Biogeosciences, 19, 1–16, 2022
https://doi.org/10.5194/bg-19-1-2022

Biogeosciences Open Access EGU

Ideas and perspectives: Enhancing research and monitoring of carbon pools and land-to-atmosphere greenhouse gases exchange in developing countries

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Received: 7 September 2021 – Discussion started: 30 September 2021
Revised: 10 January 2022 – Accepted: 10 January 2022 – Published:

Abstract. Carbon (C) and greenhouse gas (GHG) research has traditionally required data collection and analysis using advanced and often expensive instruments, complex and proprietary software, and highly specialized research technicians. Partly as a result, relatively little C and GHG research has been conducted in resource-constrained developing countries. At the same time, these are often the same countries and regions in which climate change impacts will likely be strongest and in which major science uncertainties are centered, given the importance of dryland and tropical systems to the global C cycle. Increasingly, scientific communities have adopted appropriate technology and approach (AT&A) for C and GHG research, which focuses on low-cost and low-technology instruments, open-source software and data, and participatory and networking-based research approaches. Adopting AT&A can mean acquiring data with fewer technical constraints and lower economic burden and is thus a strategy for enhancing C and GHG research in developing countries. However, AT&A can have higher uncertainties; these can often be mitigated by carefully designing experiments, providing clear protocols for data collection, and monitoring and validating the quality of obtained data. For implementing this approach in developing countries, it is first necessary to recognize the scientific and moral importance of AT&A. At the same time, new AT&A techniques should be identified and further developed. All these processes should be promoted in collaboration with local researchers and through training local staff and encouraged for wide use and further innovation in developing countries.

1 Introduction

Increasing atmospheric greenhouse gas (GHG) concentrations caused by human activities result in global warming and climate change (IPCC, 2014). Many uncertainties remain around this core of settled science, however, and many of the most critical questions with respect to GHG dynamics can only be resolved by expanded measurements and experiments in not only developed but also developing countries (Xu and Shang, 2016), given the mismatch between our carbon cycle uncertainties and existing measurement capability (Schimel et al., 2015).

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Research on C and land-to-atmosphere GHG exchange is thus critical to understand the consequences of rapidly increasing atmospheric GHG concentrations. This research should be carried out globally, in both developed and developing countries, since both have different sources and sinks of GHGs, different climate change vulnerabilities, and different capacities for mitigation and adaptation (Stell et al., 2021; López-Ballesteros et al., 2018; Ogle et al., 2014). Traditionally, this has required high-quality long-term or vast-spatial-scale (e.g., regional or continental) data collected using advanced instruments, significant computing power with complex and/or proprietary software, and skilled technicians – all expensive to develop, implement, and maintain. Due to these requirements, many developing countries cannot conduct the necessary research, and they heavily rely on the international collaboration projects driven by developed countries (Minasny et al., 2020; Vogel et al., 2019). Even in the collaboration projects, the roles of researchers of developing countries are often limited due to the technical constraints, and the projects often fail to guarantee sustainability of research in the aspect of continuing and developing further research by developing countries (Minasny et al., 2020; Bates et al., 2020; Bockarie, 2019; Vogel et al., 2019). These make it hard to fill the critical gaps in C and GHG research of developing countries (López-Ballesteros et al., 2018; Kim et al., 2016; Xu and Shang, 2016). Consequently, the lack of available data hinders developing countries from recognizing their sources or quantities of emissions, establishing national GHG inventories, and developing proper mitigation strategies (Kim et al., 2016; IPCC, 2014). Therefore, it is critical to resolve the technical constraints of enhancing C and GHG research in developing countries.

Recently, C and GHG research adopting "appropriate technology and approach" (AT&A, e.g., Murphy et al., 2009) has been proposed or carried out. This uses low-cost and low-technology instruments, open-source software and data, and participatory approaches (Peltier, 2021; Gentemann et al., 2021; Bastviken et al., 2020; Choi, 2019; Shames et al., 2016). However, while efforts to adopt AT&A have been made individually in different research fields, they have not been well known or shared for further adaptation in other research fields, especially in developing countries. Therefore, efforts are needed to develop further AT&A suitable for C and GHG research and critically assess whether they can be applicable in developing countries and if they could be a starting point for a new collaboration strategy that can be the basis for the further development of ecosystem observatories in developing countries.

Here our major objectives are to (1) identify existing gaps in C and GHG research and major barriers to conducting the research in developing countries, (2) explore currently available AT&A for C and GHG research, (3) identify major advantages and potential problems and solutions for adopting AT&A in the research, and (4) provide suggestions for further development and its implementation on the ground.

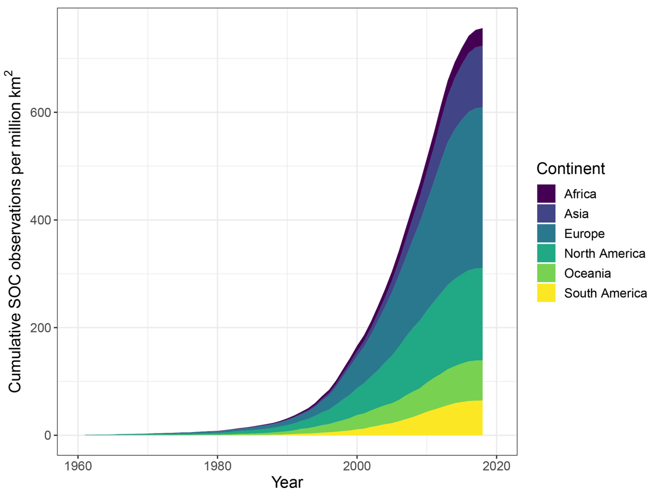

Figure 1. Number of published observations on soil organic carbon (SOC) changes driven by land management, land-use changes, and climate change (cumulative observations per million square kilometers) in each region. An observation indicates a set of measurements conducted in a site during a certain period. Data source: Beillouin et al. (2021).

2 Existing gaps in C and GHG research in developing countries

The accurate quantification of biomass and soil C pools is important for understanding the current status and monitoring the change of C budgets. For the better quantification of C pools, it is critical to monitor chronosequences and permanent plots in different ecosystems and land-use types for long-term periods (Smith et al., 2020; Hubau et al., 2020; Willcock et al., 2016). However, due to technical and economic constraints, accurate C pools and long-term monitoring data are lacking in developing countries (Beillouin et al., 2021; Li et al., 2020; Xu et al., 2019; Shi et al., 2016; Kim and Kirschbaum, 2015). For instance, most developing countries (84 out of 99 countries in Romijn et al., 2015) in the critical tropical zone reported their forest C pool using default values (Tier 1) provided in the IPCC guidelines (IPCC, 2006), rather than country-specific data (Tier 2) or higher-level methods such as repeated measurements in permanent plots (Tier 3) (Requena Suarez et al., 2019; Vargas et al., 2017; Ochieng et al., 2016; Romijn et al., 2015). Data on the effect of land management, land-use changes, and climate change on soil organic carbon (SOC) were very low in developing countries such as those in Africa (4 %), South America (9 %), and Asia (15 %) compared to North America (23 %) and Europe (39 %) (Beillouin et al., 2021) (Fig. 1).

As of 2000, soil carbon dioxide (CO_2) flux measurements had been conducted at 1815 sites in 42 countries; this had increased to 6625 sites in 75 countries by 2016 (Jian et al., 2021) (Fig. 2). Similarly, methane (CH_4) and nitrous oxide (N_2O) flux measurements have increased worldwide (Fig. 1).

Still, the majority of measurements occurred in only a few countries representing only a small part of the global soil–vegetation–climate space (Feng et al., 2020; Tan et al., 2020; Ganesan et al., 2019; National Academies of Sciences, Engineering, and Medicine, 2018; Oertel et al., 2016). For example, developed countries (those in the top one-third globally in per capita gross domestic product) along with China have provided over 60 % of the global GHG flux measurements (Fig. 2). In terms of a continental scale, measurements in Europe, North America, and Asia cover around 90 % of the global observations, while Africa and South America remain critically underrepresented (Stell et al., 2021; Jian et al., 2021; Gatica et al., 2020; Épule, 2015; Kim et al., 2013) compared to their importance in global GHG budgets (Fig. 3). For instance, a global meta-analysis on the effect of land-use change on CH_4 and N_2O emission (McDaniel et al., 2019) reported that among 62 studies included in the study, Africa and Asia comprised only 5 % and 11 %, respectively, while studies carried out in Australia and New Zealand, Europe, North America, and South America were 15 %, 21 %, 33 %, and 15 %, respectively.

Eddy covariance (EC) measurements are even more technically challenging and expensive to make than those of soil GHG flux and thus severely lacking in developing countries (Burba, 2019). By 2015, only 23 % of ecoregions globally had been sampled by EC measurements, and Africa, Oceania (excluding Australia), and South America were particularly poorly sampled (Hill et al., 2017) (Fig. 4). While there were more than 459 active EC stations globally in 2016 (Baldocchi, 2014), a total of only 11 and 41 EC stations were recording flux data across Africa (López-Ballesteros et al., 2018) and South America (Villarreal and Vargas, 2021), respectively, in 2018. At the country level, wealthy countries make EC measurements in a higher proportion of their ecoregions and with more replication (Hill et al., 2017). In addition, the few measurements collected in Africa and South America are in general not shared in the community (Villareal and Vargas, 2021; Bond-Lamberty, 2018), highlighting also a problem of data sharing and integration with the other scientific communities globally.

Various C and GHG models have been developed and adopted for estimating C and GHG budgets and dynamics (Oertel et al., 2016; Jose et al., 2016; Giltrap et al., 2010). In particular, earth system models (ESMs), especially land surface–atmosphere exchange models in combination with climate models, have been widely used to investigate climate change and mitigation studies (e.g., Community Earth System Model, Kay et al., 2015; Hurrel et al., 2013). Similarly, data-oriented and empirical models, mainly based on machine learning (ML) techniques and the large use of remote sensing (RS) data, are becoming more widely used (e.g., the FLUXCOM ensemble, Jung et al., 2020). These models and algorithms require careful parameterization and calibration at the site scale to better simulate fluxes and the potential impacts of climate and management (Reichstein et al., 2019; Hourdin et al., 2017; Giltrap et al., 2010). Due to a lack of observed C and GHG data in developing countries, they likely have not been properly validated for and localized to the environment in developing countries (De-Arteaga et al., 2018; Pal et al., 2007). Consequently, high uncertainties in the ESM, ML, and RS products hinder further use for C and GHG research in developing countries.

3 Major barriers to enhancing C and GHG research in developing countries

3.1 Technical expertise and infrastructure

Carbon and GHG research often require technical expertise and infrastructure such as advanced instruments, IT technologies, reliable and stable electric power supply and network service, highly specialized research technicians, and a well-developed transport system to ensure accessibility. These may not be available in developing countries, or it may take long periods to obtain them. Even if the required instruments and technical expertise could be obtained through external collaborations, critical issues still remain. First, the role and involvement of local researchers is often limited in the collaboration research (Minasny et al., 2020; Bates et al., 2020; Bockarie, 2019; Costello and Zumla, 2000). In general, the principal investigators (PIs) of the collaboration research are from developed countries. While the PIs often define the research line and lead the research activities, local researchers lacking relevant skills and experience are hardly involved in the planning of the research activities and play a limited role in the research such as providing logistics and assisting data collections. The limited scientific role of local researchers is exemplified by the low number of papers led by local researchers; for instance, Minasny et al. (2020) found that out of 80 published GHG emissions studies in Southeast Asian peatlands, only 35 % of the studies were first-authored by local researchers. Another important issue is that the sustainability of the research cannot be in general guaranteed (Minasny et al., 2020; Bates et al., 2020; Vogel et al., 2019). After the end of the project that supported material purchase, installation, and technical support, it is often not possible to get funding or collaborations to further support the research and monitoring activities. The limited project duration often hinders providing proper training to local researchers to ensure the continuation of the activities. Due to these reasons, developing countries cannot effectively calibrate, repair, and manage installed instruments and research activities and finally stop conducting the research furthermore.

3.2 Knowledge and information access

Access to scientific knowledge and information has become much easier than in the past due to the rapidly increasing availability and use of open-source software and data, electronic journal repositories, and online education and training

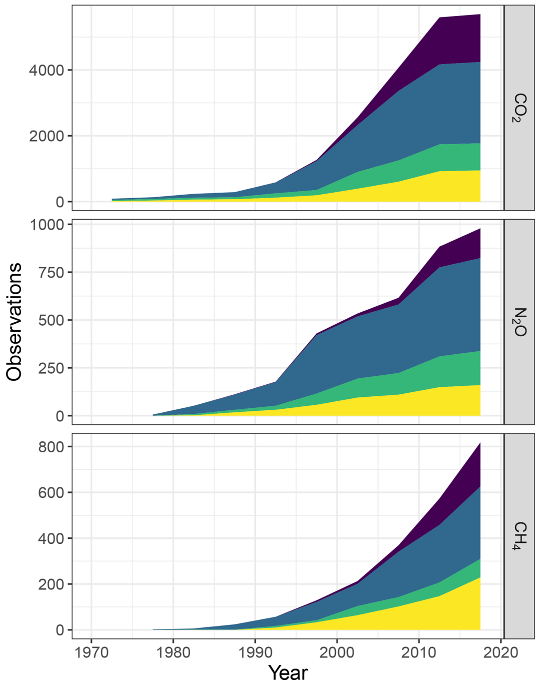

Figure 2. Cumulative observations of annual soil-to-atmosphere flux of greenhouse gases (CO_2, N_2O, and CH_4) over time. An observation indicates a set of measurements that resulted in an annual flux estimate. Colors show fraction of observations made in countries with high (top third), medium, and low (bottom third) per capita gross domestic product (GDP, listed by the World Bank) in the year of measurement. The People's Republic of China is broken out separately, as this country has a unique combination of large numbers of observations, high GDP, and large populations and thus low per capita GDP. Note differing *y*-axis scales in each panel. Data source: CO_2 – Jian et al. (2021); N_2O – Global N_2O Database (https://ecoapps.nrel.colostate.edu/global_n2o/, last access: 5 February 2022); and CH_4 – Al-Haj et al. (2020), Han and Zhu (2020), Tan et al. (2020), Gatica et al. (2020), and Feng et al. (2020).

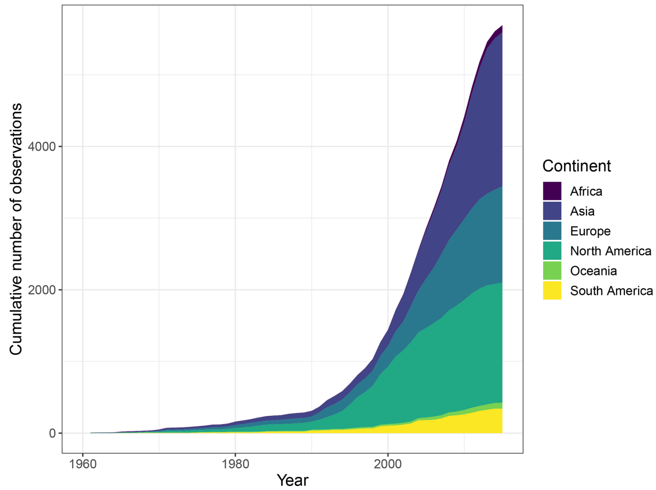

Figure 3. Number of published soil carbon dioxide flux observations (cumulative observations per million square kilometers) in each region. An observation indicates a set of measurements conducted in a site during a certain period. Data source: Jian et al. (2021).

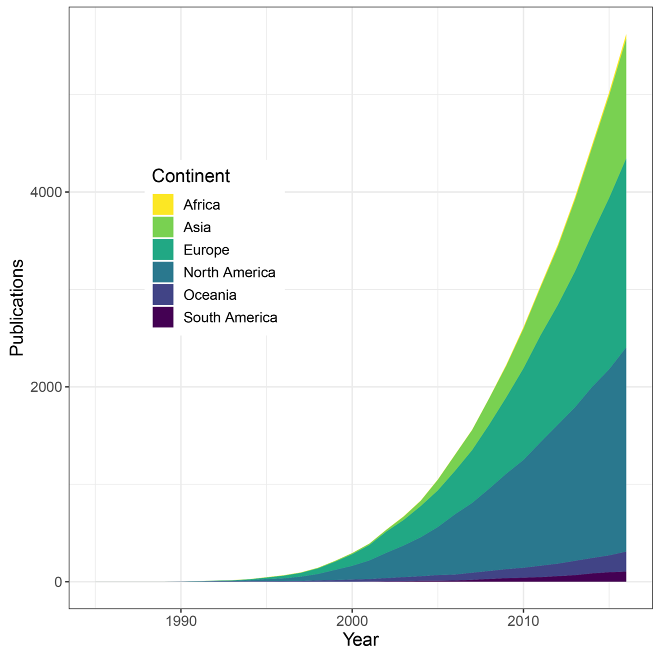

Figure 4. Cumulative numbers of publications on eddy covariance (EC) flux research conducted in different regions from 1985 to 2016. Data source: Dai et al. (2018).

courses (Lowndes et al., 2017; Hampton et al., 2015; Lausch et al., 2015). However, developing countries still have difficulties accessing them, since many still lack internet service (Ritchie, 2019; King et al., 2018; Mtebe and Raisamo, 2014); many also cannot afford journal and course subscription fees (Habib, 2011; Rose-Wiles, 2011), although the impact of this latter problem is lessening as science increasingly shifts to open-access publication and open education and training models (Iyandemye and Thomas, 2019; Pinfield et al., 2014). In addition, there is also the problem of utilizing shared knowledge and information, since the availability of free resources is often unknown, or the potential and target audience is not well clarified (Luo et al., 2020; King et al., 2018; Mtebe and Raisamo, 2014).

3.3 Socio-economic conditions

Developing countries often struggle to manage local climate-change-related emergencies such as droughts or flooding and establish adaptation strategies to these issues (IPCC, 2014). For these reasons, investment in long-term research and science on C and GHGs may receive less attention in developing countries even if needed to better understand and quantify C and GHG balances and dynamics. In addition, the costs for purchasing required instruments, hiring skilled researchers and technicians, and collecting data across large spatial or long-term temporal scales are often very high, to the extent that doing so may be beyond the financial capacity of any institute in developing countries. Consequently, financial support for C and GHG research is considered a lower priority in research and education programs or relevant policy-making processes (Atickem et al., 2019; Hook et al., 2017).

4 Appropriate technology and approach (AT&A) applicable for C and GHG research

Recently, various C and GHG research adopting AT&A has been proposed or carried out. We suggest that the use of AT&T can be a first step toward a full extension in the use of the same technologies in different developing countries. This would help, in addition to providing useful information and measurements about C stocks and GHG exchanges, to develop the background interest and competencies for ecosystem measurements and monitoring networks. Among all the possible approaches and solutions, here we summarize AT&A approaches applicable to research on C pool and dynamics, canopy physiology and structure, and GHG flux and accessing data, software, and computational resources (Table 1).

- *Biomass carbon quantification*. This is a critical, time-consuming, and laborious task, since individual trees should be counted and measured on site, where accessibility is often very limited and harsh environments hinder progress. Trained local communities can accurately quantify this (Evans et al., 2018; Zhao et al., 2016) also through “participatory research” or “citizen science” initiatives (Heigl et al., 2019; Irwin, 2018; School 2 School Initiative – https://tahmo.org/school-2-school-initiative/, last access: 5 February 2022) that have a great potential to enhance C research in developing countries (DeVries et al., 2016; Venter et al., 2015).

- *Soil carbon quantification*. Soil C pools, soil bulk density, and SOC contents are important and should be accurately determined using collected soil samples. While soil bulk density can be measured with locally available instruments (Grossman and Reinsch, 2002), alternative approaches with respect to the standard can be adopted to produce reliable SOC content data (Table 1, Gessesse and Khamzina, 2018; Apesteguia et al., 2018; Jha et al., 2014). A low-cost, field-portable reflectometer (a hardware cost of USD 350) provided precise and accurate soil C estimates in central and southern Malawi (Ewing et al., 2021).

- *Organic matter decomposition*. Commercially available tea bags were adopted to quantify the organic matter decomposition rate in various ecosystems and land-use types; they tend to be highly standardized, universally available, and cheap and are thus well-suited for global analyses of this type. Bags were buried in soils for a certain period, and then decomposition was quantified by the loss of weight over time (Marley et al., 2019; Djukic et al., 2018).

- *Canopy photosynthesis phenology and parameters*. Light-emitting diodes (LEDs) are a very cheap light source, but by using their inverse mode, LEDs can be used as spectrally selective light detectors (Mims, 1992). Using this principle, two or four channels of LED sensors in red and near-infrared bands have been used to monitor canopy photosynthesis, phenology, and leaf area index in grasslands (Ryu et al., 2010) and in tall deciduous and evergreen forests (Ryu et al., 2014); the blue spectral band was used to assess the fraction of canopy-absorbed light, and the green leaf area index was used in a rice paddy (Kim et al., 2019). Digital-camera images also offer key canopy structural information such as phenology (Richardson et al., 2018), gap fraction (Macfarlane et al., 2014), leaf area index and clumping index (Ryu et al., 2012), and leaf angle distribution (Ryu et al., 2010). Cameras’ charge-coupled devices (CCDs) work as a simple, three-band spectroradiometer (Hwang et al., 2016) that can be cheap (USD 20–30 for the one used in the smartphones), and if integrated with multiple LED spectral sensors, they can be very useful to monitor crop status, particularly important in developing countries given their limited resources in water and fertilizers.

- *Atmospheric concentrations of CO_2 and CH_4*. Studies have used low-cost sensors to monitor atmospheric concentrations of CO_2 (Peltier, 2021; Shusterman et al., 2018) and CH_4 (Peltier, 2021; Riddick et al., 2020).

- *Land–atmosphere CO_2 and CH_4 fluxes*. The same low-cost sensors have been used to measure CO_2 fluxes with chambers (Bastviken et al., 2015, 2020; Brändle and Kunert, 2019).CE1 Cheaper technologies have been also tested in EC instrumentation, e.g., using middle-cost CO_2 and H_2O analyzers (15 %–25 % of the price, Hill et al., 2017) while obtaining similar performance. Beside CO_2 and H_2O analyzers, studies found positive signs that some instruments for EC systems such as data loggers and pressure, temperature, and relative humidity sensors (Markwitz and Siebicke, 2019; Hill et al., 2017; Dias et al., 2007) can be substituted for low-cost instruments.

- *Remote sensing data*. The remote sensing community is increasingly moving towards open-access RS

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data, with free and open satellite data such as Landsat, MODIS (Moderate Resolution Imaging Spectroradiometer), AVHRR (Advanced Very High Resolution Radiometer), and the Copernicus Sentinel constellation, and it provides various benefits to scientific communities, especially the ones in developing countries (Zhu et al., 2019; Rocchini et al., 2017). Often products for direct use in GHG research such gross primary production (photosynthesis), land cover change, phenology, and wildfire maps are also provided, removing the need for raw data processing (Yan and Roy, 2018; Pettorelli et al., 2017; Roy et al., 2005). Greenhouse gas satellites such as GOSAT (Greenhouse Gases Observing Satellite), OCO-2 (Orbiting Carbon Observatory), OCO-3, and TanSat that provide column CO_2 concentration information are an important source of information in undersampled areas (Eldering et al., 2019; Yang et al., 2019). In terms of in situ measurements there is also the tendency, at least in the developed countries, to share the data openly under licenses like CC BY (Creative Commons Attribution). Examples are European CE2 Environmental Research Infrastructures under the ENVRI umbrella (https://envri.eu/, last access: 5 February 2022), such ICOS (Integrated Carbon Observation System), ACTRIS (Aerosol, Clouds and Trace gases Research Infrastructure), and LTER (Long-Term Ecosystem Research), or the American NEON (National Ecological Observatory Network) and AmeriFlux (e.g., Papale, 2020).

- *Open and free code, software, and tools*. Statistical software and visualization packages developed and adopted in scientific communities (Lowndes et al., 2017; Lausch et al., 2015) like R and Python can be shared under a GNU license (Hampton et al., 2015). This also applies to GIS (geographic information system) open-source software such as QGIS, GRASS GIS (Geographic Resources Analysis Support System), and SAGA GIS (System for Automated Geoscientific Analyses; Muenchow et al., 2019; Rocchini et al., 2017) and GHG community software shared openly like in the case of EddyPro – https://www.licor.com/env/support/EddyPro/software.html (last access: 5 February 2022) or the ONEFlux (Open Network-Enabled Flux) tool described by Pastorello et al. (2020).
- *Processing and computing tools*. Interfaces such as Jupyter Notebook and RMarkdown simplified the sharing and common development of processing routines that can be run in a thin-client environment for highly demanding computations like in the "Google Colab" tool (Ramires-Reyez et al., 2019; Bastin et al., 2019). More general cloud computing services such as Google Earth Engine (Gorelick et al., 2017) and Microsoft Azure (Agarwal et al., 2011; Ryu et al., 2019) are becoming cheaper over time (Gentemann et al., 2021) or made available via academic pricing and grant programs (e.g., Microsoft AI for Earth https://www.microsoft.com/en-us/ai/ai-for-earth-grants, last access: 5 February 2022; Google for Nonprofits https://www.google.com/nonprofits/, last access: 5 February 2022). As long as internet connectivity is available, users are not required to have direct access to high-performance computing platforms (Gentemann et al., 2021), which is a barrier in developing countries.

5 Advantages and potential problems and solutions of adopting AT&A for C and GHG research

Adopting AT&A in C and GHG research (e.g., low-cost technology; free data, software, and computational resources; and participatory and networking-based research approaches) can have various advantages (Fig. 5). In the knowledge and information aspects, it can stimulate obtaining data especially from the places where access was limited, even if at a lower quality level. It can also make it easy to share knowledge and information, democratizing access to science and the knowledge gains resulting from research. In particular, participating citizens can become interested in research outcomes, so they can implement their obtained knowledge and experiences into ordinary life and also share them with others (Pocock et al., 2019; Geoghegan et al., 2016; Cooper et al., 2007). Technically, it is easier than any time in the past – though still not trivial – to build, purchase, operate, or maintain instruments required for research. Financially, it can reduce purchasing, operating, and maintenance costs. Finally, these approaches can provide a chance to make policy makers aware of C and GHG research and its importance and thus consider C and GHG research as a priority in national science and education policy.

It is important to note that there are challenges and potential problems in adopting AT&A. First, data obtained from low-cost and low-technology instruments generally have higher uncertainties compared to advanced high-quality instruments (Peltier, 2021; Arzoumanian et al., 2019; Marley et al., 2019; Castell et al., 2017). Second, research adopting a participatory approach can have a bias in the data collection process, due to participants' lack of understanding about the task or their own self-interest (Tiago et al., 2017; Kallimanis et al., 2017). Third, data obtained from research adopting networking-based approaches may not be useful if data collection plans are not well prepared or if planned activities are not well managed. Fourth, AT&A may mitigate but does not solve the problem of technical capacity because there are cases where it does not exist yet there is a real cheaper or low-technology alternative to some of the methods. Special efforts are required to prevent such problems. First, if low-cost and low-technology instruments are used, it is necessary to monitor the quality of obtained data and validate them

Table 1. Summary of appropriate technology and approach (AT&A) applicable for carbon and greenhouse gas research. LAI: leaf area index. NIR: near infrared.

Parameter to monitor	AT&A	How does AT&A work?	References
Biomass carbon quantification	Participatory research/citizen science	Biomass carbon pools can be accurately quantified by trained local communities and through citizen science initiatives	Evans et al. (2018), Zhao et al. (2016), DeVries et al. (2016), Venter et al. (2015), Theilade et al. (2015)
Soil carbon quantification	Walkley–Black method	Substituting an elemental analyzer; applying a correction factor to estimate accurate value	Walkley and Black (1934)
	Loss-on-ignition method		Wang et al. (2013)
	Near- and mid-infrared reflectance method		Ewing et al. (2021), Tang et al. (2020), Ng et al. (2020)
Organic matter decomposition	Tea bag method	Commercially available tea bags are adopted to quantify organic matter decomposition rate	Marley et al. (2019), Djukic et al. (2018), Keuskamp et al. (2013)
Canopy photosynthesis, phenology, and structure	Light-emitting diode (LED) sensors	LEDs can be used as spectrally selective light detectors in blue, red, and NIR to estimate photosynthesis dynamic, phenology, and LAI	Kim et al. (2019), Ryu et al. (2014, 2010)
	Digital-camera images	A cheap digital camera works as a simple, three-band spectroradiometer that can be used to estimate phenology, LAI, and canopy parameters (gap fraction, clumping index, leaf angle distribution, etc.)	Richardson et al. (2018), Macfarlane et al. (2014), Ryu et al. (2012), Hwang et al. (2016)
Atmospheric concentrations of CO_2 and CH_4	Low-cost sensors	Use of low-cost gas concentration sensors and correction factors	Peltier (2021), Shusterman et al. (2018), Riddick et al. (2020), Collier-Oxandale et al. (2018)
Land–atmosphere CO_2 and CH_4O fluxes CE3	Low-cost sensors/analyzers with low-cost chambers	Substituting an advanced analyzer/logger and gas sampler	Lawrence and Hall (2020), Bastviken et al. (2015, 2020), Carbone et al. (2019), Martinsen et al. (2018)
	Middle cost analyzer and low-cost sensors for EC	Use middle-cost gas analyzers and low-cost data logger and meteorological sensors in eddy covariance systems	Markwitz and Siebicke (2019), Hill et al. (2017), Dias et al. (2007)
Remote sensing and in situ data	Free and open spectral satellite data and products	Landsat, MODIS, AVHRR, Copernicus Sentinel constellation	Zhu et al. (2019), Rocchini et al. (2017)
	Free and open greenhouse gas satellite data	GOSAT, OCO-2, OCO-3, TanSat	Eldering et al. (2019), Yang et al. (2019), Liang et al. (2017)
	In situ measurements	Measurement networks data such ICOS, ACTRIS, LTER, NEON, AmeriFlux, FLUXNET	https://envri.eu, last access: 5 February 2022; Papale (2020)
Open and free code, software, and tools	Statistical analysis and data management	Programming languages like R and Python	Lowndes et al. (2017), Hampton et al. (2015), Lausch et al. (2015)
	GIS	QGIS, GRASS GIS, SAGA GIS	Muenchow et al. (2019), Rocchini et al. (2017)
	Specific software	GHG software like EddyPro, ONEFlux tool	https://www.licor.com/env/support/EddyPro/software.html, last access: 5 February 2022; Pastorello et al. (2020)
Processing and computing tools	Processing routines and tools	Jupyter Notebook, R Markdown; share and develop routines in a collaborative way run in a thin-client environment	Ramires-Reyez et al. (2019), Bastin et al. (2019)
	Cloud computing services	Google Earth Engine, Microsoft Azure; allow also for the integration of multiple satellite RS datasets	Ryu et al. (2019), Gorelik et al. (2017), Agarwal et al. (2011)

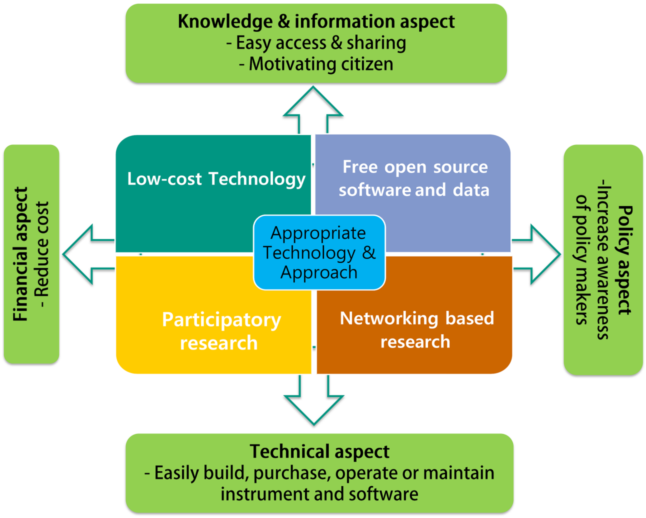

Figure 5. Major components of appropriate technology and approach (AT&A) and its benefits for enhancing carbon and greenhouse gas research in developing countries.

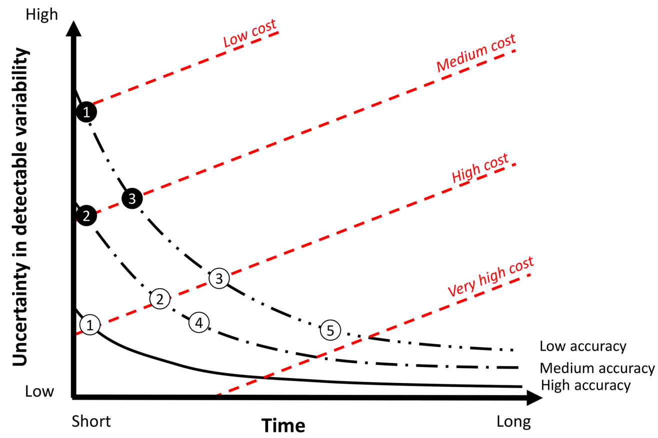

Figure 6. A conceptual diagram showing the uncertainty of detectable variability as a function of greenhouse gas measurement accuracy, time, and cost. Adopted from Baldocchi et al. (2018). Dashed red lines indicate different cost, and black lines indicate different accuracy. The red and black lines are only theoretical. With a small budget (low-cost technology for a short period), we have a lot of uncertainty in what we can detect (black 1). With a higher budget (moving to the next red line), we can either (i) go for a more accurate method for a short monitoring period (black 2) or (ii) ensure a longer monitoring period (or more frequent sampling) for the low-accuracy method (black 3). Increasing the budget even more, we have three options for the same budget: (i) a short period with high accuracy (white 1), (ii) a long period with medium accuracy (white 2), and (iii) a longer period with low accuracy (white 3). To achieve a certain level of uncertainty (same value on the y axis) it could be possible to use either (i) high-accuracy technologies for a short-term campaign (white dot 1) or (ii) lower-accuracy technologies for a longer campaign (white dot 4 or 5).

through cross-checking with advanced instruments and software (Peltier, 2021; Riddick et al., 2020; Arzoumanian et al., 2019; Rai et al., 2017). Second, to compensate for the lower accuracy and precision of low-cost and low-technology instruments, it is necessary to carefully design an experimental setup (e.g., sampling periods and replication, replication, and network sampling) and conduct statistical analyses to reduce error and bias (Riddick et al., 2020; Yoo et al., 2020; Bird et al., 2014). Third, well-prepared and easy-to-use protocols should be shared and understood among participating citizens.

Overall, for successfully adopting AT&A in C and GHG research, it is necessary to carefully evaluate the best way to achieve the aim of the study and an acceptable level of uncertainty depending on available resources including technology, time, and budget. This compromise solution can be explained in a theoretical scheme presented in Fig. 6. To achieve the aim of the study with the certain level of uncertainty (y axes) it could be possible to use either a high-accuracy technology for a short-term campaign (white dot 1) or a low-accuracy technology for a longer campaign accompanied by special efforts for quality control and validation (white dot 4 or 5). Taking this as a principle, a study adopting a low-accuracy technology (black dot 1) can reduce uncertainty by extending campaign periods (so moving along the dashed line increasing the length of the measurement period on x axes). Also increasing the number of observation points (e.g., replicates and sampling frequency) could lead to reducing uncertainty (e.g., moving from dot black 1 to 2). It is possible also to see this in terms of the available budget. Starting from the lowest cost (black dot 1), with a budget increase one can decide either to go for a higher-accuracy technology (black dot 2) or to ensure a longer campaign period (black dot 3). With an even higher available budget, one can opt for different combinations of quality of the measurements and length of the monitoring (white dots 1, 2, and 3). These imply that adopting AT&A in C and GHG research with a desired level of uncertainty can be achieved through adopting different levels of accuracy, durations of campaign, and budget. The plot in Fig. 6 is of course purely illustrative. The shape of the different curves and cost lines and the effect of the multiplication of observation points are a function of the scientific questions; performance of the instruments; and their costs, the spatial heterogeneity of the quantity measured, and their interannual variability.

6 Enhancing development and adaptation of AT&A for C and GHG research in developing countries

For further development and adaptation of AT&A for C and GHG research in developing countries, we suggested the integration of two components: (1) identifying and developing AT&A and (2) promoting AT&A for C and GHG research in developing countries.

6.1 Identifying and developing AT&A for C and GHG research

For identifying and further developing AT&A for C and GHG research, instead of focusing on a certain aspect and approach as an ad hoc solution, the integration of low-cost technology; free data, software, and computational resources; and participatory and networking-based research approaches will be an ideal model. The integration would not only reduce the uncertainties and fill the gap of each approach but also create synergistic effects, thus guaranteeing sustainability beyond an ad hoc solution (Fig. 5). As already said, low-cost technology can see the issue of low accuracy and precision (Arzoumanian et al., 2019; Marley et al., 2019), and it can be partially solved by increasing sampling replication and frequency, combining them with participatory and networking-based research approaches (Peltier, 2021; Riddick et al., 2020; Nickless et al., 2020; Morawska et al., 2018). Beside these technical aspects, through the integration, local actors take on expanded roles within the projects (e.g., development of research questions and research methodology and data collection and analysis) and can contribute to building local institutional capacity to implement relevant projects (Shames et al., 2016; Mapfumo et al., 2013). The potential for further development and adaptation of AT&A may be large enough to motivate researchers and scientific instrument companies in not only developing countries but also developed countries, since once tested they can be used to make the measurement networks denser.

6.2 Promoting AT&A for C and GHG research

It is also necessary to make further efforts for promoting identified and developed AT&A for C and GHG research in developing countries. There are various ways to promote them efficiently. First, the most effective one would be to demonstrate their usefulness through applications in different fields. This is a crucial step also to increase the demand of these new measurements. Second, it will be necessary to provide various funding opportunities for establishing scientific communities of AT&A and supporting their activities such as identifying, developing, and utilizing AT&A. Especially, political and financial decisions on the high-income countries investment in developing countries should also take into consideration the long-term perspective and periods not covered by the initial funding. Third, the awareness, training, and education of the local community is needed, for example organizing scientific conferences, workshops, and training to share knowledge and experience on AT&A. Finally, efforts to increase awareness of AT&A through educational activities such as regular curriculum, science fairs and student club activities (Pearce, 2019), and public mass media and social networking (https://www.facebook.com/ATA4GHG, last access: 5 February 2022) will be also helpful for promoting identified and developed AT&A in particular to young scientists.

The success of promoting AT&A and its sustainability will deeply rely on active collaboration between developed and developing countries (Minasny et al., 2020; Giller, 2020; Bates et al., 2020), where the developing countries' scientific communities must play a primary role in the definition of needs and approaches to follow. It is also important to have a good understanding that AT&A will bring mutual benefits to both developing and developed countries. For developing countries, AT&A will be the right solution to obtain and share new knowledge and information on C and GHG research and to motivate the preparation of the next advanced stages under technical and economical constraints. For developed countries, AT&A will provide new measurements to fill the gap in the data needed for applications, modeling, and estimations using advanced techniques. Also, AT&A diffusion will bring new research and development opportunities for the science industry working on low-cost instruments, since it will promote their development and commercialization. In addition, AT&A is well aligned with the current trends of global scientific communities moving toward open-access and data-sharing cultures (Villareal and Vargas, 2021; Bond-Lamberty, 2018; Dai et al., 2018; Harden et al., 2018).

7 Conclusions

While C and GHG research has adopted highly advanced technology and sophisticated data collection procedures, some have adopted AT&A such as low-cost technology instruments, free and shared data and software, and participatory research, and their results were in general well accepted by scientific communities. The major advantages of adopting AT&A in C and GHG research would be to reduce economic burden and technical constraints for conducting research and at the same time to motive educational bodies and ordinary citizens to promote and be involved in research. However, special attention is needed to make a suitable experimental design, develop protocols and communication strategies, and monitor the quality of obtained data because the usefulness of these measurements is a key factor to proceed in their collection and development. Overall, in terms of cost, feasibility, and performance, the integration of low-cost and low-technology, participatory and networking-based research approaches can be AT&A for enhancing C and GHG research in developing countries. For the successful promotion of AT&A and its sustainability on the ground, it is necessary to clearly identify the roles developing and developed countries play in identifying, developing, and utilizing AT&A and develop appropriate collaboration strategies between developed and developing countries. The role of the developed countries, which already invested in research projects in developing countries in the past, remains crucial and needed, but more attention should be dedicated to (1) the needs that should come also from the developing countries' priorities and (2) the real transferability and sustainability of the activities in the developing countries in order to really help the development of a local scientific community for C and GHG research. In addition, the promotion of open data access is crucial to allow for the dissemination and training needed for the future generation of scientists in the developing countries, and special care should be dedicated to the promotion of the use of available data in all academic programs. This however does not remove responsibilities of developing countries that should work, together with the local scientific communities, to increase the level of investment and international collaboration at the continental level.

Code and data availability. .TS1

Author contributions. All authors contributed to the conceptualization and writing of this document under the coordination of DGK.TS2

Competing interests. At least one of the (co-)authors is a member of the editorial board of *Biogeosciences*. The peer-review process was guided by an independent editor, and the authors also have no other competing interests to declare.

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Acknowledgements. We are grateful for the numerous researchers and technicians who provided invaluable data. It is impossible to cite all the references due to the limited space allowed, and we apologize to the authors whose work has not been cited. We are also grateful to Christopher Dorich for providing the Global N_2O Database and Zhao Bin and Shengqi Dai for providing data for Fig. 3.

Financial support. Ben Bond-Lamberty was supported by the Department of Energy Biological and Environmental Research (BER) program, as part of BER's Terrestrial Ecosystem Science program (grant no. DE-AC05-76RL01830). Dario Papale thanks the support of the ENVRI-FAIR H2020 project (no. GA 820852). Dong-Gill Kim was supported by the European Commission through the project "Supporting EU-African Cooperation on Research Infrastructures for Food Security and Greenhouse Gas Observations"(SEACRIFOG; project ID 730995) and International Atomic Energy Agency (IAEA) Coordinated Research Project "Developing Climate Smart Agricultural Practices for Carbon Sequestration and Mitigation of Greenhouse Gases" (no. CRP D15020).

Review statement. This paper was edited by Steven Bouillon and reviewed by two anonymous referees.

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