AI IN SMART FOREST MANAGEMENT: FROM DMRV SERVICES TO INTELLIGENT BIOMASS MANAGEMENT

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Abstract
Nowadays, climate change has become a very threatening issue, affecting ecological stability and sustainable management of terrestrial ecosystems worldwide. Various task force groups currently seek big data and Artificial Intelligence (AI) related solutions for retaining forest ecosystems equilibrium. Hence, there is an urged need for investing in new big data AI technologies for achieving forest ecosystem stability and resilience against abrupt climate changes. Advanced technological approaches, such as the dMRV (digital Measurement Reporting Verification) framework, integrated with AI big data management and prediction methods, may be a promising mitigation solution against radical climate change ecosystem challenges. DMRV framework is a package of established technologies such as IoT, and satellite imagery, for environmental data monitoring, enriched with AI and Blockchain for data integrity and transparency.

This paper surveys latest advances in AI-based technologies, as well as case studies in smart forest management and sustainable development. As the migration of Forestry 4.0 to Forestry 5.0 paradigm encourages Human-AI interactions, this work aims at inspiring both forest officials and scientists to invest in AI technology solutions for efficient forest management against climate change challenges.

Key words: *Forest ecosystems, AI technologies, dMRV, tree pruning biomass, Climate Smart Forestry (CSF), Sustainable Forest Management (SFM)*

Introduction

Nowadays, climate change has become a very threatening issue, affecting ecological stability and sustainable management of terrestrial ecosystems worldwide. Forest ecosystems are straightforward related with their large volume carbon sequestration capacities, however, they seem to gradually degrade through uncontrolled deforestation, and unexpected wildfires. According to Food and Agriculture Organization of the United Nations (FAO), the last three decades, the area of primary forest worldwide has been decreased by over 80 million hectares through deforestation, forest degradation, and wildfire (https://www.fao.org/state-of-forests/en/).

Moreover, in many countries, current practices for forest and agricultural tree pruning residues, still encourage their elimination by open burning in the field, thus increasing the risk of fire spreading, while simultaneously leading to uncontrolled emission of greenhouse gases (GHG). It has been estimated that the open burning of olive branches in the field emits 1600 kg CO_2/ton, 90 kg CO/ton, suspended particles 17 kg/ton, with a simultaneous loss of organic matter of 7.44 kg/ton (Kostenidou et al 2013). In Greece, residual biomass burned per each crop type lies within 4, up to 8 tn/ha per year (2021 reference year), according to national inventory report (NIR) for GHG (NIR of Greece for GHG and other Gases for the years 1990-2021, Ministry of Environment and Energy). In a circular bio-economy context, the utilization of residual tree pruning biomass is a key axis of the European Green Deal, which aims to reduce GHG emissions by 55% by 2030 compared to 1990 levels (https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en).

At the same time, regarding the 17 UN Sustainable Development Goals (SDG) in forest domain, various task force groups are seeking for big data, Artificial Intelligence (AI) related solutions for bringing back forest ecosystems equilibrium. On the other hand, Climate Smart Forestry (CSF) is an emerging paradigm in sustainable forest management (SFM), in order to tackle with the threatening challenges of climate change. CSF requires AI based, novelty and proactive forest management methods to efficiently equip modern decision making systems, that will in turn, provide forest ecosystem resilience.

Hence, there is an urged need for investing in new big data AI technologies to achieve forest ecosystem stability and resilience against abrupt climate changes. Advanced technological approaches, such as the dMRV (digital Measurement Reporting Verification) framework, integrated with AI big data management and prediction methods, may be a promising mitigation solution against radical climate change ecosystem challenges. DMRV framework is a package of established and well tested technologies, such as IoT (internet of things), and satellite imagery, for environmental data monitoring, enriched with AI methods and Blockchain structures, for data integrity and transparency.

This paper is a comprehensive review of cutting edge technologies, along with applied case studies and projects in forest domain, as a proof of indication for improvement in SMF and sustainable development. As the migration of Forestry 4.0 to Forestry 5.0 paradigm encourages human-AI interactions, we hopefully believe that this study may inspire both forest officials and scientists, to invest in AI integrated technology solutions for efficient forest management against climate change challenges.

Climate smart forestry integrated solutions for SFM

As mentioned, CSF term is directly related to the SFM and it is also associated to intelligent AI based solutions that attempt to mitigate carbon emissions, and therefore to tackle climate challenges (Nabuurs et al. 2017). Those solutions should be data driven and integrated with state of the art technologies (AI, Machine Learning, satellite imagery, IoT sensors, blockchain, etc) in order to efficiently provide flexible and resilient models against radical climate changes, that strongly affect forest ecosystems. The real challenge lies in the fact that there is still limited knowledge on the way that climate changes affect and interact with forest ecosystems. That precious knowledge should be gained, enriched, and managed properly via combined remote monitoring and intelligent AI methods and algorithms, in order to provide proactive and predictive solutions for SFM, and to build smart forest decision support systems (Keenan et al. 2019).

Table I: Smart Forest sensor types

Sensor Type	Application	Advantages	Disadvantage
GNSS and Wifi, etc.	Localization	Accurate position determination	Problems in covered terrain due to signal inconsistency
Temperature sensors	Temperature monitoring	Provide insight into temperature fluctuations and can be linked to multiple other inputs (e.g., moisture), available to measure temperature in different media	Without linkage to other data, has a very narrow application in forestry. Continuous monitoring requires a good network
Moisture and humidity sensors	Measuring water content in air or soil	Produces climate data and can be easily linked to inputs like temperature. Applications can range from humidity measurements under the canopy to determining the trafficability of forest roads.	Real-time monitoring is only possible with a good network. Setup can be complicated.
Soil pH	Determining the solubility of different nutrients in soil	Understanding the nutrient uptake capability in relation to the soil.	On-site measurements with embedded sensors cannot reach the accuracy as an in-lab measurement
RGB camera	Generates images of the surroundings	Wildlife monitoring, understanding forest road condition, and navigational aid	Processing of pure image data can be challenging. Large amounts of data are generated when high-quality video/photo is used
Thermal imaging camera	Measures heat profiles of the surroundings	Understanding of thermal gradients; useful in phenotyping; forest fire detection SAR	Large amount of data generation possible, and image processing can be challenging.
LIDAR sensor	Provides detailed topographical data	Assists in biomass estimation, forest structure analysis, and navigation	Most commonly used technologies today are expensive. Problem with rain or other contamination on the transparent window.
Multispectral cameras	Measuring multiple spectra at the same time for simple data linking	Simple setup to obtain a broad range of data that is directly linked to one another	The collection of multiple wavelengths at the same time can lead to poor performance of each detector compared to specialized ones

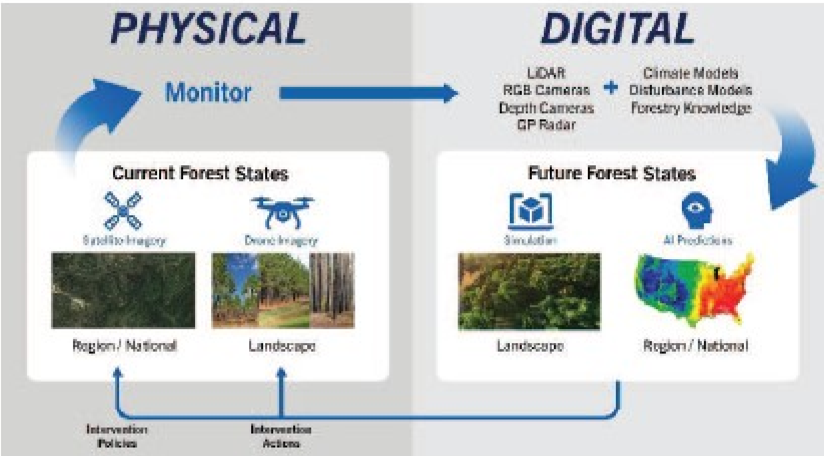
To put it simple, at first, we need to provide an automated means of measuring monitoring and collecting those dynamically evolving forest ecosystem information data, so as to build the necessary knowledge database. Normally, such data will emanate from the combined use of multiple IoT sensor cluster network implanted in designed areas within forest ecosystems (see Table I), and Proximity Detection Technologies (see Table II), at close range (lidar, cameras, UAVs etc), or remote satellite imagery (Ehrlich-Sommer et al. 2024). In this way, all raw data related with the current forest status, or timely deforestation changes, and the effects climate change eventually, has had on land, could be tracked and enrich that knowledge database. Apart from forest monitoring, those technologies could perfectly fit as a solution, to other application types, such as the monitoring and control of life cycle chain of forest or agricultural biomass, from its early origin to its finite customer consumption products. Moreover, those combined sensor and imagery technologies could enable the creation of three-dimensional (3D) forest models (Torresan et al. 2021).

Table II: Proximity Detection Technologies

Device	Application	Advantages	Disadvantage
Satellites	Remotely detect various data inputs (Temperature, moisture, images, etc.)	Ease of access to data, standardized datasets, and ability to monitor almost the entire surface of the earth	In many cases dependent on weather conditions. Continuous monitoring of a certain area is hardly possible. Large distance to the area of interest.
Drones	Remotely detecting various data inputs.	Cheap and easy to operate by a human; operation below the tree canopy is possible	Limited operation time for non-fixed wing variants; challenging to autonomize for flight below the canopy
Unmanned ground vehicles	Autonomous data collection and interaction with ground-based equipment. The potential communication link with other equipment like drones	Longer operation time compared to drones, with a high payload and is simple to use	Without external computing sources, fully autonomous maneuvering is still not possible
Existing forest machinery	Data collection	Simple sensors that do not require a lot of human interaction can gather data without interfering with the human workflow.	Complex sensors pose issues due to harsh operating conditions, e.g., LIDAR on a harvester. Therefore, they are limited to simpler sensors

Those massive raw and heterogeneous data could be exploited and processed by predictive AI models to predict e.g. the size, spread, or probability of a fire outbreak in a certain area, or the spatial progression of a currently running fire, or carbon footprint estimations of forest management activities, etc. One step beyond, when AI is combined with 3D forest modelling, and virtual reality (VR), it could provide future predictions of forest states, via a virtual forest model (see Figure 1), which is actually, its forest digital tween (Luo et al. 2023).

Figure 1: Forest Digital Tween



The perspectives of an SFM integrated solution paves a way for smart forest digital transformation establishment (Ehrlich-Sommer et al. 2024). Digital transformation is about involvement of advanced technologies for SFM, via necessitating AI integrated technology solutions as mentioned above, which are all included in dMRV paradigm framework, as we will discuss in the next paragraph.

DMRV integrated solution framework for SFM

As known, dMRV stands for digital measurement (or monitoring), reporting and verification, and it is considered as the updated "digital" version of the well tested, and established plain MRV paradigm. As its initials entail, it is a set of key technologies applied for multi stage process control activities, and particularly for real-time monitoring, data integration, and automated verification processes. It consists of four major technology pillars : 1. IoT, 2. AI, 3. Proximity Detection Technologies, and 4. Blockchain, where each one serves its own specific purpose, and altogether complement an end to end solution.

Particularly, IoT sensors and their associated network built in the surveillance field (e.g. a forest ecosystem), are used for monitoring environmental parameters (CO_2 levels, smoke levels, temperature, humidity), or carbon emissions with real-time data streams (see Table I). Then, the raw and heterogeneous data they produce from various sensor source types need to be processed and managed properly via AI algorithm dataset analysis (heterogeneous pattern identification, classification, anomaly and outlier detection). One step beyond, AI and its machine learning (ML) product models could provide predictions on various related areas, such as the probability of a fire outbreak in a certain area, or current running fires spatial progression, or carbon removal process predictions, thus improving accuracy and proactive management of carbon reduction processes.

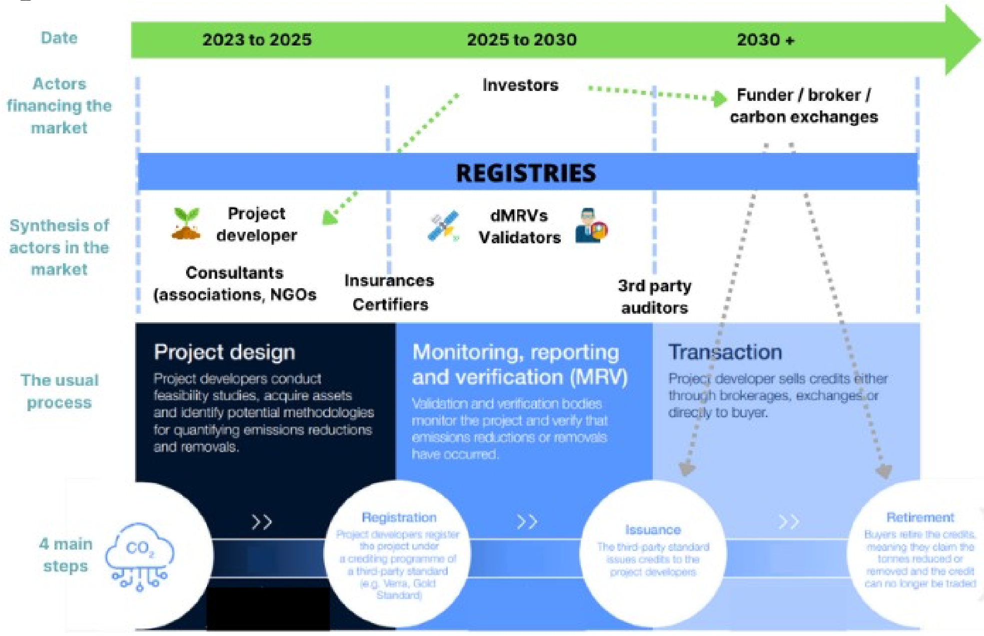
The third pillar, the remote imaging technologies (satellite imagery), along with the close range ones (lidar, cameras, UAVs etc), where both form the proximity detection technologies (see Table II), provide high-resolution images for monitoring environmental changes, and thus for tracking and verifying carbon sequestration processes. The dMRV advantages of using combined remote and close range imagery are multiple, including the reduced surveillance duration, the better field work organization, the lower costs, the improved work quality, and the elimination of various risk factors during manual inspection procedures. Moreover, dMRV synergy with AI's, Neural Network (NN) algorithms allow for faster detection and classification of aerial, satellite, and sensor monitoring data.

Finally, the blockchain completes the end to end integrated dMRV solution, acting as a decentralized ledger for recording and verifying data, maintaining unalterable records of all transactions and data entries by all ledger stakeholders, thus enhancing transparency and trust among participants during data transactions. CSF urges for dMRV integrated solutions, as it requires efficient forest management methods to support forest decision systems and thus, to address the challenges of climate change, including carbon markets and regulatory compliance of EUDR, as well.

DMRV Solutions for Carbon markets

Carbon markets could be benefited in multiple ways from the integrated dMRV solutions. Particularly, dMRV and especially its blockchain component, ensure that carbon credits are based on real, measurable, and verifiable reductions, regarding GHG emissions. In this way, dMRV improves organization sustainability reports, thus contributing to global carbon emission reductions. dMRV could be considered as a robust framework for tracking and verifying emissions reductions and other environmental impacts, and therefore, it is a significant advancement in the compliance of the voluntary carbon market (VCM) framework.

Figure 2: DRMV and carbon markets



Normally, in a typical carbon market all involved entities should be approved via an appropriate validation and verification body, which is actually a mediator (see Figure 2). Particularly, in the one end, the project developer (or else named supplier) supports carbon removal activity project, by providing all necessary assessment and documentation, which is actually a methodology complied with a standard framework (standard guidelines and methodology documents). On the other end, there is the buyer that purchases the verified credits, in order to compensate against its GHG exhausts and achieve zero neutrality. In between the two, many more entities could be involved (e.g. brokers, investors etc), but the critical intermediate entity is a third-party entity, a Validation and Verification body (VV), that provides project data integrity and transparency, standard regulatory compliance and credit custody management by requesting retirements of credits, at the end of carbon credit transaction chain. Nowadays, that VV body adopts dMRV framework, via an integrated platform, in order to deal with its validation and verification tasks in between the involved entities. Without dMRV, the integrity of the carbon credit market would be compromised, and could eventually lead to a lack of trust and decrease participation from carbon credit chain entity participants.

Many important global carbon market projects fully equipped with cutting edge technologies provide all the necessary means for a complete and robust support of carbon market transaction chain, such is the Open Forest Protocol (https://www.openforestprotocol.org/). OFP is an open platform, and particularly a digital, blockchain-based dMRV system, that measures, reports and verifies forest projects data worldwide. Along with Neutral, which is an automated carbon accounting, analysis, reporting platform for tokenized carbon credits and contracts, they both provide an end to end dMRV solution.

SFM and EUDR

It is commonly known that EUDR is a new rule framework that mostly inspects any kind of illegal deforestation activities within EU region. SFM provides a well defined, compact pathway via EUDR, for businesses and governments, and adopts best practices that would protect forest ecosystems. In doing so, the critical issue here is traceability, which necessitates accurate monitoring of any kind of forest activity throughout all the supply chain (e.g forest biomass life cycle chain, from source material origin to its finite processed ready-for-consumption product). Normally, those monitoring data are raw and heterogeneous, as they are emanated from multiple different types of monitoring sources (satellite imagery, lidar, cameras, UAVs, IoT sensors etc), and they have to be processed in order to be accurate and ready for finite decision making systems. Moreover, those data have to be verified and aligned with the existing regulatory frameworks.

Therefore, end to end integrated monitoring and verification platforms are unavoidably urged, such as the dMRV type, that may be well used for inspecting illegal activity and ensuring regulatory compliance of related sector businesses and organizations (agriculture, forestry, and supply chain sectors), which should be aligned to EUDR framework. In this way, dMRV supports SFM to gain control of its goals regarding managing forests and providing the appropriate equilibrium between resource management, protection and sustainability, on a long term basis.

AI solutions for SFM

AI and its algorithms as a part of an integrated end to end dMRV solution, or even as stand alone approaches, could definitely help to big data forest management processing, prediction modelling, and virtual 3D forest representations, as already have been mentioned above. Nowadays, there are multiple AI software tools for dealing with various forest management tasks, such as, forest simulation optimization systems, forest carbon estimation analysis and accounting systems, carbon prediction systems, geospatial forest inventory data management platforms, intelligent forestry supply chain (procurement and transportation) platforms, to name but a few. In parallel, various sustainable forest management research projects have been carried out successfully, with the adoption of integrated modern technologies, such as the Qingyuan Forest CERN project, with its homonym platform, a holographic forest intelligent data acquisition system for monitoring and displaying 3D forest structure and carbon sink (Wang et al. 2025).

Yet, the most challenging bet to win, is the "human in the loop" promising trend, which is actually a synergistic approach to continuously allow humans to control AI, and at the same time, to align AI with human values, ethics, and legal requirements, to ensure privacy, security, and safety (Holzigner et al. 2022). The human in the loop approach is defined as a set of simultaneous interactions of both computational and human agents, aimed to optimize learning behavior. It actually encourages human activity with its interactive participation with AI agents, in every single process stage, from the very beginning up to the finite end of an automated process. Hence, it indeed, puts the "human in the loop" to enable what neither a human, nor a computer could do on their own.

Forester in the loop, is a similar, remarkable approach inspired by the generic "human in the loop" concept (Holzigner et al. 2022). This approach includes various steps and pathways that encourage the ever evolving continuous human-AI interactions, throughout all forest activity process stages. Particularly, such critical human-AI interactions begin the forest monitoring process, with the forest owners interaction with heads-up displays in their helmets, or VR glasses, in order for them, to gain individual tree information. Conversely, the AI will learn from the forestry worker's experience during the monitoring process. Moreover, humans interact with a direct navigation system of a driving forest machine, via autonomous control of attached sensors. On the other hand, the expertise of the operators provides input to ML modules, so as together, to co operate, in a value-optimized manner. At the same time, machine manufacturers could be in close interaction with operators and driving forest machines, as well.

Conclusions

Forest ecosystem stability and resilience against abrupt climate changes, urgently requests for investing in new big data, AI based integrated technologies, such as the end to end dMRV framework. Such combined solutions may be promising for achieving forest ecosystem stability and resilience, against abrupt climate changes. Apart from sustainable forest management, those end to end solutions could be adopted efficiently for EUDR regulatory compliance, or carbon market robust control purposes.

The human in the loop approach, is a new concept applied successfully in those integrated solutions. Unlike the Industry 4.0 paradigm, this approach aims to integrate and increase human participation in the loop process, rather than to replace them, thereby ensuring continuous, secure, and trustworthy human-AI interactions. The migration of Forestry 4.0 to Forestry 5.0 paradigm encourages human-AI interactions, and particularly with its promising human in the loop approach, that will inspire both forest officials and scientists, to invest in AI technology solutions for efficient forest management against climate change challenges, bridging the human-centered Al gap, and the Forestry 4.0 to 5.0 gap, as well.

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