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Implementation of smart contract solutions on a distributed ledger network (blockchain) based
on physiological state variables of woody plants

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Executive Summary

Introduction

The main objective of this work is to investigate, design and implement an innovative solution based on smart contracts running on a public blockchain network to record, monitor and verify physiological state variables of woody plants. The solution enables also the possibility to emit tokens representing carbon credits with all key attributes: real, robustly quantified, additional, permanent, and uniquely claimed to ensure full transaction transparency.

The background context that triggered this research work can be defined by three, global, macro trends. The first one is the need to improve capital flow towards sustainable practices of forest management given the paramount importance of forest ecosystems for human society and planetary health. For example, forests play a pivotal role as a global carbon sink accounting for c. 45% of terrestrial carbon stocks (Bonan, 2008; Y. Pan et al., 2011). Nevertheless, in the “the state of climate action 2022 report” (Boehm et al., 2022), the World Resources Institute outlines that none of the indicators directly related to ecosystem services provided by trees is on track showing that the increase rate of “Reforestation” should be 1.5x faster and the reduction rate of “Deforestation” should be 2.5x faster. The second one is the impressive growth over the last years of the carbon credit markets both under the form of regulatory schemes and voluntary markets. For example, the voluntary carbon market quadrupled the value in 2021 reaching almost USD 2 Bln. LULUCF (Land Use, Land Use Change and Forestry) and in particular forest carbon offsets projects play a pivotal role in this market having the largest market share and growing steadily with an increase of +300% in terms of MtCO_{2e} sequestered between 2020-2021 (Ecosystem marketplace 2022). Therefore, we can say that capitals are flowing into the forestry sector but, despite this steady growth, the scientific community have raised concerns on the quality, transparency and integrity of carbon credits related to forest projects by signaling for example, systematic over-crediting (Badgley, Chay, et al., 2022), ownership and accountability issues (Streck, 2020), contracting issues due to asymmetric information (van Kooten, 2017). There is the need to improve the Monitoring, Reporting and Verification (MRV) processes of these projects by implementing advance solutions to minimize credibility failures, including double-counting, lack of transparency in the transactions and limitation in the information access of all stakeholders. The implementation of such solutions could have been utopian just few years ago, but we are currently in a timeframe where all key enablers are becoming available. There is in fact a (third) macro trend related to the emerging of a new digital stack to proper record, validate, and access to forest ecosystems’ data. Technologies such as IoT (Internet of Things) devices, satellites, drones, and microprocessors represent new real-virtual digital sockets to register the state variables of forest ecosystems at different spatial scales, from tree to forest level. Furthermore, blockchain technology can act as a technological layer to store and transact the calculated asset for a specific ecosystem service (e.g., t CO₂ sequestered in a given period of

time) without the need of a trusted third party and providing a tamper-proof full log of the evolution of ecosystem services at tree and forest level.

The work structure follows a top-down approach. In the first chapter, we introduce a theoretical framework to design a forest digital twin (FDT) that, by integrating different state variables at both tree and forest levels, creates a virtual copy of the forest to enable the system of recording, reporting, accounting, and trading of ecosystem assets generated by a forest. The chapter is reported as scientific article being published on Forests journal in 2022. In the second chapter, we narrow down the scope, and, starting from the FDT framework, we design the technical solution just related to one single ecosystem service (carbon sequestration at tree level) and relying on one single real-virtual digital socket (IoT devices monitoring radial growth). In the third chapter, we build a proof of concept of the solution for two stands of *Prunus domestica* located in Italy. We run the proof of concept in 2022 covering from the monitoring of the CO₂ accrued at tree level via the TreeTalker® IoT platform, to the tree stand information recording on a public blockchain network and the related carbon token generation. In the last chapter, we perform an economic assessment in the EU area of forest projects generating carbon credits in different scenarios and conditions such as climate region, planted species, MRV solution adopted, fire risk, project transaction costs, and carbon credit price. The goal is 1) to assess the driving factors influencing the profitability of these projects and 2) to better understand the economic impact of adopting such advance MRV solutions. We then qualitatively discuss the market price premium due to adopting such solutions. Detailed objectives of this work clustered by chapter are reported in the next section.

Objectives

The first goal (GOAL-1, chapter 1) is to propose a framework to design a forest digital twin (FDT) to combine and integrate the monitoring of the state variables of the tree and those of the related surrounding environment with the monitoring of state variables at the forest level. The objectives linked to the goals are 1) define the building blocks of a Forest Digital Twin starting from the application examples in the industrial sectors, 2) identify the real-virtual digital sockets (e.g. IoT device, Image sensing technologies, Flux Towers) and assess the level of maturity to monitor ecosystem services at tree and forest scale 3) propose how blockchain technology can be a solution for the implementation of transactions related to forest ecosystem service assets.

Starting from the concept of forest digital twin, the second goal (GOAL-2, chapter 2) is to design an advanced MRV solution for tokenizing the amount of CO₂ sequestered by a tree stand in a given period of time. A token is an unforgeable and unique digital representation of an asset being in our case a kg CO₂ sequestered. Only the owners can sell, transfer and retire their tokens providing information about provenance of the asset represented and having predefined rules regarding trading and usage limits. The objectives linked to the goal are: 1) understand the carbon credit market and point of concerns related to carbon forest offsets project, 2) translate

them into solution requirements, 3) detail the solution in terms of building blocks, the technological stack and how it operates to meet the requirements.

The third goal (GOAL-3, chapter 3) is to test on a real scenario the advanced MRV solution blueprint for tokenizing kg CO₂ sequestered by a tree stand. We utilize the Tree Talker IoT platform to monitor the radial stem growth of twenty-five *Prunus domestica* trees in two homogenous stands focusing on the estimation of the above-ground biomass carbon pool. We then simulate the carbon accrual process described from stand registration on the blockchain network to carbon token generation. The objectives linked to the goal are: 1) verify the all transactions are recorded, tamper-proof and publicly accessible; 2) ensure that the estimation of the kg CO₂ sequestered by the related tree stand and the carbon buffer set-up are monitored, reported and verified; 3) guarantee that the tokens emitted have unique ownership, can be easily transferred, retired, are thoroughly quantified and limited in the amount by the number of kg CO₂ accrued by the stand.

The four-goal (GOAL-4, chapter 4) is to perform an economic assessment of projects generating carbon credits in different scenarios and conditions such as climate region, planted species, MRV solution adopted, fire risk, project transaction costs, and carbon credit price. We focus on afforestation projects in the EU area. Objectives linked to the goal are: 1) estimate project financial return, 2) introduce the forest disturbance component and in particular, assess how the wildfire risk factor impacts the project, 3) discuss qualitatively the market price premium, meaning the additional price compared to the current carbon credit price in the voluntary market, that a buyer could pay to acquire carbon credits generated by a project implementing an advanced MRV solution described in the previous chapters.

Results Overview

Chapter 1. We introduce the innovative concept of a Forest Digital Twin to create a multi-purpose digital replica of the forest. We propose the entity tree as the key observation component. The tree is formed by three layers 1) tree and near environment physical and biotic state variables layer (e.g., sap flow and sap flux density, air quality), 2) the real-virtual digital sockets that are the tools to record and digitize the state variables (e.g., spectrometers to capture lights spectral components of the tree canopy, radial growth via dendrometry sensors) 3) the physical and physiological processes layer that the tree and its surrounding environment realize (e.g., biomass production, tree photosynthesis). We replicate the same three-layers structure also at forest level and we introduce the concept of nested approach meaning twinning multiple trees together via a common data modelling language together with the forest layers. To create a virtual copy of the tree, we suggest recording fifteen set of variables clustered by tree, soil and climate factors in the near space of the tree and we report that all real-virtual digital sockets to monitor these variables are commercially available with the exception of 1) roots growth and dynamics of the tree, 2) soil nutrients 3) soil microbiology. We report the ecosystem services and natural disturbance that can be monitored, and we propose an example of application on a

specific ecosystem service (carbon sequestration) running on a blockchain network to store the data captured and to enable economic transactions to trade carbon credits. At the time of the article, the main limitation of the study was the lack of implementation of the framework on real applications. We addressed this limitation by implementing a real case scenario as described in chapter 2 and 3.

Chapter 2. We present a solution to tokenize the carbon sequestered by a tree stand part of forest carbon project. We identify nine main issues of forest carbon projects from scientific literature ranging from monitoring and verification to entrance barrier for small landowners. We translate these issues in a set of requirements the solution should fulfil. a) Ensure data accessibility, b) allow data verifiability, c) enforce accountability, d) support actions and roles auditability, e) underpin transparent business transactions, f) grant operational payment transparency, g) be scalable to enable participation of small players. The solution is formed by six building blocks all based on open-source framework. The most relevant are: 1) the SaaS (software as a service) web application to let users interact with the smart contracts, 2) the “Carbon Data Factory” to deliver the data pipeline of the field measurements registering them on the blockchain 3) the four smart contracts running on the public Polygon blockchain network to manage transactions at project level (e.g. documentation management), at tree stand level (e.g. to confirm the carbon accrued over time) at tree level (e.g. to raise early warning asking for an increase of carbon buffer) and to tokenize the state variables measured (e.g. tree radial stem growth) in digital asset. We show how the solution building blocks collectively contribute to improve the robustness and transparency of forest carbon credit projects. Tokenization can improve the quality of carbon credits by enabling all process stakeholders to easily verify the key attributes a credit should have: being real, thoroughly quantified, additional, permanent and with unique ownership.

Chapter 3. We build a proof of concept of the solution by impersonating three roles: a carbon project manager, a project inspector and a buyer of carbon credit tokens. Between May and September 2020, we record via the Tree Talker IoT platform, the radial stem growth of 25 *Prunus domestica* (variety *Susino Prugna D'Ange*) for two homogenous stands in Modena (stand year 2010) and Policoro (stand year 2013) having a tree density of 308 and 417 trees per hectare. We show how via the SaaS application the carbon project manager can register the stands and trees on the public blockchain network and automatically record the measures converted in kg CO₂ accrued into the network having all transactions publicly available for auditing and verification purpose. We also show how to integrate the smart contracts with external web service providers via API to get access to third-party services to improve the level of robustness of the estimation or to detect disturbance early-warnings impacting the projects. For this purpose, we implement an external web-service providing the estimation of kg CO₂ accrued at stand level starting from the sample data recorded by the tree talkers. In our simulation the external web-service provides an estimation of 8500 kg CO₂ / ha for Modena and 8800 kg CO₂ / ha for Policoro, but it also detects that estimation error does not let to reach the confidence level of 95% for both stands and therefore requires the estimation to be confirmed by

an inspector before allowing any asset tokenization. All these transactions are also publicly recorded on the blockchain network showing therefore the potential and the robustness of an MRV solution combining advance real-virtual digital sockets like the Tree Talker platform and blockchain. We also show how an inspector can set a carbon buffer thus reducing the quantity available for trading. In our scenario for example, not only we have the measurement error but also, we know that up to 25 kg of biomass per tree gets removed during pruning. Therefore, we follow the guidelines proposed by Chiriaco et al., 2020 allocating 25% of the total kg CO₂ as buffer. As a final step of the simulation, the carbon manager tokenizes 1000 kg of CO₂ having them directly available in her commercial crypto wallet (we use MetaMask for our purpose). We call the tokens Tree Talker Tokens (TTK) and finally we simulate a financial transaction by transferring 100 TTK to a different crypto wallet account impersonating a potential buyer.

Chapter 4. We perform a Net Present Value (NPV) analysis of afforestation projects (duration 80 years, carbon credits generated by above and below biomass just for the first 20 years) for selected countries in the EU area. We focus on European Union area to have full homogeneity of the data and we select as a sample for this study, the country with the largest forest extension per European region as defined in (State of Europe's Forests, 2020). We select 1) Sweden (North Europe), 2) France (Central-West Europe), 3) Poland (Central-East Europe), 4) Italy (South-West Europe), 5) Greece (South-East Europe). We notice that as expected, the major factors influencing the profitability of the project are the climatic region and the planted species and that there is not significant project NPV difference between EU countries. We notice that for some countries like Poland the value added of selling carbon credits as additional source of revenue to the usual forest entrepreneurship activities is significant. In fact, from our simulation it emerges that an afforestation project having pine as planted species reports an NPV around €1.700 K whereas the expected NPV from the same forest area from usual forest entrepreneurial activity is around €400 K. We estimated the income from forest entrepreneurial activity by using the values reported in State of Europe's Forests, 2020. This can be seen as a signal of potential market opportunities for forest carbon projects in countries where the entrepreneurship income from forest management activities is limited. One key aspect that should be taken into account is the forest disturbance risk factor. We look just at the wildfire risk for forests at country level and we notice, that for countries in the Mediterranean area like Greece there is a risk to have a reduction up to 70% of the expected carbon sequestered compared to the risk-free scenario. This analysis requires additional investigation and confirmation nevertheless, it indicates that from an environmental point of view the multiplier effect of 1) booming of forest carbon projects, 2) increase in terms of events and magnitude of forest disturbance due to climate change, 3) long project lifespan, can let to an overestimation of the safety of the assets (amount of carbon sequestered) sinisterly echoing the same pattern happened with the sub-prime mortgages in the financial crisis of 2008.

The last outcome of this analysis we want to outline is that under the current and conservative market condition (average carbon credit price of €4) and for projects with a significant area (e.g., 1000 ha) an advanced monitoring solution based on flux towers seems to be already more convenient than the MRV benchmark cost of €0.8 per t CO₂ reported in the scientific literature (Bellassen et al., 2015). Furthermore, a 25% market price premium enables a forest carbon project owner to regain the same profitability by implementing an MRV solution based on an IoT network or even based on a forest digital twin solution (flux towers and IoT network). Although proper market analysis is required to assess the willingness to buy these premium credits, it seems that the market conditions for a broad adoption of the technological advancements of data collection at tree and forest level are getting promising. This could unlock the economic value of forest ecosystem services, not only related to carbon sequestration, by providing the highest data transparency and reliability and thus improving the capital flow towards sustainable and certified practices of forest management.

A Proposal for a Forest Digital Twin Framework and its Perspectives

Main goal and objectives

The content of this chapter has been published as peer-reviewed article on the “forests” journal belonging to the Special Issue “New IoT Technologies for Monitoring Forests and Their Ecosystem Services”. The content of the article has been adapted to be coherent with the structure of this document.

The main goal the chapter (GOAL-1) is to propose a framework to design a Forest Digital Twin (FDT) to combine and integrate the monitoring of the state variables of the tree and those of the related surrounding environment with the monitoring of state variables at the forest level. The objectives linked to the goals are:

- 1) Present the blueprint of a Forest Digital Twin including must-have capabilities such as risk management and the ecosystem services evaluation. For this purpose, we detail the building blocks of an FDT solution enabling the system of recording, reporting, accounting, and trading of ecosystem assets generated by a forest.
- 2) Identify and assess the level of maturity of the real-virtual digital sockets (e.g., IoT device, Image sensing technologies, Flux Towers) to monitor ecosystem services at tree and forest scale. For this purpose, we indicate the approach for twinning both the Tree and the Forest by detailing the physical and Biotic State, the Sockets, and the Processes.
- 3) Propose how blockchain technology can be deployed to implement transaction related to forest ecosystem service assets. For this purpose, we detail an End-to-End Theoretical Application of a Forest Digital Twin where blockchain technology is the mean to transact forest carbon credits.

Introduction

The value of Earth’s ecosystems for human well-being, the economy, and sustainable development has been a prominent topic in the public debate and in the global political agenda for roughly half a century. The scientific community has both conceptualized and quantified the societal benefits of functioning ecosystems through the concept of ecosystem services (ES) (Costanza et al., 1998; Reid WV et al., 2005), and it has identified the areas where the re-design of human activities to remain within the planet’s boundaries is more urgent (Rockström et al., 2009). The role of forests in contributing to ecosystem services is paramount and well-known. For example, forests play a pivotal role as a global carbon sink accounting for c. 45% of terrestrial carbon stocks (Bonan, 2008; Y. Pan et al., 2011). Mitigation actions on forests represent more than two-thirds of cost-effective Natural Climate Solutions to limit global warming to below 2 °C by 2030 and about half of the low-cost mitigation opportunities (Griscom et al., 2017). These mitigation actions on forests as a co-benefit would enhance ecosystem

services such as biodiversity (alfa, beta, gamma), water (filtration and flood control) soil enrichment, and air filtration. To this aim, forest management is increasingly required to consider multiple ecosystem services, thus, identifying the right balance among ecological, economic, and socio-cultural factors (Başkent, 2018; Lier et al., 2021).

This paper aims to propose a framework to design a forest digital twin (FDT) to ultimately exploit the technological advancements of data collection at tree level in combination with well-established forest monitoring technologies like remote sensing. Namely, the framework attempts to combine and integrate the monitoring of the state variables of the tree and those of the related surrounding environment with the monitoring of state variables at the forest level. Particular focus toward forest ecosystem services and their monitoring underpins such a design, whereby blockchain technology is proposed as a tool for the implementation of transactions related to such forest ecosystem service assets.

A digital twin is “a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity”. The design of a digital twin is motivated by a system-specific and user-defined outcome, and it relies on physical-virtual integration and historical and real-time data to build present representations and forward-looking models optimizing decision-making and effective action (*Digital Twin Consortium*®, 2021). One key aspect of the digital twin is the “twinning”: the synchronization of the virtual and physical states via measurement of the physical entity and the related update of the virtual entity so that both states are “equal” (Jones et al., 2020). Digital twin technology is currently widely used where it occupies a core pillar of the Industry 4.0 revolution, specifically manufacturing (Fuller et al., 2020). Via technological innovation and gains, it is rapidly entering into new application fields, including Earth’s ecosystems (Bauer et al., 2021). Indeed, the European Commission considers the development of high-precision Earth’s digital models one of the pillars of the European Green Deal and Digital Strategy and launched in 2021 “Destination Earth” with the goal to deliver the first two digital twins on extreme natural events and climate change adaptation by 2024 (*Destination Earth / Shaping Europe’s Digital Future*, 2021). Twinning the Earth’s ecosystems is possible because of the advancement of data collection where we have experienced an explosion of the amount of data recorded in different ways, making use of innovations in technologies associated with IoT (Internet of Things) devices, satellites, drones, and microprocessors. Nanotechnologies, superior computational power, 5G wireless broadband connectivity, and semiconductors are the technology enablers of this phenomenon. Consequently, there is an emerging digital stack that is pivotal to proper recording, validation, and access to ecosystems’ data. Furthermore, proper recording of data both in terms of volumes and quality will unlock the potential of AI-based solutions (Renda, 2019). This new data stream and related modelling can not only contribute to the ES estimation (Nitoslawski et al., 2021) but also have the added benefit of being coupled with technologies like blockchain for tracking the ES valued assets.

Blockchain technology allows mutually mistrusting entities to implement value transactions with no need of a central authority while offering tamper-proof and transparent data storage

(Nakamoto, 2008) and therefore, although a blockchain network cannot guarantee the end-to-end correctness of data registered by sources such as IoT devices, it can store smart contracts and trigger actions based on these values (Wüst & Gervais, 2017). Therefore, autonomous digital entities can be built by implementing smart contracts for sustainable management of natural assets, thus improving ownership, traceability, incentives mechanisms, and governance (Chapron, 2017). Applied to the Forest Digital Twin, the advantage of blockchain technology is not in the evaluation of ecosystem services specifically. Blockchain technology can act, however, as a technological layer to store and transact the calculated asset for a specific ecosystem service (e.g., unique identifier of the amount of C sequestered by a particular stand in one year) without the need of a trusted third party. Furthermore, the technology could provide a tamper-proof full log of the recorded state variables both at tree and forest level values to reconstruct the evolution of the forest ecosystem services.

In this paper, we propose the building blocks of an FDT solution enabling the system of recording, reporting, accounting, and trading of ecosystem assets generated by a forest. The aim is to provide a high-level blueprint to use as a reference for project implementation and to adapt and expand based on project peculiarities. This blueprint aims at ensuring the following benefits:

1. enhance monitoring and verifiability of forest ecosystem services status;
2. reduce the risk posture of the health of forest ecosystem services by implementing early warning mechanisms based on the tracking of state variables at tree and forest levels;
3. increase liquidity of the ecosystem assets and improve the capital flow towards sustainable practices of forest management.

Results and discussion: framework description

The building blocks of the proposed FDT solution are illustrated in Figure 1 and are detailed in the next sections. We defined the building blocks starting from the literature review conducted by Jones et al. (Jones et al., 2020) on digital twins systematizing their recurrent characteristics. The conceptual framework first identifies two separated spaces: real and virtual. At the core of the real space stands the tree as the fundamental component of the forest ecosystem. Indeed, trees are the building blocks of the observation components to be included in the FDT. The tree is formed by three layers: the first is the tree and near environment physical and biotic state variables layer (e.g., sap flow and sap flux density, air quality), the second includes the real –virtual digital sockets that are the tools to record and digitize the state variables (e.g., spectrometers to capture lights spectral components of the tree canopy, radial growth via dendrometry sensors), the third is the physical and physiological processes layer that the tree and its surrounding environment realize (e.g., biomass production, tree photosynthesis). This model is replicated for multiple trees, re-reported in the Figure as 1 to n. We propose a nested approach putting the forest layers on top of the trees' layers. We define as nested approach the twinning of multiple trees together with the forest entity using a common data modelling language.

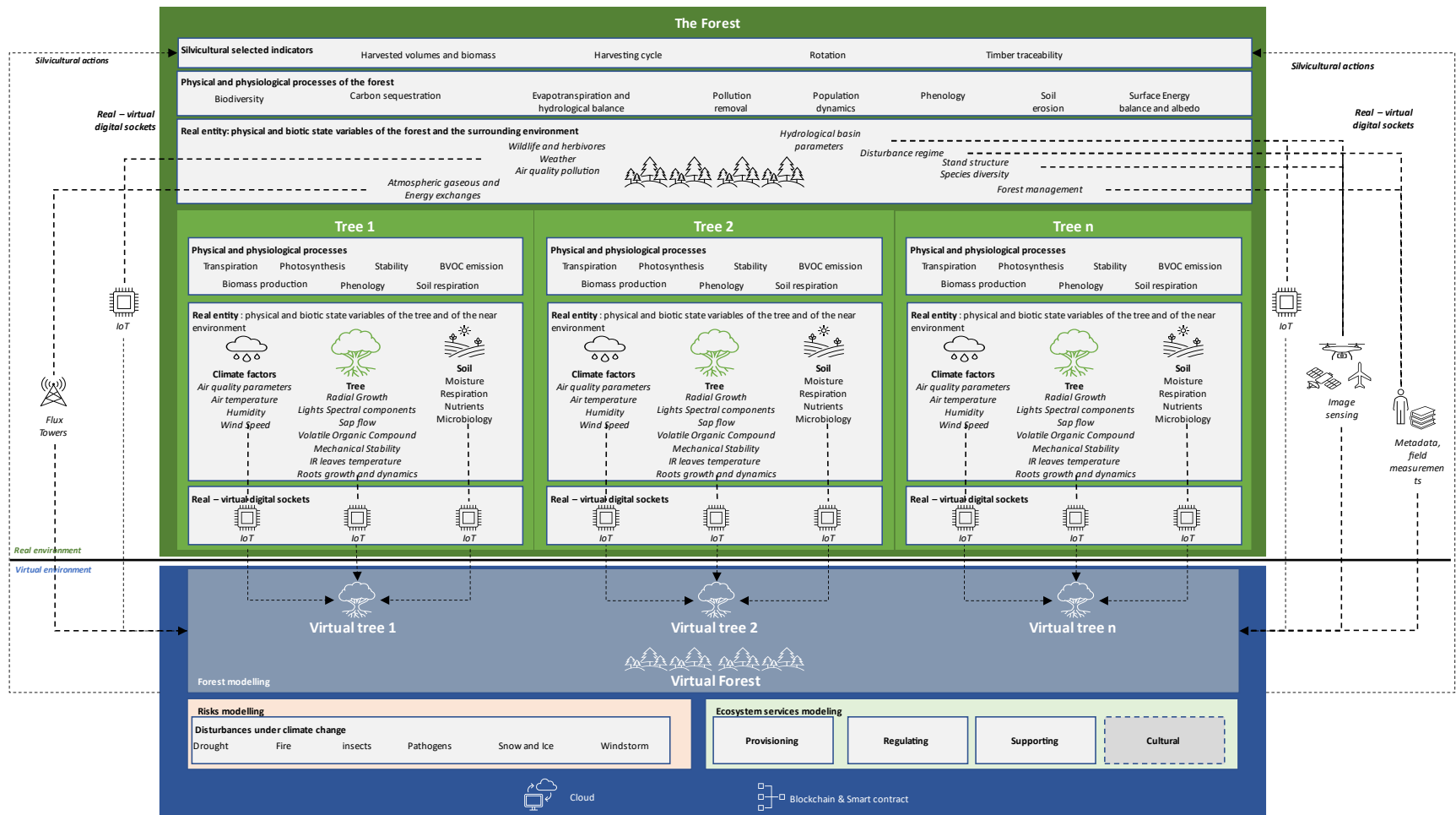


Figure 1. Forest digital twin framework

Following the same concept of the tree, the forest is formed by the same three layers but operating at a higher spatial level: first, the physical and biotic state variables of the forest and the surrounding environment (e.g., the atmospheric gaseous and energy ex-changes), second, the real–virtual sockets capturing and digitizing the key data of forest status (e.g., LiDAR remote sensing for assessing forest disturbance regime), and third, the physical and physiological processes of the forest (e.g., evapotranspiration and hydro-logical balance). This nested design principle enables to integrate over time and for different spatial scales (from tree to forest) the related physical and physiological processes by using, in an integrated manner, a wide range of technological means for implementing the real–virtual sockets. Furthermore, it considers biotic and abiotic interactions among trees enabling the prediction of the forest not only by a sum of tree behaviors but also from their interactions, taking into account also non-linear effects at forest stand scale. This approach could be important, for example, for a better understanding of drought-induced tree and forest mortality (Hartmann et al., 2018). In fact, although much progress has been made so far to monitor and to model the causes of tree mortality due to extreme events, the current understanding of tree physiological responses to drought and heat still does not enable a realistic estimate of forest mortality episodes under rapid climate change (Trugman et al., 2021). An FDT can contribute to generating a relevant amount of data to model the ecophysiological mechanisms at different scales influencing the tree response under stress.

The real environment at the forest level could ultimately implement a set of indicators to monitor the impact of silvicultural actions. We suggest the following four main indicators:

- Harvested volumes and biomass: whereby routine silvicultural intervention for raw material procurement or biomass removal for successional or sanitation purposes may be fed back into the FDT providing necessary information on past actions to inform future interventions;
- Harvesting cycle: established harvesting cycles, not only as planning tools, may also be embedded where scenarios based on the virtual component of the FDT simulations offers additional information under certain temporal scales and their respective outcomes, e.g., mean annual increment (MAI) stand or forest level, or at tree level average sawlog volume (ASV);
- Rotation: similar to harvest cycles, rotation age information could be continuously assessed and modified under a scenario-based predefined objective or simulated to reflect changes in abiotic and biotic limitation, including changes in timber market conditions;
- Timber traceability: tracing harvest removals (sawlog or biomass) from forest to landing to sawmill with a specific identifier or barcode, which may be tagged as either part of the blockchain ledger or as a specific subset within the FDT to clearly trace raw material forest source and additional repository functions.

For the purpose of this paper, we define the real-virtual digital sockets as the data connections measuring the state variables of the trees and the forest, this includes:

- IoT device: a device or a system of devices equipped with a unique identifier that measures physical and/or biotic parameters that transmit and receive signals over a network. In this context, this classification includes (list no exhaustive): sap flow sensors, diameter growth sensors, sound piezometric sensors, soil moisture sensors, air quality sensors, digital cameras to capture animal movements, weather stations;
- Image sensing technologies: remote sensing (satellite images and light detection and ranging (LiDAR) technology operated by drones and planes) and terrestrial laser scanners;
- Flux towers: measures of gas exchanges (carbon dioxide and water vapor exchange) between the forest ecosystem and the atmosphere;
- Field measurements and metadata: measurements in-situ performed by individuals and usage of additional data sources (e.g., forest inventories).

Symmetrically to the real environment, at the core of the virtual environment stand the virtual entities of trees made by the data captured and the models of the related real physical and physiological processes. At a higher nested level stands the virtual entity of the forest formed by the tree virtual entities plus the data captured at the forest level and the related models of the forest's physical and physiological processes. The virtual space is where the forest models could operate (e.g., species distribution models, individual-based models, dynamic global vegetation models), benefiting from a continuous stream of information (Maréchaux et al., 2021). Ultimately, this set of information and models act as an input for the models for risk mitigation and early warnings and for the estimation and management of the forest ecosystem services.

We suggest this nested approach in the virtual environment to address multiple ecosystem services with different levels of granularity including (Baskent et al., 2020):

- the compositional context (from vegetation association and habitat types to single stand characterization);
- the temporal context (from strategic planning to operations);
- the spatial scale (from regional to single stand);
- the spatial context (for example, to manage the harvest units or wild habitat patterns);
- the decision-making context (from multi-decisions/multi-stakeholder to single stakeholder).

Therefore, to meet this design principle, the simultaneous collection and integration of state variables and process models at both tree and forest levels is a prerequisite the FDT should meet.

Ultimately, we propose to operationalize the virtual environment of the FDT on two main technologies: (1) cloud computing and (2) blockchain and smart contracts. Virtual entities and models of the real environment exist in a virtual environment based on the continuous collection and analysis of data. In this respect, on the basis also of gray literature review, cloud computing provides over the internet an evolving list of services for the set-up of an FDT such as servers,

storage and database, networking, connectivity and control services (e.g., for IoT devices), computational scalability, data engineering, and analytics capabilities to process a continuous stream of data from multiple sources (de Donno et al., 2019). Some cloud providers also offer digital twin capabilities as a platform as a service solution (PaaS) to build relationships based on the digital models of the environment to be modelled (*What Is Azure Digital Twins? - Azure Digital Twins / Microsoft Docs*, 2021). However, in the future, we envisage an increasing use of scalable edge computing technologies which could deploy FDT AI predictions at locale scale (e.g., park management office, timber companies, etc.) thanks to the rapid expansion of GPU multi-cores parallel computing technologies (e.g., JetsonNano, etc.) with a significant cost re-duction and network reliability.

Blockchain and Smart contracts (low-level code scripts running on a blockchain platform (Zou et al., 2021) have the advantage of unlocking the economic value of forest ecosystem services. In this respect, the virtual environment of the FDT is suggested to implement an accounting system to ensure the highest transparency, reliability, and thoroughness of the data enabling automatic validation of the data collected at tree level with the data collected at the larger forest scale. Without such a solution, with the growth of data collection and models outputs, recording, reporting, accounting, and trading of forest ecosystem assets will be still affected by potential credibility failures, including double-counting, lack of transparency in the transactions, and limitation in the information access (Streck, 2020; van Kooten, 2017). This distributed ledger should act as a trusted source of forest's status and ensure interoperability and integration among different implementations of FDT.

Blockchain and smart contract technology could fit for purpose because it covers all the essential components we identified as required to develop a ledger of the digital forest to fully unlock the value of the forest ecosystem services (Yaga et al., 2019):

- enable different actors to have access and operate on the data recorded in a decentralized way on the basis of the specific use cases;
- transfer of digital assets and information without requiring a trusted third party: value sharing related to digitized natural assets like a carbon credit or like any value linked to a forest ecosystem service is fundamental, and the potential variety of actors and use cases enabled by the FDT make the establishment of a trusted third party difficult to realize;
- clear data ownership: digital identifiers for forest ecosystem services evaluations (e.g., wood production, carbon sequestered, pollution removal) linked to a trusted ownership mechanism are mandatory for accountability and transparency;
- enable monitoring activities: depending on the use cases, the public sector, the scientific community, and civil society should have real-time access to the transactions. Data reconciliation must be an “off of the shelf” capability to minimize disputes and manual efforts. A full log of transactions must also be available to reconstruct the evolution of the forest ecosystem services.

One key aspect to be considered during the technical design phase of the FDT is to limit the carbon footprint generated by the blockchain platform underpinning the transactions (Stoll et al., 2019). Therefore, it is required to use a blockchain platform that does not generate an exponential growth of energy consumption to add blocks to the ledger and to increase performance.

Compared to generally used forest management and decision support systems (Segura et al., 2014), we identify two main advantages that the FDT framework would bring:

- thanks to a cloud-native design, similar to the digital twin implementations for manufacturing, the solution would underpin the collection, storage, and analysis of data recorded in different ways and forms (e.g., IoT, remote sensing, and national forest inventories), creating a new data lake from tree to forest level available for modelling;
- the punctual monitoring at tree level, could enable a better prediction of the impact of forest management actions on ecosystem services. A clear example could be the impact evaluation of biomass removal via harvesting for a stand. Monitoring the state variables of the trees forming the stand via IoT devices would enable the daily collection of data pre- and post-harvesting, for example: for radial growth (via growth sensors), canopy health (via spectrometer), tree competition (via GPS), and stem water usage (via transient thermal dissipation probs), thus providing a continuous stream of data for assessing the impact of the forest management activities.

Twinning the tree: the physical and biotic state, the sockets, and the processes

To create a digital twin of the tree, we suggest measuring and recording 15 sets of variables clustered by tree (IR leaves temperature, lights spectral components, radial growth, roots growths and dynamics, sap flow, volatile organic, tree mechanical stability), by the soil where the tree stands (soil microbiology, moisture, nutrients, respiration) and, by the climate factors in the near space of the tree (air temperature, air quality parameters, humidity, wind speed). The real–virtual sockets should be made by IoT devices operating in wireless mode to ensure the highest level of resolution and frequency (ideally sub-hour). To our best knowledge, the technological means to implement this type of connection are already available, with the exception of:

- roots growth and dynamics of the tree: expensive, limited to white-light imaging, and often requiring human intervention (Rahman et al., 2020) ;
- soil nutrients: reduced commercial availability (L. Burton et al., 2020);
- soil microbiology: under development for specific use cases (Sylvain et al., 2018).

This set of data enables the process-based modeling in semi-real time mode of at least seven physical and physiological processes of the tree and of its surrounding environment: BVOC (biogenic volatile organic compounds) emission, tree biomass production, tree phenology, tree photosynthesis, soil respiration, tree stability, tree transpiration de-fining , therefore, the behavior of the virtual entity tree within the virtual forest. Table 1 reports the state variables and the related IoT connections and gaps. Furthermore, it provides a selection of scientific references

demonstrating the usage of these variables and IoT connections for the analysis of the physical and physiological processes of the tree and its surrounding environment.

Table 1: Twinning the tree. The table reports the state variables and the related IoT availability to realize the real-virtual socket. It also indicates the main relevance (✓) of the variables to model the physical and physiological processes for the tree virtual entity, and it provides selected references for each state variable typology.

Typologies of State Variables	IoT Availability	Physical and Physiological Processes: Variables Relevance for Process Modeling and Selected References						
		BVOC Emission	Biomass Production	Phenology	Photosynthesis	Soil Respiration	Stability	Transpiration
Tree	Mechanical stability	Available		✓			✓	
				(Gougherty et al., 2018; Valentini et al., 2019)				
	IR leaves temperature	Available	✓	✓	✓			✓
				(Simon et al., 2018)				
	Light spectral components	Available	✓	✓	✓			✓
				(Ryu et al., 2012; Valentini et al., 2019)				
	Radial growth	Available	✓	✓	✓			✓
				(Matasov et al., 2020)				
	Roots growth and dynamics	Reduced availability	✓	✓	✓	✓	✓	✓
Soil				(Rahman et al., 2020)				
	Sap flow	Available	✓	✓	✓			✓
				(Matasov et al., 2020; Simon et al., 2018; Zhang et al., 2014)				
	Volatile organic	Available	✓	✓	✓			
				(Churkina et al., 2017; Livesley et al., 2016)				
	Microbiology	Reduced availability	✓	✓	✓	✓		✓
				(Lau & Lennon, 2011; O'Brien et al., 2021; Sylvain et al., 2018)				
	Moisture	Available	✓	✓	✓	✓	✓	✓
				(Rosenbaum et al., 2012)				
Microclimate factors *	Nutrients	Reduced availability	✓	✓	✓	✓		✓
				(L. Burton et al., 2020)				
	Respiration	Available	✓	✓	✓	✓		
Microclimate factors *				(Barba et al., 2018; Lammirato et al., 2018)				
	Available	✓	✓	✓	✓	✓	✓	✓
				(Kim et al., 2019; Matasov et al., 2020; Simon et al., 2018)				

* Microclimate factors include air temperature, air quality parameters, humidity, and wind speed.

Twinning the forest: the physical and biotic state, the sockets, and the processes

To create a digital twin of the forest we suggest measuring and recording state variables related to 9 clusters: air quality and pollution, atmospheric gaseous and energy exchanges, disturbance regime, forest management, hydrological basin parameters, species diversity, stand structure, weather, wildlife and herbivores. The real–virtual sockets could consist of:

- IoT devices for monitoring air quality and pollution, weather, wildlife, and herbivores;
- image sensing technologies for monitoring species diversity and stand structure;
- flux towers to monitor atmospheric gaseous and energy exchanges;
- field measurements and metadata analysis for monitoring forest management activities and tree competitions;
- combinations of these monitoring means for disturbance regime (remote sensing and metadata) and for the hydrological basin (remote sensing and IoT).

With the exception of the monitoring related to the status of forest management activities and tree competition, to our best knowledge, all other state variables can be gathered via technological means remotely connected, thus enabling a continuous generation of stream of data. This flow of information enables the modelling of at least eight physical and physiological processes of the forest, forming the behaviour of the FDT in the virtual space: biodiversity, carbon sequestration, evapotranspiration, phenology, population dynamics, pollution removal, soil erosion, surface energy balance and albedo. Table 2 summarizes the state variables, the real-virtual sockets, the processes, and a selection of scientific references.

Table 2: Twinning the forest. The table reports the state variables and the related real-virtual socket. It also indicates the main relevance (□) of the measured variables to model the physical and physiological processes representing the forest virtual entity, and it provides selected references for each state variable typology.

Typologies of State Variables	Real–Virtual Sockets	Physical and Physiological Processes: Variables Relevance for Process Modeling and Selected References							
		Carbon Sequestration	Phenology	Population Dynamics	Biodiversity	Pollution Removal	Soil Erosion	Evapotranspiration and Hydrological Balance	Surface Energy Balance and Albedo
Air quality and pollution	IoT		✓	✓	✓	✓			
		(Takahashi et al., 2020)							
Atmospheric gaseous and energy exchanges	Flux towers	✓	✓	✓	✓	✓		✓	✓
		(FLUXNET, 2021; Morfopoulos et al., 2021)							
Disturbance regime	Immage sensing/metadata	✓	✓	✓	✓	✓	✓	✓	✓
		(Kane et al., 2014; Senf & Seidl, 2020)							
Forest management	Field measurements and metadata	✓	✓	✓	✓	✓	✓	✓	✓
		(Felipe-Lucia et al., 2018)							
Hydrological basin parameters	Remote sensing, IoT	✓	✓	✓	✓		✓	✓	✓
		(O’Grady et al., 2021)							
Species diversity	Remote sensing	✓	✓	✓	✓	✓	✓	✓	✓
		(Guo et al., 2017; Rautiainen et al., 2018)							
Stand structure	Remote sensing, IoT	✓	✓	✓	✓	✓	✓	✓	✓
		(Asner et al., 2012; Bothmann et al., 2017; Jucker et al., 2017; Niță, 2021; Quegan et al., 2019; Vaglio Laurin et al., 2019)							
Weather	IoT	✓	✓	✓	✓	✓	✓	✓	✓
		(Jin et al., 2019)							
Wildlife and herbivores	IoT	✓	✓	✓	✓		✓	✓	✓
		(Castro et al., 2019; Davies & Asner, 2014)							

Risk Management and Early-Warnings

Risk management and early-warning mechanisms should be a must-have capability of the FDT for two main reasons: first, to support forest risk mitigation actions; second, to provide distinctive information to key forest stakeholders. Notable examples of distinctive information could be:

- (1) the risk of reversals impacting the asset value provided by an ecosystem service shared with a potential buyer (e.g., risk of windstorm hindering the forest's potential of carbon sequestration);
- (2) signals of the forest's health degradation for the scientific community (e.g., increasing episodes of hydraulic failure, carbon starvation, insects, and pathogens).

Ideally, by adopting common standards for tracking and reporting, multiple implementations of FDT could build a global network like Fluxnet, thus, generating a distinctive globally data-driven repository for the scientific community. Furthermore, reliable data on threats affecting forest ecosystems can improve risk awareness and foster the implementation of mitigation actions (Blennow et al., 2014). The FDT could implement, as required risk management capability, the risk modelling of the disturbances under climate change, including on the basis of the relevance for specific FDT implementation of fire, drought, wind, snow and ice, insects, and pathogens (Seidl et al., 2017). This risk component is proposed as mandatory not only because it is considered as a key risk factor of forest ecosystem status but also because it is instrumental for the creation of a shared risk monitoring capability among different FDT implementations. It is important to outline that forest disturbances and risks are by nature interlinked (P. J. Burton et al., 2020), and have different temporal and spatial resolutions, therefore, the risk models cannot be built in silos, but they should follow an integrated approach.

Ecosystem services evaluation: the value of tree monitoring

Forest-related ecosystem services present a specific suite of opportunities and pitfalls given their inherent complexity. They are dynamic systems changing in space and time with various hierarchical system processes and dependencies interwoven in a complex matrix of both natural succession and anthropogenic induced change. Hence, the importance of dynamic approaches toward the quantification, preservation, and enhancement should be of the utmost importance and much has been achieved in forest ecosystem service quantification and optimization. (Baskent E, 2020; Başkent, 2021)

As a design principle, the FDT should provide as distinctive capability the evaluation of forest ecosystem services based on the state variables collected at both tree and forest levels, bridging the gap between static field measurements and autonomous data acquisition. One notable example of the advantage that this capability could bring in this context is the study provided by (Klosterman et al., 2014), where the authors used near-surface digital repetition photography and satellite remote sensing to estimate landscape-scale phenological metrics. This study highlights that under specific conditions (heterogeneous land with lower fractional forest cover), late spring phenology estimations derived from satellite remote sensing occur later than the projections from

near-surface measurements. Therefore, using just remote sensing data to estimate the phenology of deciduous trees could result in a lower estimation of the annual sums of net productivity for the forest. As such, access to real-time data sources from IoT and simulated responses via a digital twin could possibly harmonize or better refine such estimations with a bottom-up approach.

The monitoring of physical and physiological processes at tree level, reported in paragraph 3.2, enables as a minimum capability the estimation of ecosystem services (Matasov et al., 2020) reported in Table 3, providing a new set of data that can integrate the evaluation of ecosystem services at the forest level. For example, the punctual estimation of carbon removal at tree level can integrate the evaluation of the amount of carbon retained in a forest ecosystem for the carbon pool “carbon in aboveground biomass” usually calculated following the methods “gain and loss”, or “stock change” (H.S. Eggleston et al., 2006).

Other physical and physiological processes monitored at tree level can also play the role of contributing indicators for the estimation of other ecosystem services like the monitoring of tree BVOC emission and photosynthesis for pollination ecosystem service.

Table 3: Ecosystem services evaluation at tree level based on continuous monitoring of the physical and physiological processes.

Ecosystem Service	Type	Unit	Measure Frequency	Tree/Soil Physical and Physiological Processes Monitored
Timber production	Provisioning	m3 volume growth	yearly on a daily stream of data	Biomass production
C removal	Regulating	kg C sequestered and stored	Twice per year (vegetative period and remaining year) on a daily stream of data	Biomass production/net primary production
C removal	Regulating	kg C sequestered and stored	yearly on a daily stream of data	Soil respiration
Particulate absorption on tree canopy	Regulating	g/m ²	daily	Phenology
Gaseous pollutants removal on tree canopy	Regulating	g/m ²	daily	Phenology
Water runoff	Regulating	% based on indirect LAI (leaf area index)	daily	Phenology
Water runoff	Regulating	l/hour	daily	Transpiration
Water runoff	Regulating	Soil volumetric water content	daily	Soil moisture
Energy balance regulation	Regulating	W/m ²	daily	Transpiration

Putting all together: an end-to-end theoretical application of a forest digital twin

The scenario reported in describes as an example of end to end flow a forest manager aiming at generating credits for the ecosystem services from the forest (e.g., carbon sequestration under the form of carbon credit) to sell them to a credit market (e.g., the voluntary carbon trading market). An important element of this framework is the overcoming of using a third party for certification, which is usually an expensive and complicated burden for the seller.

The scenario is presented in three distinctive phases: (1) “before the trade,” (2) “trade and settlement,” (3) “post-settlement and retirement” (*Taskforce on Scaling Voluntary Carbon Markets > Homepage*, 2022). The scenario reports the interaction of multiple stakeholders and the role of the FDT to implement the transactions among stakeholders via a set of smart contracts overcoming the need for a trusted third party. As a first step, the forest manager defines the state variables of trees and forests and identifies and implements the physical–virtual digital sockets that will realize the twinning. In this phase, the forest manager should also define the spatial scale and the com-positional, temporal, and decision-making contexts (Baskent et al., 2020). For the sake of this, the FDT should provide interfaces to ingest this information from the forest manager. Then, the forest manager ensures an account on a standard-setter’s registry for the related credit and the distributed ledger solution of the FDT. The FDT should provide the possibility to connect and share information with standard setters as tradable credits usually adhere to standards for verification. Notable examples for the case of carbon credits are the Gold Standard, Verra’s VCS Program, American Carbon Registry, and the Climate Action Reserve (*Homepage - The Gold Standard*, *Homepage - American Carbon Registry*, *Home page Verra - Standards for a Sustainable Future*).

The FDT then implements four critical steps: first, it verifies data connections, second, it defines the physical and physiological processes and ecosystem services that can be monitored and valued at tree and forest level, and third, it outlines main risks and sets early-warnings measures. A notable example could be the suggestion of creating a basket of set-aside credits based on the probability of unexpected events (e.g., wildfire, pests) like the Forest Buffer Account for carbon credits (*U.S. Forest Projects - | California Air Resources Board*, 2015). The output of these steps are inputs for the first smart contract recording them in the ledger and notifying the forest manager. Using the digital ledger already in this initial set-up phase ensures that also the forest background data, the project set-up, and the future adjustment (e.g., selection of the physical–virtual connections) from the forest manager can be immutably recorded, thus giving the stakeholders access to the entire track of the project information and reducing information asymmetry. This information can, for example, simplify the evaluation of the eligibility of the project, the estimation of the carbon baseline for proving additionality, and the assessment of permanence. For example, the FDT could provide wildfire risk probability in the project region, thus estimating the expected risk of this reversal undermining the permanence of the sequestered carbon to optimize the buffer account for carbon credits.

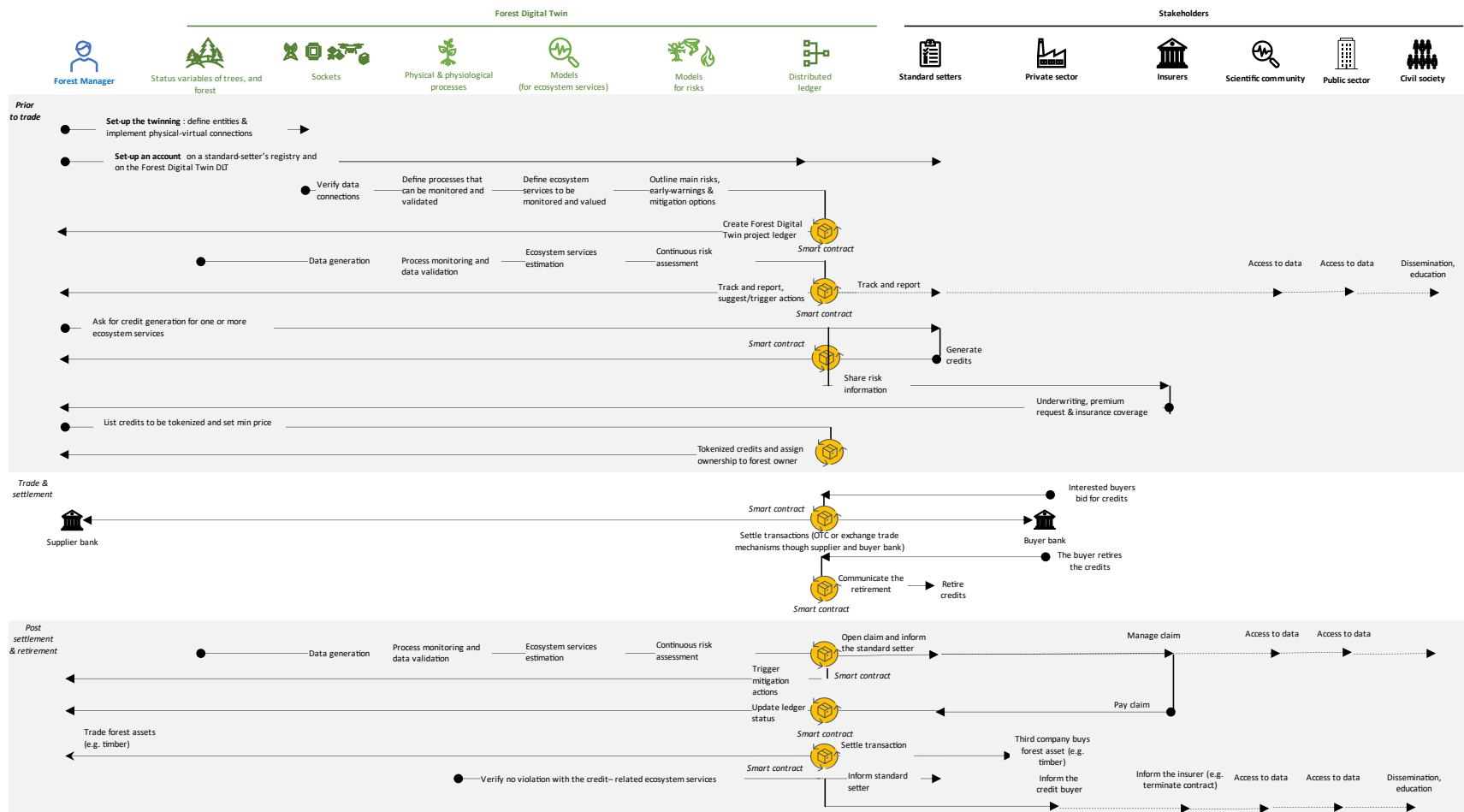


Figure 2: An end-to-end theoretical application of a forest digital twin.

After this set-up phase, the twinning can take place. The state variables of the tree, the surrounding environment, and the forest, based on the established connections, can be recorded (data generation) and the related processes modelled and monitored. These data would feed the models defined in the set-up phase to estimate ecosystem services (e.g., biomass production for carbon sequestration) and risks (e.g., wildfire). The second smart contract should track and report progress not only to the standard setters but also to other stakeholders like the scientific community. Two notable examples of triggers for this second smart contract could be (1) the communication to the standard-setter of the carbon sequestered above the established business as usual scenario giving therefore an early indication of the potential credits that the project can generate (2) the early-warning communication to the scientific community of cases of hydraulic failures of trees tracked via IoT devices due to drought and heatwaves.

The FDT could then deploy a third smart contract to support the forest manager in the certification of performance for the specific ecosystem service (e.g., carbon sequestration) and related conversion to credits. For example, the entire data history of the project could be readily available to the validation and verification bodies as part of the standard-setter's procedure to certify the credits. To mitigate the impact related to the risk of unintentional reversals, it could be beneficial to introduce the interaction already at this stage with insurance carriers. Insurers can, in fact, provide compensation for losses in case of reversals, and advanced monitoring solutions combined with machine learning capabilities can improve the attractiveness of nature-based solutions as an asset class where to invest (Repman M et al., 2021).

The fourth smart contract simply implements the tokenization of the carbon credits (the asset) and assigns the ownership to the forest manager, who is able to proceed with the trading process. The tokenization can also implement the split of the asset into sub-parts in a fully transparent manner, thus enabling the trading at different levels of aggregation of the asset.

Figure 2 also reports the trade and settlement phase where the forest manager, via the fifth smart contract, settles the transaction with buyers, and the standard-setter retires the credits. The FDT solution can bring distinctive value for both the buyer and the seller in this phase because the tradable credit of a specific ecosystem service (e.g., carbon credit) first, is based on a set of data easily auditable and, second, it can be combined with information status and value estimation of other ecosystem services (e.g., air and water filtration, biodiversity) generated by the same forest making, therefore, the credit more attractive for a potential buyer and not just a commodity.

In the post-settlement and retirement phase, the FDT continues to collect data feeding the modes for risk management and ecosystem services. In this phase, the implementation of the smart contract would mitigate the risk of fraud (e.g., data tampering) and will ease the communication process (e.g., by triggering a notification of loss towards the insurer in case of an event due to a natural catastrophe).

Ultimately, the last smart contract could cover the willingness to trade the forest as-sets (for example, timber production) on top of the credit generation. Once the forest manager sets the transaction with the buyer, the smart contract could (1) verify that there is no violation with the condition for the credit generation related to the ecosystem asset sold, (2) inform the standard-setter and the buyer, (3) trigger the termination of the insurance contract and (4) inform the public sector and the civil society on the destination of usage of the timber produced triggering, therefore, stakeholder consultations. This last set of transactions, which are fully monitored and auditable, could enable the implementation of innovative solutions like buildings as a global carbon sink (Churkina et al., 2020) to further unlock the value of the forests, thus improving the flow of capital in the forest sector.

Conclusion

The literature on digital twins in a forest systems context appears novel. The potential of using a forest digital twin to integrate different types of data sources to create a multi-purpose digital replica of the forest has not been fully realized nor explored in-depth prior. In fact, novel technological improvements in the systems of recording the state variables of forest ecosystems both at tree and forest levels and the availability of quickly scalable cloud services like servers, storage and database, networking, and connectivity enable the possibility to look at forest ecosystems via the integrated analysis of various data sources. These data sources have different spatial, temporal, and dimensional properties, notably associated with a method of data capture and synthesis. For example, satellite images with varying resolutions and time capture periods, temporal changes in forest carbon flux recorded by flux tower systems, and real-time monitoring of tree sap flow. Not to mention data from national forest inventories and newer techniques for capturing forest information such as mobile LiDAR scanner and subsequent data obtained in field measurements.

The fundamental hypothesis behind the FDT is that it is not only a repository for information gained by the capture and integration of real and physical environment data, but that it represents a novel data-driven systems approach, modulated with the integration of currently emerging sensor applications and connectivity via IoT. This IoT connectivity enables the integration of ecophysiological processes at tree level with the detailed forest structures data sets, thus extending in both spatial and temporal domains forest monitoring capabilities.

In this study, we suggested a coherent framework to integrate these data sources starting from the concept of Digital Twin already used in other industries, namely manufacturing. The FDT framework is open by definition, meaning that it could serve as a basis to build applications from achieving pure scientific purposes to implementing sustainable forest management practices. Regardless of the purpose of the application, we propose some key design principles that should be considered; (1) twinning the tree and the related surrounding environment as the fundamental unit of the forest—this design principle could ensure the highest data granularity by having a stream of information on the physical and physiological processes of trees forming the forest. (2)

Integrate the data from the trees with data sources at stand and forest level—this would unlock the possibility to cross-validate and enhance the results of models applied at a forest level. (3) Assess the risk posture of the forest and define how the data collected can provide early warnings on the major threats the forest faces. Forest main disturbances under climate changes should always be assessed. (4) Define the ecosystem services to be monitored and use the data at tree level to support the estimation of these ecosystem services at the forest level. (5) Consider the usage of blockchain technology to store the data captured and to enable economic transactions on the ecosystem services monitored.

The main limitation of the study at this stage is the lack of implementation of the framework on real applications. The end-to-end testing of FDT concept is paramount to validate and refine the model based on the results of concrete use cases. As reported in Tables 1 and 2, applications monitoring selected state variables at both tree and forest levels are available, but to our best knowledge, an attempt to combine multiple monitoring applications at different scales having the recording of the state variables of the tree as the core entity of the solution is currently missing. We, therefore, suggest as an immediate next research direction the implementation of the framework on a use case to prove the following key hypothesis: (1) the recording of the state variables at tree level can enrich and cross-validate the monitoring of the physical and physiological processes at forest level (2) the measures of ecosystem services can be stored as an asset on a blockchain network with a tree-level granularity without the need of a trusted third party thus providing an accessible and tamper-proof full log of measures. The use case should have a limited and well-defined scope focusing therefore on a specific ecosystem service like carbon sequestration. Once this use case proves to be successful, the model should be tested on both other ecosystem services and framework components (e.g., monitoring the impact of forest management actions, risk simulation, and early warnings). The second main research direction should focus on the standardization of data sharing protocols among different digital twin implementations (including entities attributes and data sources). This aspect was beyond the scope of the article, but it represents a limitation of FDT model at this stage because the adoption of digital twin solutions applied to Earth's ecosystems is expected to grow over the next years and the proliferation of protocols and governance practices also linked to the multiple data sources can generate technical debt, interoperability issues, and governance obstacles thus reducing the value that this type of solution applied to forests would generate at a local and global scale.

Tokenizing ecosystem service assets: solution blueprint for tree carbon sequestration

Main Goal and objectives

The main goal of the chapter (GOAL-2) is to present a solution blueprint for tokenizing the amount of CO₂ sequestered by a tree stand in a given period of time. A token is an unforgeable and unique digital representation of an asset being in our case a kg CO₂ sequestered. Only the owners can sell and transfer their tokens providing information about provenance of the asset represented and having predefined rules regarding trading and usage limits. The objectives linked to the goal are:

- 1) Describe why there is a need of new solutions to improve the management of forest carbon projects. For this purpose, we detail:
 - a. The importance of forest carbon sequestration to mitigate climate change effects;
 - b. The pivotal role forest carbon projects play in the carbon markets steady growth;
 - c. The concerns about of the real benefits of these projects.
- 2) Define how the solution proposed can contribute to mitigate these concerns. For this purpose, we present:
 - a. A review of the forest carbon project major issues from the scientific community;
 - b. A list of ten main requirements the solution proposed should implement;
 - c. A mitigation map “issues vs requirements”;
- 3) Detail the solution, the technological stack, and how it operates to meet the requirements. For this purpose, we report:
 - a. A list of open-source frameworks and components used for the solution design;
 - b. The building blocks of the solution and the technical architecture;
 - c. A functional and technical description of every block.

The blueprint will then be tested in the next chapter on an applied case.

Introduction

Climate change and the importance of carbon sequestration from LULUCF sector

Climate change is the “defining issue of our time”, as recently stated by the United Nations, “and we are at a defining moment” (*Climate Change | United Nations*, 2022). During 2022, the world experienced its fifth warmest year on record and the eighth in a row with temperatures higher than 1°C above the pre-industrial level (*Global Climate Highlights | Copernicus*, 2022). A recent assessment by IPCC (2022) showed that, in 2019, one-fifth of GHGs globally were emitted by agriculture, forestry, and other land uses, amounting to 13 GtCO₂e. Net anthropogenic releases of carbon dioxide, methane, and nitrous oxide increased by an average of 1.6% per year over the last 10 years, and CO₂ emissions accounted for about half of all GHG emission from this sector.

Even if current 2030 climate pledges are fully implemented, global warming will reach between 2.4°C and 2.8°C by the end of the century (IPCC 2022; Climate Action Tracker 2021). A recent assessment (Boehm et al., 2022) of progress across 40 indicators of systems change has shown that none – including targets on forests – are on track to reach their 2030 targets, as shown in Figure 1. Today, nearly 100 countries (representing about 75% of global emissions), 1,100 cities, and 7,500 companies have announced a target to reach net-zero emissions (ibidem). Getting on track will require an enormous acceleration in effort and action. Limiting global temperature rise to 1.5°C, so to meet the Paris Agreement, would thus require urgent transformation across all systems and sectors – from agriculture to mobility, building, housing etc. This will require immediate action to protect, restore, and manage more sustainably the world’s natural carbon sinks and stores, i.e., forests, mangroves, and peatlands, to preserve their ability to sequester carbon. According to the IPCC (2022), these measures could help mitigate between 4.2 GtCO_{2e} and 7.3 GtCO_{2e} per year at relatively low costs (up to \$100/tCO_{2e}) from 2020 to 2050. However, efforts to protect these ecosystems are largely inadequate (Boehm et al., 2022).

Figure 1: Summary of global progress (forests and land targets). Source: Boehm et al. 2022: 96

INDICATOR	MOST RECENT DATA POINT (YEAR)	2030 TARGET	2050 TARGET	TRAJECTORY OF CHANGE	ACCELERATION FACTOR	STATUS
Deforestation (Mha/yr)	5.7 (2021)	1.9	0.31		2.5x ^a	
Reforestation (total Mha)	130 (total gain, 2000–2020)	100	300		1.5x ^b	
Peatland degradation (Mha/yr)	0.78 (annual average, 1990–2008)	0	0		Insufficient data	
Peatland restoration (total Mha)	No historical data	15	20		Insufficient data	
Mangrove loss (ha/yr)	32,000 ^c (annual average, 2017–2019)	4,900	N/A		N/A; U-turn needed	
Mangrove restoration (total Mha)	0.015 ^d (total gain, 1999–2019)	0.24	N/A		Insufficient data	

According to the IPCC report, the entire LULUCF sector plays a crucial role in climate change as it offers relevant near-term mitigation opportunities while simultaneously underpinning food production, timber resources, biodiversity conservation, and other renewable resources. The report highlights that forests and natural ecosystems hold the greatest potential for mitigation efforts from 2020 to 2050. Notably, strategies such as reducing deforestation, sequestering carbon in agriculture, promoting afforestation, and implementing reforestation initiatives demonstrate the most substantial potential for reducing carbon emissions.

Forests cover about 31% of the land surface and store most of the world's terrestrial carbon. The world's total carbon stock of forests, including living biomass and soil organic matter, has declined from 668 Gt in 1990 to 662 Gt in 2020, as a result of the slight decrease in the global total growing stock of trees, from 560 billion m³ in 1990 to 557 billion m³ in 2020, due to a net decrease in forest area (FAO; UNEP, 2020).

Looking at Europe, the impact of climate change has been observed in the occurrence of record temperatures, as well as severe droughts, floods, with both human and monetary costs. In the last decade, the mean annual temperature in the EU has increased by about 2°C compared with pre-industrial period. Data reported by the Member States, show that the EU has fully achieved its 2020 climate and energy targets, being GHG emissions 32% below 1990 levels in 2020, thus by far exceeding the 2020 target of a 20% reduction. Despite the 5% increase in 2021, compared with 2020 levels, mainly due to the post-Covid economic recovery, GHG emissions remained below the 2020 targets EEA (2022). The pathway towards achieving the climate neutrality target in 2050, as established by the European Green Deal, and the aim of achieving net negative emission levels, thereafter, will require an increase in the EU natural sink size.

The land use, land use change, and forestry (LULUCF) sector is a net sink at the EU level. In 2020, it removed from the atmosphere 230 MtCO₂e, i.e., 7% of the EU's total GHG emissions. However, since 2014 a persistent decline has been observed, including in 2021, it decreased in size by 8% compared with 2020. Moreover, based on existing measures, it is predicted that the net sink will continue to decrease towards 2030. The European Climate Law, which entered into force in July 2022, increased the 2030 target to a reduction of at least 55% in net GHG emissions by 2030, compared with 1990 levels, which amount to a decline of emissions by 134MtCO₂e per year on average in the period 2021-2030.

European Union certification framework for carbon removals

The European Climate Law calls for an increase in the volume of the carbon sink by 2030 to achieve the objective of climate neutrality by 2050. Projections indicate that the net natural sink would decrease by 2030 to 190MtCO₂e per year with existing measures, while additional measures currently planned by Member States would increase it to 209MtCO₂e. Forest carbon sequestration is a cost-effective solution to control the increase in CO₂ concentrations in the atmosphere: among others, (Bosetti et al., 2011), (Michetti & Rosa, 2012), (Gren & Zeleke, 2016). Planting more trees and restore drained organic soils are additional measures defined to increase the EU's land use sink. This requires urgent action, as forest mitigation options take several years to result in removals. In this context, it is important to outline the recent EU Regulation Proposal (*EUR-Lex - 52022PC0672*, 2022) that introduces the Certification Framework for Carbon Removals within the European Community. The overarching goal of this initiative is to foster the production of high-quality carbon benefits to target the long-term goals of climate neutrality within 2050 set in the European Green Deal by creating a thriving market for carbon removals. More specifically, this forward-looking proposal aims to establish a robust and transparent

system for certifying carbon removal projects within the European Union having the following targets:

- Establish a governance framework for EU certification harmonized among the countries of the union;
- Ensure the highest quality of carbon removals in the EU;
- Enhance public trust in carbon removal actions by ensuring transparency, verifiability and by implementing a solid certification process based on public registries of carbon removals.

The regulation defines four quality criteria (Q.U.A.L.I.T.Y) that carbon benefits should be meet:

- Quantification: to accurately measure carbon removal activities and to demonstrate that these initiatives deliver clear benefits for the climate;
- Additionality: to ensure that carbon removal activities go beyond existing practices and law requirements;
- Long-term storage: to guarantee permanent storage by linking the validity of the certificates to the duration of carbon storage;
- Sustainability: to enforce that carbon removal activities preserve or support sustainability objectives such as climate change adaptation, water and marine resources, biodiversity, and circular economy.

Therefore, this legislation framework can foster in sectors such as agriculture and forestry, advanced carbon farming practices underpinned by cutting-edge monitoring techniques to achieve sustainable enhancement of carbon storage in soils and forests, to reduce the release of carbon from soils, and to simultaneously establish new business models that benefit farmers and foresters.

Carbon trading markets overview

A carbon offset credit is a “transferrable instrument certified by governments or independent certification bodies to represent an emission reduction of one metric ton of CO₂ or an equivalent amount of other GHGs”. A public or private entity can buy a carbon offset credit in the carbon credit market, “retire” it and claim a related cut of its own GHG reduction goals (Carbon Offset Guide, 2022)

The carbon trading market exists both under the form of regulatory schemes and voluntary markets. Meeting the Paris Agreement target of limiting global warming to a 1.5 C increase above the preindustrial level, requires that global annual greenhouse gas (GHG) emissions are cut by 50 percent of current levels by 2030 and reduced to net-zero by 2050. With this purpose, several actors, such as the EU and the US already have set mandatory carbon markets for specific industry sectors and gases. Other sectors, without any regulatory mandate, have pledged to offset carbon their GHG emissions through voluntary carbon markets. Overall, carbon credit markets experienced a 48% growth 2021 representing the biggest year-on year

increase since 2012 with the total number of credits issued increasing from 327 to 478 million (World Bank, 2022).

Voluntary carbon credits enable organizations, businesses or individuals to compensate or neutralize emissions by financing projects that avoid/reduce or remove/sequester GHG emissions from other sources. Voluntary carbon market almost quadrupled the value in 2021 reaching almost USD 2 Bln. The main driving factors of this significant growth are boost of project based on Nature Based Solutions and rising prices due to the increase of the demand from corporation with commitment of net-zero emission (World Bank, 2022) (Ecosystem Market Place, 2022).

It is estimated that, in 2030, depending on different price scenarios and other conditions, the Voluntary Carbon market size could be between \$5 billion and \$30 billion at the lowest end of the spectrum, and up to over \$50 billion at the highest end (Taskforce on Scaling Voluntary Carbon Markets, 2022). According to this report, voluntary carbon markets will need to grow by more than 15-fold by 2030 in order to deliver the 1.5-degree pathway of the Paris agreement, but innovation is needed to ensure quality standards and transparency. Compliance markets are established through regulation that limit or cap the amount of GHG that can be emitted to the atmosphere. The emitters can either reduce their GHGs emissions or buy carbon credits from entities that sequester GHGs from the atmosphere. Existing compliance markets include the EU ETS, China ETS, California's Cap-and-Trade Program. As reported in Figure 3 and Figure 4, 55 ETS schemas are implemented, scheduled or under consideration globally covering GHG emissions for 8.9 GtCO₂e in 2022 (Carbon Pricing Dashboard, World Bank, 2022).

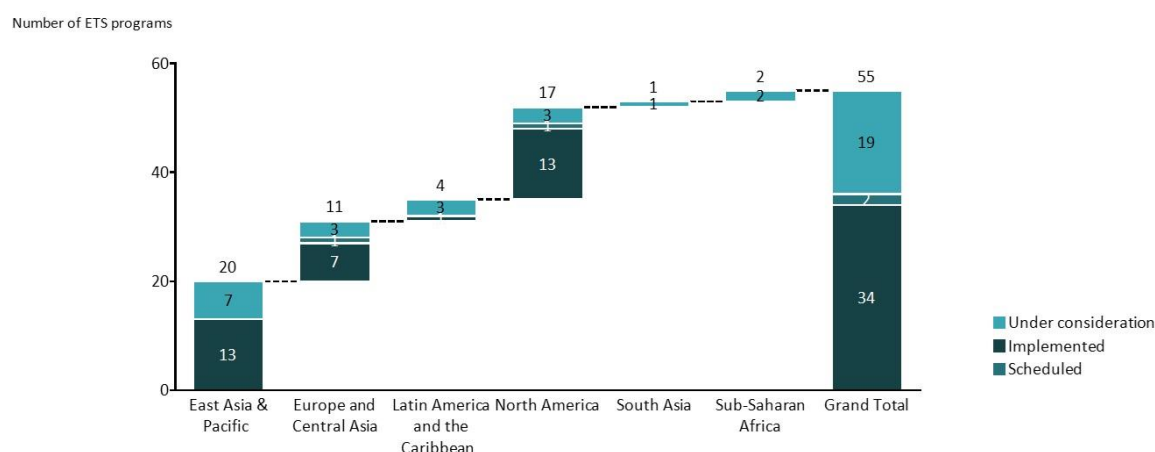


Figure 3: Number of ETS programs in 2022. Source: Author elaboration based on World Bank data (2022)

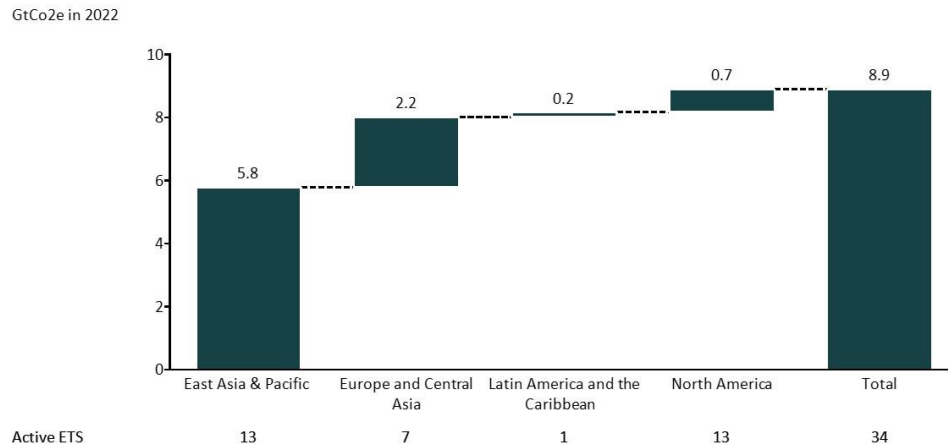


Figure 4: Cumulated coverage of GHG emissions by active ETS in 2022. Author elaboration based on World Bank data (2022)

Focus on forest carbon credits: steady market growth and major concerns

Forest-related projects for the generation of carbon credits can be clustered in two main categories (Grafton et al., 2021): Afforestation and Reforestation (A&R) and Forest Conservation including both Improved Forest Management initiatives and REDD+ (Reducing Emission from Deforestation and Forest Degradation) which is the international initiative incentivizing countries via the access to the carbon market to implement forest restoration and protection projects to enhance carbon stocks (Warsaw Framework for REDD-plus | UNFCCC). A project to be eligible for the issuing of carbon credits must demonstrate the sequestration of carbon on top of a business-as-usual scenario thus proving:

- **Additionality:** contribution to climate change mitigation by removing GHG from the atmosphere on top of the baseline that shall correspond to the standard carbon removal performance of comparable activities in similar social, economic, environmental and technological circumstances and take into account the geographical context (*EUR-Lex - 52022PC0672*, 2022).
- **Permanence:** assurance that the net carbon uptake is not reduced by returning it in the atmosphere due to human activities and forest natural disturbances (e.g., fire, pest) (Gren & Zeleke, 2016);
- **Leakage accounting:** removal of the shift of carbon emissions from the project area from the total account of carbon credits (*EUR-Lex - 52022PC0672*, 2022)

Forest Carbon credits should also adhere to standards for verification. Examples are the Gold Standard, Verra's VCS Program, American Carbon Registry, and the Climate Action Reserve (Certify a Project | The Gold Standard, Homepage - Climate Action Reserve : ; Homepage — American Carbon Registry; Verra - Standards for a Sustainable Future)

Carbon Credit issuances from forest-related projects have experienced a steady increase in terms of volumes for both Compliance and Voluntary markets over the last years so that in the Compliance Market, forest credits accounts for the majority of the share of credits as reported in Figure 5 based on the last data available from the World Bank (Carbon Pricing Dashboard, World Bank, 2022).

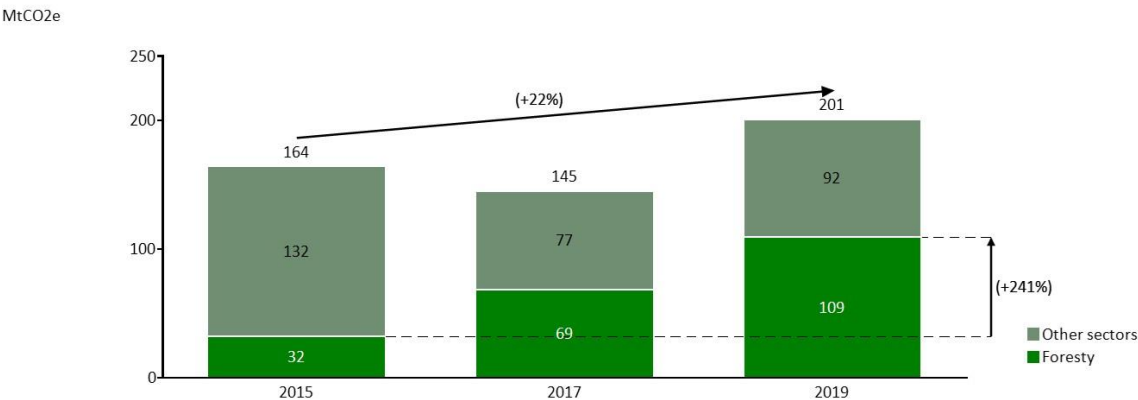


Figure 5: Carbon credits – compliance markets: transaction volumes of forest-related projects vs other sectors. Author elaboration based on World Bank data (2022)

It is important to mention the impressive growth of the carbon credit issuances in the voluntary carbon markets in 2021-2022 where the forestry and land use sector increased four times the total volumes of crediting becoming the sector with the largest market share as reported in Figure 6.

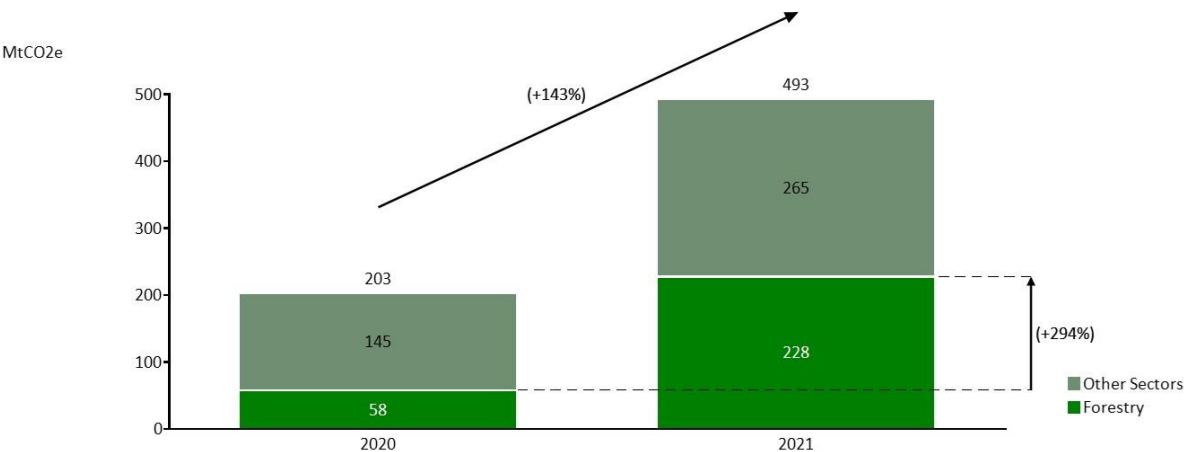


Figure 6: Carbon credits – voluntary markets: Transaction volumes of forest-related projects vs other sectors. Source: Author elaboration based on Ecosystem Market Place data (2022)

Despite the steady growth of both voluntary and compliance carbon credit markets over the last years, the scientific community have outlined significant point of concerns on the quality, transparency and integrity of carbon credits related to forest projects. These concerns can seriously undermine the real climate benefits of this type of projects and of the carbon market overall. For example, (Badgley, Freeman, et al., 2022) digitized and compared offset project records versus detailed forest inventory data demonstrating that under the California Air Resources Board (CARB) excess credits were issued for a value of more USD 400 M consisting of around 30 M tCo₂ as of September 2020. The root cause of this credit over-estimation is that the program issues credits to projects generating carbon stocks just above the national average therefore incentivizing adverse selection for project areas that can naturally outperform the given carbon sequestration baseline. The problem of adverse selection is just one of the issues forest carbon projects present. In the next sections of the chapter, we review them systematically to nail down the main requirements for the solution blueprint proposed.

A new digital stack as an opportunity to enhance forest carbon projects

As extensively described in the first chapter, the impressive advancement in data collection from tree to forest level enable proper ways to record and validate at different spatial scale forest ecosystems services like carbon sequestered. Blockchain technology, thanks to smart contracts that are low-level code scripts running on a blockchain platform (Zou et al., 2021), allows to tokenize this information (e.g., amount of CO₂ sequestered by a tree stand in a period of time) thus creating a unique and unforgeable digital representation (tokens) of the state variables of forest ecosystem services. Only the owners can sell and transfer their tokens providing information about provenance of the asset represented and having predefined rules regarding trading and usage limits.

There are already several applications of blockchain technology in the forestry sector having promising potential in many areas such as sustainable forestry, reducing illegal logging and protecting biodiversity (He & Turner, 2022). Also, the carbon credit market is experiencing an increase of forestry project relying on blockchain technology during the pilot phase (Kotsialou et al., 2022). The generation of a token can be linked via a smart contract to a pre-established quantity of CO₂ sequestered by trees measured and verified by the pre-established physical-virtual sockets reported in the first chapter. The deployment and execution of this type of contracts into a public blockchain would ensure full transparency on the trading of these tokens as all transactions are public available, including when a token is removed from the market and no further transactions area allowed. This type of smart contracts can also be audited and verified thus ensuring that every token represents a carbon credit with all its key attributes: real, robustly quantified, additional, permanent, and uniquely claimed (World Bank, 2022). In the next sections of the chapter, we propose a solution to implement this type of tokens and then we show an applied example in the chapter 3.

Material and methods

The design of the solution blueprint to tokenize carbon sequestered by tree stands has been developed by following two main steps. The first step was to analyze the concerns that forest carbon projects raise for the purpose of understanding major root causes and translating them in requirements that the solution should meet. Both scientific and gray literature were reviewed. Research focused on scientific literature was performed using Scopus, Web of Science and Google Scholar. Examples of keywords include “Forest Carbon Projects”, “additionality”, “permanence”, “transparency”, “monitoring”, “governance”, “data access”, “accountability”, “ownership” and their combinations. The screening considered only sources published in English over the past 10 years. The searching activity ended in April 2022. In order to complement the scientific literature review, also gray sources were reviewed and reported as reference where required.

The second step was to select the list of frameworks and tools to design the solution architecture to fulfil the requirements identified and implemented as part of the proof of concept described in the next chapter. We identified all open-source frameworks with an active user community. We selected Polygon for the reduced carbon footprint generated while underpinning the transactions. List of frameworks, tools and references are reported in Table 4.

Table 4: list of frameworks and tools to implement the solution.

	Item	Type	Description	Reference
1	Polygon	Blockchain network	Sidechain scaling solution running alongside opensource Ethereum blockchain and increasing Ethereum’s network scalability with lower transaction fees and energy consumption	https://www.polygon.technology/developers
2	IPFS	File System	Peer-to-peer distributed file system for storing and accessing files, websites, applications, and data	https://ipfs.tech/
3	Chainlink	Blockchain middleware	Middleware that enables connection from any blockchain towards off-chain data and services	https://chain.link/
4	OpenZeppelin	Smart Contract library	set of open-source, reusable, tested and community-reviewed contracts for the Ethereum network written in Solidity	https://www.openzeppelin.com/
5	Brownie	Development and testing framework	Python-based development and testing framework for smart contracts in the Ethereum runtime environment (Ethereum Virtual Machine)	https://eth-brownie.readthedocs.io/en/stable/
6	Metamask	Crypto Wallet	Browser extension that provides all functionality to deal with digital assets (key vault, secure login, token wallet and exchange)	https://metamask.io/
7	Solidity	Programming Language	Programming language for writing smart contract running on Ethereum blockchain and sidechains	https://soliditylang.org/

8	Python	Programming Language	General purpose programming language with global wide-spread adoption in data science fields	https://www.python.org/psf-landing/
9	Java Script	Programming language	General purpose programming language with global wide-spread adoption in web application development	https://developer.mozilla.org/en-US/docs/Web/JavaScript

We also used Docker to build container images of the applications and deploy them into the cloud service Render for the Proof of Concept described in Chapter 3.

Results and discussion

Solution requirements

Forest Carbon Projects are important to reduce deforestation (Guizar-Coutiño et al., 2022) but they present still several key issues undermining their impact and credibility as effective initiatives to contrast climate change. Based on our review of the scientific literature, we identified the following main issues reported with selected references:

1. Lack of efficient monitoring and accelerated verification: (West et al., 2020, 2023)
2. Contracting issues due to asymmetric information (van Kooten, 2017a)
3. Ownership and accountability: (Streck, 2020)
4. No accounting for other ecosystem services (Lawrence et al., 2022)
5. Carbon buffer pools undercapitalized: (Badgley, Chay, et al., 2022)
6. Transparent and effective risk mitigation to ensure carbon credit permanence (Gren & Zeleke, 2016)
7. Adverse selection (Badgley, Freeman, et al., 2022)
8. Socio-economic issues not addressed (C. Pan et al., 2022)
9. Barrier to participation for small landowners (Wise et al., 2019)

It is important to outline that a technical solution cannot be seen as a silver bullet to solve alone all issues related to forest carbon projects, but it can provide a technical backbone to foster best practices and transparency thus improving the overall quality and reliability of these projects versus their stakeholders. The table below reports the major issues of forest carbon projects identified together with the main solution requirements proposed to mitigate them. Every requirement is mapped against an issue by using one out of two categories: must have, nice to have. These categories indicate the importance of the requirement to mitigate a specific issue. A detailed description of the requirements is in the following list:

- a. **Ensure accessibility:** provide a public, tamper-proof full log of the recorded state variables of tree and forest eco-physiological processes;
- b. **Allow verifiability:** give constant access to estimation methods of natural assets digitized and other third-party services;
- c. **Enforce clear accountability:** underpin transparent life cycle of project documentation (approvals, ownerships, versioning);
- d. **Support actions and roles auditability:** track interventions at tree and stand level;

- e. **Underpin transparent business transactions:** allow change ownership and payments/financial securities execution directly linked to the natural assets digitized (e.g., to carbon accrued from a stand in a certain period of time);
- f. **Grant operational payment transparency:** execute (semi)-automated payment for activities performed at tree and stand level (e.g., silvicultural intervention);
- g. **Enable participation of small players:** reduce entrance costs, provide out-of-the-box monitoring and risk mitigation solution (e.g., carbon buffer pool sharing);
- h. **Maximize carbon permanence:** ensure a thorough carbon buffer management and an end-to-end natural asset life cycle (e.g., transparent integration with timber supply chain);
- i. **Ease proof of carbon additionality:** define punctual baseline mitigating adverse selection;
- j. **Support Early Warning mechanisms:** detect signals of forest ecosystems' degradation and reflect the risk in the natural asset tradability (e.g., carbon buffer increase).

Table 5: Main issues of forest carbon projects (red) and solution requirements to mitigate them (gray) with relative importance (green): must have & nice to have.

Main Issues of forest carbon projects from scientific literature	Solution requirements identified to address these issues and relative importance									
	(a) Ensure data accessibility	(b) Allow data verifiability	(c) Enforce accountability	(d) Support actions and roles auditability	(e) Underpin transparent business transactions	(f) Grant operational payment transparency	(g) Scalable solution to enable participation of small players	(h) Maximise carbon permanence	(i) Ease proof of carbon additionality	(l) Support Early Warning mechanisms
(1) Monitoring verification	<i>Must have</i>	<i>Must have</i>	<i>Nice to have</i>	<i>Must have</i>	<i>Must have</i>	<i>Must have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Must have</i>	<i>Must have</i>
(2) Asymmetric information	<i>Must have</i>	<i>Must have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Must have</i>	<i>Must have</i>	<i>Nice to have</i>	<i>Must have</i>	<i>Must have</i>	<i>Must have</i>
(3) Ownership & accountability	<i>Must have</i>	<i>Must have</i>	<i>Must have</i>	<i>Must have</i>	<i>Must have</i>	<i>Must have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Nice to have</i>
(4) No ecosystem services	<i>Must have</i>	<i>Must have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Must have</i>
(5) Buffer pools undercapitalized	<i>Must have</i>	<i>Must have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Must have</i>	<i>Nice to have</i>	<i>Must have</i>
(6) Transparent & Effective risk mitigation	<i>Must have</i>	<i>Must have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Must have</i>	<i>Nice to have</i>	<i>Must have</i>
(8) Adverse selection	<i>Must have</i>	<i>Must have</i>	<i>Must have</i>	<i>Must have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Must have</i>	<i>Must have</i>	<i>Nice to have</i>
(8) Socio-economic issues	<i>Must have</i>	<i>Must have</i>	<i>Must have</i>	<i>Must have</i>	<i>Must have</i>	<i>Must have</i>	<i>Must have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Nice to have</i>
(9) Barrier for small landowners	<i>Must have</i>	<i>Must have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Nice to have</i>	<i>Must have</i>	<i>Nice to have</i>	<i>Must have</i>	<i>Nice to have</i>

Solution description

Starting from this list of requirements we designed the building blocks of the solution as reported in Figure 7. In this diagram, the solution is divided in six main components: C1) a software as a service solution (SaaS) for managing the project, C2) a public blockchain network where the project smart contracts run, C3) a data factory to ingest and elaborate the state variables of the forest/stand in scope of the project, C4) a blockchain middleware to connect the smart contracts with third party data and services outside the blockchain, C5) external (third party) web services, C6) a peer-to-peer distributed file system to store unstructured information (documents) in full transparency and auditability. Every component is linked to the requirements described in the previous section that mainly contributes to implement.

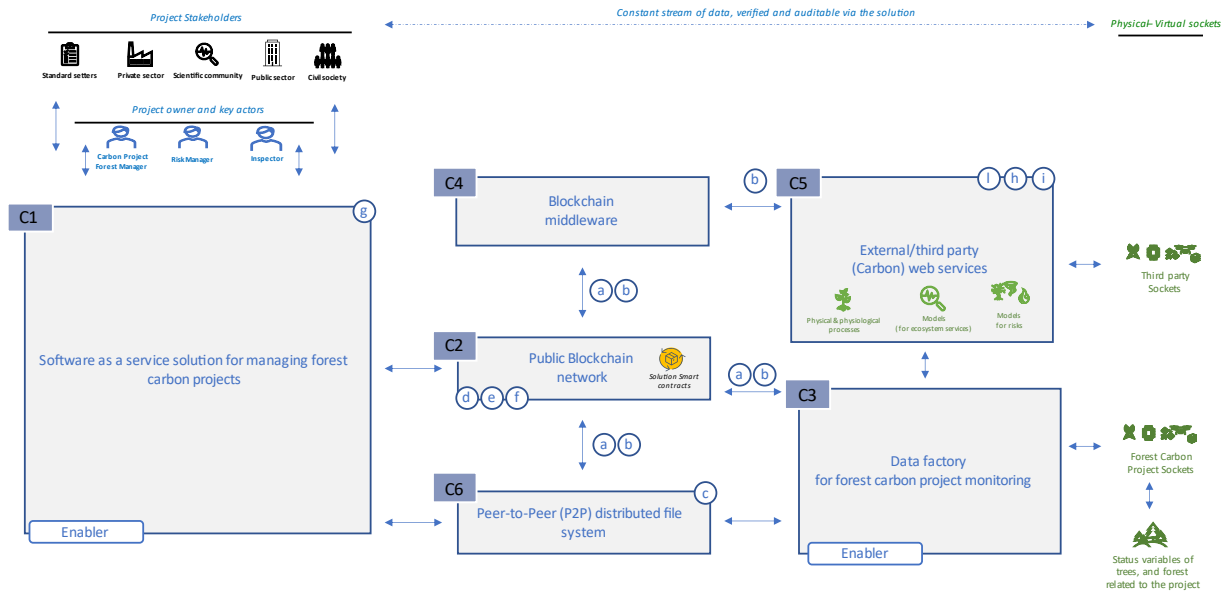


Figure 7: Building blocks of the solution to tokenize the CO₂ sequestered by tree stands linked to the solution requirements.

Figure 8 reports the technical implementation of every component required to realize the proof of concept on tree stands described in the next chapter. Dotted lines and dark gray boxes represent potential future extensions like establishing MQTT connection (messaging protocol for IoT devices) between the blockchain middleware and the IoT network on the field. In the next section we describe in detail all components.

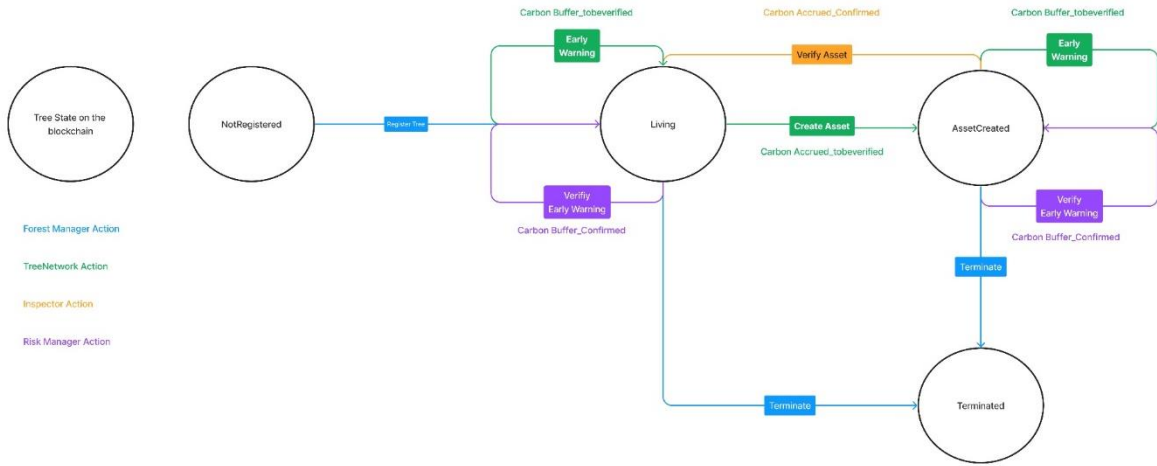
important to outline that the Inspector and Risk Manager roles are not required to be physical persons but can also be solutions such as drones, terrestrial Lidars, Flux Towers, or remote sensing services that are allowed to execute transactions on the blockchain network.

(C2) The carbon data factory is responsible to deliver the data pipeline of the field measurements of the forest carbon project. Therefore, it has to: 1) ingest the measured state-variables of the ecophysiological processes at tree, stand and forest level; 2) validate, clean and eventually transform the data; 3) store them in a data lake and/or a data warehouse; 4) present them; 5) record selected state-variables on the blockchain (e.g., amount of CO₂ accrued). Eventually it can also implement machine learning or advance analytics algorithm for specific use case. In the solution proposed, the carbon data factory is enabled to interact with the blockchain network having a specific role of “IoT network”.

(C3) The smart contracts are the core of the entire application and once the carbon project is defined, the Carbon Forest Manager deploys them on the public blockchain network Polygon to make them operative. We defined four smart contracts:

1. **TreePlot contract** assigned to manage a homogenous plot of monitored trees (single stratum). The contract implements the following functions:
 - a. Record, update, terminate a tree monitored. Role: Forest Manager;
 - b. Register carbon accrued by tree. Role: IoT Network;
 - c. Confirm carbon accrued per tree. Role: Inspector;
 - d. Raise early warning and suggest carbon buffer. Role: IoT Network;
 - e. Review and confirm carbon buffer. Role: Risk Manager;
 - f. Make all data accessible and aggregated at plot level. Role: public function.
2. **TreeStand contract** assigned to manage a tree stand part of the carbon project. The contract implements the following functions:
 - a. Record, Update and Terminate a Stand. Role: Forest Manager;
 - b. Call APIs from third party services (e.g., estimation CO₂ accrued per stand, risk estimation for carbon accrual per stand) based on data recorded at tree level. Role: Forest Manager;
 - c. Confirm carbon accrued per stand. Role: Inspector;
 - d. Confirm carbon buffer per stand. Role Risk Manager;
 - e. Implement validation rules for the TreeStand contract based on Stand information;
 - f. Implement validation rules for TreeStandToken contract regarding the amount of CO₂ available for tokenization.

Figure 9: Actions, Roles and state diagram of a monitored tree implemented in the TreePlot contract. Same model applied also at Stand Level



3. **TreeStandToken contract** assigned to manage tokens linked to the kg CO₂ sequestered a stand level. The contract creates ERC20 tokens so call “fungible tokens”: there is no difference among tokens in terms of value, special rights or behavior so that they can act as a medium exchange currency. One token corresponds to one kg CO₂. The contract implements the following function:

- a. Emit tokens based on the following formula:

$$\text{Tokens available}_t = \text{kg CO}_2\text{accrued}_t - \text{kg CO}_2\text{tokenized}_t - \text{kg CO}_2\text{Buffer}_t$$

where t is the day and the year of the project and for t = 0 $\text{Tokens available}_t = 0$
 Role: Forest Manager

- b. Burn tokens: the owner of the token is allowed to destroy them (retire them from the market)

Once tokens are emitted, the owner can transfer them as part of the standard functionality of the blockchain (similar to any other digital coin). The relationship among Tree Plot Contract, Tree Stand Contract and Tree Stand Token Contract including roles, main functions and entities is reported in Figure 10.

4. **CarbonProject contract** assigned to manage the project documents and set controls for the other contracts. The contract creates ER721 non-fungible tokens (NFT). “Non-Fungible” means that tokens are unique, distinct and not interchangeable. The contract assigns an NFT token to the Uniform Resource Identifier (URI) of project key documentations stored in a peer-to-peer distributed file system (C6). The contract implements the following functions:

- a. Assign an NFT token to the Uniform Resource Identifier (URI) of project key documentations stored in a peer-to-peer distributed file system (C6);
- b. Store the key document data as NFT metadata for implementing logic validation for the other project carbon contracts and further integration with other platforms.

Once NFT token is emitted and linked to a specific URI, the owner can transfer ownership as part of the standard functionality of the blockchain (similar to any other NFT). In case of change in the contract, a new Uniform Resource Identifier and a new NFT token must be created thus ensuring full traceability and auditability.

(C4) This component is the blockchain middleware that enables smart contracts (in our case the TreeStand contract) to communicate to services outside the polygon chain. This is a key feature as it enables off-chain computation and data elaboration. Service providers like Chainlink enables APIs or other type of communication protocols such as MQTT. The value of this approach is that a carbon project implementing this capability allow external providers and the scientific community to contribute to the project by providing specific value-added services.

(C5) This component represents potential services providers. Example of services could be:

- Estimation of the overall project carbon fluxes based on monitoring performed a plot level;
- Automatic confirmation that the total amount of 1) above and below ground biomass and of 2) soil carbon content claimed by carbon project is in line with the values registered in national forest inventories for that specific area;
- Estimation of risk of reversals to refine project carbon buffer (e.g., risk of windstorm hindering the forest's potential of carbon sequestration);
- Detection of early warning signals nearby project's area of forest's health degradation (e.g., increasing episodes of hydraulic failure, carbon starvation, insects, and pathogens);
- Verification of additionality by comparing carbon sequestered by a stand against historical trends in the same area.

The list is open by definition and can grow depending on the market needs and project peculiarities. For example, the adverse selection issue described by Badgley et al. (2021) could have been mitigated by implementing a digital service that compares the forest inventory data versus the carbon offset claims and report the result on the blockchain so that all stakeholders (the issuer, the standard owner and the buyer) are aware of this warning that is also tracked for future auditing purpose.

(C6) This component indicates the peer-to-peer distributed file system to store and archive project documentation in combination with smart contracts (Nizamuddin et al., 2019). Rather than using a Unique Resource Identified to locate data (so called URL), this solution uses an URI as unique content identifier (no location) to retrieve data from different sources (peers). Thanks to the distributed network of peers (nodes) storing the data, service provider like the opensource

IPFS enable deduplication, high performance and resilient access to data also to people with poor internet connection.

Conclusion

Forests are global carbon sink and play a pivotal role to mitigate climate change. Forest carbon projects are getting more and more relevance in both compliance and voluntary carbon credit markets. In the compliance market, carbon credits generated by forest projects increased by 241% in the period 2015 – 2019. In the voluntary market this growth is of + 294% in the period 2020 – 2021 thus becoming the type of project with the major market share. Despite this steady growth, forest carbon projects present still several issues such as lack of efficient monitoring, clear ownership, undercapitalized carbon buffer pools, risk mitigation and adverse selection. Thanks to impressive innovations in technologies linked to IoT devices, satellites, drones, and microprocessors, there is the possibility to build new solutions to address these issues. Furthermore, combining these advanced solutions for forest ecosystem data collection with a blockchain architecture can ensure the highest accessibility and reliability of the project data unlocking the possibility to perform financial transactions in full transparency.

In this chapter we presented a solution to tokenize the carbon sequestered by a tree stand part of forest carbon project. The solution fulfills a set of requirements ranging from ensuring full data accessibility & verifiability to enabling early-warning mechanisms. The solution is all based on open-source framework and components. We showed how the solution building blocks collectively contribute to improve the robustness and transparency of forest carbon credit projects. Smart contracts running on a public blockchain play a pivotal role in the solution as they enable the possibility to transform via tokenization the state variables measured (e.g., tree radial stem growth) in digital asset. Tokenization can improve the quality of carbon credits by enabling all process stakeholders to easily verify the key attributes a credit should have been real, thoroughly quantified, additional, permanent and with unique ownership.

In the next chapter, we implement a proof of concept to test on a real case the design of the solution.

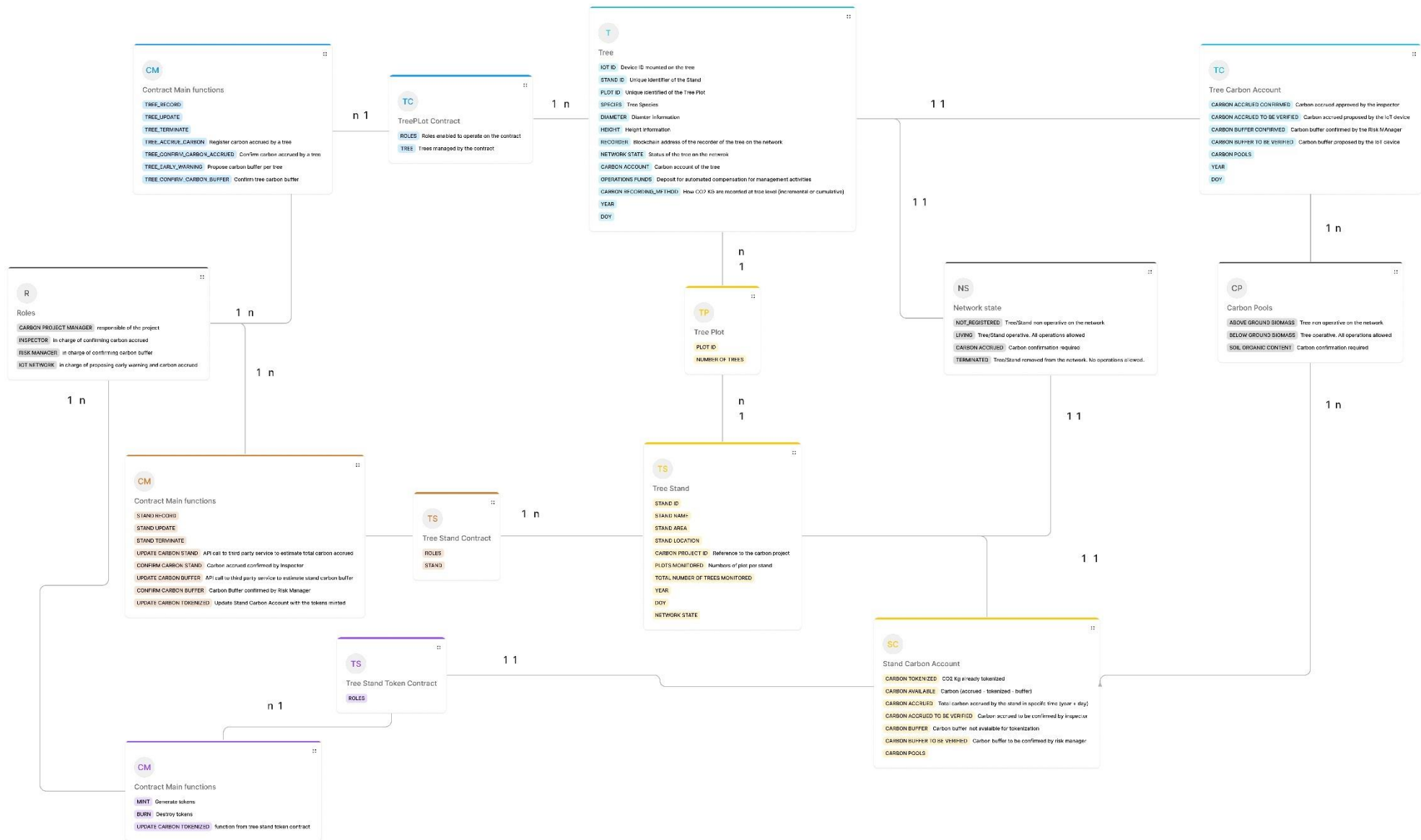


Figure 10: Relationship among Tree Plot Contract, Tree Stand Contract and Tree Stand Token Contracts including roles, main functions and entities

Experimental design and testing: applied example on a single-stratum tree site

Goals of the chapter

The main goal of the chapter (GOAL-3) is to test on a real scenario the solution blueprint for tokenizing kg CO₂ sequestered by a tree stand. We utilize the Tree Talker IoT platform to monitor the radial stem growth of twenty-five *Prunus domestica* trees in two homogenous stands focusing on the estimation of the above-ground biomass carbon pool. We then simulate the end to end process described in chapter two from stand registration on the blockchain network to carbon token generation. The objectives linked to the goal are:

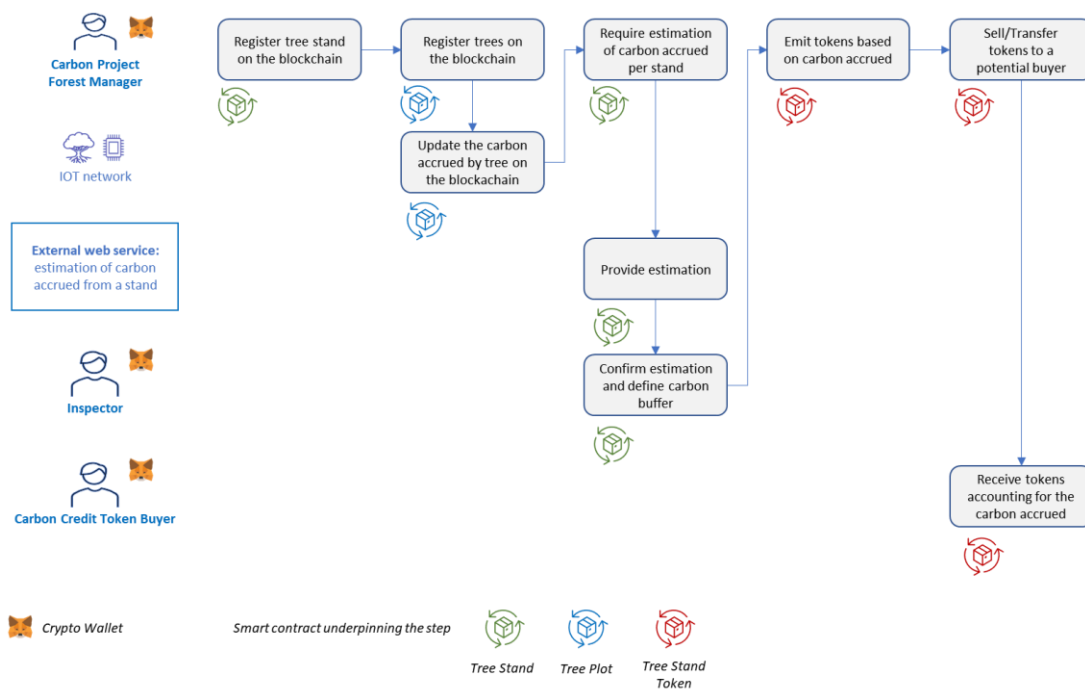
- 1) Verify that all transactions are recorded, tamper-proof and publicly accessible. For this purpose, we implement:
 - a. Three smart contracts deployed on polygon blockchain test network;
 - b. Three roles: carbon manager, stand inspector and carbon tokens buyer;
 - c. Web application to interact with the contracts.
- 2) Ensure that the radial stem growth is recorded, and that the estimation of the kg CO₂ sequestered by the related tree stand and the carbon buffer set-up are monitored, reported and verified. For this purpose, we implement:
 - d. Estimation and recording of CO₂ sequestered at tree level into the network;
 - e. External carbon web-service for the CO₂ estimation at stand level;
 - f. Verification and carbon buffer setting by a third party (inspector role).
- 3) Guarantee that the tokens emitted have unique ownership, can be easily transferred, are thoroughly quantified and limited in the amount by the number of kg CO₂ accrued by the stand. For this purposed we test:
 - g. Controls on the possibility to emit tokens;
 - h. Ability to access and transfer token from personal crypto wallets;
 - i. Transparency on transfer transactions.

In the introduction we describe the scenario in detail.

Introduction

We build a proof of concept implementing the scenario described in Figure 11 reported below. The timeline of the proof of concept is from May to September 2022. We impersonate three roles: a carbon project manager, a project inspector, and a buyer of carbon credit tokens. As first step, the carbon project manager registers two tree stands on the blockchain network. These are homogenous stands of *Prunus domestica* (variety *Susino Prugna D'Angeles*) and are in Modena area, Emilia-Romagna and Policoro area, Basilicata, both in Italy. Full description of the stands is reported in the material and method section. Secondly, the manager records on the network the trees having the stem radial growth monitored by the Tree Talker IoT devices with daily frequency. Once the trees are registered, the carbon data factory derives the biomass and the CO₂ accrued and registers this information on the blockchain network. Given the small daily increment of the tree biomass, we set a monthly blockchain registration to reduce transaction cost. At the end of August, the carbon project manager requests to estimate the CO₂ accrued at stand level to an external web service implemented specifically for this proof of concept. The web service returns a range of values that gets recorded on the network. At this stage, there is the need to verify the estimation and define the related carbon buffer. For this purpose, we impersonate an inspector role reviewing the CO₂ accrued proposed by the third-party service and eventually defining a carbon buffer. The manager emits the tokens base on the carbon confirmed (1 token equals 1 kg CO₂ accrued) and she transfers them to a potential buyer. All transactions are recorded on the polygon blockchain network publicly available with clear ownership, time stamp and tamper-proof. We defined the tokens as TTK (Tree Tokens). It is important to outline that the need of implementing this process is required as monitoring devices like the Tree Talkers cover just specific carbon additional activities (e.g., additional biomass) and cannot be used in the carbon market to estimate other activities due to the need for further analysis and calculations, such as subtracting a leakage or applying a buffer as insurance.

Figure 11: End-to-End scenario covered in the proof of concept.



Material and methods: Policoro and Modena sites description

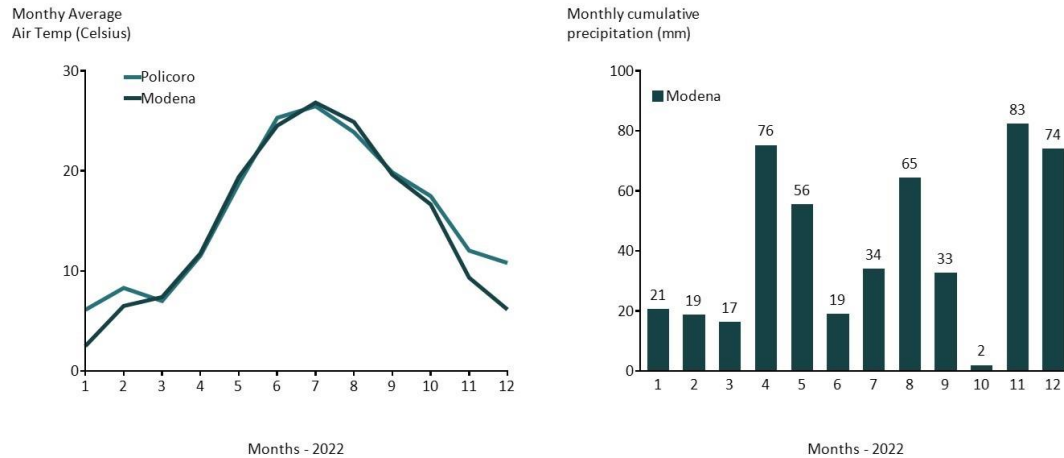
To build the proof of concept of the solution described in Chapter 2, two homogenous stands of *Prunus domestica* (variety *Susino Prugna D'Ange*s) were chosen. *Prunus domestica* is a deciduous tree of small - medium size and it is grown mainly for the fruit crop. Flowering starts usually in early spring followed by the fruits ripening in September. With homogenous stand, we intend that the area can be stratified into a one single layer as tree species, age class, management practices and stoking levels can be considered uniform. The stands are in Modena area, Emilia-Romagna, Italy (44°38'52.19"N, 10°55'31.4"E) and in Policoro, Basilicata, Italy (40° 12' 50.7" N, 16° 40' 46.7" E). The stands deliver intensive agriculture activity for the firm (MonteRé - Coltivazioni Italiane). Information about the stands is reported in Table 6

Table 6: Stands in scope of the PoC.

Stand	Year	Ha	trees	Spacing (Sesto d'impianto)	trees / ha
Modena	2010	5,3	1630	6.5 m x 5 m	308
Policoro	2013	7,5	3125	6 m x 4 m	417

Both locations present temperate climate as reported in Figure 12

Figure 12: Monthly Average Air Temp and cumulative Precipitation for Modena and Policoro locations



During the period of the proof of concept, Radial stem of the trees is of 30-40 cm and height of 3-4 meters. We monitored radial stem changes of 10 trees for the stand in Policoro and of 15 trees for the stand in Modena. Trees monitored are part of a transect and not randomly distributed given the high uniformity of the stand. Radial stem changes are captured by the current non-contact electronic dendrometer produced commercially by SHARP electronics and modified in-house by the Nature 4.0 firm. The sensor uses infrared light to emit a pulse of light which is reflected from the stem surface to a PSD array at time intervals of every hour. The sensor is integrated in the TreeTalker+ version 3.2. The Tree Talker is an IoT platform which can monitor continuously at a sub-hour frequency the physical and functional parameters of the tree i.e., the water transport inside the tree, the diameter growth, the quantity and quality of tree foliage and microclimate and soil parameters (temperature, humidity). The device transmits data, and it can be deployed on clusters of woody-plants in both forest and agricultural sites with different characteristics (e.g., climate, land cover/usage, topography, tree species, age, stand density). TreeTalkers implement wireless communication (using a new LoRa low power chipset) to a Tree Talker Cloud, acting as gateway of the cluster of tree talkers deployed in the plot. The Tree Talker Clouds connects to cellular network thanks to a modem with internet connectivity thus enabling the transmission of the data to a web server (Matasov et al., 2020; Valentini et al., 2019). In our scenario the radial stem changes per single tree are deployed on an FTP server and converted to cumulative CO₂ accrued by using allometric equations and parametric values to estimate dry matter provided by Wu et al., 2012.

Figure 13: Tree Talker device monitoring radial stem growth.



Figure 14: Wireless station receiving the data from the Tree Talkers and sending them via GSM to central server.



Figure 15: Overview of trees monitored for the stand in Modena.



Results and discussion

Preliminary phase: Contracts deployment

As first activities, we deploy the contracts on the polygon test network using brownie development framework. The contracts and all details (e.g., publisher, transaction) are publicly visible in the polygonscan website (<https://mumbai.polygonscan.com/>) being a public blockchain network.

Figure 16: Deployment of forest stand smart contract by carbon forest manager.

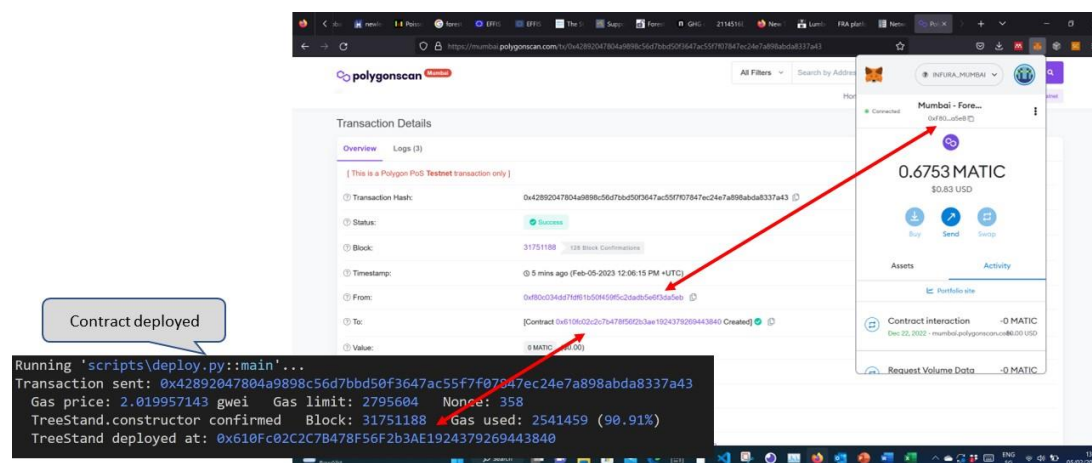


Figure 17: deployment of TreeStand and TreeStandToken on the polygon (test) network

```
Running 'scripts\deploy.py::main'...
Transaction sent: 0xe79269dad697ef1df064c9b7fc9f800064081d1e8025e30f1f6dd3f3c00b3039
Gas price: 1.500000015 gwei Gas limit: 2383530 Nonce: 359
TreePlot.constructor confirmed Block: 31754657 Gas used: 2166846 (90.91%)
TreePlot deployed at: 0xFF9C31A469708B332Dce182445d9b0f4C018F50
Transaction sent: 0x6d6a33194743511b5bdd4c26babc19029a6dcf4d49079c50fb4f20c46d96e6aa
Gas price: 1.500000015 gwei Gas limit: 1394263 Nonce: 360
TreeStandToken.constructor confirmed Block: 31754672 Gas used: 1267512 (90.91%)
TreeStandToken deployed at: 0xcc5D6c9b42e40808694ebD2ab425d7C9F44CaCdA
```

Once contracts are successfully deployed on the network, we can start the project set-up phase where the carbon project manager registers both stand and trees information.

Set-up phase: stand and trees registered on the network

The project manager accesses the web application via the crypto wallet (Metamask) pre-installed on the browser. The crypto wallet is the personal repository where a user stores her private keys to transact assets (crypto currencies, tokens) on a blockchain network.

Figure 18: Authentication into the SaaS solution via crypto Wallet

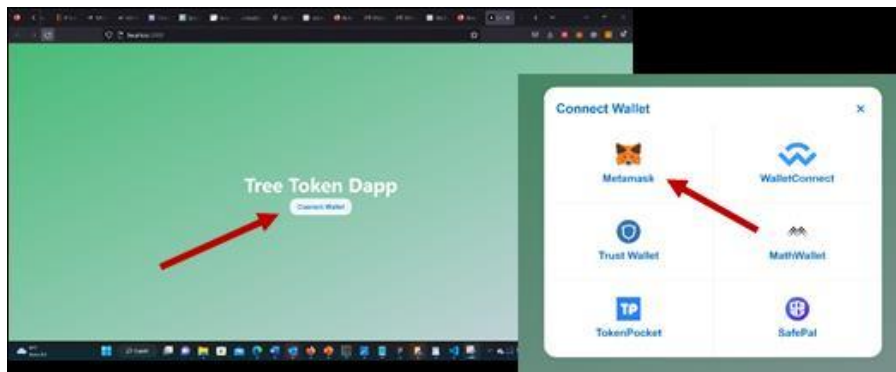
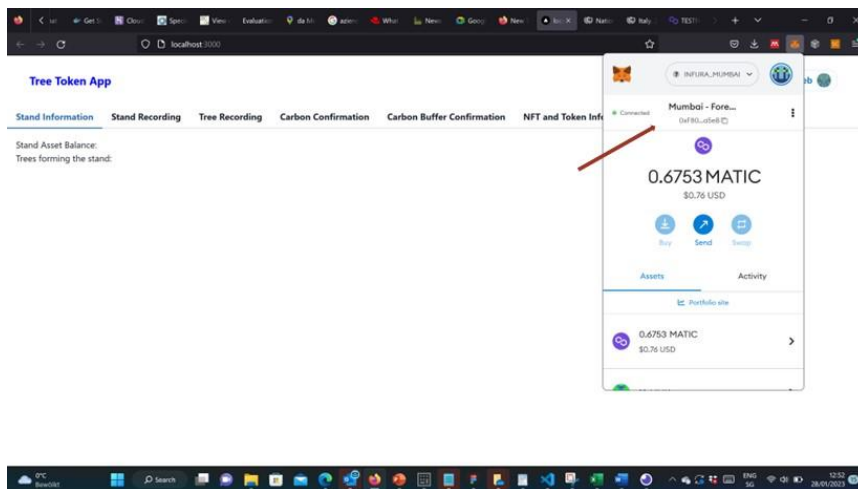


Figure 19: Landing page of the SaaS solution where the manager can interact with the smart contracts signing all transactions via her crypto wallet.



The manager registers the stand on the network entering all the required information. In our scenario she registers just one hectare. She has to sign the transaction via the wallet so that the contract Tree Stand can execute the operation. As for the contracts' deployment, the registration is visible in the application but also public and accessible by everyone in the Polygon test network.

Figure 20: Registration of the stand and confirmation of the transaction via smart wallet

The image shows a web browser displaying a 'Stand Register Form' on the left and a mobile wallet confirmation screen on the right. The form fields are as follows:

- Stand id: 1
- Stand Name: Modena - 44°38'52.19"N, 10°55'31.4"E
- Stand area (ha): 1
- Carbon Project: PoC_Ph4
- Carbon Pool: 1 - Above ground biomass
- Plots monitored: 1
- Total number of trees monitored: 308
- Year: 2022
- Day: 140

A green 'Submit' button is at the bottom of the form. The mobile wallet screen on the right shows a confirmation for a transaction with the following details:

- Estimated gas fee: 0.000043 MATIC
- Site suggested: Likely in < 30 seconds
- Max fee: 0.00004337 MATIC
- Total: 0.00104337 MATIC
- Amount + gas fee: 0.00104337 MATIC

The wallet screen has 'Reject' and 'Confirm' buttons.

Figure 21: Public access and verification of the transaction data

The image shows the PolygonScan website displaying transaction details for a specific transaction. The transaction is confirmed and its details are as follows:

- Transaction Hash: 0x411963227a386a00b10b17225b0b0b43c394c0c275307047163462
- Status: Success
- Block: 31754910
- Timestamp: @ 19 secs ago (Feb-05-2023 02:51:39 PM +UTC)
- From: 0x80c034c79481b509085c2b0c4d03a5eb
- To: Contract 0x4106020207b4799502b3a102437620443040
- Value: 0 MATIC (\$0.00)
- Transaction Fee: 0.000496618504966185 MATIC (\$0.00)
- Txn Type: 0 (Legacy)
- Gas Limit: 364,186
- Input Data:

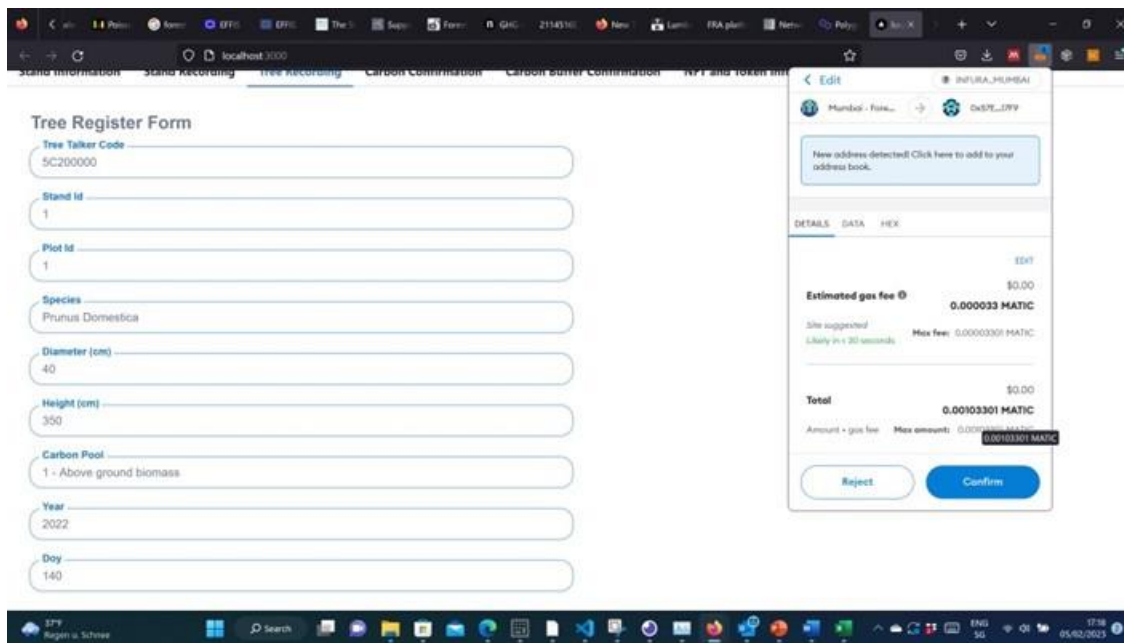
The input data is shown in a table:

#	Name	Type	Data
0	_stand_id	string	1
1	_stand_name	string	Modena - 44°38'52.19"N, 10°55'31.4"E
2	_stand_area	string	1
3	_carbon_project	string	PoC_Ph4
4	_carbon_pool	string	1

A callout box points to the input data table with the text: 'Stand information recorded and visible'.

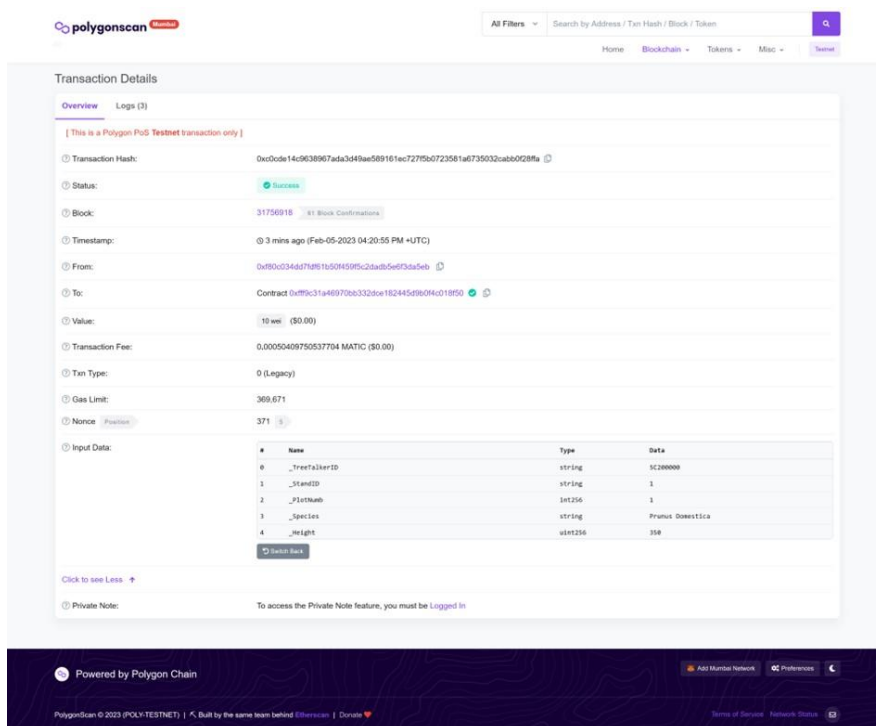
Similar to the registration of the stand, the manager registers the trees on the network entering all the required information.

Figure 22: Registration of the tree and confirmation of the transaction via crypto wallet



and she has to sign the transaction so that the TreePlot contract can perform the registration.

Figure 23: Public access and verification of the transaction data of tree recording



Once completed the registration, all trees are in state living as described in Figure 9 of the previous chapter and the carbon accrual phase can start.

Carbon accrual phase: continuous recording of carbon sequestered at tree level

In the carbon accrual phase, the carbon data factory retrieves the daily radial growth from measured by the IoT devices for every tree stored on an FTP server transformed in cumulative CO₂ accrued. It then performs transactions to the blockchain network to register the value of CO₂ accrued per single tree. As the carbon manager, also the carbon data factory needs an account (private key) to operate on the network. This operation is done programmatically by storing account variables in dedicated .env file. For the purpose of this work, we monitor via the Tree Talkers the CO₂ captured by trees in the two stands during the period of the proof of concept (May – August). Values registered are reported in the figures below:

Figure 24: Cumulative kg CO₂ sequestered by trees monitored– Modena stand

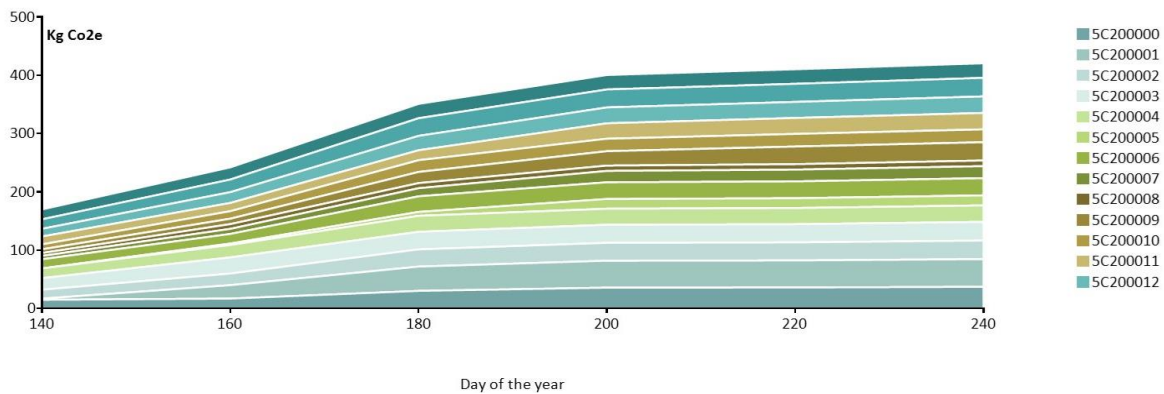


Figure 25: Cumulative kg CO₂ sequestered by trees monitored – Policoro stand

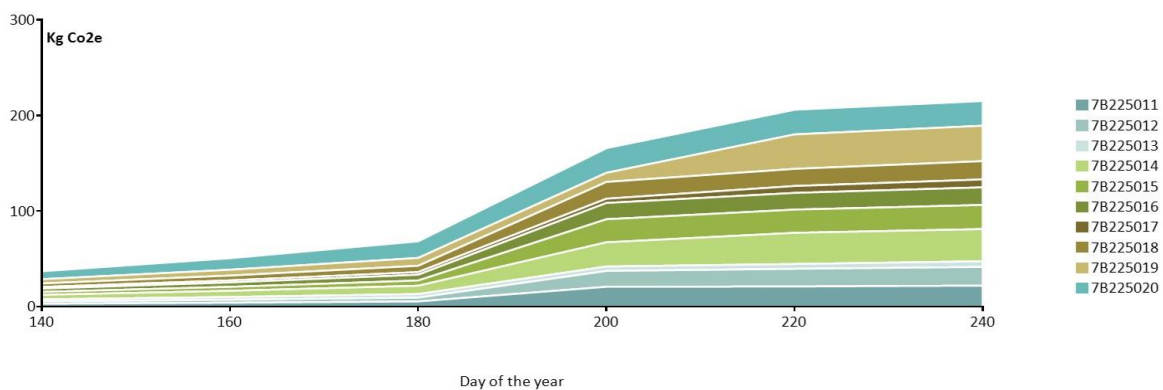
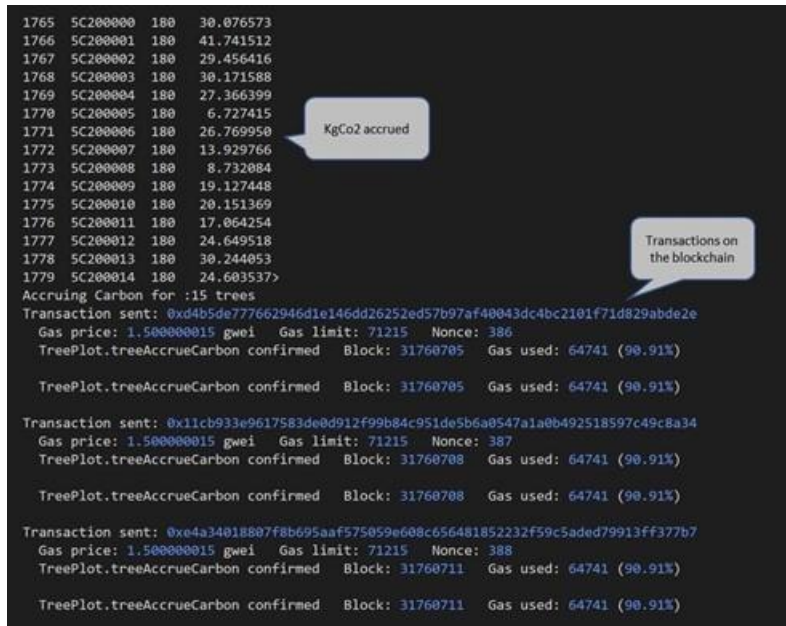
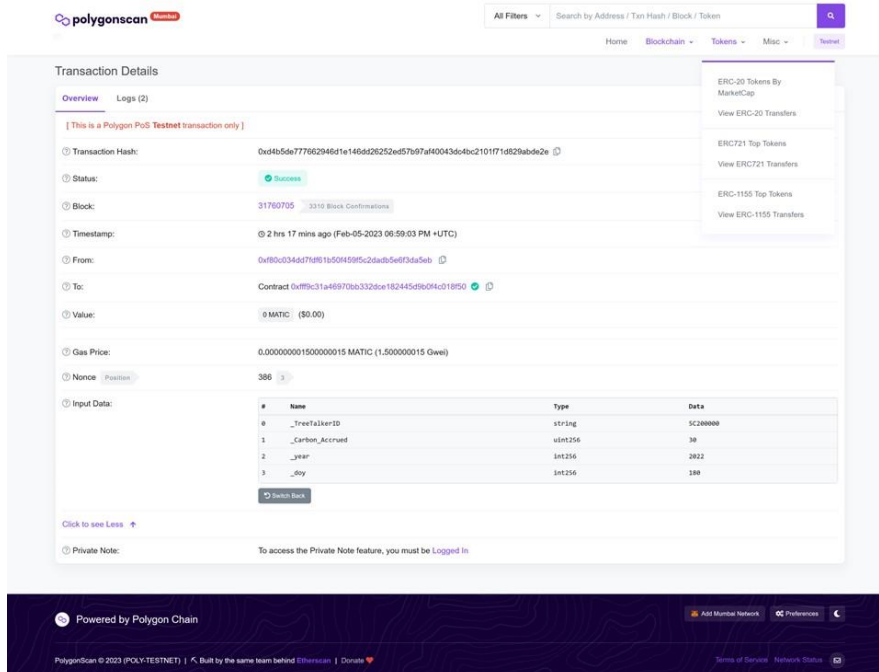


Figure 26: Data factory retrieves kg Co2 data from Tree Talker server via FTP and registers them on the blockchain



The data factory registers on the blockchain network the value of CO₂ recorded as reported in Figure 26. Also in this case, the transactions are publicly available thus making fully transparent the carbon monitoring mechanism of the project (Figure 27)

Figure 27: kg CO₂ recorded on the network for the Tree Talker device 5C20000 at end of June (180 day)



Stand carbon estimation phase: request to an external service

At the end of the monitoring phase, the manager decides to estimate the value of CO₂ accrued at stand level for the “above ground biomass” carbon pool. She requires this estimation to an external service provider by triggering a transaction of the StandCarbon Contract. For the purpose of this proof of concept we have built an example of this service provider. As described in chapter 2 “external” means that these types of services are not necessarily built as part of a specific carbon project, but they can be provided by third parties (e.g., academia, private sector) in order to improve the level of robustness of the CO₂ estimations and the detection of disturbance early-warnings impacting the project.

Smart contracts, thanks to blockchain middleware solutions, enable and track this type of requests thus increasing the overall transparency of the project. The service we built delivers an estimation of the kg CO₂ accrued for the above-ground biomass carbon pool per stand based on the measurements provided by the Tree Talkers. The service assumes that the measures refer to one single homogenous stratum of trees. The service is accessible via web REST APIs. APIs stand for Application Protocol Interface, and it is a mainstream technical solution for building and integrating software applications. In our scenario both the data factory and the Tree Stand smart contract call these APIs.

Figure 28: Carbon web service for the estimation of carbon accrued at stand level

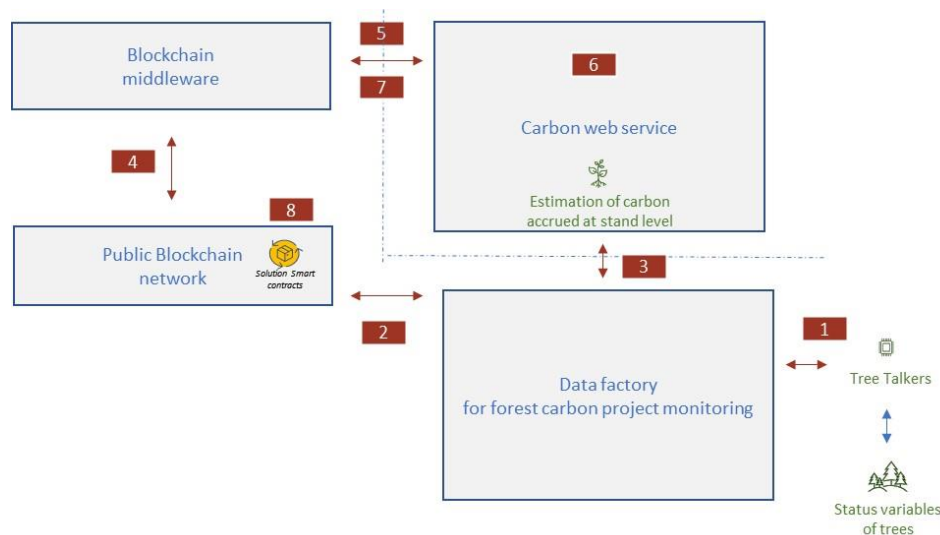


Figure 28 reports the solution components involved in this phase and the related steps:

- 1) Tree Talkers record the radial growth of monitored trees;
- 2) The Data Factory converts radial growth to kg CO₂, and it registers the value on the blockchain network;

- 3) The Data factory calls the API exposed by the web service to share information required for the estimation;
- 4) The manager triggers the smart contract function to receive the CO₂ estimation at stand level;
- 5) The blockchain middleware (chainlink) performs the API call;
- 6) The web service provides the estimation;
- 7) The middleware passes the information to the smart contract;
- 8) The smart contract registered the proposed estimation on the network.

The estimation service exposes the endpoints (APIs) reported in Figure 29:

Figure 29: API end points to interact with the stand carbon estimation service (<https://carbon-webserver.onrender.com/swagger-ui>)

stands Operations on stands ^	
GET	/stand/{stand_id} ▾
PUT	/stand/{stand_id} ▾
DELETE	/stand/{stand_id} ▾
GET	/stand ▾
POST	/stand ▾
trees Operations on trees ^	
GET	/tree/{_IoTdevice} ▾
PUT	/tree/{_IoTdevice} ▾
GET	/tree ▾
POST	/tree ▾

The data are passed in standard JSON format. For our purpose, we defined the structure as reported in Figure 30 where a stand contains an array data structure of trees

Figure 30: Data structure of stand and tree for the stand carbon estimation service

```

Stand ▾ {
  year* > [...]
  carbon_project* > [...]
  confidence_interval_bottom* > [...]
  confidence_interval_top* > [...]
  trees ▾ [
    readOnly: true
    PlainTree ▾ {
      height* > [...]
      C_Kg_buffer* > [...]
      year* > [...]
      C_Kg_accrued* > [...]
      diameter* > [...]
      doy* > [...]
      carbon_pool* > [...]
      carbon_recording_method* > [...]
      plot* > [...]
      IoTdevice* > [...]
      species* > [...]
    }
  ]
  C_Kg_accrued_proposed* > [...]
  trees_number* > [...]
  plot_size_warning* > [...]
  doy* > [...]
  carbon_pool* > [...]
  stand_name* > [...]
  id > [...]
  inspector_required* > [...]
  sample_normality_warning* > [...]
  confidence_level* > [...]
  C_Kg_buffer_proposed* > [...]
}

```

Once the smart contract calls the API with the method `get/[stand_id]`. The services implement the following:

- It calculates the coefficient of variation C_v of the sample where n is equal to the last observations recorded at the same day (Kg CO₂ accrued per tree monitored), μ_n is the mean and σ_n is the standard deviation

$$C_v = \frac{\sigma_n}{\mu_n}$$

- It calculates the presence of any outlier in case there are values outside 1.5 times the interquartile range (IQR)

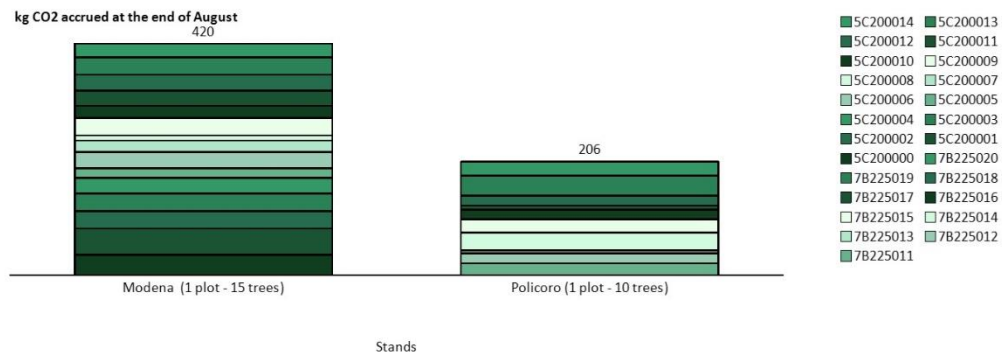
After the statistical assessment, the service calculates the confidence interval of the kg CO₂ mean accrued by the tree population with a confidence level of 95% by using the t student distribution with the degrees of freedom $d = n - 1$. In case of major departure from normality due to strongly asymmetric and presence of outliers so that the confidence interval is larger than 10% of the mean (Pearson et al., 2007) the service returns a warning flag in the response to alert the receiver that the estimation should be carefully assessed asking for a verification of the Inspector.

After the definition of the confidence interval the service checks the size of the sample against the total number of trees. For the purpose of this study, we set the threshold at 3% as standard used by the Tree Talker platform. If the sample size is smaller than the threshold, the service returns a warning to alert the receiver that the estimate should be confirmed by the Inspector.

The service then returns in the JSON response the top and bottom kg CO₂ values of the confidence interval multiplied by the number of trees forming the stand together with the warning flags requiring data verification. The response values are recorded on the blockchain network by the Tree Stand Contract.

In our example the manager performs the request of the estimation for both Modena and Policoro stands for the 28th of August (240 day of the year) via the web application. The values of kg CO₂ accrued until that day for the plots of the two stands are reported in Figure 31. The two stands account for one thousand trees each.

Figure 31: Cumulative Kg CO₂ accrued in the monitored plots Modena and Policoro stands (August 28)



The transactions get recorded on the blockchain as reported in Figure 32 (Modena stand) where we share the request and the response performed by the Chainlink middleware and the estimated value of CO₂ recorded. Confidence intervals of the CO₂ estimated per stand with the related warnings are reported in Table 7.

Figure 32: Estimation request and response for the accrued CO₂ for the Modena stand (1 ha, 308 trees)

Txn Hash	Method	Logs
0x3d1fd3ff0c4dbd7b90... # 31924660 7 mins ago	0x6ae0bc76	RequestCarbonAccrued (index_topic_1 bytes32 requestId, uint256 Carbon_accrued) [topic0] 0x93d747404360798a82494f870d5f1e17d12ee8457c1a059f515a6c94bb7cd49f [topic1] 0xa9c7aa27c1d135df342c41c6bff6a1528493948f566d3c34d76996c00580270e Num → 8.5e+32 Estimation of the Co2 accrued by the stand recorded on the network
0x3d1fd3ff0c4dbd7b90... # 31924660 7 mins ago	0x6ae0bc76	ChainlinkFulfilled (index_topic_1 bytes32 id) [topic0] 0x7cc135e0cebb02c3480ae5d740... [topic1] 0xa9c7aa27c1d135df342c41c6bff6a1528493948f566d3c34d76996c00580270e Response fulfilled
0x26933f70b754f7589c4... # 31924656 7 mins ago	0x5f956d1a requestVolumeD (string)	ChainlinkRequested (index_topic_1 bytes32 id) [topic0] 0xb5e6e01e79f91267dc17b4e6314d5d4d03593d2ceee0fbb452b750bd70ea5af9 [topic1] 0xa9c7aa27c1d135df342c41c6bff6a1528493948f566d3c34d76996c00580270e

Figure 33: JSON response from the carbon web service

```
{
  "C_Kg_accrued_proposed": 8500,
  "C_Kg_buffer_proposed": 2125,
  "carbon_pool": 1,
  "carbon_project": "PoC_PhD",
  "confidence_interval_bottom": 7001,
  "confidence_interval_top": 9999,
  "confidence_level": 0.95,
  "doy": 240,
  "id": 1,
  "inspector_required": 1,
  "plot_size_warning": 0,
  "sample_normality_warning": 1,
  "stand_name": "Stand_Modena"
}
```

Table 7: Proposed estimation of Kg CO₂ for the stands and related warning status

Stand	Confidence interval_Top	Confidence interval_Bottom	Accrued CO ₂ value proposed	Sample Normality warning	Sampe size warning	Inspector required
Modena	9999 Kg CO ₂	7001 Kg CO ₂	8500 Kg CO ₂	Yes	No	Yes
Policoro	11739 Kg CO ₂	5857 Kg CO ₂	8798 Kg CO ₂	Yes	Yes	Yes

Buffer definition phase: definition of the carbon available for trading

To emit and trade the carbon tokens, the solution requires an Inspector to assess the validity of the kg CO₂ estimated at stand level and set a so-called carbon buffer: a quantity of kg CO₂ accrued that cannot be traded but must be stored to as a contingency to assure carbon permanence. In our scenario, the review of an inspector is also required because of the sample normality and sample size warning reported in the previous section. Furthermore, due to the management activity on the stands we know that on yearly average 25 kg of biomass per tree gets removed during pruning. We simulate that via web application the inspector decides to implement a 25% of the total kg CO₂ accrued as carbon buffer following the guidelines proposed by Chiriaco et al., 2020. As reported in Figure 34 the stand carbon balance gets updated on the network.

Figure 34: CO₂ account for Modena stand registered on the network and publicly available: kg tokenized (0), kg available (6375), kg accrued (8500), kg buffer (2125), carbon pool (1 - above ground biomass), year (2022) and doy (240)

7. Stands

<input> (string)

1

Query

stand_id string, stand_name string, stand_area string, carbon_project string, plots_monitored int256, CarbonAccount tuple, total_trees int256

[Stands method Response]

>> stand_id string: 1
 >> stand_name string: Stand_Modena
 >> stand_area string: Modena 44°38'52.19"N - 10°55'31.4"E
 >> carbon_project string: PoC_PhD
 >> plots_monitored int256: 1
 >> CarbonAccount tuple: 0,6375,8500,2125,1,2022,240
 >> total_trees int256: 308

Carbon trading phase: tokenization and transition

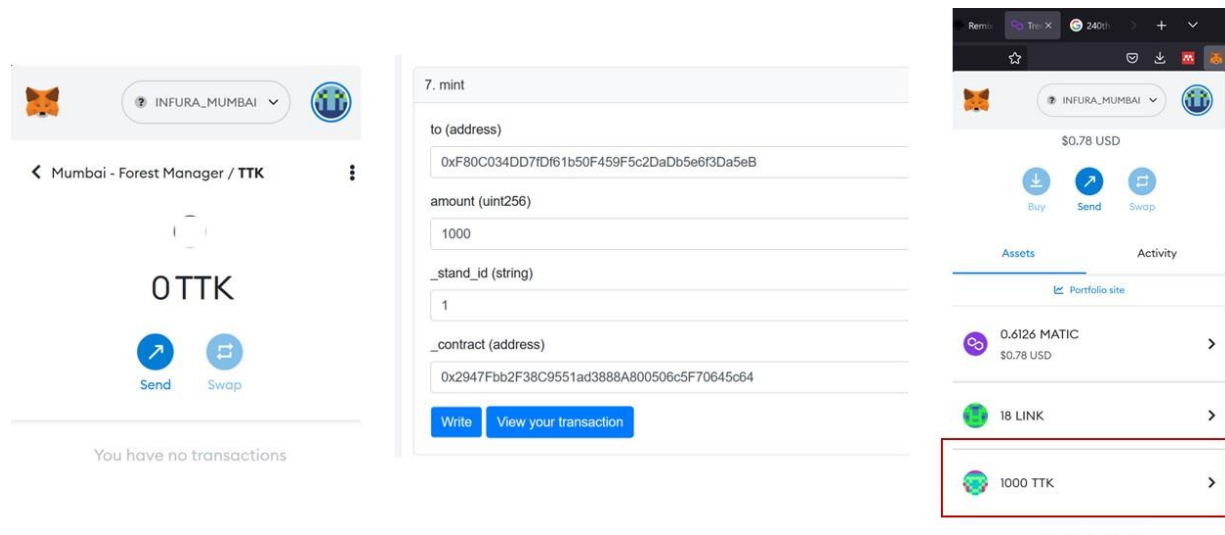
Once the carbon buffer at stand level has been confirmed by the inspector, the carbon manager can emit the Tree Tokens (TTK). As mentioned, we defined in the Tree Stand contract that one TTK is equal to one kg CO₂. Therefore, the forest manager has the budget reported in Table 8

Table 8: Balance of kg CO₂. for the stands at the end of the monitored period

Stand	kg CO ₂ tokenized	kg CO ₂ available	kg CO ₂ accrued	kg CO ₂ buffer
Modena	0	6375	8500	2125
Policoro	0	6599	8798	2199

The manager decides to tokenize 1000 kg of CO₂. from Modena stand. She executes via the web application the transaction that gets recorded on the network: and she can see the value of 1000 TTK available in her crypto wallet.

Figure 35: TTK balance in the crypto wallet before and after the transaction



On the network, the balance for the Modena stand is updated as reported in Figure 36 where the amount of kg CO₂ available is decreased to 5375 and the amount of tokens generated is increased by 1000, enabling therefore the manager to emit just the amount of kg CO₂ estimated by a third party and approved by the Inspector.

Figure 36: Stand carbon balance updated after tokenization of 1000 kg CO₂. Available CO₂ decreased to 5375 kg

<input> (string)

Query

└─ stand_id string, stand_name string, stand_area string, carbon_project string, plots_monitored int256, CarbonAccount tuple, total_trees int256

[Stands method Response]

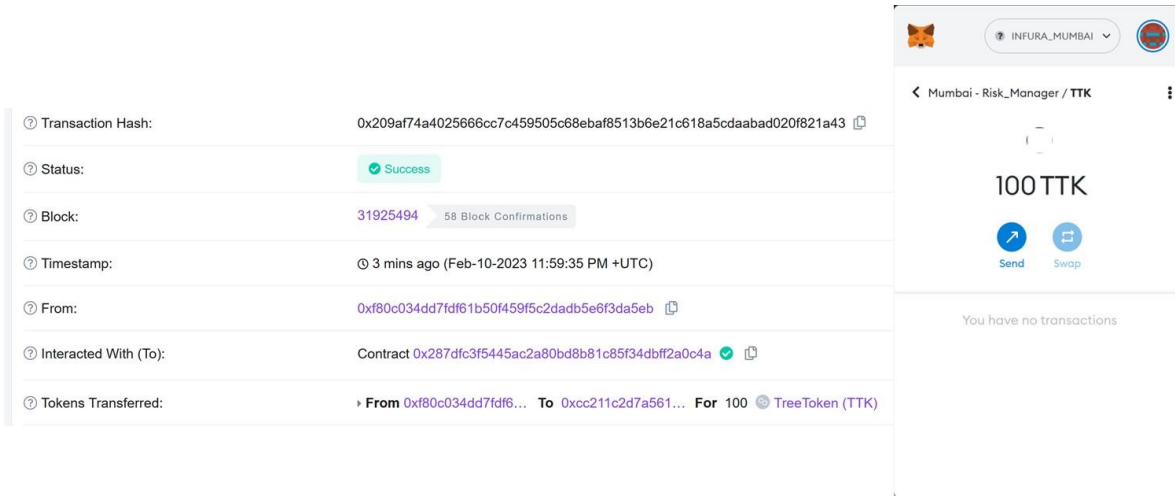
```

>> stand_id string: 1
>> stand_name string: Stand_Modena
>> stand_area string: Modena 44°38'52.19"N - 10°55'31.4"E
>> carbon_project string: PoC_PhD
>> plots_monitored int256: 1
>> CarbonAccount tuple: 1000,5375,8500,2125,1,2022,240
>> total_trees int256: 308

```

She then decides to transfer 100 TTK tokens from her crypto wallet to a potential buyer that can therefore claim ownership on these tokens and on the related amount of kg of CO₂ sequestered they represents. The token transfer functionality is an out of the box capability available on the blockchain as it encompasses the possibility to transfer asset in fully traceable way thus solving the issue of the double spending and the need of a central authority. Once, the transfer transaction is performed the new owner receives in her wallet tokens that are backed by a real asset, robustly quantified, additional, permanent, and uniquely claimed. It is important to outline that a carbon credit can in case be transferred many times only until it is not used for the offsetting of a specific amount of emissions and at that point it must be revoked by the system. TTK tokens must therefore have the property to be “burnable” thus allowing token holders to destroy their tokens so that it can be recognized off-chain.

Figure 37: Asset transfer recording and visualization of the 100 TTK (equal to 100 kg CO₂) to a new owner



Conclusion

In this chapter, we were able to show that the combination of blockchain technology and the Tree Talker IoT platform to daily record the radial stem growth of trees enables the possibility to fully monitor, report and verify the total value of kg CO₂ accrued by a stand for the above-ground biomass during a defined period of time. We delivered a web application acting as a SaaS (Software as a service solution) to interact with the smart contracts via browser and with the personal crypto wallet. In this way, users do not incur in any set-up software cost and activities. We showed that the solution can integrate via standard API calls with external web services to get key insights. For this purpose, we implemented a web-service to estimate the total kg CO₂ accrued by a stand based on the data from the monitored tree plot. The service also provides an indication of the statistical significance of the data collected and the need to have an in-situ control by an inspector. All this feedback is immutably recorded on the blockchain to improve the overall controls quality during the project lifecycle. Finally, we tested the possibility to tokenize the kg CO₂ accrued thus allowing the transferring of tokens in a transparent and auditable way with clear asset ownership. It is important to outline that this model can be easily extended to other tree and forest ecosystem services related to the LULUCF sector by integrating additional physical-virtual digital sockets (e.g. flux towers, terrestrial lidars, other IoT devices). The solution is in fact open by design and it is able to manage independently different type of state variables at both tree and forest levels as long as the nested approach proposed in chapter one for a forest digital twin is implemented (twinning of multiple trees together with the forest entity using a common data modeling language). The common data modeling language ensures that data ingestion, data modelling and data sharing is standardized thus ensuring interoperability with the blockchain and external web-service providers. This approach can unlock the possibility to deliver “premium” tokens representing the value not only of the kg CO₂ accrued (carbon sequestration) but also of other key ecosystem services such as g/m² for the particulate

absorption on tree canopy, soil volumetric water content for the water runoff or W/m^2 for the tree energy balance.

Forest carbon offset projects and MRV solutions: an economic assessment

Goals of the chapter

The main goal of the chapter (GOAL-4) is to perform an economic assessment of afforestation projects generating carbon credits in different scenarios and conditions such as 1) climate region, planted species, MRV solution adopted, fire risk, project transaction costs, and carbon credit price. We focus on the EU area. In general, a project can be considered economically viable when its economic benefits exceed costs (Assessing project feasibility - World Bank) including all externalities and environmental impacts. For the purpose of this study, we narrow the scope of the analysis focusing just on the financial aspects and on the following objectives:

- 1) Estimate the project financial return:
 - a. Identify main revenues and financial costs project components;
 - b. Estimate the net present value (NPV) of the project;
 - c. Assess the value added of the project in terms of NPV increase compared to the NPV generated by forest entrepreneurial activities in EU;
- 2) Assess how the wildfire risk factor impacts the project:
 - a. Estimate the expected reduction of project NPV;
 - b. Estimate the expected reduction of project biomass generated;
 - c. Discuss how project lifespan and location influence the wildfire risk;
- 3) Discuss qualitatively the market price premium, meaning the additional price compared to the current carbon credit price in the voluntary market, that a buyer could pay to acquire carbon credits generated by a project implementing an advanced MRV solution.
 - a. Introduce the implementation costs of an advance MRV solution;
 - b. Identify the minimum market price premium compared the current carbon credit price;
 - c. Perform a qualitative benefit analysis generated by the minimum market price premium under different carbon price scenarios and current MRV cost benchmark.

Material and methods

Model structure and assumptions

We focus on European Union area to have full homogeneity of the data and we select as a sample for this study, the country with the largest forest extension per European region as defined in (State of Europe's Forests, 2020). We select 1) Sweden (North Europe), 2) France (Central-West Europe), 3) Poland (Central-East Europe), 4) Italy (South-West Europe), 5) Greece (South-East Europe).

Table 9: European countries in scope of this study and related forest extension. Source: (State of Europe's Forests, 2020)

Region	Country	Forest extension (1000 ha)
North Europe	Sweden	27980
Central-West Europe	France	16836
Central-East Europe	Poland	9420
South-West Europe	Italy	9297
South-East Europe	Greece	3903

For our estimation, we apply the Net Present Value (NPV) methodology also used in afforestation projects (Hou et al., 2019) reported in the equation below. We estimate the cashflow baseline per hectare (CBL) in the forestry sector in absence of forest carbon project and we sum up the carbon project revenues (R) and costs (C) to be realized over the project life span (T). We discount all three components by a discount rate (d) to make them comparable.

$$NPV = \sum_{t=0}^T \frac{CBL_t}{(1+d)^t} + \sum_{t=0}^T \frac{R_t}{(1+d)^t} - \sum_{t=0}^T \frac{C_t}{(1+d)^t}$$

The cash flow baseline per hectare is estimated as the sum of the yearly intrapreneurial income (operating surplus) plus five-years depreciation of the gross fixed capital in the forest sector. Following Eurostat definition, the intrapreneurial income corresponds to the profit before taxes usually adopted in business accounting. Project revenues depend on the net carbon sequestered per year multiplied by the yearly market price of the related carbon credits. We consider the net carbon sequestered (t CO₂/ha/year) coming from 1) the carbon pools derived by planting trees (above and below ground biomass, soil organic content) and 2) the avoided carbon emission generated by another land use applicable in the absence of project as proposed in the OECD working paper by (Grafton et al., 2021). For the purpose of this simulation, we consider agriculture as other land use. Namely, agriculture is the major alternative land use for forests (FAO; UNEP, 2020). Other options could have been grazing and land used for urbanization. We also analysed this last carbon pool separately as the EU Regulation Proposal Framework for Carbon Removals states that only potential GHG emissions increase due to the implementation of the carbon removal activity should be included, but not the avoided carbon emissions generated by any other land use applicable in the absence of project. We anyway not fully

removed this carbon pool from our analysis to evaluate the impact on the profitability of the projects and on the type of tree plantation in case of removal. Following the conservative approach defined by Chiriaco et al., 2020 we assume that just the net carbon sequestered during the first twenty years of the project can be available for trading reduced by a carbon buffer defined as percentage (25%) of the net carbon sequestered.

One of the most prominent issue about carbon forest project is the permanence of the carbon sequestered during the entire project life span. Forests are subject to both natural anthropogenic disturbances such as wildfire, pests, extreme events, illegal logging and forest conversion to other land uses. The impact of these disturbances is supposed to increase in the near future due to climate change. In our simulation, we focus on wildfire risk. For the project, we proxy the forest wildfire hazard rate at country level by assessing the yearly fraction of burn forest hectares versus the total forest hectares in the country. To be conservative, we average the three highest values of the last ten years of observations, and we assume this value to be constant for the project lifespan. We don't differentiate between fire severity, and we assume the worst-case scenario: a high intensity wildfire replacing the stand and releasing all carbon accrued in the project until the occurrence of the event. By having the hazard rate constant, we estimate the probability p of one single fire event as a Poisson distribution where λ is the hazard rate of the fire event, t is the project timeline.

$$p_f(t) = e^{-\lambda t}$$

We differentiate project costs in 1) transaction costs and 2) MRV (monitoring, reporting and verification) costs. For the purpose of this work, we consciously treated separately the expenses related to the MRV. We compare two types of MRV costs 1) MRV cost benchmark available in literature, 2) the cost of building an advanced MRV solution as described in chapter two. To be conservative, we assume that advanced MRV solution do not bring any additional revenue from other ecosystem services other than the one from carbon sequestration. This is a conservative approach since the monetary compensation for other forest ecosystem services such as air and water regulation, water supply, flood and soil erosion control, habitat for biodiversity are already in place in many countries and not only in Europe. One notable example outside Europe, it is the Gross ecosystem Product (GEP) (Ouyang et al., 2020). GEP condenses in a unique monetary metric the value of ecosystem services from multiple sources, therefore policy makers can use it to foster green economic growth in combination with the Gross domestic product (GDP) and other economic indicators. China is using GEP to sustain green growth for example by implementing compensation mechanisms like transfer payments between different geographic areas.

Data source

In this section, we describe the data sources used in the financial projections reported in the “results and discussion” paragraph of the chapter. A summary of the data sources is reported in Table 13. For the discount rate applied for the NPV calculation we use the average rate of the

30- years US treasury bond from 2022 to 2000 almost equal to 3.5% per year. The following data sources are presented starting from revenues to cost components.

All estimations of carbon removal rate are in t CO₂ / ha / year. For the estimation of the CO₂ removal rates for the carbon pools related to biomass accumulation we rely on the data provided by (Bernal et al., 2018) reported in the table below and clustered by selected planted species and climatic regions applicable to the countries in scope of our analysis.

Table 10: Global carbon dioxide removal rates from forest landscape restoration activities. Source: Bernal et al. 2018

Planted species	Climatic region	Removal rate (t CO ₂ ha ⁻¹ year ⁻¹)	Half CI95
Oak	Temperate, humid	9.5	3.5
Oak	Temperate, dry	5.3	3.5
Eucalyptus	Temperate, all	37.9	5.5
Broadleaf	Boreal	8	1
Broadleaf	Temperate, all	11.8	1.4
Pine	Boreal	10.2	4.9
Pine	Temperate, humid	21.1	4.5
Pine	Temperate, dry	7.6	2
Conifer	Boreal	4.5	1
Conifer	Temperate, humid	11.6	3.6
Conifer	Temperate, dry	6.4	1.9

We use data provided by country in the National Inventory Reports until 2020 (*National Inventory Submissions* / UNFCCC, 2022) to forecast changes due to afforestation projects in the Soil Carbon Content (SOC) in the upper 30 cm of terrain. For the emission savings due to the alternative use of land we consider the country average per hectare in case of agriculture use reported by the World Bank in the (*World Development Indicators* / DataBank, 2023).

Table 11: Emission savings due alternative use of land (agriculture). Source: World Bank.

Region	Country	Removal rate (t CO ₂ ha ⁻¹ year ⁻¹)
North Europe	Sweden	2.167
Central-West Europe	France	2.358
Central-East Europe	Poland	2.179
South-West Europe	Italy	2.005
South-East Europe	Greece	1.012

For the estimation of cash flow baseline generated by forest enterprises in Europe we rely on the data available in State of Forest Europe 2020. We sum up the entrepreneurial income and the depreciation per region for the last year monitored (2015) and we apply the 2% as the average yearly growth between 2000 – 2015 (period of data availability) for the duration of the project. Depreciation is calculated as the gross fixed capital invested per hectare per year on a life span of 5 years. Also in this case, we apply and yearly growth of the capital investment of 3% as the one registered between 2000 – 2015 in Europe.

Table 12: 2015 Entrepreneurial income and gross fixed capital in the European regions. Source: State of Forest Europe 2020

Region	Entrepreneurial income €/ha / year	Gross fixed capital €/ha /year
North Europe	94.7	25.5
Central-West Europe	122	30.1
Central-East Europe	6.6	15.4
South-West Europe	212	18.1
South-East Europe	27.2	3.9

We rely on the World Development Indicators (WDI) to evaluate the land opportunity cost by using the ten years average of the monetary value added per hectare of agricultural land per country. We use the same methodology provided by (Grafton et al., 2021) to estimate the transaction costs. We assume transaction cost as percentage of the area preparation costs under the hypothesis that the more the implementation of the project is complex the more the set-up phase will incur in higher cost. To estimate the applied percentage to the area preparation cost, we consider as a proxy the average value of the ease-of-doing-business index from WDI database (2015-2019) scaled in a range between 10% to 90%. In the preparation costs we include 1) cost of labor 2) cost of materials. As source of the cost of labor we consider the value added per employed person available in WDI (EUR/person/year) per country in the agriculture sector. For afforestation project we assume two to five working days per hectare for site preparation (e.g., mounding, chopping, trenching,) and planting. We do not include additional forest management costs as a dedicate cost item as these activities are already covered in the forest entrepreneurial income to avoid double counting.

For the MRV cost benchmark we rely on the average value of €0.8 per t CO₂e provided by (Bellassen et al., 2015) for reforestation projects. For the cost of building an advance MRV solution we assess two types of physical-digital sockets in the simulation: 1) flux-towers measuring the overall exchanges (carbon dioxide and water vapor exchange) between the project area and the atmosphere (Fluxnet, 2021); 2) the Tree-Talker IoT platform to monitor the physical and functional parameters at tree level. We estimate Flux-tower's coverage of one hundred hectares, a cost of fifty thousand EUR per tower on a monitoring area of at least 50% of the total project area. Flux-towers have the advantage of large and continuous monitoring footprints. Furthermore, by monitoring overall carbon dioxide exchange they also include the measure of carbon flux generated by SOC. The level of monitoring uncertainties (defined as the coefficient of variation) is about 5-15% (Sonn et al., 2022) whereas the best performance is obtained in cases of homogeneous tree stands like afforestation projects in scope of our analysis. Tree-Talker IoT platform as described in previous chapters can monitored functional parameters of the tree such as radial stem growth. The measurement footprint is at tree level, and we assume a coverage a of 1-3% of the total trees per hectare. Total cost per device is around three hundred EUR. This MRV approach follows the principles of nested design of a forest digital twin described in chapter 1 where we integrate over time and for different spatial scales (from tree to forest) the

related physical and physiological processes by using, in an integrated manner, multiple technological means. For the risk of wildfire, we rely on the data provided by Copernicus European Forest Fire Information System (EFFIS, 2023) providing at country level, the total number of hectare/years experiencing wildfire

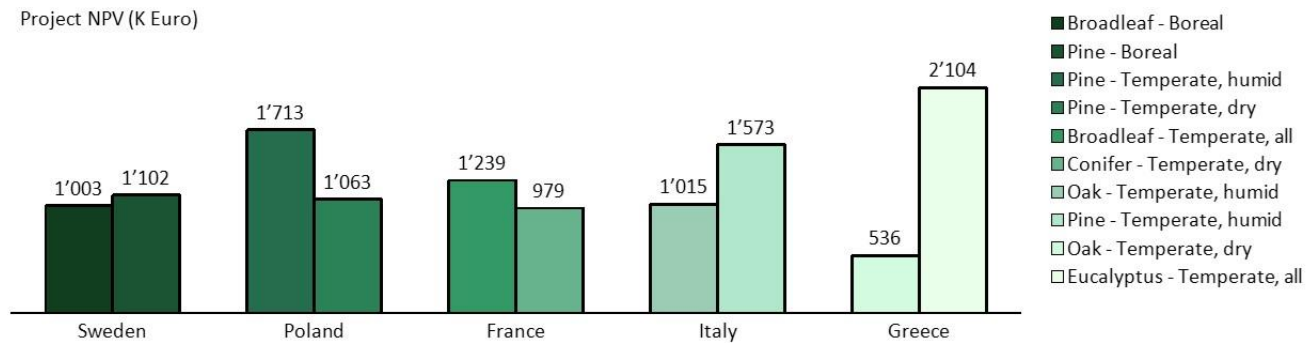
Table 13: data sources used for the financial modelling

c	Model component	Unit of Measure	Reference
1	NPV discount rate	%	US treasury bond from 2022 to 2000
2	Net carbon sequestered from biomass	t CO ₂ / ha / year	Bernal et al. 2018
3	Net carbon sequestered form SOC	t CO ₂ / ha / year	National Inventory Reports
4	Avoided emission from other land use	t CO ₂ / ha / year	WDI
5	Income and depreciation for EU forest enterprise (cash flow baseline)	t CO ₂ / ha / year	(State of Europe's Forests, 2020)
6	Carbon buffer	%	ISMEA
7	Project transaction costs	€	WDI
8	MRV cost benchmark	€ / t CO ₂	database/OECD (Bellassen et al., 2015)
9	Wildfire risk	%	EFFIS

Results and discussion

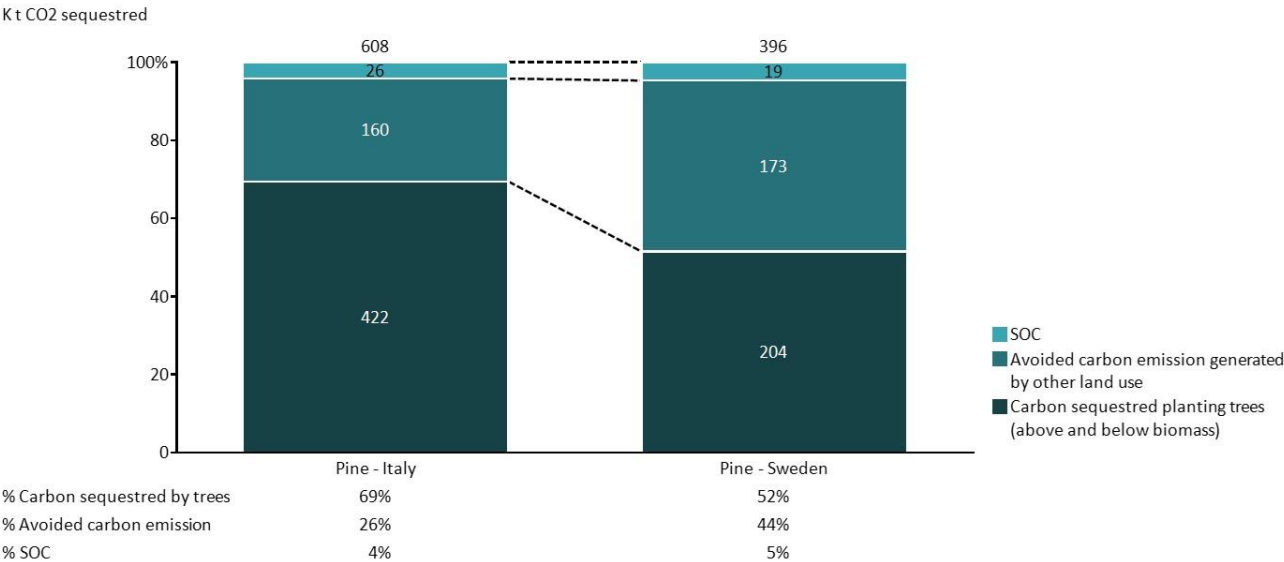
We assume an afforestation project for an area of 1000 ha with lifespan of 80 years and CO₂ accrued incrementally available for carbon credit emission just for the first 20 years. At the beginning of the project, we assume a carbon credit price of €4 (*Carbon Credits.Com*, 2023) aligned to the lowest value in 2022 for the voluntary carbon market with an annual growth of 4% in line with the International Energy Agency CO₂ Price Projections (Global Energy and Climate Model Documentation, 2022). It is important to outline that carbon prices can vary substantially based on factors such as location, project type and market dynamics. Discussing the price dynamics for carbon credits is out of the scope of this study, therefore we used the most conservative value as starting point for the analysis. Following the settled objectives, firstly we estimate the project NPV. We perform the analysis for different planted species in the selected countries in line with their main climate regions (FAO; UNEP, 2020). Figure 38 reports selected project NPVs clustered by country and planted species. As expected, the type of planted species and the climate region greatly influence the project NPV as we can see in the Greece and Poland examples compared to the country differences (e.g., cost structure, avoided carbon emissions due to agriculture activities).

Figure 38: Afforestation project NPV for different countries, climate regions and planted species



In fact, as reported in Figure 39 for Italy and Sweden project examples, if we analyze the carbon pools contribution to the CO₂ sequestered per project, we can notice that the average major avoidance of carbon emissions due missing agriculture land use in Sweden does not compensate the reduction of the carbon pools for above and below biomass thus remaining the major driving factor of revenues.

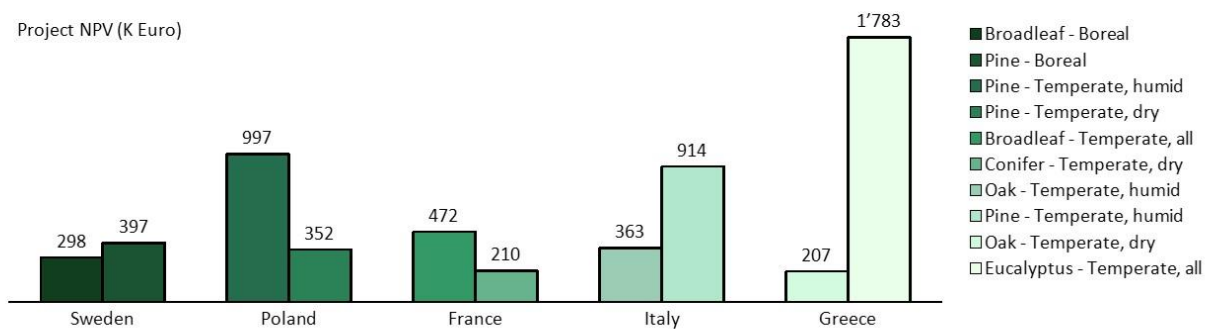
Figure 39: carbon pools contribution to the total CO₂ sequestered for an afforestation projects of pine in Italy and Sweden



Nevertheless, the relative impact of the component “Avoided carbon emission” is significant for all countries as reported in Figure 40, where compared to Figure 38 this component is removed. From this analysis, as a preliminary result, it emerges that without including the carbon pool

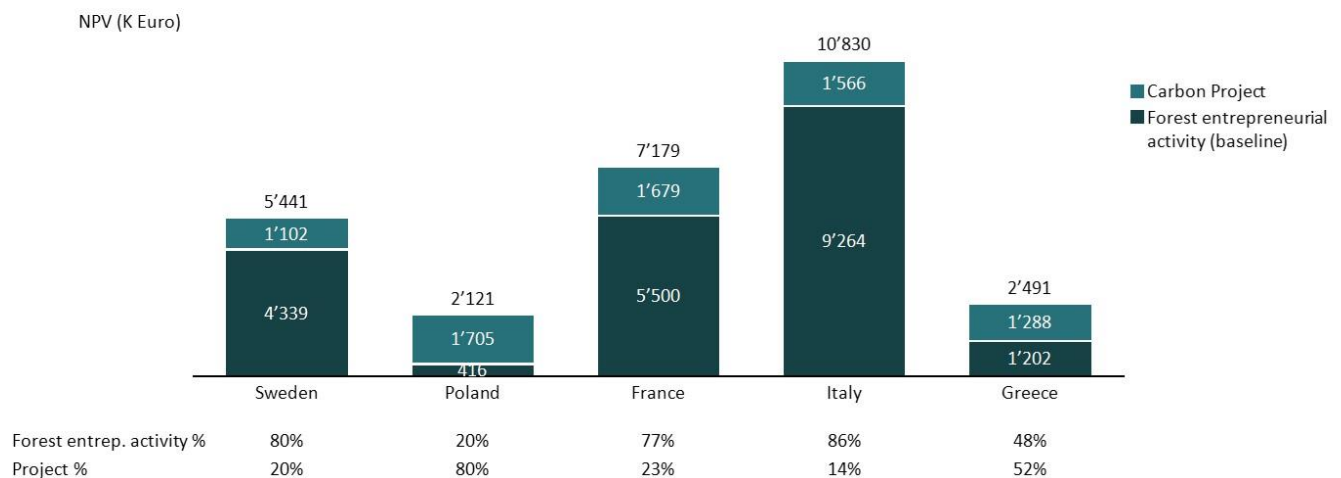
“Avoided carbon emission” there could be the tendency to implement afforestation projects relying on non-native species given the highest sequestration potential that generates higher returns (Eucalyptus in Greece).

Figure 40: Afforestation project NPV for different countries, climate regions and planted species, without the “Avoided carbon emission” carbon pool



Interestingly, we see significant country differences in terms of relative project value added when we sum up the NPV generated by an afforestation project to the expected NPV generated by forest entrepreneurial activities based on average income per hectare (State of Europe’s Forests, 2020). This outcome suggests that areas where forest entrepreneurial activities have low profitability could benefit from this type of projects as additional and significant source of profit. For example, implementing a forest carbon credit project in Poland could contribute up to 80% to total NPV as reported in Figure 41.

Figure 41: Absolute and relative NPV contribution of an afforestation project (planted species: pine) to the NPV expected due to forest entrepreneurial activities



When we introduce the risk of wildfire we can notice scenarios with significant differences. Figure 42 reports the risk free amount of CO₂ sequestered and the expected value once we introduce the fire risk at country level. The difference among countries is significant. In countries like Greece for example at the end of project lifetime the value drops up to 70%. This behaviour cannot be compensated just by carbon buffer as reported in Figure 43 where the expected CO₂ released in the atmosphere is reported (reduced permanence).

Figure 42: Expected value of CO₂ sequestered during the project lifespan (1000 ha, planted species pine)

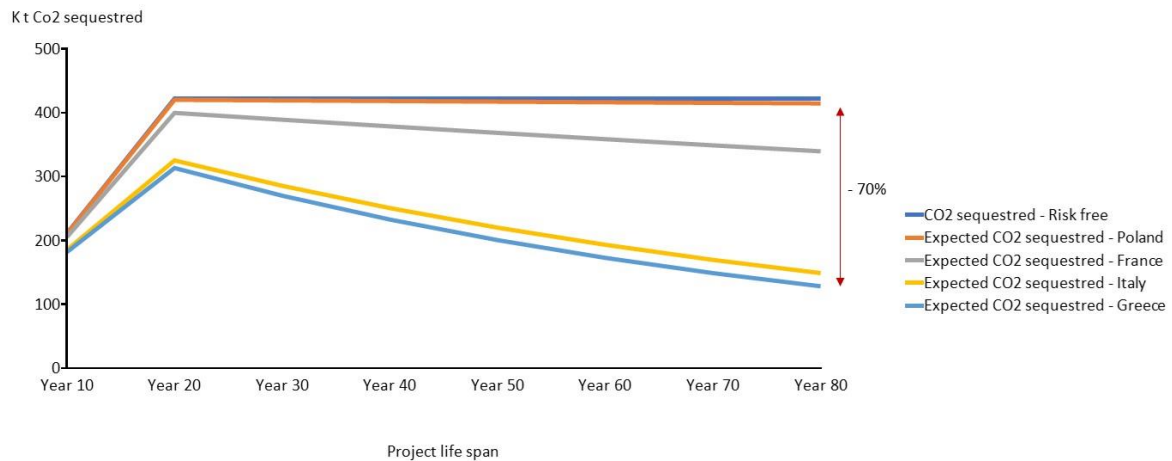
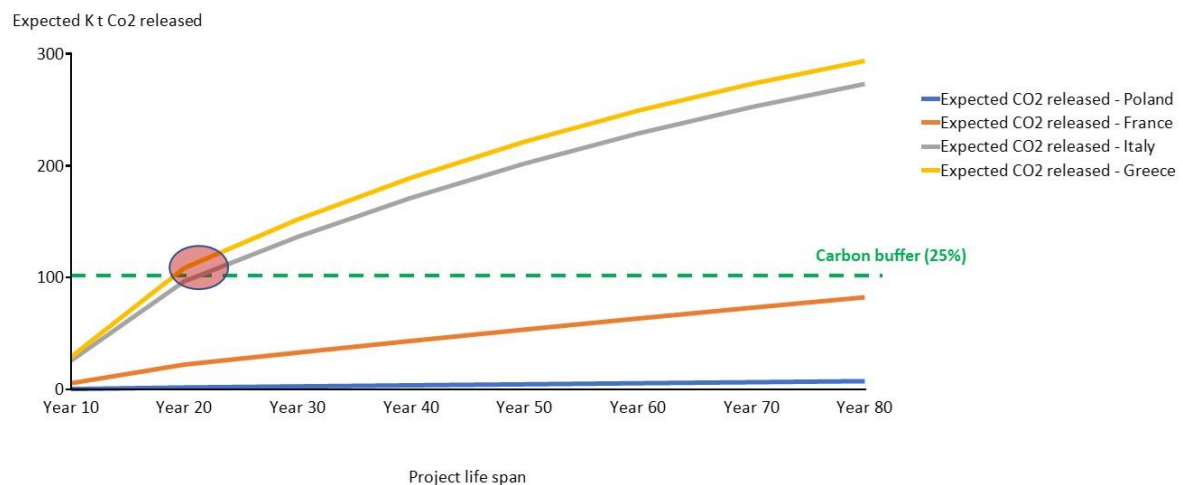


Figure 43: Expected CO₂ released in the atmosphere during the project lifespan (1000 ha, planted species pine)

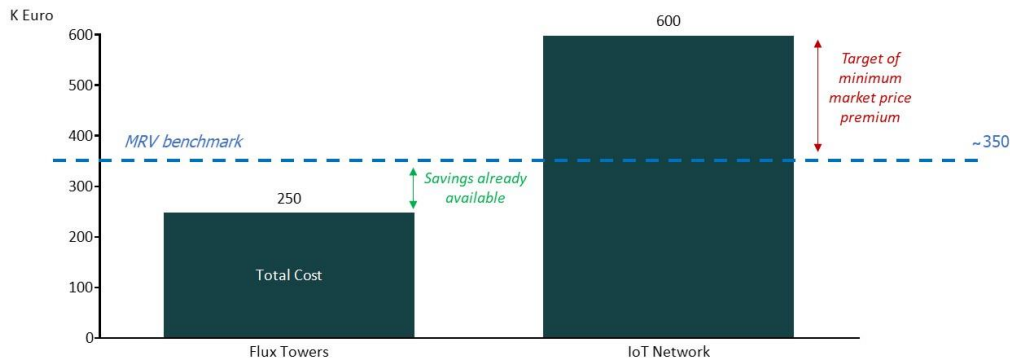


These first results suggest therefore the need to fully integrate as mandatory the risk modeling of the disturbances under climate change such as fire, drought, wind, snow and ice, insects, and pathogens based on the project peculiarities in order to assess not only the carbon buffer and mitigation measures but also the correct project life span. Having a project life span set “a priori”

can be a strong liability to ensure carbon permeance impacting both the environmental and the financial benefits of the projects. From a financial point of view, this type of risk can be mitigated via insurance contracts. Instead, from an environmental point of view the following three combined factors 1) the increase in number of forest carbon project 2) the increase of forest disturbances due to climate change and 3) the long project life span can let to an overestimation of the safety of the assets (amount of carbon sequestered) sinisterly echoing the same pattern happened with the sub-prime mortgages in the financial crisis of 2008.

As last objective of this analysis, we compare the cost of implementing an advance MVR solution as described in the previous chapters again MVR cost benchmark. Figure 44 shows that having an MVR approach based on flux towers can be more convenient than the MVR benchmark cost. Furthermore, the state variables measured (flux of kg CO₂ in this scenario) can be managed in the solution described in the previous chapters thus not only automating all the verification and reporting processes but also mitigating all the main carbon project issues described in Table 5 such as enforce clear accountability, auditability, and transparent business transactions.

Figure 44: Comparison of estimated MRV costs (no actualized) for an afforestation project of 1000 ha having pines as planted species. MRV benchmark equal to €0.8 per t CO₂e.



An MVR solution based on IoT network is more expensive than the MVR benchmark. Therefore, we perform a sensitivity analysis on the afforestation project NPV (1000 ha, planted species pine) by varying the carbon credit price of 1 t CO₂e starting from the current 2022-2023 value of around €4 to identify the minimum market price premium that would be required to obtain a NPV value equal or higher than €1600 K representing the expected NPV of the same project with MVR benchmark cost. As reported in

Carbon credit Price (voluntary market)	Project NPV based on the MRV solution		
	Based on Flux Towers	Based on IOT network	Forest Digital Twin

(Flux Towers + IoTs)			
4 EUR	€1'607 K	€1'338 K	€1'147 K
5 EUR	€2'080 K	€1'812 K	€1'620 K
6 EUR	€2'553 K	€2'285 K	€2'093 K

Table 14, we notice that a price of €5 generates a higher NPV thus enabling the project owner to obtain a comparable profit. This represents a +25% market price premium. It is important to notice that with this price increase even a Forest Digital Twin solution described in chapter 1 (multiple physical – virtual digital sockets operating in a nested approach at tree and stand /forest level) generates a higher NPV. Proper market analysis to assess the willingness of purchase from buyers this type of “premium” credits is required although out of the scope of this study.

Table 14: Price sensitivity analysis on project NPV for different MRV solutions. Green cells indicate a value higher than the NPV obtained considering MRV benchmark cost.

Carbon credit Price (voluntary market)	Project NPV based on the MRV solution		
	Based on Flux Towers	Based on IOT network	Forest Digital Twin (Flux Towers + IoTs)
4 EUR	€1'607 K	€1'338 K	€1'147 K
5 EUR	€2'080 K	€1'812 K	€1'620 K
6 EUR	€2'553 K	€2'285 K	€2'093 K

Conclusion

We looked at the economic aspects of forest carbon projects in the EU areas and we noticed that, as expected, the major factors influencing the profitability of the project are the climatic regions and the planted species and that there is not significant project NPV difference between EU countries. We also noticed that for some countries like Poland the value added of selling carbon credits as additional source of revenue to the usual forest entrepreneurship activities is significant. This can be seen as a signal of potential market opportunities for forest carbon projects in countries where the entrepreneurship income from forest management activities is limited. One key aspect that should be taken into account is the forest disturbance risk factor. We looked just at the wildfire risk for forests at country level and we noticed, that for countries in the Mediterranean area there is a risk to have a reduction up to 70% of the expected carbon sequestered compared to the risk-free scenario. This analysis requires additional investigation and confirmation for example, there is the need of 1) adding other forest disturbances such to extreme events and pests; 2) including also the climate change factor in the disturbance risk evolution over time, 3) reducing the spatial scale from country level to more homogenous areas. Nevertheless, these preliminary results show that to maximize the likelihood of carbon permanence the disturbance risk factor should not be managed just in terms of carbon buffer but also by considering the project lifespan duration. As suggested by (Churkina et al., 2020) this could imply that reducing the project lifespan and transforming the project forest biomass into high quality forest products, can be a successful strategy to maximize carbon permanence under high-risk disturbance scenarios. Without such analysis and a consequent and

consistent course of actions, there is a risk that from a financial and environment point of view, the safety of the asset (CO₂ accrued) generated by forest carbon projects is overestimated thus opening the door to potential bubble that could burst in the future due to the worsening of climate conditions and the increase of these type of projects as mean for carbon sinks. Last but not least, we looked at the impact on profitability of the different MRV solutions. We noticed that, under the current market condition an advanced monitoring solution based on flux towers seems to be more convenient than the MRV benchmark cost of €0.8 per t CO₂. Furthermore, a 25% market price premium enables a forest carbon project owner to regain the same profitability by implementing a MRV solution based on IoT network or even based on a forest digital twin. Although proper market analysis is required to assess the willingness to buy these premium credits, it seems that the market conditions to exploit the value of the technological advancements of data collection at tree and forest level are getting promising. This could unlock the economic value of forest ecosystem services, not only related to carbon sequestration, and, in combination with the solution described in chapter 2 and 3 can provide the highest data transparency and reliability to improve the capital flow towards sustainable practices of forest management.

References

- Asner, G. P., Mascaró, J., Muller-Landau, H. C., Vieilledent, G., Vaudry, R., Rasamoelina, M., Hall, J. S., & van Breugel, M. (2012). A universal airborne LiDAR approach for tropical forest carbon mapping. *Oecologia*, 168(4), 1147–1160. <https://doi.org/10.1007/S00442-011-2165-Z/FIGURES/8>
- Assessing Project Feasibility and Economic Viability Public Private Partnership*. (n.d.). Retrieved February 20, 2023, from <https://ppp.worldbank.org/public-private-partnership/assessing-project-feasibility-and-economic-viability>
- Badgley, G., Chay, F., Chegwidien, O. S., Hamman, J. J., Freeman, J., & Cullenward, D. (2022). California's forest carbon offsets buffer pool is severely undercapitalized. *Frontiers in Forests and Global Change*, 5, 154. <https://doi.org/10.3389/FFGC.2022.930426/BIBTEX>
- Badgley, G., Freeman, J., Hamman, J. J., Haya, B., Trugman, A. T., Anderegg, W. R. L., & Cullenward, D. (2022). Systematic over-crediting in California's forest carbon offsets program. *Global Change Biology*, 28(4), 1433–1445. <https://doi.org/10.1111/GCB.15943>
- Barba, J., Lloret, F., Poyatos, R., Molowny-Horas, R., & Yuste, J. C. (2018). Multi-temporal influence of vegetation on soil respiration in a drought-affected forest. *IForest - Biogeosciences and Forestry*, 11(2), 189. <https://doi.org/10.3832/IFOR2448-011>
- Baskent E. (2020). A Framework for Characterizing and Regulating Ecosystem Services in a Management Planning Context. *Forests*. <https://doi.org/10.3390/f11010102>
- Başkent, E. Z. (2018). A review of the development of the multiple use forest management planning concept. *International Forestry Review*, 20(3), 296–313. <https://doi.org/10.1505/146554818824063023>
- Başkent, E. Z. (2021). Assessment and valuation of key ecosystem services provided by two forest ecosystems in Turkey. *Journal of Environmental Management*, 285, 112135. <https://doi.org/10.1016/J.JENVMAN.2021.112135>
- Baskent, E. Z., Borges, J. G., Kašpar, J., & Tahri, M. (2020). A design for addressing multiple ecosystem services in forest management planning. *Forests*, 11(10), 1–24. <https://doi.org/10.3390/f11101108>
- Bauer, P., Stevens, B., & Hazeleger, W. (2021). A digital twin of Earth for the green transition. In *Nature Climate Change* (Vol. 11, Issue 2, pp. 80–83). Nature Research. <https://doi.org/10.1038/s41558-021-00986-y>
- Bellassen, V., Stephan, N., Afriat, M., Alberola, E., Barker, A., Chang, J. P., Chiquet, C., Cochran, I., Deheza, M., Dimopoulos, C., Foucherot, C., Jacquier, G., Morel, R., Robinson, R., & Shishlov, I.

- (2015). Monitoring, reporting and verifying emissions in the climate economy. *Nature Climate Change* 2015 5:4, 5(4), 319–328. <https://doi.org/10.1038/nclimate2544>
- Bernal, B., Murray, L. T., & Pearson, T. R. H. (2018). Global carbon dioxide removal rates from forest landscape restoration activities. *Carbon Balance and Management*, 13(1), 1–13. <https://doi.org/10.1186/S13021-018-0110-8/FIGURES/4>
- Blennow, K., Persson, J., Wallin, A., Varemán, N., & Persson, E. (2014). Understanding risk in forest ecosystem services: implications for effective risk management, communication and planning. *Forestry: An International Journal of Forest Research*, 87(2), 219–228. <https://doi.org/10.1093/FORESTRY/CPT032>
- Boehm, S., Jeffery, L., Levin, K., Hecke, J., Schumer, C., Fyson, C., Majid, A., Jaeger, J., Nilsson, A., Naimoli, S., Thwaites, J., Cassidy, E., Waite, R., Wilson, R., Castellanos, S., Singh, N., Lee, A., & Geiges, A. (2022). State of Climate Action 2022. *World Resources Institute*. <https://doi.org/10.46830/WRIRPT.22.00028>
- Bonan, G. B. (2008). Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science*, 320(5882), 1444–1449. https://doi.org/10.1126/SCIENCE.1155121/SUPPL_FILE/BONAN_SOM.PDF
- Bosetti, V., Lubowski, R., Golub, A., & Markandya, A. (2011). Linking reduced deforestation and a global carbon market: implications for clean energy technology and policy flexibility. *Environment and Development Economics*, 16(4), 479–505. <https://doi.org/10.1017/S1355770X10000549>
- Bothmann, L., Menzel, A., Menze, B. H., Schunk, C., & Kauermann, G. (2017). Automated processing of webcam images for phenological classification. *PLOS ONE*, 12(2), e0171918. <https://doi.org/10.1371/JOURNAL.PONE.0171918>
- Burton, L., Jayachandran, K., & Bhansali, S. (2020). Review—The “Real-Time” Revolution for In situ Soil Nutrient Sensing. *Journal of The Electrochemical Society*, 167(3), 037569. <https://doi.org/10.1149/1945-7111/AB6F5D>
- Burton, P. J., Jentsch, A., & Walker, L. R. (2020). The Ecology of Disturbance Interactions. *BioScience*, 70(10), 854–870. <https://doi.org/10.1093/BIOSCI/BIAA088>
- Carbon Credits.com*. (2023). https://carboncredits.com/carbon-prices-today/?gclid=Cj0KCQjw7aqkBhDPArisAKGa0oKtLpkvth82JvG12Ni3ijO7cfMF8x48DMFujhN42pxpfo1hzkdARqQaAg54EALw_wcB
- Carbon Pricing Dashboard | Up-to-date overview of carbon pricing initiatives*. (n.d.). Retrieved January 14, 2023, from https://carbonpricingdashboard.worldbank.org/map_data

- Castro, I., de Rosa, A., Priyadarshani, N., Bradbury, L., & Marsland, S. (2019). Experimental test of birdcall detection by autonomous recorder units and by human observers using broadcast. *Ecology and Evolution*, 9(5), 2376–2397. <https://doi.org/10.1002/ECE3.4775>
- Certify a Project | The Gold Standard*. (n.d.). Retrieved December 15, 2021, from <https://www.goldstandard.org/take-action/certify-project>
- Chapron, G. (2017). The environment needs cryptogovernance. *Nature* 2017 545:7655, 545(7655), 403–405. <https://doi.org/10.1038/545403a>
- Chiriaco, Perugini, Bellotta, & Foderà. (2020). *Linee guida per la definizione di uno standard per l'attuazione di un meccanismo volontario di riduzione e compensazione delle emissioni zootecniche a livello di distretto agricolo-zootecnico-forestale*.
- Churkina, G., Kuik, F., Bonn, B., Lauer, A., Rü Diger Grote, Il, Tomiak, K., & Butler, T. M. (2017). *Effect of VOC Emissions from Vegetation on Air Quality in Berlin during a Heatwave*. <https://doi.org/10.1021/acs.est.6b06514>
- Churkina, G., Organschi, A., Reyer, C. P. O., Ruff, A., Vinke, K., Liu, Z., Reck, B. K., Graedel, T. E., & Schellnhuber, H. J. (2020). Buildings as a global carbon sink. *Nature Sustainability* 2020 3:4, 3(4), 269–276. <https://doi.org/10.1038/s41893-019-0462-4>
- Climate Action Reserve - Climate Action Reserve : Climate Action Reserve*. (n.d.-a). Retrieved December 15, 2021, from <https://www.climateactionreserve.org/>
- Climate Action Reserve - Climate Action Reserve : Climate Action Reserve*. (n.d.-b). Retrieved January 15, 2023, from <https://www.climateactionreserve.org/>
- Climate Change | United Nations*. (2022). <https://www.un.org/en/global-issues/climate-change>
- Climate Change 2022: Mitigation of Climate Change - IPCC*. (n.d.). Retrieved March 14, 2023, from <https://www.ipcc.ch/report/ar6/wg3/>
- Costanza, R., de Groot, R., Farberll, S., Grassot, M., Hannon, B., Limburg, K., Naeem, S., O, R. V, Paruelo, J., Raskin, R. G., & Suttonllll, P. (1998). *The value of the world's ecosystem services and natural capital*.
- Davies, A. B., & Asner, G. P. (2014). Advances in animal ecology from 3D-LiDAR ecosystem mapping. *Trends in Ecology & Evolution*, 29(12), 681–691. <https://doi.org/10.1016/J.TREE.2014.10.005>
- de Donno, M., Tange, K., & Dragoni, N. (2019). Foundations and Evolution of Modern Computing Paradigms: Cloud, IoT, Edge, and Fog. *IEEE Access*, 7, 150936–150948. <https://doi.org/10.1109/ACCESS.2019.2947652>
- Destination Earth | Shaping Europe's digital future*. (2021). <https://digital-strategy.ec.europa.eu/en/policies/destination-earth>

- Digital Twin Consortium®. (2021). <https://www.digitaltwinconsortium.org/>
- EFFIS - Welcome to EFFIS. (n.d.). Retrieved February 12, 2023, from <https://effis.jrc.ec.europa.eu/>
- EUR-Lex - 52022PC0672. (2022). <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0672>
- FAO; UNEP. (2020). The State of the World's Forests 2020. In *The State of the World's Forests 2020*. FAO and UNEP. <https://doi.org/10.4060/ca8642en>
- Felipe-Lucia, M. R., Soliveres, S., Penone, C., Manning, P., van der Plas, F., Boch, S., Prati, D., Ammer, C., Schall, P., Gossner, M. M., Bauhus, J., Buscot, F., Blaser, S., Blüthgen, N., de Frutos, A., Ehbrecht, M., Frank, K., Goldmann, K., Hänsel, F., ... Allan, E. (2018). Multiple forest attributes underpin the supply of multiple ecosystem services. *Nature Communications* 2018 9:1, 9(1), 1–11. <https://doi.org/10.1038/s41467-018-07082-4>
- FLUXNET. (2021). <https://fluxnet.org/>
- Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital Twin: Enabling Technologies, Challenges and Open Research. *IEEE Access*, 8, 108952–108971. <https://doi.org/10.1109/ACCESS.2020.2998358>
- Global Climate Highlights | Copernicus. (2022). <https://climate.copernicus.eu/global-climate-highlights-2022>
- Global Energy and Climate Model Documentation, I. (2022). *Global Energy and Climate Model Documentation*, IEA. www.iea.org/t&c/
- Gougherty, A. v., Keller, S. R., Kruger, A., Stylinski, C. D., Elmore, A. J., & Fitzpatrick, M. C. (2018). Estimating tree phenology from high frequency tree movement data. *Agricultural and Forest Meteorology*, 263, 217–224. <https://doi.org/10.1016/J.AGRFORMET.2018.08.020>
- Grafton, R. Q., Chu, H. L., Nelson, H., & Bonnis, G. (2021). *A global analysis of the cost-efficiency of forest carbon sequestration*. <https://doi.org/10.1787/e4d45973-en>
- Gren, I. M., & Zeleke, A. A. (2016). Policy design for forest carbon sequestration: A review of the literature. *Forest Policy and Economics*, 70, 128–136. <https://doi.org/10.1016/J.FORPOL.2016.06.008>
- Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. v., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., ... Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America*, 114(44), 11645–11650. <https://doi.org/10.1073/PNAS.1710465114/-/DCSUPPLEMENTAL>
- Guizar-Coutiño, A., Jones, J. P. G., Balmford, A., Carmenta, R., & Coomes, D. A. (2022). A global evaluation of the effectiveness of voluntary REDD+ projects at reducing deforestation and

- degradation in the moist tropics. *Conservation Biology*, 36(6), e13970.
<https://doi.org/10.1111/COBI.13970>
- Guo, X., Coops, N. C., Tompalski, P., Nielsen, S. E., Bater, C. W., & John Stadt, J. (2017). Regional mapping of vegetation structure for biodiversity monitoring using airborne lidar data. *Ecological Informatics*, 38, 50–61. <https://doi.org/10.1016/J.ECOINF.2017.01.005>
- Hartmann, H., Moura, C. F., Anderegg, W. R. L., Ruehr, N. K., Salmon, Y., Allen, C. D., Arndt, S. K., Breshears, D. D., Davi, H., Galbraith, D., Ruthrof, K. X., Wunder, J., Adams, H. D., Bloemen, J., Cailleret, M., Cobb, R., Gessler, A., Grams, T. E. E., Jansen, S., ... O'Brien, M. (2018). Research frontiers for improving our understanding of drought-induced tree and forest mortality. *New Phytologist*, 218(1), 15–28. <https://doi.org/10.1111/NPH.15048>
- He, Z., & Turner, P. (2022). Blockchain Applications in Forestry: A Systematic Literature Review. *Applied Sciences* 2022, Vol. 12, Page 3723, 12(8), 3723. <https://doi.org/10.3390/APP12083723>
- Home | Climate Action Tracker. (n.d.). Retrieved March 14, 2023, from <https://climateactiontracker.org/>
- Homepage — American Carbon Registry. (n.d.-a). Retrieved December 15, 2021, from <https://americancarbonregistry.org/>
- Homepage — American Carbon Registry. (n.d.-b). Retrieved January 15, 2023, from <https://americancarbonregistry.org/>
- Hou, G., Delang, C. O., Lu, X., & Olschewski, R. (2019). Valuing Carbon Sequestration to Finance Afforestation Projects in China. *Forests* 2019, Vol. 10, Page 754, 10(9), 754.
<https://doi.org/10.3390/F10090754>
- H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, & K. Tanabe (Eds.). (2006). *IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*.
- Jin, H., Jönsson, A. M., Olsson, C., Lindström, J., Jönsson, P., & Eklundh, L. (2019). New satellite-based estimates show significant trends in spring phenology and complex sensitivities to temperature and precipitation at northern European latitudes. *International Journal of Biometeorology*, 63(6), 763–775. <https://doi.org/10.1007/S00484-019-01690-5>
- Jones, D., Snider, C., Nassehi, A., Yon, J., & Hicks, B. (2020). Characterising the Digital Twin: A systematic literature review. *CIRP Journal of Manufacturing Science and Technology*, 29, 36–52.
<https://doi.org/10.1016/j.cirpj.2020.02.002>
- Jucker, T., Caspersen, J., Chave, J., Antin, C., Barbier, N., Bongers, F., Dalponte, M., van Ewijk, K. Y., Forrester, D. I., Haeni, M., Higgins, S. I., Holdaway, R. J., Iida, Y., Lorimer, C., Marshall, P. L., Momo, S., Moncrieff, G. R., Ploton, P., Poorter, L., ... Coomes, D. A. (2017). Allometric equations for integrating remote sensing imagery into forest monitoring programmes. *Global Change Biology*, 23(1), 177–190. <https://doi.org/10.1111/GCB.13388>

- Kane, V. R., North, M. P., Lutz, J. A., Churchill, D. J., Roberts, S. L., Smith, D. F., Mcgaughey, R. J., Kane, J. T., & Brooks, M. L. (2014). *Assessing fire effects on forest spatial structure using a fusion of Landsat and airborne LiDAR data in Yosemite National Park*. <https://doi.org/10.1016/j.rse.2013.07.041>
- Kim, E. S., Cho, H. B., Heo, D., Kim, N. S., Kim, Y. S., Lee, K., Lee, S. H., & Ryu, J. (2019). Precision monitoring of radial growth of trees and micro-climate at a Korean Fir (*Abies koreana* Wilson) forest at 10 minutes interval in 2016 on Mt. Hallasan National Park, Jeju Island, Korea. *Journal of Ecology and Environment*, 43(1), 1–20. <https://doi.org/10.1186/S41610-019-0117-4/TABLES/5>
- Klosterman, S. T., Hufkens, K., Gray, J. M., Melaas, E., Sonnentag, O., Lavine, I., Mitchell, L., Norman, R., Friedl, M. A., & Richardson, A. D. (2014). Evaluating remote sensing of deciduous forest phenology at multiple spatial scales using PhenoCam imagery. *Biogeosciences*, 11, 4305–4320. <https://doi.org/10.5194/bg-11-4305-2014>
- Kotsialou, G., Kuralbayeva, K., & Laing, T. (2022). Blockchain's potential in forest offsets, the voluntary carbon markets and REDD+. *Environmental Conservation*, 49(3), 137–145. <https://doi.org/10.1017/S0376892922000157>
- Lammirato, C., Lebender, U., Tierling, J., & Lammel, J. (2018). Analysis of uncertainty for N₂O fluxes measured with the closed-chamber method under field conditions: Calculation method, detection limit, and spatial variability. *Journal of Plant Nutrition and Soil Science*, 181(1), 78–89. <https://doi.org/10.1002/JPLN.201600499>
- Lau, J. A., & Lennon, J. T. (2011). Evolutionary ecology of plant-microbe interactions: Soil microbial structure alters selection on plant traits. *New Phytologist*, 192(1), 215–224. <https://doi.org/10.1111/J.1469-8137.2011.03790.X>
- Lier, M., Köhl, M., Korhonen, K. T., Linser, S., & Prins, K. (2021). Forest relevant targets in EU policy instruments - can progress be measured by the pan-European criteria and indicators for sustainable forest management? *Forest Policy and Economics*, 128, 102481. <https://doi.org/10.1016/J.FORPOL.2021.102481>
- Livesley, S. J., McPherson, E. G., & Calfapietra, C. (2016). The Urban Forest and Ecosystem Services: Impacts on Urban Water, Heat, and Pollution Cycles at the Tree, Street, and City Scale. *Journal of Environmental Quality*, 45(1), 119–124. <https://doi.org/10.2134/JEQ2015.11.0567>
- Maréchaux, I., Langerwisch, F., Huth, A., Bugmann, H., Morin, X., Reyer, C. P. O., Seidl, R., Collalti, A., Dantas de Paula, M., Fischer, R., Gutsch, M., Lexer, M. J., Lischke, H., Rammig, A., Rödig, E., Sakschewski, B., Taubert, F., Thonicke, K., Vacchiano, G., & Bohn, F. J. (2021). Tackling unresolved questions in forest ecology: The past and future role of simulation models. *Ecology and Evolution*, 11(9), 3746–3770. <https://doi.org/10.1002/ECE3.7391/FORMAT/PDF>
- Matasov, V., Marchesini, L. B., Yaroslavtsev, A., Sala, G., Fareeva, O., Seregin, I., Castaldi, S., Vasenev, V., & Valentini, R. (2020). IoT Monitoring of Urban Tree Ecosystem Services: Possibilities and Challenges. *Forests 2020, Vol. 11, Page 775*, 11(7), 775. <https://doi.org/10.3390/F11070775>

- Michetti, M., & Rosa, R. (2012). Afforestation and timber management compliance strategies in climate policy. A computable general equilibrium analysis. *Ecological Economics*, 77, 139–148. <https://doi.org/10.1016/J.ECOLECON.2012.02.020>
- MonteRé ★ *Coltivazioni Italiane*. (n.d.). Retrieved January 24, 2023, from <https://www.montere.it/it/>
- Morfopoulos, C., Müller, J. F., Stavrakou, T., Bauwens, M., de Smedt, I., Friedlingstein, P., Prentice, I. C., & Regnier, P. (2021). Vegetation responses to climate extremes recorded by remotely sensed atmospheric formaldehyde. *Global Change Biology*. <https://doi.org/10.1111/GCB.15880>
- Nakamoto, S. (2008). *Bitcoin: A Peer-to-Peer Electronic Cash System*. www.bitcoin.org
- National Inventory Submissions | UNFCCC. (2022). <https://unfccc.int/ghg-inventories-annex-i-parties/2022>
- Niță, M. D. (2021). Testing Forestry Digital Twinning Workflow Based on Mobile LiDAR Scanner and AI Platform. *Forests* 2021, Vol. 12, Page 1576, 12(11), 1576. <https://doi.org/10.3390/F12111576>
- Nitoslawski, S. A., Wong-Stevens, K., Steenberg, J. W. N., Witherspoon, K., Nesbitt, L., & Konijnendijk van den Bosch, C. C. (2021). The Digital Forest: Mapping a Decade of Knowledge on Technological Applications for Forest Ecosystems. *Earth's Future*, 9(8), e2021EF002123. <https://doi.org/10.1029/2021EF002123>
- Nizamuddin, N., Salah, K., Ajmal Azad, M., Arshad, J., & Rehman, M. H. (2019). Decentralized document version control using ethereum blockchain and IPFS. *Computers & Electrical Engineering*, 76, 183–197. <https://doi.org/10.1016/J.COMPELECENG.2019.03.014>
- O'Brien, A. M., Ginnan, N. A., Rebolleda-Gómez, M., & Wagner, M. R. (2021). Microbial effects on plant phenology and fitness. *American Journal of Botany*, 108(10), 1824–1837. <https://doi.org/10.1002/AJB2.1743>
- O'Grady, J., Zhang, D., O'Connor, N., & Regan, F. (2021). A comprehensive review of catchment water quality monitoring using a tiered framework of integrated sensing technologies. *The Science of the Total Environment*, 765. <https://doi.org/10.1016/J.SCITOTENV.2020.142766>
- Ouyang, Z., Ouyang, Z., Song, C., Song, C., Zheng, H., Zheng, H., Polasky, S., Polasky, S., Xiao, Y., Xiao, Y., Bateman, I. J., Liu, J., Liu, J., Ruckelshaus, M., Shi, F., Xiao, Y., Xu, W., Xu, W., Zou, Z., ... Daily, G. C. (2020). Using gross ecosystem product (GEP) to value nature in decision making. *Proceedings of the National Academy of Sciences of the United States of America*, 117(25), 14593–14601. <https://doi.org/10.1073/PNAS.1911439117>
- Pan, C., Shrestha, A., Innes, J. L., Zhou, G., Li, N., Li, J., He, Y., Sheng, C., Niles, J. O., & Wang, G. (2022). Key challenges and approaches to addressing barriers in forest carbon offset projects. *Journal of Forestry Research*, 33(4), 1109–1122. <https://doi.org/10.1007/S11676-022-01488-Z/TABLES/3>

- Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., Phillips, O. L., Shvidenko, A., Lewis, S. L., Canadell, J. G., Ciais, P., Jackson, R. B., Pacala, S. W., McGuire, A. D., Piao, S., Rautiainen, A., Sitch, S., & Hayes, D. (2011). A large and persistent carbon sink in the world's forests. *Science*, 333(6045), 988–993.
https://doi.org/10.1126/SCIENCE.1201609/SUPPL_FILE/PAPV2.PDF
- Pearson, T. R. H., Brown, S. L., & Birdsey, R. A. (2007). *United States Department of Agriculture Measurement Guidelines for the Sequestration of Forest Carbon*. <http://www.nrs.fs.fed.us/>
- Quegan, S., le Toan, T., Chave, J., Dall, J., Exbrayat, J. F., Minh, D. H. T., Lomas, M., D'Alessandro, M. M., Paillou, P., Papathanassiou, K., Rocca, F., Saatchi, S., Scipal, K., Shugart, H., Smallman, T. L., Soja, M. J., Tebaldini, S., Ulander, L., Villard, L., & Williams, M. (2019). The European Space Agency BIOMASS mission: Measuring forest above-ground biomass from space. *Remote Sensing of Environment*, 227, 44–60. <https://doi.org/10.1016/J.RSE.2019.03.032>
- Rahman, G., Sohag, H., Chowdhury, R., Wahid, K. A., Dinh, A., Arcand, M., & Vail, S. (2020). SoilCam: A Fully Automated Minirhizotron using Multispectral Imaging for Root Activity Monitoring. *Sensors* 2020, Vol. 20, Page 787, 20(3), 787. <https://doi.org/10.3390/S20030787>
- Rautiainen, M., Lukeš, P., Homolová, L., Hovi, A., Pisek, J., & Möttus, M. (2018). Spectral Properties of Coniferous Forests: A Review of In Situ and Laboratory Measurements. *Remote Sensing* 2018, Vol. 10, Page 207, 10(2), 207. <https://doi.org/10.3390/RS10020207>
- Reid WV, Mooney HA, Cropper A, & et al. (2005). *Ecosystems and human well-being - Synthesis: A Report of the Millennium Ecosystem Assessment*. Washington D.C. Island Press.
- Renda, A. (2019). The Age of Foodtech: Optimizing the Agri-Food Chain with Digital Technologies. In *Achieving the Sustainable Development Goals Through Sustainable Food Systems* (pp. 171–187). Springer, Cham. https://doi.org/10.1007/978-3-030-23969-5_10
- Repman M, Schelske O, Colijn D, & Prasad S. (2021). *The insurance rationale for carbon removal solutions*, Swiss Re Institute.
- Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., ... Foley, J. A. (2009). A safe operating space for humanity. *Nature* 2009 461:7263, 461(7263), 472–475. <https://doi.org/10.1038/461472a>
- Rosenbaum, U., Bogen, H. R., Herbst, M., Huisman, J. A., Peterson, T. J., Weuthen, A., Western, A. W., & Vereecken, H. (2012). Seasonal and event dynamics of spatial soil moisture patterns at the small catchment scale. *Water Resources Research*, 48(10). <https://doi.org/10.1029/2011WR011518>
- Ryu, Y., Verfaillie, J., Macfarlane, C., Kobayashi, H., Sonnentag, O., Vargas, R., Ma, S., & Baldocchi, D. D. (2012). Continuous observation of tree leaf area index at ecosystem scale using upward-pointing

- digital cameras. *Remote Sensing of Environment*, 126, 116–125.
<https://doi.org/10.1016/J.RSE.2012.08.027>
- Segura, M., Ray, D., & Maroto, C. (2014). Decision support systems for forest management: A comparative analysis and assessment. *Computers and Electronics in Agriculture*, 101, 55–67.
<https://doi.org/10.1016/J.COMPAG.2013.12.005>
- Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., Petr, M., Honkaniemi, J., Lexer, M. J., Trotsiuk, V., Mairota, P., Svoboda, M., Fabrika, M., Nagel, T. A., & Reyer, C. P. O. (2017). Forest disturbances under climate change. *Nature Climate Change* 2017 7:6, 7(6), 395–402. <https://doi.org/10.1038/nclimate3303>
- Senf, C., & Seidl, R. (2020). Mapping the forest disturbance regimes of Europe. *Nature Sustainability* 2020 4:1, 4(1), 63–70. <https://doi.org/10.1038/s41893-020-00609-y>
- Simon, H., Lindén, J., Hoffmann, D., Braun, P., Bruse, M., & Esper, J. (2018). Modeling transpiration and leaf temperature of urban trees – A case study evaluating the microclimate model ENVI-met against measurement data. *Landscape and Urban Planning*, 174, 33–40.
<https://doi.org/10.1016/J.LANDURBPLAN.2018.03.003>
- Sonn, Y. K., Yoo, J. H., Luyima, D., Lee, J. H., Chun, J. H., Kang, Y. G., Oh, T. K., & Cho, J. (2022). Development of Models to Estimate Total Soil Carbon across Different Croplands at a Regional Scale Using RGB Photography. *International Journal of Environmental Research and Public Health*, 19(15). <https://doi.org/10.3390/ijerph19159344>
- State of Europe’s Forests. (2020). *State of Europe’s Forests*. www.foresteuropa.org
- Stoll, C., Klaaßen, L., & Gellersdörfer, U. (2019). The Carbon Footprint of Bitcoin. *Joule*, 3(7), 1647–1661.
<https://doi.org/10.1016/J.JOULE.2019.05.012>
- Streck, C. (2020). Who Owns REDD+? Carbon Markets, Carbon Rights and Entitlements to REDD+ Finance. *Forests* 2020, Vol. 11, Page 959, 11(9), 959. <https://doi.org/10.3390/F11090959>
- Sylvain, M., Lehoux, F., Morency, S., Faucher, F., Bharucha, E., Tremblay, D. M., Raymond, F., Sarrazin, D., Moineau, S., Allard, M., Corbeil, J., Messaddeq, Y., & Gosselin, B. (2018). The EcoChip: A Wireless Multi-Sensor Platform for Comprehensive Environmental Monitoring. *IEEE Transactions on Biomedical Circuits and Systems*, 12(6), 1289–1300.
<https://doi.org/10.1109/TBCAS.2018.2878404>
- Takahashi, M., Feng, Z., Mikhailova, T. A., Kalugina, O. v., Shergina, O. v., Afanasieva, L. v., Heng, R. K. J., Majid, N. M. A., & Sase, H. (2020). Air pollution monitoring and tree and forest decline in East Asia: A review. *Science of The Total Environment*, 742, 140288.
<https://doi.org/10.1016/J.SCITOTENV.2020.140288>
- Taskforce on Scaling Voluntary Carbon Markets > Homepage. (2022). <https://www.iif.com/tsvcm>

- The Art of Integrity: Ecosystem Marketplace's State of the Voluntary Carbon Markets 2022 Q3 - Forest Trends.* (n.d.). Retrieved January 14, 2023, from <https://www.forest-trends.org/publications/the-art-of-integrity-ecosystem-marketplaces-state-of-the-voluntary-carbon-markets-2022-q3/>
- Trends and projections in Europe 2022 — European Environment Agency.* (n.d.). Retrieved March 14, 2023, from <https://www.eea.europa.eu/publications/trends-and-projections-in-europe-2022>
- Trugman, A. T., Anderegg, L. D. L., Anderegg, W. R. L., Das, A. J., & Stephenson, N. L. (2021). Why is Tree Drought Mortality so Hard to Predict? *Trends in Ecology & Evolution*, 36(6), 520–532. <https://doi.org/10.1016/J.TREE.2021.02.001>
- U.S. Forest Projects - | California Air Resources Board.* (2015). <https://ww2.arb.ca.gov/our-work/programs/compliance-offset-program/compliance-offset-protocols/us-forest-projects/2015>
- Vaglio Laurin, G., Ding, J., Disney, M., Bartholomeus, H., Herold, M., Papale, D., & Valentini, R. (2019). Tree height in tropical forest as measured by different ground, proximal, and remote sensing instruments, and impacts on above ground biomass estimates. *International Journal of Applied Earth Observation and Geoinformation*, 82, 101899. <https://doi.org/10.1016/J.JAG.2019.101899>
- Valentini, R., Marchesini, L. B., Gianelle, D., Sala, G., Yarovslavtsev, A., Vasenev, V. I., & Castaldi, S. (2019). New tree monitoring systems: from Industry 4.0 to Nature 4.0. *Annals of Silvicultural Research*, 43(2), 84–88. <https://doi.org/10.12899/asr-1847>
- van Kooten, G. C. (2017a). Forest carbon offsets and carbon emissions trading: Problems of contracting. *Forest Policy and Economics*, 75, 83–88. <https://doi.org/10.1016/J.FORPOL.2016.12.006>
- van Kooten, G. C. (2017b). Forest carbon offsets and carbon emissions trading: Problems of contracting. *Forest Policy and Economics*, 75, 83–88. <https://doi.org/10.1016/J.FORPOL.2016.12.006>
- Verra - Standards for a Sustainable Future.* (n.d.). Retrieved December 15, 2021, from <https://verra.org/>
- Warsaw Framework for REDD-plus | UNFCCC.* (n.d.). Retrieved January 15, 2023, from <https://unfccc.int/topics/land-use/resources/warsaw-framework-for-redd-plus>
- West, T. A. P., Börner, J., Sills, E. O., & Kontoleon, A. (2020). Overstated carbon emission reductions from voluntary REDD+ projects in the Brazilian Amazon. *Proceedings of the National Academy of Sciences of the United States of America*, 117(39), 24188–24194. https://doi.org/10.1073/PNAS.2004334117/SUPPL_FILE/PNAS.2004334117.SAPP.PDF
- West, T. A. P., Wunder, S., Sills, E. O., Börner, J., Rifai, S. W., Neidermeier, A. N., & Kontoleon, A. (2023). *Action needed to make carbon offsets from tropical forest conservation work for climate change mitigation.* <https://doi.org/10.48550/arxiv.2301.03354>
- What is a Carbon Offset? - Carbon Offset Guide.* (n.d.). Retrieved January 14, 2023, from <https://www.offsetguide.org/understanding-carbon-offsets/what-is-a-carbon-offset/>

- What is Azure Digital Twins? - Azure Digital Twins | Microsoft Docs*. (2021).
<https://docs.microsoft.com/en-us/azure/digital-twins/overview>
- Wise, L., Marland, E., Marland, G., Hoyle, J., Kowalczyk, T., Ruseva, T., Colby, J., & Kinlaw, T. (2019). Optimizing sequestered carbon in forest offset programs: Balancing accounting stringency and participation. *Carbon Balance and Management*, 14(1), 1–11. <https://doi.org/10.1186/S13021-019-0131-Y/FIGURES/4>
- World Bank. (2022). *State and Trends of Carbon Pricing 2022*. <https://doi.org/10.1596/978-1-4648-1895-0>
- World Development Indicators | DataBank*. (2023). <https://databank.worldbank.org/source/world-development-indicators>
- Wu, T., Wang, Y., Yu, C., Chiarawipa, R., Zhang, X., Han, Z., & Wu, L. (2012). Carbon Sequestration by Fruit Trees - Chinese Apple Orchards as an Example. *PLOS ONE*, 7(6), e38883. <https://doi.org/10.1371/JOURNAL.PONE.0038883>
- Wüst, K., & Gervais, A. (2017). *Do you need a Blockchain?*
- Yaga, D., Mell, P., Roby, N., & Scarfone, K. (2019). *Blockchain Technology Overview*. <https://doi.org/10.6028/NIST.IR.8202>
- Zhang, Z., Tian, F., Hu, H., & Yang, P. (2014). A comparison of methods for determining field evapotranspiration: Photosynthesis system, sap flow, and eddy covariance. *Hydrology and Earth System Sciences*, 18(3), 1053–1072. <https://doi.org/10.5194/HESS-18-1053-2014>
- Zou, W., Lo, D., Kochhar, P. S., Le, X. B. D., Xia, X., Feng, Y., Chen, Z., & Xu, B. (2021). Smart Contract Development: Challenges and Opportunities. *IEEE Transactions on Software Engineering*, 47(10), 2084–2106. <https://doi.org/10.1109/TSE.2019.2942301>