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

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Abstract:	Research infrastructures play a key role in launching a new generation of integrated long-term, geographically distributed observation programmes for monitoring of climate change, a better understanding of its impacts on global ecosystems and the evaluation of possible mitigation and adaption strategies. The pan-European Integrated Carbon Observation System (ICOS) Research Infrastructure combines carbon and greenhouse gas (GHG; H2O, CO2, CH4, N2O) observations for the atmosphere, terrestrial ecosystems and oceans. High-precision measurements are obtained using standardised methodologies, are centrally processed and made openly available in a traceable and verifiable fashion with detailed metadata. The ecosystem station network of ICOS aims to cover the variability in climate, land cover and management practices throughout Europe. In addition to GHG flux measurements, a large set of complementary information such as microclimate, management practices, vegetation and soil characteristic is collected to support the interpretation, spatial upscaling and modelling of observed ecosystem carbon and GHG dynamics. The sampling design was developed and formulated in protocols by the scientific community. It represents a trade-off between a suitable dataset and practical feasibility. The use of the data products by different data user communities is crucial for ICOS in order to achieve its scientific potential and societal value.
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Abstract

Research infrastructures play a key role in launching a new generation of integrated long-term, geographically distributed observation programmes for monitoring of climate change, a better understanding of its impacts on global ecosystems and the evaluation of possible mitigation and adaption strategies. The pan-European Integrated Carbon Observation System (ICOS) Research Infrastructure combines carbon and greenhouse gas (GHG; H_2O, CO_2, CH_4, N_2O) observations for the atmosphere, terrestrial ecosystems and oceans. High-precision measurements are obtained using standardised methodologies, are centrally processed and made openly available in a traceable and verifiable fashion with detailed metadata. The ecosystem station network of ICOS aims to cover the variability in climate, land cover and management practices throughout Europe. In addition to GHG flux measurements, a large set of complementary information such as microclimate, management practices, vegetation and soil characteristic is collected to support the interpretation, spatial upscaling and modelling of observed ecosystem carbon and GHG dynamics. The sampling design was developed and formulated in protocols by the scientific community. It represents a trade-off between a suitable dataset and practical feasibility. The use of the data products by different data user communities is crucial for ICOS in order to achieve its scientific potential and societal value.

Keywords

ICOS, protocol, GHG exchange, carbon cycle, standardised monitoring

Introduction

Anthropogenic climate change is one of the greatest global challenges that our society will face in the 21st century and beyond. The major driving force of recent and future anthropogenic climate change is the human perturbation of the biogeochemical and energy cycles, including the well-documented strong increases in atmospheric greenhouse gas (GHG) concentrations, especially carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), and changes in the global water cycle 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 belong to 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 capping any increase in global warming in the 21st century to an average air temperature below 2 °C above pre-industrial levels (Rogelj *et al.*, 2016). A prerequisite for successful climate change mitigation and adaptation efforts is a 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. *In-situ* measurements, integrating the Earth system domains atmosphere, terrestrial and freshwater ecosystems and 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 Research Infrastructure that provides these high-quality, high-precision observations in a standardised, traceable and verifiable manner for the three Earth system domains (hereafter terrestrial and freshwater ecosystems referred to as 'terrestrial ecosystems' only). The focus of these efforts is on the carbon (C) cycle and GHGs. Observations of energy, water and nitrogen (N) cycle components are only partly included in the ICOS portfolio and not explicitly addressed in this paper.

The benefits of long-term, integrated and standardised *in-situ* observations

The atmosphere, terrestrial ecosystems and oceans are closely interconnected through energy and matter exchange (e.g. the cycling of C, N and water). Respective reservoirs, which can be sources or 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. Particularly, 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 the global uptake of anthropogenically emitted CO_2 by terrestrial ecosystems and oceans has doubled from 1960 (2.4±0.8 Pg C a^{-1}) to 2010 (5.0±0.9 Pg C a^{-1})

in response to the increased atmospheric CO_2 concentration. 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 is an ongoing discussion on the magnitude at which terrestrial ecosystems and oceans individually contribute to changes in the atmospheric CO_2 budget, the location and status of the dominant large-scale CO_2 sinks and how they might change in the future (Ciais *et al.*, 1995, Canadell *et al.*, 2007, Pan *et al.*, 2011, Levin, 2012, Wanninkhof *et al.*, 2013). The latest estimates (C Budget 2016) of the Global Carbon Project (GCP) for the global terrestrial and oceanic uptake were of 2.7±1.0 Pg C a^{-1} and 2.6±0.5 Pg C a^{-1}, respectively, which together offset the current annual anthropogenic CO_2 emissions by 47 % (Le Quéré *et al.*, 2017). In general, such estimates benefit from decreasing uncertainties obtained from empirical and model-based quantifications of the components of the global biogeochemical cycles. However, some discrepancies between the components remain, raising 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). In view of the vulnerability of C pools (e.g. 25 Pg in European forest soils; De Vos et al., 2015), there is no doubt that a lack of long-term routine sampling, proper standardisation as well as sufficient temporal and spatial coverage still presents a considerable limiting factor for a thorough understanding and quantification of the global biogeochemical as well as water and energy cycles and the fate of natural and anthropogenic GHG emissions (Le Quéré *et al.*, 2016). In addition, monitoring approaches need to integrate observations of the atmosphere, terrestrial ecosystems and oceans to allow for the detection of potentially missing sources, sinks and driving processes.

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 a crucial requirement to, at least partly, understand the spatio-temporal scales of environmental variability, to attribute changes to a particular forcing process as well as to identify the 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 inform on the ecosystem responses to short-term anomalies and extreme events (Reichstein *et al.*, 2007). In view of the expected strong environmental changes in the next few decades, such long-term datasets should cover at least 20 years. The continuous monitoring of GHG concentrations and fluxes is also crucial for GHG projections and climate-related scenarios such as Representative Concentration Pathways (RCPs; van Vuuren *et al.*, 2014). Long-term observations with a high level of standardisation further build the capacity for cross-site synthesis activities. They can help to reveal regional and global GHG flux patterns, support compulsory GHG emission inventories and independent GHG emission report verification, and define and evaluate climate change mitigation and adaptation strategies as e.g. climate-smart land-use management practices (Ceschia *et al.*, 2010, Bellassen and Luyssaert, 2014).

Modelling capabilities are rapidly growing along with the complexity of our Earth system understanding. This increases the demand for standardised, traceable and verifiable, high-precision *in-situ* observations to develop the models, to better constrain parameterisations, to independently evaluate model performance and to reduce the uncertainties of model predictions (Bonan *et al.*, 2012, Schmid, 2012). This demand is of particular significance for bottom-up model approaches, estimating C and N fluxes at specific sites, and C and GHG budgets on regional and global scale (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 Earth System Models (ESM), with special regard to their 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-priory knowledge for inverse modelling and can be utilised to evaluate the performance of top-down modelling approaches that are based on GHG concentration measurements in the atmosphere (Schuster *et al.*, 2013, Wanninkhof *et al.*, 2013, Kountouris *et al.*, 2016, Houweling *et al.*, 2017, Marcolla *et al.*, 2017). Inverse modelling approaches are extremely useful in determining a regional GHG budget, however, they are heavily dependent on a dense observational network (Villani *et al.*, 2010). Additionally, *in-situ* observations are crucial for the validation of remote sensing products (airborne and satellite observations of e.g. CO_2 and CH_4, radiation and pigment indices, and related products). Despite recent methodological progress, satellite observations are not yet able to deliver the consistent and calibrated GHG observations, necessary to quantify the changes in global C and N budgets (Levin, 2012).

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

The International Biological Program (IBP, 1964-1974), which is often referred to as one of the first realised Big Science projects in biology, facilitated interesting insights into ecosystem behaviour in relation to climate change, e.g. the GHG exchange with the atmosphere, and fundamentally benefit subsequent efforts for long-term ecological and environmental observation networks (e.g. LTER). However, already during the 1950s the first attempts were made to develop specific GHG (esp. CO_2) observation and data assimilation programmes (e.g. Fonselius, 1958). Thanks to multiple initiatives within an active and persistent scientific community, a number of GHG concentration and flux measurement networks and projects for terrestrial ecosystems, atmosphere and oceans were developed in Europe over the past decades (see Fig. 1 and Table A3), many of them with a strong support of the scientific program of the European Commission and national funding sources. Most network approaches, especially in the beginning, were geographically limited and only covered one or two of the three domains. In case of terrestrial ecosystems, often these GHG networks focussed more on certain ecosystem types and on specific factors than on an adequate coverage of all key processes and components of the C cycle and biosphere-atmosphere GHG exchange. Furthermore, metadata and observations supporting the analysis and interpretation of the measurements were often neglected, hampering in-depth process understanding and the reproducibility of the results. Data gaps in time series, abrupt changes in measurement techniques and data processing resulted in limited consistency as well as data comparability and compatibility, and consequent uncertainty in analysis outcomes and model predictions. Data precision conventions were also mostly absent, contributing another factor to modelling uncertainties. The accuracy of model calculations is limited by model structure (our understanding of the processes) as well as on the quality of empirical data inputs for model parameterisation. The data were often stored in different formats and archives separately for each network, hampering the scientific potentials of data sharing and assimilation in models especially crucial for approaches integrating all three Earth system domains. 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 represented limitations for confident extrapolation of the short-term datasets to long-term trends, these projects still raised important questions with regard to our understanding of C and GHG dynamics within and across ecosystems. The urgent necessity of a thorough, consistent and long-term data collection and analysis approach integrating the three earth system domains and addressing the challenges of predicting ecosystem response to climate change, initiated the transition from a short-term project-based network framework to ICOS as a highly integrated RI over the last 15 years.

ICOS within the European and global observation and research program landscape

Two processes have significantly influenced this transition from short-term approaches to a European RI. The first is the formulation of global observational necessities in the Subsidiary Body for Scientific and Technical Advice (SBSTA) of the United Nations Framework Convention on Climate Change (UNFCCC). ICOS is thereby based 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) with a sub-system called ‘Essential Carbon Variables’. The two systems are documented in the Implementation Plan of the Global Climate Observation System (GCOS). Being deeply rooted in these variable systems, ICOS aims to evolve towards the European pillar of a future global 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 the biogeochemical cycles in light of a changing climate. This approach will enable ICOS to significantly contribute to a number of scientific network programmes such as the WMO-driven Integrated Global Greenhouse Gases Information System (IG^{3}IS), the Group on Earth Observation (GEO) Carbon and GHG Initiative (GEO-C), and the European Earth Observation Programme (COPERNICUS).

The second important milestone for the transition to a European RI has been the development of the European Research Infrastructures programme in the consolidated framework 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 in a RI of pan-European interest corresponding to the long term needs of the European research communities. The standardisation of the ICOS observations, strongly supported by the ESFRI process, is a prerequisite for the transition from networks to an infrastructure in Europe. ICOS has an active role in the development of the European Environmental Research Infrastructure (ENVRI) landscape as well. The consolidation of the ESFRI landscape is being driven by fostering interoperability with other ENVRIs (e.g. IAGOS, ACTRIS, Lifewatch, AnaEE, eLTER RI; EuroArgo and EMSO; see Table A3) yielding synergies from joint measurement strategies, common standards, 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, long-term (≥ 20 years) and high-precision observations of lower atmosphere GHG concentrations as well as biosphere-atmosphere GHG fluxes. The observations are complemented by a large set of multi-disciplinary data required to reveal changes in ecosystem processes and for the interpretation and modelling of the observed GHG concentrations and fluxes (see 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 at enabling the understanding and quantification of the GHG balance of the European continent and adjacent regions as well as monitoring and evaluating GHG 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 standardisation level to obtain a thorough picture of the C cycle and GHG exchange processes and their spatial and temporal variability across Europe and adjacent regions. A major challenge has been and still is to provide cross-domain integration while maintaining high quality scientific outcome in each domain at the same time. The implementation of ICOS has been based on the bottom-up development of measurement standards and protocols through the involvement of the scientific community. Furthermore, ICOS implements attributes which were identified to be important for effective observation networks (Baldocchi *et al.*, 2012), including an integrated data management, facilitating effective data sharing and assimilation, and a scientific network with frequent communication and joint scientific development.

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, it aims on a high comparability in complementing measurements with existing networks (e.g. ICP Forests) to facilitate upscaling. However, some flexibility to adjust 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 implementation.

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 yields comparable data products of adequate and known quality with an estimate of their uncertainty. Various levels of openly available data products are archived for the long-term repository by the Carbon Portal (https://www.icos-cp.eu), as common database of ICOS, with a data set identifier system and clearly defined data usage policies (https://otc.icos-cp.eu/data-policy), ensuring verifiable and reproducible transparent science. The data is well-documented, including the initial system configuration and its modifications as well as the study site characteristics and regularly updates on site developments such as management, disturbances or the occurrence of extreme climatic events.

GHG observations in terrestrial ecosystems

The terrestrial biosphere plays a central role in regulating climate through physical, chemical and biological processes (Bonan *et al.*, 2012). It reacts to climate change with both positive and negative climate-ecosystem feedback mechanisms (Heimann and Reichstein, 2008, Arneth *et al.*, 2010, Frank *et al.*, 2015). In order to understand the strong links between terrestrial ecosystems and the regional and global climate systems, knowledge of terrestrial C pathways and GHG exchange processes is needed. However, the terrestrial C cycle is currently the global C budget component with the highest observed variability and greatest measurement uncertainties (Bloom *et al.*, 2016, Le Quéré *et al.,* 2016). A growing observation database continuously improves our understanding of these interactions between terrestrial ecosystems and the climate system (Valentini *et al.*, 2000, Baldocchi, 2008) as for example indicated by the recent discovery of the relation of climate extremes with the C cycle and associated climate feedbacks (e.g. Ciais *et al.*, 2005, Reichstein *et al.*, 2007, 2013, Frank *et al.*, 2015, Xiao *et al.*, 2016).

Since the 1990s the routine use of the eddy covariance technique for tower-based C, water and heat flux measurements has provided continuous observations over multiple years at a variety of sites in different climatic zones and biomes. Such measurements were identified as critical tools for the quantification of global and regional GHG exchange rates, especially when conducted in combination with remote sensing and ESMs. 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 via the covariance of the mean deviations in vertical wind velocity and the respective scalar (Dejardins and Lemon, 1974, Aubinet *et al.*, 2000). Continuous EC systems are characterised by a minimal disturbance of the environment and a low maintenance demand, however, depending on the scalar of interest and the instrumentation. The physical complexity of EC method necessitates a well-planned setup of the standardised (uniform) instrumentation as well as reproducible raw data processing, gap filling and thorough quality assessment of the processed data. Among the large range of potential applications of EC GHG flux measurements is the investigation of abiotic and biotic controls and the ecosystem response to environmental perturbations on distinct time scales across different sites, the derivation of GHG budgets, inter-annual and inter-site comparisons as well as spatial scaling of GHG exchange (Baldocchi 2003). In addition, latent and sensible heat flux measurements are vital for the assessment of the energy budget at the biosphere-atmosphere interface, the quality control of GHG fluxes and the evaluation of the water use efficiency of the studied ecosystem. Generally, surface heat fluxes are among the key drivers of small and large-scale climate dynamics (Mamadou *et al.*, 2014), and respond to and re-enforce climate change feedbacks (DeFries *et al.*, 2002). Continuous data on evapotranspiration, sensible heat and friction velocity (u*) are important for meteorological studies.

Since the early 2000s standardisation in data provision and processing 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, see Table A3). The FLUXNET database provided important new insights on the course and consequences of environmental change (Baldocchi, 2003, 2008, Falge *et al.*, 2002, Law *et al.*, 2002, Schwalm *et al.*, 2009, 2017, Migliavacca *et al.*, 2011). 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 facilitated a considerable progress in our understanding of processes and impacts of environmental change, e.g., for the European continent (Ciais *et al.*, 2005, Jung *et al.*, 2007).

For forests, intensive long-term ecosystem monitoring was established and harmonised in Europe already in the 1980s, with the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) under the frame of United Nations Economic Commission for Europe (UNECE). The network with a survey on a representative 16x16 km grid and several hundred intensive monitoring sites was initiated due to raising concerns about the effects of biogeochemical alterations induced by air pollutants and included also regular C and N pool and flux measurements but no consistent terrestrial biosphere-atmosphere GHG exchange measurements (ICP Forests, 2010; Danielewska *et al.*, 2013, Ferretti and Fischer, 2013).

The concept of the ICOS ecosystem domain

The ICOS network of terrestrial ecosystem stations aims to represent the variability in climate, land cover and management throughout Europe. It covers natural terrestrial ecosystem types which are most relevant on the European continent, comprising forest, cropland, grassland and wetland and it further includes stations in some more specific ecosystem types such as heath/ shrubland, short rotation forestry (SRF) as well as urban environment. Moreover, lake ecosystems are considered within the network as a part of the global freshwater system. Whereas croplands, grasslands, forests and wetlands represent the main natural terrestrial contributions to Europe´s GHG exchange and have been commonly observed within the past GHG observation programmes (see e.g. GHG Europe), SRF, heath/ shrublands, urban environments and lakes were only rarely included in these programmes. Lakes were only recently recognised as important component of the global C cycle (Tranvik *et al.*, 2009). Holgerson and Raymond (2016) estimated a C loss by non-running inland waters of 0.58 Pg C a^{-1}, which is about one-third of the global terrestrial C uptake (Le Quéré *et al.*, 2017). Urban environments are included considering that the proportion of people living in cities is steadily increasing in Europe (European Union, 2016) and globally (United Nations, 2014). According to Churkina *et al.* (2016) urbanisation is becoming an important player in the global C cycle, whereby the impact of cities extends their emissions from burning fossil fuels and land use change.

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

A major challenge during the design phase of any ecosystem observation network is to identify the set of environmental variables to be measured and the temporal frequency and spatial scale to thoroughly understand the complex terrestrial C and GHG dynamics? An answer is a balancing act between a suitable dataset according to our current knowledge of the underlying processes, and the practical feasibility of an ambitious measurement plan in terms of budget, human resources and long-term infrastructure deployment over time. Expert discussions within the ICOS Ecosystem Monitoring Station Assemblies (MSA) and the Ecosystem Thematic Centre (ETC) have yielded a trade-off for the ICOS ecosystem stations that is built on the experiences of previous monitoring and experimental research networks. This experience included 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 a careful consideration of the requirements from multiple data user categories. Potential categories for ICOS data users include the scientific and remote sensing communities, information service providers (e.g. COPERNICUS projects), public and private entities (e.g. for the verification of their emission inventories), national and international scientific programmes and environmental agencies monitoring the C cycle and GHG exchange, as well as educational organisations (Kaukolehto and Vesala, 2014). Fisher *et al.* (2017) recently highlighted the importance of an early integration of observations with modelling activities to benefit future modelling syntheses.

Similar to most of the recent national and international GHG monitoring programs (Baldocchi *et al.*, 2012, Baldocchi, 2014), an eddy covariance (EC) flux measurement system is at the core of all ICOS ecosystem stations. However, the ecosystem station network is much more than just a flux-tower network. It comprised measurements of GHG storage change in the ecosystem and ecosystem/soil-atmosphere GHG flux measurements by chambers. A broad set of complementary measurements is added 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 stations are classified according to their level of standardisation into Class 1 (highest level), Class 2 (intermediate level) and Associated Stations (lowest level) to facilitate flexibility in the setup and to assure the participation by the scientific community. Class 1 Stations represent ‘supersites’, where standardised, continuous high-frequency measurements of the key C cycle compounds (including CH_4 in case of relevance for the ecosystem, e.g. wetland), meteorology, and also N compounds in agroecosystems are made. These stations are especially valuable for in-depth studies of biophysical processes and model parameterisations (Skiba *et al.*, 2009). The spatial spread of measurements is provided by a dense network of Class 2 stations, with focus on key measurements crucial for investigating GHG fluxes on various spatial scales. However, the station classification does not necessarily mirror the instrumental complexity and the expenditure of work (station setup, measurement surveys, maintenance etc.) at the stations.

The standardised procedures for the key observations required at ICOS ecosystem stations are described in 13 measurement protocols within this issue of International Agrophysics. Specific instruction documents provide the guide to their practical implementation. However, the ICOS methodology will further develop over time, by reformulating measurements requirements according to the experiences and implementing new technological achievements. The protocols and instructions facilitate consistent and comparable high-quality measurements that are essential for contributing to the overall goals of ICOS. A two-stage labelling process by the ETC assures that all ICOS stations fulfil the specific requirements of the ICOS station classes. It is required for both newly established and existing measurement 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 criteria such as EC footprint, including fetch homogeneity, canopy conditions as well as the physiographic setting, are important to be met from an EC theory point of view, whereby the station construction can be still optimised during the 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 in case no appropriate open space is found near forest sites for weighing gauge measurements (Dengel *et al.*, this issue). 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 data (calculated by station team, half-hourly) has to be submitted only once a year.

Measurement overview

Site characterisation

An essential aspect of ICOS datasets is a sufficiently detailed site characterisation (Saunders *et al.*, this issue). It includes information on the general site conditions (ecosystem type and target area dimension, geographic location, soil type, climate normals, topography, etc.) and station PI contact details. An additional description of the site history (for as long as records are available) is particularly useful for the assessment of any residual impacts of former site conditions and management on the measurements. As most landscapes possess a certain degree of heterogeneity depending on the spatial scale, an initial soil and vegetation survey and information on the main wind directions is required to determine the optimal position of the study site and the flux tower. In addition, the spatial design for representative soil and vegetation samplings needs to be defined. The site characterisation further includes regularly updated information on the measurement infrastructure, site management practices (e.g. harvest, grazing), soil cultivation and site amendments, as well as abiotic and biotic disturbance events. Information on the lateral C and N losses triggered by management and disturbances is crucial for a more complete understanding of biogeochemical cycles at the ecosystem scale (Kutsch *et al.*, 2010, Osborne *et al.*, 2010) and thus are required for ICOS ecosystem stations. The site characterisation is documented and regularly updated for all dynamic variables at timescales relative to the collection of these information (e.g. for soil organic carbon stocks (SOCS) at least every ten years) to provide a coherent assessment of the site. It is an important prerequisite for the setup of new ICOS ecosystem stations, as it allows for the selection of the specific site and the positioning of the EC tower and sampling plots for soil and vegetation measurements. Along with detailed metadata records the tracking and documentation of site characteristics is furthermore important to allow transparency and traceability of the measurement setup and observations and to facilitate a comprehensive understanding of the site for the data end user. Such information is valuable for the interpretation of the measured fluxes as, e.g., the EC flux contribution that is investigated by footprint analysis (Vesala *et al.*, 2008) can be linked to the soil and vegetation patterns within the EC source area.

Continuous and periodic measurements

The current requirements and recommendations for both continuous and periodic measurements at ICOS ecosystem station of Class 1 and Class 2 for the different ecosystem types are summarised in Table A1. The list excludes the ecosystem types SRF, heath/ shrubland, urban environment and lake, as the respective sets of required variables are still under discussion (January 2018). A regularly updated list of requirements is maintained at the ICOS webpage (http://www.icos-etc.eu/icos/variables).

Concentrations and fluxes of GHGs and energy

Tower-based EC flux measurements (particularly CO_2, H_2O and turbulent heat fluxes; Rebmann *et al.*, this issue, Sabbatini *et al.*, this issue) are required at each ICOS ecosystem station. CH_4 and N_2O EC flux measurements (Nemitz *et al.*, this issue) need to be included at certain sites where these gases are of importance, for example in wetlands (CH_4) and agricultural fields (N_2O). Complementary to the EC measurements, automated ecosystem and soil chamber measurements (closed-dynamic chamber system; Pavelka *et al.*, this issue; Norman *et al.*, 1997) play an important role in the ICOS methods portfolio and are required for Class 1 Stations. They have been the prevailing method to measure biosphere-atmosphere GHG exchange in terrestrial ecosystems (e.g. Livingston and Hutchinson 1995), before EC became the standard option (Aubinet *et al.*, 2012). Nonetheless, chamber measurements are still important for quantifying soil-atmosphere GHG exchange and for the partitioning of net fluxes of CO_2 (net ecosystem exchange, NEE) into respiration and gross primary production, and for the validation of the EC data at ecosystems with short canopy. They are also helpful for assessing the contribution of ground vegetation or soil to EC flux measurements in forests. However, experience has shown, that the chamber methodology is sensitive to local atmospheric concentration gradients and vertical exchange (Brændhold *et al.*, 2017), which, along with the disturbance of the natural environment of the measurement spot, needs to be considered when comparing with EC flux data. Recommended campaign measurements of CO_2, CH_4 and N_2O with manual chambers can further help to determine the spatial heterogeneity of the GHG fluxes within the EC footprint.

Storage change in the air column underneath the EC system

As the EC method measures turbulent fluxes at a certain height above the surface of the vegetation, storage of gases and heat in the air below the sensors are key measurement components for the ecosystem mass and energy balance, particularly on intra-daily time scales (Nicolini *et al.*, 2018). This relates particularly, although not exclusively to the sites with tall (EC measurement height > 4 m) and dense canopies. Therefore, a concept for optimised storage flux measurement, also considering horizontal heterogeneity, was developed for ICOS stations (see Montagnani *et al.*, this issue, for GHG storage flux measurements). The measured and the computed gas storage fluxes are used for the completion of the half-hourly turbulent EC flux measurements, providing more accurate diurnal flux patterns required for parameterisations of vegetation and soil process models. In addition, heat storage within the ecosystem is of high importance for the energy balance closure (EBC) that represents a key quality assessment of the EC system performance (Aubinet *et al.*, 2000, Wilson *et al.*, 2002, Kobayashi *et al.*, 2012, Stoy *et al.*, 2013). Apart from the air column underneath the sensor, heat storage fluxes are measured in soils (using soil temperature profiles and heat flux plates) and water bodies (using water temperature profiles). In addition, in forest ecosystems it is recommended to conduct trunk and branch temperature measurements to determine the biomass heat storage term.

Microclimate

Measurements of the microclimate are required for the monitoring of site-specific climatic trends, and as environmental drivers for process models and for the flux post-processing, analysis and interpretation. Ambient air temperature, pressure and relative humidity measurements are also crucial for validation and corrections in the processing of EC data (Rebmann *et al.*, this issue).

Measurements of precipitation belong to the measurement requirements at ICOS ecosystem stations (Dengel *et al.*, this issue), as precipitation is one of the most important abiotic variables related to plant growth and soil processes, and valuable for the detection of extreme events and trends with potential effects on GHG dynamics. In addition, the timing and intensity of precipitation events can provide valuable indications for the EC data quality control. This is why these measurements must be made close to the flux tower with the same temporal resolution as the time-averaged EC fluxes (30 min).

Radiation (Carrara *et al.*, this issue) is a fundamental part of the measurement set at ICOS ecosystem stations as it represents the major control on the majority of physical and biological processes on Earth. It drives ecosystem energy and C fluxes, directly, by providing energy for photosynthesis, and indirectly, by impacting on temperature and water availability. Temperature and water availability are the two major parameters affecting photosynthesis and respiration, and also evapotranspiration and N dynamics in the soil. Radiation measurements further provide valuable information on the characteristics of the land surface, including vegetation phenology and snow cover. Apart from its relevance for general process-based understanding, radiation represents an important model input parameter e.g. for biogeochemical models (Sitch *et al.*, 2008). In addition, it serves as an input parameter for gap-filling and partitioning of NEE measured by the EC system (Papale *et al.*, 2006, Moffat *et al.*, 2007, Lasslop *et al.*, 2010). As part of the energy balance, net radiation supports a sensor-independent quality assessment for EC measurements. Several radiation components are measured routinely at Class 1 and Class 2 stations in most ecosystem types and include net radiation (four-component radiometer) as well as incoming and outgoing photosynthetic photon flux density (PPFD).

A back-up meteorological station, required at ecosystem stations of Class 1 and Class 2, ensures the availability of meteorological variables controlling GHG exchange for quality assurance and gap-filling.

Vegetation

Vegetation is responsible for the majority of terrestrial biosphere-atmosphere CO_2 fluxes and also plays a role in soil CH_4 and N_2O exchange. For example, the presence of vascular plants in wetland areas and the littoral of lakes facilitates the direct transport of CH_4 from the lower soil layers to the atmosphere (plant-mediated transport; Bastviken *et al.*, 2004). The rhizosphere supplies the necessary organic C and N sources essential for N_2O production by nitrification/ denitrification (Christensen *et al.*, 1990, Giles *et al.*, 2012, Butterbach-Bahl *et al.*, 2013). Observations within ICOS consider distinct vegetation characteristics and dynamics. For instance, foliar analyses (Loustau *et al.*, this issue) including leaf mass to area (LMA) ratio and nutrient concentrations support the determination of the spatial and temporal variations of foliage traits that strongly control radiative transfer, photosynthesis, autotrophic respiration, plant growth and C allocation between above- and below-ground plant organs. The measurement of the Green Area Index (GAI, one-sided photosynthetically active surface area of standing vegetation per unit of ground area) or Plant Area Index (PAI, surface area of all aboveground standing vegetation per unit of ground area; Bréda, 2003) in forest ecosystems is aimed at directly explaining observed biosphere-atmosphere fluxes of terrestrial ecosystems, whereas aboveground biomass (AGB) and litter biomass are primarily measured to estimate yearly aboveground net primary production (ANPP; Gielen *et al.*, this issue). Annual ANPP is an important component of the annual C budget and key to determine the role of vegetation (in terms of C allocation in plants) on the C sink capacity of ecosystems and their response to environmental changes. Phenological observations of plants (Wingate *et al.*, this issue) inform on seasonal plant responses to alterations of key environmental variables driven by climate change (Richardson *et al.*, 2013). In turn, variations in plant phenology directly affect the seasonality of C, water and energy exchanges between terrestrial ecosystems and the atmosphere (Wingate *et al.*, 2015) and thereby often represent the dominant control of terrestrial biosphere-atmosphere exchange.

Soil characteristics

Soil organic C stocks (SOCS) contain two to three times the amounts of C that is stored in the vegetation or in the atmosphere (Batjes, 1996; Le Quéré *et al.*, 2016; Stockmann *et al.*, 2015). The soil is thus a major component of the terrestrial C cycle. Monitoring the temporal changes in the soil C and, additionally, in N stocks is needed to close the ecosystem mass balance of these elements and to assess the role of terrestrial ecosystems in the global C and N cycle. As such, the behaviour of the soil as a GHG source or sink needs to be quantified with precision within ICOS ecosystems (Arrouays *et al.*, this issue). SOC and soil N stocks are also vital for understanding the long-term inter-annual variability and decadal trends of C and N exchange at large scales (Hungate *et al.*, 2003, Melillo *et al.*, 2011, Ahlstrom *et al.*, 2015). Assessing SOCS and soil N stocks along with estimates of changes in vegetation biomass and lateral C and N fluxes provides independent estimates of net ecosystem C and N exchange in the long-term, for comparison with direct EC measurements (Hopkinson *et al.*, 2008, Jones *et al.*, 2017). Information on soil type and physical and chemical characteristics play a crucial role in understanding and closing the water budget and thus accurately calculating ecosystem responses to changes in precipitation regimes as well as ecosystem water use efficiency. Considering the indicated changing frequencies and lengths of droughts across Europe in the course of climate change (IPCC, 2012, Stagge *et al.*, 2017), having temperature and moisture measurements in soils (Op de Beeck *et al.*, this issue) is essential to, e.g., improve soil moisture modelling in ESMs and to provide datasets linking such climatic extremes to long-term changes in ecosystem functions (Frank *et al.*, 2015).

Spatial and temporal sampling design

The spatial and temporal sampling design at ICOS ecosystem stations is a keystone for the standardisation of the observations. Due to the variability of the individual observed variables, the measurements need to be done in distinct temporal frequencies and replications, they are characterised by different spatial coverage and are designed in order to ensure their representativeness for the target area. The target area of an ecosystem station is defined as a sufficiently homogeneous area for monitoring by the EC system. It should include the majority of the footprint area contributing to the EC fluxes during most atmospheric conditions. The EC footprint differs between stations due to ecosystem type and associated measurement height, roughness length and prevailing atmospheric conditions. Sampling plots are placed inside the target area, a sampling point is located in the centre of each plot.

Air temperature and gas concentration profiles for storage quantification are measured on the EC tower. Microclimate measurements are placed either in close vicinity to the sonic anemometer (air temperature, pressure, relative humidity) or at a sufficient distance from the tower to avoid shading and flow distortion. In terms of vegetation and soil characteristics, the sampling plots are classified into two categories with distinct spatial sampling strategies and specific measurement sets depending on the ecosystem types: continuous measurement plots and sparse measurement plots (see Saunders *et al.* and Gielen *et al.*, this issue). Automatic soil chambers need to be installed within the EC footprint to capture the soil efflux temporal variability. In order to investigate the spatial heterogeneity of GHG fluxes, additional manual chamber surveys are recommended within the footprint area in case of tall canopies, and in similar areas but outside the EC footprint in case of short canopies to avoid the chambers being obstacles for the EC measurements.

The required temporal sampling frequencies of the observations are listed in Table A1. Microclimatic observations and storage terms used within the EC data processing workflow and for flux analysis must have the same temporal resolution as the averaged EC flux data (30 min). It is though sufficient to measure all other complementing variables on a less frequent basis. Automatic soil efflux chamber measurements needs to be carried out at a minimum temporal resolution of one measurement (< 5 min) per hour per gas and per chamber at least during the growing season. Manual chamber surveys should cover seasonal changes and ecosystem specific events such as fertilisation/harvest. As changes in SOCS and N stocks are only detectable over larger timescales (decades, Conen *et al.*, 2003) such measurements are mandatory only every five to ten years. The temporal sampling design for repeated vegetation measurements primarily follows the course of phenology. Management and disturbance events (e.g. harvest, wind throw, fire, insects and drought) are further constraints for the temporal sampling design of vegetation measurements, except for foliar analyses. Phenological observations with automated digital cameras should be acquired continuously at a daily timescale to facilitate the linkage to climatic variables and measured fluxes.

Current status and outlook

As of January 2018 the ICOS ecosystem station network comprises 76 stations in 12 countries observing seven terrestrial ecosystem types, i.e. cropland, forest, grassland, wetland, heath/ shrubland, SRF and urban environment and further one lake representing a freshwater ecosystem (Fig. 2; see https://www.icos-cp.eu for updated information). For three of these ecosystem stations (in cropland, grassland, wetland) the class labels are already approved, transferring the network into the operational status. Together with the stations that are still in the labelling step 1 and 2 (Candidate ICOS ecosystem stations), they form a basic framework that is in the process of refinement by adding further stations, aiming to represent European climatic conditions, land cover and management.

Figure 2a shows that current stations are particularly concentrated in Central-European and Scandinavian countries, and missing in many Mediterranean and Southeast/East European countries. This lack might be related to 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 two stations in French Guiana (two forest stations) are not included in the figure, as they do not belong to the European continent in a non-political view. The station distribution indicates, that the network is best representing upper midrange annual air temperatures (MAT) and precipitation (MAP), considering the European mean of MAT and MAP of about 4.7 °C and 648 mm, respectively. The most apparent lack concerns regions with MAT < -2 °C and only a few stations, located in Northern Scandinavia, represent regions with MAT < 0 °C. High MAP is poorly represented in combination with MAT < 10 °C. The four main ecosystem types of the ICOS ecosystem network (forest, cropland, grassland, wetland) are accounting for 93 % of the stations (see Fig. 2c). 46 % of ICOS ecosystem stations on the European continent are located in forests, nearly representing 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 Spitzbergen, Franz Josef Land and Novaya Zemlya). Forest stations are well spread among the climatic variability covered by the network. The station classes are almost equally distributed among the stations (Fig. 2c), however, with large differences between the ecosystem types. The inclusion of further stations, which can be either existing measurement stations joining ICOS or newly established stations, should strategically address the deficiencies and gaps. 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.

Together with the National Ecological Observatory Network (NEON) in the US, ICOS is currently the globally leading representative of the environmental RIs focussing on C and GHG observations. While ICOS observations cover atmosphere, terrestrial ecosystems and oceans with a focus on C and GHG dynamics, NEON is restricted to terrestrial and freshwater ecosystems and bridges the gap to more ecologically focussed communities (Bonan *et al.*, 2012). ICOS will serve as an observation network prototype beyond Europe with its well thought through set of measurement requirements and standardised protocols. 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 which are reproducible and based on *in-situ* measurements.
2. The pan-European Research Infrastructure ICOS provides *in-situ* long-term (≥ 20 years) observations of GHG (H_2O, CO_2, CH_4, N_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 mitigation and adaptation strategies.
4. The ICOS ecosystem station network provides GHG flux and complementary measurements for terrestrial ecosystems, including microclimate, vegetation and soil characteristics, and helps to identify and understand their 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 intensities allows for a high level of participation in the network and distinct data applications.
6. The methodological framework for ICOS ecosystem stations is described in a coherent set of guidelines (see this issue), which 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 syntheses and straightforward data assimilation in models.
8. The success of ICOS depends on the use of its products by the distinct user communities, thus stakeholder and end-user communication is crucial for ICOS in order to achieve its scientific potential and societal value.

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Figures

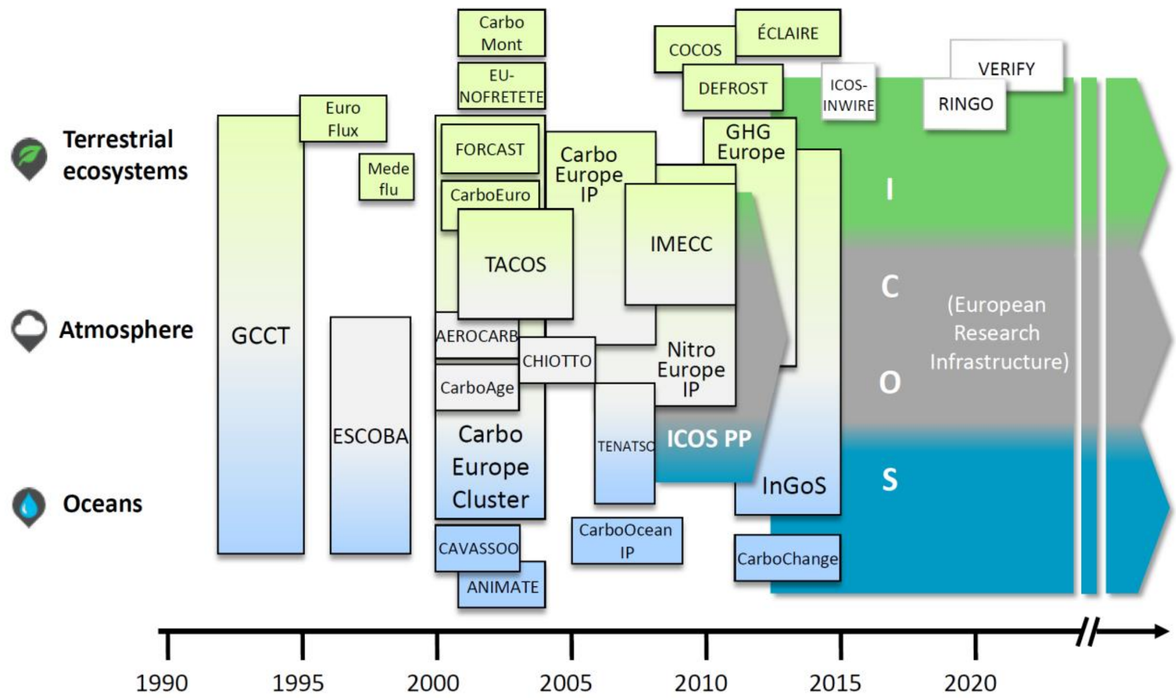


Fig. 1 (Werner Kutsch and Daniela Franz)

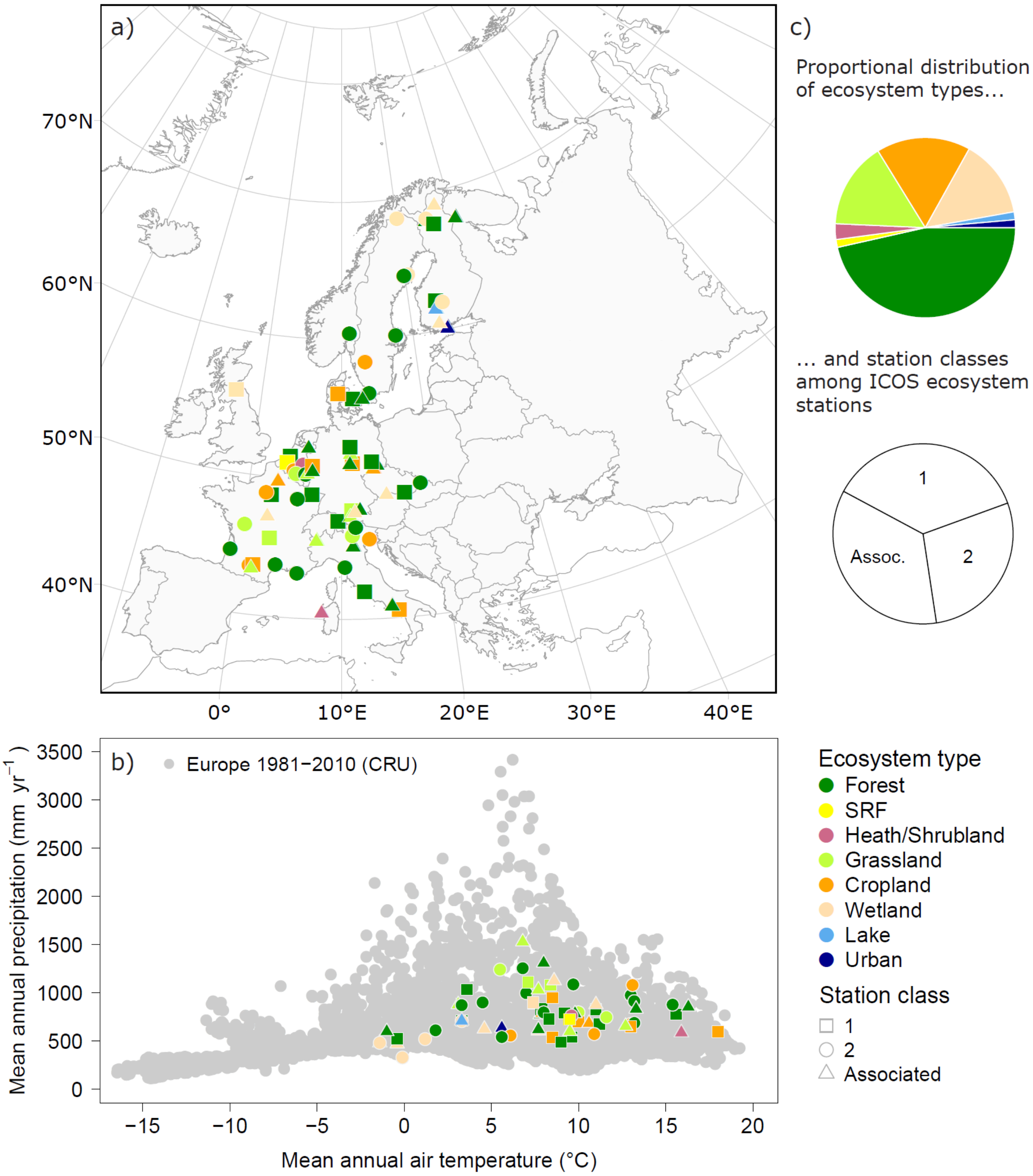


Fig. 2 (Daniela Franz)

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 H 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, H_2O profiles	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 height	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 meteo station (TA, RH, incoming SW, precip.)	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 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 air temperature
MAT	Mean annual precipitation
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 North, Central and South America)	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 Forest	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 Biodiversity and Ecosystem Research	ERIC since 2017	http://www.lifewatch.eu
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

Figure captions

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

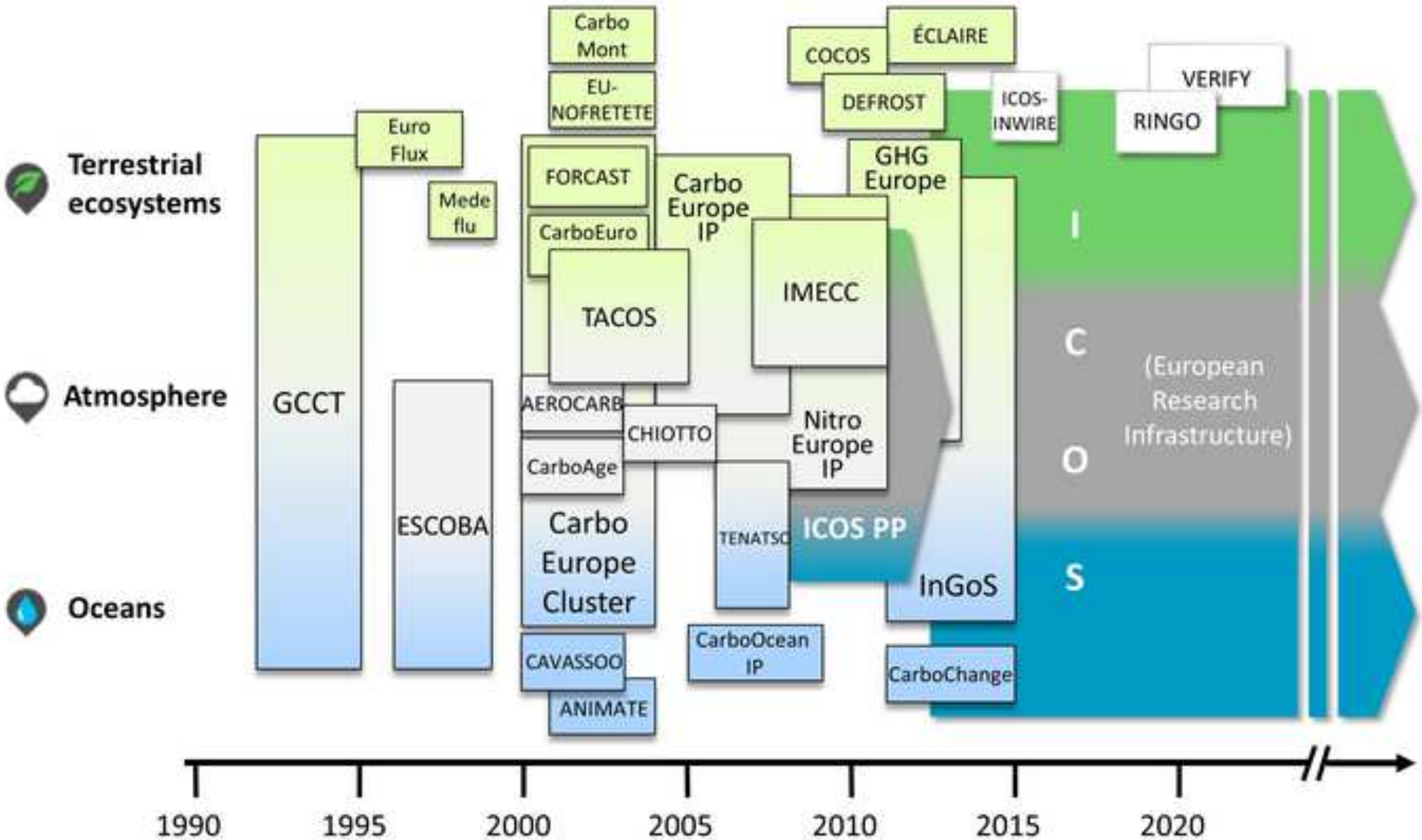
Fig. 2: Overview of ICOS ecosystem stations (Candidate stations and stations with approved label) as of January 2018. Colours indicate the ecosystem types (SRF = Short rotation forestry), geometrical shapes the station classes (see lower panel legend). Stations in Greenland and French Guiana are not included here. a) Spatial distribution of the 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.

Manuscript title	Towards long-term standardised carbon and greenhouse gas observations for monitoring Europe´s terrestrial ecosystems
Authors	Franz, Daniela et al.
Submission date	16 Jan 2018
Section/ Category	GHG balance

Highlights of the article

- The Integrated Carbon Observation System (ICOS) is a pan-European research infrastructure providing standardised, long-term (≥ 20 years) *in-situ* carbon and greenhouse gases (H_2O, CO_2, CH_4, N_2O) observations for the atmosphere, terrestrial ecosystems and oceans.
- The article introduces the terrestrial ecosystem domain of ICOS and highlights its importance for the overarching goals of ICOS.
- The methodological portfolio implemented at ICOS ecosystem stations is described in a coherent set of guidelines, which were developed by the scientific community and represent a trade-off between a suitable dataset and practical feasibility.
- 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 observation networks to an integrated research infrastructure.

Figure 1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ESCOBA
Carbo Mont
EU-NOFRETETE
FORCAST
CarboEuro
TACOS
AEROCARB
CarboAge
CHIOTTO
Carbo Europe Cluster
CAVASSOO
ANIMATE
Carbo Europe IP
IMECC
Nitro Europe IP
TENATSO
CarboOcean IP
COCOS
DEFROST
ÉCLAIRE
GHG Europe
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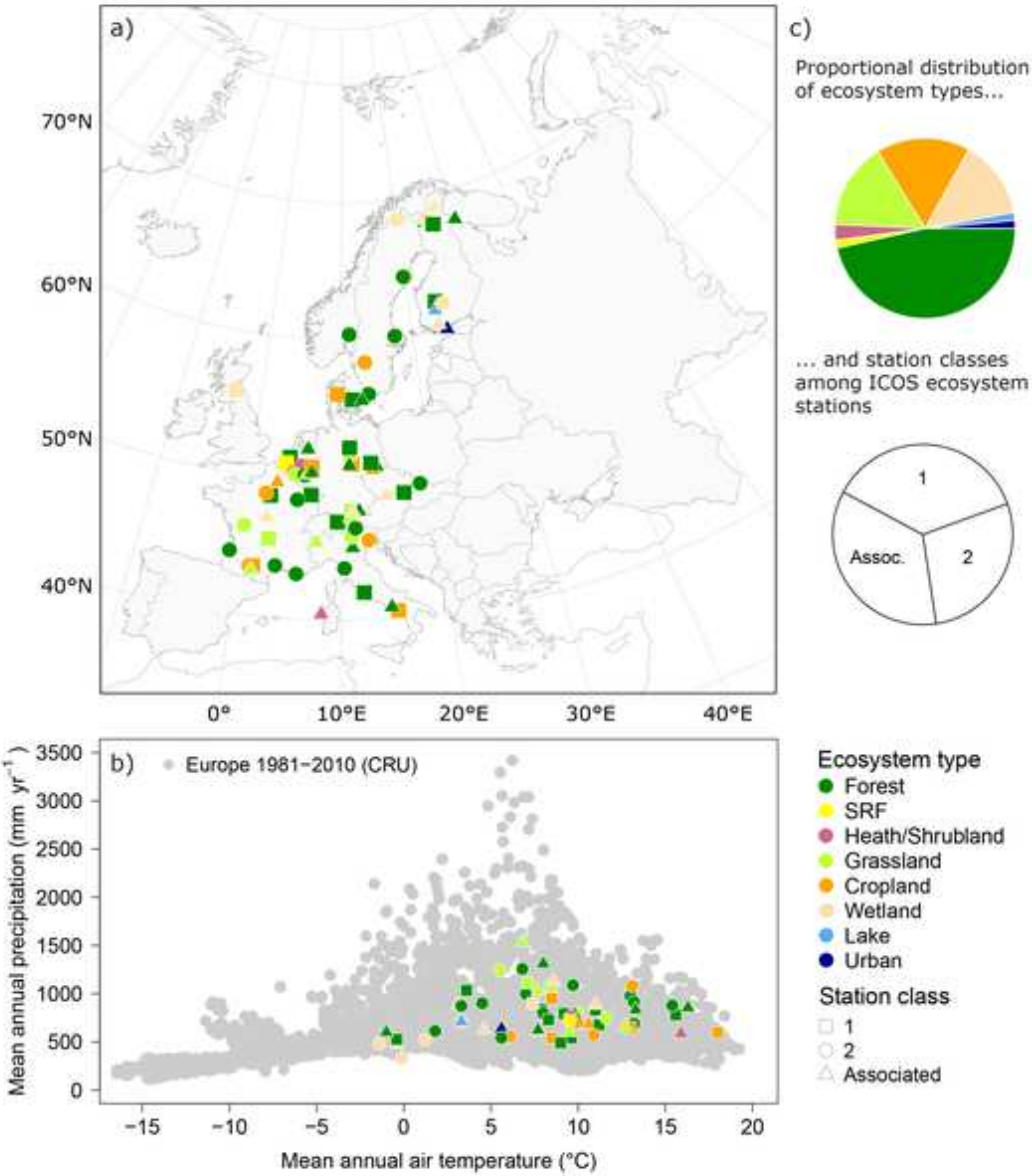
Figure 2


a)
70°N
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40°E
c)
Proportional distribution of ecosystem types...
... and station classes among ICOS ecosystem stations
1
Assoc.
2
b)
Europe 1981–2010 (CRU)
Mean annual precipitation (mm yr⁻¹)
3500
3000
2500
2000
1500
1000
500
0
−15
−10
−5
0
5
10
15
20
Mean annual air temperature (°C)
Ecosystem type
Forest
SRF
Heath/Shrubland
Grassland
Cropland
Wetland
Lake
Urban
Station class
1
2
Associated