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Forest digital twin via big data integration: Current advances and future perspectives

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Table S1. The most relevant publications on forest digital twins from 2021 to 2025

Year	Author	Title	Scope of applications	Country	Journal/conference
2021	Huang et al.	Walking through the forests of the future: using data-driven virtual reality to visualize forests under climate change	visualise forest for the future under climate change	USA	International Journal of Geographical Information Science
2021	Klippel et al.	Embodied digital twins for environmental applications	potential theoretical grounding of embodied digital twins	USA	ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences
2021	Mõttus et al.	A methodology for implementing a digital twin of the Earth's forests to match the requirements of different user groups	forest carbon stocks	Finland	GI_Forum
2021	Nita	Testing forestry digital twinning workflow based on mobile LiDAR scanner and AI platform	forest management	Romania	Forests
2021	Sahal et al.	4.0 towards Forestry 4.0: Fire detection use case	forest fire detection	Ireland	Sensors
2021	Wallgrün et al.	Embodied digital twins of forest environments	the concept of forest digital twins	USA	GIScience 2021 Short Paper Proceedings
2022	Bae et al.	Automatic flight plan creation tool with digital twin for monitoring forest fire on mountain trail through UAV	monitoring forest fire	Korea	1st International Workshop on Intelligent Software Engineering
2022	Buonocore et al.	A proposal for a forest digital twin framework and its perspectives	framework proposal	Italy	Forests
2022	Hejtmánek et al.	Forest digital twin as a relaxation environ-ment: A pilot study	forest bathing	Czech Republic	Frontiers in Virtual Reality
2022	Jang et al.	Forestry digital twin with machine learning in Landsat 7 data	forestry canopy, species and distribution	China	Frontiers in Plant Science
2022	Lv et al.	Editorial: Digital twins of plant and forest	editorial on the research topic	China	Frontiers in Plant Science
2022	Li et al.	Digital twinning of all forest and non-forest trees at national level via deep learning	forest management	Denmark	Research Square
2022	Nie et al.	Artificial intelligence and digital twins in sustainable agriculture and forestry: A survey	a review	China	Turkish Journal of Agriculture and Forestry
2022	Qi et al.	A case study of the relationship between vegetation coverage and urban heat island in a coastal city by applying digital twins	effect of vegetation coverage on the urban thermal environment	China	Frontiers in Plant Science
2022	Sanchez-Guzman et al.	Modeling a simulated forest to get burning times of tree species using a digital twin	forest fires	Ecuador	Proceedings of the IEEE 12th Annual Computing and Communication Workshop and Conference

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Table S1. To be continued

Year	Author	Title	Scope of applications	Country	Journal/conference
2022	Wang et al.	Integrating real tree skeleton reconstruction based on partial Computational Virtual Measurement (CVM) with actual forest scenario rendering: A solid step forward for the realization of the digital twins of trees and forests	tree structure	China	Remote Sensing
2022	Yun et al.	A novel digital twin architecture with similarity-based hybrid modeling for supporting dependable disaster management systems	wildfire scenario	South Korea	Sensors
2022	Yusup et al.	Population structure and spatial distribution pattern of *Populus euphratica* riparian forest under environmental heterogeneity along the Tarim River, Northwest China	forest stand structure and spatial distribution pattern	China	Frontiers in Plant Science
2023	Döllner et al.	Forests in the digital age: Concepts and technologies for designing and deploying forest digital twins	forest ecosystem service	Germany	The 28th International ACM Conference on 3D Web Technology
2023	Iwaszczuk et al.	Potential of mobile mapping to create digital twins of forests	MLS application to forest digital twin	Germany	The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences
2023	Koning et al.	Digital twins: Dynamic model-data fusion for ecology	a review	Netherlands	Trends in Ecology & Evolution
2023	Li et al.	Framework of virtual plantation forest modeling and data analysis for digital twin	forest experimentation and management	China	Forests
2023	Liu et al.	Reconstructing the digital twin of forests from a 3D library: Quantifying trade-offs for radiative transfer modeling	impact of forest subsampling on RT modelling	Belgium	Remote Sensing of Environment
2023	Qiu et al.	Forest digital twin: A new tool for forest management practices based on Spatio-Temporal Data, 3D simulation Engine, and intelligent interactive environment	forest management	China	Computers and Electronics in Agriculture
2023	Silva et al.	Forest digital twin: A digital transformation approach for monitoring greenhouse gas emissions	monitoring greenhouse gas emissions	Brazil	Polytechnica
2023	Sujaswara and Hasegawa	Evaluating the potential of UAV structure-from-motion for generating forest digital twin: Performing DBH estimation and wood-leaf classification	performing DBH estimation and wood-leaf classification	Japan	available at SSRN
2023	Zamari	A proposal for a wildfire digital twin framework through automatic extraction of remotely sensed data: The Italian case study of the Susa Valley	forest wildfire management	Italy	doctoral dissertation

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Year	Author	Title	Scope of applications	Country	Journal/conference
2023	Zhong et al.	Reduced-order digital twin and latent data assimilation for global wildfire prediction	forest wildfire prediction	United Kingdom	Natural Hazards and Earth System Sciences
2024	Afsar et al.	Prototype biodiversity digital twin: forest biodiversity dynamics	forest management	Finland	Research Ideas and Outcomes
2024	Ambarwari et al.	Conceptual model of graph-based individual tree and its utilization in digital twin and metaverse of urban forest	urban forest structure	Indonesia	International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences-ISPRS Archives
2024	Aydin and Oktug	Employing digital twin to forest fire management systems	forest fire management	Turkiye	9th International Conference on Computer Science and Engineering
2024	Chen et al.	Towards the digital twin of urban forest: 3D modeling and parameterization of large-scale urban trees from close-range laser scanning	urban forest structure	China	International Journal of Applied Earth Observation and Geoinformation
2024	Damaševičius and Maskeliūnas	A reinforcement learning-based adaptive digital twin model for forests	forest ecosystems	Lithuania	4th International Conference on Applied Artificial Intelligence
2024	Hoppen et al.	Smart forestry – A Forestry 4.0 approach to intelligent and fully integrated timber harvesting	forest timber harvesting	Germany	International Journal of Forest Engineering
2024	Huang et al.	Modeling of wildfire digital twin: Research progress in detection, simulation, and prediction techniques	forest wildfires	China	Fire
2024	Karolos et al.	Advancing forest biodiversity conservation with the EL-BIOS digital twin: An integration of LiDAR and multispectral earth observation data	forest biodiversity	Greece	Tenth International Conference on Remote Sensing and Geoinformation of the Environment
2024	Li et al.	Research on forest resource supervision technology based on digital twin UAV	forest fire management	China	IEEE 7th Advanced Information Technology, Electronic and Automation Control Conference
2024	Murtiyoso et al.	Virtual forests: A review on emerging questions in the use and application of 3D data in forestry	education and training, communication among stakeholders	Switzerland	International Journal of Forest Engineering
2024	Ozel and Petrovic	Green urban scenarios: A framework for digital twin representation and simulation for urban forests and their impact analysis	framework for urban forest	Netherlands	Arboriculture & Urban Forestry
2024	Padmakumar and Shanthakumar	Artificial intelligence and remote sensing for climate-resilient precision forestry management	forest management	Canada	The 4th International Electronic Conference on Forests

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Year	Author	Title	Scope of applications	Country	Journal/conference
2024	Rammer et al.	The individual-based forest landscape and disturbance model iLand: Overview, progress, and outlook	forest dynamics at the level of individual trees	Germany	Ecological Modelling
2024	Subedi et al.	Exploring the potential application of machine learning techniques in forest management planning	forest planning	Canada	The 4th International Electronic Conference on Forests
2024	Tagarakis et al.	Digital twins in agriculture and forestry: A review	a review	Greece	Sensors
2024	Wang et al.	RFWNet: A multi-scale remote sensing forest wildfire detection network with digital twinning, adaptive spatial aggregation, and dynamic sparse features	forest wildfire models	China	IEEE Transactions on Geoscience and Remote Sensing
2024	Zohdi	A machine-learning enabled digital-twin framework for next generation precision agriculture and forestry	framework for digital twin	USA	Computer Methods in Applied Mechanics and Engineering
2025	Li et al.	Review and perspectives of digital twin systems for wildland fire management	wildland fire management	China	Journal of Forestry Research
2025	Wang et al.	Climatesmart forestry: An AIenabled sustainable forest management solution for climate change adaptation and mitigation	forest under climate change adaptation and mitigation	USA	Journal of Forestry Research
2025	Dao et al.	A semantic digital twin-driven framework for multi-source data integration in forest fire prediction and response	a semantic digital twin-driven framework	China	Forests
2025	Sasaki and Abe	A digital twin architecture for forest restoration: integrating AI, IoT, and Blockchain for smart ecosystem management	a digital twin architecture	Thailand	Future Internet
2025	Jo et al.	Construction of tree-based forest management digital twin database with airborne laser surveying	forest management	South Korea	Sensors & Materials
2025	Tam et al.	Toward a digital twin to improve the training and performance of forestry operators	review about forestry operators	Belgium	International Journal of Forest Engineering
2025	Li et al.	Forest fire analysis prediction and digital twin verification: A trinity framework and application	forest fire prediction	China	Forests
2025	Väätäinen et al.	Toward a digital twin of forest roads – Road weather stations for monitoring road condition and trafficability in Eastern Finland	a digital twin of forest roads	Finland	International Journal of Forest Engineering

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Year	Author	Title	Scope of applications	Country	Journal/conference
2025	Das	High-resolution remote sensing and ecosystem modelling for climate-resilient forests: A review of digital-twin approaches	a review article	Bangladesh	SSRN
2025	Ortu et al.	Digital twin for real-time forest fire monitoring and response	forest fire detection	Italy	Seventh International Conference on Information Technology and Computer Communications
2025	Fan et al.	A digital twin approach to forest fire re-ignition: Mechanisms, prediction, and suppression visualization	forest fire re-ignition	China	Forests

DBH – diameter at breast height; MLS – mobile laser scanning; RT – radiative transfer

Scope of applications means the main idea of the forest digital twin from their publication; country only denotes the first affiliation of the first author