Topola/Poplar **2025**, 216, 27-40 e-ISSN: 2620-1593

DOI: 10.5937/topola2516027Z
UDC: 577.19:630*9

Review paper

Biogenic volatile organic compounds as mediators of forest ecosystem services for human health

Martina Zorić[1]*, Velisav Karaklić[1], Marko Ilić[1], Zoran Novčić[1], Sreten Vasić[1], Olivera Kalozi[2], Lazar Kesić[1]

[1] University of Novi Sad, Institute of Lowland Forestry and Environment, Novi Sad, Serbia
[2] University of Novi Sad, Faculty of Agriculture, Department of Fruit Growing, Viticulture, Horticulture and Landscape Architecture, Novi Sad, Serbia

* Corresponding author: Martina Zorić; E-mail: martinazoric@uns.ac.rs

Received: 9 October 2025; **Revised:** 27 October 2025; **Accepted:** 18 November 2025

Abstract: Forests provide a wide range of ecosystem services essential for human well-being, including provisioning, regulating, and cultural benefits. Among these, the emission of biogenic volatile organic compounds (BVOCs) by trees has emerged as a key factor mediating physiological and psychological health effects. BVOCs, particularly terpenes and phytoncides, influence immune function, reduce stress, support cardiovascular and respiratory health, and contribute to mental well-being. Forest-based therapeutic practices, such as Shinrin-Yoku (forest bathing): capitalize on these natural compounds, demonstrating measurable improvements in mood, stress hormone levels, and immune parameters. Beyond direct health benefits, BVOCs interact with atmospheric chemistry, affecting air quality and urban environmental conditions. Despite growing evidence, the mechanisms linking specific tree species and BVOC profiles to health outcomes remain insufficiently understood, and interdisciplinary collaboration between forestry, medical sciences, and urban planning is limited. This review synthesizes current knowledge on forest ecosystem services and BVOCs in the context of human health, highlighting chemical ecology, therapeutic applications, and potential risks in urban environments. It further identifies knowledge gaps and outlines future research directions to guide forest management, urban green space design, and public health strategies. By integrating ecological, physiological, and environmental perspectives, forests and their volatile compounds can be effectively leveraged as nature-based tools to promote sustainable health and well-being.

Keywords: forest ecosystem services, BVOCs, terpenes, phytoncides, forest therapy, human health.

1. Introduction

Human survival has always been intertwined with the gifts of nature-water, nutrient cycles, and the sustenance provided by food. For centuries, societies lived in close harmony with natural environments, drawing both material resources and a sense of balance from them. The rise of industrialization, however, marked a turning point: rapid urbanization drew people into densely populated, polluted, and increasingly artificial surroundings. This detachment from nature is now closely associated with the rise of so-called 'modern diseases,' ranging from mental health challenges such as stress and depression to physical conditions including hypertension and cancer (Nilsson et al. 2011; Balwan and Kour, 2021). This health decline underscores the growing importance of ecosystem services (ES): which offer nature-based solutions to mitigate these modern ailments and enhance human well-being (Boyd and Banzhaf, 2007; MEA, 2005). Since the Millennium Ecosystem Assessment (MEA, 2005) and The Economics of Ecosystems and Biodiversity (TEEB): ES have become central to valuing biodiversity in sustainable development (TEEB, 2010). As major providers of these services, forests-which cover ~31% of global land-play a vital role by offering provisioning, regulating, and cultural benefits, including biodiversity conservation, carbon sequestration, water regulation, and health improvements (Orlović et al. 2012; Jenkins and Schaap, 2018). Scientific evidence indicates that forests exert measurable positive effects on human health, in part through biogenic volatile organic compounds (BVOCs) such as terpenes, which can modulate immune function, support cardiovascular and respiratory health, and alleviate psychological stress (Cho et al. 2017; Antonelli et al. 2020; Wolf et al. 2020). Forest-based interventions, including Shinrin-Yoku (immersive nature exposure): are increasingly recognized as non-invasive approaches with quantifiable health benefits (Larenas-Linnemann et al. 2020; Antonelli et al. 2022). Yet, the mechanisms linking specific tree species and BVOCs to health outcomes are not fully understood, limiting targeted application and forest management for health (Doimo et al. 2020; Bach Pages et al. 2020). BVOCs also influence atmospheric chemistry, affecting ozone formation and particulate matter in urban air, thereby indirectly impacting human health (Calfapietra et al. 2013; Mei et al. 2021). Terpenes, the most chemically diverse plant metabolites, show species-, genotype-, and environment-dependent patterns, with their profiles varying across time and space (Kesselmeier and Staudt, 1999; Ashour et al. 2018; Kopaczyk et al. 2020). This complexity demands detailed BVOC characterization to understand their ecological and therapeutic roles. Significant gaps remain in identifying beneficial tree species/genotypes and optimal conditions for maximizing BVOC health benefits. Limited interdisciplinary collaboration between forestry and medical sciences hinders progress in translating ecological insights into preventive healthcare and urban greening (Bach Pages et al. 2020; Doimo et al. 2020). This review synthesizes current knowledge on forests and their biogenic BVOCs in human health promotion, highlights forest therapy and BVOC chemical ecology research, and calls for interdisciplinary approaches to guide future studies and design therapeutic green spaces to improve public health.

2. Forest ecosystem services

Blew (1996) noted that the term "*ecosystem*" varies depending on focus - organisms, ecological processes, or geographic areas with distinct soil, climate, and biosphere conditions. More recent definitions view ecosystems as dynamic, complex systems where plants, animals, microorganisms, and humans interact continuously (MEA, 2005). Humans have long relied on ecosystem components, now conceptualized as ecosystem services (ES): defined as all benefits derived from nature that enhance well-being and quality of life (Boyd and Banzhaf, 2007). As a key bioeconomic factor, ES transform natural resources - plants, animals, soil, water, air - into goods and services vital to human societies (D'Amato et al. 2020). However, intensified resource use from rapid societal development has caused widespread degradation, biodiversity loss, and habitat disruption, prompting new management frameworks including in forestry (Rapport et al. 1998; Regier et al. 1996; Ruokamo et al. 2023). The ES concept emerged in the late 1960s but gained momentum in the late 1990s and 2000s, driven by the need to raise awareness about biodiversity's importance for human survival (Mengist and Soromessa, 2019). The Millennium Ecosystem Assessment (MEA, 2005) was the first major global evaluation, highlighting complex ecosystem interactions and trade-offs, such as between provisioning and regulating services. The Economics of Ecosystems and Biodiversity (TEEB, 2010) further emphasized economic valuation to promote conservation. Recently, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019) advanced scientific understanding and policy relevance of ES globally, informing biodiversity conservation and sustainable development. The EU Forest Strategy (European Commission, 2021) integrates ES into forest policies to enhance biodiversity, climate mitigation, and human well-being through sustainable forestry. The Millennium Ecosystem Assessment (2005) defines ecosystem services as the benefits that people obtain from ecosystems, encompassing provisioning, regulating, cultural, and supporting services (Reid et al. 2005). These sustain biodiversity and produce goods like seafood, timber, pharmaceuticals, and maintain ecosystem functions essential for humans (Daily, 1997; Costanza et al. 1997). However, as humans increasingly dominate and rapidly alter ecosystems – particularly anthropogenic ones (Vitousek et al. 1997) – understanding and preserving forest ecosystem services becomes ever more critical.

Forests provide diverse goods and services globally, regionally, and locally, such as timber, wood products, and many others contributing to human well-being (MEA, 2005). European forests supply provisioning services like timber, but also crucial regulating services such as soil protection, water and air purification, and climate regulation (Jenkins and Schaap, 2018; Forest Europe, 2020). Forests also support cultural and spiritual values (Jenkins and Schaap, 2018). Vizzarri et al. (2014) highlight forests as primary ES sources foundational for human life and society. Key services include timber and non-wood products, biodiversity conservation, water and soil protection, carbon sequestration, natural disaster protection, recreation, relaxation, and education (Dodev et al. 2020). Forest ES can be direct – obtained or used directly – or indirect, which are not spatially limited (Mengist and Soromessa, 2019; Haefele et al. 2016). Direct services include timber, fibers, bioenergy, clean water, traditional medicines, and cultural values such as landscape aesthetics and ecotourism (Mengist and Soromessa, 2019). Regulating services derive from ecosystem processes like erosion control, climate regulation, pollination, and protection from hazards like floods. Cultural services provide intangible benefits influencing well-being, aesthetics, spiritual values, recreation, and education. Supporting services sustain life via soil formation, nutrient cycling, photosynthesis, and habitat provision (MEA, 2005; De Groot et al. 2012; Englund et al. 2017; Mengist and Soromessa, 2019). Forests also represent income sources for owners and users relying on sustainable management for profits (Romeiro et al. 2022). Responsible forest management mitigates climate change impacts and improves quality of life. Forests host over 80% of terrestrial species and provide food, raw materials for pharmaceuticals, drinking water, and support recreational, cultural, and spiritual activities for millions worldwide (Jenkins and Schaap, 2018). Li et al. (2019) report the global forest sector employs over 18 million people directly and supports more than 45 million jobs indirectly, contributing over USD 1.29 trillion to global GDP. Despite this, approximately 40% of original forests have been lost due to agriculture and industrialization, with remaining forests fragmented and degraded (MEA, 2005; Matthews et al. 2000; Wade et al. 2003). Europe's approach has shifted from exploitation to sustainable use with growing recognition of intangible forest goods and services (Aldous, 2006; Fuller et al. 2010).

3. Therapeutic and health benefits of forests

Forests and trees play a critical role in supporting human health and well-being, offering benefits that are both direct – through the use of natural resources – and indirect, through psychological and physiological effects of exposure to forest environments. These benefits are increasingly acknowledged in medical literature and are driving the development of forest-based therapeutic practices worldwide.

3.1. Forest-based therapeutic practices

Therapeutic engagement with forest environments can occur through casual contact or structured programs. A range of nature-based practices has emerged in recent decades, including forest therapy, forest bathing (*Shinrin-Yoku*): and integrative methods such as Kneipp therapy when combined with forest exposure (Tsunetsugu et al. 2010; Schuh and Immich, 2022). All these approaches emphasize the immersive presence of individuals in forested environments, though they differ in formality, infrastructure, and clinical integration. One of the most prominent and widely studied methods is *Shinrin-Yoku*, which literally translates to "forest bathing" or "bathing in the forest atmosphere." Developed by Japan's Forestry Agency in 1982, the practice was part of a national health strategy aimed at combating rising levels of stress and chronic disease associated with rapid technological advancement and urbanization (Tsunetsugu et al. 2010). It was officially introduced into Japanese medicine during the 1980s and is now embedded within public health promotion (Park et al. 2007; Hansen et al. 2017). *Shinrin-Yoku* involves slow, mindful walking through forested areas with deliberate engagement of all five senses-touch, sight, hearing, smell, and taste. This sensory interaction is believed to foster deep relaxation and physiological regulation. The practice does not require physical exertion or specialized equipment and can be adapted to people of all ages and health conditions. The institutionalization of forest therapy varies globally. Japan, South Korea, and Germany have formally integrated forest-based therapies into their healthcare systems, supported by infrastructure, trained guides, and medical professionals (Zhang and Ye, 2022). In contrast, in countries like China and the United States, forest bathing tends to be a more informal activity, usually practiced independently or guided by non-medical professionals. Despite these differences, all approaches share the understanding that human interaction with forests contributes to overall well-being.

3.2. Physiological and immune system benefits

A substantial number of empirical studies have confirmed the wide-ranging physiological benefits of forest exposure. Among the most frequently reported effects are reductions in cardiovascular and stress-related markers. Exposure to forest environments has been shown to reduce blood pressure, heart rate, and levels of salivary cortisol – a hormone closely associated with stress response (Li, 2010; Park et al. 2010; Lee et al. 2011; Li et al. 2011; Lee et al. 2014; Ochiai et al. 2015; Han et al. 2016; Song et al. 2017; Li, 2022). These responses have been consistently observed in both healthy individuals and those with pre-existing conditions. Another important area of research relates to the immune system. Several studies have demonstrated that time spent in forests can enhance the activity and count of Natural Killer (NK) cells, a type of lymphocyte involved in the body's defence against infections and tumors (Li et al. 2008; Li et al. 2009; Han et al. 2016; Sunjaya and Sunjaya, 2018). NK cell activity increased significantly after forest therapy sessions, and the effects were observed to persist for several days post-exposure. Further physiological improvements have been observed in metabolic function. In a landmark study by Ohtsuka et al. (1998): patients with non-insulin-dependent diabetes who engaged in forest walks of 3 to 6 kilometers exhibited marked reductions in blood glucose levels. These results suggest that forest-based interventions may serve as complementary strategies in the management of chronic conditions such as diabetes and cardiovascular diseases. In addition to the physiological outcomes, forest exposure has been linked to improved respiratory function and enhanced air quality. Forests reduce airborne pollutants and produce beneficial biogenic volatile organic compounds (BVOCs): some of which – such as phytoncides – are thought to have anti-inflammatory and antimicrobial effects (Mazzoleni et al. 2024). Thus, forest air may contribute to respiratory health, particularly in urbanized settings where air pollution is a major public health concern.

Beyond physical health, the mental and emotional benefits of forests are increasingly recognized. Nature exposure is associated with reductions in anxiety, depression, anger, and stress, as well as improved mood, attention, and emotional resilience. These outcomes are particularly relevant in light of the growing mental health crisis in urban populations. Forest exposure has been shown to reduce symptoms of anxiety in both clinical and non-clinical populations (Tsunetsugu et al. 2011; Lee et al. 2014; Kobayashi et al. 2015). Decreases in salivary cortisol after forest walks reflect a downregulation of the stress response system (Tsunetsugu et al. 2010; Li, 2022). Improvements in emotional state have also been documented, including reductions in negative emotions such as anger, fatigue, and confusion (Park et al. 2011; Song et al. 2018). Several studies point to the therapeutic value of forests for individuals with depressive symptoms. Morita et al. (2007; 2011) found that forest exposure significantly alleviated symptoms of depression and contributed to enhanced feelings of vitality and well-being. Similarly, Ulrich et al. (1991) and Pretty et al. (2007) highlighted the role of natural environments in reducing psychological distress and fostering positive affect. Cognitive benefits have also been observed. Forest settings appear to support attention restoration and cognitive recovery from mental fatigue, which may be particularly beneficial for people living in high-stress urban contexts or working in cognitively demanding professions. Improved sleep quality and overall life satisfaction have been reported following regular forest visits (Song et al. 2019). The COVID-19 pandemic has further underscored the importance of access to green spaces. During periods of lockdown and restricted mobility, people increasingly sought refuge in forests and peri-urban green areas, using nature as a coping mechanism for stress and isolation (McCunn, 2021). This shift has reignited public interest in nature-based healing and prompted calls for improved integration of green infrastructure in urban planning.

Despite the abundant evidence supporting the positive health effects of forests, many of the underlying mechanisms remain insufficiently explored. A review by Doimo et al. (2020) concluded that the forest-health relationship is still under-researched and called for more targeted studies to identify forest-specific factors responsible for physiological and psychological benefits. Understanding the contribution of specific environmental parameters – such as biodiversity, tree species composition, forest structure, and emitted VOCs – is crucial for developing effective nature-based interventions. Additionally, there is a need for standardized protocols in forest therapy research, including consistent exposure durations, participant profiles, and measurement techniques. Such standardization would facilitate cross-study comparisons and provide stronger scientific foundations for integrating forest therapy into formal healthcare practices. As climate change and urbanization continue to pose health challenges, forests offer a promising, nature-based resource for improving population health. Future forest management strategies should consider the therapeutic potential of green spaces, particularly in urban and peri-urban contexts where access to nature is limited. Integrating scientific knowledge of forest-human interactions into public health and urban planning policies could lead to more resilient, healthier communities (Bach Pagès et al. 2020).

4. VOCs

Biogenic volatile organic compounds (BVOCs) emitted by trees are recognized as key forest parameters contributing to human health improvement (Li, 2010). Besides their direct health benefits, BVOCs also influence air quality (Grote et al. 2016): indirectly affecting human well-being. Previous studies have analyzed tree-derived BVOCs for their role in urban ozone formation (Calfapietra et al. 2013; Fitzky et al. 2019) and their capacity to reduce harmful particulate matter (PM) in urban air (Mei et al. 2021). BVOCs encompass diverse volatile organic substances, excluding CO_2 and CO, including terpenes, alkanes, alkenes, aldehydes, ketones, alcohols, esters, ethers, and acids (Kesselmeier and Staudt, 1999). Plants produce hundreds of thousands of low-molecular-weight compounds, classified as primary metabolites (common to all organisms) and secondary metabolites, the latter being biosynthesized only in specific plant groups (Pichersky and Gang, 2000). Secondary metabolites, including volatile organic compounds, play vital roles in plant reproduction, defence, inter-species interactions, and exhibit bioactivities such as antimicrobial, anti-inflammatory, antioxidant, antidiabetic, and anticancer effects (Mun and Townley, 2021). These compounds are produced in various plant organs like flowers, fruits, leaves, stems, and roots (Farré-Armengol et al. 2016). The biosynthesis of secondary metabolites is complex and regulated temporally and spatially by plant genetics and environmental factors (Picazo-Aragonés et al. 2020). Although many biosynthetic pathways remain unclear, numerous enzymes are involved (Pichersky and Gang, 2000). Epigenetic studies are increasingly important to elucidate these pathways (Picazo-Aragonés et al. 2020). Volatile organic compounds are also valuable as chemotaxonomic markers in plant systematics, with their chemical profiles reflecting geographic and environmental interactions that impact surrounding ecosystems (Picazo-Aragonés et al. 2020).

4.1. Role of BVOC

Volatile organic compounds (VOCs) produced by plants result from their adaptation to environmental conditions and interactions with abiotic and biotic factors (Dudareva et al. 2013; Picazo-Aragonés et al. 2020). Plants activate VOC biosynthesis in response to stresses such as pathogens, mechanical injury, or extreme temperatures (Ueda et al. 2012). Besides stress responses, VOCs are also synthesized to attract pollinators, signal injury within the plant, and communicate warnings to neighbouring plants and organisms. Although VOC profiles are generally species-specific, their composition can vary among individuals and depends strongly on the plant's developmental stage (Gibney and Nolan, 2010; Kopaczyk et al. 2020). VOCs play a crucial role in defense against pathogens and enhance resistance to abiotic stress (Heil and Silva Bueno, 2007; Koornneef and Pieterse, 2008; Dudareva et al. 2013; Salam et al. 2023). Upon stress exposure, plants increase VOC biosynthesis not only to protect themselves but also to warn neighbours of potential threats (Brosset and Blande, 2021; Darragh et al. 2021; Salam et al. 2023). Plants possess a complex immune signalling system where pathogen attacks activate systemic acquired resistance (SAR): with VOCs-mainly monoterpenes-acting as communication modulators within and between plants (Eccleston et al. 2022). This plant-to-plant communication, originally termed allelopathy by de Candolle in 1832, refers to reciprocal biochemical interactions. Baldwin and Schultz (1983) showed that plants use secondary metabolites to alert others to damage or pathogens. Upon uptake of VOCs, plants may synthesize new compounds that influence photosynthesis, nutrient uptake, and metabolism, affecting their physiological state (Brosset and Blande, 2022). Beyond plant interactions, VOCs also affect human health. Numerous studies have documented positive health effects of VOCs (Cho et al. 2017; Antonelli et al. 2020; Wolf et al. 2020). However, some research warns of potential negative impacts caused by photochemical reactions of VOCs in urban atmospheres, where plant-derived VOCs can react with pollutants to form harmful compounds (Jaars et al. 2018).

4.2. Terpenes

Terpenes, also known as isoprenoids or terpenoids, are secondary plant metabolites whose primary function is protection against stress, damage, and pathogenic microorganisms (Milić, 1997; Kebert et al. 2022). They represent the most diverse class of plant secondary metabolites, with over 55,000 compounds identified to date and approximately 1,000 new structures added annually (Ashour et al. 2018; Ninkuu et al. 2021). Terpenes possess a characteristic carbon skeleton composed of five-carbon isoprene units (C_5H_8) and are classified based on the number of these units according to the isoprene rule first proposed by Wallach in 1887 (Milić, 1997; Ninkuu, 2021). The main classes include hemiterpenes (C_5H_8): monoterpenes ($C_{10}H_{16}$): sesquiterpenes ($C_{15}H_{24}$): diterpenes ($C_{20}H_{32}$): sesterterpenes ($C_{25}H_{40}$): triterpenes ($C_{30}H_{48}$): tetraterpenes or carotenoids ($C_{40}H_{56}$): and polyterpenes (C_5H_8)_x (Milić, 1997). The biosynthesis of terpenes was demonstrated in 1956 by isolating mevalonic acid, a key intermediate in their production. Terpene biosynthesis begins with acetyl-CoA, which is converted into mevalonic acid, followed by the formation of isopentenyl pyrophosphate (IPP) and dimethylallyl pyrophosphate (DMAPP): the precursors of terpenes (Ninkuu, 2021). Terpenes are mostly assembled by linking isoprene units "head-to-tail," although exceptions exist (Milić, 1997). Forests are a major source of terpenes, particularly monoterpenes and sesquiterpenes (Šimpraga et al. 2019; Hodzic et al. 2016). Monoterpenes consist of two isoprene units and are structurally classified as acyclic, monocyclic, or bicyclic. Sesquiterpenes, containing three isoprene units, are categorized into acyclic, monocyclic, bicyclic, and tricyclic types (Ninkuu, 2021). Some terpenes, including mono- and sesquiterpenes, are volatile, while others like diterpenes are partially volatile or non-volatile depending on the number of isoprene units (Ninkuu, 2021). Once emitted into the atmosphere, these compounds are highly reactive, and their concentrations vary with environmental factors such as temperature, sunlight, presence of other compounds, and seasonal changes. Additionally, subterranean and aerial allelopathic interactions within ecosystems influence their atmospheric composition (Kesselmeier and Staudt, 1999; Wang, 2018; Hellén et al. 2018; Kopaczyk et al. 2020).

4.3. BVOCs and human health and wellbeing

Volatile organic compounds (VOCs) of plant origin-particularly those emitted by trees-represent a crucial interface between forest ecosystems and human health. These compounds encompass a broad range of chemical classes, including terpenes, aldehydes, ketones, alcohols, and others, and are released from various plant organs into the atmosphere. Once airborne, VOCs interact with environmental factors such as temperature, sunlight, and air pollutants, influencing not only ecological dynamics but also human health both directly and indirectly.

Numerous studies have demonstrated that VOCs emitted in natural environments, particularly forests, positively influence human physiological and psychological parameters. Exposure to forest air enriched with biogenic VOCs is linked to reductions in stress hormones such as cortisol, lowered blood pressure, enhanced immune function, and improved mood (Li, 2010; Song et al. 2017). In this way, VOCs are key contributors to the health benefits observed during nature exposure and forest therapy. However, in urban environments with high anthropogenic pollution, plant-emitted VOCs may react photochemically with nitrogen oxides (NO_x): leading to the formation of ground-level ozone and secondary organic aerosols (SOAs): both detrimental to human health (Calfapietra et al. 2013; Jaars et al. 2018). Thus, while VOCs mediate important plant–environment and plant–human interactions, their effects depend heavily on environmental context and air quality. It is essential to differentiate VOCs from phytoncides, a subset of plant-emitted VOCs with specific bioactive properties such as antimicrobial and anti-inflammatory effects. Whereas VOCs encompass a broad range of compounds involved in ecological signalling, plant defence, and air chemistry, phytoncides refer specifically to VOCs with therapeutic potential. Recognizing this dual role of plant VOCs – as both health-promoting agents and possible air pollutants – underlines the need for context-specific research and careful planning of urban greening and forest-based health interventions.

4.4. Phytoncides

The term phytoncides derives from the Greek words *phyto* (plant) and *cide* (to kill) and refers to volatile organic compounds produced by plants that act as defence mechanisms against pathogens and pests, including bacteria, fungi, and insects (Tokin, 1980). Forest-derived VOCs, primarily mono- and sesquiterpenes, function as phytoncides and are key forest parameters linked to positive human health effects (Cheng et al. 2009; Li et al. 2011). Certain terpenes in trees, such as α-pinene and β-pinene, exhibit anti-inflammatory, anticancer, and sedative activities (Paduch et al. 2007; Salehi et al. 2019; Khoshnazar et al. 2019). Limonene and linalool also show anticancer, anti-inflammatory, antimicrobial, and sedative effects (Hafidh et al. 2018; Kim et al. 2019; Iwasaki et al. 2016; Lee et al. 2018; Liu et al. 2020). Other phytoncidal terpenes include terpinolene, camphene, camphor, and α-cadinol (Wen et al. 2007; Sokolova et al. 2014; Vallianou and Hadzopoulou-Cladaras, 2016; Kim et al. 2019). Regarding human health, these compounds can improve conditions such as Parkinson’s disease, multiple sclerosis, allergic reactions, asthma, and aging symptoms (Sunjaya and Sunjaya, 2018). Italian studies suggest lower COVID-19 mortality in southern Italy may relate to exposure to antiviral plant-derived VOCs (Roviello and Roviello, 2021). Phytoncides stimulate the olfactory sense, which is connected to instincts and emotions, and are believed to exert a stronger influence on humans during forest therapy than other forest parameters (Tsunetsugu et al. 2010). Coniferous species release higher concentrations of VOCs than deciduous trees, making them more effective in emitting these compounds (Meneguzzo et al. 2019).

5. Future perspectives

The investigation of biogenic volatile organic compounds (BVOCs) and their multifaceted effects on human health and the environment represents a complex scientific endeavour that necessitates close collaboration among diverse disciplines. Despite the increasing recognition of the significant role that BVOCs play in linking forest ecology, atmospheric processes, and public health, a persistent challenge remains: the insufficient integration and cooperation between forestry researchers, atmospheric scientists, medical professionals, and urban planners. Addressing this challenge requires the establishment of collaborative research platforms and the integration of ecological knowledge into urban planning and public health strategies.

Forests and their emitted biogenic volatile organic compounds (BVOCs) have a profound and multifaceted impact on human health. The current body of research underscores that exposure to forest environments and inhalation of BVOCs can contribute significantly to the prevention and mitigation of various diseases, including respiratory, cardiovascular, metabolic, and mental health disorders. These natural ecosystems provide both direct and indirect health benefits, ranging from improved immune function and reduced stress hormone levels to enhanced psychological well-being. The preventive potential of forests extends beyond individual health, encompassing public health and community resilience, especially within the context of rapid urbanization and global environmental change. By preserving and integrating forest ecosystems and urban green spaces into city landscapes, societies can harness the therapeutic properties of BVOCs and forest environments as natural, cost-effective complements to conventional healthcare strategies. To fully realize this potential, coordinated efforts are required across multiple sectors. Future research should prioritize interdisciplinary approaches that bring together urban planners, medical researchers, and forestry experts. Such collaboration is crucial to develop evidence-based guidelines for urban green infrastructure design, forest management, and public health policies that optimize BVOC exposure and forest accessibility. Moreover, there is a need for enhanced monitoring and analytical tools to better understand the variability of BVOC emissions and their physiological effects across diverse populations and environments. Long-term epidemiological studies and controlled clinical trials are also essential to substantiate the causal links between forest exposure, BVOC inhalation, and health outcomes.

In practice, urban planners should incorporate knowledge about BVOC-emitting vegetation into green space design to maximize health benefits while minimizing potential adverse effects, such as ozone formation. Forestry specialists must continue to balance sustainable forest management with ecosystem service delivery, ensuring the maintenance of high-quality forest environments that support both biodiversity and human health. In conclusion, fostering interdisciplinary collaboration not only advances scientific discovery, but also catalyzes the translation of complex ecological interactions into tangible societal benefits. Forests and their volatile organic compounds represent vital natural resources for advancing public health and well-being. The future success in leveraging these benefits lies in overcoming disciplinary boundaries, embracing integrative research, and embedding ecological knowledge into health and urban policies to promote sustainable, health-supportive human-environment interactions.

Acknowledgements:

This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia under contract number 451-03-136/2025-03/200197 and by the Autonomous Province of Vojvodina, Provincial Secretariat for Higher Education and Scientific Research, under contract number 003830502 2025 09418 003 000 000 001 04 002.

References:

1. Aldous., D.E. (2006): Social, environmental, economic, and health benefits of green spaces. Proceedings of XXVII International Horticultural Congress-IHC2006: International Symposium on Horticultural Plants in Urban and Peri-Urban 762: 171–186.
2. Antonelli, M., Donelli, D., Barbieri, G., Valussi, M., Maggini, V., Firenzuoli, F. (2020): Forest volatile organic compounds and their effects on human health: A state-of-the-art review. International Journal of Environmental Research and Public Health 17(18): 6506.
3. Antonelli, M., Donelli, D., Carlone, L., Maggini, V., Firenzuoli, F., Bedeschi, E. (2022): Effects of forest bathing (shinrin-yoku) on individual well-being: An umbrella review. International Journal of Environmental Health Research 32(8): 1842–1867.
4. Ashour, M., Wink, M., Gershenzon, J. (2010): Biochemistry of terpenoids: monoterpenes, sesquiterpenes and diterpenes. In: Wink, M. (Ed.): Annual plant reviews volume 40: biochemistry of plant secondary metabolism. p. 258–303.
5. Bach Pagès, A., Peñuelas, J., Clarà, J., Llusià, J., Campillo López, F., Maneja, R. (2020): How should forests be characterized in regard to human health? Evidence from existing literature. International Journal of Environmental Health Research 17(3): 1027.
6. Baldwin, I.T., Schultz, J. C. (1983): Rapid changes in tree leaf chemistry induced by damage: evidence for communication between plants. Science 221(4607): 277–279.
7. Balwan, W. K., Kour, S. (2021): Lifestyle Diseases: The Link between Modern Lifestyle and threat to public health. Saudi Journal of Medical and Pharmaceutical Sciences 7(4): 179-84.
8. Blew, R. D. (1996): On the definition of ecosystem. Bulletin of the Ecological Society of America 77(3): 171–173.
9. Boyd, J., Banzhaf, S. (2007): What are ecosystem services? The need for standardized environmental accounting units. Ecological Economics 63(2–3): 616–626.
10. Brosset, A., Blande, J. D. (2022): Volatile-mediated plant–plant interactions: volatile organic compounds as modulators of receiver plant defence, growth, and reproduction. Journal of Experimental Botany 73(2): 511–528.
11. Calfapietra, C., Fares, S., Manes, F., Morani, A., Sgrigna, G., Loreto, F. (2013): Role of Biogenic Volatile Organic Compounds (BVOC) emitted by urban trees on ozone concentration in cities: A review. Environmental Pollution 183: 71–80.
12. Cheng, W.W., Lin, C.T., Chu, F.H., Chang, S.T., Wang, S.Y. (2009): Neuropharmacological activities of phytoncide released from Cryptomeria japonica. Journal of Wood Science 55: 27-31.
13. Cho, K.S., Lim, Y.R., Lee, K., Lee, J., Lee, J.H., Lee, I.S. (2017): Terpenes from forests and human health. Toxicological Research 33: 97–106.
14. Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O Meill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., Van Den Belt, M. (1997): The value of the world's ecosystem services and natural capital. Nature 387(6630): 253–260.
15. D'Amato, D., Bartkowski, B., Droste, N. (2020): Reviewing the interface of bioeconomy and ecosystem service research. Ambio 49, 1878-1896.
16. Daily, G. C. (Ed.): (1997): Nature's services: societal dependence on natural ecosystems. Island press.
17. Darragh, K., Orteu, A., Black, D., Byers, K. J., Szczerbowski, D., Warren, I. A., Rastas, P., Pinharanda, A., Davey, J.W., Fernanda Garza, S., Abondano Almeida, D., Merril, R.M., McMillan, W.O., Schulz, S., Jiggins, C. D. (2021): A novel terpene synthase controls differences in anti-aphrodisiac pheromone production between closely related Heliconius butterflies. PLoS Biology 19(1): e3001022.
18. De Groot, R., Brander, L., Van Der Ploeg, S., Costanza, R., Bernard, F., Braat, L. Cristie, M., Crossman, N., Ghermandi, A., Hein, L., Hussain, S., Kumar, P., McVittie, A., Portela, R.,

Rodriguez, L.C., ten Brink, P., Van Beukering, P. (2012): Global estimates of the value of ecosystems and their services in monetary units. Ecosystem Services 1(1): 50–61.

19. Dodev, Y., Zhiyanski, M., Glushkova, M., Shin, W. S. (2020): Forest welfare services-the missing link between forest policy and management in the EU. Forest Policy and Economics 118: 102249.
20. Doimo, I., Masiero, M., Gatto, P. (2020): Forest and wellbeing: Bridging medical and forest research for effective forest-based initiatives. Forests 11(8): 791.
21. Dudareva, N., Klempien, A., Muhlemann, J.K., Kaplan, I. (2013): Biosynthesis, function and metabolic engineering of plant volatile organic compounds. New Phytologist 198(1): 16–32.
22. Eccleston, L., Brambilla, A., Vlot, A. C. (2022): New molecules in plant defence against pathogens. Essays in Biochemistry 66(5): 683–693.
23. Englund, O., Berndes, G., Cederberg, C. (2017): How to analyse ecosystem services in landscapes-A systematic review. Ecological Indicators 73: 492–504.
24. European Commission. (2021): New EU forest strategy for 2030 (COM(2021) 572 final): European Commission.
25. Farré-Armengol, G., Filella, I., Llusia, J., Peñuelas, J. (2016): Bidirectional interaction between phyllospheric microbiotas and plant volatile emissions. Trends in Plant Science 21(10): 854–860.
26. Fitzky, A. C., Sandén, H., Karl, T., Fares, S., Calfapietra, C., Grote, R., Sunier, A., Rewald, B. (2019): The interplay between ozone and urban vegetation-BVOC emissions, ozone deposition, and tree ecophysiology. Frontiers in Forests and Global Change 2: 50.
27. Forest Europe (2020): State of Europe's forests 2020. Ministerial Conference on the Protection of Forests in Europe.
28. Fuller, R. A., Irvine, K. N., Gaston, K. J. (2010): Interactions between people and nature in urban environments. Urban Ecology: 134–171.
29. Gibney, E.R., Nolan, C.M. (2010): Epigenetics and gene expression. Heredity 105(1): 4–13.
30. Grote, R., Samson, R., Alonso, R., Amorim, J. H., Cariñanos, P., Churkina, G., Fares, S., Le Thiec, D., Norgaards Mikkelsen, T., Paoletti, E., Tiwary, A., Calfapietra, C. (2016): Functional traits of urban trees: air pollution mitigation potential. Frontiers in Ecology and the Environment 14(10): 543–550.
31. Haefele, M., Loomis, J., Bilmes, L.J. (2016): Total economic valuation of the national park service lands and programs. Report. Colorado State University, Fort Collins, Colorado (30 June):
32. Hafidh, R.R., Hussein, S.Z., MalAllah, M.Q., Abdulamir, A.S., Abu Bakar, F. (2018): A high-throughput quantitative expression analysis of cancer-related genes in human HepG2 cells in response to limonene, a potential anticancer agent. Current Cancer Drug Targets 18(8): 807–815.
33. Han, J.W., Choi, H., Jeon, Y.H., Yoon, C.H., Woo, J.M., Kim, W. (2016): The effects of forest therapy on coping with chronic widespread pain: Physiological and psychological differences between participants in a forest therapy program and a control group. International Journal of Environmental Research and Public Health 13(3): 255.
34. Hansen, M.M., Jones, R., Tocchini, K. (2017): Shinrin-yoku (forest bathing) and nature therapy: A state-of-the-art review. International Journal of Environmental Research and Public Health 14(8): 851.
35. Heil, M., Silva Bueno, J.C. (2007): Within-plant signaling by volatiles leads to induction and priming of an indirect plant defense in nature. Proceedings of the National Academy of Sciences 104(13): 5467–5472.
36. Hellén, H., Praplan, A.P., Tykkä, T., Ylivinkka, I., Vakkari, V., Bäck, J., Petäjä, T., Kulmala, M., Hakola, H. (2018): Long-term measurements of volatile organic compounds highlight the importance of sesquiterpenes for the atmospheric chemistry of a boreal forest. Atmospheric Chemistry and Physics 18(19): 13839–13863.

37. IPBES, W. (2019): Intergovernmental science-policy platform on biodiversity and ecosystem services. Summary for policy makers of the global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. IPBES Secretariat, Bonn, Germany.
38. Iwasaki, K., Zheng, Y.W., Murata, S., Ito, H., Nakayama, K., Kurokawa, T., Sano, N., Nowatari, T., O Villareal, M., Nagano, Y.N., Isoda, H., Matsui, H., Ohkohchi, N. (2016): Anticancer effect of linalool via cancer-specific hydroxyl radical generation in human colon cancer. World Journal of Gastroenterology 22(44): 9765.
39. Jaars, K., Vestenius, M., van Zyl, P.G., Beukes, J.P., Hellen, H., Vakkari, V., Venter, M., Josipovic, M., Hakola, H. (2018): Receptor modelling and risk assessment of volatile organic compounds measured at a regional background site in South Africa. Atmospheric Environment 172: 133–148.
40. Jenkins, M., Schaap, B. (2018): Forest ecosystem services. Background analytical study, 1.
41. Kebert, M., Kostić, S., Zlatković, M., Stojnic, S., Čapelja, E., Zorić, M., Kiprovski, B., Budakov, D., Orlović, S. (2022): Ectomycorrhizal fungi modulate biochemical response against powdery mildew disease in *Quercus robur* L. Forests 13(9): 1491.
42. Kesselmeier, J., Staudt, M. (1999): Biogenic volatile organic compounds (VOC): an overview on emission, physiology and ecology. Journal of Atmospheric Chemistry 33: 23–88.
43. Khoshnazar, M., Bigdeli, M. R., Parvardeh, S., Pouriran, R. (2019): Attenuating effect of α-pinene on neurobehavioural deficit, oxidative damage and inflammatory response following focal ischaemic stroke in rat. Journal of Pharmacy and Pharmacology 71(11): 1725–1733.
44. Kim, M. G., Kim, S. M., Min, J. H., Kwon, O. K., Park, M. H., Park, J. W., Anh, H.I., Hwang, J. Y., Oh, S. R., Lee, J.W., Ahn, K. S. (2019): Anti-inflammatory effects of linalool on ovalbumin-induced pulmonary inflammation. International Immunopharmacology 74: 105706.
45. Kobayashi, H., Song, C., Ikei, H., Kagawa, T., Miyazaki, Y. (2015): Analysis of individual variations in autonomic responses to urban and forest environments. Evidence-Based Complementary and Alternative Medicine, 2025.
46. Koornneef, A., Pieterse, C. M. (2008): Cross talk in defense signaling. Plant Physiology 146(3): 839–844.
47. Kopaczyk, J. M., Warguła, J., Jelonek, T. (2020): The variability of terpenes in conifers under developmental and environmental stimuli. Environmental and Experimental Botany 180: 104197.
48. Larenas-Linnemann, D., Rodríguez-Pérez, N., Arias-Cruz, A., Blandón-Vijil, M. V., Del Río-Navarro, B. E., Estrada-Cardona, A., Geredam J. E., Luna-Pech, J.A., Navarrete-Rodríguez, E.M., Onuma-Takane, E., Pozo-Beletran, C.F., Rojo-Gutiérrez, M. I. (2020): Enhancing innate immunity against virus in times of COVID-19: Trying to untangle facts from fictions. World Allergy Organization Journal 13(11): 100476.
49. Lee, J., Park, B. J., Tsunetsugu, Y., Ohira, T., Kagawa, T., Miyazaki, Y. (2011): Effect of forest bathing on physiological and psychological responses in young Japanese male subjects. Public Health 125(2): 93–100.
50. Lee, J., Tsunetsugu, Y., Takayama, N., Park, B. J., Li, Q., Song, C., Komatsu, M., Ikei, H., Tyrväinen, L., Kagawa, T., Miyazaki, Y. (2014): Influence of forest therapy on cardiovascular relaxation in young adults. Evidence-based Complementary and Alternative Medicine, 2014.
51. Li, Q. (2010): Effect of forest bathing trips on human immune function. Environmental Health and Preventive Medicine 15: 9–17.
52. Li, Q. (2022): Effects of forest environment (Shinrin-yoku/Forest bathing) on health promotion and disease prevention-the Establishment of "Forest Medicine"- Environmental Health and Preventive Medicine 27: 43–43.
53. Li, Q., Kobayashi, M., Wakayama, Y., Inagaki, H., Katsumata, M., Hirata, Y., Shimizu, T., Kawada, T., Park, B.J., Ohira, T., Kagawa, T., Miyazaki, Y. (2009): Effect of phytoncide from

trees on human natural killer cell function. International Journal of Immunopathology and Pharmacology 22(4): 951–959

54. Li, Q., Morimoto, K., Kobayashi, M., Inagaki, H., Katsumata, M., Hirata, Y., Suzuki, H., Li, Y.J., Wajayama, Y., Kaeada, T., Park, B.J., Ohira, T., Matsui, N., Kagawa, T., Miyazaki, Y., Krensky, A. M. (2008): Visiting a forest, but not a city, increases human natural killer activity and expression of anti-cancer proteins. International Journal of Immunopathology and Pharmacology 21(1): 117–127.
55. Li, Q., Otsuka, T., Kobayashi, M., Wakayama, Y., Inagaki, H., Katsumata, M., Hirata, Y., Li, Y., Hirata, K., Shimizu, T., Suzuki, H., Kawada, T., Kagawa, T. (2011): Acute effects of walking in forest environments on cardiovascular and metabolic parameters. European Journal of Applied Physiology 111: 2845–2853.
56. Li, Y., Mei, B., Linhares-Juvenal, T. (2019): The economic contribution of the world's forest sector. Forest Policy and Economics 100: 236–253.
57. Liu, X., Cai, J., Chen, H., Zhong, Q., Hou, Y., Chen, W., Chen, W. (2020): Antibacterial activity and mechanism of linalool against Pseudomonas aeruginosa. Microbial Pathogenesis 141: 103980.
58. Matthews, E., Payne, R., Rohweder, M., Murray, S. (2000): Pilot analysis of global ecosystems: forest ecosystems. World Resources Institute.
59. McCunn, L.J. (2021): The importance of nature to city living during the COVID-19 pandemic: Considerations and goals from environmental psychology. Cities and Health 5(sup1): S223-S226.
60. MEA (2005): Millennium ecosystem assessment. Ecosystems and their services. Island Press, Washington, DC.
61. Mei, P., Malik, V., Harper, R. W., Jiménez, J. M. (2021): Air pollution, human health and the benefits of trees: A biomolecular and physiologic perspective. Arboricultural Journal 43(1): 19–40
62. Meneguzzo, F., Albanese, L., Bartolini, G., Zabini, F. (2019): Temporal and spatial variability of volatile organic compounds in the forest atmosphere. International Journal of Environmental Research and Public Health 16(24): 4915.
63. Mengist, W. Soromessa, T. (2019): Assessment of forest ecosystem service research trends and methodological approaches at global level: a meta-analysis. Environmental Systems Research 8(1): 22.
64. Milić, B. L. (1997): Terpeni. Tehnološki fakultet, Univerzitet u Novom Sadu, Novi Sad, Srbija.
65. Morita, E., Fukuda, S., Nagano, J., Hamajima, N., Yamamoto, H., Iwai, Y., Nakashima, T., Shirakawa, T.J.P.H. (2007): Psychological effects of forest environments on healthy adults: Shinrin-yoku (forest-air bathing, walking) as a possible method of stress reduction. Public Health 121(1): 54–63.
66. Morita, E., Imai, M., Okawa, M., Miyaura, T., Miyazaki, S. (2011): A before and after comparison of the effects of forest walking on the sleep of a community-based sample of people with sleep complaints. BioPsychoSocial Medicine 5(1): 1–7.
67. Mun, H., Townley, H.E. (2021): Nanoencapsulation of plant volatile organic compounds to improve their biological activities. Planta Medica 87(03): 236–251.
68. Nilsson, K., Sangster, M., Konijnendijk, C.C. (2011): Forests, trees and human health and well-being: Introduction (pp. 1–19): Springer Netherlands.
69. Ninkuu, V., Zhang, L., Yan, J., Fu, Z., Yang, T., Zeng, H. (2021): Biochemistry of terpenes and recent advances in plant protection. International Journal of Molecular Sciences 22(11): 5710.
70. Ochiai, H., Ikei, H., Song, C., Kobayashi, M., Takamatsu, A., Miura, T., Kagawa, T., Li, Q., Kumeda, S., Imai, M., Miyazaki, Y. (2015): Physiological and psychological effects of forest therapy on middle-aged males with high-normal blood pressure. International Journal of Environmental Research and Public Health 12(3): 2532–2542.

71. Orlović, S., Galić, Z., Stojnić, S., Klašnja, B. (2012): Monitoring of forest ecosystems in Serbia. Essays on Fundamental and Applied Environmental Topics (Ed. DT Mihailovic): NOVA Science Publisher. p. 253–276.
72. Paduch, R., Kandefer-Szerszeń, M., Trytek, M., Fiedurek, J. (2007): Terpenes: substances useful in human healthcare. Archivum Immunologiae et Therapiae Experimentalis 55: 315-327.
73. Park, B.J., Furuya, K., Kasetani, T., Takayama, N., Kagawa, T., Miyazaki, Y. (2011): Relationship between psychological responses and physical environments in forest settings. Landscape and urban planning 102(1): 24–32.
74. Park, B.J., Tsunetsugu, Y., Kasetani, T., Hirano, H., Kagawa, T., Sato, M., Miyazaki, Y. (2007): Physiological effects of shinrin-yoku (taking in the atmosphere of the forest) – using salivary cortisol and cerebral activity as indicators, Journal of Physiological Anthropology 26(2): 123–128.
75. Park, B.J., Tsunetsugu, Y., Kasetani, T., Kagawa, T., Miyazaki, Y. (2010): The physiological effects of Shinrin-yoku (taking in the forest atmosphere or forest bathing): evidence from field experiments in 24 forests across Japan. Environmental Health and Preventive Medicine 15: 18–26.
76. Picazo-Aragonés, J., Terrab, A., Balao, F. (2020): Plant volatile organic compounds evolution: Transcriptional regulation, epigenetics and polyploidy. International Journal of Molecular Sciences 21(23): 8956.
77. Pichersky, E., Gang, D.R. (2000): Genetics and biochemistry of secondary metabolites in plants: an evolutionary perspective. Trends in Plant Science 5(10): 439–445.
78. Pretty, J., Peacock, J., Hine, R., Sellens, M., South, N., Griffin, M. (2007): Green exercise in the UK countryside: Effects on health and psychological well-being, and implications for policy and planning. Journal of Environmental Planning and Management 50(2): 211–231
79. Rapport, D.J., Costanza, R., McMichael, A.J. (1998): Assessing ecosystem health. Trends in Ecology and Evolution 13(10): 397–402.
80. Regier, H.A., Baskerville, G.L., Clark, W.C., Munn, R.E. (1996): Sustainable redevelopment of regional ecosystems degraded by exploitive development. United States Department of Agriculture Forest Service General Technical Report PNW. p. 21–44.
81. Reid, W.V., Mooney, H.A., Cropper, A., Capistrano, D., Carpenter, S.R., Chopra, K., Zurek, M.B. (2005): Ecosystems and human well-being-Synthesis: A report of the Millennium Ecosystem Assessment. Island Press.
82. Romeiro, J. M. N., Eid, T., Antón-Fernández, C., Kangas, A., Trømborg, E. (2022): Natural disturbances risks in European Boreal and Temperate forests and their links to climate change–A review of modelling approaches. Forest Ecology and Management 509: 120071
83. Roviello, V., Roviello, G.N. (2021): Less COVID-19 deaths in southern and insular Italy explained by forest bathing, Mediterranean environment, and antiviral plant volatile organic compounds. Environmental Chemistry Letters: 1–11.
84. Ruokamo, E., Savolainen, H., Seppälä, J., Sironen, S., Räisänen, M., Auvinen, A.P. (2023): Exploring the potential of circular economy to mitigate pressures on biodiversity. Global Environmental Change 78: 102625.
85. Salam, U., Ullah, S., Tang, Z.H., Elateeq, A.A., Khan, Y., Khan, J., Ali, S. (2023): Plant metabolomics: An overview of the role of primary and secondary metabolites against different environmental stress factors. Life 13(3): 706.
86. Salehi, B., Upadhyay, S., Erdogan Orhan, I., Kumar Jugran, A., Jayaweera, S.A., Dias, D., Sharifi-Rad, J. (2019): Therapeutic potential of α-and β-pinene: A miracle gift of nature. Biomolecules 9(11): 738.
87. Schuh, A., Immich, G. (2022): How to Discover and Utilise the Forest for Your Health. In Forest Therapy-The Potential of the Forest for Your Health (pp. 89–117): Berlin, Heidelberg: Springer Berlin Heidelberg.

88. Šimpraga, M., Ghimire, R.P., Van Der Straeten, D., Blande, J. D., Kasurinen, A., Sorvari, J., Kivimäenpää, M. (2019): Unravelling the functions of biogenic volatiles in boreal and temperate forest ecosystems. European Journal of Forest Research 138: 763–787.
89. Sokolova, A.S., Yarovaya, O.I., Korchagina, D.V., Zarubaev, V.V., Tretiak, T.S., Anfimov, P.M., Salakhutdinov, N.F. (2014): Camphor-based symmetric diimines as inhibitors of influenza virus reproduction. Bioorganic and Medicinal Chemistry 22(7): 2141–2148.
90. Song, C., Ikei, H., Miyazaki, Y. (2017): Sustained effects of a forest therapy program on the blood pressure of office workers. Urban Forestry and Urban Greening 27: 246–252.
91. Song, C., Ikei, H., Kagawa, T., Miyazaki, Y. (2019): Effects of walking in a forest on young women. International Journal of Environmental Research and Public Health 16(2): 229.
92. Song, C., Ikei, H., Park, B.J., Lee, J., Kagawa, T., Miyazaki, Y. (2018): Psychological benefits of walking through forest areas. International Journal of Environmental Research and Public Health 15(12): 2804.
93. Sukhdev, P., Wittmer, H., Miller, D. (2014): The economics of ecosystems and biodiversity (TEEB): challenges and responses. Nature in the Balance: the Economics of Biodiversity 135-152.
94. Sunjaya, A.F., Sunjaya, A.P. (2018): Protective effects of phytoncides against Cancer. Advanced Science Letters 24(9): 6837–6840.
95. TEEB (2010): The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations. In: Kumar, P. (coordinating lead author: de Groot, R.) Earthscan, London and Washington.
96. Tokin, B.P., Kamiyama, K.A. (1980): Mysterious phytoncide in plants. Kodansha, Tokio, Japan.
97. Tsunetsugu, Y. (2011): Physiological effects of visual, olfactory, auditory, and tactile factors in the forest environment. Forest Medicine 169–181.
98. Tsunetsugu, Y., Park, B.J., Miyazaki, Y. (2010): Trends in research related to "Shinrin-yoku" (taking in the forest atmosphere or forest bathing) in Japan. Environmental Health and Preventive Medicine 15(1): 27–37.
99. Ueda, H., Kikuta, Y., Matsuda, K. (2012): Plant communication: mediated by individual or blended VOCs? Plant Signaling and Behavior 7(2): 222–226.
100. Ulrich, R.S., Simons, R.F., Losito, B.D., Fiorito, E., Miles, M.A., Zelson, M. (1991): Stress recovery during exposure to natural and urban environments. Journal of Environmental Psychology 11(3): 201–230.
101. Vallianou, I., Hadzopoulou-Cladaras, M. (2016): Camphene, a plant derived monoterpene, exerts its hypolipidemic action by affecting SREBP-1 and MTP expression. PLoS One 11(1): e0147117.
102. Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M. (1997): Human domination of Earth's ecosystems. Science 277(5325): 494-499.
103. Vizzarri, M., Lasserre, M., Sallustio, B., Tavone, L. (2014): Natural capital and bioeconomy: challenges and opportunities for forestry. Annals of Silvicultural Research 38(2): 62–73.
104. Wade, T.G., Riitters, K.H., Wickham, J.D., Jones, K.B. (2003): Distribution and causes of global forest fragmentation. Conservation Ecology 7(2): 7.
105. Wang, M. (2018): Characteristics of BVOC Emissions from a Swedish Boreal Forest. Doctoral dissertation, Lund University.
106. Wen, C.C., Kuo, Y.H., Jan, J.T., Liang, P.H., Wang, S.Y., Liu, H.G., Yang, N.S. (2007): Specific plant terpenoids and lignoids possess potent antiviral activities against severe acute respiratory syndrome coronavirus. Journal of Medicinal Chemistry 50(17): 4087–4095.
107. Wolf, K.L., Lam, S.T., McKeen, J.K., Richardson, G.R., Van Den Bosch, M., Bardekjian, A.C. (2020): Urban trees and human health: A scoping review. International Journal of Environmental Research and Public Health 17(12): 4371.
108. Zhang, Z., Ye, B. (2022): Forest therapy in Germany, Japan, and China: Proposal, development status, and future prospects. Forests 13(8): 1289.