowledge with AI systems to create more holistic and inclusive conservation strategies? Furthermore, what frameworks are needed to minimize the environmental impact of deploying these technologies at scale?

By raising these questions, we aim to provoke thoughtful discussion within the scientific and conservation communities. While AI holds immense promise for addressing complex ecological challenges, its responsible application requires a balance between innovation and sustainability. Through interdisciplinary collaboration and ethical foresight, these tools can evolve to become more inclusive, equitable, and aligned with the long-term goals of conservation.

The advancements achieved in this research lay a solid foundation for exploring new avenues in ecological monitoring and conservation. Expanding the scope of testing beyond mistletoe detection to other ecological challenges offers promising opportunities to further validate and refine these methodologies. For instance, the same UAV-acquired imagery and machine learning frameworks could be adapted to detect other invasive species, such as bark beetles or parasitic vines, which similarly threaten forest health. Additionally, the texture and spectral analysis techniques employed here could be applied to assess broader forest health indicators, such as identifying early signs of disease or monitoring vegetation recovery after disturbances.

Emerging technologies present exciting possibilities for enhancing the scalability and precision of these efforts. Vision Transformers, a state-of-the-art architecture for image analysis, could be employed to capture complex spatial relationships and improve detection accuracy in highly heterogeneous environments. By leveraging their ability to process global context within imagery, Vision Transformers may provide a more comprehensive understanding of ecological patterns.

A critical next step is the piloting of these methodologies in real-world deployments. Collaborations with local conservation practitioners and forestry agencies will be essential to adapt these tools to the specific needs and constraints of field applications. Pilot programs could serve as testing grounds for refining workflows, addressing usability challenges, and building trust among end-users. Additionally, partnerships with community-based organizations could facilitate the integration of local ecological knowledge, enriching the data and increasing the relevance of AI-driven insights.

Interdisciplinary collaboration was a cornerstone of this project, driving both its successes and its evolution in addressing the ecological challenge of mistletoe infestations. By integrating expertise from CentroGeo, ITM, and ITPA, as well as leveraging partnerships with SECTEI, SEDEMA, CORENA, and the UNAM-Huawei Innovation Space, the team successfully bridged technical innovation with ecological applications. This collaborative framework facilitated the development of advanced methodologies, from the design of spectral indices to the implementation of deep learning models, ensuring that each phase of the project was informed by a diverse range of perspectives and skills. Similarly, access to high-performance computing resources through institutional partnerships allowed the team to overcome significant computational challenges, accelerating the refinement of deep learning models and enabling detailed performance evaluations.

However, this collaboration also revealed inherent challenges that underscore the complexity of interdisciplinary research. Differences in disciplinary priorities and methodologies occasionally led to misalignments in project goals and expectations. For example, while technical partners prioritized computational efficiency and accuracy, ecological collaborators often emphasized the interpretability and field applicability of the tools being developed. Effective communication and iterative feedback loops are essential in resolving these tensions, but they also highlighted the need for clearer frameworks to align multidisciplinary objectives from the outset.

Reflecting on these experiences, several lessons emerge that could inform future interdisciplinary projects. First, establishing clear, shared goals at the beginning of a project can help align priorities and reduce friction between disciplines. Second, creating structured communication channels—such as regular workshops or collaborative platforms—can facilitate ongoing dialogue and ensure that all voices are heard throughout the research process. Finally, fostering a culture of mutual respect and openness to diverse perspectives is critical for maximizing the potential of interdisciplinary teams.

A key priority for future research and implementation is fostering dialogue that not only refines AI applications for mistletoe detection but also raises awareness of the ecological threat it poses. This dialogue must extend beyond scientists and technical experts to include policymakers, conservation practitioners, and the general public. While mistletoe is often romanticized, it is essential to communicate its grave impact on forests, where unchecked infestations weaken trees, reduce biodiversity, and disrupt critical ecosystem services. Engaging communities in this conversation can help shift perceptions and build support for necessary conservation measures.

Involving local communities is particularly important, as their traditional ecological knowledge can enhance AI-driven approaches and ground them in practical realities. Collaborative frameworks are needed to ensure that detection tools and management strategies are accessible and actionable, particularly in under-resourced areas where mistletoe infestations could be most severe. Furthermore, public education initiatives can help bridge the gap between the cultural symbolism of mistletoe and the ecological urgency of its control, fostering a shared understanding of the problem and the solutions required.

As we advance these efforts, it is crucial to ensure that AI applications remain equitable, transparent, and aligned with ecological stewardship. The future of mistletoe management depends not only on technological innovation but also on our ability to engage and empower all stakeholders, from conservation scientists to the broader community. By combining advanced tools with widespread awareness and collaborative action, we can protect forests from the devastating impact of mistletoe infestations while fostering sustainable conservation practices.

Conclusions

This work critically examines the role of AI and remote sensing in addressing the ecological challenges posed by mistletoe infestations, offering insights into the methodologies and approaches that have shaped this emerging field. By leveraging GP, texture descriptors, and CNNs, our research highlights both the potential and limitations of these technologies in ecological conservation. GP demonstrated its effectiveness in developing spectral indices tailored to specific ecological challenges, providing a starting point for automation in mistletoe detection. Similarly, texture-based machine learning methods, while valuable for capturing spatial patterns, evidenced the constraints of handcrafted features in complex and heterogeneous environments.

The shift toward deep learning, particularly through CNNs, reflects an evolution in methodology that not only addressed earlier limitations but also revealed the scalability and adaptability of AI-driven solutions for conservation. These advancements serve as a critical reflection on the application of cutting-edge technologies in ecological monitoring, illustrating how AI can transform labor-intensive tasks into scalable, efficient processes. However, they also raise important questions about the practicality and accessibility of these approaches, particularly in resource-limited settings.

While the methodologies and insights presented in this work demonstrate significant potential for addressing ecological challenges, they are accompanied by critical limitations that warrant further exploration. Environmental variability complicates the generalization of these models. The performance of machine learning and deep learning approaches, optimized for specific ecological contexts, may degrade in heterogeneous environments characterized by diverse vegetation types, seasonal changes, or fluctuating light conditions. Addressing this variability will require adaptive methodologies capable of learning from diverse datasets, coupled with extensive field validation to ensure robustness across ecological settings.

Computational demands also present a significant challenge, particularly for resource-intensive deep learning models. The energy consumption and infrastructure required to train and deploy these systems raise important questions about their environmental and practical sustainability. Collaborative efforts, such as leveraging edge computing for real-time analysis or optimizing hardware configurations for efficiency, represent critical avenues for mitigating these constraints.

The integration of AI into ecological conservation demands sustained interdisciplinary collaboration, grounded in both ethical foresight and practical deployment strategies. The complexities of mistletoe detection and broader ecological challenges require expertise from diverse fields, including computational sciences, ecology, and social sciences, to ensure that technological advancements remain contextually relevant and inclusive. Future efforts must prioritize partnerships that bridge the gap between cutting-edge research and actionable conservation practices, fostering collaboration among researchers, policymakers, and local communities.

The practical deployment of AI tools also presents critical opportunities for innovation. Real-world implementation, supported by field trials and user-centric design, will be key to refining these technologies and ensuring their usability by non-specialist stakeholders, such as park managers and conservation workers. Integrating emerging technologies like Vision Transformers and edge computing could further enhance the adaptability and efficiency of AI-driven solutions, making them more accessible and sustainable.

Looking forward, the role of AI in conservation is poised to expand far beyond mistletoe detection. These tools offer immense potential to tackle diverse challenges, from monitoring biodiversity to mitigating the impacts of climate change. However, their impact will ultimately depend on our ability to align technological progress with the principles of sustainability, equity, and transparency.

By fostering interdisciplinary dialogue and embracing a forward-thinking approach, the scientific community can advance AI applications that not only address immediate ecological threats but also contribute to the broader goal of sustainable development. The path ahead is both challenging and filled with opportunity, requiring collective action, ethical reflection, and a commitment to collaboration that transcends disciplinary boundaries. Through these efforts, AI can become a transformative force in conservation, driving innovation while safeguarding the planet for future generations.

CRediT authorship contribution statement

Juan Carlos Valdiviezo-Navarro: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Mauricio G. Orozco-del-Castillo:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT in order to improve readability. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

We express our gratitude to Secretaría del Medio Ambiente (SEDEMA) for the support during field work. We also recognize the efforts of our team to develop this project: Paola Andrea Mejía Zuluaga, León Felipe Dozal García, Alejandra Aurelia López Caloca, Alejandro Téllez Quiñones, Adriana Lizzette Luna Nieves, Amilcar Morales Gamas, and Mario Ledesma Arriola (CentroGeo); Nivia Iracemi Escalante García, Eduardo Flores Gallegos, and José Ernesto Olvera González (TecNM/ITPA); Nora L. Cuevas Cuevas, Carlos Bermejo-Sabbagh, William Orozco-González, and Pedro A.G. Ortiz-Sánchez (TecNM/ITM). Part of this work has been financed by Secretaria de Educación, Ciencia, Tecnología e Innovación (SECTEI) of Mexico City through Grant Number 3581c24.

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