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Prevention and management of forest fires in an immersive environment

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Abstract. The global trend of innovative development of society positions virtual reality (VR) technologies as an integral tool in the management process. The study aims to analyse the potential of using immersive technologies in the system of forest fire prevention and management. The research was conducted using special scientific methods – experimentation and statistical methods descriptive and inferential statistics. The study determined that immersive technologies are now rapidly developing from the position of innovation to a practical range of tools. The study established that their implementation in the paradigm of environmental management policy is positioned as a prospective necessity and a factor in intensifying the quality of preventive environmental protection. The essence of the phenomenon of immersive technologies is specified, and their components, in particular, objective, virtual and augmented reality, are described. The potential of immersive technologies in the concept of expanding the toolkit of a modern industry specialist is investigated. The study proved that the use of VR applications has a significant potential for a positive impact on reducing the number of forest fires and improving the state of forest ecosystems. The specifics of the use of immersive technologies in the concept

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of forest fire prevention and management were analysed in the study. An example of the use of virtual reality technologies in the process of modelling the situation of fire prevention in a certain forest area using a VR application in the educational environment is presented. In the process of studying the features of virtual reality technologies in environmental modelling, the advantages and risks of their integration are highlighted. The results of the study can be effectively used in the practical process of implementing the concept of ensuring a sustainable environment in terms of forest fire prevention

Keywords: virtual reality; augmented reality; application; modelling; preventive protection

Introduction

Global climate change and anthropogenic pressure are causing a significant increase in the frequency and intensity of forest fires in most regions of the world. Wildfires cause significant potential economic losses due to the destruction of forest resources, and infrastructure, and impacts on the tourism industry and biodiversity, which makes it imperative to develop effective strategies for preventing and controlling wildfires. Addressing these issues requires a comprehensive approach that synergises planning, risk management, research and active public engagement. Innovative digitalisation capabilities and immersive technologies should be given a priority role in the modern forest fire prevention system. The concept of using immersive technologies to prevent and manage forest fires is based on the potential of virtual reality technologies to simulate situational variations, which can be successfully implemented in training and educational programmes. The key aspect of the topic under study is the study of the preventive impact of immersive technologies in the educational environment on the prevention of forest fires, the overall reduction of their number and destructive power.

The issues of implementing virtual reality technologies in the environmental sector, as well as developing measures to optimise sectoral programmes in the context of sustainable development, are reflected in the works of

modern researchers (Buil *et al.*, 2016). D. Hamilton *et al.* (2021) argue that it is advisable to use the method of immersion in virtual reality as a universal analytical tool. The researchers conducted a systematic review of studies on quantitative learning outcomes and experimental design, demonstrating the significant potential of the technologies under study. M.A. Kuhail *et al.* (2022) implemented analytics of practical experience of immersive learning. The researchers believe that a modern environmental management system should be based on the synergy of traditional and immersive preventive methods of environmental protection. The authors demonstrate the effectiveness of such synergies by highlighting the recent achievements of certain experimental studies and pilot projects. Some scientists, in particular, G. Makransky & G.B. Petersen (2021), argue that the effectiveness of the cognitive-affective model of immersive learning is a prerequisite for the successful development of educational programmes, including for the prevention and management of undesirable and threatening environmental phenomena.

C. Chen (2022) analysed the practical experience of optimising the paradigm of managerial innovation in terms of convergence of the main traditional principles and the latest tools of immersive technologies. Scientists address the need to study the potential of the

latter in the concept of the actual problem of conservation of biological resources for sustainable development of regions. Scientists such as V.W. Lee *et al.* (2020) investigated the concepts of optimising the environmental management process using immersive virtual reality and non-immersive virtual reality in the educational environment. Scientists point out that virtual reality has significant prospects for development, so its progressive advancement in the educational and managerial spheres will lead to their obvious qualitative growth and effective functioning. Scientists are convinced that the improvement of virtual reality technologies contributes to modernisation in the field of management, which is related to the intensification of scientific and technological achievements.

Related risks and challenges were explored by R. Liu *et al.* (2022) by analysing basic solutions in the context of the concept under study. The authors emphasize the problematic issues of disclosing the relationship between immersive technologies academic achievements, and scientific motivation, thus providing insights into the integration of immersive tools into the existing system of social progress. The work of contemporary scholars, in particular, S. Aguayo & C. Eames (2023) position monitoring as an important element in the implementation of optimal measures for the implementation of immersive technologies. Scientists have conducted several studies on the use of immersive learning in mixed reality to improve environmental education. The results of the study of S. Aguayo & C. Eames (2023) show that the possibilities of innovative immersive technologies can significantly improve the understanding of environmental science, facilitating knowledge of environmental literacy, and attitudinal and behavioural change. The implications include rethinking the tools of the management environment with self-educational mobile learning,

as well as the priority of tactile and sensory capabilities of virtual reality for the environmental preventive direction of management policy.

Furthermore, T. Chandler *et al.* (2021) addressed the possibilities of modelling ecosystem reference conditions in virtual reality. Their study aimed to prove that virtual reality can be used to recreate virtual landscapes as an immersive, visceral experience and convey ecosystem dynamics to users effectively and engagingly. Scientists have proved the significant potential of virtual reality in terms of the outlined issues, but at the same time, they have identified the need for further research on related risks and challenges to improve the use of this tactic in a secure concept. The basis for research in this area is the work of J.C. Sneed *et al.* (2021), which provides the basics of immersion technology, which, according to the authors, can be a way to more thoroughly study the structure of the relationship between humans and nature, with the levelling of certain obstacles to personal access to nature.

The results of the research of these scientists characterise the problems, achievements and current state of the system of implementation of virtual reality technologies in environmental protection strategies. Despite their significant significance, the priority of promising areas for optimising the management system in the chosen direction has not been fully determined, and the issues of transforming approaches to ensuring the safety of the process of using virtual reality technologies remain poorly understood. The study aims to investigate the potential of immersive technologies for forest fire prevention and management.

Materials and Methods

The study was carried out using special scientific methods, such as experimentation and statistical methods. The methodological and theoretical basis of the study was a systematic

approach, as well as the accepted concepts of complexity and dialectic. The systemic concept has created the preconditions for an effective analysis of the phenomenon under study as a systemic phenomenon in the entirety of inter-relationships.

An experimental method was used in the study, which involved the use of virtual reality technologies in the educational school environment. A certain area of the forest was designated, where a fire prevention situation was modelled using the FLAIM Systems VR software. A specific forest area was explored using VR, focusing on the preconditions, factors and consequences of forest fires. FLAIM Trainer was used to recreate the stress and uncertainty of real-life situations, conveying not only visuals but also tactile sensations. The complex simulates behaviour by heating the user with a thermal vest, recreating the experience of acting in scenarios with different locations of flame sources.

The experiment with VR technologies was conducted at school. The experiment was carried out at the Guangzhou Academy of Fine Arts (China). The sample for this study consisted of 277 students with different levels of experience and knowledge of the subject. The sample was selected on the principle of random sampling, as students were selected from one educational institution that had access to the necessary technologies and resources. The sample was divided into two groups: one that used a meta-environment (138 students) and another that used a traditional virtual environment (139 students). Students were randomly assigned to each group. The study was conducted in compliance with all the standards set out in the Helsinki Declaration (1975).

The meta-environment included virtual and real elements such as physical objects and real-time feedback. The traditional virtual environment was a purely digital environment that did not include any real-world elements.

The students in both groups completed a series of tasks and assessments designed to measure their level of learning, engagement and satisfaction with the learning process.

Inferential statistics were used to test hypotheses and draw conclusions about the general population based on the samples. A paired-sample t-test was conducted to determine whether there was a statistically significant difference between the pre-training and post-training knowledge scores, indicating whether the training programme was effective in improving the knowledge of the participants.

Descriptive statistics were used to summarise and describe the characteristics of the data, such as mean, median, mode, standard deviation and range. This identified patterns and trends in the data. In addition, inferential statistics were used to conclude the larger population from the sample data.

Results

The number of forest fires is growing globally and regionally. Understanding fire drivers and assessing where fires are likely to occur are critical factors in developing more effective plans to mitigate wildfire initiation and identify risk areas. The fact that fires do not occur by chance, but are caused by people or natural processes, and are significantly dependent on permanent and variable environmental factors, should be recognised. Assessing the occurrence of a fire requires a comprehensive temporal and spatial analysis. As the experience of foreign countries shows, large forest fires can last for months, and even technologically advanced countries sometimes cannot effectively counteract this element. In countries with extremely dry and hot summers (the Mediterranean, the southern United States, some countries of Central and Latin America, and Western Europe), the number of simultaneously active forest fires sometimes reaches tens or even hundreds.

Forest fires are uncontrolled ignition and burning of vegetation that spreads spontaneously within the forest area. The main root causes of forest fires are human activity, as well as lightning discharges, spontaneous combustion of peat crumbs and agricultural arson during the fire-hazardous season. The latter includes the period from the moment the snow cover melts in the forest until the emergence of a full green cover or the onset of stable rainy autumn weather. Forest fires have a devastating effect on trees and shrubs, as well as on timber harvested in the forest. As a result of their spread, water conservation, protection and other practical functions of the forest are significantly reduced, flora and fauna, auxiliary structures are destroyed, biodiversity is threatened, and in some places, settlements are threatened. In addition, wildfires pose a serious threat to adjacent agricultural land, animals and people. Depending on the nature of the fire and the composition of the forest, forest fires are divided into grassland, upland and ground fires (peatland burning). According to the level of intensity, forest fires can be weak (burning depth does not exceed 25 cm), medium (25-50 cm) and strong (more than 50 cm). It is worth noting that the intensity of combustion depends on the condition and level of combustible materials, wind strength, terrain slope, time of day and several other factors. Fires differ in the speed of fire spread. For a strong bottom fire, this value does not exceed 1 m/min, for a strong fire – more than 3 m/min, and for a weak top fire. At the same time, a strong grass fire can reach speeds of up to 100 m/min.

The identification of a forest fire is due to the activities of ground-based observation posts. In addition, ground and aerial patrols of forests are common. The process of directly extinguishing a large fire is conditionally differentiated into certain stages, including fire reconnaissance, localisation (eliminating the

variability of new fire spread), and firefighting, i.e., extinguishing the fire, and patrolling the burned areas. Localising a fire is the most difficult and time-consuming task. The procedure for localising a forest fire is implemented in two stages. Initially, the fire contour is directly impacted, followed by the construction of barrier ditches and strips, and the treatment of peripheral fire areas using specialised methods to prevent the potential for renewed fire spread.

The following methods and technical means are actively used to extinguish forest fires:

- ◆ knocking down the fire along the fire contour with branches;
- ◆ covering the fire with soil along the fire contour;
- ◆ start of annealing (counter bottom and top fires);
- ◆ extinguishing the burning circuit with water;
- ◆ use of special chemicals;
- ◆ causing artificial precipitation;
- ◆ laying barrier strips (ditches) on the path of fire spread.

The timing of firefighting operations is also important. The most appropriate times for this are evening and early morning. Recently, immersive technologies have become particularly popular as components of management systems, including in the field of environmental protection. The most popular immersive technologies include augmented reality (AR) and virtual reality (VR). These technologies create the preconditions for effective interaction, modelling and forecasting in three dimensions. In this case, a regular smartphone is used to create augmented reality, and a helmet and glasses are used for virtual reality.

Immersive technologies are identified as a way of integrating virtual content into the physical environment, which creates conditions for effective interaction. At the same time, the user is aware of the virtual components as

an integral part. The spectrum of immersive technologies covers several different applications and tools that can be used to integrate, immerse or interact with simulated environments and objects (Sahal *et al.*, 2021). The Australian start-up FLAIM Systems is positioned as a successful functional model of virtual reality applications for practical purposes. The primary product of the company is the FLAIM Trainer virtual reality firefighting training system. It provides a safe and cost-effective way to replicate the stress and uncertainty of real-life situations to better prepare a professional for a challenge. FLAIM Trainer conveys not only visuals but also tactile sensations. The complex simulates behaviour by heating the user with a thermal vest, reproducing the experience of actions in scenarios with different locations of flame sources (Abid, 2020; Khan *et al.*, 2022).

The trainer monitors real-time training data, including task speed, air and water usage, stress levels, trainee movements and attention, and interaction with objects such as gas meters, electrical boxes, and the fire itself (van Wees *et al.*, 2021). VR realistically displays all the fire, smoke, water and extinguisher foam, as well as heat, thanks to a special thermal suit that can heat the firefighter depending on proximity to the virtual fire. A virtual reality program was also used, which involved a classroom (a room in the complex was used, which made it possible to implement a 360° digital projection) (Pang *et al.*, 2022). By crossing the boundaries of traditional educational methods, 3D modelling, and virtual reality help students intensify the development of critical thinking, imagination, and stress resistance. The immersive environment was used to teach ecology classes on forest fire prevention.

Among the main qualitative characteristics of the implemented virtual reality technologies in the process of implementing the innovative concept of forest fire prevention and management

in an immersive environment are the immersion effect, immersive visual and auditory experience, stimulation of creativity and optimisation of operational management decision-making. The technologies under study provide users with a realistic visual and audio experience that mimics reality; and helps students better understand abstract concepts by creating interactive visualisations of complex processes, objects and phenomena. Virtual reality can immerse in a virtual environment to explore and learn about various subjects with greater detail and realism. The immersive environment will provide the effect of the so-called “live presence” of the subject, which will facilitate the perception of the learning material (Sivrikaya & Küçük, 2022). Immersive technologies are being integrated into the educational process to improve learning and create an immersive experience. Their interactivity and ability to create realistic situations allow learners to experience the material more deeply and engagingly.

Despite a range of positive aspects of the effects of immersive technologies, the use of the latter is accompanied by several risks, disadvantages and challenges. Among them, it is worth highlighting the rather high cost and difficult availability of the necessary technical equipment. The vast majority of virtual reality technologies are quite expensive, especially in the context of financial constraints and structured budgeting (Nesterov, 2023). In addition, the implementation of virtual reality technologies in the educational and administrative environment requires specialists to have the necessary skills and proper training to use these technologies in practice. A separate risk is the destruction of the connection with reality, as virtual reality technologies can focus attention on virtual scenarios, distracting from real-life situations. Prolonged use of immersive technologies can cause health deterioration in the form of discomfort, and impaired vision

and memory. There is also a risk that the active implementation of virtual reality technologies may lead to an over-reliance on digital learning and management tools, which will negatively affect the development of other skills and social skills. In addition, given the rapid development of immersive technologies, it is currently difficult to define standards and criteria for the use of these technologies in educational and administrative processes.

The implementation of the technology with the addition and clarification of appropriate content and visual models actively motivates the development of spatial imagination and intensifies the understanding of

the essence of the problem helps to assimilate content through visual representation, identifies the creation of imaginary spaces for unsolved problems, and reproduces real-life situations (Hantson *et al.*, 2022). As a result of an experiment in the educational environment involving virtual reality technology on forest fire prevention and management, students realised several important truths and dispelled several myths. They clarified that forest fires are caused not only by human negligence. Lightning or summer drought in the forest are situations where humans do not influence the outbreak of a fire, but the fire can instantly break out and spread (Fig. 1-3).



Figure 1. Visualisation of a forest fire using VR technology

Source: compiled by the authors

As a result of an experiment in the educational environment involving virtual reality technology on forest fire prevention and management, students realised several important truths and dispelled several myths. They

clarified that forest fires are caused not only by human negligence. Lightning or summer drought in the forest are situations where humans do not influence the outbreak of a fire, but the fire can instantly break out and spread.

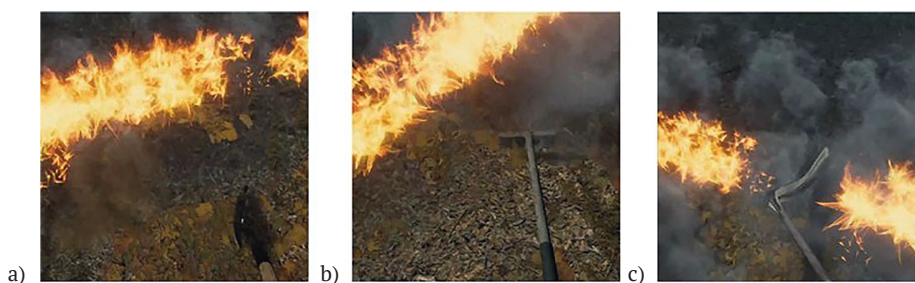


Figure 2. Visualising the impact of different tools on the scenario using VR technology

Note: a – a shovel, b– rake to remove fuel and stop the fire from spreading, c – a poker on the flames to remove oxygen and smother the fire

Source: compiled by the authors



Figure 3. Practicing firefighting measures in the forest using VR technology

Source: compiled by the authors

The experiment involved the use of a 3D interactive educational environment based on immersive technologies. Using virtual reality technology that simulates realistic disaster scenarios, combined with embodied cognition theory, which suggests that cognition is not only a function of the brain but also depends on the body and its interaction with the environment, this research has the potential to create a more realistic and effective learning experience. By combining virtual reality technology with

embodied cognition theory, the experiment aimed to create a more effective and efficient training experience for disaster response. Innovative principles aimed at optimising the mitigation and prevention of the causes of forest fires, with the identification of the most effective measures for their preventive prevention, are considered relevant. The latest principles establish the priority of preventive measures that should be effectively implemented through the state forest management system.

In addition, in an integrated global community, member states can receive additional targeted funding to increase the resilience of territories to wildfires and to vary joint project cooperation in the identified area at the level of the global community.

The guiding principles of the modern wildfire management paradigm stipulate the need to forecast future trends in wildfires and actively implement innovative tools for their monitoring at the global and national levels. This concept of wildfire management should be coordinated with the goals of effective afforestation, as well as maximum conservation and regeneration of forest resources. This approach will help reduce the scale and frequency of forest fires. Forest fires are ranked as one of the four biggest potential environmental threats of the future, along with the effects of irreversible climate change, risks to food security and the spread of unknown diseases. This requires proper equipment for effective prevention and rapid response to large forest fires, which cause the most serious damage to forest biodiversity and put its existence at risk. An effective approach to wildfire management within the modern management paradigm implies the priority of preventive measures, which should be implemented both at the national level and at the regional and local management levels, depending on the range of responsibilities of the relevant authorities and officials. An effective management paradigm in the field of wildfires can practically increase the resilience of forest landscapes to fire. The structure of the management system in the field of forest fires is positioned as the basic concept of forest fire prevention. It identifies the boundaries of responsibility for protection against forest fires, including their prevention and management, and defines the functions of responsible persons and bodies for planning and practical forest management. These responsibilities are

often assigned to different organisations or departments, which necessitates effective communication between them, the establishment of a system of rapid information exchange to develop common approaches and division of competence, and the development of a common strategy for risk and improved forest fire management.

Forecasting the drivers and potential risks of forest fires is seen as a necessary part of forest management. The implementation of an effective forecasting system contributes to the formation and maintenance of sustainable forest landscapes based on a reliable preliminary assessment of forest fire risks in synergy with effective forest management and anthropogenic impacts. The rational planning strategy includes several stages, including identification of the forest area to be surveyed, assessment of related risks, and ongoing monitoring and control. Furthermore, a specific contingency plan is necessary to ensure that the relevant services and authorised managers are prepared to respond promptly and effectively to unforeseen events. Since climate and weather conditions often have a decisive influence on the development of wildfires, the selection of planning strategies requires that indicators of changing climate conditions and their consequences be addressed (Yerzhanova *et al.*, 2021). In addition, when designing infrastructure development and urban planning activities in areas adjacent to fire-prone forests, potential risks should be considered, and real dangers identified. The planning system is comprehensive and involves extensive consultations with stakeholders and authorised representatives to raise their awareness and agree on the aspects of interaction. For managing existing forest resources and planning the creation or regeneration of future forest plantations, the right choice of forest management model is crucial for managing their vulnerability to wildfire. Several nuances,

addressed or ignored in the practical implementation of the management paradigm in the field of forest fires, have a significant impact on the success of preventing large-scale destructive consequences. When planting trees, it should be borne in mind that, in the best-case scenario, the tree species chosen for planting should be adapted to the current and, especially, the forecast climatic conditions. In this regard, preference should be given to deciduous species that demonstrate more resistant properties to forest fires. In addition, appropriate varieties of native species adapted to the local soil and water conditions should be selected.

It is considered expedient to maintain the proper condition of old-growth forests, which have significant benefits for biodiversity conservation and regulation of carbon content in the atmosphere. In addition, old-growth forests create a locally more humid microclimate, which potentially reduces the risk of forest fires. Competent management of fuel loads plays an important role in the effective prevention of forest fires. The fuel can intensively support the combustion process during a forest fire. Fuel management can minimise the additional risks of intensified burning, and therefore planned and controlled burning and collection of woody biomasses for heating are often used as preventive measures. Given this, the skills of managing forest fuel loads and their distribution are considered necessary for optimising the forest fire management system, understanding the dynamics of their spread and developing appropriate effective methods of fighting forest fires. The human factor within the management paradigm of wildfires is considered in different concepts. Humans are often both the cause and

the victim of forest fires, so the anthropogenic factor has a significant niche in any forest fire prevention strategy. Awareness of potentially hazardous activities and the preconditions for uncontrolled forest fires significantly reduces the risk of the latter occurring. The problem of forest fires is characterised on a global scale, so the relevant authorities should work to raise public awareness. This is especially true for tourism when travelling across the continent, as tourists are mostly unaware of local risks, do not speak the local language and do not have emergency communication information, which increases the risk of uncontrolled fires in forests (Mashika *et al.*, 2024).

At the global level, joint efforts to combat the spread of forest fires are being implemented on an ongoing basis. The global community regularly demonstrates solidarity in the form of firefighting helicopters and aircraft, firefighting equipment and teams of experts. The modern global integrated environment offers several opportunities for financing the implementation of practical measures that contribute to preventive forest fire management. Existing financial instruments can be effectively used by stakeholders or authorities to improve forest management to intensify forest resilience, implement targeted campaigns to establish local fire brigades, and raise public awareness. In addition to active financial and practical support for forest fire prevention, the international community is also developing programmes to regenerate forest lands destroyed by fire. An important role is played by advising land and forest managers and forest owners. The conceptual model of the forest fire prevention system in modern society is shown in Figure 4.

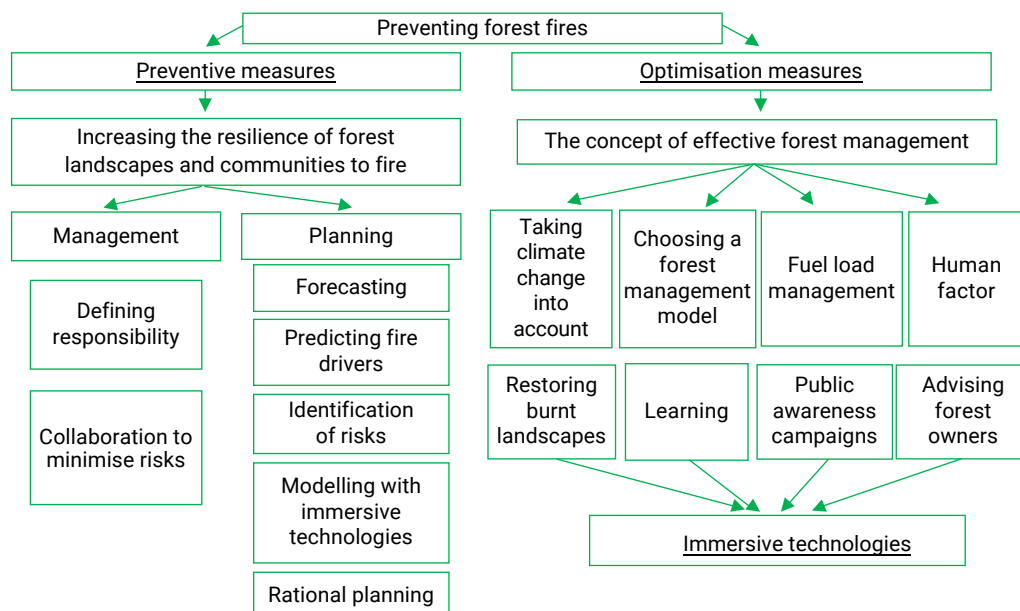


Figure 4. Conceptual model of forest fire prevention using immersive technologies

Source: compiled by the authors

During the experiment, inferential statistics were used to test hypotheses and draw conclusions about the general population based on the samples. A paired-sample t-test was conducted to determine whether there was a statistically significant difference between the pre-training and post-training knowledge scores, indicating whether the training programme was effective in improving the knowledge of the participants. The null and alternative hypotheses are formulated. The null hypothesis was that there would be no difference between the pre-training and post-training knowledge assessment. The alternative hypothesis was that there would be a difference between the pre-training and post-training knowledge assessment. The average difference between the pre-training knowledge assessment and the post-training knowledge assessment was calculated: Average difference = Post-training knowledge score – Pre-training knowledge score.

Average difference = $8.5 - 5.6 = 2.9$. Calculate the standard deviation of the difference (1):

$$SD = \sqrt{[(\text{sum}(\text{Post-training knowledge score} - \text{Pre-training knowledge score})^2) / (n - 1)]}. \quad (1)$$

The t-value was calculated using the formula (2):

$$t = (\text{Mean difference} - \text{hypothetical difference}) / (\text{SD} / \sqrt{n}). \quad (2)$$

A hypothetical difference of 0 was used, as the proposed null hypothesis states that there is no difference between the pre-training and post-training knowledge assessment (3):

$$t = (2.9 - 0) / (1.01 / \sqrt{10}) = 9.08. \quad (3)$$

The degrees of freedom were determined:

$$df = n - 1 = 9. \quad (4)$$

A critical t-value was found in the t-distribution table with 9 degrees of freedom and a

significance level of 0.05. The critical t-value is 2.306. The calculated t-value was compared with the critical t-value. If the calculated t-value is greater than the critical t-value, the null hypothesis is rejected, and it is concluded that there is a statistically significant difference between the pre-training and post-training knowledge assessment. Descriptive statistics were used to summarise and describe the characteristics of the data, such as mean, median, mode, standard deviation and range. This identified patterns and trends in the data. In addition, inferential statistics were used to conclude the larger population from the sample data. Regression analysis can also be used in the future to model the relationship between two or more variables and predict future results. For example, linear regression can be used to determine the relationship between game performance and user satisfaction. Machine learning can be used to analyse and predict data patterns, such as a decision tree algorithm to identify the factors that are most important in predicting user satisfaction. Network analysis can be used within the framework of immersive technologies to study the structure and dynamics of a social network to identify key players or communities in the network.

The study convincingly demonstrates that the use of virtual reality technologies in the educational and management process has significant advantages over the traditional process methodology, as it actively involves the sensory system and the emotional sphere. The experiment determined that roads in forested areas are not always in satisfactory condition, which can cause sparking or vehicle failure. The need to comply with the ban on open fires, bonfires and the use of grills in forests and open fields was emphasised. The study emphasised that it is unacceptable to leave the forest as is, as well as to leave garbage in the forest, as it can become a source of fire. The app can be used to

monitor the weather forecast and determine when the weather becomes too hot and dry, as the forest is particularly vulnerable to fires on these days. The skills of promptly reporting a fire were practised. The author proves the inexpediency of attempts to extinguish a forest fire on their own, given the potential danger to life and health. This situational awareness, enhanced by the virtual reality programme, highlighted the fact that fire prevention is not only about individual awareness and responsibility but also about a range of random factors that require systematic and technical training to overcome the consequences quickly.

Discussion

Understanding the dynamics of the environment, particularly the forest environment, can be challenging, especially when using traditional representations such as graphs, maps or photographs. Immersive visualisations and experiences using virtual reality technologies offer an intuitive approach to abstract concepts, but they are difficult to create scientifically. The experiment managed to combine environmental modelling and virtual reality to provide an immersive experience for sustainable forest management.

The results of the study position the phenomenon of immersive technologies as an innovative promising element of the system of effective implementation of the concept of sustainable forest management. According to the results of scientific research by modern scientists, in particular, B.T. Pham *et al.* (2020), integrated management of the prevention of destructive phenomena in the system of environmental protection is, in particular, a systematic and coordinated approach to the management and prevention of forest fires. The latter is positioned as a convergence of the potential of various methods and practices for preventive protection, timely identification and

effective control of forest fire risks. These conclusions correlate with the modelling implemented in the experimental part of the current study, opening new vectors of synergy potential between integrated management and virtual reality technologies.

Given the outlined concept of sustainable development of forest resources, some scientists, in particular, J.C. Sanabria & J. Arámburo-Lizárraga (2017), emphasise the need to transform the existing management system into sectoral management. Modern scientists of relevant scientific fields, in particular E. Zhu *et al.* (2015), confirm that one of the most effective means to optimise the situation is the active use of modern tools of virtual reality technologies. S. Perey *et al.* (2011) also addressed the need to develop effective tools for integrated management processes based on the maximum disclosure of the interaction potential of modern innovative solutions developed using virtual reality technologies. Analysing the conclusions of the researchers in the concept of preventive training and educational systems based on virtual reality technologies, the study determined that there is a strategic opportunity to optimise the management paradigm in the field of forest fires based on immersive learning technologies.

According to Y. Arifin *et al.* (2018), the priority and the basis of user experience in the field of virtual reality technologies in management will belong to augmented reality applications. At the same time, some researchers, in particular Y.M. Tang *et al.* (2022), emphasise the obvious intensification of forest management efficiency through integrated management using virtual reality technologies, arguing that such conclusions can be made by using a combination of different methods and strategies, which leads to greater efficiency in controlling forest fires. According to the researchers, the optimal combination of a set of methods creates a reliable barrier against the spread of destructive

phenomena. The results of the researchers correlate with the conclusions of the experiment implemented in the current study, since the methodology of integrated forest fire management contributes to the conservation and rational use of resources, since within the framework of the studied approach, natural resources are controlled as accurately as possible and in the smallest practicable areas.

According to S.O. Semerikov *et al.* (2021), the management concept involving the potential of virtual reality technologies should level the phenomenon of imbalance in the field under study. Scientists define integrated forest fire management as a means of reducing costs. The opinion of the scientists is noteworthy, as despite the cost of implementing integrated management systems using VR tools, in the long run, this approach minimises forest loss and prevents significant regeneration costs. During the analytical part of the study, a close relationship was established between the level of integration of forest ecosystem monitoring processes and the effectiveness of the fire safety system. The conclusions of scientists confirm the expediency of integrating VR technology tools into a significant part of management processes in the field of forest fire management (Maroungkas *et al.*, 2023).

According to Y. Shen *et al.* (2022), the main goal of the preventive management paradigm for fire prevention is to increase environmental awareness and education of the population. Scientists emphasise that insufficient access to modern technologies and innovative solutions involving the potential of virtual reality technologies and unreadiness for their practical implementation are the most significant factors limiting the potential of integrated management in the field of research. According to scientists, ensuring fire safety in the forest environment involves the implementation of an effective policy to minimise anthropogenic

impact on natural resources and maximise the ecological compatibility of forest management processes. These conclusions are consistent with the results of the current study in terms of positioning a comprehensive integrated approach as the only effective solution in the process of transforming the forest management system. At the same time, virtual reality technologies are assigned a range of functions to increase the environmental awareness of society and develop the necessary actions to prevent and respond quickly to forest fires (Belytskyi *et al.*, 2023), as proven by the current study.

The results of the current study led to the conclusion that it is necessary to ensure effective interaction between authorities at different levels of government, society and business involved in forestry production to implement integrated approaches to forest fire management. The scientific positions of E. Erturk & G.B. Reynolds (2020), and K.H. Cheng (2021) synergise the proposed approach in terms of accelerating the positive dynamics of the process of transformation of the management paradigm in the field of convergence of effective management and environmental safety in the forest. According to the researchers, integrated forest management contributes to human well-being. Reducing the number of forest fires minimises the risk of poisoning for people and biodiversity. At the same time, C. Seufert *et al.* (2022) identify specific prerequisites for the functioning of an effective educational and management paradigm in the field of environmental protection and the basis of an integrated approach, focusing on the need for an appropriate resource base and the readiness of society for dynamic change. The author is convinced that it is possible to ensure high efficiency of implementation of integrated forest fire management using economic methods while noting that the process is inversely related since the economic and environmental

spheres of activity have determining factors of mutual influence. The opinion of the author is noteworthy, as the current study proved that maximum results in the field of research can be achieved as a result of the convergence of traditional and innovative approaches to monitoring the state of forest lands and environmental indicators in general.

The issue of integrated wildfire management is becoming more urgent in parallel with the trend of increasing dependence on forestry efficiency in the management decision-making system, and in this context, the principle of environmental safety should be a top priority. Sustainable management in an unstable environmental situation has significantly expanded its scope of operation, confirming the effectiveness of implementing innovative technological solutions and opportunities to optimise most areas of life (Kerimkhulle *et al.*, 2023). At the same time, scientists M. Coban *et al.* (2022) addressed the vectoriality of integrated management in forestry, and the need to form effective mechanisms and carry out comprehensive measures to prevent forest fires. According to scientists, the integrated management of the latter is positioned as a basic modern tool in the control and monitoring system that successfully combines efficiency with the principles of environmental sustainability. Abandoning outdated, exhausting approaches to forest management in favour of integrated management helps ensure an appropriate level of fire safety, helps preserve resource potential and stimulates sustainable development of the industry. Additionally, N. Enyedy & S. Yoon (2021) propose to use the potential of VR tools in the form of training technologies for forest fire management within the framework of sustainable management, revealing its functionality in terms of increasing the effectiveness of preventive measures, creating safe and reasonable approaches to forest

management, and optimising the handling of targeted protective equipment. In addition, the study highlights priority areas for targeted investment that intensify the environmental sustainability of integrated management systems in the field of forest fire prevention. The authors emphasise that the proposed concept does not have any potential negative environmental consequences. According to the researchers, national forestry development strategies should include synchronisation with the concepts of the green development course. The opinion of the authors is noteworthy, as the results of the current study confirm the effectiveness of integrated solutions in the process of fighting forest fires, monitoring environmental parameters, and greening forestry production, which should be used to the maximum extent possible in the further development of educational processes.

Despite significant scientific achievements in the field of integrated wildfire management as a basis for building environmental resilience, the issue of their large-scale practical adaptation to the realities of Thailand remains unresolved. The development of an innovative approach to the management paradigm in the field of forestry management in the concept of convergence of the most effective immersive technologies, tools and methods for optimising the industry under study in the direction of sustainable development is considered promising. In addition, modelling modern educational content with immersion in the virtual reality of the forest environment leads to better results in intensifying environmental awareness, as an immersive environment with a sense of real presence leads to higher engagement and motivation, and deeper cognitive processing of educational material. The use of virtual reality educational applications has significant opportunities that are not available when using traditional educational technologies.

Conclusions

The rapid innovative development of the modern information society is closely linked to the adaptive renewal and intensive transformation of the environmental management system, the effectiveness of which is based on deep immersion in the digital information environment. Immersive education and training technologies can become an important functional tool in the forest management process, helping to minimise the number of forest fires. At the moment, this is not the cheapest way to study and not everyone can afford it. Nevertheless, the number of VR and AR products indicates the demand for this format. These technologies, such as others, will become more accessible over time and can truly become a regular part of the educational process.

The study determined that immersive technologies are currently developing rapidly from the position of innovation to a practical range of tools. Their implementation in the paradigm of environmental management policy is positioned as a promising necessity and a factor in intensifying the quality of preventive environmental protection. As a result of specifying the essence of the phenomenon of immersive technologies, their components, in particular, objective, virtual and augmented reality, are allocated. The study presents an example of the use of virtual reality technologies in the process of modelling the situation of fire prevention in a certain forest area using a virtual reality application (VR application) in an educational environment. In the process of studying the features of virtual reality technologies in environmental modelling, the advantages and risks of their integration are highlighted. Based on the data obtained, the article analyses the potential of immersive technologies to minimise the risks of forest fires, while introducing the latest control and monitoring systems.

The experiment was conducted with the use of virtual reality technologies in the educational school environment. A certain area of the forest was selected, where a fire prevention situation was modelled using the FLAIM Systems VR software, focusing on the preconditions, factors and consequences of forest fires. FLAIM Trainer was used to recreate the stress and uncertainty of real-life situations, conveying not only visuals but also tactile sensations. As a result of the experiment, the situation was analysed using a virtual reality programme, which made it possible to understand several important factors that require systemic and technical training to quickly overcome the consequences and prevent forest fires. Given the experiment, it is worth noting certain limitations of the study, which are due to the limited sample and statistical methods used. In this regard, the variability of certain indicators, such as the relationship between two or more variables and the prediction of future outcomes, could not be fully considered in the experiment, which is worth

testing in future studies. In the future, regression and network analysis and machine learning can be used for modelling and forecasting, determining relationships and decision tree algorithms. Network analysis should be used within the framework of immersive technologies to study the structure and dynamics of a social network.

Thus, the use of immersive technologies in the management of the forest fire prevention system significantly expands the toolkit of a modern specialist. Virtual reality technologies can be used to design a virtual environment, and develop a scenario for interacting with visual interactive material, which helps to improve the efficiency of the educational and management process.

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Conflict of Interest

None.

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Запобігання та управління лісовими пожежами в імерсивному середовищі

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Анотація. Глобальний тренд інноваційного розвитку суспільства позиціонує технології віртуальної реальності (VR) як невід'ємний інструмент в управлінському процесі. Метою дослідження є аналіз потенціалу використання імерсивних технологій у системі запобігання та ліквідації лісових пожеж. Дослідження проводилося з використанням спеціальних наукових методів – експерименту та статистичних методів описової та інференційної статистики. У ході дослідження визначено, що імерсивні технології зараз стрімко розвиваються від позиції інновації до практичного спектру інструментів. Встановлено, що їх впровадження в парадигмі політики природокористування позиціонується як перспективна необхідність і чинник інтенсифікації якості превентивної охорони довкілля. Уточнено сутність феномену

імерсивних технологій та охарактеризовано їх складові, зокрема, об'єктивну, віртуальну та доповнену реальність. Досліджено потенціал імерсивних технологій в концепції розширення інструментарію сучасного фахівця галузі. Дослідження довело, що використання VR-додатків має значний потенціал позитивного впливу на зменшення кількості лісових пожеж та покращення стану лісових екосистем. У дослідженні проаналізовано специфіку використання імерсивних технологій у концепції запобігання та управління лісовими пожежами. Наведено приклад використання технологій віртуальної реальності в процесі моделювання ситуації запобігання пожежі на певній лісовій ділянці за допомогою VR-додатку в освітньому середовищі. У процесі дослідження особливостей використання технологій віртуальної реальності в екологічному моделюванні виокремлено переваги та ризики їх інтеграції. Результати дослідження можуть бути ефективно використані в практичному процесі реалізації концепції забезпечення сталого розвитку довкілля в частині профілактики лісових пожеж

Ключові слова: віртуальна реальність; доповнена реальність; застосування; моделювання; превентивний захист