Integration of forest monitoring Big Data for addressing local to global challenges on forest ecosystems within the framework of the Paris Agreement

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Assessing the capacity of forest ecosystems to adapt to climate change and its role in mitigating climate change requires strong scientific knowledge and data. For this purpose, a holistic forest approach is needed, collecting varied data on multiple scales. Two relevant examples of forest data harmonization at European and global level are presented in this article.

Forests and global change in relation to the Paris Agreement

The Paris Agreement brings all nations into a common cause to mitigate climate change and adapt to its current and forecast impacts. A number of articles of the Paris Agreement involve, directly or indirectly, forest ecosystems as a key component for achieve the climate change mitigation targets, i.e., keeping a global temperature rise this century well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 °C. Particularly, Articles 4 and 5 of the Paris Agreement deal with the need for reducing the growth rate of atmospheric CO_2 by increasing carbon sequestration wheile Article 2 puts the focus on reducing radiative imbalance at the top of the atmosphere by increasing albedo, and Article 7 highlights that this should be achieved without increasing air temperature nor decreasing precipitation (Luyssaert *et al.*, 2018). Additionally, the agreement aims to strengthen the ability of countries to deal with the impacts of climate change (UNFCCC).

In this regard, recent research suggested that forest managers and policy makers should rather put the focus on the adaptation of forest ecosystems to climate change to ensure the future supply of the wide array of ecosystem services provided by forests (Luyssaert *et al.*, 2018); ultimately, this represents the main challenge that will also determine the future capacity of forests to act as carbon sinks. Indeed, this research showed that different forestry alternatives, mainly focused on climate change mitigation at the European level, would result in side effects that would somehow level out the supposed climate change mitigation effects. In the end, without forest adaptation to global change, the climate change mitigation role of forests may be jeopardized. This is particularly relevant for forest ecosystems in the Mediterranean basin, for which the expected impacts of climate change are huge, and where forest growth and survival are already strongly limited by water scarcity, i.e., carbon sequestration "costs" water (Birot, 2011), and water provisioning is a key ecosystem service within an increasingly arid context.

Additionally, the Kyoto Protocol obliges developed countries to provide the political and legal framework to meet the Protocol's expectations, being mandatory to reduce the occurrence of main threats, such as landslides, floods, and desertification processes, whose frequency has rapidly risen in the Mediterranean regions most susceptible to climatic changes (Savy *et al.* 2012).

Therefore, rather than just focusing on carbon sequestration and storage, climate-smart forestry in Mediterranean forests and beyond must explicitly acknowledge the huge amount of ecosystem services that they provide (including climate change mitigation, but also many others), as well as the related risks and threats to the delivery of such ecosystems services in a global change context, by focusing on global (rather than just climate) change adaptation in order to ensure their future supply. This is well in line with a number of initiatives ranging from the regional to global level related to the key role of forest ecosystems in the provision of multiple ecosystem services.

Forest monitoring-related international processes

The United Nations Conference on Environment and Development (UNCED), known as the Rio or Earth Summit, was a United Nations conference focused on environmental challenges at a global level (UN 1992). As a result, relevant international processes and agreements were initiated: The Rio Declaration on Environment and Development, the Agenda 21 and the Forest Principles, the Convention on Biological Diversity (CBD), the Framework Convention on Climate Change (UNFCCC) and the United Nations Convention to Combat Desertification (UNCCD).

The CBD is an international legally binding treaty aiming to develop national strategies for the conservation and sustainable use of biological diversity. Forest biodiversity is one of the seven thematic programmes established corresponding to major biomes. In the tenth meeting of the Conference of the Parties (Japan, 2010) a revised and updated Strategic Plan for Biodiversity, including the Aichi Biodiversity Targets, for the 2011-2020 period was adopted. This includes the adoption of urgent actions to halt the loss of biodiversity in order to ensure that by 2020 ecosystems are resilient and continue to provide essential services. To ensure this, pressures on biodiversity have to be reduced, ecosystems restored, biological resources are sustainably used and benefits arising out of utilization of genetic resources are shared in a fair and equitable manner. There are three Aichi Targets forest-related. Target 5 specifies that the rate of loss of all natural habitats, including forests, is at least halved and where feasible brought close to zero, and degradation and fragmentation has to be significantly reduced (www.cbd.int).

The UNFCCC is an international environmental treaty with the objective to "*stabilize greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*" (UNFCCC 2009). The convention provides a framework for international treaties called "protocols". The Kyoto Protocol was signed in 1997, establishing legally-binding obligations for developed countries to reduce their GHG emissions (Vidal *et al.* 2016). In this framework, the European Parliament and the Council of the

European Union, having regard to the treaty on the functioning of the European Union, adopted Regulation 2018/241 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU. It states that for the periods from 2021 to 2025 and from 2026 to 2030, each Member State (MS) shall ensure that emissions do not exceed removals, calculated as the sum of total emissions and total removals. For that, each MS shall determine its forest reference level (FRL) as the average annual net emissions or removals resulting from managed forest land in the mentioned periods based on the continuation of sustainable forest management practice.

The United Nations Convention to Combat Desertification (UNCCD) is a legally-binding international agreement linking the environment and the development of sustainable land management. The UNCCD specifically concerns the arid, semi-arid and dry sub-humid areas in the world, known as drylands (www.unccd.int). Forests are crucial for the Convention as they are crucial to avoiding soil erosion, being the relevant afforestation and reforestation means to rehabilitate degraded lands. In the Conference of Parties of the UNCCD (Turkey, 2015), the Parties engaged with the Land Degradation Neutrality (LDN) Target Setting Programme. LDN has been defined as "*A state whereby the amount and quality of land resources, necessary to support ecosystem functions and services and enhance food security, remains stable or increases within specified temporal and spatial scales and ecosystems*". It was developed to guide countries in activating this definition through the implementation of strategies to address land degradation and achieve LDN.

Holistic, multi-scale and multi-sourced forest monitoring in the Big Data Era

Conceptual framework

Assessing the key role of forests in global change adaptation and mitigation requires sound scientific information (and data) (Grassi *et al.*, 2017). Data on forest ecosystems can be obtained mainly from forest monitoring efforts, where different forest attributes and variables may be measured in order to characterize in a reliable way forest resource information for policy development, planning and sustainable management. To be able to properly address the aforesaid global change-related challenges, forest monitoring needs to be, therefore, consistent with the necessity of considering the complexity of human-forest ecosystem relationships and the maintenance of the huge array of forest ecosystem services, in addition to permitting an understanding of the complexity of forest dynamics and functioning. In the context of global change emergency in the Big Data Era, integrated, holistic, multi-scale and multi-sourced forest monitoring is needed (Fig. 1).

Multiple data sources, items and spatio-temporal scales

In this regard, on one hand, forest monitoring needs to encompass the integration of heterogeneous data from multiple spatio-temporal scales (from the individual trees to

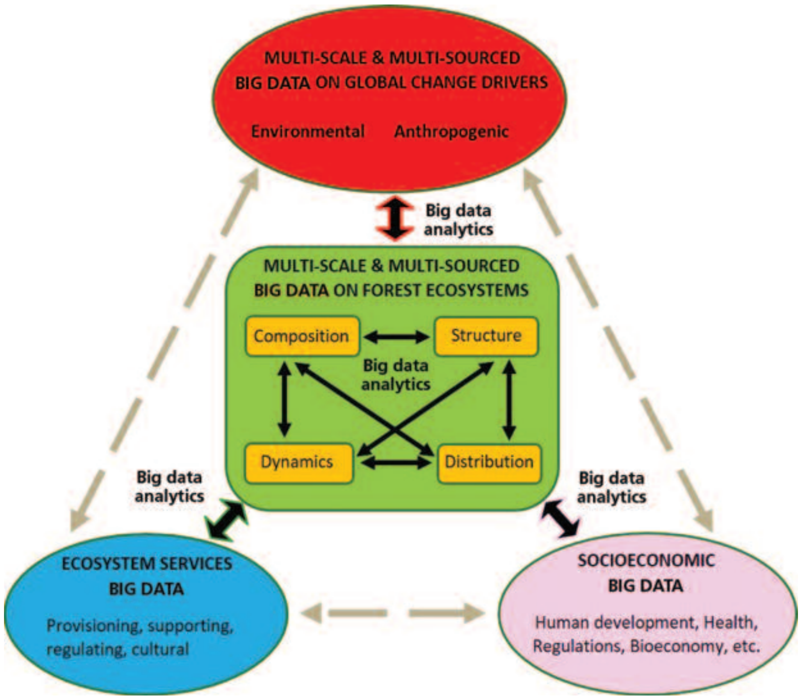

Fig. 1: Conceptual framework of the holistic, multi-scale and multi-sourced forest monitoring data integration needs concerning the functioning of forest ecosystems and their supply of multiple ecosystem services for human wellbeing in a context of global change.

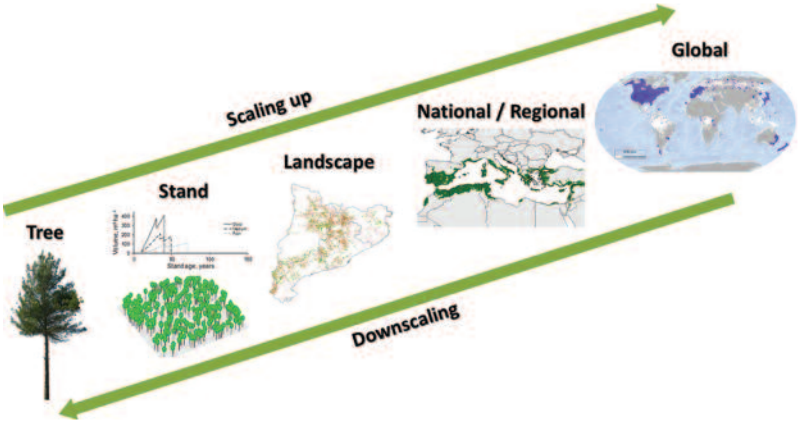

Fig. 2: Data sources from different spatial scales.

the global level, and from different temporal resolutions and monitoring occasions) (Fig. 2).

Moreover, forest monitoring needs to encompass the integration of heterogeneous big data retrieved from multiple sources, monitoring techniques and forest ecosystem attributes at the aforesaid different spatial-temporal scales (Fig. 3):

– Data from experiments and intensive small-scale monitoring;

– Data from National Forest Inventories (NFIs);

– Data from Regional networks, e.g. the ICP Forests European monitoring networks on forest conditions: Level I (16 x 16 km throughout Europe) and Level II (around 500 plots in selected forest ecosystems);

– Data from globally-distributed network and infrastructures, e.g. ILTER (International Long-Term Ecological Research), integrated by long-term research sites including forest ecosystem, biodiversity, critical zone and socio-ecological research;

– Data from specific studies but at global scale, e.g. International Tree-Ring-Data-Bank, which is the world's largest public archive of tree ring data;

– Data from Remote Sensing techniques, from local to national and global levels, e.g. LiDAR (PNOA - https://pnoa.ign.es, GEDI - https://gedi.umd.edu), satellite imagery, etc.;

– Data from genomic and genetic sources, e.g. TreeGenes or The Hardwood Genomics Database;

– Data from Citizen Science, e.g. Alerta Forestal - http://www.alertaforestal.com/es, GBIF - https://www.gbif.org).

Therefore, forest monitoring systems, information and data should focus on trying to address and monitor such forest complexity (from the point of view of both ecosystem functioning and provision of ecosystem services) in order to feed science and policy-making with sound information. This requires both smart forest monitoring systems as well as proper tools for analyzing complex information from multiple sources at multiple scales (Data Science).

Integrated, holistic forest monitoring data : approaches, tools and benefits

Approaches and tools

There are two main techniques for obtaining comparable data when integrating different data sets: harmonisation and standardisation (Köhl *et al.* 2000). Standardisation implies that all parties need to apply the same definitions, and even field protocols. Harmonisation only implies that the final estimates need to be comparable, being possible to use existing data series and definitions instead of establishing new or parallel data acquisition systems (Vidal *et al.* 2016). Harmonisation is therefore relevant for wide networks with long data series (e.g. NFIs) and for adpating collected data to changing information requirements over time. Standardization is probably the best option when a new network is going to be established, and common protocols can be designed from the very first moment (e.g. ICP Forests Networks), since this is the most accurate way to have comparable data and information over spatial-temporal scales.

Fig. 3: Examples of multi-sourced forest monitoring data at multiple spatial scales. From left to right: i) local-level experiments and monitoring of forest fungi and tree dynamics, ii) Citizen Science (e.g. Alerta Forestal: pests and other threats), iii) NFIs, and iv) Remote sensing data at multiple scales and resolutions (global: GEDI lidar, national: PNOA lidar).

Like most scientific disciplines, forest monitoring is at the stage of increasingly accelerated information availability, expanding the volume of data globally (Mansuy 2016). Big Data offer huge promise for all sectors but there are both technical and economic challenges. The acquisition, processing, integration and storage of large volumes of data are expensive and time-consuming and, additionally, data ownership and sharing needs to be taken into account (Mansuy 2016). Nevertheless, big data technology and data science (e.g., artificial intelligence) are experiencing a huge development worldwide, allowing for unprecedented big data analytics and perspectives and there is a clear increase of international collaboration although major investments would be needed. However, gathering and being able to analyze huge amounts of forest monitoring data is not enough. For successful and efficient data sharing and analysis, key issues such as data accessibility, transparency, security and communication become critical. In this regard, initiatives such as GO FAIR Guiding Principles for scientific data management and stewardship (https://www.go-fair.org/) intend to provide guidelines to improve the findability, accessibility, interoperability and reuse of digital assets. In the same vein, in the European framework, the INSPIRE Directive aims to create a homogenous European Union spatial data infrastructure for the purposes of EU environmental policies and policies or activities which may have an impact on the environment. This European Spatial Data Infrastructure will enable the sharing of environmental spatial information, facilitate public access to spatial information across Europe and assist in policy-making across boundaries (https://inspire.ec.europa.eu). INSPIRE provides non-binding Technical Guidance documents describing standards, technologies and practices for different datasets such as coordinate reference systems or habitats and biotopes.

Benefits of multi-scale and multi-sourced forest monitoring data integration

There are several benefits from integrating forest monitoring data from multiple scales and sources. What is the value of rather local monitoring data compared to more global monitoring data, and vice versa? Several complementarities can be described; Forest monitoring at local scale can provide:

– Experimental data from highly intensive local studies and monitoring can provide valuable knowledge for extrapolation at broader scales;

– Data on specific forest ecosystem features seldom monitored in forest ecosystems at broader scales (e.g. fungal dynamics);

– Accurate information on forest dynamics & drivers operating at smaller scales.

Forest monitoring at landscape to global scales can provide:

– New data & knowledge not available at a more local level (e.g., LiDAR-based, spatially continuous forest structure);

– Context and further insights by providing a broader observational and analytical framework compared to more local forest knowledge and dynamics;

– Information on forest dynamics & drivers operating at larger scales.

Examples of integration and harmonization of forest monitoring data

The European National Forest Inventory Network (ENFIN). Examples of data harmonization and integration

NFIs are the primary source of forest information for most countries to provide national and international information. The information they record is guided by forest attributes, ecosystems and classifications in line with national history, geographic location, climatic conditions and biophysical characteristics (Vidal *et al.* 2016) and therefore, information collected in different countries cannot be directly compared (Mc Roberts *et al.* 2012). The ENFIN group enhance co-operation between national forest inventory organizations, to: (i) provide harmonised forest inventory information on European forests; (ii) promote knowledge-sharing; (iii) maintain updated forest information systems; (iv) ensure continuous improvements; (v) maximise the synergy between NFIs and other European and International-level data collection systems;

and (vi) ensure openness to new requirements on forest data for emerging policy needs (EC 2013) (Vidal *et al.* 2016). ENFIN has developed a harmonisation process of building reference definitions and bridges (Alberdi *et al.* 2016) which has been considered in several related projects. In the framework of DIABOLO (Distributed, Integrated and Harmonised Forest Information for Bioeconomy Outlooks) Horizon 2020 project (http://diabolo-project.eu/), conformed by 33 scientific institutions in 25 European countries, several variables and developing methods were harmonized (Packalen *et al.* 2019). Some of the main outputs are the following:

– Harmonised and improved estimation of different forest variables such as volume or shrub cover (Gschwantner *et al.* 2016; Alberdi *et al.* 2018);

– Estimation procedures that combine NFIs information data and auxiliary information from remote sensing and maps (Kirchohoefer *et al.* 2017);

– New NFIs-based models or protocols, e.g. for non-wood forest products (Pasalodos-Tato *et al.* 2017) or forest biodiversity-related attributes (de la Fuente *et al.* 2018);

– Rapid disturbance detection approach (Hirschmugl *et al.* 2017);

– Harmonised forest sector scenarios (Vauhkonen & Packalen 2017).

There have been also Framework Contracts with the Joint Research Centre, for provision of forest data and services with a consortium of ENFIN members. To achieve the requirements, a data platform was developed by integrating harmonized plot data at the European scale and providing harmonized estimates. It is worth mentioning, for instance, the provision of harmonised data on tree species distribution on a 1km x 1km INSPIRE grid (San Miguel Ayanz *et al.* 2016).

The Global Forest Biodiversity Initiative (GFBI) : global harmonization of multi-scale and multi-sourced forest monitoring data

The Global Forest Biodiversity Initiative (GFBI– http://www.gfbinitiative.org/) is an international multi-stakeholder network of foresters and forest scientists established in 2016, with the aim of better assessing forest biodiversity, functioning and ecosystem services based on global ground-sourced data of tree-level forest inventories, as well as of addressing prominent scientific questions on the ecology and management of forests worldwide (Liang & de-Miguel, 2018). The GFBI database currently covers more than 75 countries with ~1.3 million forest inventory plots with individual tree-level data such as species composition and tree size; this probably makes it the largest database of integrated individual tree-level forest inventory data worldwide. The GFBI data are managed at the GFBI Data Center established and developed by the GFBI Hub located at the University of Lleida (Spain), in close collaboration with the other GFBI Hubs. The GFBI Data Management System allows for integrating local to global forest monitoring data from multiple sources, and data sharing according to the GFBI bylaws and data standards. This forest monitoring data integration and harmonization initiative has led to unprecedented research outcomes about forest diversity and ecosystem functioning at the global level, e.g. on the relationship between forest diversity and productivity (Liang *et al.* 2016) or on the global biogeography of forest tree symbioses (Steidinger *et al.* 2019), contributing to a breakthrough in our knowledge on forest ecosystems worldwide.

Conclusions

Finally, by way of conclusion, we intend to stress that forest monitoring itself (i.e. data gathering only) is not enough to deepen our knowledge at multiple scales on forest dynamics, its drivers, the provision of ecosystem services and the related socioeconomic impacts. Combining in a smart and useful way such complex information on forest ecosystems from a wide array and diversity of forest monitoring systems and forest monitoring objectives will represent a groundbreaking tipping point, enhancing new scientific knowledge and decision-making at multiple scales. The big challenges ahead are, therefore, to: i) integrate multi-scale and multi-sourced forest monitoring big data through harmonization and standardization initiatives, together with high-level computing capacities and artificial intelligence in order to extract valuable, meaningful and useful information for decision-making; and ii) make all these big data, knowledge and facilities available not only to the scientific community but also to policy- and decision-makers. If information cannot be reached or used by a broad array of society's key stakeholders to shed light on national- to global-level challenges in relation to forests and global change, then we will not make the most from so much valuable information. Indeed, future human wellbeing largely depends on our shared knowledge on the impacts of global change on forest ecosystems.

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Summary

Integration of multi-sourced and multi-scale forest monitoring data for addressing local to global challenges on forest ecosystems within the framework of the Paris Agreement

The Paris Agreement involves, directly or indirectly, forest ecosystems as a key component to achieve climate change mitigation targets. Recent research suggests that forest managers and policy makers should rather put the focus on the adaptation of forest ecosystems to climate change (as other international processes demand), this representing the main challenge that will also determine the capacity of forests to act as carbon sinks. This is particularly relevant for forest ecosystems in the Mediterranean basin, for which the expected impacts of climate change are huge, and where forest growth and survival are strongly limited by water scarcity. Assessing the ability of forest ecosystems to adapt to climate change together with their key role in climate change mitigation requires sound scientific information (and data). For this purpose, in the Big Data Era, holistic, multi-sourced, and multi-scale forest monitoring is required together with Data Science to encompass the integration of heterogeneous data from: i) multiple spatio-temporal scales, and ii) multiple sources and monitoring techniques. Two relevant examples of forest data harmonization at European and global scales are highlighted. The additional big challenge is to make data available to the scientific community, managers and decision-makers to be able to address, from multiple perspectives, the global challenges in relation to forests.

Résumé

Intégration, dans le cadre de l'Accord de Paris, de données forestières pour répondre aux défis locaux et globaux que rencontrent les écosystèmes forestiers

L'Accord de Paris implique, directement ou indirectement, les écosystèmes forestiers comme variable clé pour atteindre les objectifs d'atténuation des changements climatiques. Des recherches récentes suggèrent que les gestionnaires forestiers et les décideurs politiques devraient plutôt mettre l'accent sur l'adaptation des écosystèmes forestiers aux changements climatiques (comme d'autres démarches internationales le demandent), ce qui représente le principal défi qui déterminera également la capacité des forêts à agir comme puits de carbone. Ceci est particulièrement important pour les écosystèmes forestiers du bassin méditerranéen, pour lesquels les impacts attendus des changements climatiques sont massifs et où la croissance et la vitalité des forêts sont fortement limitées par l'économie en l'eau. L'évaluation de la capacité des écosystèmes forestiers à s'adapter aux changements climatiques et leur rôle clé dans l'atténuation des changements climatiques exigent des connaissances scientifiques solides (et des données).

Dans ce but, à l'ère du Big Data, une approche forestière holistique est nécessaire, recueillant des données variées sur des échelles multiples, en utilisant la science des données, pour intégrer des données hétérogènes : i) échelles spatio-temporelles multiples ; ii) sources multiples et techniques variées de pilotage.

Deux exemples pertinents d'harmonisation des données forestières à l'échelle européenne et mondiale sont mis en évidence. Le grand enjeu ensuite consiste à mettre les données à la disposition de la communauté scientifique, des gestionnaires et des décideurs afin qu'ils soient en mesure de relever, à partir de points de vue variés, les défis globaux liés aux forêts.

Resumen

Big Data para abordar los desafíos locales y globales en relación con los ecosistemas forestales en el marco del Acuerdo de París

La integración de datos de inventarios forestales de múltiples fuentes y múltiples escalas para abordar los desafíos (desde locales hasta globales) de los ecosistemas forestales en el marco del Acuerdo de París, es clave para lograr los objetivos de mitigación del cambio climático. Investigaciones recientes sugieren que los políticos y gestores forestales deberían centrarse en la adaptación de los ecosistemas forestales al cambio climático (como exigen otros procesos internacionales). Este es el principal desafío que, además, determina la capacidad de los bosques para actuar como sumideros de carbono. Esto es particularmente relevante para los ecosistemas forestales en la cuenca mediterránea, para los cuales los impactos esperados del cambio climático son enormes, y donde el crecimiento y la supervivencia de los bosques están fuertemente limitados por la escasez de agua. Evaluar la capacidad de los ecosistemas forestales para adaptarse al cambio climático junto con su papel clave en la mitigación del cambio climático requiere de datos y de una información científica robusta y fiable. Para este propósito, en la Era del Big Data, se requiere de datos forestales holísticos que, unidos a la Ciencia de Datos, permitan abarcar la integración de datos heterogéneos: i) de múltiples escalas espacio-temporales, y ii) procedentes de múltiples fuentes de información y técnicas de inventario. Se destacan dos ejemplos relevantes de armonización de datos forestales a escala europea y mundial. El gran desafío adicional es hacer que los datos estén disponibles para la comunidad científica, los administradores y los encargados de la toma de decisiones para poder abordar, desde múltiples perspectivas, los desafíos mundiales en relación con los bosques.