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Artificial intelligence, blockchain, and extended reality: emerging digital technologies to turn the tide on illegal logging and illegal wood trade

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ABSTRACT Illegal logging which often results in forest degradation and sometimes in deforestation remains ubiquitous in many places around the globe. Managing illegal logging and illegal wood trade constitutes a global priority over the next few decades. Scientific, technological, and research communities are committed to respond rapidly, evaluating the opportunities to capitalize on emerging digital technologies for treating this formidable challenge. The innovative potentials of these emerging digital technologies at tackling illegal logging-related challenges are here investigated. We propose a novel system, WoodchAInX, combining explainable artificial intelligence (X-AI), next-generation blockchain, and extended reality (XR). Our findings on the most effective means of leveraging each technology's potential and the convergence of the three technologies infer a vast promise for digital technology in this field. Yet, we argue that, overall, digital transformations will not deliver fundamental, responsible and sustainable benefits without revolutionary realignment.

KEYWORDS: Next-generation blockchain, digital twins, explainable artificial intelligence, extended reality, illegal wood trade.

Illegal logging: a problem of a global scale

In recent years, talk on the benefits of forests and woods to humans has grown more fashionable. This context, however, is not something new as forests and woodlands are essential to human existence on Earth and wood runs like a vein throughout human history. The earliest evidence for woodworking comes from residues of a 1.5-million-year-old acacia wood clinging to stone hand axes, most likely used to carve spears (Glausiusz 2020).

Today, wood has become even more highly valued and used for fine and intelligent furniture, technological paper, textiles, biofuels, bioplastics, high-value chemicals and materials, and other everyday innovative products thanks to its special structure and ultrastructure, attractive aesthetics, and its sense of naturalness and warmth (Harfouche et al. 2022). While the impact of wood consumption on forests has been benign for much of the human history, today's increasing global demand for wood and wood products calls for urgent action to establish sustainable wood production and consumption patterns. However, efforts towards achieving this goal will have to resolve the inherent illegalities.

Illegal logging involves illegal practices related to tree felling, processing, transporting, and buying or selling of wood and wood products, in contravention of national and international laws. It takes place in many forms, from logging in prohibited areas or logging without permits in conflict zones and remote or border areas and extends to breaking the law at any point along the wood supply chain (e.g., mixing legal with illegal wood and wood products). Illegal logging is mainly driven by the increasing demand for wood and wood products, but several other causes have been identified, including forest conversion, which involves the clearing of natural forests for other land uses, mainly agriculture and urbanization. In addition, poverty and lack of access to high-quality, affordable health care can further incentivize poor families to rely on illegal logging to raise cash to meet critical health care needs (Jones et al. 2020). Its illegal and therefore clandestine nature prohibits exact assessment of the amounts of illegally logged wood. However, according to a 2021 Interpol report on forestry crime, illegally logged wood accounts for 15-30% of the global wood trade, valued at 51-152 billion USD annually (Interpol 2021). The consequences of these forestry crimes are recognized ecologically, economically and socially. Ecologically, illegal logging is a major factor in forest degradation and, sometimes, even in deforestation in the geographies where it is prevalent, threatening entire ecosystems and contributing to climate change (Grant and Chen 2021). Economically, the global wood industry is influenced by depressing international wood prices, thereby reducing the financial viability of legally managed forestry (Grant and Chen 2021). Social impact is the most serious though, since illegal logging threatens the livelihoods (e.g., consumption of wild foods in regions where affordable alternatives are scarce) of more than a billion forest-dependent people (World Wildlife Fund 2011). In addition, without forests as buffer, logging exposes people to animals, leading to closer contact between humans and wildlife which can result in outbreaks of zoonotic diseases (Bang and Khadakkar 2020).

Ending illegal logging and illegal deforestation offers a solution for safeguarding forests for the sake of humans, their health, their societies and the environment. International efforts to rout out illegal logging consist primarily of laws designed to discourage the illegal harvest of wood or trade in wood coming from illegal sources (Dormontt et al.

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2015). Logging and trade restrictions are imposed primarily through the convention on international trade in endangered species of wild fauna and flora (CITES), which lists species in one of three appendices depending on the degree of protection required (Dormontt et al. 2015). In Europe, Timber Regulation (Regulation EU no. 995/2010 of the European Parliament) counters the trade in illegally harvested timber and timber products through three key obligations: *(i)* it prohibits, for the first time, the placing of illegally harvested timber and products derived from such timber on the EU market; *(ii)* it requires EU traders who place timber products on the EU market for the first time to exercise 'due diligence'; *(iii)* it facilitates the traceability of timber and timber products by obliging economic operators of the supply chain to keep records of their suppliers and customers because, once on the market, the timer and timber products may be sold and/or transformed before they reach the final consumer.

Although this is a step in the right direction, currently, wood regulatory compliance throughout the supply chain is determined primarily through paper-based systems involving documentation typically including declarations of activity, such as forest inventories and felling forms, log production reports, transport documents, sales reports, and different tally and balance sheets designed to capture the flow of wood in and out of various points in the supply chain (Lowe et al. 2016). At different checkpoints throughout the supply chain, wood and wood products are verified through the examination of the aforementioned documentation and through physical inspections. These documents, however, can be inappropriately associated with illegally logged wood or might be forged (Lowe et al. 2016), making it difficult to distinguish between genuine and fake documents, and thus, leaving room for fraudulent activities. Capitalizing on emerging digital technologies, relevant key stakeholders of the wood supply chain might be able to address these problems. For example, the use of artificial intelligence (AI) for wood identification has been proposed as a solution to enforce regulations and verify wood regulatory compliance along the supply chain (Shugar et al. 2021). Blockchain has been suggested as a technology for the procurement of trustworthy timber (Munoz et al. 2021, Komdeur and Ingenbleek 2021, Vilkov and Tian 2019). Extended reality (XR) has also been put forward to help people visualize and realize how illegal logging and rampant deforestation threaten the very existence of forests (TIME USA 2019). Whilst the first generation of these technologies have provided means to thwart illegal logging and illegal wood trade, they share a number of limitations that inhibit their widespread application, including, but not limited to, the black box nature of AI and the lack of models' transparency which can lead to untrustworthy and biased predictions (Harfouche et al. 2022, 2019), and the inefficiency of processing transactions on blockchain (Gervais et al. 2016) which might limit its scalability. Besides, the proposed solutions are not without shortcomings. Corruption in forestry administrations and custom services can lead to the alteration and forging of the AI-based wood identification results. Additionally, illegal loggers or illegal traders might be able to register falsified information into the blockchain since those systems rely on manual data entry. Finally, without the ability to trace the origin of wood and wood products, XR will not be able to help consumers make informed purchasing decisions, even if they understand and acknowledge the serious impact of illegal logging. Plus, XR has not been used to its full potential. It can be leveraged for training, capacity building, and raising awareness to strengthen legal logging and benefit the local population.

In this paper, we aim to address these gaps by proposing a global-scale system, 'WoodchAInX', that combines three cutting-edge digital technologies, explainable AI (X-AI), next-generation blockchain, and XR to keep track of where and how wood is produced and traded, and to help all stakeholders of the wood supply chain, including consumers, answer questions such as how sustainable is the furniture in their homes, the paper, fabric, and bioplastic they use, the wood and biofuel they burn, or the timber that goes into their building structures. Combining the proposed digital technologies to answer these questions will promote sustainability and responsibility, and drive all stakeholders to make informed purchasing choices to ultimately put an end to illegal logging and illegal wood trade, safeguarding global climate commitments, advancing sustainable development goal (SDG) targets (Fig. 1), Ecohealth (i.e., a field of research, education and practice that adopts systems approaches to promote the health of people, animals, and ecosystems in the context of social and ecological interactions; Parkes et al. 2014), planetary health (i.e., a solutions-oriented, transdisciplinary field and social movement focused on analyzing and addressing the impacts of human disruptions to Earth's natural systems on human health and all life on Earth; Planetary Health Alliance 2022), and One health (i.e., an interdisciplinary approach stressing connections between human, animal and environmental health; Gibbs 2014, Rabinowitz et al. 2018) efforts, and radically improving the way the world's forest resources are governed.

Figure 1 - Workflows from data collection to outcomes of each of the three emerging digital technologies covered in this paper.

Emerging digital technologies for advancing research and innovation in the fight against illegal logging and illegal wood trade

Explainable artificial intelligence (X-AI): a new weapon

One of the most challenging issues in combating illegal logging and illegal wood trade is the identification of wood specimens found in trade, which is imperative to assess illegally logged and transported wood. The current state-of-the-art for wood identification in the field relies on experienced practitioners using hand lenses, specialized identification keys, atlases of woods, and field manuals (Ravindran et al. 2018). However, accumulating such expertise is time-consuming and access to training is relatively rare compared to the international demand for field wood identification (Ravindran et al. 2018). AI has been making great strides in image classification and might be able to answer this demand. AI has been defined as the science of studying, designing, and developing intelligent computer systems that can perform tasks that normally require human intelligence (Harfouche et al. 2022). The machine learning (ML) approach to AI, in which intelligent systems learn and derive models from training datasets, and its specialized branch, deep learning (DL) that leverages neural networks to spot patterns in complex data (Harfouche et al. 2022) have shown promising results in wood identification. For example, ML algorithms such as naive Bayes and random forest (RF) were used to discriminate endangered wood species listed in CITES from their look-alikes (Liu et al. 2022); convolutional neural network (CNN) DL algorithm was used to classify 12 Greek wood species, including three softwood and nine hardwood species (Kırbaş and Çifci 2022), six Korean softwood species (Kwon et al. 2019), and 10 neotropical tree species from the well-known and commercially important large family of Meliaceae hardwood (Ravindran et al. 2018). The DL algorithm, mask region-based CNN (Mask R-CNN) was employed to analyze the intrinsic variability of wood anatomical features in conifers, alder, beech, and oak (Resente et al. 2021). While these examples rely on red–green–blue (RGB) imaging data on the macroscopic or microscopic level, AI can analyze data coming from different sensors, imaging techniques, and spectrometers, including X-ray fluorescence (XRF) spectrometry, which could become a vital tool to halt illegally traded wood. XRF is a rapid elemental identifier that has been employed extensively in various fields for the characterization of materials (Shugar et al. 2021). Yet, the real value of XRF spectrometers is that they are relatively cheap, have a small footprint, are portable and handheld, and are rapid and easy to use (Shugar et al. 2021). As an example of AI applications, a CNN was trained using data from XRF spectrometry to identify 48 different wood species (Shugar et al. 2021). It is important to note that AI is also capable of performing simultaneous analysis of data generated by different sensors, imaging techniques, and spectrometers of the same tree (Harfouche et al. 2022), fusing multiple data sources together to further improve its prediction, and thus, wood identification.

Beside wood identification, AI can also be helpful in various tasks related to wood such as counting the number of logs in a truck and calculating their diameter (Rahman et al. 2011), which, if done manually, can take a substantial amount of time. This technology has the potential to be applied in storage facilities such as wood shelters, or in any means of log transportation in the supply chain, including trains, boats, and airplanes. Once an image of the logs is taken, using, for example, a smartphone's camera, it gets uploaded to a remote server where AI can analyze it and, as a result, the log count, the diameter of each log and their volume become instantly available. Results can then be easily shared with other stakeholders at different steps in the supply chain to make sure that no illegal logs are being introduced. More importantly, AI can greatly assist in adequate and continuous forest monitoring, which can be an effective strategy to curb illegal logging that produces significant canopy gaps that can be easily detected with remote and proximal sensing. For example, with the support of satellite technologies that allow for increasingly detailed and continuous surveillance of forest canopies, the CubeSat constellations that work in unison to collect data at the centimeter-scale multiple times per day, and the enormous troves of data that can be gathered through the deployment of drones, AI could soon map the location and canopy size of every tree on Earth. For example, a CNN can be employed to analyze big multispectral satellite imagery data, at a spatial resolution of 0.5 m. As a result, more than 1.8 billion trees over a large area in West Africa were identified and mapped with detailed information on the location and size of every individual canopy (Brandt et al. 2020). This revolution in observational capabilities will undoubtedly drive fundamental changes in how we think about, monitor, model, and manage global terrestrial ecosystems (Hanan and Anchang 2020); it holds great promise for combating illegal logging.

Despite their successes, complex AI models operate as black boxes and require a leap of faith to believe their predictions (Harfouche et al. 2019). To address this issue, researchers have introduced X-AI by developing new approaches and techniques to make these models explainable, allowing humans to observe how predictions of an AI model came to be (Harfouche et al. 2022, 2019). X-AI have typically been divided into two dichotomies: explanations produced by *post hoc* models and those by interpretable by design models (Harfouche et al. 2022). *Post hoc* algorithms are not connected to the internal design of black box models. Instead, they are employed after black box models are trained and seek to understand the predictions by perturbing the input data and identifying which perturbations were most likely to change the predictions (Harfouche et al. 2022). In contrast, interpretable by design algorithms do not need an additional (*post hoc*) algorithm to be explainable; they provide their own explanations, which are faithful to what the model actually computes (Rudin 2019). Being explainable, X-AI will increase technical confidence and generate trust in its models. It will also help guide its users to make better, informed, and responsible decisions (Harfouche et al. 2022, 2019, Streich et al. 2020).

The large amount of training data (reference libraries) needed for training X-AI models (Fig. 1) can become a major bottleneck in the fight against illegal logging and illegal wood trade. With a limited number of prelabeled training examples, models can perform poorly and might generate biased predictions. While publicly available reference datasets are becoming more abundant for tree species at risk of illegal logging, accelerating data collection and expanding species coverage could be done through 'forest and wood citizen science', by developing applications (apps) for local experts and citizens to upload training images of species, taken from different angles. But the identification of undescribed species will remain a challenge since their presence will be rare in training datasets. Luckily, various strategies can be applied to help X-AI models learn from small datasets. For example, X-AI algorithms can train models with lower complexity to avoid overfitting, transfer knowledge from models previously trained on related tasks using transfer learning, train and accumulate knowledge from multiple small datasets using cumulative learning, or use the cosine loss function to train models (Harfouche et al. 2022). Alternatively, small datasets can be augmented by producing new, meaningful, sufficient, and realistic data in a process called oversampling which can be achieved by generating new synthetic data, or by performing geometric transformations on existing imaging data (Harfouche et al. 2022). Notably, virtual reality (VR) simulations can enable endless streams of accurate synthetic data to increase diversity in datasets and to increase the robustness of X-AI models (Nakhle and Harfouche 2022).

While remote and proximal sensing data, in addition to data generated from various sensors, cameras, and handheld instruments, analyzed with X-AI can soon create a global georeferenced database of trees and help to rapidly identify wood being logged and traded, sometimes, additional testing could be needed to verify their regulatory compliance. DNA profiling of unprocessed and processed wood materials, with the aid of X-AI, has received significant attention as an ideal tool to identify wood species and to trace the geographic origin of wood and timber products. By reading the tree DNA sequence at particular parts of the genome, individuals can be assigned to a particular group (i.e., species, genotypes) on the basis of similarities and differences in their DNA compared with reference data (Lowe et al. 2016). Thus, for successful wood identification, it is paramount that robust DNA reference databases are built before the tool can be made useful. Here too, citizen science can be of great help to build such databases where, using the same app to collect X-AI training data, users can be asked to collect and label a leaf from every tree they add to the database. DNA of the trees can then be extracted from the collected leaves and added to a database. For example, a project conducted by world resources institute and funded by both the Norwegian government and the US forest service is aiming to catalog the DNA of bigleaf maple trees on the west coast, from southern California to British Columbia (Mason and Parker-Forney 2018). To collect samples, the project has teamed with adventure scientists to train citizen science volunteers to pluck leaves from trees while also recording data about their locations and sizes. The resulting DNA could then be used to identify maple wood, pointing to the geographic location it came from, and whether it was logged from a protected region.

Next-generation blockchain: a policeman on the block

Blockchain, the technology that underpins cryptocurrencies, offers a new paradigm for storing, validating, and transferring information, bringing transparency and traceability into the wood industry to police illegal logging. This powerful technology makes it possible to create a decentralized, immutable, and tamper-proof digital ledger, or an append-only database, that allows its users to obtain continuously updated local copies of data and to be involved in how each record is integrated into it. In other words, blockchain provides a permanent, publicly held record of information and transactions that nobody owns or can edit, yet anybody can view or add to (Sipthorpe et al. 2022).

Blockchain made its public debut in 2008 when Satoshi Nakamoto, who was revealed to be a pseudonym, introduced the world to the first-generation blockchain, i.e., 'blockchain 1.0', which led to the rise of the first working cryptocurrency, bitcoin (Nakamoto 2008). Unknown to many, the origin of blockchain can be traced back to 1991, when Stuart Haber and Wakefield Scott Stornetta proposed computationally practical procedures that use a cryptographically secured chain of data blocks to store time-stamped digital documents in a way that they could not be tampered with (Haber and Stornetta 1991).

The main idea behind blockchain is to offer a decentralized ecosystem in which users come to agreement on shared information, without the need for centralized verification or a third-party authority. And since data within the blockchain are time-stamped and added sequentially, their traceability is guaranteed. But to outgrow the functionality of blockchain 1.0 which was limited to cryptocurrency, 'blockchain 2.0' made it possible to execute autonomous computer programs, known as smart contracts, when pre-defined conditions are met. While blockchain 2.0 allowed for programmable transactions, it created the need for less resource-heavy blockchains, which the third generation of blockchains tried to fill up. 'Blockchain 3.0' made blockchain more scalable and enabled the development of decentralized apps (DApps), which give smart contracts a frontend user interface to run user-friendly applications. The new generation of blockchain, known as 'blockchain 4.0', aims to deliver a business-usable environment via DApps and to enable all industrial peer-to-peer business models to be mainstream without extensive blockchain developer skills (Loy et al. 2022). This makes blockchain 4.0 a promising technological innovation for tracking the origin of wood products and clamping down on illegal logging and illegal wood trade. When applied to the wood supply chain, blockchain can establish trust among all stakeholders by providing an open record of transactions that anyone can query to validate the legitimacy of the wood and the wood products, and the legality of their sources. Blockchain has been suggested as a solution to track and certify wood volumes (Munoz et al. 2021), to stop illegal wood trade between Russia and China (Vilkov and Tian 2019), and to ease the complex job of wood procurement officers in companies that seek to purchase wood products from trustworthy origins (Komdeur and Ingenbleek 2021).

However, several challenges currently hinder the widespread application of blockchain in combating illegal logging and illegal wood trade. A major challenge is that all proposed systems are based on trust. Here, different stakeholders might falsify information, starting from the initial data inserted into the blockchain. This difficulty may be reduced by leveraging sensors, cameras, and spectral signatures, in addition to remote sensing and GPS data, as well as X-AI to inform decisions made by stakeholders and to justify the information they provide. Another formidable challenge is the lack of scalability of blockchain technology, where it can take many minutes for large-scale DApps to process a single transaction. The next-generation blockchain aims to address this problem by creating a completely new architecture that uses drastically smaller block sizes for building chains, making it possible for large-scale DApps to process transactions in few seconds.

The next generation blockchain should improve upon existing ones through enhancements in efficiency, efficacy, stability, performance and security. Requiring minimal computing resources, next-generation blockchain should be able to run, not only on computers with powerful central processing units (CPUs) and graphics processing units (GPUs), but also on standard computers as well as on smartphones and single-board computers (e.g., a Raspberry Pi), expanding the blockchain and giving everyone the chance to join it. In addition, since X-AI is being designed to analyze data on quantum computers (Harfouche et al. 2022), next-generation blockchain should also implement quantum computing algorithms in order for those to be able to join the distributed networks. Leveraging quantum bits, quantum computers will offer the advantage of exponentially faster transaction validation and blocks searching. Interestingly, researchers can simulate quantum circuits on classical computers using free and open-source software development kits such as Cirq or Qiskit, and the cu*Quantum* software library, to leverage the power of GPUs and parallel computing to perform faster calculations (Harfouche et al. 2022).

Extended reality (XR) and digital twins are coming of age

XR has come a long way since the first head-mounted display was built in the 1960s (Harfouche and Nakhle 2020) to encompass an ever-expanding vision of what it can accomplish in the fight against illegal logging. XR is a combination of interactive and immersive technologies that add to or change our experience of reality, including *(i)* VR, the technology that immerses users into interactive virtual environments based on 3D representation and simulation of the real world; *(ii)* augmented reality (AR), the technology that superimposes valuable visual content and information over a live view of the real world to provide users with an enriched version of reality; *(iii)* mixed reality (MR), the technology that intertwines virtual with real environments by overlaying and anchoring digital content to the real world, and by allowing users to interact with both real and digital objects in real-time (Nakhle and Harfouche 2022). XR technologies make it possible to bring forests, wood, sawmills, and woodworking workshops to the classrooms to teach, train, and build capacity in wood science and technology and help learners, trainees, and the next generation of woodworkers and wood professionals to: *(i)* explore the wood processing journey and the end uses of these renewable forest products in fine and intelligent furniture, technological paper, textiles, biofuels, bioplastics, high-value chemicals and materials, and other everyday innovative products; *(ii)* acquire practical skills and knowhow in a realistic, bias-free, and safe environment where they can interact with trainers and simulated woodworking equipment instead of real ones, where a single mistake can be life-altering or deadly; *(iii)* foster a sense of purpose and empowerment to maximize their potential. As an example, the Australian forest education alliance developed a VR app, called ForestVR, that showcases various forest environments and processing mills to help teachers provide learners with virtual excursions, delivering a unique immersive learning experience of places and sites that are not always available for access otherwise (Forest Learning 2021). Another app, world wildlife fund forest brand-named 'WWF Forests', leverages AR to bring the experience of exploring a forest into the home of its users, and enables them to visualize information about forest sustainability (World Wildlife Fund 2020). Such immersive environments can be leveraged to simulate deforestation, biodiversity loss, and climate change, highlighting their negative effects on human lives, and raising awareness about the impact of illegal logging on the planet. Furthermore, the immersive 3D data visualization capabilities of XR can be leveraged to augment the human understanding of wood anatomy. For example, a VR system was designed and implemented to assist learners visualize X-ray computed tomography scans of wood in an immersive 3D environment to help them understand their complex anatomy (Feng et al. 2020). The same technology can be used to visualize and study some of the anatomical features that are essential for the identification of wood, which could serve as a potent tool to stop illegal logging. Moreover, the simulation of wood anatomy in VR could also be useful to generate synthetic datasets to train X-AI models to identify wood (Nakhle and Harfouche 2022).

XR is also a powerful tool for immersive team communication which can be a cornerstone of success for collaborative decision making (Nakhle and Harfouche 2022), especially in supply chains. For example, using the holoportation immersive holographic communication technology that captures 3D models of people and objects, and transmits them anywhere in real-time, MR allows users to interact with each other remotely, as if they were physically present in the same location (Orts-Escolano et al. 2016). This can be extremely useful in curbing illegal logging, specifically when identifying wood, where procurement officers can get remote assistance from data scientists and wood identification experts to validate predictions made by X-AI (Fig. 2).

Of equal importance, XR has the capacity to help to crack down on illegal logging through the digital twins technological innovation, which can be defined as a computational model that evolves over time to represent the structure and behavior of a corresponding physical asset (Nature computational science editorial 2022) and a real-time, virtual replica of biological entities. Unlike virtual environments and simulations, and moving beyond the off-line and static data basis, digital twins are driven by data collected from cameras and sensors in near-real-time, and thus, they mirror almost every facet of physical or biological objects (Tao and Qi 2019), such as forests, allowing an increasingly comprehensive modeling and prediction of the development of forests, and a better understanding of forest disturbances (e.g., logging). In addition, digital twins can, for example, record the complete history of a tree in the forest to serve as a digital memory that can be used to reconstruct its past or trace its origin, even if the physical tree no longer exists in real life. Digital twins could also be used to calculate the economic value of forests and to evaluate the impacts associated with wood harvesting and transportation. In this regard, a Finnish company has developed a 'digital forest twin' in VR to optimize forest-based supply chains, to spot and prevent potential forest damage, to steer trade in wood, and to plan and model functions related to wood, purchasing, harvesting and transportation (Spets 2022). Another digital twin of a forest in Gansu Province, China, was created using historical satellite remote sensing data, and AI was leveraged to predict what would the forest look like in the future (Jiang et al. 2022).

X-AI and next-generation blockchain will come into play to create digital twins in XR environments. Provided sufficient sensor coverage, data availability and computational power, digital twins enable easy access to immersive 3D digital maps of farms, entire forests and plantations, bringing unlimited opportunities, from phenotypic features to forest resource inventory measurement capabilities, including, but not limited to, automated measurement of wood quantity, such as forest biomass and felled or fallen wood, which makes digital twins and XR, powered by X-AI and blockchain, an effective tool for detecting and tracking illegal logging and illegal wood trade.

WoodchAInX to turn the tide on illegal logging at a global scale

Complex international wood supply chains make it extremely difficult for individuals, businesses, and governments to validate whether purchased wood has been sourced from legal or illegal wood harvest. We propose a tripartite system named hereafter the WoodchAInX which combines next-generation blockchain, X-AI, and XR to prevent illegal logging and illegal wood trade (Fig. 2). WoodchAInX aims to promote security, traceability, transparency, swiftness, and accountability along the wood supply chain, and to ensure regulatory compliance. It combines all of a wood or a wood product's data from every single source in the supply chain – farms, forests, plantations, sawmills, export and import points, woodworking workshops, paper and pulp factories, pellet factories, biorefineries, and retailers – under one secure digital system. The system allows all stakeholders along the supply chain to get predictive insights about the sources of wood and wood products, and about the risk of those being illegally logged or traded. It imparts digital identities to each of the supply chain stakeholders and represents wood and wood products as digital assets on the blockchain. All relevant stakeholders use their digital identities to record information on wood (e.g., date, time, and location of logging, wood species, logs length, diameter, and count, etc.) at each step of the supply chain. This enables individuals, businesses, and governments to check which stakeholder validated the legality of wood or wood products at each step, allowing them to trace the journey of the wood they have bought and see if it comes from a legal source. The digital system also traces changes in wood volume along the supply chain to ensure that no additional wood is being included from unknown sources.

The WoodchAInX requires every decision on whether to fell a tree to be based on X-AI analysis, where results are immutably secured on the blockchain. This minimizes the risk of arbitrary and baseless felling decisions. Thus, the first step takes place at the time of logging, where a tree would be scanned by an AR app installed on a smartphone or a tablet device (Fig. 2). Using the camera on the device, or an XRF spectrometer, the AR app, leveraging X-AI, identifies the species of the tree. The app then uses the GPS sensor on the device to capture the coordinates of the tree and registers all acquired information on the blockchain. Next, through remote and proximal sensing data, and through further X-AI analysis, the digital system geolocates the tree and automatically checks against a database of prohibited logging areas to finally confirm if the tree can be logged. Once logged, individual trees are uniquely marked according to their taxon and place of logging using an intelligent tag such as quick response (QR) code, radio-frequency identification (RFID), or stardust, a cheaper alternative dust-like material that can be sprayed onto wood and detected with a handheld device (Nogueron et al. 2016).

When logs are then transported to log yards and cut in sawmills (Fig. 2), at any of these two steps, illegal wood might be added to otherwise legal consignments. This illegal augmentation of wood loads can be identified by the routine verification with the proposed AR app which involves scanning the intelligent tag on the wood, geolocating the site of logging, and extracting features such as wood species, wood volume, logs count, logs diameter, and logs length. Here, additional testing through DNA profiling could prove useful to ensure correct wood identification and to pinpoint its true geographic origin. The app then queries the blockchain to match these features with previous records, and thus, detects any wood that might have been added illegally, pinpointing the location of potential illegal loggers.

After cutting, wood is most often processed. This step represents an important point for verification, as information on the origin of processed wood can be easily lost or obscured. Depending on the type of processing, new intelligent tags are generated and attached to the processed wood, linking those to the wood from which they were processed (Fig. 2). The processed wood is then revalidated with the AR app to ensure that no illegally processed wood has made its way into the supply chain.

Afterwards, the point of export presents another opportunity for the effective verification routine because, at this step, illegal wood can be smuggled across borders and then used to augment legal shipments bound for export (Fig. 2). By verifying the geographic origin and volume of wood at this point, illegally added wood can be detected. Next, the point of import provides another robust verification point where customs authorities often deal with shipments originating from multiple supplying sources. This makes it challenging to link wood and wood products back to an individual tree. Here, forest tree species identification and geographic origin verification of wood, as well as matching the results with the information provided by the blockchain, will be important for determining the regulatory compliance and legality of a shipment.

Woodworking workshops, paper and pulp factories, pellet factories, and biorefineries are also able to verify whether their wood sources are legal by querying the blockchain. Then, after transforming processed wood into end-products, including, among others, wood for construction, furniture, technological paper, textiles, biofuels, bioplastics, and high-value chemicals and materials, following the same process, WoodchAInX generates new intelligent tags for the final products to be tagged with (Fig. 2). The new tags carry on all previous information about the journey of the wood used for production.

Finally, at the point of sale in wood retailers, the same verification technology allows traders and consumers to ensure that end-products come from legally logged wood and helps them to make informed purchasing decisions (Fig. 2).

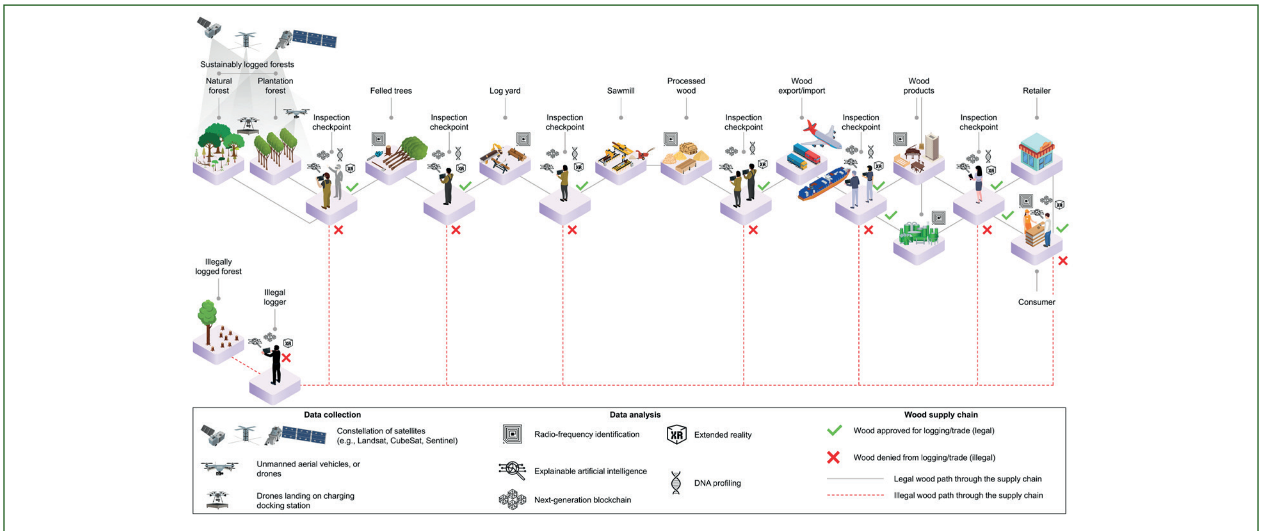
How WoodchAInX gains an edge with human-AI collaboration

WoodchAInX relies heavily on X-AI-based data analysis. But, despite the predictive successes of X-AI, its predictions are not perfect, and there has not been a single model that is able to reach 100% accuracy in real-world scenarios. Thus, the proposed WoodchAInX system should not make unsupervised decisions relying on X-AI predictions. Instead, it should leverage a human-centric X-AI architecture such as that proposed by Harfouche et al. which promises to embed human knowledge into its architecture and to combine it with connections and correlations automatically discovered in big data (Harfouche et al. 2022). Such architecture will enable the monitoring of inputs and outputs of the algorithms, provide more human-comprehensible explanations for their decisions, deliver superior performance, mitigate bias, and aid in verifying the adherence of models to ethical and sociolegal values (Harfouche et al. 2022). In addition, human-centric X-AI will keep a human-in-the-loop for harmonious human and AI system symbiosis and will enable bidirectional interaction such that human intelligence and AI are brought together to collectively achieve superior results and continuously improve by learning from each other (Harfouche et al. 2022). This gives WoodchAInX the potential to reveal illicit activities that are otherwise easily disguised, bringing a new level of transparency and accountability to the international wood trade to crack down on illegal logging (Fig. 1).

High-performance computing and digital inclusion powering WoodchAInX

The expansive WoodchAInX workloads required by X-AI to analyze wood big data and by XR for modeling and simulating virtual environments, as well as the digital forest twins and wood twins, will need more and more computing power. As workloads evolve rapidly, the hardware infrastructure supporting WoodchAInX becomes critical. To meet this need, exascale supercomputers can

Figure 2 - WoodchAInX applied to the wood supply chain to crack down on illegal logging.



perform a billion billion (1018) floating point operations per second (FLOPS) and deliver reliable performance by supporting a mix of CPUs and GPUs in a parallel and heterogeneous computing setting (Harfouche et al. 2022). As an example, exascale computing proved helpful to plant scientists and computational biologists to achieve breakthroughs in designing multi-criteria crop ideotypes, mapping global climatypes, revealing the underlying biologically relevant interactions, and, consequently, accelerating food and energy plant breeding programs (Streich et al. 2020). Fusing X-AI, blockchain, and XR together with exascale computing is key to assist WoodchAInX in prohibiting illegal logging and illegal wood trade along the wood supply chain.

The advent of high-performance computing has thrown a spotlight on the digital divide, where the benefits of supercomputers are still far from being equitably distributed. The ability to access supercomputers through high-speed internet networks is becoming increasingly important to join the fight against illegal logging, and is needed not just in rich countries, but all over the world. However, not everyone has access to this hardware infrastructure. This might hamper the fight against illegal logging until availability and accessibility issues are addressed by effective ethical approaches (Harfouche et al. 2021). It is time to tighten and bridge this growing gap between low-income and high-income countries that have access to advanced digital technologies. To bridge the digital divide, measures must be taken to ensure access to supercomputers and high-speed internet connectivity for all. However, providing access to these infrastructures and services is unlikely to solve the problem, as inequality in digital skills and expertise are additional sources of the digital gap. WoodchAInX potential or interested users must be trained alongside new digital technologies, including X-AI, blockchain, and XR, to promote the best usage of this system in the fight against illegal logging. Digital inclusion and digital literacy are thus promising opportunities to close the digital divide gap and halt illegal logging.

Concluding remarks and future perspectives

Illegal logging is frustrating the world's plans to save biodiversity, mitigate climate change, improve the livelihoods of indigenous and local people living in forests, eliminate losses of tax revenue for a country's economy and strengthen the legitimacy of the forest sector. Researchers are increasingly concerned that the world is running behind schedule to combat illegal logging, meet ambitious targets to protect biodiversity, and ensure planetary health and human well-being.

WoodchAInX, combining X-AI, next-generation blockchain, XR and digital twins, has been advocated for turning the tide on illegal logging. Guiding stakeholders to make better, informed, and responsible decisions will bring us closer towards addressing sustainability challenges that should include, amongst others, the monitoring of illegal logging and illegal wood trade, the achievement of the ambitious SDGs and targets of the 2030 global sustainability agenda of the United Nations, and the advancement of Ecohealth, planetary health, and One health efforts.

Despite the increasing potency and transformative potential of digital technology, X-AI, next-generation blockchain, XR and digital twins have so far received insufficient attention in discussions on sustainable development. Their exploitation should be evidence-based (Corona 2018). The influence of these cutting edge technologies in basic and applied forest and wood science research is very likely to grow as sensor-based, high resolution, real-time dynamic data and new smart tools become available, but users will not commit themselves unless we can get sufficient resources, scientific investments, skilled labor and refined digital technology infrastructures that allow enhanced data processing, analysis and interpretation.

We anticipate that leaps in X-AI and ML techniques, amongst other complementary technologies including exascale computing, will play a fundamental role in realizing the benefits of digital forest twins and 'digital wood twins' across the full gamut of the SDGs.

If we are to realize the potential of these digital technologies to help turn the tide on illegal logging, critical social and ethical challenges and rich–poor digital divides must first be addressed to ensure they are implemented responsibly and to support better planning decisions not only in high-income nations, but also in low-income nations, where illegal logging and illegal wood trade occur most frequently, leaving no-one behind. This must be done not just efficiently but also fairly, equitably, and sustainably. Thinking of or researching impactful digital technology affirms our commitment to innovation, sustainability, responsibility, and transparent wood supply chains.

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References

Bang A., Khadakkar S. 2020 - *Biodiversity conservation during a global crisis: consequences and the way forward.* In: Proceedings of the National Academy of Sciences 117 (48): 29995–29999. doi:10.1073/pnas.2021460117

Brandt M., Tucker C. J., Kariryaa A., Rasmussen K., Abel C., Small J., Chave J., Rasmussen L. V., Hiernaux P., Diouf A. A., Kergoat L., Mertz O., Igel C., Gieseke F., Schöning J., Li S., Melocik K., Meyer J., Sinno S. et al. 2020 - *An unexpectedly large count of trees in the West African Sahara and Sahel.* Nature 587 (7832): 78–82. doi:10.1038/s41586-020-2824-5

Corona P. 2018 - *Communicating facts, findings and thinking to support evidence-based strategies and decisions.* Annals of Silvicultural Research 42: 1-2. doi: 10.12899/ASR-1617

Dormontt E. E., Boner M., Braun B., Breulmann G., Degen B., Espinoza E., Gardner S., Guillery P., Hermanson J. C., Koch G., Lee S. L., Kanashiro M., Rimbawanto A., Thomas D., Wiedenhoeft A. C., Yin Y., Zahnen J., Lowe A. J. 2015 - *Forensic timber identification: it's time to integrate disciplines to combat illegal logging.* Biological Conservation 191: 790–798. doi:10.1016/j.biocon.2015.06.038

Feng D., Liu Y., Mazloomi M. S., Limaye A., Turner M., Evans P. D. 2020 - *A virtual reality system to augment teaching of wood structure and protection.* International Wood Products Journal 11 (2): 46–56. doi:10.1080/20426445.2020.1737773

Forest Learning 2021 - *ForestVR.* [Online] Available: https://forestlearning.edu.au/forestvr.html. [October 4, 2022]

Gervais A., Karame G. O., Wüst K., Glykantzis V., Ritzdorf H., Capkun S. 2016 - *On the security and performance of proof of work blockchains.* In: Proceedings of the 2016 ACM SIGSAC Conference on Computer and Communications Security. E. Weippl (Ed.), New York, USA, ACM doi:10.1145/2976749.2978341

Gibbs E. P. J. 2014 - *The evolution of One Health: a decade of progress and challenges for the future.* Veterinary Record 174 (4): 85–91. doi:10.1136/vr.g143

Glausiusz J. 2020 - *Wood — the vein that runs through human history.* Nature 588 (7836): 26–27. doi:10.1038/d41586-020-03378-y

Grant J., Keong Chen H. 2021 - *Using wood forensic science to deter corruption and illegality in the timber trade.* Targeting Natural Resource Corruption: Topic Brief

Haber S., Stornetta W. S. 1991 - *How to time-stamp a digital document.* Journal of Cryptology 3 (2): 99–111. doi:10.1007/BF00196791

Hanan N. P., Anchang J. Y. 2020 - *Satellites could soon map every tree on Earth.* Nature 587 (7832): 42–43. doi:10.1038/d41586-020-02830-3

Harfouche A. L., Jacobson D. A., Kainer D., Romero J. C., Harfouche A. H., Scarascia Mugnozza G., Moshelion M., Tuskan G. A., Keurentjes J. J. B., Altman A. 2019 - *Accelerating climate resilient plant breeding by applying next-generation artificial intelligence.* Trends in Biotechnology 37 (11): 1217–35. doi:10.1016/j.tibtech.2019.05.007

Harfouche A. L., Nakhle F. 2020 - *Creating bioethics distance learning through virtual reality.* Trends in Biotechnology 38 (11): 1187–1192. doi:10.1016/j.tibtech.2020.05.005

Harfouche A. L., Nakhle F., Harfouche A. H., Sardella O. G., Dart E., Jacobson D. 2023 - *A primer on artificial intelligence in plant digital phenomics: embarking on the data to insights journey.* Trends in Plant Science 28 (2): 154-184 doi:10.1016/j.tplants.2022.08.021

Harfouche A. L., Petousi V., Meilan R., Sweet J., Twardowski T., Altman A. 2021 - *Promoting ethically responsible use of agricultural biotechnology.* Trends in Plant Science 26 (6): 546–559. doi:10.1016/j.tplants.2020.12.015

Harfouche A., Romagnoli M., Corona P. 2022 - *Under the "publish or perish" mantra and the race for grants, insights to catalyze research into wood science.* Annals of Silvicultural Research 48 (2): 116-118. doi:http://dx.doi.org/10.12899/asr-2407

Interpol 2021 - *Forestry crime.* [Online] Available: https://www.interpol.int/en/Crimes/Environmental-crime/Forestry-crime. [October 4, 2022]

Jiang X., Jiang M., Gou Y., Li Q., Zhou Q. 2022 - *Forestry digital twin with machine learning in Landsat 7 data.* Frontiers in Plant Science 13: 916900. doi:10.3389/fpls.2022.916900

Jones I. J., MacDonald A. J., Hopkins S. R., Lund A. J., Liu Z. Y.-C., Fawzi N. I., Purba M. P., Fankhauser K., Chamberlin A. J., Nirmala M., Blundell A. G., Emerson A., Jennings J., Gaffikin L., Barry M., Lopez-Carr D., Webb K., De Leo G. A., Sokolow S. H. 2020 - *Improving rural health care reduces illegal logging and conserves carbon in a tropical forest.* In: Proceedings of the National Academy of Sciences 117 (45): 28515–24. doi:10.1073/pnas.2009240117

Kırbaş İ., Çifci A. 2022 - *An effective and fast solution for classification of wood species: a deep transfer learning approach.* Ecological Informatics 69: 101633. doi:10.1016/j.ecoinf.2022.101633

Komdeur E. F. M., Ingenbleek P. T. M. 2021 - *The potential of blockchain technology in the procurement of sustainable timber products.* International Wood Products Journal 12 (4): 249–257. doi:10.1080/20426445.2021.1967624

Kwon O., Lee H. G., Yang S.-Y., Kim H., Park S.-Y., Choi I.-G., Yeo H. 2019 - *Performance enhancement of automatic wood classification of Korean softwood by ensembles of convolutional neural networks.* Journal of the Korean Wood Science and Technology 47 (3): 265–276. doi:10.5658/WOOD.2019.47.3.265

Liu S., He T., Wang J., Chen J., Guo J., Jiang X., Wiedenhoeft A. C., Yin Y. 2022 - *Can quantitative wood anatomy data coupled with machine learning analysis discriminate CITES species from their look-alikes?* Wood Science and Technology 56 (5): 1567–1583. doi:10.1007/s00226-022-01404-y

Lowe A. J., Dormontt E. E., Bowie M. J., Degen B., Gardner S., Thomas D., Clarke C., Rimbawanto A., Wiedenhoeft A., Yin Y., Sasaki N. 2016 - *Opportunities for improved transparency in the timber trade through scientific verification.* BioScience 66 (11): 990–998. doi:10.1093/biosci/biw129

Loy A. C. M., Lim J. Y., How B. S., Yoo C. K. 2022 - *Blockchain as a frontier in biotechnology and bioenergy applications.* Trends in Biotechnology 40 (3): 255–258. doi:10.1016/j.tibtech.2021.09.006

Mason J., Parker-Forney M. 2018 - *DNA testing can save trees from illegal logging – and you can help.* [Online] Available: https://www.wri.org/insights/dna-testing-can-save-trees-illegal-logging-and-you-can-help. [October 4, 2022]

Munoz F., Zhang K., Shahzad A., Ouhimmou M. 2021 - *LogLog: a blockchain solution for tracking and certifying wood volumes.* In: proceeding 2021 IEEE International Conference on Blockchain and Cryptocurrency (ICBC). S. Kanhere (Ed.), Sydney, Australia, IEEE doi:10.1109/ICBC51069.2021.9461153

Nakamoto S. 2008 - *Bitcoin: a peer-to-peer electronic cash system* [Online] Available: https://bitcoin.org/bitcoin.pdf. [October 4, 2022]

Nakhle F., Harfouche A. 2022 - *Extended reality gives digital agricultural biotechnology a new dimension.* Trends in Biotechnology doi:https://doi.org/10.1016/j.tibtech.2022.09.005

Nogueron R., Cheung L., Kaldjian E. 2016 - *5 technologies help thwart illegal logging by tracing wood's origin.* [Online] Available: https://www.wri.org/insights/5-technologies-help-thwart-illegal-logging-tracing-woods-origin. [October 4, 2022]

Nature Computational Science Editorial 2023 - *A look back at 2021.* Nature Computational Science 2 (1): 1–1. doi:10.1038/s43588-022-00195-3

Orts-Escolano S., Rhemann C., Fanello S., Chang W., Kowdle A., Degtyarev Y., Kim D., Davidson P. L., Khamis S., Dou M., Tankovich V., Loop C., Cai Q., Chou P. A., Mennicken S., Valentin J., Pradeep V., Wang S., Kang S. B. et al. 2016 - *Holoportation.* In: Proceedings of the 29th Annual Symposium on User Interface Software and Technology. New York, NY, USA, ACM doi:10.1145/2984511.2984517

Parkes M., Waltner-Toews D., Horwitz P. 2014 - *Ecohealth.* In: "Encyclopedia of Quality of Life and Well-Being Research." A. Michalos (Ed.), Dordrecht, Springer Netherlands doi:10.1007/978-94-007-0753-5_4172

Planetary Health Alliance 2022 - *Planetary Health.* [Online] Available: https://www.planetaryhealthalliance.org/planetary-health. [October 4, 2022]

Rabinowitz P. M., Pappaioanou M., Bardosh K. L., Conti L. 2018 - *A planetary vision for one health.* BMJ Global Health 3 (5): e001137. doi:10.1136/bmjgh-2018-001137

Rahman A., Yella S., Dougherty M. 2011 - *Image processing technique to count the number of logs in a timber truck.* In: "Signal and Image Processing (SIP 2011)". K. Ramamohan Rao (Ed.), Dallas, USA, ACTAPRESS doi:10.2316/P.2011.759-060

Ravindran P., Costa A., Soares R., Wiedenhoeft A. C. 2018 - *Classification of CITES-listed and other neotropical Meliaceae wood images using convolutional neural networks.* Plant Methods 14 (1): 25. doi:10.1186/s13007-018-0292-9

Resente G., Gillert A., Trouillier M., Anadon-Rosell A., Peters R. L., von Arx G., von Lukas U., Wilmking M. 2021 - *Mask, train, repeat! artificial intelligence for quantitative wood anatomy.* Frontiers in Plant Science 12: 767400. doi:10.3389/fpls.2021.767400

Rudin C. 2019 - *Stop explaining black box machine learning models for high stakes decisions and use interpretable models instead.* Nature Machine Intelligence 1 (5): 206–15. doi:10.1038/s42256-019-0048-x

Shugar A. N., Drake B. L., Kelley G. 2021 - *Rapid identification of wood species using XRF and neural network machine learning.* Scientific Reports 11 (1): 17533. doi:10.1038/s41598-021-96850-2

Sipthorpe A., Brink S., Van Leeuwen T., Staffell I. 2022 - *Blockchain solutions for carbon markets are nearing maturity.* One Earth 5 (7): 779–791. doi:10.1016/j.oneear.2022.06.004

Spets B. 2022 - *Digital Forest Twin.* [Online] Available: https://www.tietoevry.com/en/industries/forest-pulp-paper-and-fibre/forest-solutions/wood-and-fibre-ecosystem-and-integration/digital-forest-twin/ [October 4, 2022]

Streich J., Romero J., Gazolla J. G. F. M., Kainer D., Cliff A., Prates E. T., Brown J. B., Khoury S., Tuskan G. A., Garvin M., Jacobson D., Harfouche A. L. 2020 - *Can exascale computing and explainable artificial intelligence applied to plant biology deliver on the United Nations sustainable development goals?* Current Opinion in Biotechnology 61: 217–225. doi:10.1016/j.copbio.2020.01.010

Tao F., Qi Q. 2019 - *Make more digital twins.* Nature 573 (7775): 490–491. doi:10.1038/d41586-019-02849-1

TIME USA 2019 - *Go inside the Amazon rain forest with TIME's AR experience.* [Online] Available: https://time.com/longform/inside-amazon-rain-forest-vr-app/ [October 4, 2022]

Vilkov A., Tian G. 2019 - *Blockchain as a solution to the problem of illegal timber trade between Russia and China: SWOT analysis.* International Forestry Review 21 (3): 385–400. doi:10.1505/146554819827293231

World Wildlife Fund 2011 - *Forests for a living planet.* [Online] Available: https://awsassets.panda.org/downloads/living_forests_chapter_1_26_4_11.pdf. [October 4, 2022]

World Wildlife Fund 2020 - *WWF Forests.* [Online]Available: https://www.worldwildlife.org/pages/wwf-forests [October 4, 2022]