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Discussions

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

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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 skilled 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 the same countries and regions in which climate-change impacts will likely be strongest, and in which major science uncertainties are centred, 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 be characterized by 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.

Key words: Carbon, Greenhouse gas, Developing countries, Low-cost technology, Open source software, Open data, Participatory research, Appropriate technology and approach

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-world countries (Xu and Shang, 2016), given the mismatch between our carbon-cycle uncertainties and existing measurement capability (Schimel et al., 2015).

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, it 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; Vogetl 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; Vogetl 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 retard developing countries to recognize their sources or quantities of emissions, establish national GHG inventories, and develop proper mitigation strategies (Kim et al., 2016; IPCC, 2014). Therefore, it is critically required to resolve the technical constraints for 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, efforts to adopt AT&A have been made individually in different research fields and 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, 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 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 for 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.

2 Existing gaps in C and GHG research in developing countries

Accurate quantification of biomass and soil C pools is important for understanding current status and monitoring change of C budgets. For 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. 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). Various global meta-analyses reporting the effect of land-use changes on soil organic carbon (Li et al., 2020; Xu et al., 2019; Shi et al., 2016; Kim and Kirschbaum, 2015) have found low amounts of data available from developing countries such as Africa and Asia compared to Europe and North America.

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. 1). 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., 2020; 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. 1). In terms of 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. 2). 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 Europe and North America were 21% and 33%, 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. 3). 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 (Villareal 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 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 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 ESMs, ML, and RS products hinder further use for C and GHG research in developing countries.

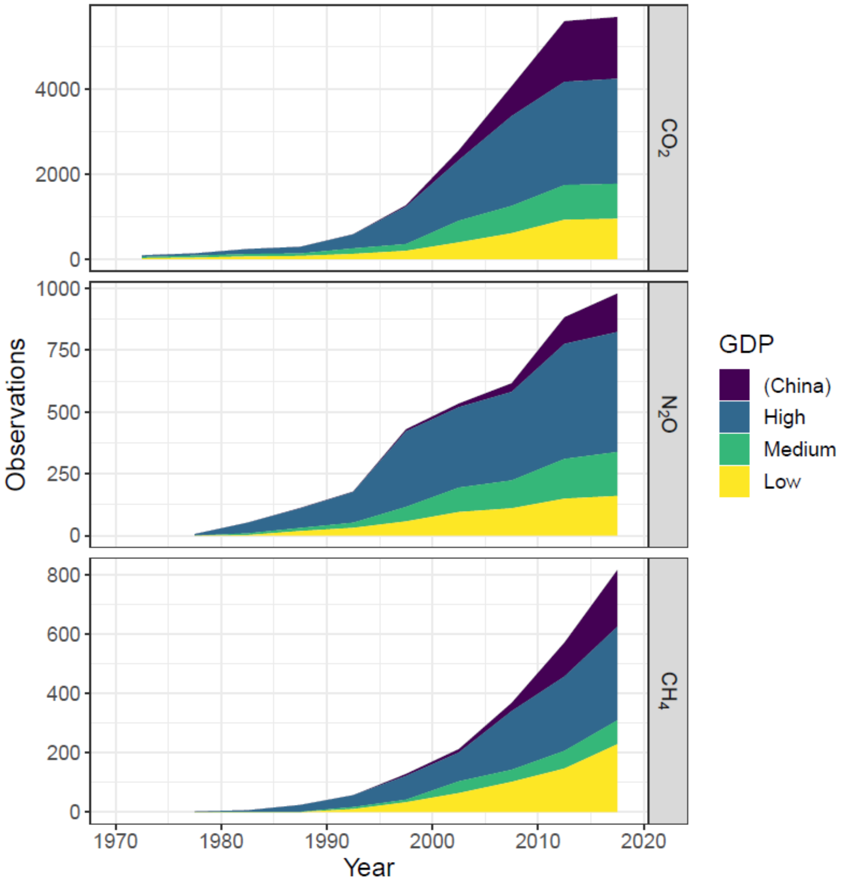

Figure 1: Cumulative observations of annual soil-to-atmosphere flux of greenhouse gases (CO_2, N_2O, and CH_4) over time. An observation indicates a set of measurements that resulted in an annual flux estimate. Colors show fraction of observations made in countries with high (top third), medium, and low (bottom third) per-capita gross domestic product (GDP, listed by World Bank) in the year of measurement. The People's Republic of China is broken out separately, as this country is 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/); CH_4 – Al-Haj et al. (2020), Han et al. (2020), Tan et al. (2020), Gatica et al. (2020), and Feng et al. (2020).

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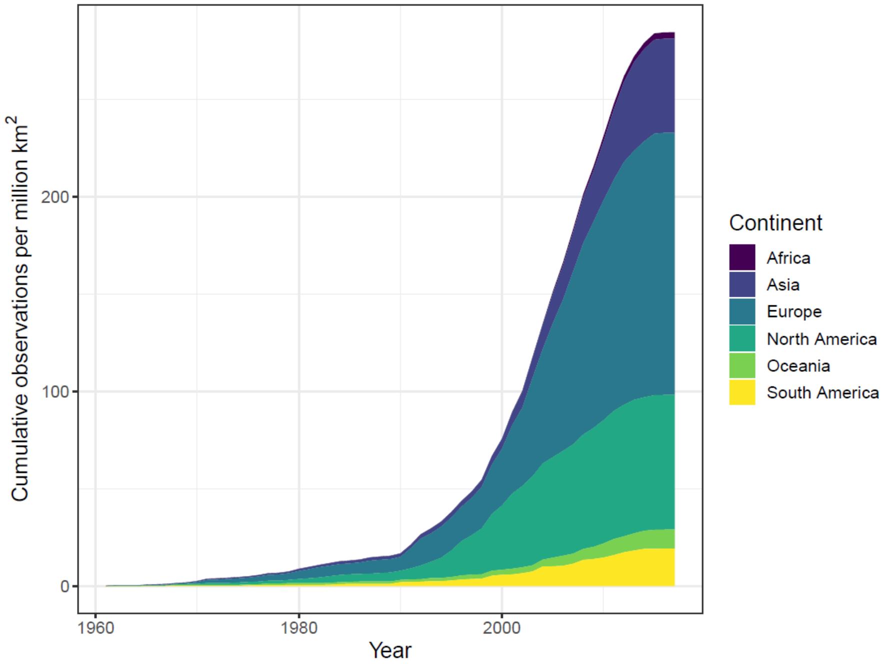

Figure 2: Number of published soil carbon dioxide flux observations (cumulative observations per million km^2) in each region. An observation indicates a set of measurements conducted in a site during a certain period. Data source: Jian et al. (2021)

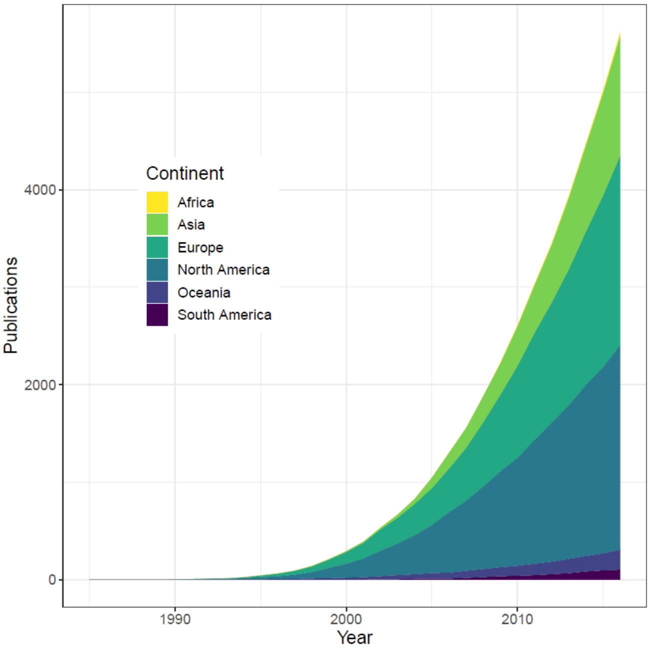

Figure 3: Cumulative numbers of publications on eddy covariance (EC) flux research conducted in different regions from 1985 to 2016. Data source: Dai et al. (2018).

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

3.1 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 on-line education and training courses (Lowndes et al., 2017; Hampton et al., 2015; Lausch et al., 2015). H\owever, 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 a 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).

3.2 Technical expertise and infrastructure

Carbon and GHG research often require technical infrastructure such as advanced instruments, IT technologies, electric power, network service, and skilled technicians. These may not be available in developing countries, or it may take long periods to obtain them due to logistical issues**.** Even if the required materials and skilled technicians could be obtained, for example 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 of the collaboration research are from developed countries. While the PIs define the research line and lead the research activities local researchers lacking relevant skills and experience are hardly involved in the planning process 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 minor 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 project funding the purchase of required materials and technical support is finished, it is often not possible to get the further required materials and supporting from external collaboration. The limited project duration often hinders providing a proper training to local researchers to ensure the continuation of the activities. Due to the reasons, developing countries cannot effectively manage installed instrument and research activities, and finally stop conducting the research furthermore.

3.3 Socio-economic conditions

Developing countries often struggle to manage locally occurring climatic events such as droughts or flooding and establish adaptation strategies to the issues (IPCC, 2014). As a result, research and science managers may give less attention to C and GHG dynamics and mitigation issues, and the importance of C and GHG research may not be well recognized. In addition, the costs for purchasing required instrument, 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 have been proposed or carried out. Among all the possible approaches and solutions, here we summarize AT&A applicable for research on C pool and dynamics, canopy physiology and structure, and GHG flux, and accessing to data, software, and computational resources. 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 the different developing countries. This would help, in addition to provide useful information and measurements about C stocks and GHG exchanges, to develop the background interest and competences for ecosystem measurements and monitoring networks.

4.1 Biomass and soil carbon pool and dynamics

Quantifying the biomass C pool is critical, for example, but challenging to perform accurately: this is a time-consuming and laborious task, since individual tree should be counted and measured on site, where accessibility is often very limited and harsh environments hinder progress. Studies have found that biomass C pools in forests can however be accurately quantified by trained local communities at almost one-third the cost compared to experts (Evans et al., 2018; Zhao et al., 2016; DeVries et al., 2016). Practices involving non-professionals into research activities are often called 'participatory research' or 'citizen science' (Heigl et al., 2019; Irwin, 2018; Pocock et al., 2018). Many studies have demonstrated that collaboration with ordinary citizens has a great potential to enhance C research in developing countries (DeVries et al., 2016; Venter et al., 2015; Theilade et al., 2015).

To quantify soil C pools, soil bulk density and soil organic carbon (SOC) contents should be accurately determined using collected soil samples. Soil bulk density can be measured with locally available instruments including a dry oven and a balance (Grossman and Reinsch, 2002). However, to accurately determine SOC contents, advanced techniques and instruments are required. The most accurate measurements are done with an elemental analyzer (e.g., CN analyzer), which is expensive and has high operation and maintenance costs (Gessesse and Khamzina, 2018; Wang et al., 2012). Alternatively, there are three different options to determine SOC contents with low cost. One is the Walkley-Black method (Walkley and Black, 1934), another is the loss-on-ignition method (Wang et al., 2013), the other is near- and mid-infrared reflectance method (Ewing et al., 2021; Tang et al., 2020; Ng et al., 2020). These methods can produce reliable SOC content data (Ewing et al., 2021; Gessesse and Khamzina, 2018; Apesteguia et al., 2018; Nóbrega et al., 2015). For instance, using the loss-on-ignition and Walkley-Black methods have found that, applying a correction factor, it is possible to estimate the SOC content with a good level of accuracy (Ethiopia- Gessesse and Khamzina, 2018; India- Jha et al., 2014; China- Wang et al., 2012; Brazil- Dieckow et al., 2007; Belgium- Lettens et al., 2007). A low-cost, field-portable reflectometer (a hardware cost of US$350) provided precise and accurate soil C estimates in central and southern Malawi (Ewing et al., 2021).

Appropriate technology has also been adopted to quantify organic matter decomposition. For example, commercially available tea bags were adopted to quantify organic matter decomposition rate in various ecosystems and land-use types; they tend to be highly standardized, universally available, and cheap, and thus well-suited for global analyses of this type. Bags were buried in soils for a certain period and then decomposition quantified by the loss of weight over time (Marley et al., 2019; Djukic et al., 2018; Keuskamp et al., 2013).

4.2 Canopy physiology and structure

Recent advances in inexpensive but reliable near-surface remote sensing systems may offer new opportunities to monitor plant physiology continuously in developing countries. 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 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). Four channels of LED sensors including blue, green, red and near-infared bands were used to monitor multi-layer canopy phenology in tall deciduous and evergreen forests (Ryu et al., 2014). Recently, a system that integrates LED sensors, micro camera, microcomputer, micro controller, and internet module was developed (for ~220 $USD per system) and tested in a rice paddy to monitor vegetation indices, the fraction of canopy-absorbed light, and green leaf area index (Kim et al., 2019). If further validated, this approach holds the potential to bring canopy monitoring techniques to a much wider range of individuals, institutions, and countries in the developing world.

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). In particular, the use of raw images holds great potential as the camera's charge-coupled device (CCD) linearly responds to light intensity, which enables us to use a cheap digital camera as a simple, three bands spectroradiometer (Hwang et al., 2016). It is notable that micro cameras used in smartphones allow us to record raw images and the price is only 20-30$. The effect of climate change on agricultural production is particularly important in developing countries given their limited resources in water and fertilizers. Deploying a sensing network that integrates multiple LED spectral sensors and digital cameras will be very useful to monitor crop status at the cost of only a few hundred dollars.

4.3 Greenhouse gas flux

Low-cost technology combined with networking based research approach has also been adopted in GHG research. Studies have utilized 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; Collier-Oxandale et al., 2018) and to measure CO_2 fluxes with chambers (Bastviken et al., 2020 and 2015; Brändle and Kunert, 2019; Martinsen et al., 2018). Some studies have also demonstrated how to build low-cost gas sampling and analysis instruments (Carbone et al., 2019; Martinsen et al., 2018; Bastviken et al., 2015). For instance, Bastviken et al. (2015) utilized a low-cost CO_2 logger to measure CO_2 fluxes in terrestrial and aquatic environments. They replaced an expensive and high precision CO_2 analyzer and data logging system with a low-cost CO_2 logger which was originally produced for industrial uses, and with careful practices, bias and accuracy remain good enough for many carbon-cycle applications. Carbon exchange between the land surface and atmosphere has also been investigated using cheaper technologies than commonly used EC instrumentation. For example, Hill et al. (2017) found that substituting middle-cost analyzers (15-25% the price) for conventional CO_2 and H_2O analyzers provided qualitatively similar performance. Beside CO_2 and H_2O analyzers, studies found positive signs that some instruments for EC systems such as anemometers, dataloggers, 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.

4.4 Access to data, software, and computational resources

Free and easy access to resources like data, software, and computational resources is an important aspect that can leverage the scarcity of direct measurements in developing countries and allow local scientists to develop interest, competences, and experience. The remote sensing community is increasingly moving towards open access RS data, with free and open satellite data such as Landsat, MODIS, AVHRR, and Copernicus Sentinels 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, allowing a direct use without the need of raw data processing (Yan and Roy, 2018; Pettorelli et al., 2017; Roy et al., 2005). Also, greenhouse gas satellites such as GOSAT, OCO-2, 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; Liang et al., 2017). 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 the CC-BY (Creative Common). Examples are European Research Infrastructures under the ENVRI umbrella (https://envri.eu/) such ICOS, ACRTIS, LTER or the American NEON and AmeriFlux.

Statistical software and visualization packages have been developed and adopted in scientific communities (Lowndes et al., 2017; Hampton et al., 2015; Lausch et al., 2015) like in case of R and Python that are used and shared under a GNU license (Hampton et al., 2015). The same is valid for GIS open source software such as QGIS, GRASS GIS, and SAGA GIS (Muenchow et al., 2019; Rocchini et al., 2017) and for codes specific for GHG community that are now also shared openly (like in case of EddyPro- https://www.licor.com/env/support/EddyPro/software.html or the ONEFlux tool described by Pastorello et al., 2020).

Processing and data evaluation and interpretation capacities have been further simplified by the development of notebook interfaces such as Jupyter Notebooks and R Markdown. They help to share and develop routines in a collaborative way and they can be run in a thin-client environment for highly-demanding computations like in the Jupyter notebook based service ‘Google Colab’ that provides a free deep learning playground. These new data interfaces are thus playing essential roles in climate change science (Ramires-Reyez et al., 2019; Bastin et al., 2019). More in general cloud computing services are becoming cheaper or free over time (Gentemann et al. 2021) like in case of Google Earth Engine (Gorelik et al., 2017) and Microsoft Azure (Agarwal et al., 2011) which also allow the integration of multiple satellite RS datasets (Ryu et al., 2019). 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. These companies have often academic pricing and grant programs, which are a good opportunity for research in developing countries (e.g., Microsoft AI4Earth https://www.microsoft.com/en-us/ai/ai-for-earth-grants; Google for Nonprofits https://www.google.com/nonprofits/).

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. 4). In knowledge and information aspect, 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 instrument required for research. Financially, it can reduce cost for purchasing, operating and instrument-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.

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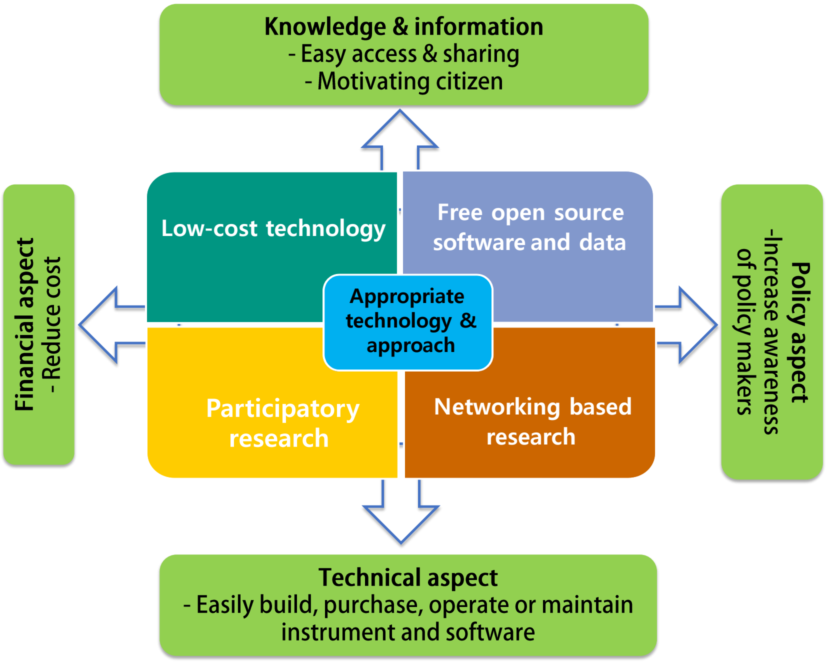

Figure 4: Major components of appropriate technology and approach (AT&A) and its benefits for enhancing carbon and greenhouse gas research in developing countries

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 instrument have generally higher uncertainties compared to advanced high quality instrument (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 planned activities are not well managed. Fourth, AT&A may mitigate, but does not solve, the problem of technical capacity in less-developed countries. Special efforts are required to prevent such potential problems. First, if low-cost and low-technology instruments are utilized for the research, it is necessary to monitor the quality of obtained data and validate them through cross-checking with advanced instrument 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 experimental set-up (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 needed 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. 5. To achieve the aim of the study with the certain level of uncertainty (Y axes) it could be possible to either use a high accuracy technology for a short-term campaign (white dot 1) or a low accuracy technology for a longer campaign accompanying with 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 measurements 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 black 2). It is possible also to see this in terms of budget available. Starting from the lowest cost (black 1) with an increase of budget one can either decide to go for a higher accuracy technology (black dot 2) or to ensure a longer period of campaign (black dot 3). With increasing budget even more, 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. 5 is of course purely illustrative. The shape of the different curves and cost lines and the effect of the multiplication of observation points are function of the scientific questions, performances of the instruments and their costs, spatial heterogeneity of the quantity measured, and their interannual variability.

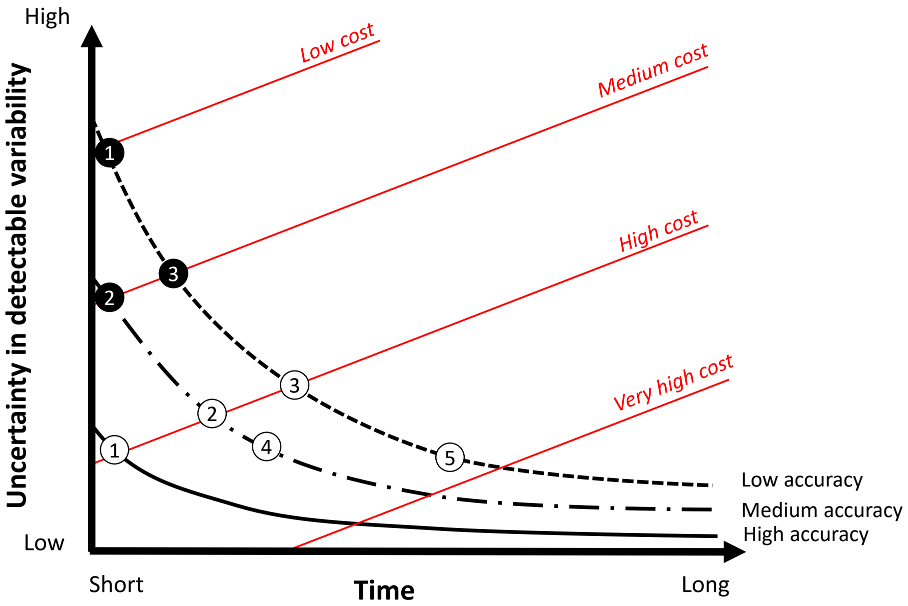

Fig. 5: A conceptual diagram showing the uncertainty of detectable variability as a function of greenhouse gas measurement accuracy, time, and cost. Adopted from Baldocchi et al. (2018). Red lines indicate different cost and black lines indicate different accuracy. The red and black lines are only theoretical. With a small budget (low-cost technology for a short period), we have a lot of uncertainty in what we can detect (black 1). Adding more 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 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).

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, 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. 4). 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). Potentials for further development and adaptation of AT&A may be large enough to motivate researchers and scientific instrument companies not only in 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 needed to provide various funding opportunities for establishing scientific communities of AT&A and supporting their activities such as identifying, developing and utilizing AT&A. 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 fair and student club activities (Pearce, 2019), public mass media and social networking (https://www.facebook.com/ATA4GHG) 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 county scientific communities must have 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 preparing next advanced stages under technical and economical constraints. For developed countries, AT&A will provide useful means to fill the gap of data, which needs for the application, modeling, and estimations using advanced techniques they already have. Also AT&A will bring new research and development opportunities for science industry since it will promote development and utilization of low-cost instruments, which have not got attention from mainstream of science industry. In addition, AT&A is well aligned with the current trends of global scientific communities moving toward to 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 procedure some have adopted AT&A such as low-cost technology instrument, 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 citizen 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 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, 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 successful promotion of AT&T and its sustainability on the ground, it is required to clearly identify the roles developing and developed countries in identifying, developing, and utilizing AT&A and develop appropriate collaboration strategies between developed and developing countries. The role of the developed countries, that 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 the dissemination and training needed for the future generation of scientists in the developing countries and a special care should be dedicated to the promotion of the available data use 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 continental level.

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