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Reviews and syntheses: Enhancing research and monitoring of land-to-atmosphere greenhouse gases exchange in developing countries

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Abstract. 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 GHG research has been conducted in resource-constrained developing countries and a critical data gap exists in these regions. 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 centered, given the importance of dryland and tropical systems to the global carbon cycle and climate. Increasingly, scientific communities have adopted appropriate technology and approach (AT&A) for GHG research, including 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 GHG research in developing countries. However, AT&A can be characterized by higher uncertainties; these can often be mitigated by carefully designing experimental set-up, providing clear protocols for data collection, and monitoring and validating the quality of obtained data. For implementing this approach in GHG research of developing countries, first, it is 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. Finally, these processes should be promoted 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

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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 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 GHG emissions is 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 (López-Ballesteros et al., 2018; Ogle et al., 2014). However, GHG research has not been widely conducted globally. 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 thus critical gaps in GHG research exist (López-Ballesteros et al., 2018; Kim et al., 2016; Xu and Shang, 2016). In developing countries, even though all available GHG measurements are collected for further analysis they have a problem with representativeness of the complex and heterogeneous environments due to lack of data (e.g., see Villareal and Vargas, 2021). The resulting data gaps hinder our understanding of GHG dynamics at regional and global scales (Schimel et al., 2015, Xu and Shang, 2016). At the same time, due to lack of available data, developing countries often do not recognize their sources or quantities of emissions and fail to establish proper mitigation strategies (Kim et al., 2016; IPCC, 2014).

Recently, 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, and in many cases has resulted in valuable research results accepted by international scientific communities (Choi, 2019; Shames et al., 2016; DeVries et al., 2016; Bastviken et al., 2015). 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 GHG research, critically assess whether they can be applicable in developing countries, and provide suggestions for further development.

The major objectives of this study were to 1) identify existing gaps and priorities in GHG research and major barriers for conducting the research in developing countries, 2) explore currently available AT&A to fill the gaps in 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 GHG research in developing countries

2.1 Quantification of carbon pools

Accurate quantification of biomass and soil carbon pools is important for understanding current status and monitoring change of carbon budgets. For better quantification of carbon pools, it is critical to monitor chronosequences and permanent

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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 carbon pools and long-term monitoring data are lacking in developing countries. For instance, most developing countries (e.g., 84 out of 99 countries; Romijn et al., 2015) in the critical tropical zone reported their forest carbon 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).

2.2 Observation of GHG fluxes

As of 2000, soil CO_2 flux measurements had been conducted at 1815 sites in only 42 countries; this had increased to 6625 sites in 75 countries by 2016 (Jian et al., 2021) (Fig. 1 and 2). Similarly, methane (CH_4) and nitrous oxide (N_2O) flux measurements have increased worldwide (Fig. 2). The substantial increases in measurements might be attributed to increased interest in the research area, and quickly-developing, highly advanced instruments using relevant technologies. Still, the majority of measurements occurred in only a few countries (representing only a small part of the global soil-vegetation-climate space) (Fig. 2) (Feng et al., 2020; Tan et al., 2020; Ganesan et al., 2020; National Academies of Sciences, Engineering, and Medicine, 2018; Oertel et al., 2016; Kim et al., 2013). 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 continental scale, measurements in Europe, North America and Asia cover around 90 % of the global observations, while Africa and South America remain critically underrepresented (Jian et al., 2021; Épule, 2015; Kim et al., 2013; Dutaur and Verchot, 2007) compared to their importance in global GHG budgets (Fig. 3).

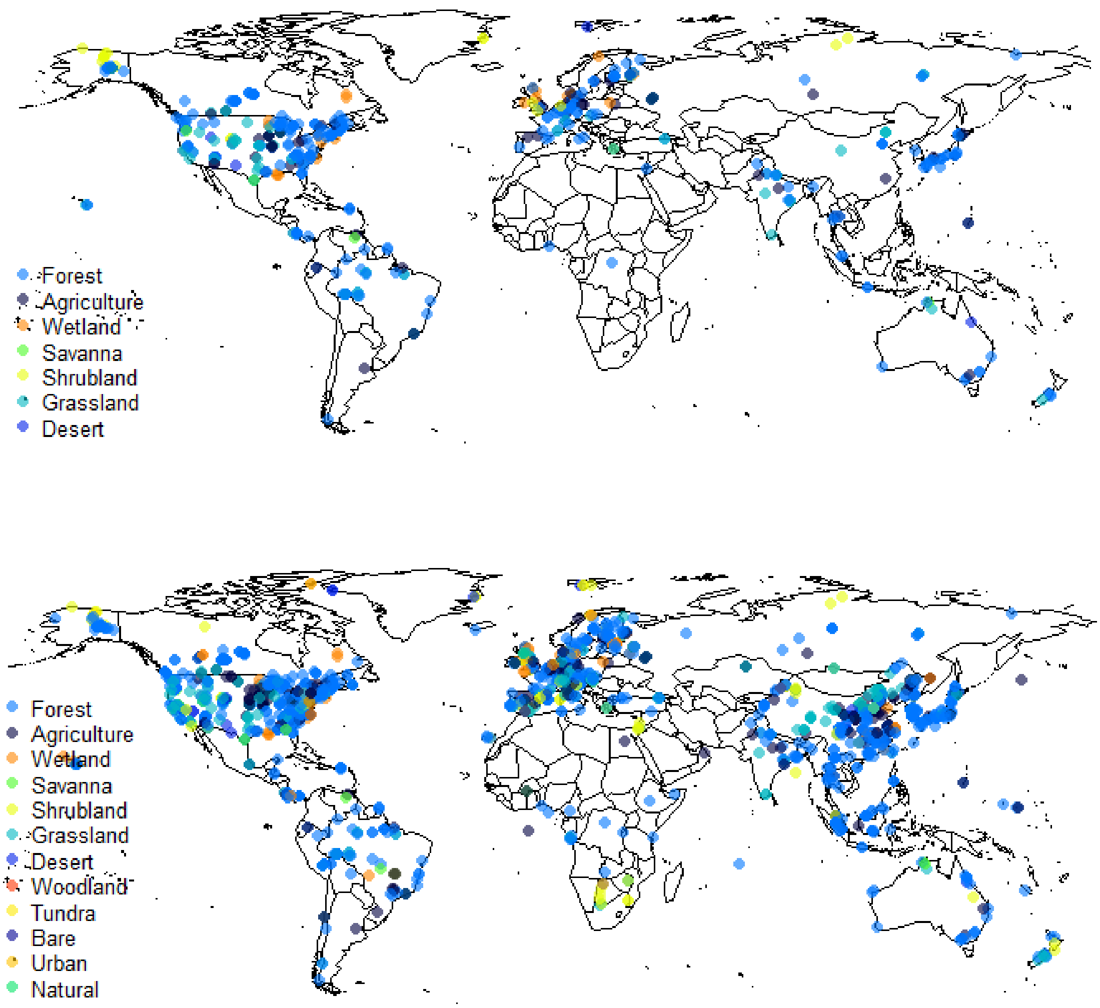

Figure 1: Global distribution of observed soil carbon dioxide fluxes by 2000 (above) and 2016 (below). Data Source: Jian et al. (2021). Created by Giacomo Nicolini.

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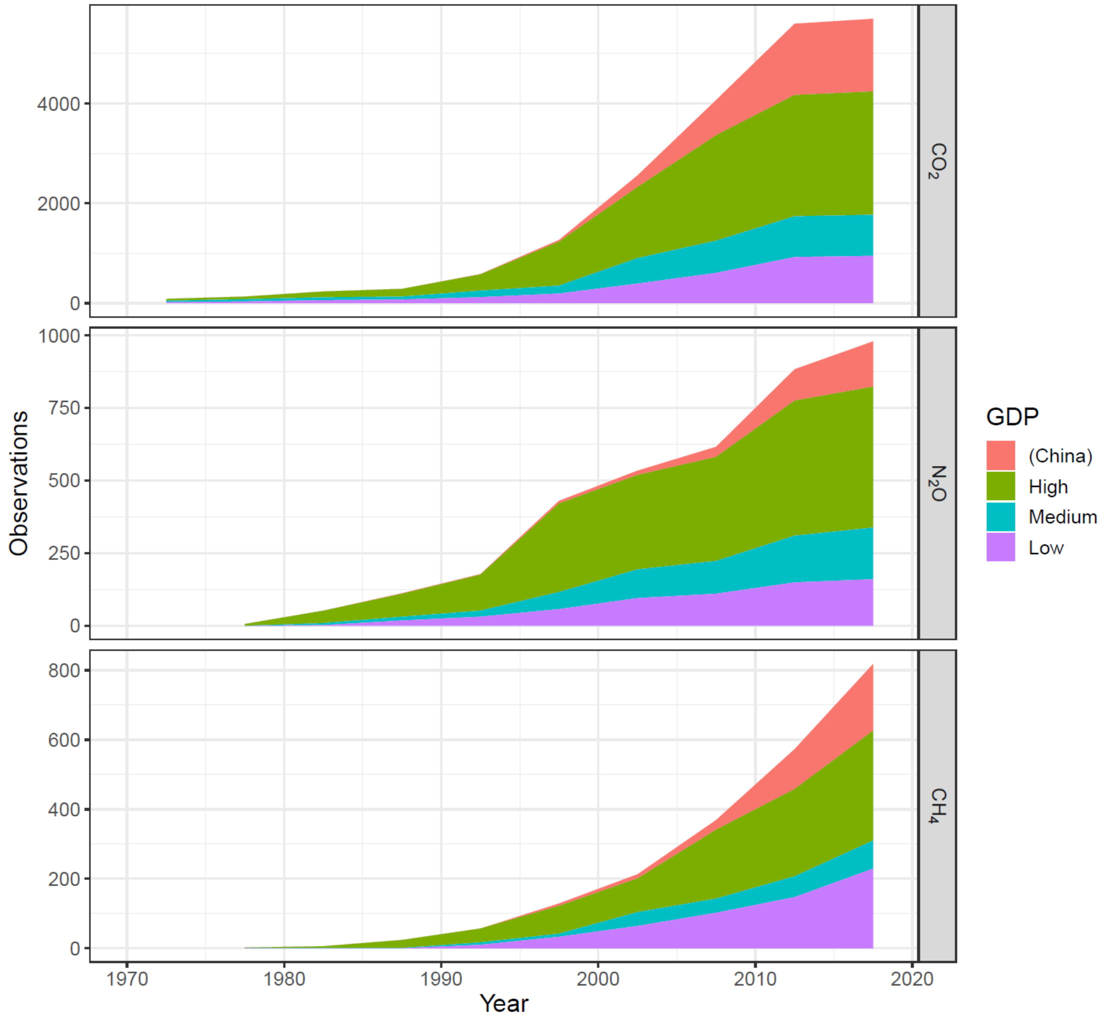

Figure 2: Cumulative observations of annual soil-to-atmosphere flux of greenhouse gases (CO_2, N_2O, and CH_4) over time. An observation indicates a set of measurements that resulted in an annual flux estimate. Colors show fraction of observations made in countries with high (top third), medium, and low (bottom third) per-capita gross domestic product (GDP, listed by 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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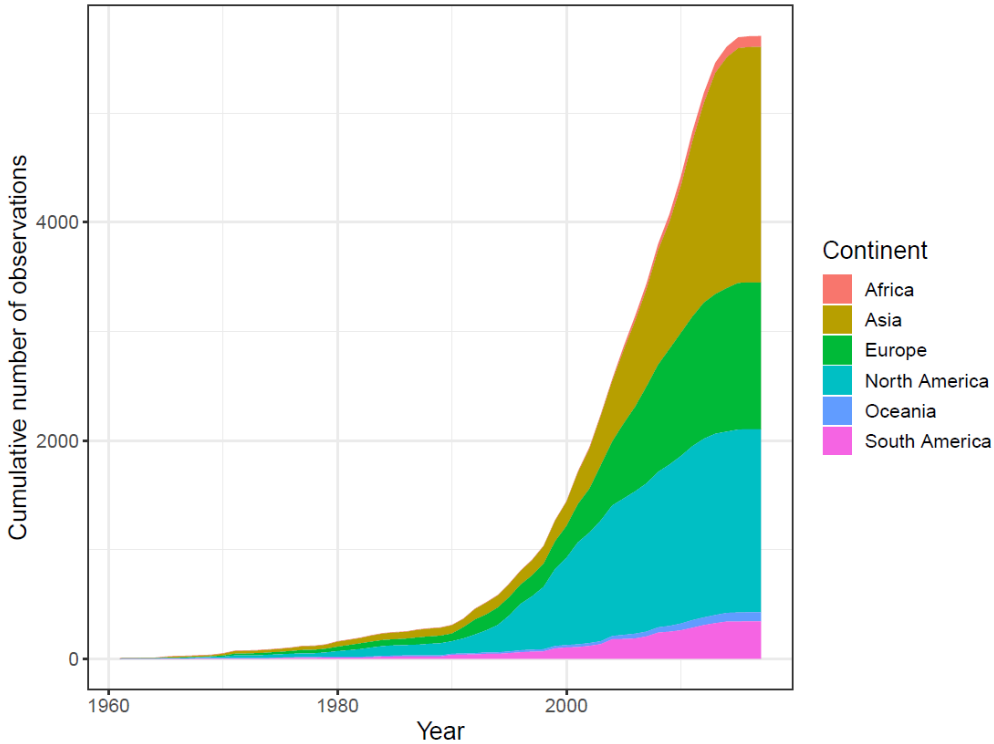

120 **Figure 3: Number of published soil carbon dioxide flux observations in each region. An observation indicates a set of measurements conducted in a site during a certain period. Data source: Jian et al. (2021)**

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 (Fig. 4 and 5). 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. 5). 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 integration.

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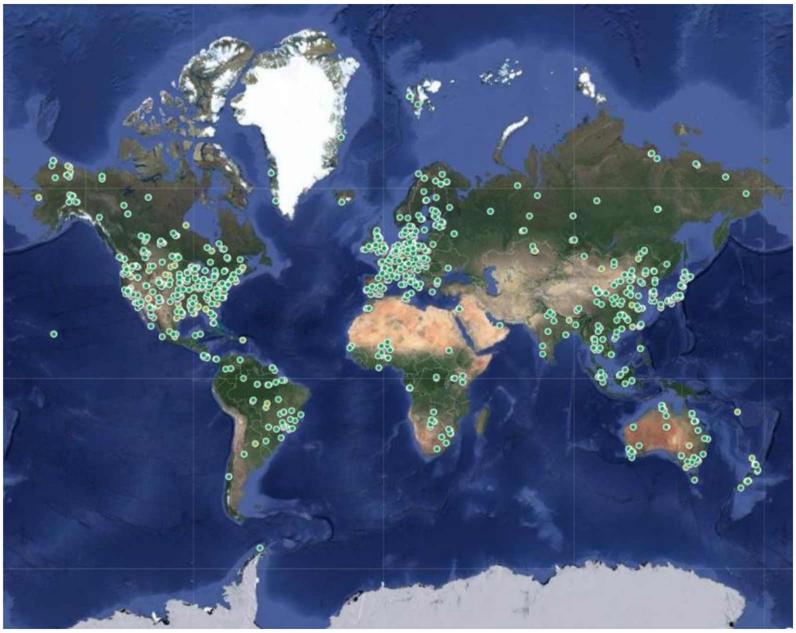

Figure 4: Map of past and present eddy covariance measurement locations (a total of 2029 measurement locations). Source: Burba (2019).

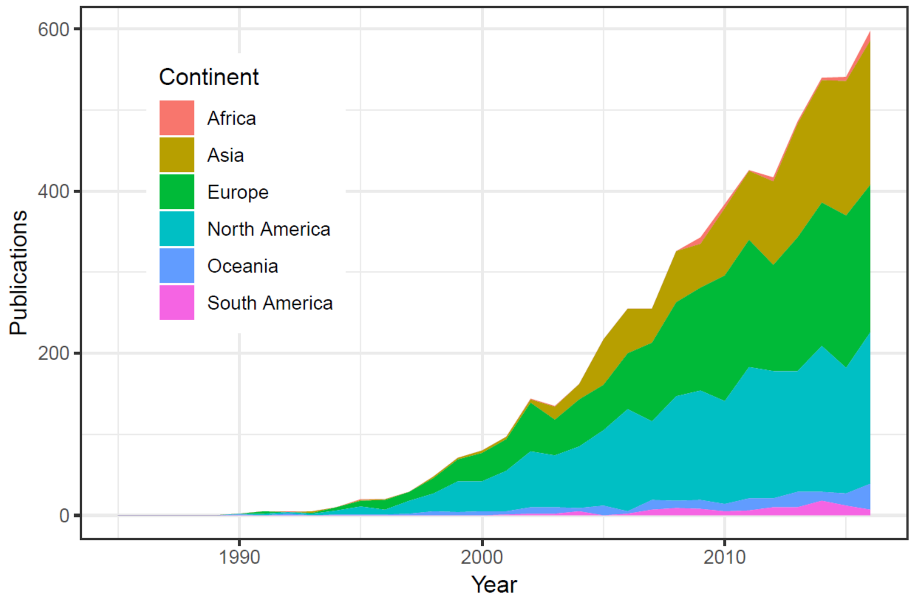

Figure 5: Number of annual publications on eddy covariance (EC) flux research conducted in different regions from 1985 to 2016. Data source: Dai et al. (2018).

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2.3 Land-use change related GHG research

Land-use change affects GHG fluxes (Han and Zhu, 2020; Tan et al., 2020; McDaniel et al., 2019; Shi et al., 2016; Kim and Kirschbaum, 2015) and occurs mainly in developing countries due to agricultural expansion following deforestation to meet increasing demand of food and bioenergy feed stocks (Harris et al., 2015; Lambin and Meyfroidt, 2011). Therefore, it is very important to better understand and quantify the effect of land-use change on GHG emissions in developing countries. Various global meta-analyses reporting the effect of land-use changes on soil organic carbon (Shi et al., 2016; Kim and Kirschbaum, 2015) and CH_4 and N_2O emission (Han and Zhu, 2020; Tan et al., 2020; McDaniel et al., 2019; van Lent et al., 2015) have found low amounts of data available from developing countries such as Africa and Asia compared to Europe and North America. 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. These results suggest that significant gaps exist in GHG emission research in developing countries (Kim et al., 2016 and 2013), particularly as most current land-use change globally occurs in these regions (Hurtt et al., 2011).

2.4 Agriculture and global change related GHG research

To accurately quantify agricultural GHG emissions and develop mitigation strategies of the emissions, it is critical to investigate GHG emissions in various agricultural land management types in different environment and regions. However, current agricultural GHG emission data are mainly from developed countries (e.g., North America, Central-West Europe, and East Asia) with only a few specific management types (e.g., intensively managed crop and grasslands). Only limited amounts of data have come from developing countries (Liu et al., 2018; Charles et al., 2017; Rezaei Rashti et al., 2015; Kim et al., 2013). Similarly, research on effects of global changes such as elevated CO_2 concentrations (Wang et al., 2018; Liu et al., 2018), warming (Zhou et al., 2016; Liu et al., 2015), precipitation variation driven drying or wetting (Congreves et al., 2018; Kim et al., 2012), fire (Ribeiro-Kumara et al., 2020; Aragão et al., 2018) and N addition/deposition (Deng et al., 2020; Li et al., 2018) on GHG emissions has been conducted mainly in a few developed countries. The resulting lack of data causes serious uncertainties in our understanding on the effects and hinders our progress to develop strategies for mitigating any negative impacts (IPCC, 2014).

2.5 Greenhouse gas data for modeling, machine learning and remote sensing

Computer models are frequently used to simulate biogeophysical and biogeochemical processes at multiple spatial scales, and are thus crucial in understanding the dynamics and sensitivities of these processes and predict ecosystem responses under different climate and management scenarios. 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

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widely used to investigate climate change and mitigation studies (e.g., Community Earth System Model- Kay et al., 2015; Hurrel et al., 2013). However, these models require careful parameterization and calibration (Hourdin et al., 2017; Giltrap et al., 2010) and due to a lack of observed C and GHG data in developing countries, likely have not been properly validated for and localized to the environment in developing countries (Pal et al., 2007).

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). However these algorithms require large observational dataset to be trained (Reichstein et al., 2019) that should, to ensure robust results, be representative of the entire modelled domain (Papale et al., 2015). When these observed variables are lacking, ML and RS algorithms, like all statistical models, are vulnerable to mis-prediction in particular in the under-represented conditions (De-Arteaga et al., 2018; Jin et al., 2015). The current lack of data on C and GHG in developing countries causes imbalanced input for ML and RS algorithms, since the majority of data (whether in a spatial or carbon-budget sense) come from regions in the developed world (De-Arteaga et al., 2018). Consequently, high uncertainties in the ML and RS products hinder further use for C and GHG research.

3 Major barriers for enhancing GHG research in developing countries

3.1 Knowledge and information aspect

Greenhouse gas research is a rapidly expanding scientific field and relevant knowledge and information have been rapidly increasing (Fig. 2 and 4). Traditionally, developing countries have had a weak capacity to stay updated with scientific knowledge and technical information. This is changing, as the combination of open source software, open access journals, open data initiatives, and web-based knowledge systems have made access to knowledge and information much easier than previously. For instance, the majority of new knowledge and information including GHG research is available through increasingly web-based electronic journal repositories. However, developing countries still have difficulties accessing them, since many still lack internet service (Ritchie, 2019); many also cannot afford subscription fees (Habib, 2011; Rose-Wiles, 2011), although the impact of this latter problem is lessening as science increasingly shifts to open-access publication models (Iyandemye and Thomas, 2019; Pinfield et al., 2014). Even open access cannot solve the problem of language, however, and the central role of English in the international science community inevitably puts researchers from non-English-speaking countries at a disadvantage.

3.2 Technical aspect

Greenhouse gas research often requires technical infrastructure such as advanced instruments, computers, software, electric power and 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 (Minasny et al., 2020). First, the role and involvement

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of local researchers can be limited in the research. In collaborative research projects, the Principal Investigators are in general from developed countries that economically support the projects and there is the risk that local researchers play limited roles in the scientific activities, due to lack of skills and experience and limited project duration that often prevent providing a proper training to local researchers (Minasny et al., 2020; Bockarie, 2019; Costello and Zumla, 2000). 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 GHG emissions research in South East 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. After the project funding the purchase and first installations and management is finished, it is often not possible to get the further required materials and supporting from external collaboration and the local researchers cannot carry on the research furthermore- the research is either suspended until a new project comes or completely abolished.

3.3 Socio-economic aspect

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 GHG dynamics and mitigation issues, and the importance of GHG research may not be well recognized. In addition, the costs for purchasing required instrument and technologies, hiring experienced and 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 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 GHG research in developing countries

4.1 Biomass and soil carbon pool and dynamics

To address or at least mitigate many of the problems described above, low-cost technology and participatory approaches have been adopted to investigate biomass and soil carbon pool and dynamics. Quantifying the biomass carbon 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 carbon 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 carbon pools, soil bulk density and soil organic carbon 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

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balance (Grossman and Reinsch, 2002). However, to accurately determine soil organic carbon 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 two different options to determine soil organic carbon contents with low cost. One is the Walkley-Black method (Walkley and Black, 1934), which determines soil organic carbon contents through organic matter oxidation by a potassium dichromate-sulfuric acid mixture and back titration of excess dichromate. Another is the loss-on-ignition method (Wang et al., 2013), which determines soil organic carbon contents through heating soil samples at high temperature to combust soil organic matter or carbonate and measuring weight losses.

These methods can produce reliable soil carbon content data (Gessesse and Khamzina, 2018; Apesteguia et al., 2018; Nóbrega et al., 2015). For instance, studies comparing the results of the CN analyzer, the loss-on-ignition and Walkley-Black methods have found that applying a correction factor to the loss-on-ignition or Walkley-Black method can increase the accuracy of the method analyzing soil carbon content (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). These results suggest that low-cost and low-technology methods can be applied for determining soil carbon contents.

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 periods and then decomposition quantified by the loss of weight over time (Djukic et al., 2018; Houben et al., 2018; Keuskamp et al., 2013). Studies using this approach have obtained scientifically acceptable quality of data on decomposition in different ecosystems and land-use types (Houben 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 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 has also been adopted in GHG research. Studies have utilized low-cost sensors to monitor atmospheric concentrations of CO_2 (Shusterman et al., 2018) and CH_4 (Riddick et al., 2020; Collier-Oxandale et al., 2018; Eugster et al., 2012) 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 Remote sensing

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). For instance, after Landsat data became free in 2008 the number of data downloads increased enormously (Zhu et al. 2019). The number of RS "products" or analysis ready data (ARD) are also increasing and they are usually open and free, which indicates end-users do not have to download and process raw images by themselves (Zhu, 2019; Qiu et al., 2018). These products include gross primary production (photosynthesis), land cover change, phenology, and fire (Yan and Roy, 2018; Pettorelli et al., 2017; Roy et al., 2005), which form important components in GHG research. This is a great benefit to developing countries where internet bandwidth and speed are not good to download the data, and computing power for processing the data is limited.

New RS instruments may even, in some cases, substitute for or obviate measurements that previously required local measurements. Greenhouse gas satellites such as GOSAT, OCO-2, OCO-3, and TanSat provide column CO_2 concentration information around the world (Eldering et al., 2019; Yang et al., 2019; Liang et al., 2017). Since they regularly monitor CO_2 column-averaged dry-air mole fraction (XCO_2) and are also open for public use, they can be another great resource for developing countries to study GHG magnitudes and dynamics in absence of precise high quality concentration measurements from tall towers. In addition, low-cost unmanned aerial vehicles equipped with digital cameras provide image data for estimating above ground biomass in forest (Li et al., 2019; Jayathunga et al., 2018; Mlambo et al., 2017).

4.5 Free open source software, data and computational resources

Free and open source 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) and are replacing commercial software like in case of R and Python shared under a GNU license (Hampton et al., 2015). For spatial data management using geographic information system (GIS), free and open source software such as QGIS, GRASS GIS, and SAGA GIS are widely used (Muenchow et al., 2019; Rocchini et al., 2017); there is accordingly less need for expensive commercial GIS software. The codes specific for GHG community 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). Open source software currently interoperates smoothly with new and heterogeneous data formats (e.g., Hierarchical Data Format (HDF), NetCDF, and JSON) and distributional data protocols (Rocchini et al., 2017; Lausch et al., 2015).

In addition, notebook interfaces such as Jupyter Notebooks and R Markdown help to share and develop in a collaborative way and using existing codes that can be run in a thin-client environment for highly-demanding computations; researchers implement their algorithms only with standard web browsers while calculations are done on remote servers. The Jupyter notebook based service 'Google Colab' 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). The current trend developing and adopting standardized and open source software is a great benefit to developing countries.

Cloud computing services are also becoming cheaper or free over time. It is already possible to download/process RS data via cloud computing service such as Google Earth Engine (Gorelik et al., 2017) and Microsoft Azure (Agarwal et al., 2011) which 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, which is a barrier in developing countries and even for many smaller institutions/individuals in developed ones. When heavy-duty computing is required, these companies have 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/).

Since stable electric power supply and network bandwidth are required for seamless cloud computing (Ritchie, 2019) cloud computing may not be an appropriate option in developing countries with poor electric power reliability and network

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services. For such environments, a container-based technology such as Docker (Kozhirbayev and Sinnott, 2017) can be an alternative option. A container may incorporate an interface to larger high performance computing facilities, or cloud computing platforms can be obtained once and then run on personal devices without having a network connection. Processing can be done later in the cloud without requiring complex synchronous operation. These open data and computing resources can thus be very useful for developing countries.

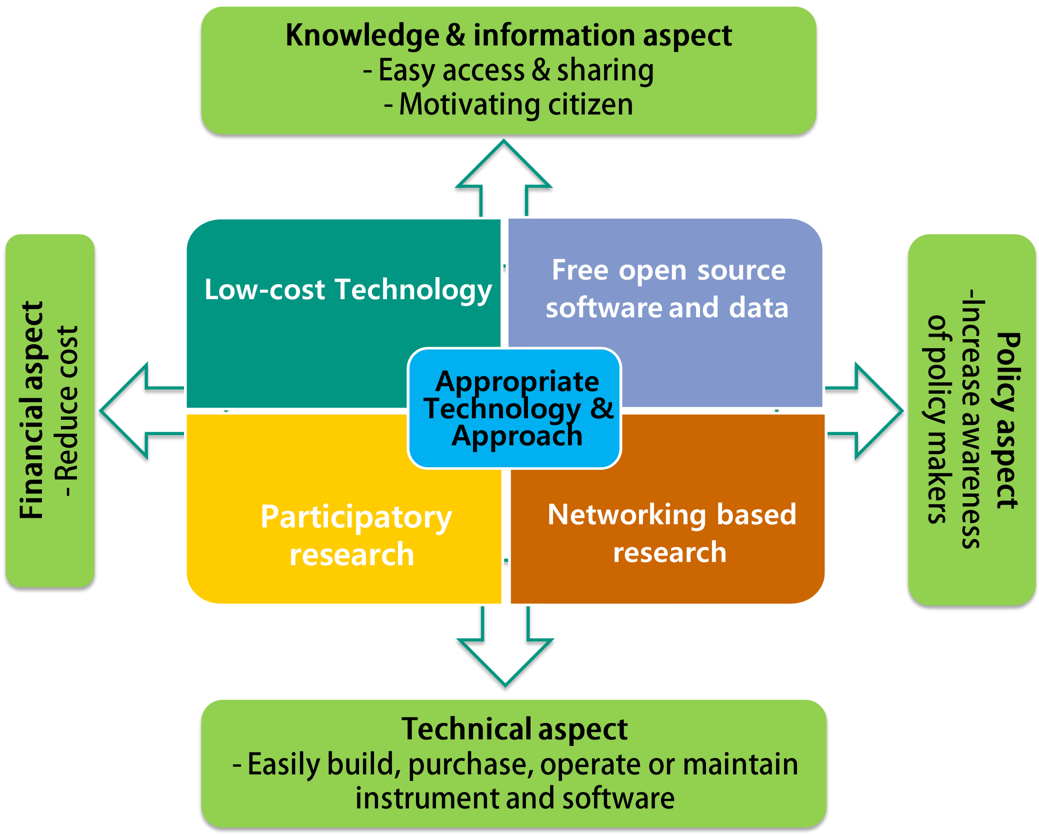

Figure 6: Major components of appropriate technology and approach (AT&A) and its benefits for enhancing greenhouse gas research in developing countries

5 Advantages and potential problems and solutions of adopting appropriate technology and approach (AT&A) for GHG research

Adopting AT&A in GHG research can have various advantages (Fig. 6). In knowledge and information aspect, it can stimulate obtaining data especially from the places where access was limited. It can also make it easy to share knowledge and

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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 and software 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 GHG research and its importance, and thus consider 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 instrument may have high uncertainties compared to advanced high quality instrument (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 or open source software 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 (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 protocols with as easy as possible applicability for planned activities and communication should be shared and understood among participating citizens.

Overall, for successfully adopting AT&A in 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 scheme presented in Fig. 7. To achieve the aim of the study with the certain level of uncertainty it could be possible to either use a high accuracy technology for a short-term campaign (green dot 1) or a low accuracy technology for a longer campaign accompanying with special efforts for quality control and validation (green dot 4 or 5). Taking this as a principle, a study adopting a low accuracy technology can reduce uncertainty by extending campaign periods and adding special efforts (move from orange dot 1 to green dot 3). There is also the possibility that increasing number of observation points (e.g., replicates, and sampling frequency) could lead to reducing uncertainty. On the other hand, with an increase of budget (from the orange dot 1) one can either decide to go for a higher accuracy technology (orange dot 2) or to ensure a longer period of campaign accompanying with special efforts (orange dot 3), which result in different levels of uncertainty. With increasing budget even more, the aim of the study can be achieved with various levels of uncertainty: i) a short campaign period with high accuracy (green dot 1), ii) a long campaign period with medium accuracy (green dot 2), and iii) a longer campaign period with low accuracy (green dot 3). These imply that adopting AT&A in GHG

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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. 7 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.

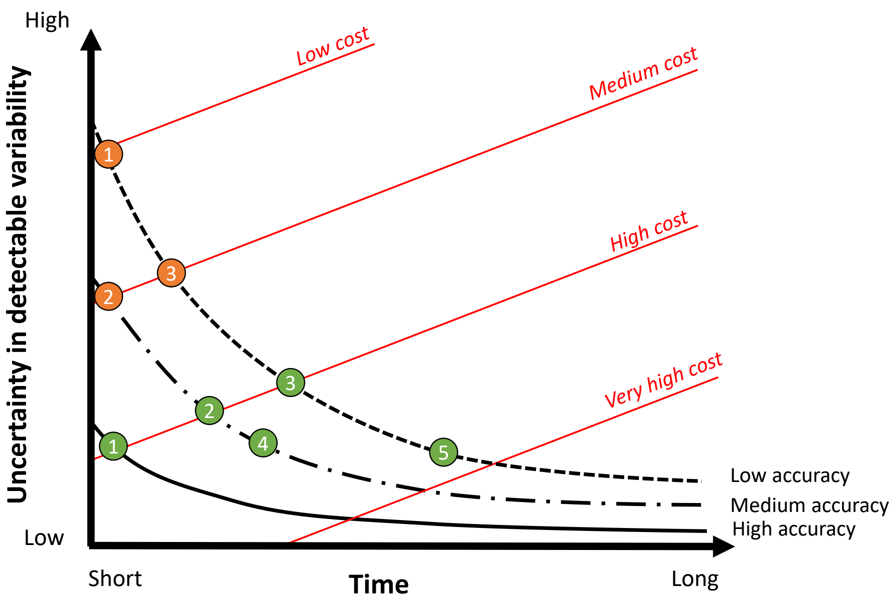

Fig. 7: A conceptual diagram showing the uncertainty of detectable variability as a function of greenhouse gas measurement accuracy, time, and cost. Adopted from Baldocchi et al. (2018). Red lines indicate different cost and black lines indicate different accuracy. The red and black lines are only theoretical. With a small budget (low-cost technology for a short period), we have a lot of uncertainty in what we can detect (orange 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 (orange 2) or ii) ensure a longer monitoring period (or more frequent sampling) for the low accuracy method (orange 3). Increasing even more, we have three options for the same budget: i) a short period with high accuracy (green 1), ii) a long period with medium accuracy (green 2), and iii) a longer period with low accuracy (green 3).

6 A strategy for enhancing development and adaptation of AT&A for GHG research in developing countries

For further development and adaptation of AT&A for GHG research in developing countries, we suggested the integration of three components: 1) recognizing importance of AT&A, 2) identifying and developing AT&A and 3) promoting AT&A for GHG research in developing countries.

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6.1 Recognizing the importance of AT&A for GHG research

A few GHG researches have already adopted AT&A including low-cost sensors and instrument, citizen science and network approach and their results have been well accepted by scientific communities. In terms of cost, feasibility and performance, GHG research adopted with AT&A can be suitable for developing countries. Therefore, we think that it is important to recognize that AT&A is necessary for GHG research of developing countries and it can contribute to filling critical gap in GHG research of developing countries. This recognition should stimulate new research and investment in the field in order to help the selection of the best options and the quantification of their limits. This includes the activity of users, in particular by modelers, that should test, contribute to develop and finally demonstrate the scientific role of these measurements.

6.2 Identifying and developing AT&A for GHG research

Integration of low-cost technology, free open source software and data, participatory research and networking based research approaches will be an ideal model for identifying and further developing AT&A for GHG research (Fig. 6).

1) Low-cost technology

Low-cost technology for GHG research would be various but it can include low-cost and less advanced instruments (e.g., sensor, monitor, data logger), analysis method and commercially available inexpensive materials. Potentials for further development and adaptation of low-cost technology may be large enough to motivate researchers not only in developed countries but also developing countries. Scientific instrument companies could get involved in this since the low-cost technologies once tested can be used to make the measurement networks denser in developed countries as well. The crucial validation against standard high quality and cost system is an aspect that should be considered in future projects and activities.

2) Free open source software and data

Recently various free open source software has been developed and rapidly adopted in research fields. Similarly, various data has been freely shared through scientific communities. Free open source software and data can contribute to enhancing GHG research in developing countries since they can reduce economic burden and increase accessibility of data and new information. The sharing and the access to codes developed by researchers is important to favorite the knowledge and use in developing countries. Therefore, it is important to stimulate the use of sharing platforms like GitHub for codes and open data policies like Creative Common for data.

3) Participatory research

Studies found that participatory research approach such as collaboration with ordinary citizens has a great potential to enhance GHG research in developing countries (DeVries et al., 2016; Venter et al., 2015; Theilade et al., 2015). Beside these technical aspects, through the approach, local actors take on expanded roles

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within the projects (ex. development of research questions and research methodology and data collection and analysis), can contribute to building local institutional capacity to implement carbon and climate change adaptation projects (Shames et al., 2016; Mapfumo et al., 2013). This can include also training of scientists from developing countries. On this there are already educational initiatives where students from developing countries can get access to fellowships to enroll in study programs abroad (e.g., the Erasmus Mundus initiative by the European Union)

4) Networking based research

A simple parameter measured in a place (e.g., CO_2 concentration, decomposition of organic matter) may not be useful to understand complexity of GHG dynamics. However, if the parameter can be measured in different places at the same time the potential of the data in term of contribution to scientific advance can be far beyond a simple parameter itself (Nickless et al., 2020; Morawska et al., 2018; Chandler et al., 2017; Keuskamp et al., 2013). The integration on multiple measurements can also fill the gap of each approach and also can create synergies. For instance, low cost and low technology can have certain uncertainties due to low accuracy and precision of instrument. The issue can be resolved by increasing sampling replication and frequency with spatial variability through participatory research and networking based research approaches (Riddick et al., 2020). This should encourage the development of large, possibly cross-countries initiatives and also to the direct collaboration among developing countries.

6.3 Promoting AT&A for GHG research

It is also necessary to make further efforts for promoting identified and developed AT&A for GHG research in developing countries. There are various ways to promote them efficiently. First, the most effective option for promoting AT&A will be to demonstrate their usefulness through applications in different field. 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). For bring active collaboration, initially, it is 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 GHG research and to motivate preparing next advanced stages under technical and economical constrains. 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), for example with the Internet of Things (IoT) concept.

Common collaboration projects between developed and developing countries are for these reasons crucial to answer all the needs, that should be carefully considered in the project preparation and design. In particular it is important to identify the roles of developing and developed countries in identifying, developing and utilizing AT&A and develop appropriate collaboration strategies for aiming training, development of scientific leadership and long-term sustainability of the activities after the end of the projects (the projects should incubate locally grown and independent projects continuing progress on AT&A).

7 Conclusions

While GHG research has adopted highly advanced technology and sophisticated data collection procedure some have adopted AT&A such as low-cost and low- technology instrument, open source software and data and participatory research and their results were well accepted by scientific communities. The major advantages of adopting AT&A in GHG research would be to reduce economic burden and technical constrains for conducting research and at the same time to motive ordinary citizen to 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. 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 GHG research in developing countries. For implementation of AT&A, it is first necessary to recognize importance of GHG research, the contribution of these lower quality stream of data and role of AT&A in developing countries. At the same time, further efforts are needed to identify or newly develop various AT&As for GHG research and promote them 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 to the transferability and sustainability of the activities would help to the development of a GHG local scientific community. In addition, the promotion of open data access is crucial to allow the dissemination and training needed for the future generation of sciences in the developing countries. This however doesn't 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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