

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 [highly specialized research technicians](#). Partly as a result, relatively little C and GHG research has been conducted in resource-constrained developing countries. At the same time, [these are often the same countries](#) and regions in which climate-change impacts will likely be strongest, and in which major science uncertainties are 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 have higher uncertainties; these can often be mitigated by carefully designing experiments, providing clear protocols for data collection, and monitoring and validating the quality of obtained data. For implementing this approach in developing countries, it is first necessary to recognize the scientific and moral importance of AT&A. At the same time, new AT&A techniques should be identified and further developed. All these processes should be promoted in collaboration with local researchers and through training local staff and encouraged for wide use and further innovation in developing countries.

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

44 capacities for mitigation and adaptation (Stell et al., 2021; López-Ballesteros et al., 2018; Ogle et al., 2014). Traditionally, this
45 has required high quality long-term or vast spatial scale (e.g., regional, or continental) data collected using advanced
46 instruments, significant computing power with complex and/or proprietary software, and skilled technicians—all expensive to
47 develop, implement, and maintain. Due to these requirements, many developing countries cannot conduct the necessary
48 research and they heavily rely on the international collaboration projects driven by developed countries (Minasny et al., 2020;
49 Vogetl et al., 2019). Even in the collaboration projects, the roles of researchers of developing countries are often limited due
50 to the technical constraints and the projects often fail to guarantee sustainability of research in the aspect of continuing and
51 developing further research by developing countries (Minasny et al., 2020; Bates et al., 2020; Bockarie, 2019; Vogetl et al.,
52 2019). These make it hard to fill the critical gaps in C and GHG research of developing countries (López-Ballesteros et al.,
53 2018; Kim et al., 2016; Xu and Shang, 2016). Consequently, the lack of available data hinder developing countries from
54 recognizing their sources or quantities of emissions, establishing national GHG inventories, and developing proper mitigation
55 strategies (Kim et al., 2016; IPCC, 2014). Therefore, it is critical to resolve the technical constraints on enhancing C and GHG
56 research in developing countries.

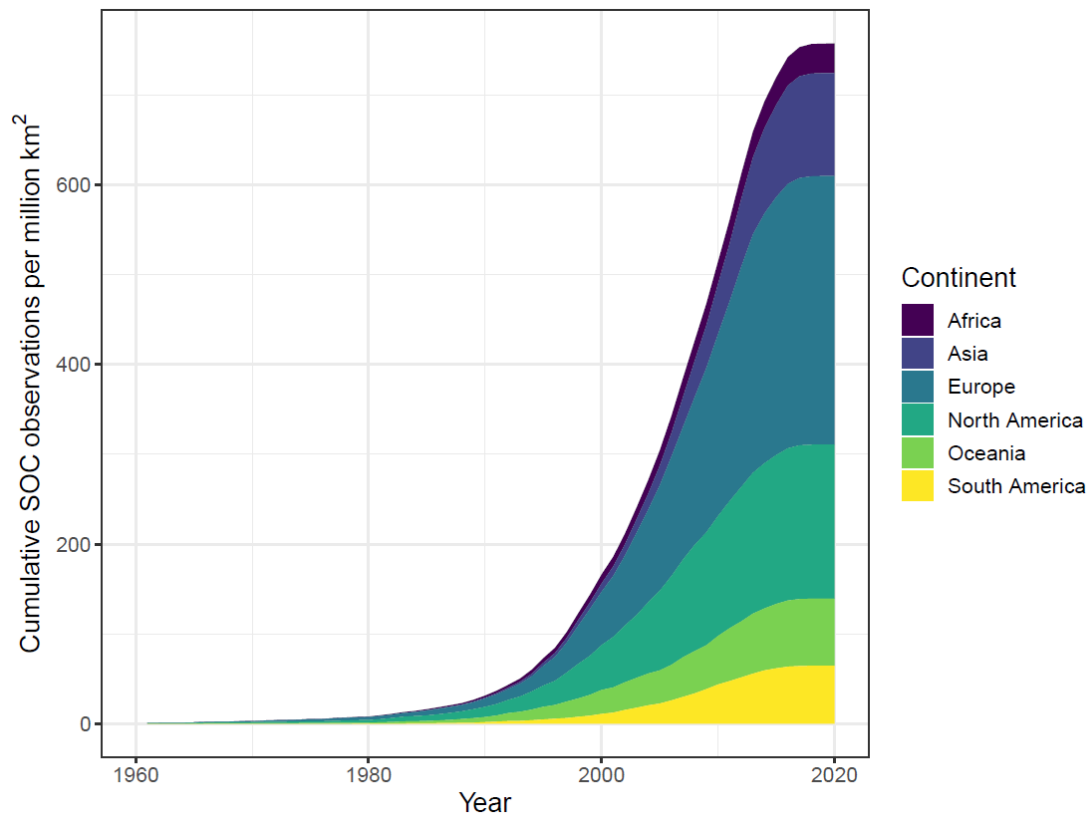
57 Recently, C and GHG research adopting “appropriate technology and approach” (AT&A, e.g., Murphy et al., 2009)
58 has been proposed or carried out. This uses low-cost and low-technology instruments, open source software and data, and
59 participatory approaches (Peltier, 2021; Gentemann et al., 2021;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

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

69 **2 Existing gaps in C and GHG research in developing countries**

70 Accurate quantification of biomass and soil C pools is important for understanding current status and monitoring
71 change of C budgets. For better quantification of C pools, it is critical to monitor chronosequences and permanent plots in
72 different ecosystems and land-use types for long-term periods (Smith et al., 2020; Hubau et al., 2020; Willcock et al., 2016).
73 However, due to technical and economic constraints, accurate C pools and long-term monitoring data are lacking in developing
74 countries (Beillouin et al., 2021; Li et al., 2020; Xu et al., 2019; Shi et al., 2016; Kim and Kirschbaum, 2015). For instance,
75 most developing countries (84 out of 99 countries in Romijn et al., 2015) in the critical tropical zone reported their forest C
76 pool using default values (Tier 1) provided in the IPCC guidelines (IPCC, 2006), rather than country-specific data (Tier 2) or
77 higher-level methods such as repeated measurements in permanent plots (Tier 3) (Requena Suarez et al., 2019; Vargas et al.,
78 2017; Ochieng et al., 2016; Romijn et al., 2015). [Data on the effect of land management, land-use changes, and climate change
80 on soil organic carbon \(SOC\) were very low in developing countries such as Africa \(4%\), South America \(9%\), and Asia
81 \(15%\) compared to North America \(23%\) and Europe \(39%\) \(Beillouin et al., 2021\) \(Fig. 1\).](#)

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84 **Figure 1: Number of published observations on soil organic carbon (SOC) changes driven by land management, land-**
 85 **use changes, and climate change (cumulative observations per million km²) in each region. An observation indicates a**
 86 **set of measurements conducted in a site during a certain period. Data source: Beillouin et al. (2021)**

87

88 As of 2000, soil carbon dioxide (CO₂) flux measurements had been conducted at 1815 sites in 42 countries; this had
 89 increased to 6625 sites in 75 countries by 2016 (Jian et al., 2021) (Fig. 2). Similarly, methane (CH₄) and nitrous oxide (N₂O)
 90 flux measurements have increased worldwide (Fig. 1). Still, the majority of measurements occurred in only a few countries
 91 representing only a small part of the global soil-vegetation-climate space (Feng et al., 2020; Tan et al., 2020; Ganesan et al.,
 92 2020; National Academies of Sciences, Engineering, and Medicine, 2018; Oertel et al., 2016). For example, developed
 93 countries (those in the top one-third globally in per-capita gross domestic product) along with China have provided over 60 %
 94 of the global GHG flux measurements (Fig. 2). In terms of continental scale, measurements in Europe, North America and
 95 Asia cover around 90 % of the global observations, while Africa and South America remain critically underrepresented (Stell
 96 et al., 2021; Jian et al., 2021; Gatica et al. 2020; Épule, 2015; Kim et al., 2013) compared to their importance in global GHG
 97 budgets (Fig. 3). For instance, a global meta-analysis on the effect of land-use change on CH₄ and N₂O emission (McDaniel
 98 et al., 2019) reported that among 62 studies included in the study, **Africa and Asia comprised only 5% and 11%, respectively,**
 99 **while studies carried out in Australia/New Zealand, Europe, North America, and South America were 15%, 21%, 33%, and**
 100 **15%, respectively.**

101 Eddy covariance (EC) measurements are even more technically challenging and expensive to make than those of soil
 102 GHG flux, and thus severely lacking in developing countries (Burba, 2019). By 2015, only 23% of ecoregions globally had
 103 been sampled by EC measurements and Africa, Oceania (excluding Australia) and South America were particularly poorly
 104 sampled (Hill et al., 2017) (Fig. 4). While there were more than 459 active EC stations globally in 2016 (Baldocchi, 2014) a
 105 total of only 11 and 41 EC stations were recording flux data across Africa (López-Ballesteros et al., 2018) and South America
 106 (Villareal and Vargas, 2021), respectively in 2018. At the country level, wealthy countries make EC measurements in a higher
 107 proportion of their ecoregions and with more replication (Hill et al., 2017). In addition, the few measurements collected in

108 Africa and South America are in general not shared in the community (Villareal and Vargas, 2021; Bond-Lamberty, 2018),
109 highlighting also a problem of data sharing and integration with the other scientific communities globally.

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

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122 **3 Major barriers for enhancing C and GHG research in developing countries**

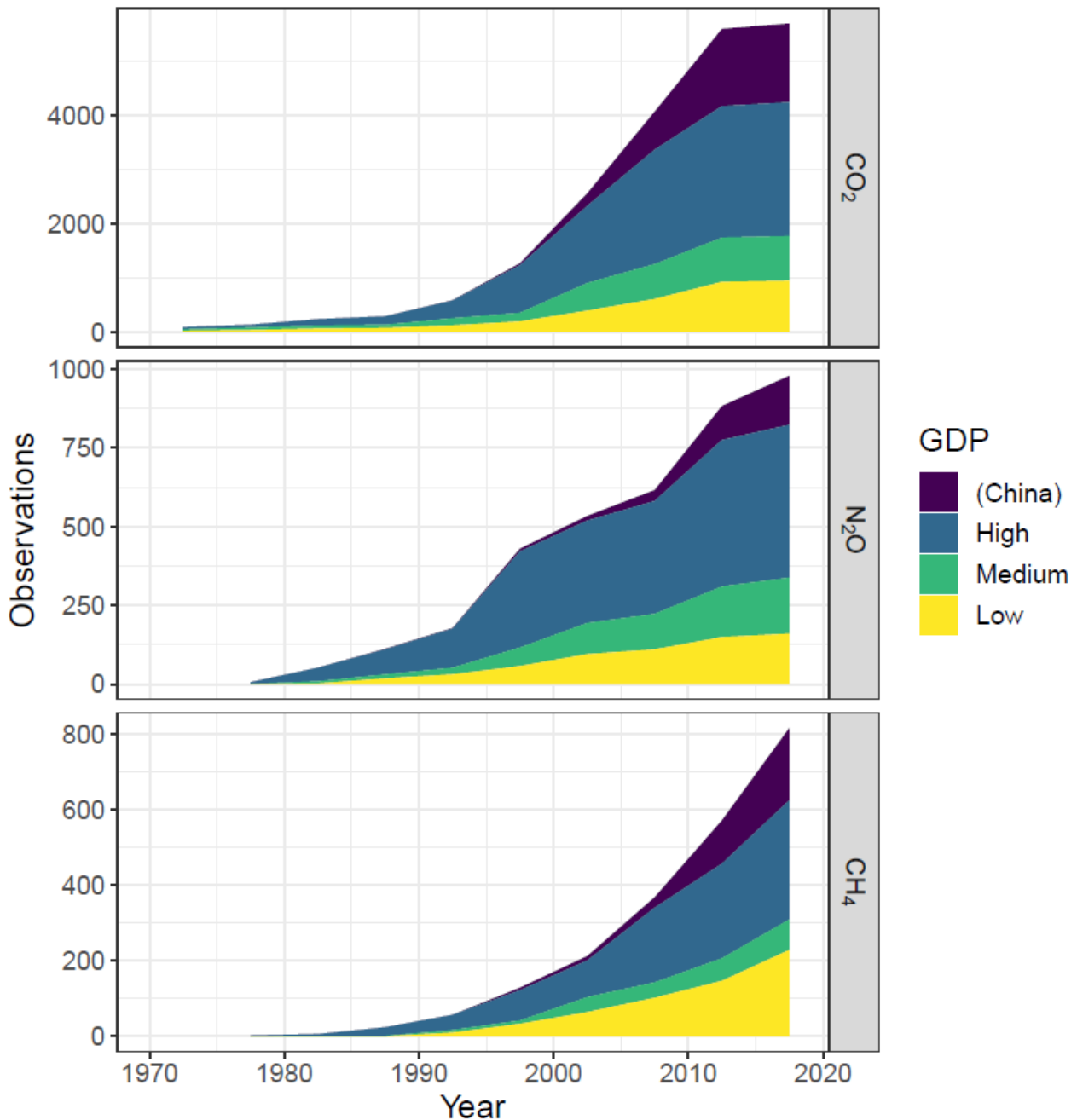
123 **3.1 Technical expertise and infrastructure**

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

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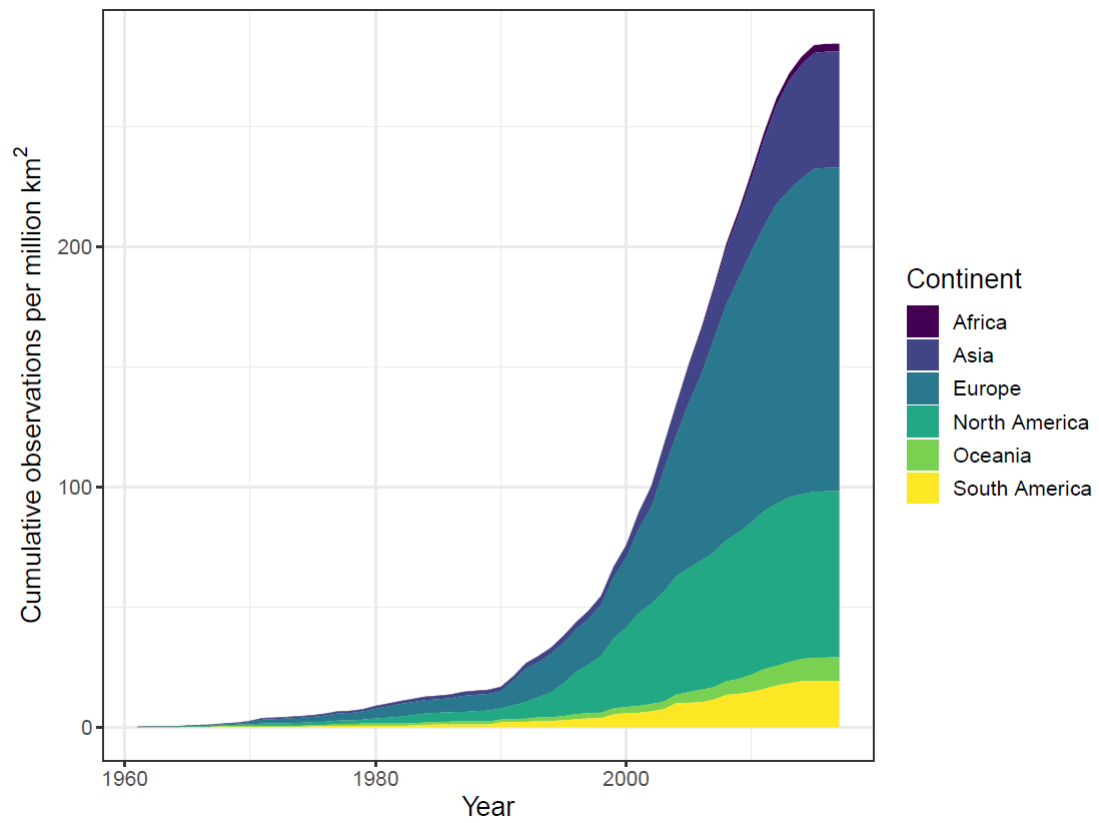


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145 **Figure 2: Cumulative observations of annual soil-to-atmosphere flux of greenhouse gases (CO₂, N₂O, and CH₄) over**
 146 **time. An observation indicates a set of measurements that resulted in an annual flux estimate. Colors show fraction of**
 147 **observations made in countries with high (top third), medium, and low (bottom third) per-capita gross domestic**
 148 **product (GDP, listed by World Bank) in the year of measurement. The People’s Republic of China is broken out**
 149 **separately, as this country is a unique combination of large numbers of observations, high GDP, and large populations**
 150 **and thus low per-capita GDP. Note differing y-axis scales in each panel. Data source: CO₂ – Jian et al. (2021); N₂O –**
 151 **Global N₂O Database (https://ecoapps.nrel.colostate.edu/global_n2o/); CH₄ – Al-Haj et al. (2020), Han et al. (2020), Tan**
 152 **et al. (2020), Gatica et al. (2020), and Feng et al. (2020).**

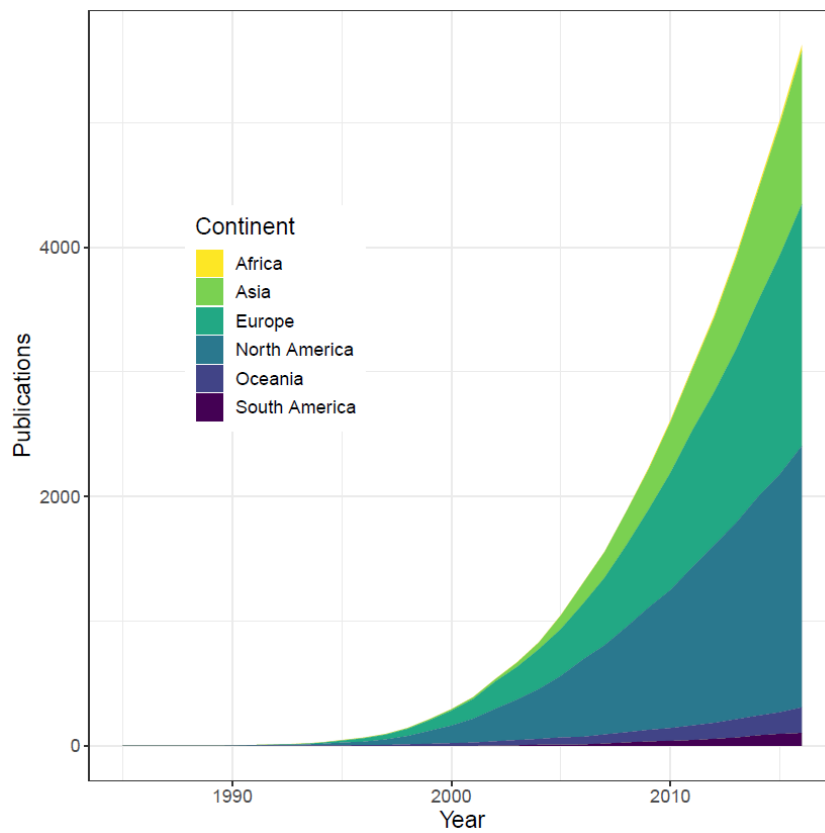
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Figure 3: Number of published soil carbon dioxide flux observations (cumulative observations per million km²) in each region. An observation indicates a set of measurements conducted in a site during a certain period. Data source: Jian et al. (2021)



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

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164 3.2 Knowledge and information access

165 Access to scientific knowledge and information has become much easier than in the past due to the rapidly increasing
166 availability and use of open source software and data, electronic journal repositories, and on-line education and training courses
167 (Lowndes et al., 2017; Hampton et al., 2015; Lausch et al., 2015). However, developing countries still have difficulties
168 accessing them, since many still lack internet service (Ritchie, 2019; King et al., 2018; Mtebe and Raisamo, 2014); many also
169 cannot afford journal and course subscription fees (Habib, 2011; Rose-Wiles, 2011), although the impact of this latter problem
170 is lessening as science increasingly shifts to open-access publication and open education and training models (Iyandemye and
171 Thomas, 2019; Pinfield et al., 2014). In addition, there is also a problem of utilizing shared knowledge and information since
172 the availability of free resources is often unknown or the potential and target audience is not well clarified (Luo et al., 2020;
173 King et al., 2018; Mtebe and Raisamo, 2014).

174

175 3.3 Socio-economic conditions

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

184

185 4 Appropriate technology and approach (AT&A) applicable for C and GHG research

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

192

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

199 - **Soil carbon quantification:** Soil C pools, soil bulk density and SOC contents are important and should be
200 accurately determined using collected soil samples. While soil bulk density can be measured with locally
201 available instruments (Grossman and Reinsch, 2002), alternative approaches with respect to the standard can
202 be adopted to produce reliable SOC content data (Table 1, Gessesse and Khamzina, 2018; Apestequia et al.,
203 2018; Jha et al., 2014). A low-cost, field-portable reflectometer (a hardware cost of US\$350) provided
204 precise and accurate soil C estimates in central and southern Malawi (Ewing et al., 2021).

- 205 - **Organic matter decomposition:** Commercially available tea bags were adopted to quantify organic matter
 206 decomposition rate in various ecosystems and land-use types; they tend to be highly standardized,
 207 universally available, and cheap, and thus well-suited for global analyses of this type. Bags were buried in
 208 soils for a certain period and then decomposition quantified by the loss of weight over time (Marley et al.,
 209 2019; Djukic et al., 2018).
- 210 - **Canopy photosynthesis phenology and parameters:** Light emitting diodes (LEDs) are a very cheap light
 211 source, but by using their inverse mode, LEDs can be used as spectrally selective light detectors (Mims,
 212 1992). Using this principle, two or four channels of LED sensors in red and near-infrared bands have been
 213 used to monitor canopy photosynthesis, phenology, and leaf area index in grasslands (Ryu et al., 2010) and
 214 in tall deciduous and evergreen forests (Ryu et al., 2014) and the using the blue spectral band to assess
 215 fraction of canopy-absorbed light, and green leaf area index in a rice paddy (Kim et al., 2019). Digital camera
 216 images also offer key canopy structural information such as phenology (Richardson et al., 2018), gap fraction
 217 (Macfarlane et al., 2014), leaf area index and clumping index (Ryu et al., 2012), and leaf angle distribution
 218 (Ryu et al., 2010). Cameras' charge-coupled devices (CCD) work as a simple, three bands spectroradiometer
 219 (Hwang et al., 2016) that can be cheap (20-30\$ for the one used in the smartphones) and if integrated with
 220 multiple LED spectral sensors can be very useful to monitor crop status, particularly important in developing
 221 countries given their limited resources in water and fertilizers.
- 222 - **Atmospheric concentrations of CO₂ and CH₄:** Studies have used low-cost sensors to monitor atmospheric
 223 concentrations of CO₂ (Peltier, 2021; Shusterman et al., 2018) and CH₄ (Peltier, 2021; Riddick et al., 2020).
- 224 - **Land-Atmosphere CO₂ and CH₄ fluxes:** The same low cost sensors have been used to measure CO₂ fluxes
 225 with chambers (Bastviken et al., 2020 and 2015; Brändle and Kunert, 2019). Cheaper technologies have
 226 been also tested in EC instrumentation e.g. using middle-cost CO₂ and H₂O analyzers (15-25% the price,
 227 Hill et al. 2017) obtaining similar performance. Beside CO₂ and H₂O analyzers, studies found positive signs
 228 that some instruments for EC systems such as datalogger, pressure, temperature, and relative humidity
 229 sensors (Markwitz and Siebicke, 2019; Hill et al., 2017; Dias et al., 2007) can be substituted for low-cost
 230 instruments.
- 231 - **Remote sensing data:** The remote sensing community is increasingly moving towards open access RS data,
 232 with free and open satellite data such as Landsat, MODIS, AVHRR, and Copernicus Sentinels constellation
 233 and it provides various benefits to scientific communities, especially the ones in developing countries (Zhu
 234 et al., 2019; Rocchini et al., 2017). Often products for direct use in GHG research such gross primary
 235 production (photosynthesis), land cover change, phenology, and wildfire maps are also provided, removing
 236 the need for raw data processing (Yan and Roy, 2018; Pettorelli et al., 2017; Roy et al., 2005). Greenhouse
 237 gas satellites such as GOSAT, OCO-2, OCO-3, and TanSat that provide column CO₂ concentration
 238 information are an important source of information in undersampled areas (Eldering et al., 2019; Yang et
 239 al., 2019). In terms of in situ measurements there is also the tendency, at least in the developed countries, to
 240 share the data openly under licenses like the CC-BY (Creative Common). Examples are European Research
 241 Infrastructures under the ENVRI umbrella (<https://envri.eu/>) such ICOS, ACRTIS, LTER or the American
 242 NEON and AmeriFlux (e.g., Papale 2020).
- 243 - **Open and free codes, software and tools:** Statistical software and visualization packages developed and
 244 adopted in scientific communities (Lowndes et al., 2017; Lausch et al., 2015) like R and Python shared under
 245 a GNU license (Hampton et al., 2015). GIS open source software such as QGIS, GRASS GIS, and SAGA
 246 GIS (Muenchow et al., 2019; Rocchini et al., 2017). GHG community software 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 Computing tools:** Interfaces such as Jupyter Notebooks and R Markdown simplified the sharing and common development of processing routines that can be run in a thin-client environment for highly-demanding computations like in the “Google Colab” tool (Ramires-Reyez et al., 2019; Bastin et al., 2019). More general cloud computing services such as Google Earth Engine (Gorelik et al., 2017) and Microsoft Azure (Agarwal et al., 2011; Ryu et al., 2019) are becoming cheaper over time (Gentemann et al. 2021) or made available via academic pricing and grant programs (e.g., Microsoft AI4Earth <https://www.microsoft.com/en-us/ai/ai-for-earth-grants>; Google for Nonprofits <https://www.google.com/nonprofits/>). 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.

Table 1. Summary of appropriate technology and approach (AT&A) applicable for carbon and greenhouse gas research

Parameter to monitor	AT&A	How AT&A works?	References
Biomass carbon quantification	Participatory research/citizen science	Biomass carbon pools can be accurately quantified by trained local communities and through citizen science initiatives	Evans et al., 2018; Zhao et al., 2016; DeVries et al., 2016; Venter et al., 2015; Theilade et al., 2015
Soil carbon quantification	Walkley-Black method	Substituting an elemental analyzer; applying a correction factors to estimate accurate value	Walkley and Black, 1934
	Loss-on-ignition method		Wang et al., 2013
	Near- and mid-infrared reflectance method		Ewing et al., 2021; Tang et al., 2020; Ng et al., 2020
Organic matter decomposition	Tea bag method	Commercially available tea bags are adopted to quantify organic matter decomposition rate	Marley et al., 2019; Djukic et al., 2018; Keuskamp et al., 2013
Canopy photosynthesis, phenology and structure	Light emitting diodes (LEDs) sensors	LEDs can be used as spectrally selective light detectors in blue, red and NIR to estimate photosynthesis dynamic, phenology and LAI	Kim et al., 2019; Ryu et al., 2014; Ryu et al., 2010
	Digital camera images	A cheap digital camera works as a simple, three bands spectroradiometer that can be used to estimate phenology, LAI and canopy parameters (gap fraction, clumping index, leaf angle distribution etc.)	Richardson et al., 2018; Macfarlane et al., 2014; Ryu et al., 2012; Hwang et al., 2016
Atmospheric concentrations of CO ₂ and CH ₄	Low-cost sensors	Use of low cost gas concentration sensors and correction factors	Peltier, 2021; Shusterman et al., 2018; Riddick et al., 2020; Collier-Oxandale et al., 2018
Land-Atmosphere CO ₂ and CH ₄ fluxes	Chambers with low cost sensors	Substituting an advanced CO ₂ analyzer/logger and gas sampler	Bastviken et al., 2020 & 2015; Carbone et al., 2019; Martinsen et al., 2018
	Middle cost analyser and low cost sensors for EC	Use middle-cost gas analyzers and low cost datalogger and meteo sensors in Eddy Covariance systems	Markwitz and Siebicke, 2019; Hill et al., 2017; Dias et al., 2007
Remote sensing and in situ data	Free and open spectral satellite data and products	Landsat, MODIS, AVHRR, Copernicus Sentinels constellation	Zhu et al., 2019; Rocchini et al., 2017

	Free and open greenhouse gas satellite data	GOSAT, OCO-2, OCO-3, TanSat	Eldering et al., 2019; Yang et al., 2019; Liang et al., 2017
	In-situ measurements	Measurement networks data such ICOS, ACTRIS, LTER, NEON, AmeriFlux, FLUXNET	https://envri.eu ; Papale 2020.
Open and free codes, software and tools	Statistical analysis and data management	Programing languages like R and Python	Lowndes et al., 2017; Hampton et al., 2015; Lausch et al., 2015
	GIS	QGIS, GRASS GIS, SAGA GIS	Muenchow et al., 2019; Rocchini et al., 2017
	Specific software	GHG software like EddyPro, ONEFlux tool	https://www.licor.com/env/support/EddyPro/software.html ; Pastorello et al., 2020
Processing and Computing tools	Processing routines and tools	Jupyter Notebooks, R Markdown; share and develop routines in a collaborative way run in a thin-client environment	Ramires-Reyez et al., 2019; Bastin et al., 2019
	Cloud computing services	Google Earth Engine, Microsoft Azure; allow also the integration of multiple satellite RS datasets	Ryu et al., 2019; Gorelik et al., 2017; Agarwal et al., 2011

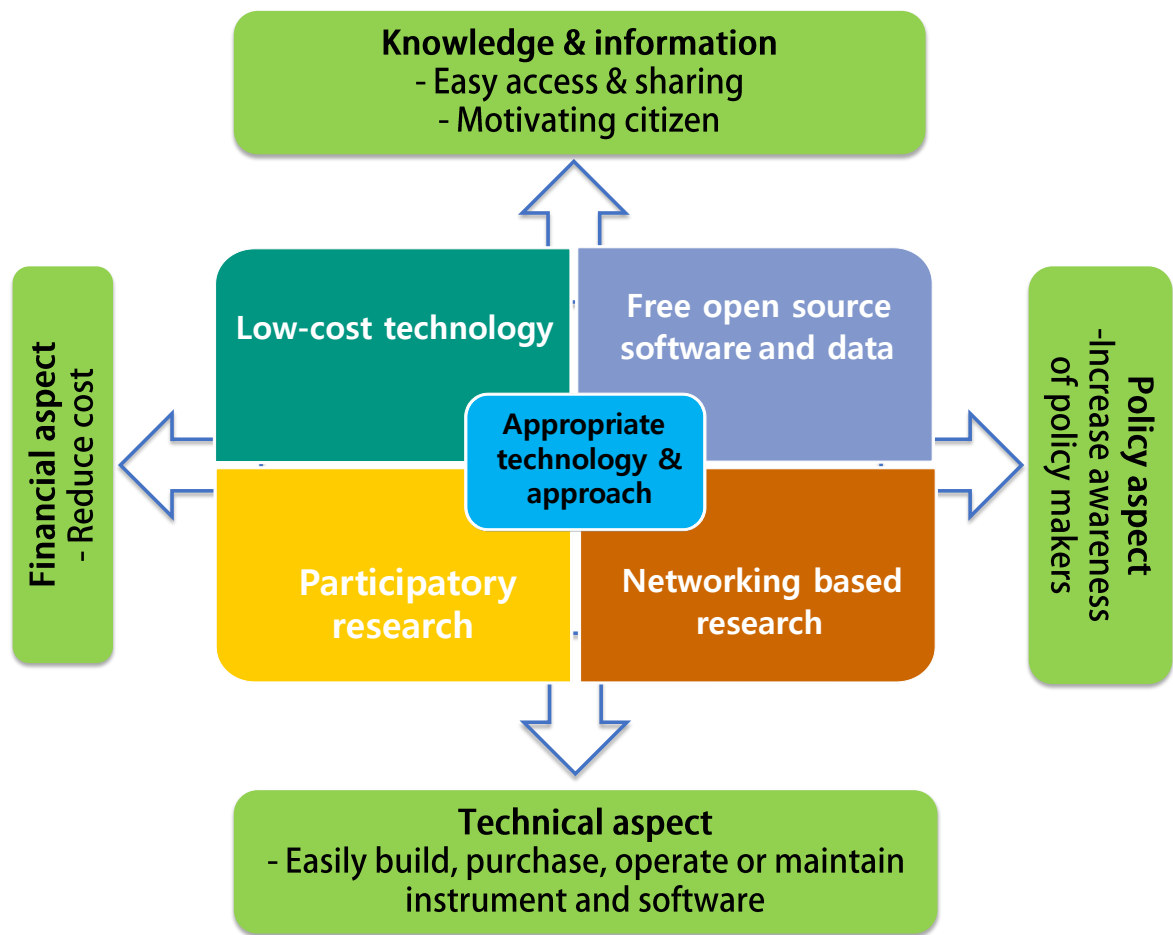
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265 **5 Advantages and potential problems and solutions of adopting AT&A for C and GHG research**

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

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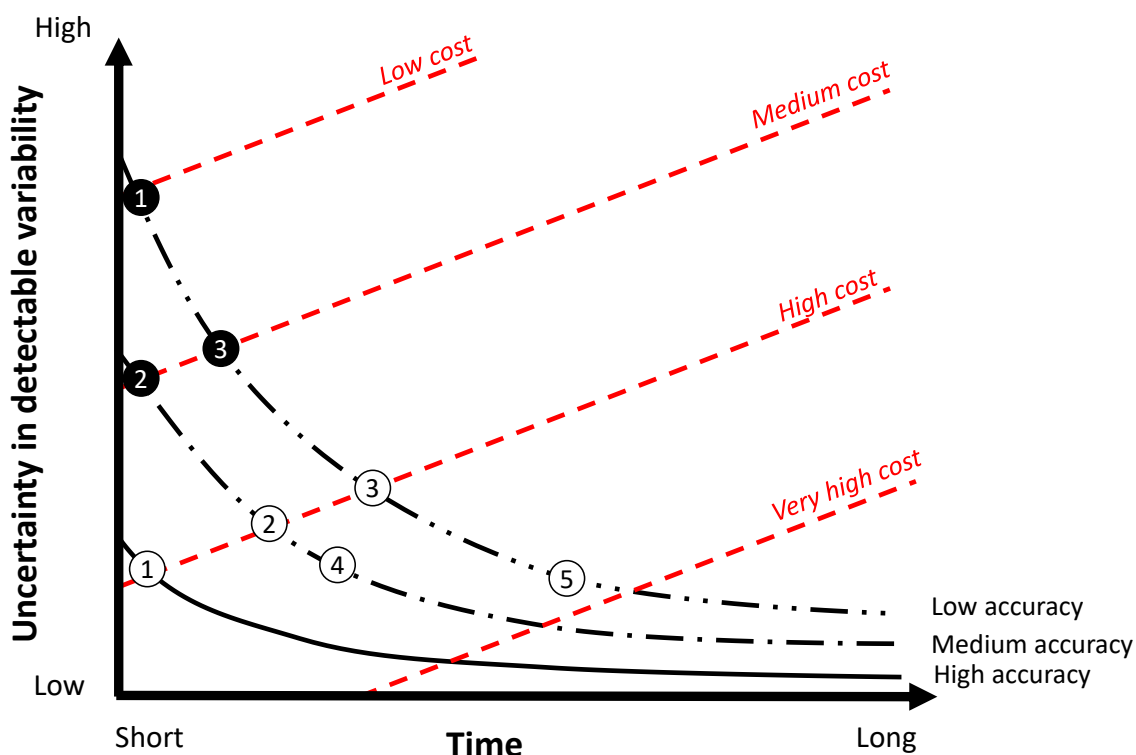
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279 **Figure 5: Major components of appropriate technology and approach (AT&A) and its benefits for enhancing carbon**
280 **and greenhouse gas research in developing countries**
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282 It is important to note that there are challenges and potential problems in adopting AT&A. First, data obtained from
283 low-cost and low-technology instrument have generally higher uncertainties compared to advanced high-quality instrument
284 (Peltier, 2021; Arzoumanian et al., 2019; Marley et al., 2019; Castell et al., 2017). Second, research adopting a participatory
285 approach can have a bias in the data collection process, due to participants' lack of understanding about the task or their own
286 self-interest (Tiago et al., 2017; Kallimanis et al., 2017). Third, data obtained from research adopting networking based
287 approaches may not be useful if data collection plans are not well prepared or planned activities are not well managed. **Fourth,**
288 **AT&A may mitigate, but does not solve, the problem of technical capacity because there are cases where it does not exist yet**
289 **a real cheaper or low-tech alternative to some of the methods.** Special efforts are required to prevent such problems. First, if
290 low-cost and low-technology instruments are used, it is necessary to monitor the quality of obtained data and validate them
291 through cross-checking with advanced instrument and software (Peltier, 2021; Riddick et al., 2020; Arzoumanian et al., 2019;
292 Rai et al., 2017). Second, to compensate for the lower accuracy and precision of low-cost and low-technology instruments, it
293 is necessary to carefully design experimental set-up (e.g., sampling periods and replication, replication, and network sampling)
294 and conduct statistical analyses to reduce error and bias (Riddick et al., 2020; Yoo et al., 2020; Bird et al., 2014). Third, well-
295 prepared and easy to use protocols should be shared and understood among participating citizens.

296 Overall, for successfully adopting AT&A in C and GHG research, it is needed to carefully evaluate the best way to
297 achieve the aim of the study and an acceptable level of uncertainty depending on available resources including technology,
298 time, and budget. This compromise solution can be explained in a theoretical scheme presented in Fig. 6. To achieve the aim
299 of the study with the certain level of uncertainty (Y axes) it could be possible to either use a high accuracy technology for a

300 short-term campaign (white dot 1) or a low accuracy technology for a longer campaign accompanying with special efforts for
 301 quality control and validation (white dot 4 or 5). Taking this as a principle, a study adopting a low accuracy technology (black
 302 dot 1) can reduce uncertainty by extending campaign periods (so moving along the dashed line increasing the length of the
 303 measurements period on X axes). Also increasing the number of observation points (e.g., replicates, and sampling frequency)
 304 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
 305 available. Starting from the lowest cost (black 1) with an increase of budget one can either decide to go for a higher accuracy
 306 technology (black dot 2) or to ensure a longer period of campaign (black dot 3). **With an even higher available budget**, one can
 307 opt for different combinations of quality of the measurements and length of the monitoring (white dots 1, 2 and 3). These
 308 imply that adopting AT&A in C and GHG research with a desired level of uncertainty can be achieved through adopting
 309 different levels of accuracy, durations of campaign, and budget. The plot in Fig. 6 is of course purely illustrative. The shape
 310 of the different curves and cost lines and the effect of the multiplication of observation points are function of the scientific
 311 questions, performances of the instruments and their costs, spatial heterogeneity of the quantity measured, and their interannual
 312 variability.

313



314

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

325

326 **6 Enhancing development and adaptation of AT&A for C and GHG research in developing countries**

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

330

331 **6.1 Identifying and developing AT&A for C and GHG research**

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

345

346 **6.2 Promoting AT&A for C and GHG research**

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

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

370 7 Conclusions

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

390

391 Acknowledgements

392 B.B.-L. was supported by the DOE Office of Biological and Environmental Research (BER), as part of BER's
 393 Terrestrial Ecosystem Science Program (grant number: DE-AC05-76RL01830). D.P. thanks the support of the ENVRI-FAIR
 394 H2020 project (GA 820852). D.-G.K. was supported by the European Commission through the project 'Supporting EU-African
 395 Cooperation on Research Infrastructures for Food Security and Greenhouse Gas Observations'(SEACRIFOG; project ID
 396 730995) and International Atomic Energy Agency (IAEA) Coordinated Research Project (CRP D1.50.20) 'Developing
 397 Climate Smart Agricultural Practices for Mitigation of Greenhouse Gases'. Authors appreciated Christopher Dorich for
 398 providing *Global N₂O Database* and Zhao Bin and Shengqi Dai for providing data for Fig.3.

399

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