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Review

Towards long-term standardised carbon and greenhouse gas observations for monitoring Europe´s terrestrial ecosystems: a review

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A b s t r a c t. Research infrastructures play a key role in launching a new generation of integrated long-term, geographically distributed observation programmes designed to monitor climate change, better understand its impacts on global ecosystems, and evaluate possible mitigation and adaptation strategies. The pan-European Integrated Carbon Observation System combines carbon and greenhouse gas (GHG; CO_2, CH_4, N_2O, H_2O) observations within the atmosphere, terrestrial ecosystems and oceans. High-precision measurements are obtained using standardised methodologies, are centrally processed and openly available in a traceable and verifiable fashion in combination with detailed metadata. The Integrated Carbon Observation System ecosystem station network aims to sample climate and land-cover variability across Europe. In addition to GHG flux measurements, a large set of complementary data (including management practices, vegetation and soil characteristics) is collected to support the interpretation, spatial upscaling and modelling of observed ecosystem carbon and GHG dynamics. The applied sampling design was developed and formulated in protocols by the scientific community, representing a trade-off between an ideal dataset and practical feasibility. The use of open-access, high-quality and multi-level data products by different user communities is crucial for the Integrated Carbon Observation System in order to achieve its scientific potential and societal value.

K e y w o r d s: ICOS, GHG exchange, carbon cycle, standardised monitoring, observational network

INTRODUCTION

Anthropogenic climate change is one of the greatest global challenges that our society faces in the 21st century and beyond. The major driving force of recent and future anthropogenic climate change is the human perturbation of biogeochemical and energy cycles, including the well-documented escalation of atmospheric greenhouse gas (GHG) concentrations, especially carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) since pre-industrial times (IPCC, 2013, Kirschke *et al.*, 2013; Jackson *et al.*, 2016). In view of the expected threats associated with climate change, the development of mitigation and adaptation strategies are among the top priorities of international governance. The Paris Agreement, which builds upon the United Nations Framework Convention on Climate Change (UNFCCC), entered into force in 2016 with the aim of limiting 21st-century global mean air temperatures to a maximum of 2°C above pre-industrial levels (Rogelj *et al.*, 2016). A prerequisite for successful climate change mitigation and adaptation efforts is knowledge of the key drivers, characteristics and impacts of climate change on ecosystem processes, which can only be obtained through geographically extensive, robust, consistent and reliable long-term observations (Seneviratne *et al.*, 2018). *In-situ* measurements, integrating the Earth system domains (1) atmosphere, (2) terrestrial and freshwater ecosystems (hereafter referred to as 'terrestrial ecosystems' only) and (3) ocean through continental-scale research infrastructures (RIs) with broad geographical representativeness, are most appropriate for these purposes (Ciais *et al.*, 2014; Papale *et al.*, 2015; Kumar *et al.*, 2016). The Integrated Carbon Observation System (ICOS) is a pan-European RI that provides high-precision observations in a standardised, traceable and verifiable manner for the three Earth system domains. The focus of these challenging efforts is on the carbon (C) cycle and GHGs (CO_2, CH_4, N_2O, H_2O). Observations of energy, water and nitrogen (N) cycle components are only partly included in the ICOS portfolio and not addressed in detail in this paper.

Benefits of long-term, integrated *in-situ* observations as provided by ICOS

The atmosphere, terrestrial ecosystems and oceans are closely interconnected through energy and matter exchange (such as latent heat and the cycling of C and N). Respective sources and sinks interact with each other and the rates at which the elements are sequestered or released vary in response to changing biotic and abiotic conditions. For CO_2, Ballantyne *et al.* (2012) provided a mass balance analysis based on global atmospheric CO_2 concentration measurements and emission inventories. They estimated that global uptake of anthropogenically emitted CO_2 by terrestrial ecosystems and oceans doubled from 1960 (2.4±0.8 Pg C a^{-1})

to 2010 (5.0±0.9 Pg C a^{-1}) in response to increased atmospheric CO_2. Ballantyne *et al.* (2012) stated that the total uptake during these 50 years corresponds to 55% of the anthropogenic CO_2 emitted during the same period. However, there are ongoing discussions about the magnitudes of effects on the atmospheric CO_2 budget by terrestrial ecosystems and oceans individually, the location and status of the dominant large-scale CO_2 sinks, and the future evolution of sinks and sources (Ciais *et al.*, 1995; Canadell *et al.*, 2007; Pan *et al.*, 2011; Levin, 2012; Wanninkhof *et al.*, 2013). The estimates from the Global Carbon Project (GCP) for the global terrestrial and oceanic C uptake in 2017 were of 2.7±1.0 Pg C a^{-1} and 2.6±0.5 Pg C a^{-1}, respectively, which together offset 47% of current annual anthropogenic CO_2 emissions (Le Quéré *et al.*, 2018). In general, such estimates and scenarios for the global C cycle improve with measurement precision and refined modelling of the global biogeochemical cycles, but still involve considerable uncertainties (Peters, 2018). Discrepancies between the C cycle components raise the question of whether we are still missing essential reservoirs and processes that influence the budgets and if our current observational strategies are appropriate to resolve them (Ballantyne *et al.*, 2012; Levin, 2012; Le Quéré *et al.*, 2016). Monitoring approaches need to integrate observations of the atmosphere, terrestrial ecosystems and oceans to allow detection of potentially missing sources, sinks and driving processes. It is clear that a lack of long-term routine sampling, with standardisation and sufficient temporal and spatial coverage, continues to limit understanding and quantification of global biogeochemical cycles including natural and anthropogenic GHG emissions (Le Quéré *et al.*, 2016).

The time scale of climate-related changes and the turnover times of the major C pools range from months to millennia. Long-term atmospheric, biogeochemical and ecological datasets are crucial to better understand the spatio-temporal scales of environmental variability, to attribute changes to a particular forcing process and to identify temporally shifted or gradually changing ecological responses (Bonan *et al.*, 2012; Baldocchi *et al.*, 2012). Long-term observations reveal susceptibilities and critical shifts in ecosystem functioning and services, and identify ecosystem responses to short-term anomalies and extreme events (Reichstein *et al.*, 2007; Chu *et al.*, 2017). With strong environmental changes expected in the next few decades, such long-term datasets should cover a relevant timeframe ($\geq$ 20 years).

Continuous monitoring of GHG concentrations and fluxes is also crucial for GHG projections and to foresee climate-related scenarios such as Representative Concentration Pathways (RCPs; van Vuuren *et al.*, 2011). Long-term observations with a high level of standardisation further build the capacity for cross-site synthesis activities. Long-term observations can help to reveal spatial GHG flux patterns and produce continental- and global-scale flux maps by combining network flux data, remote sensing and coupled ecosystem-climate models (Baldocchi, 2014). They can further support compulsory GHG emission inventories and independent GHG emissions verification, and help define and evaluate climate change mitigation and adaptation strategies such as climate-smart land-use management practices (Ceschia *et al.*, 2010; Bellassen and Luyssaert, 2014).

Modelling capabilities are rapidly growing with our understanding of the Earth system and sophisticated data assimilation techniques, and are improving the quality of climatic and ecological predictions (Millar *et al.*, 2017; Goodwin *et al.*, 2018; Niu *et al.*, 2014). This increases the demand for *in-situ* observations for model development, in order to better constrain parameterisations, to independently evaluate model performance, and to reduce uncertainties in model predictions (Bonan *et al.*, 2012; Schmid, 2012). Such demand is particularly significant for bottom-up model approaches that estimate C and GHG budgets at local, regional and global scales (e.g. Jung *et al.*, 2009, 2011; Osborne *et al.*, 2010; Schulze *et al.*, 2010; Smith *et al.*, 2010; Zhu *et al.*, 2014; Kondo *et al.*, 2015; Zscheischler *et al.*, 2017), and for Earth System Models (ESMs), that include biogeochemical components and biosphere-atmosphere flux algorithms (Williams *et al.*, 2009; Bonan *et al.*, 2012; Baldocchi *et al.*, 2012). Furthermore, *in-situ* observations provide a priori knowledge for inverse modelling and can validate top-down modelling approaches based on atmospheric GHG concentration measurements (Wanninkhof *et al.*, 2013; Houweling *et al.*, 2017; Leip *et al.*, 2018). Inverse modelling approaches are extremely useful in determining a regional GHG budget, but depend strongly on a dense observational network (Villani *et al.*, 2010; Kadygrov *et al.,* 2015). Additionally, *in-situ* observations are needed to validate airborne and satellite remote sensing products (such as gross primary production, pigment indices, vegetation indices and related products), which are increasingly applied to quantify the changes in global C and N budgets.

Evolution of European GHG observations from project-based networks to a research infrastructure

The International Biological Program (IBP, 1964-1974) was among the first implemented Big Science projects in biology. It provided insights into ecosystem responses to climate change, *e.g.* the GHG exchange between ecosystems and the atmosphere, and inspired subsequent long-term ecological and environmental observation networks such as LTER (Long Term Ecological Research). However, already during the 1950s attempts were made to develop CO_2 observation and data assimilation programmes (Fonselius, 1958). An active and persistent scientific community developed many international GHG concentration and flux measurement networks and programmes for

terrestrial ecosystems, atmosphere and oceans. These arose in Europe and elsewhere over recent decades (Fig. 1, Table A3), with strong support from the European Commission and national funding sources. Particularly the early network approaches were geographically limited and only covered one or two of the three domains. In the case of terrestrial ecosystems, GHG networks often focussed more on certain ecosystem types and on specific rather than comprehensive coverage of key processes and components of the C cycle and biosphere-atmosphere GHG exchange. The eddy covariance (EC) technique was initially applied for campaigns of a few months only instead of long-term monitoring. It involves the use of expensive precision devices, which further limited the spatial coverage of these direct flux measurements. Furthermore, in earlier programmes and networks metadata and observations supporting the analysis and interpretation of the measurements were often neglected or not published, hampering in-depth process understanding and the reproducibility of the results. Varying measurement techniques and data processing procedures resulted in limited comparability, and consequently increased the uncertainty in analysis outcomes and model predictions. Data precision conventions were also mostly absent, adding to modelling uncertainties which depend both on model structure (representing our understanding of the processes) and on the quality of parameterisation data. Furthermore, data were often stored in different formats and archived separately for each project/network, limiting the potential benefits of data sharing and integrative model assimilation. However, the scientific outcome of these early network initiatives was often of the highest quality and reflected the state-of-the-art methodology available at the time. While frequent scientific reorientation and short project durations limited the confident extrapolation of short-term datasets to long-term trends, these early initiatives still raised important questions about our understanding of C and GHG dynamics within and across ecosystems. The urgent need for a thorough, consistent and long-term data collection and analysis approach integrating the three Earth system domains, initiated the transition from a short-term, project-based framework to ICOS as a highly integrated RI over the last 15 years.

ICOS within the European and global observation and research landscape

Two milestones significantly influenced the development of ICOS as a European RI. The first was the formulation of global observational necessities by the Subsidiary Body for Scientific and Technical Advice (SBSTA) of the United Nations Framework Convention on Climate Change (UNFCCC). ICOS is thereby based on a sub-system of the 'Essential Climate Variables' (ECVs; physical, chemical or biological variables or groups of linked variables that critically contribute to the characterisation of the Earth's climate) called 'Essential Carbon Cycle Variables'. Deeply rooted in this (sub-)system – documented in the Implementation Plan of the Global Climate Observation System (GCOS) – ICOS aims to evolve into the European pillar of a future global

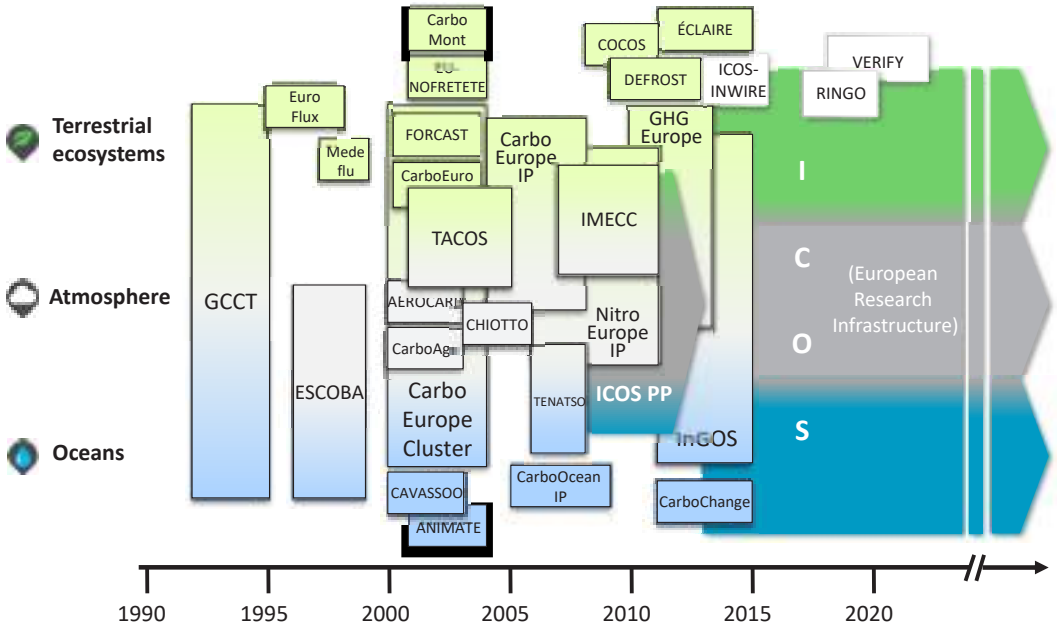

Fig. 1. The evolution of (selected) European project-based C, N and GHG observation networks and programmes for the three Earth system domains towards ICOS as integrated RI. Acronyms are explained in Tables A2 and A3. The white boxes on the right indicate recent ICOS projects.

GHG observation system. With this future growth in mind, ICOS is developing a comprehensive cross-domain array of atmosphere, terrestrial ecosystem and ocean observations, as required for an in-depth understanding and conceptualisation of biogeochemical cycles evolving under a changing climate. This approach will enable ICOS to significantly contribute to a number of scientific network programmes such as the World Meteorological Organisation (WMO)-driven Integrated Global Greenhouse Gases Information System (IG^3IS), the Group on Earth Observation (GEO) Carbon and GHG Initiative (GEO-C), and the European Earth Observation Programme (COPERNICUS).

The second milestone for the transition to a European RI was the development of the European Strategic Forum for Research Infrastructures (ESFRI). ESFRI put ICOS on its first roadmap in 2006 and identified it as a 'Landmark' in 2016, transforming ICOS into an RI of pan-European interest corresponding to the long term needs of the European research communities. ICOS has an active role in the development of the European Environmental Research Infrastructure (ENVRI) landscape as well. Consolidation of the ESFRI landscape is pursued via interoperability with other ENVRIs (*e.g.* IAGOS, ACTRIS, Lifewatch, AnaEE, eLTER RI; EuroArgo and EMSO; Table A3), yielding synergies from joint measurement strategies, common standards, and the co-location of sites or common data life cycles.

The pan-European research infrastructure ICOS

ICOS is a distributed European RI providing *in-situ* standardised, traceable and verifiable, high-precision observations of lower atmosphere GHG concentrations as well as biosphere-atmosphere GHG fluxes, where measurements are intended to last for ≥ 20 years. The observations are complemented by a large set of multi-disciplinary data required to document changes in ecosystem composition, structure and functioning and for the interpretation and modelling of the observed GHG concentrations and fluxes (Table A1). The overarching goal of ICOS is to facilitate high-quality research on the status, future responses and driving forces of GHG and C cycle dynamics, as well as the role of atmospheric, terrestrial and oceanic systems in the development of, and response to, future climate change. ICOS aims to enhance our understanding of the GHG balance of the European continent and adjacent regions, in addition to evaluating GHG emission mitigation and adaptation strategies (Gielen *et al.*, 2017). Its mission also includes education, capacity building and the promotion and implementation of technological advancements.

The RI provides a network of measurement stations classified based on their level of standardisation to obtain a comprehensive picture of C cycle and GHG dynamics and their spatial and temporal variability across Europe and adjacent regions. A major challenge is to provide cross-domain integration while maintaining high quality scientific outcomes in each domain (Gielen *et al.*, 2017). The implementation of ICOS has been based on the bottom-up development of measurement standards and protocols, which has been led by the scientific community. Furthermore, ICOS implements the attributes that were identified to be important for effective observation networks, including an integrated data management structure, facilitating effective data sharing and assimilation, and a scientific network engaged with frequent communication, dissemination and joint scientific development (Baldocchi *et al.*, 2012).

ICOS follows the monitoring principles of the GCOS and the measurement recommendations from the Global Earth Observation System of Systems (GEOSS). Data collection, processing and archiving are harmonised and standardised. Furthermore, ICOS aims to ensure comparability with the set of ancillary measurements made within existing networks such as the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) to facilitate upscaling. However, some flexibility to adjust the measurements to local site conditions and to benefit from technological innovations during the life-time of the infrastructure is retained. New measurement techniques and instruments are consolidated and thoroughly tested before they can be applied at the stations.

An overview on the organisational structure of ICOS is presented in Gielen *et al.* (2017). The individual institutions contributing to the national networks provide data from the standardised stations that are processed and quality controlled by the Central Facilities. The centralised data processing, which is based on open-source scripts, yields comparable data products of adequate and known quality and includes an estimate of their uncertainty. Various levels of data products are archived for the long-term storage in the repository offered by the Carbon Portal (https://www.icos-cp.eu). The ICOS database represents a common, open-access archive with a data set identifier system and clearly defined data usage policies (https://www.icos-ri.eu/sites/default/files/cmis/ICOS%20RI%20Data%20Policy.pdf). This ensures verifiable, reproducible and transparent science, and accelerates scientific progress while returning scientific impact for the data producers (Nosek *et al.*, 2015; Dai *et al.*, 2018).

GHG OBSERVATIONS IN TERRESTRIAL ECOSYSTEMS

The terrestrial biosphere plays a central role in regulating the climate through physical, chemical and biological processes (Bonan *et al.*, 2012), and reacts to changes in climate with both positive and negative climate-ecosystem feedback mechanisms (Heimann and Reichstein, 2008; Arneth *et al.*, 2010; Frank *et al.*, 2015). In order to better understand the links between terrestrial ecosystems and both the regional and global climate systems, improved knowledge of terrestrial C pathways and GHG exchange

processes are required. However, the terrestrial C cycle represents the component of the global C budget with the highest observed variability and greatest measurement uncertainties (Bousquet *et al.*, 2000; Bloom *et al.*, 2016; Le Quéré *et al.,* 2016). A growing observational network and associated database will therefore continuously improve our understanding of the interactions between terrestrial ecosystems and the climate system (Valentini *et al.*, 2000; Baldocchi, 2008). For example, recent findings have highlighted the relationship between climatic extremes and the associated climate feedbacks of the terrestrial C cycle (Ciais *et al.*, 2005; Reichstein *et al.*, 2007; 2013, Frank *et al.*, 2015; Xiao *et al.*, 2016).

Since the 1990s the routine use of EC technique for tower-based C, water and heat flux measurements has provided continuous observations over multiple years at a variety of sites and biomes in different climatic zones. Such measurements were identified as critical tools for the quantification of global and regional GHG dynamics, especially when conducted in combination with remote sensing observations and ESMs (Baldocchi, 2014). The EC approach is an established and robust technique to quantify turbulent exchanges of scalars, such as trace gases, momentum and energy, between the Earth's surface and the atmosphere (Aubinet *et al.*, 2000). Fluxes of the variables of interest are calculated through the covariance of the mean deviations in vertical wind velocity and the respective scalar of interest (Desjardins and Lemon, 1974; Aubinet *et al.*, 2000). These quasi-continuously measurement systems impose minimal disturbance on the environment once operational, and recent technological advances have resulted in a new generation of EC instrumentation characterised by low-power and maintenance demands, depending on the scalar of interest. The fundamental utility and application of EC GHG flux measurements includes an assessment of the ecosystem response to environmental perturbations across various sites. This then allows for the derivation of GHG budgets, inter-annual and inter-site comparisons as well as the spatial scaling of GHG exchange (Baldocchi, 2003, 2014; Baldocchi *et al*., 2017).

Since the early 2000s standardisation in GHG flux data acquisition, processing and provision has been improved with the development of FLUXNET (Baldocchi *et al.*, 2001), a global network of regional flux tower networks, such as CarboEurope IP, AmeriFlux, Fluxnet-Canada, Asiaflux, CarboAfrica (Sub-Saharan Africa) and OzFlux (Australia and New Zealand, Table A3). The FLUXNET database has already provided important new insights into the course and consequences of environmental change (Baldocchi, 2005, 2008; Falge *et al.*, 2002; Law *et al.*, 2002; Schwalm *et al.*, 2009, 2017; Richardson *et al.*, 2010; Migliavacca *et al.*, 2011; Keenan *et al.*, 2013; Wolf *et al.*, 2016) and will further benefit in the future from the inclusion of ICOS data facilitated by its open-access policy. In addition, the rapid development of new measurement techniques including infrared gas analysers and laser absorption spectrometers, and an increasing number of modelling approaches at various spatio-temporal scales have resulted in considerable progress in our understanding of the processes and impacts of environmental change, *e.g*., for the European continent (Ciais *et al.*, 2005; Jung *et al.*, 2007).

Long-term EC datasets (> 20 years) are currently available for particular forest sites such as the Harvard Forest (Massachusetts, US, since 1991; Urbanski *et al.*, 2007), the Takayama Forest (Japan, since 1993; Saigusa *et al.*, 2005), Howland Forest (Maine, US, since 1996; Hollinger *et al.*, 2004), the Anchor Station Tharandt (Germany, since 1996; Grünwald and Bernhofer, 2007), Sorø Forest (Denmark, since 1996; Pilegaard *et al.*, 2011), the SMEAR II field measurement station (Hyytiälä, Finland, since 1996; Ilvesniemi *et al.*, 2009) and the mountain forest station in Davos (Switzerland, since 1997; Etzold *et al.*, 2011). The latter four stations are ICOS Candidate stations (currently undergoing either step 1 or 2 in the station labelling process). For forest ecosystems, intensive long-term monitoring activities were established and harmonised in Europe in the 1980s, through the ICP Forests under the frame of United Nations Economic Commission for Europe (UNECE). However, this network does not include the quasi-continuous terrestrial biosphere-atmosphere GHG exchange measurements implemented by ICOS (UNECE ICP Forests Programme Co-ordinating Centre, 2016; Danielewska *et al.*, 2013, Ferretti and Fischer, 2013).

First European cropland stations were established in the early 2000s and results were integrated by Ceschia *et al.* (2010), Osborne *et al.* (2010), Eugster *et al.* (2010) and Kutsch *et al.* (2010). Some of these early stations, namely Borgo Cioffi (Italy, since 2001; Vitale *et al.*, 2016), Gebesee (Germany, since 2001; Anthoni *et al.*, 2004), Klingenberg (Germany, since 2004; Prescher *et al.*, 2010), Grignon (France, sine 2004; Loubet *et al.*, 2011) and Lonzée (Belgium, since 2004; Aubinet *et al.*, 2009) have been running continuously since then and will now be continued within ICOS.

Similarly, most European long-term grassland stations were established in the early 2000s, including Neustift (Austria, since 2001; Wohlfahrt *et al.*, 2008), Laqueuille (France, since 2002; Soussana *et al.*, 2007) Grillenburg (Germany, since 2002; Soussana *et al.*, 2007) and Monte Bondone (Italy, since 2002; Marcolla *et al.*, 2011), whereby the latter three are contributing to the ICOS ecosystem station network. Early results were integrated for Europe by Gilmanov *et al.* (2007) and Soussana *et al.* (2007) and globally by Gilmanov *et al.* (2010) and Soussana *et al.* (2010).

Long-term EC measurements over wetlands have been started in the late 1990s, *e.g.* at Kaamanen (Finland, since 1997; Aurela *et al.*, 2004), Zackenberg (fen, Greenland, since 1996; Soegaard *et al.*, 2000) and the Mer Bleue peatland (Canada, since 1998; Lafleur *et al.*, 2003). Apart from Kaamanen and Zackenberg, ICOS ecosystem stations with

long-term measurements of at least one decade include Degerö (Sweden, since 2001; Peichl *et al.*, 2014), Abisko-Stordalen Palsa Bog (Sweden, since 2001; Christensen *et al.*, 2012), Siikaneva (Finland, since 2005; Rinne *et al.*, 2007), Třeboň (Czech Republic, since 2006; Dušek *et al.*, 2012) and Auchencorth Moss (UK, since 2002; Helfter *et al.*, 2015).

The ICOS ecosystem station network

The ICOS network of terrestrial ecosystem stations aims to represent the variability in climate and land cover throughout Europe. It covers the four main terrestrial ecosystem types which are most relevant to access GHG exchange across the European continent (forests, croplands, grasslands and wetlands) and which have been commonly observed within historic GHG observation programmes (*e.g*. GHG Europe). The network further includes stations in more locally dominant ecosystem types: heath/ shrublands, short rotation forestry (SRF) plantations, freshwater lakes and urban environments. Lakes have been included within the ICOS ecosystem network due to their importance in the global C and GHG cycle (Cole *et al.*, 1994, 2007; Battin *et al.*, 2009; Tranvik *et al.*, 2009). Holgerson and Raymond (2016) estimated a net C loss from non-running inland waters of 0.58 Pg C a^{-1}, which is about one-fifth of the global terrestrial C uptake (Le Quéré *et al.*, 2018). The inclusion of urban environments into the ICOS ecosystem network is justified due to the role of these areas as a major source of anthropogenic GHGs, and the ongoing trend of urbanisation in Europe (The European Union, 2016) and across the globe (United Nations, 2014). Common GHG monitoring approaches in cities are typically based on emission inventories aggregated for different sectors (road transport, industry, *etc*.). In comparison, the EC method has the advantage of integrating the heterogeneous urban GHG sources and sinks with sufficient spatio-temporal resolution to distinguish the contributing processes and their drivers, despite methodological limitations (limited footprints and complex surfaces with specific roughness) (Velasco and Roth, 2010; Liu *et al.*, 2012).

Sampling design at ecosystem stations: a balancing act between a comprehensive setup and practical feasibility

A major challenge during the design phase of any ecosystem observation network is the identification of the essential environmental variables to be measured, their temporal frequency and spatial representativeness. The answer represents a trade-off between an ideal dataset that enhances our current process understanding and addresses key knowledge gaps, and the practical feasibility of an ambitious measurement plan in terms of budget, human resources and the sustainability of long-term infrastructure deployment. The ICOS Ecosystem Monitoring Station Assembly (MSA) and the Ecosystem Thematic Centre (ETC) have devised a trade-off that is built on the experiences of previous monitoring and experimental research networks. These include the identification of key components for GHG observations in terrestrial ecosystems (variables and sampling design) combined with general recommendations on the structure of monitoring networks (Hari *et al.*, 2009, 2016; Baldocchi *et al.*, 2012; Paoletti *et al.*, 2014; Kulmala, 2018) and the careful consideration of the requirements from multiple data user categories. The potential users of ICOS data include the scientific communities as well as national and international programmes and environmental agencies, information service providers (*e.g.* COPERNICUS projects), public and private entities as well as educational organisations (Kaukolehto and Vesala, 2014). Fisher *et al.* (2018) recently highlighted the need to integrate observations with stakeholder requirements at an early stage of network design, *e.g*. the data requirement for modelling activities and syntheses.

Similar to most of the recent national and international GHG monitoring initiatives (Baldocchi, 2014; Baldocchi *et al.*, 2012), EC flux measurements are at the core of all ICOS ecosystem stations. However, the ecosystem station network goes far beyond an EC flux-tower network. It comprises an optimised system to measure the storage change of GHGs in the air column underneath the EC system in addition to chamber-based soil-atmosphere GHG flux measurements. A broad set of ancillary measurements (including soil and vegetation characteristics) are also implemented to observe site-specific abiotic and biotic conditions (Pilegaard *et al.*, 2011) and to support the analysis, interpretation, scaling and modelling of GHG fluxes (Fernández-Martínez *et al.*, 2017; Keenan *et al.*, 2013; Wu *et al.*, 2013).

The ICOS ecosystem stations are categorised according to the number of variables measured and replicated design, and are classified as Class 1, Class 2 and Associated Stations (Table A1). The various levels of station designs facilitate flexibility in the site setup requirements and will ensure greater participation by the scientific community. Class 1 Stations represent ‘supersites’ with the most extensive standardised measurement criteria including continuous high-frequency measurements of the key C cycle compounds such as CO_2 and CH_4 where relevant for the particular ecosystem (*e.g.* wetlands or lakes) or N compounds in agroecosystems. These stations are especially valuable for in-depth studies of biophysical processes and model parameterisations (Skiba *et al.*, 2009). The spatial spread of measurements across Europe is provided by a dense network of Class 2 stations, where fewer variables and replications of these measurements are required. However, the same level of measurement accuracy is required for station Classes 1 and 2. The measurement setup at Associated stations has to follow a less rigid level of standardisation, however, these stations still undergo an evaluation in order

to meet ICOS data quality conventions while increasing the spatial representativeness of the different ecosystem types within the network.

The standardised procedures for the key observations required at ICOS ecosystem stations are described in 13 measurement protocols published in this issue of International Agrophysics, while specific instruction documents provide a guide to their practical implementation (www.icos-etc.eu/documents/instructions). However, the ICOS methodology is expected to further develop over time by revised measurement requirements according to the practical experience of the network and by implementing new technological developments following extensive testing periods. The protocols and instructions facilitate harmonised and comparable high-quality measurements that are essential for contributing to the overall goals of ICOS. A two-stage labelling process by the ETC ensures that all ICOS ecosystem stations fulfil the specific requirements of the ICOS station classes. The labelling process is required for both newly established and existing ecosystem stations applying to join the ICOS ecosystem network. In the first stage the suitability of the proposed station is evaluated in terms of characteristics and contribution to the network (*e.g.* representativeness and number of similar stations already included in ICOS). Technical evaluation criteria such as EC footprint, including fetch homogeneity, canopy conditions as well as the physiographic setting, are important theoretical assumptions to be met for EC measurements. However, the station setup can still be optimised during the ongoing labelling process. In the second stage the protocols for the station class specific variables need to be correctly implemented at the station. The station PI can ask for exceptions to the protocols if the standard methodology cannot be applied, *e.g.* an optical precipitation measurement instrument is admissible as an exception where no appropriate open space can be found near forest sites for weighing gauge measurements (Dengel *et al.*, 2018). These site specific exceptions are documented and publicly available for the data user community. Furthermore, at this second stage robust data collection and transfer to the ETC needs to be established for Class 1 and Class 2 Stations, whereas for Associated Stations the data (calculated by station team, half-hourly) has to be submitted once a year.

Measurement overview

Site characterisation

An essential aspect of ICOS datasets is a sufficiently detailed site characterisation (Saunders *et al.*, 2018). This includes information on the general site conditions, a description of the site history and an initial soil and vegetation survey with information on the main wind directions. The site characterisation further includes regularly updated information on site management practices and related lateral fluxes, soil cultivation and site amendments, as well as abiotic and biotic disturbance events. It is documented and regularly updated for all dynamic variables at timescales relative to the collection of the information (*e.g.* for soil organic carbon stocks (SOCS) at least every ten years) to provide a coherent assessment of the site. The site characterisation is an especially important tool during the setup of new ICOS ecosystem stations, as it is necessary for selecting the target area, positioning the EC tower and sampling plots for soil and vegetation measurements. Along with detailed metadata records (station PI contact details, observed variables, instruments installed, their location, specifications, calibrations *etc*.) the tracking, documentation and sharing of site characteristics is also important to gain transparency and traceability of the measurement setup and observations and to facilitate a comprehensive understanding of the site conditions for the data end user.

Continuous measurements and repeated surveys

The variables required for continuous measurement and repeated surveys at ICOS Class 1 and Class 2 ecosystem stations are summarised in Table A1 for the different ecosystem types. This list excludes the ecosystem types heath/shrubland, SRF, urban environment and lake, as the respective required variables are still under discussion (June 2018). A regularly updated list of requirements is maintained at the ICOS webpage (http://www.icos-etc.eu/icos/variables).

The specification of the spatial and temporal sampling design is a key aspect for the standardisation of the observations. Due to the specific variability of the variables of interest, the measurements need to be taken at distinct temporal frequencies and replications. They are characterised by different spatial coverage and the sampling design is designed in order to ensure representativeness for the target area. The target area of an ecosystem station is defined as a sufficiently homogeneous area for monitoring by the tower-based EC system (30 min averaged fluxes), that is required at each ICOS ecosystem station. The target area should include the majority of the footprint area contributing to the EC fluxes during most atmospheric conditions. The EC footprint differs between stations because of the ecosystem type and the associated measurement height, roughness length and prevailing atmospheric conditions. Continuous and sparse sampling plots for vegetation and soil characteristics are placed inside the target area (Saunders *et al.*, 2018; and Gielen *et al.*, 2018).

Whereas EC flux measurements of CO_2, H_2O and turbulent heat fluxes (Rebmann *et al.*, 2018; Sabbatini *et al.*, 2018) are mandatory at each ICOS Class 1 and Class 2 ecosystem station, CH_4 and N_2O EC flux measurements (Nemitz *et al.*, 2018) only need to be included at sites where these gases are of importance, for example in wetlands (CH_4) and agricultural fields (N_2O). Complementary to the EC measurements, automated soil chamber measurements (Pavelka *et al.*, 2018) are also part of the portfolio.

Chambers need to be installed within the EC footprint, capturing the temporal variability of ecosystem respiration with a minimum temporal resolution of one measurement per hour per gas and per chamber at least during the growing season. In order to investigate the spatial heterogeneity of GHG fluxes, additional manual soil chamber surveys are recommended and should cover seasonal changes and ecosystem specific events such as fertilisation/harvest.

As the EC method measures turbulent fluxes at a prescribed height above the vegetation surface, a concept for optimised measurements of the storage change in the air column underneath the EC system, considering horizontal heterogeneity, was developed for ICOS stations (for GHG storage flux measurements, Montagnani *et al.*, 2018). Air temperature and gas concentration profiles for storage quantification are measured on the EC tower. In addition to the air column beneath the above-canopy sensors, heat storage fluxes are also measured in soils and water bodies.

Mandatory microclimate measurements are taken either in close vicinity to the sonic anemometer (ambient air temperature, barometric pressure and relative humidity) or at a sufficient distance from the tower to avoid shading and flow distortion (radiation, Carrara *et al.*, 2018; precipitation, Dengel *et al.*, 2018). A back-up meteorological station ensures the availability of meteorological variables controlling GHG exchange for quality assurance and gap-filling.

The portfolio of observations at ICOS ecosystem stations further includes distinct vegetation characteristics and dynamics, including foliar analyses (Loustau *et al.*, 2018), green area index (GAI) or, alternatively in forest ecosystems, plant area index (PAI) and the yearly aboveground net primary production (ANPP; Gielen *et al.*, 2018), as well as plant phenology (Hufkens *et al.*, 2018). The temporal sampling design for repeated vegetation measurements primarily follows the course of phenological events. Management and disturbance events (*e.g.* harvest, wind throw, fire, pest infestation, and drought) are further constraints for the temporal sampling design of vegetation measurements. Phenological observations acquired consecutively at a daily timescale by automated digital cameras facilitate the link with climatic variables and measured fluxes (Wingate *et al.*, 2015).

In addition, continuous soil temperature and moisture measurements are crucial variables at ICOS ecosystem stations (Op de Beeck *et al.*, 2018). The behaviour of the soil as a GHG source or sink is determined on the basis of changes in SOC and soil N stocks (Arrouays *et al.*, 2018), that are measured every five to ten years as their changes are detectable only over larger timescales (decades, Conen *et al.*, 2003).

Current status and outlook

As of June 2018 the ICOS ecosystem station network is comprised of 77 stations in 12 countries observing seven terrestrial ecosystem types, i.e. cropland, forest, grassland, wetland, heath/ shrubland, SRF, an urban environment and one lake representing a freshwater ecosystem (Fig. 2, https://www.icos-cp.eu for updated information). The stations form a basic framework that is in the process of refinement through addition of further stations, that aim to represent European climatic conditions and land cover.

Figure 2a shows that current ICOS ecosystem stations are concentrated in Central-European countries and Southern Scandinavia, and missing in many Mediterranean and Southeast/East European countries. This lack of representativity in certain regions is related to, for instance, country-specific financial support for participation in ICOS. The climatic variability of the current station network in comparison to the whole European continent is shown in Fig. 2b. The three ICOS ecosystem stations in Greenland (two heathland and one wetland station) and similarly the three stations in French Guiana (two forest stations, one grassland station) are not included in this figure, as they do not belong geographically to the European continent. The station distribution indicates, that the network is best representing the upper to mid range annual air temperature (MAT) and precipitation (MAP) regimes (University of East Anglia Climatic Research Unit: CRU TS4.01), considering the European mean MAT and MAP of about 4.7°C and 648 mm, respectively. The most apparent lack of representation concerns regions with MAT <-2°C. Only a few stations, located in Northern Scandinavia, represent regions with MAT < 0°C. Other regions of the European climate space poorly represented by the network are areas combining high MAP with MAT <10°C in addition to those with the driest climatic conditions (<500 mm). The four main ecosystem types of the ICOS ecosystem network (forests, croplands, grasslands, wetlands) account for 93% of the stations (Fig. 2c). 46% of ICOS ecosystem stations on the European continent are located in forests, representing close to their actual proportional coverage of about 49% on the European continent (European Forest Institute, Päivinen *et al.*, 2001; Schuck *et al.*, 2001; Kempeneers *et al.*, 2011; excluding south-eastern parts of the Volga region and the polar archipelagos Svalbard, Franz Josef Land and Novaya Zemlya). Forest ecosystem stations represent best the climatic variability covered by the network. The station classes are almost evenly distributed among the stations (Fig. 2c), however, large differences exist between the ecosystem types.

The inclusion of further stations, that can be either existing measurement stations joining ICOS or newly established stations, should ideally strategically address the gaps within the spatial distribution of the sites. However, country-specific funding and scientific priorities will determine how equally distributed across Europe the ecosystem (and further the atmospheric and oceanic) observations within ICOS will be.

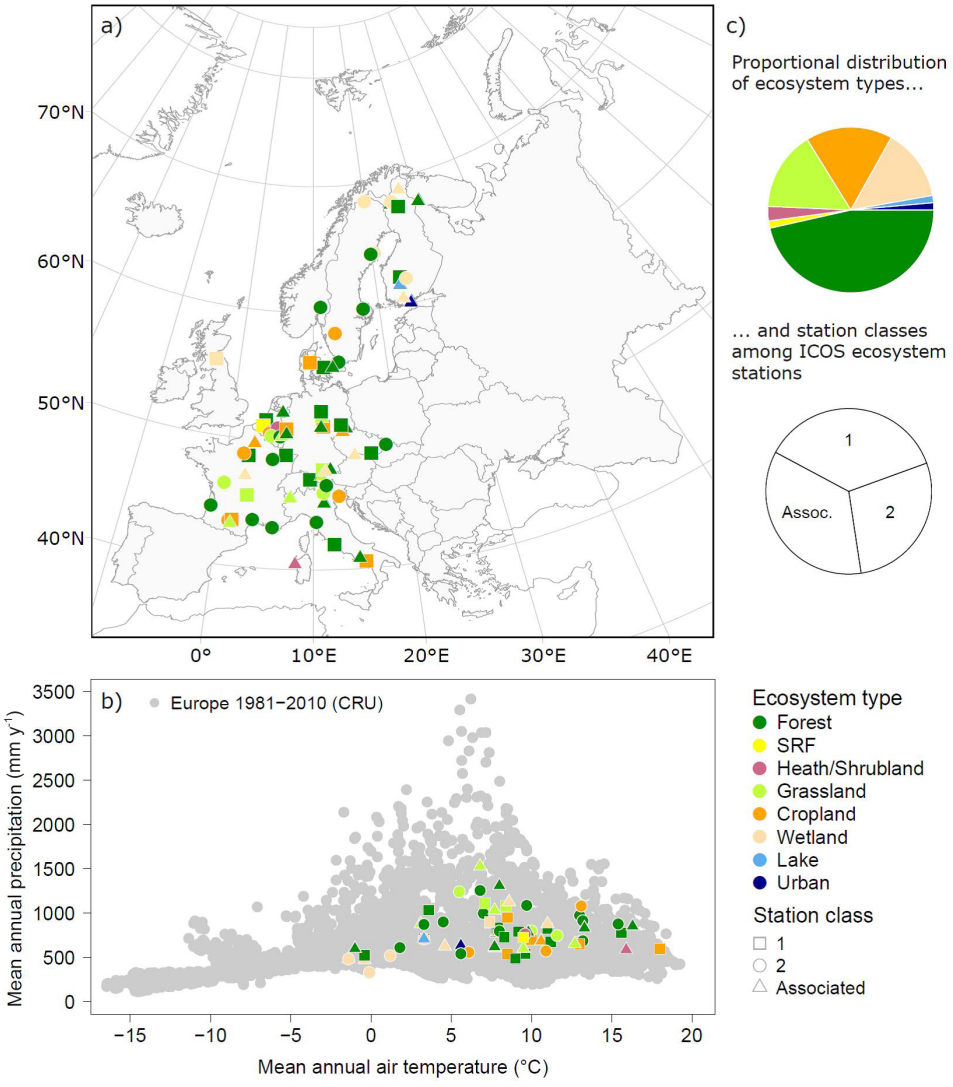

Fig. 2. Overview of ICOS ecosystem stations (Candidate stations and stations with approved label) as of January 2018. Colours indicate the ecosystem types (SRF = Short rotation forestry), and shapes the station classes (see lower panel legend). Stations in Greenland and French Guiana are not included here. a) Spatial distribution of stations on the European continent. Data sources: ArcGis, 2012 (European continent); NOAA, 2016 (Coastlines and European countries). b) Climatological distribution of stations with regard to MAT and MAP (note that averaging periods for both MAT and MAP vary for the different stations) in comparison to MAT and MAP for the reference period 1981-2010 on the European continent for 0.5° grid cells (filled grey circles). Data sources: ArcGis, 2012 (European continent); University of East Anglia Climatic Research Unit (CRU TS4.01). c) Proportional distribution of ecosystem types and station classes among the stations.

The ICOS ecosystem protocols published in this International Agrophysics issue and the related specific instruction documents mark an important milestone in the developmental evolution of a network of stations to a coherent infrastructure where standardisation is a key feature. The ecosystem stations are currently implementing their compliance to the standards. For four of these stations (one in cropland, grassland, wetland and forest) the class labels are already approved, now transferring the network into the operational status. The ICOS RI as a whole is currently developing strategies to be highly standardised and innovative at the same time. This strategy has several components:

- Global scientific and technical cooperation with large RIs in other regions and within FLUXNET. Furthermore, a research dialogue working towards political decision making where societal demands are translated into scientific questions and connected observational technologies.
- Cooperation with industrial partners to develop better instrumentation and new methods. In this cooperation, the network of ICOS ecosystem stations and the related scientific and technical competence can be seen as a platform for innovation.
- Internal processes to further develop the ICOS standards. These processes have been defined by internal rules and procedures that ensure the participation of all involved parties.

ICOS is currently among the globally leading environmental RIs focused on C and GHG observations. While ICOS observations span the atmosphere, terrestrial ecosystems and oceans with a focus on C and GHG dynamics, other observation networks may be restricted to terrestrial and freshwater ecosystems and bridge the gap to more ecologically focussed research and conservation communities (Bonan *et al.*, 2012). In its cross-domain approach connecting ecosystem observations with similarly standardised observations in the atmosphere and ocean ICOS will serve as a prototype beyond Europe. It already includes several geographically adjacent key regions in Africa and Eurasia (atmospheric and oceanic domains). ICOS is also a regional contributor to the GCP investigating the global C cycle and other interacting biogeochemical cycles and is actively promoting and following the development of a global GHG observation system.

CONCLUSIONS

1. Climate change research requires integrated, standardised, high-precision and long-term observations of C, N, GHGs, water and energy that are reproducible and based on *in-situ* measurements.

2. The pan-European RI ICOS provides *in-situ* long-term ($\geq$ 20 years) observations of GHG (CO_2, CH_4, N_2O, H_2O) fluxes and concentrations in Europe and adjacent regions. A key characteristic of ICOS is the integration of the three domains atmosphere, terrestrial ecosystems and oceans.

3. The observations facilitate in-depth studies on the GHG balance, the C cycle, current and future climate feedbacks, and the evaluation of suitable climate change mitigation and adaptation strategies.

4. The ICOS ecosystem network provides GHG fluxes and ancillary measurements for terrestrial ecosystems, including microclimate, vegetation and soil characteristics, and helps to identify and understand the GHG exchange dynamics and their role in C cycling with regard to climate change.

5. Seven terrestrial and one freshwater ecosystem types are monitored in the ICOS ecosystem network: croplands, forests, grasslands, wetlands, heath/shrublands, SRF, urban environments and lakes. The grouping of ecosystem stations into three classes with different standardisation requirements allows for a high level of participation in the network and distinct data applications.

6. The methodological framework for the ICOS ecosystem network is described in a coherent set of guidelines (see the papers of this issue), that were developed by the scientific community during an extensive discussion process. The guidelines justify which environmental variables are necessary in order to understand the C and GHG dynamics and how they need to be measured.

7. The high level of standardisation of the hardware, software and methods employed by ICOS increases the utility and reliability of the resulting data products. The degree of standardisation achieved in ICOS can be considered as the biggest innovation in the transition from networks to an integrated RI. In the ecosystem domain, standardisation is facilitating inter-annual and inter-site comparability, cross-site synthesis and straightforward data assimilation in models.

8. The success of ICOS depends on the use of its free and open-access multi-level data products by the user communities, thus the communication of stakeholders and end-users is crucial for ICOS in order to achieve its scientific potential and societal value.

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Appendix

Table A1: Observation requirements and recommendations defined for ICOS Station Classes 1 and 2 for different ecosystem types (1 = mandatory for ICOS Station Class 1; 2 = mandatory for ICOS Station Class 2; Fac = facultative/ optional; N.R. = not required). The complete lists of variables for heath/ shrublands, SRF, urban environments and lakes are currently under discussion. For Associated Stations the standardisation is limited to a basic set of regular observations[1].

Variable group	Variable	Ecosystem type				Acquisition frequency
		Forest	Grassland	Cropland	Wetland	
Fluxes, storage & concentrations	CO_2, H_2O and sensible heat fluxes (EC)	1 & 2	1 & 2	1 & 2	1 & 2	10-20 Hz
	CH_4 and N_2O fluxes (EC)	1	1	1	1	10 Hz
	Air H_2O concentration	1	1	1	1	1 Hz
	CO_2 profile	1 & 2	1 & 2	1 & 2	1 & 2	1 Hz
	Air temperature and humidity profile	1 & 2	1 & 2	1 & 2	1 & 2	0.033-1 Hz
	CH_4 and N_2O profiles	1	1	1	1	1 Hz
	Soil CO_2 fluxes (automatic chambers)	1	1	1	1	0.1-1 Hz
	CH_4 and N_2O fluxes (automatic chambers)	1	1	1	1	0.1-1 Hz
	Manual chamber surveys	Fac	Fac	Fac	Fac	0.1-1 Hz (CO_2), 15 min (CH_4, N_2O)
Microclimate	Air pressure	1 & 2	1 & 2	1 & 2	1 & 2	≥ 0.033 Hz
	Wind speed and direction (additional to 3D sonic)	1	1	1	1	≥ 0.033 Hz
	Total high accuracy precipitation	1 & 2	1 & 2	1 & 2	1 & 2	≥ 0.017 Hz
	Snow depth	1 & 2	1 & 2	1 & 2	1 & 2	≥ 0.017 Hz
	Incoming, outgoing, net SW and LW radiation	1 & 2	1 & 2	1 & 2	1 & 2	≥ 0.05 Hz
	Incoming PPFD	1 & 2	1 & 2	1 & 2	1 & 2	≥ 0.05 Hz
	Outgoing PPFD	1 & 2	1 & 2	1 & 2	1 & 2	≥ 0.05 Hz
	Diffuse PPFD and/or SW radiation	1	1	1	1	≥ 0.05 Hz
	PPFD below canopy + ground reflected	Fac	Fac	Fac	N.R.	≥ 0.05 Hz
	Incoming SW radiation (high quality)	Fac	Fac	Fac	Fac	≥ 0.05 Hz
	Spectral reflectance	Fac	Fac	Fac	Fac	≥ 0.05 Hz
	Backup meteorological station (TA, RH, incoming SW, precipitation)	1 & 2	1 & 2	1 & 2	1 & 2	≥ 0.033 Hz (TA, RH), ≥ 0.05 Hz (SW), ≥ 0.017 Hz (precip.)
Vegetation	AGB	1 & 2	1 & 2	1 & 2	1 & 2	≥ 2 times/ year
	GAI, PAI (forest)	1 & 2	1 & 2	1 & 2	1 & 2	≥ 2 times/ year
	Litterfall	1	1	1	1	≤ 2 weeks (litter prod.)
	LMA and Leaf nutrient content	1 & 2	1 & 2	1 & 2	1 & 2	1-3 times/ year
	Phenology-Camera pictures	1	1	1	1	> 6-8 images/ day
	Tree diameter (continuous)	1	N.R.	N.R.	N.R.	NA
	Trunk and branches temperature	Fac	N.R.	N.R.	N.R.	NA
	Management and disturbances information	1 & 2	1 & 2	1 & 2	1 & 2	dep. on site conditions
	C and N import/export by management	1 & 2	1 & 2	1 & 2	1 & 2	dep. on site conditions
Soil	Soil temperature profile	1 & 2	1 & 2	1 & 2	1 & 2	≥ 0.017 Hz
	Soil heat flux density	1 & 2	1 & 2	1 & 2	1 & 2	≥ 0.017 Hz
	Water table depth	1 & 2	1 & 2	1 & 2	1 & 2	≥ 0.017 Hz
	Soil water content profile	1 & 2	1 & 2	1 & 2	1 & 2	≥ 0.017 Hz
	Soil C content	1 & 2	1 & 2	1 & 2	1 & 2	≤ 10 years
	Soil N content	Fac	Fac	Fac	Fac	≤ 10 years
	Soil water N content	Fac	Fac	Fac	Fac	NA
	DOC concentration	Fac	Fac	Fac	Fac	NA
Water bodies	O_2, ρCO_2 and ρN_2O concentration profile	N.R.	N.R.	N.R.	Fac	NA
	O_2 and ρCO_2 surface concentration	N.R.	N.R.	N.R.	Fac	NA

[1]The requirements for Associated stations include: EC sensible heat flux, concentration and flux of H_2O and one more GHG (CO_2, CH_4 or N_2O), GHG storage flux (vertical profile; forest ecosystems only), incoming solar radiation (SW or PPFD), ambient air temperature, relative humidity, precipitation, horizontal wind speed and wind direction, Leaf Area Index (LAI; total one-sided area of leaf tissue per unit ground surface area; Bréda, 2003) or GAI measured at its annual maximum, AGB and average soil texture, information on management practices and disturbances.

Table A2: Acronyms used in the paper.

Acronym	Full name
AGB	Aboveground biomass
ANPP	Aboveground net primary production
C	Carbon
EBC	Energy balance closure
EC	Eddy covariance
ECV	Essential climate variable
ERIC	European Research Infrastructure Consortium
ESM	Earth system model
ETC	Ecosystem Thematic Centre
GAI	Green area index
GHG	Greenhouse gas
ICOS PP	ICOS Preparatory Phase
LAI	Leaf Area Index
LMA	Leaf mass to area
LW	Long-wave
MAP	Mean annual precipitation
MAT	Mean annual air temperature
MSA	Monitoring Station Assembly
N	Nitrogen
NEE	Net ecosystem exchange
PPFD	Photosynthetic photon flux density
PI	Principal investigator
RCP	Representative concentration pathways
RI	Research infrastructure
SOCS	Soil organic carbon stocks
SRF	Short rotation forestry
SW	Short-wave

Table A3: Acronyms of research programmes and infrastructures, projects, observation networks, etc., their runtimes and links for further information.

Acronym	Full name	Runtimes	Links for further information
ACTRIS	Aerosols, Clouds and Trace gases Research Infrastructure	ongoing since 2011	http://actris2.nilu.no/
AEROCARB	Airborne European regional observation of the carbon balance	2000-2003	http://cordis.europa.eu/project/rcn/52175_de.html
AnaEE	Analysis and experimentation on Ecosystems	ongoing since 2011	https://www.anaee.com
ANIMATE	Atlantic network of interdisciplinary moorings and timeseries for Europe	2001-2004	http://cordis.europa.eu/project/rcn/60097_de.html
AmeriFlux	(Flux tower network in the Americas)	ongoing since 1996	http://ameriflux.lbl.gov
Asiaflux	(Flux tower network in Asia)	ongoing since 1999	http://www.asiaflux.net
CarboAfrica	Quantification, understanding and prediction of carbon cycle, and other GHG gases, in Sub-Saharan Africa	ongoing since 2006	http://cordis.europa.eu/project/rcn/81403_de.html
CarboAge	Age-related dynamics of carbon exchange in European forests. Integrating net ecosystem productivity in space and time.	2000-2003	http://cordis.europa.eu/project/rcn/51253_en.html
CarboChange	Changes in carbon uptake and emissions by oceans in a changing climate	2011-2015	https://carbochange.w.uib.no
CarboEuroFlux	An investigation on carbon and energy exchanges of terrestrial ecosystems in Europe	2000-2003	http://www.cordis.europa.eu/project/rcn/52172_en.html
CarboEurope IP	(Assessment of the European Terrestrial Carbon Balance)	2004-2008	http://www.carboeurope.org
CarboEurope Cluster	-	2000-2004	http://www.copernicus.eu/projects/carbo-europe
CarboMont	Effects of land-use changes on sources, sinks and fluxes of carbon in European mountain areas	2001-2004	https://www.uibk.ac.at/carbomont
CarboOcean IP	(Marine carbon sources and sinks assessment)	2005-2009	http://www.carboocean.org
CAVASSOO	Carbon variability studies by ships of opportunity	2000-2003	http://cordis.europa.eu/project/rcn/52983_en.html
CHIOTTO	Continuous high-precision tall tower Observations of greenhouse gases	2003-2006	http://www.chiotto.org/summary.html
COCOS	Coordination action carbon observation system	2008-2011	http://cordis.europa.eu/project/rcn/90996_en.html
COPERNICUS	European Earth Observation Programme	ongoing since 1998	http://www.copernicus.eu
DEFROST	Depicting Ecosystem-Climate Feedbacks from Permafrost, Snow and Ice	2009-2013	http://www.toppforskningsinitiativet.org/en/programmer-1/program-2/prosjekter/ncoe-defrost
ÉCLAIRE	Effect of climate change on air pollution impacts and response strategies for European ecosystems	2011-1015	http://www.eclaire-fp7.eu
eLTER RI	Integrated European Long-Term Ecosystem & Socio-Ecological Research Infrastructure	ongoing since 2002	http://www.lter-europe.net/elter-esfri
EMSO	European Multidisciplinary Seafloor and water-column Observatory	ERIC since 2016	http://www.emso-eu.org

ENVRI	European Environmental Research Infrastructure	ENVRI project 2011-2014, ENVRI community ongoing	http://envri.eu/
ESCOBA	European Study of Carbon in the Ocean, Biosphere and Atmosphere	1996-1999	http://cordis.europa.eu/project/rcn/30856_de.html
ESFRI	European Strategic Forum for Research Infrastructures	Ongoing since 2002	https://ec.europa.eu/research/infrastructures/index_en.cfm?pg=esfri
EuroArgo	European contribution to the Argo programme	ongoing since 2008	http://www.euro-argo.eu
Euroflux	(Long-term carbon dioxide and water vapour Fluxes of European forests and interactions with the climate system)	1995-1998	http://cordis.europa.eu/project/rcn/30818_en.html
EU-NOFRETETE	Nitrogen Oxides Emissions from European Forest Ecosystems	2001-2004	http://cordis.europa.eu/project/rcn/58308_en.html
FORCAST	Forest Carbon - Nitrogen Trajectories	2000-2003	http://cordis.europa.eu/project/rcn/51619_de.html
Fluxnet-Canada	(Canadian flux tower network)	1993-2014 and currently integrated in AmeriFlux	https://daac.ornl.gov/FLUXNET/guides/FLUXNET_Canada.html,
FLUXNET	(Network of regional EC tower networks)	ongoing since 1997	http://fluxnet.fluxdata.org;
(GCCT)	The global terrestrial carbon cycle and its perturbation by man and climate	1993-1995	http://cordis.europa.eu/project/rcn/5213_de.html
GCOS	Global Climate Observation System	ongoing since 1992	https://public.wmo.int/en/programmes/global-climate-observing-system
GCP	Global Carbon Project	Ongoing since 2001	http://www.globalcarbonproject.org
GEO	Group on Earth Observation	Ongoing since 2005	https://www.earthobservations.org
GEO-C	GEO Carbon and GHG Initiative	Ongoing since 2017	https://www.earthobservations.org/activity.php?id=113
GEOSS	Global Earth Observation System of Systems	ongoing since 2005	https://www.earthobservations.org/geoss.php
GHG Europe	Greenhouse gas management in European land use systems	2010-2013	http://www.ghg-europe.eu
IAGOS	In-service Aircraft for a Global Observing System	ongoing since 2005	https://www.iagos.org
IBP	International Biological Program	1964-1974	http://www.nasonline.org/about-nas/history/archives/collections/ibp-1964-1974-1.html
ICOS	Integrated Carbon Observation System	ongoing since 2008, ERIC since 2016	https://www.icos-ri.eu
ICOS-INWIRE	ICOS - Improved sensors, network and interoperability for GMES	2013-2015	http://www.icos-inwire.lsce.ipsl.fr/welcome.html;
ICP Forests	International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests	ongoing since 1985	http://icp-forests.net
IG^{3}IS	Integrated Global Greenhouse Gases Information System	ongoing since 2015	http://www.wmo.int/pages/prog/arep/gaw/ghg/IG3IS-info.html
IMECC	Infrastructure for measurements of the European carbon cycle	2007-2011	http://imecc.ipsl.jussieu.fr/Data2.html
InGOS	Integrated non-CO_2 greenhouse gas observing system	2011-2015	http://www.ingos-infrastructure.eu
IOCCP	International Ocean Carbon Coordination Project	ongoing since 2005	http://www.ioccp.org
Lifewatch	E-Science European Infrastructure for	ERIC since	http://www.lifewatch.eu

	Biodiversity and Ecosystem Research	2017	
LTER	Long Term Ecological Research	LTER (US) since 1980, LTER-Europe launched in 2003	https://www.ilter.network; http://www.lter-europe.net
Medeflu	(Flux measurement network in the Mediterranean region)	1997-1999	Miglietta and Peressotti (1999)
NEON	National Ecological Observatory Network	fully operational from 2018 onwards	http://www.neonscience.org;
NitroEurope IP	(Integrated European research into the nitrogen cycle)	2006-2011	http://www.nitroeurope.eu;
OzFlux	(Australian and New Zealand flux tower network)	ongoing since 2001	http://www.ozflux.org.au/index.html
RINGO	Readiness of ICOS for Necessities of Integrated Global Observations	2017-2020	https://www.icos-ri.eu/ringo
SBSTA	Subsidiary Body for Scientific and Technical Advice	-	http://unfccc.int/bodies/body/6399.php
TACOS	Terrestrial and Atmospheric Carbon Observing System infrastructure	2001-2005	http://cordis.europa.eu/project/rcn/58165_en.html
TENATSO	Tropical Eastern North Atlantic Time-Series Observatory	2006-2008	http://outreach.eurosites.info/outreach/DeepOceans/station.php?id=4
UNECE	United Nations Economic Commission for Europe	ongoing since 1947	https://www.unece.org/info/ece-homepage.html
UNFCCC	United Nations Framework Convention on Climate Change	adopted in 1992	http://unfccc.int/2860.php
VERIFY	Observation-based system for monitoring and verification of greenhouse gases	2018-2022	https://sc5.easme-web.eu/?p=776810
WMO	World Meteorological Organisation	ongoing since 1950	https://public.wmo.int