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


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Abstract. 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; CO₂, CH₄, N₂O, H₂O) 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 (ICOS) is a pan-European RI that provides high-precision observations in a standardised, traceable and verifiable manner for the three 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 (CO₂, CH₄, N₂O, H₂O). 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 CO₂, Ballantyne et al. (2012) provided a mass balance analysis based on global atmospheric CO₂ concentration measurements and emission inventories. They estimated that global uptake of anthropogenically emitted CO₂ by terrestrial ecosystems and oceans doubled from 1960 (2.4±0.8 Pg C a⁻¹) to...
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 (≥ 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; Belllassen 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

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**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 (IG³IS), 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 (ENVR) landscape as well. Consolidation of the ESFRI landscape is pursued via interoperability with other ENVRI (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 tech-
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 (Kaukoaho 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 CO₂, H₂O and turbulent heat fluxes (Rebmann et al., 2018; Sabbatini et al., 2018) are mandatory at each ICOS Class 1 and Class 2 ecosystem station, CH₄ and N₂O EC flux measurements (Nemitz et al., 2018) only need to be included at sites where these gases are of importance, for example in wetlands (CH₄) and agricultural fields (N₂O). 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 above-ground 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 representativeness 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.
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.

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.
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 (≥ 20 years) observations of GHG (CO₂, CH₄, N₂O, H₂O) 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.

ACKNOWLEDGMENTS

Many scientists and engineers have contributed to the development of ecosystem flux measurements during the past decades. The basic idea for the ICOS protocols was to integrate as many of them into working groups as possible to achieve a broad consensus and even impact beyond the Research Infrastructure itself. Not all of them are on the list of co-authors of this paper or of other papers in this special issue. Notwithstanding, the authors acknowledge their contribution to the process and particularly want to mention Ernst-Detlef Schulze, Han Dolman, Riccardo Valentini, Reinhart Ceulemans and Philippe Ciais for their early engagement in EU projects from the 1990s on and for bringing ICOS to the ESFRI roadmap in the early 2000s. Dario Papale, Ivan Janssens and Denis Loustau are thanked for their intense work in the ICOS Ecosystem Thematic Centre for standardisation of the network and their constructive contributions towards the definition of the protocols.

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Conflict of interest: The Authors declare no conflict of interest.

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Fonselius S., 1958. Map and coordinates of the chemical and CO₂ stations Western Europe. Tellus, 10(1), 170-171.


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 observations1.

<table>
<thead>
<tr>
<th>Variable group</th>
<th>Variable</th>
<th>Ecosystem type</th>
<th>Acquisition frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Forest</td>
<td>Grassland</td>
</tr>
<tr>
<td>Fluxes, storage &amp; concentrations</td>
<td>CO₂, H₂O and sensible heat fluxes (EC)</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<tr>
<td></td>
<td>CH₄ and N₂O fluxes (EC)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Air H₂O concentration</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>CO₂ profile</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<tr>
<td></td>
<td>Air temperature and humidity profile</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<tr>
<td></td>
<td>CH₄ and N₂O profiles</td>
<td>1</td>
<td>1</td>
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<tr>
<td></td>
<td>Soil CO₂ fluxes (automatic chambers)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>CH₄ and N₂O fluxes (automatic chambers)</td>
<td>1</td>
<td>1</td>
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<tr>
<td></td>
<td>Manual chamber surveys</td>
<td>Fac</td>
<td>Fac</td>
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<tr>
<td>Microclimate</td>
<td>Air pressure</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<td></td>
<td>Wind speed and direction (additional to</td>
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<td>1</td>
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<td></td>
<td>3D sonic)</td>
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<td></td>
<td>Total high accuracy precipitation</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<td></td>
<td>Snow depth</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<tr>
<td></td>
<td>Incoming, outgoing, net SW and LW</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<tr>
<td></td>
<td>radiation</td>
<td></td>
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<tr>
<td></td>
<td>Incoming PPFD</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<tr>
<td></td>
<td>Outgoing PPFD</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<tr>
<td></td>
<td>Diffuse PPFD and/or SW radiation</td>
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<td>1</td>
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<tr>
<td></td>
<td>PPDF below canopy + ground reflected</td>
<td>Fac</td>
<td>Fac</td>
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<tr>
<td></td>
<td>Incoming SW radiation (high quality)</td>
<td>Fac</td>
<td>Fac</td>
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<td></td>
<td>Spectral reflectance</td>
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<td>Fac</td>
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<td>Backup meteorological station (TA, RH,</td>
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<td></td>
<td>incoming SW, precipitation)</td>
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<td></td>
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<td>Vegetation</td>
<td>AGB</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<tr>
<td></td>
<td>GAI, PAI (forest)</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<td></td>
<td>Litterfall</td>
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<tr>
<td></td>
<td>LMA and Leaf nutrient content</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<tr>
<td></td>
<td>Phenology-Camera pictures</td>
<td>1</td>
<td>1</td>
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<tr>
<td></td>
<td>Tree diameter (continuous)</td>
<td>N.R.</td>
<td>N.R.</td>
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<tr>
<td></td>
<td>Trunk and branches temperature</td>
<td>Fac</td>
<td>N.R.</td>
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<tr>
<td></td>
<td>Management and disturbances information</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<tr>
<td></td>
<td>C and N import/export by management</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<td>Soil temperature profile</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<td></td>
<td>Soil heat flux density</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<td></td>
<td>Water table depth</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<td></td>
<td>Soil water content profile</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<td></td>
<td>Soil C content</td>
<td>1 &amp; 2</td>
<td>1 &amp; 2</td>
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<td></td>
<td>Soil N content</td>
<td>Fac</td>
<td>Fac</td>
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<td></td>
<td>Soil water N content</td>
<td>Fac</td>
<td>Fac</td>
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<tr>
<td></td>
<td>DOC concentration</td>
<td>Fac</td>
<td>Fac</td>
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<tr>
<td>Water bodies</td>
<td>O₂, pCO₂ and pN₂O concentration profile</td>
<td>N.R.</td>
<td>N.R.</td>
</tr>
<tr>
<td></td>
<td>O₂ and pCO₂ concentration</td>
<td>N.R.</td>
<td>N.R.</td>
</tr>
</tbody>
</table>

1The requirements for Associated stations include: EC sensible heat flux, concentration and flux of H₂O and one more GHG (CO₂, CH₄ or N₂O), 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.

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full name</th>
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<tbody>
<tr>
<td>AGB</td>
<td>Aboveground biomass</td>
</tr>
<tr>
<td>ANPP</td>
<td>Aboveground net primary production</td>
</tr>
<tr>
<td>C</td>
<td>Carbon</td>
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<tr>
<td>EBC</td>
<td>Energy balance closure</td>
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<tr>
<td>EC</td>
<td>Eddy covariance</td>
</tr>
<tr>
<td>ECV</td>
<td>Essential climate variable</td>
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<tr>
<td>ERIC</td>
<td>European Research Infrastructure Consortium</td>
</tr>
<tr>
<td>ESM</td>
<td>Earth system model</td>
</tr>
<tr>
<td>ETC</td>
<td>Ecosystem Thematic Centre</td>
</tr>
<tr>
<td>GAI</td>
<td>Green area index</td>
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<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
</tr>
<tr>
<td>ICOS PP</td>
<td>ICOS Preparatory Phase</td>
</tr>
<tr>
<td>LAI</td>
<td>Leaf Area Index</td>
</tr>
<tr>
<td>LMA</td>
<td>Leaf mass to area</td>
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<tr>
<td>LW</td>
<td>Long-wave</td>
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<tr>
<td>MAP</td>
<td>Mean annual precipitation</td>
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<tr>
<td>MAT</td>
<td>Mean annual air temperature</td>
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<tr>
<td>MSA</td>
<td>Monitoring Station Assembly</td>
</tr>
<tr>
<td>N</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>NEE</td>
<td>Net ecosystem exchange</td>
</tr>
<tr>
<td>PPFD</td>
<td>Photosynthetic photon flux density</td>
</tr>
<tr>
<td>PI</td>
<td>Principal investigator</td>
</tr>
<tr>
<td>RCP</td>
<td>Representative concentration pathways</td>
</tr>
<tr>
<td>RI</td>
<td>Research infrastructure</td>
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<tr>
<td>SOCS</td>
<td>Soil organic carbon stocks</td>
</tr>
<tr>
<td>SRF</td>
<td>Short rotation forestry</td>
</tr>
<tr>
<td>SW</td>
<td>Short-wave</td>
</tr>
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<td>Acronym</td>
<td>Full name</td>
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<td>---------------------------------------------------------------------------</td>
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<tr>
<td>ACTRIS</td>
<td>Aerosols, Clouds and Trace gases Research Infrastructure</td>
</tr>
<tr>
<td>AnaEE</td>
<td>Analysis and experimentation on Ecosystems</td>
</tr>
<tr>
<td>AmeriFlux</td>
<td>(Flux tower network in the Americas)</td>
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<tr>
<td>Asiaflux</td>
<td>(Flux tower network in Asia)</td>
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<td>CarboAfrica</td>
<td>Quantification, understanding and prediction of carbon cycle, and other GHG gases, in Sub-Saharan Africa</td>
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<td>Changes in carbon uptake and emissions by oceans in a changing climate</td>
</tr>
<tr>
<td>CarboMont</td>
<td>Effects of land-use changes on sources, sinks and fluxes of carbon in European mountain areas</td>
</tr>
<tr>
<td>COPERNICUS</td>
<td>European Earth Observation Programme</td>
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<tr>
<td>eLTER RI</td>
<td>Integrated European Long-Term Ecosystem &amp; Socio-Ecological Research Infrastructure</td>
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<tr>
<td>EMSO</td>
<td>European Multidisciplinary Seafloor and water-column Observatory</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>EuroArGo</td>
<td>European contribution to the Argo programme</td>
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<td>GCP</td>
<td>Global Carbon Project</td>
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<td>GEO</td>
<td>Group on Earth Observation</td>
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<td>GHG Europe</td>
<td>Greenhouse gas management in European land use systems</td>
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<td>IAGOS</td>
<td>In-service Aircraft for a Global Observing System</td>
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<td>ICOS</td>
<td>Integrated Carbon Observation System</td>
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<td>ICP Forests</td>
<td>International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests</td>
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<td>IOCCP</td>
<td>International Ocean Carbon Coordination Project</td>
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<tr>
<td>Lifewatch</td>
<td>E-Science European Infrastructure for</td>
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<td>----------</td>
<td>---------------------------------------------------------------</td>
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<tr>
<td><strong>Medeflu</strong></td>
<td>(Flux measurement network in the Mediterranean region)</td>
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<tr>
<td><strong>NEON</strong></td>
<td>National Ecological Observatory Network</td>
</tr>
<tr>
<td><strong>NitroEurope IP</strong></td>
<td>(Integrated European research into the nitrogen cycle)</td>
</tr>
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<td><strong>SBSTA</strong></td>
<td>Subsidiary Body for Scientific and Technical Advice</td>
</tr>
<tr>
<td><strong>UNECE</strong></td>
<td>United Nations Economic Commission for Europe</td>
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<tr>
<td><strong>WMO</strong></td>
<td>World Meteorological Organisation</td>
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