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ANALYZING THE POTENTIAL OF ARTIFICIAL INTELLIGENCE IN OPTIMIZING FOREST MANAGEMENT PROCESSES IN POLAND

ANALIZA POTENCJAŁU SZTUCZNEJ INTELIGENCJI W OPTYMALIZACJI PROCESÓW GOSPODARKI LEŚNEJ W POLSCE

Summary

The integration of AI into forestry management represents a transformative development for the field, promising substantial improvements in operational efficiency and strategic foresight. This paper explores the multifaceted applications of AI in forestry, including enhanced forest monitoring, predictive analytics, spatial planning, and the management of tourist traffic, each contributing to more sustainable forest management practices. The paper highlights the substantial benefits of AI, such as optimizing resource allocation and increasing accuracy in threat detection and response. It also addresses significant challenges, including high initial costs, the necessity for specialized training, and ethical considerations related to data privacy and employment impacts. Examples from various national contexts illustrate the global relevance and adaptability of AI technologies in forestry. The discussion underscores the need for international collaboration and

Streszczenie

Integracja sztucznej inteligencji z zarządzaniem leśnictwem stanowi transformację w tej dziedzinie, obiecując znaczną poprawę wydajności operacyjnej i strategicznego przewidywania. W artykule dokonano przeglądu wieloaspektowych zastosowań sztucznej inteligencji w leśnictwie, obejmujących ulepszone monitorowanie lasów, analitykę predykcyjną, planowanie przestrzenne i zarządzanie ruchem turystycznym, z których każde przyczynia się do bardziej zrównoważonych praktyk zarządzania lasami. W artykule omówiono znaczące korzyści płynące ze sztucznej inteligencji, w tym optymalizację alokacji zasobów i zwiększoną dokładność wykrywania zagrożeń i reagowania na nie. Z drugiej strony, artykuł omawia również istotne wyzwania, takie jak wysokie koszty początkowe, konieczność specjalistycznego szkolenia oraz kwestie etyczne związane z prywatnością danych i wpływem na zatrudnienie. Przykłady z różnych kontekstów krajowych ilustrują globalne znaczenie i możliwości adaptacji

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robust training programs to fully harness the potential of AI while mitigating its risks. Ethical and social implications are explored, emphasizing the importance of transparent and accountable AI systems in forestry.

Keywords: AI, forestry management, predictive analytics, spatial planning

technologii AI w leśnictwie. Dyskusja podkreśla potrzebę międzynarodowej współpracy i solidnych programów szkoleniowych, aby w pełni wykorzystać potencjał sztucznej inteligencji, jednocześnie łagodząc związane z nią zagrożenia. Zbadano implikacje etyczne i społeczne, podkreślając znaczenie przejrzystych i odpowiedzialnych systemów AI w leśnictwie.

Słowa kluczowe: AI, gospodarka leśna, analityka predykcyjna, planowanie przestrzenne

Introduction

Artificial intelligence (AI) in forestry has advanced significantly, enhancing forest management through machine learning and big data analytics. Deep learning models interpret complex satellite and aerial imagery, aiding forest condition monitoring and predictive analysis. Additionally, IoT technologies enable real-time data collection, improving decision-making for sustainable forestry.

The integration of advanced technologies in forestry has demonstrated considerable potential in enhancing biodiversity conservation, forest monitoring, and management. For example, applications in Indian forestry have been shown to improve monitoring and management of forest resources, although adoption has been slower compared to other regions. This is primarily due to challenges in accessing big data and digital technologies (Shivaprakash et al., 2022).

In the realm of smart farm and forest operations, human-centered approaches (HCAI) have been identified as crucial for integrating machine learning capabilities with expert knowledge. This enhances the robustness and explainability of models, making them more reliable for critical applications in forestry (Holzinger et al., 2022). Furthermore, the use of machine learning in decision-making processes in forest management has been explored. For instance, research utilizing RGB imagery from drones has demonstrated the potential to replace traditional aerial and satellite hyperspectral imagery, thereby accelerating the detection and classification of unhealthy and dead trees. This can lead to quicker responses to forest threats (Budnik et al., 2023).

IoT technologies play a significant role in collecting real-time data, which is essential for making informed decisions in sustainable forestry. The integration of machine learning with remote sensing technologies, such as LiDAR and satellite imagery, enables the creation of detailed digital twins of forest environments. This approach facilitates precise monitoring and

management practices by providing accurate data on tree dimensions, health, and spatial distribution (Niță, 2021).

In addition, the ART3MIS-AI framework has been developed to augment remote sensing imagery with intelligent capabilities. This system improves the responsiveness and efficiency of forestry management by providing detailed, real-time data on forest conditions, which is crucial for effective conservation and restoration efforts (Gandikota et al., 2022). Intelligent systems and IoT technologies are transforming forestry management by enhancing data collection, analysis, and decision-making processes.

Potential applications of AI to enhance forestry management in Poland

Forest condition monitoring

AI technologies have shown considerable promise in enhancing forest condition monitoring in Poland, providing new tools and methods for analyzing and managing forest ecosystems. Drones equipped with LIDAR technology improve both the accuracy and efficiency of forest structure and health analysis. Machine learning models can process vast amounts of data collected by drones to identify issues such as defoliation, pest infestations, and other forest health indicators (Figure 1). Applications using drones and RGB imagery have demonstrated effectiveness in automatically detecting and classifying unhealthy and dead trees, thereby enabling quicker responses to forest threats (Budnik et al., 2023). This method can replace traditional aerial and satellite hyperspectral imagery, thus reducing the time required for forestry treatments.

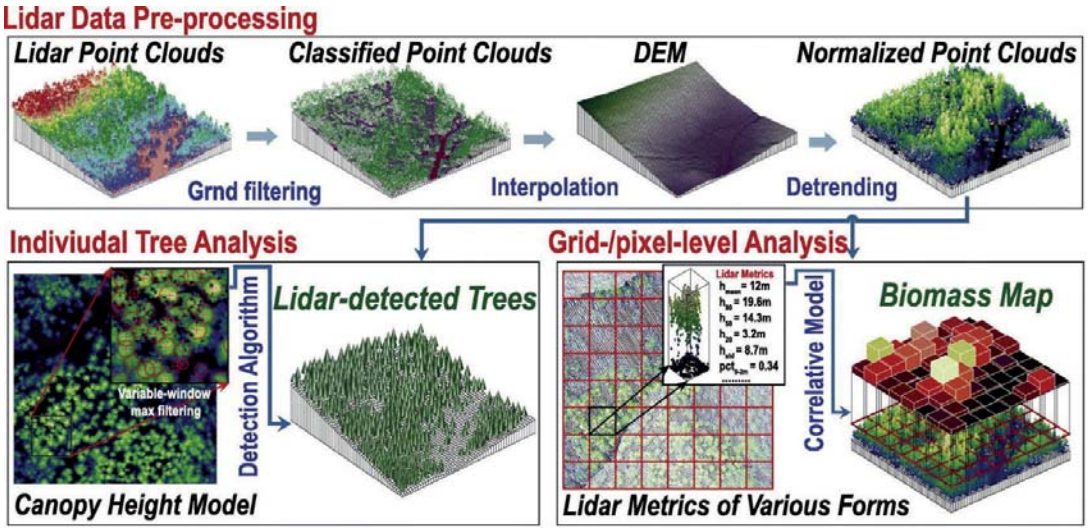


Figure 1. A typical workflow for deriving forest information from LiDAR point clouds, covering both single-tree and plot-level analyses

Source: https://commons.wikimedia.org/wiki/File:Lidar_forestry.png#file (access 01.09.2024).

Satellites such as Landsat 9 provide extensive, long-term data on forest conditions, which are essential for large-scale environmental monitoring and interventions. The integration of AI with satellite imagery enhances the ability to interpret complex data and monitor changes in forest ecosystems over time. This approach is crucial for understanding broad trends and making informed decisions for forest conservation and management (Gandikota et al., 2022).

The integration of drones, satellites, and IoT sensors creates a comprehensive real-time monitoring system for assessing forest health. IoT sensors placed in forests can collect real-time data on various environmental parameters, which, when combined with data from drones and satellites, provide a holistic view of forest conditions (Figure 2). This integrated approach allows for more accurate and timely interventions, enhancing the overall effectiveness of forest management practices (Niță, 2021).

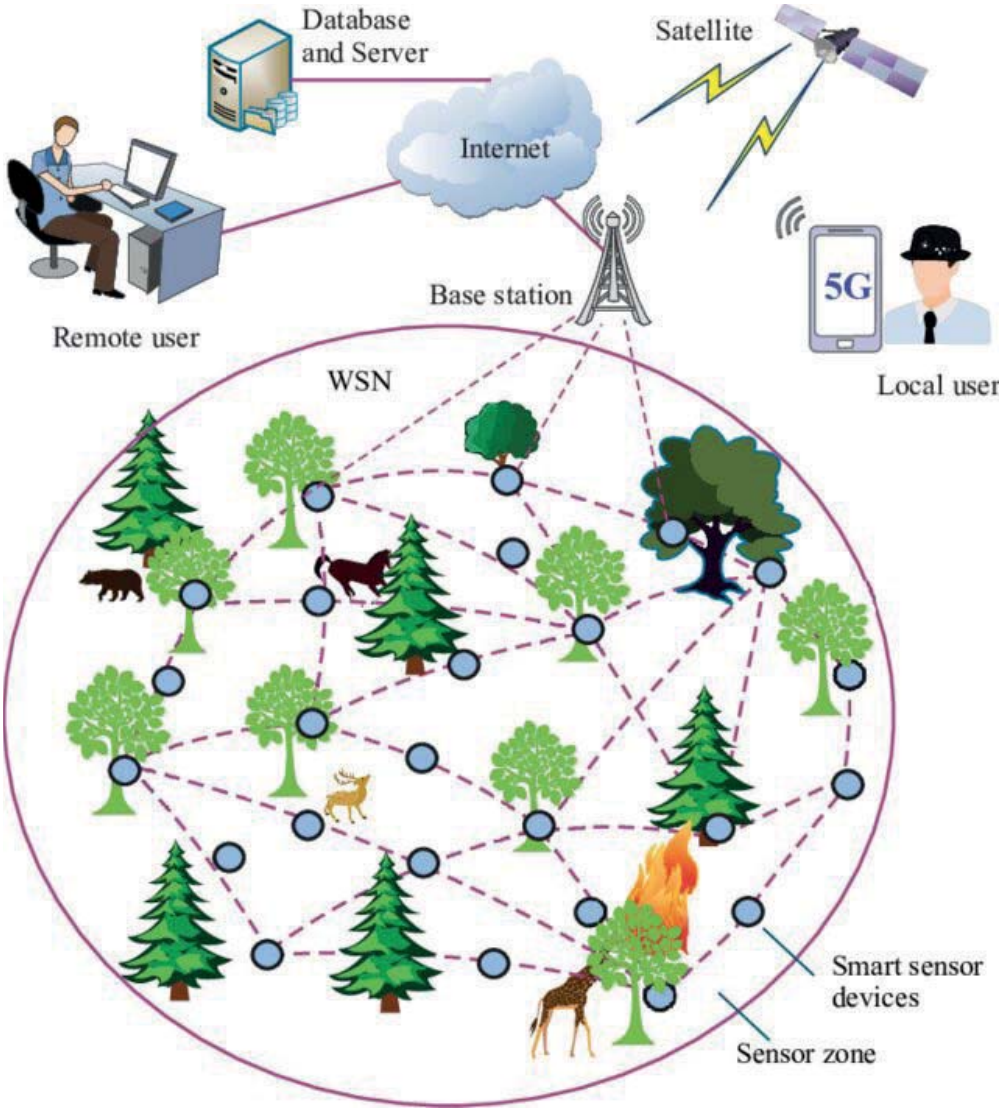


Figure 2. IoT-based Wireless Sensor Networks for early detection of forest fire.

Source: Tan et al., 2022.

Biodiversity management

AI technologies are increasingly being employed to manage and conserve biodiversity in Poland, leveraging advanced tools and methodologies to address ecological challenges. AI systems analyze data from various sources, such as satellites, drones, sensors, and camera traps, to monitor and conserve biodiversity effectively. These systems can process vast amounts of data to provide real-time insights into ecosystem health and species populations. For instance, systems like ART3MIS, which integrate remote sensing imagery, improve the responsiveness and efficiency of forestry conservation and restoration efforts, enabling a deeper understanding of biodiversity dynamics (Gandikota et al., 2022).

Machine learning algorithms play a crucial role in identifying plant and animal species and predicting environmental impacts on biodiversity. These algorithms can analyze diverse data types, including spectral, morphological, and genetic data, to accurately classify species and assess their distribution. By leveraging such technologies, it becomes possible to make informed decisions regarding conservation strategies and interventions. For example, research has shown that intelligent systems can enhance the identification and classification of plant species, thereby improving the accuracy of biodiversity assessments (Sen et al., 2021).

Additionally, tools like the Ecosystem Services Identification and Inventory (ESII) support data-driven decision-making by assessing ecosystem services. These tools help quantify the benefits that ecosystems provide to humans, such as carbon sequestration, water purification, and recreational opportunities. By integrating advanced technologies into ecosystem service assessments, policymakers and conservationists can develop more effective strategies for managing and protecting natural resources (Lewers, 2023).

However, the implementation of AI in biodiversity management is not without challenges. Data standardization, system interoperability, and data quality assurance are critical issues that need to be addressed to maximize the effectiveness of AI applications. Ensuring that data from different sources are compatible and of high quality is essential for reliable analysis and decision-making. Moreover, the integration of AI technologies requires robust frameworks and guidelines to ensure ethical and effective use, highlighting the need for ongoing research and collaboration among scientists, technologists, and policymakers (Stenhouse et al., 2023).

Predictive algorithms and forecasting models

Predictive algorithms have become indispensable tools in long-term forest management, offering the ability to forecast future conditions and develop scenarios to minimize risks. These algorithms, powered by advanced

ML (ML) and deep learning (DL) techniques, analyze extensive datasets to provide accurate predictions essential for sustainable forest management. Predictive models help in forecasting various aspects of forest ecosystems, including tree growth, biomass accumulation, and carbon sequestration. For instance, studies have shown that combining National Forest Inventory (NFI) data with satellite images and airborne laser scanning (ALS) technology can predict forest growing stock volume (GSV) with high accuracy. These models are crucial for planning and managing forest resources efficiently, ensuring that future forest conditions are anticipated and adequately managed (Hawryło et al., 2020).

Moreover, AI algorithms are used to forecast environmental hazards such as forest fires, droughts, and tree diseases. These models analyze historical data on climate, vegetation, and past incidents to predict potential future hazards. For example, ML techniques have been employed to enhance the accuracy of forest fire predictions, allowing for early interventions and better preparedness. This proactive approach significantly mitigates the adverse impacts of such events on forest ecosystems (Patil et al., 2023).

Hybrid models, which integrate ML with traditional ecological models, have proven effective in simulating small-scale processes like cloud formation and river flows. These models enhance the precision of climate forecasts, providing detailed insights into how various climatic factors interact and influence forest dynamics. By incorporating geographical and climatic data, these models can simulate the impacts of different climate scenarios on forest ecosystems, aiding in the development of robust forest management strategies (Gandikota et al., 2022).

Furthermore, AI-driven forecasting models are not only limited to predicting physical and environmental changes but also extend to socio-economic impacts. For instance, models predicting the economic implications of forest management decisions, such as the financial outcomes of different forest utilization strategies, are being developed. These models support decision-makers in balancing ecological sustainability with economic viability (Wyrobek, 2018).

Automation and robotics in forestry

The implementation of automation and robotics in forestry has significantly advanced forest management practices, particularly in Poland, enhancing efficiency, accuracy, and safety across various operations.

Autonomous robots are employed to plant tree seedlings with high precision, improving survival rates and accelerating reforestation efforts. For example, Milrem Robotics has developed an autonomous tree planting robot capable of planting up to 300 seedlings per hour. This innovation not only

speeds up the reforestation process but also ensures a higher survival rate of the seedlings due to precise planting techniques (Visser & Obi, 2021).

Robotics play a critical role in logging operations, where autonomous machines perform precise cuts, minimizing damage to surrounding trees and enhancing safety, especially in inaccessible or hazardous areas. These robotic systems are equipped with advanced sensors and AI algorithms that allow them to execute complex tasks with minimal human intervention, thereby reducing the risk of accidents and improving operational efficiency (Bołoz & Biały, 2020). Drones and robotic vehicles equipped with advanced sensors, such as multispectral cameras and LiDAR, are used for forest monitoring. These technologies enable the continuous assessment of tree health, detection of pests and diseases, and monitoring of environmental parameters. The integration of these tools allows for real-time data collection and analysis, facilitating proactive management and timely interventions in forest ecosystems (Boĭtsov et al., 2021).

Autonomous vehicles are increasingly used to transport timber through challenging terrain, significantly reducing accidents, increasing efficiency, and lowering labor costs. Autonomous forwarders, for instance, navigate through forests using AI and GPS technology, transporting harvested timber from the forest to processing areas with minimal human oversight. This automation not only improves safety but also optimizes the logistics of timber transport, enhancing overall productivity (Aguiar et al., 2020).

Decision support systems (DSS) in forest management

The integration of Decision Support Systems (DSS) in forest management represents a significant advancement in leveraging advanced technologies to improve decision-making processes, risk management, and overall forest sustainability. AI-driven DSS utilize various techniques to integrate diverse data sources for real-time processing and prediction, thus enhancing forest resource management. These systems enable forest managers to analyze and interpret vast amounts of environmental data, providing valuable insights into forest conditions and assisting in the development of effective management strategies. For instance, the web-based DSS known as wSADfLOR facilitates stakeholder access to management tools that enhance forest planning by analyzing trade-offs between ecosystem services and providing remote access to management planning methods and forest simulators (Marto et al., 2019).

DSS plays a crucial role in predicting and mitigating risks associated with forest management, such as wildfires and climatic shifts. By integrating AI algorithms, these systems can forecast potential threats and suggest preventative measures. For example, AI applications in forestry have been

shown to improve the accuracy of wildfire predictions, enabling quicker response times and better preparedness. These predictive capabilities are vital for minimizing the adverse impacts of environmental hazards on forest ecosystems (Budnik et al., 2023). Moreover, a geospatial DSS developed within the Life+ project SOILCONSWEB supports integrated forest knowledge at the landscape level, providing operational tools for forest resources management and multipurpose planning, thus addressing the complexity of managing forest ecosystems under changing climatic conditions (Marano et al., 2019).

Recommendations for practitioners

The integration of AI technologies in forest management requires a structured approach to effectively harness their potential. First, it is crucial to identify specific needs and goals within forest management to select the most appropriate tools and algorithms. By understanding the challenges and objectives, practitioners can ensure that the technologies deployed are tailored to their requirements, thereby optimizing resource allocation and achieving desired outcomes. Staff training is a critical component. Ensuring that foresters and managers are well-versed in new technologies is essential for the successful adoption and utilization of intelligent systems. Training programs should cover the technical aspects of these tools, data analysis, and interpretation, as well as their practical applications in everyday forest management activities.

Data protection and privacy are paramount when implementing such systems. Practitioners must adhere to data protection regulations and ensure that all data collection and processing activities comply with relevant laws. This not only protects sensitive information but also builds trust among stakeholders and the public regarding the use of technology in forestry. Investing in modern technical infrastructure is essential to support these systems. This includes acquiring robust servers, ample data storage solutions, and reliable communication networks. Such infrastructure ensures that tools can process large datasets efficiently and provide real-time insights, which are crucial for responsive and proactive forest management.

Implementing algorithms tailored to local conditions is crucial for accurate and effective forest management. Practitioners should test and adapt these algorithms to suit specific environmental and operational contexts. Continuous monitoring and optimization of algorithm performance are necessary to ensure they remain effective under changing conditions. For instance, accelerated decision-making processes in forest management can significantly improve by replacing traditional imagery with RGB data from

drones, enhancing the detection and classification of unhealthy and dead trees (Budnik et al., 2023).

Regular evaluation and reporting of implementation results are vital for continuous improvement. By systematically assessing the outcomes of these applications, forest managers can identify areas for enhancement and document progress. This iterative process helps in refining tools and methodologies, ensuring they meet the evolving needs of forest management. Moreover, reporting these results fosters transparency and accountability, facilitating better stakeholder engagement and support.

Spatial, recreational, and historical planning

Spatial planning in forestry, enhanced by Artificial Intelligence (AI), optimizes the development of forest infrastructure and recreational trails through meticulous analysis of spatial data, including terrain, soil types, climate, and biodiversity. Algorithms integrate with Geographic Information Systems (GIS) to craft detailed and accurate maps crucial for planning and real-time environmental monitoring, often referred to as GeoAI. This integration significantly enhances the precision and responsiveness of spatial planning initiatives (Torresan et al., 2021). Predictive capabilities are pivotal in managing forest resources by identifying areas prone to erosion or degradation. Through the analysis of historical and real-time data, models forecast environmental impacts on forest soil and vegetation, guiding proactive erosion control strategies and maintaining ecosystem stability (Stryamets & Striamets, 2021).

Furthermore, intelligent systems facilitate the sustainable development of recreational areas within forests, assessing and mapping suitable locations for trails and amenities to enhance visitor experiences while conserving the natural environment. This approach ensures that recreational activities are managed sustainably, promoting conservation and public enjoyment (Gorzym-Wilkowski & Trykacz, 2022). Technology also plays a crucial role in managing tourist traffic within forested areas. Systems like the Monitoring System of Tourist Traffic (MSTT) employ pyroelectric sensors in Stołowe Mountains National Park to monitor visitor flows in real-time, adapting to varying tourist activity levels and minimizing environmental impacts (Rogowski, 2020). Intelligent traffic systems integrate advanced algorithms with GIS to dynamically adjust tourist routes based on current conditions, enhancing visitor experiences and protecting ecosystems from excessive foot traffic (Oleśniewicz et al., 2020).

Historical planning benefits from technology by analyzing diverse data sources to uncover long-term patterns and trends in forest usage and management. This historical perspective is invaluable for understanding

the impacts of management practices and guiding future interventions, preserving the cultural and historical significance of forest landscapes for future generations (Witkowski, 2020). Predictive models, essential in forestry management, use historical data to forecast ecological changes, aiding in the strategic planning of forest resources. In Poland, models combining National Forest Inventory data with satellite imagery and airborne laser scanning technology estimate forest growing stock volume with high accuracy, ensuring sustainable management practices (Hawryło et al., 2020). The deployment of edge computing and real-time processing technologies further enhances forest management by allowing on-site data processing and rapid response capabilities, crucial for addressing immediate environmental changes such as forest fires or pest infestations (Stryamets & Striamets, 2021). By continuously monitoring environmental conditions and utilizing predictive models, forest managers can anticipate and address potential issues effectively. This proactive approach not only maintains forest health and resilience but also prepares ecosystems to adapt to future climatic and environmental changes (Wertz & Wilczyński, 2022).

Education and training

Incorporating AI technology into forestry requires comprehensive education and training programs to equip professionals with the necessary knowledge and skills. Training in AI technology for forestry professionals should encompass data analysis, predictive modeling, and system management. Developing these skills enables professionals to effectively utilize AI tools for forest management and conservation. For example, an educational program designed to foster AI proficiency among forestry professionals highlighted the need for long-term courses that combine online and offline components, targeting both new employees and middle managers (Oh & Shinn, 2023).

Ethical and legal training is also essential to ensure the responsible use of advanced technologies in forestry. Professionals must be educated on the ethical considerations and legal frameworks governing such applications. This includes understanding data privacy, consent, and the ethical implications of technology-driven decisions. By incorporating ethical and legal training into educational programs, forestry professionals can make informed decisions that respect both environmental and societal norms. Studies emphasize the importance of responsible usage and the need for ongoing ethical education to navigate the complexities of deploying these systems in sensitive ecological contexts (Holzinger et al., 2022).

Implementing IoT sensors for real-time environmental monitoring and data collection from satellites and drones is crucial for modern forestry management. These sensors provide continuous data streams that can be

analyzed to monitor forest health, detect changes, and respond to environmental threats promptly. The integration of such technologies requires practitioners to be proficient in the operation and maintenance of IoT systems, ensuring the reliability and accuracy of the collected data (Stryamets & Striamets, 2021). Regular evaluation and reporting of technology implementation results are vital for continuous improvement. By systematically assessing the outcomes of these applications, forest managers can identify areas for enhancement and document progress.

This iterative process helps refine tools and methodologies, ensuring they meet the evolving needs of forest management. Moreover, reporting these results fosters transparency and accountability, facilitating better stakeholder engagement and support.

Discussion

Advanced technologies significantly enhance operational efficiency and precision in monitoring forest resources. By leveraging intelligent systems, forest managers can process large datasets from diverse sources, enabling real-time analysis and decision-making. For instance, data-driven systems have been shown to improve the accuracy of forest inventories, leading to better resource management (Budnik et al., 2023). Additionally, these systems enable rapid responses to environmental threats such as fires and pest invasions. Predictive models can forecast these events, allowing for timely preventive measures and mitigating potential damage (Shivaprakash et al., 2022). Automation reduces labor costs and minimizes human errors, enhancing safety and efficiency in forest operations. The use of autonomous robots for tasks such as tree planting and logging exemplifies how technology can streamline operations and improve outcomes (Holzinger et al., 2022).

Despite its benefits, the implementation of AI technologies in forestry faces several challenges. High initial costs for acquiring and installing advanced systems can be prohibitive, particularly for smaller organizations or those with limited budgets (Mederski et al., 2021). Comprehensive staff training is essential to equip forestry professionals with the necessary skills to utilize these systems effectively. This requires significant investment in education and continuous professional development to keep pace with technological advancements (Oh & Shinn, 2023). Integrating these systems also involves managing complex datasets from various sources, which can be challenging in terms of maintaining data quality and ensuring interoperability (Williamson et al., 2021). Ensuring the robustness and reliability of such systems is crucial, especially in dynamically changing environments where small perturbations can lead to significant impacts on model outcomes (Holzinger et al., 2022).

The application of advanced technologies in forestry has seen significant advancements across various countries, utilizing these tools to tackle specific environmental and management challenges. In the United States, intelligent systems are extensively used to monitor forest health and predict fire risks. These systems integrate meteorological, topographical, and vegetative data to provide comprehensive analyses and forecasts. Models process real-time data from various sensors to predict wildfire occurrences, enabling prompt response and mitigation strategies. For example, the ART3MIS system enhances the responsiveness of forestry management by integrating remote sensing imagery with advanced capabilities, thereby improving the accuracy of fire risk predictions and the efficiency of intervention strategies (Gandikota et al., 2022). This approach not only helps in preventing large-scale forest fires but also aids in preserving biodiversity and reducing economic losses associated with forest fires (Pandey et al., 2022).

In Sweden, the Heureka system represents a sophisticated tool designed to integrate diverse data sources for sustainable and economically viable forest management. The Heureka system supports decision-making processes by providing detailed simulations and analyses of forest growth, yield, and economic outcomes. This system enables forest managers to balance various objectives such as timber production, biodiversity conservation, and recreational use. By utilizing comprehensive data integration and advanced modeling techniques, the Heureka system ensures that forestry practices are both ecologically sustainable and economically profitable (Angelstam et al., 2020).

In Poland, technologies like drones and predictive algorithms are employed to monitor forest conditions and forecast threats. Drones equipped with algorithms and RGB imagery have been shown to effectively detect and classify unhealthy and dead trees, facilitating timely responses to forest health issues (Budnik et al., 2023). Predictive models based on National Forest Inventory data and satellite imagery are used to forecast forest growing seasons and assess the impacts of climate change on forest ecosystems (Wertz & Wilczyński, 2022). These data-driven approaches enhance the ability of forest managers to anticipate and mitigate potential threats, ensuring the long-term health and sustainability of forest resources.

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