# 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

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

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

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

## 2 Existing gaps in C and GHG research in developing countries

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

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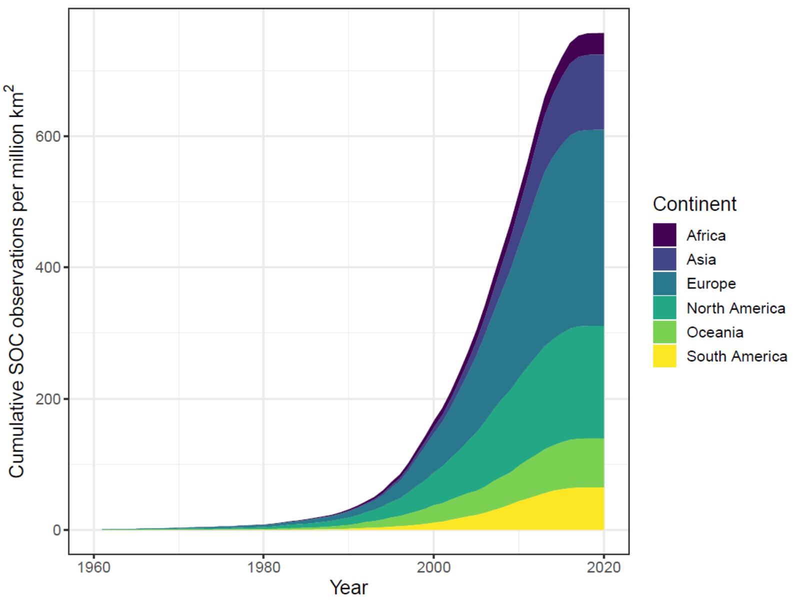

**Figure 1: Number of published observations on soil organic carbon (SOC) changes driven by land management, land-use changes, and climate change (cumulative observations per million km$^2$) in each region. An observation indicates a set of measurements conducted in a site during a certain period. Data source: Beillouin et al. (2021)**

As of 2000, soil carbon dioxide ($CO_2$) flux measurements had been conducted at 1815 sites in 42 countries; this had increased to 6625 sites in 75 countries by 2016 (Jian et al., 2021) (Fig. 2). Similarly, methane ($CH_4$) and nitrous oxide ($N_2O$) flux measurements have increased worldwide (Fig. 1). Still, the majority of measurements occurred in only a few countries representing only a small part of the global soil-vegetation-climate space (Feng et al., 2020; Tan et al., 2020; Ganesan et al., 2020; National Academies of Sciences, Engineering, and Medicine, 2018; Oertel et al., 2016). For example, developed countries (those in the top one-third globally in per-capita gross domestic product) along with China have provided over 60 % of the global GHG flux measurements (Fig. 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 (Stell et al., 2021; Jian et al., 2021; Gatica et al. 2020; Épule, 2015; Kim et al., 2013) compared to their importance in global GHG budgets (Fig. 3). For instance, a global meta-analysis on the effect of land-use change on $CH_4$ and $N_2O$ emission (McDaniel et al., 2019) reported that among 62 studies included in the study, Africa and Asia comprised only 5% and 11%, respectively, while studies carried out in Australia/New Zealand, Europe, North America, and South America were 15%, 21%, 33%, and 15%, respectively.

Eddy covariance (EC) measurements are even more technically challenging and expensive to make than those of soil GHG flux, and thus severely lacking in developing countries (Burba, 2019). By 2015, only 23% of ecoregions globally had been sampled by EC measurements and Africa, Oceania (excluding Australia) and South America were particularly poorly sampled (Hill et al., 2017) (Fig. 4). While there were more than 459 active EC stations globally in 2016 (Baldocchi, 2014) a total of only 11 and 41 EC stations were recording flux data across Africa (López-Ballesteros et al., 2018) and South America (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

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

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

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

### 3.1 Technical expertise and infrastructure

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

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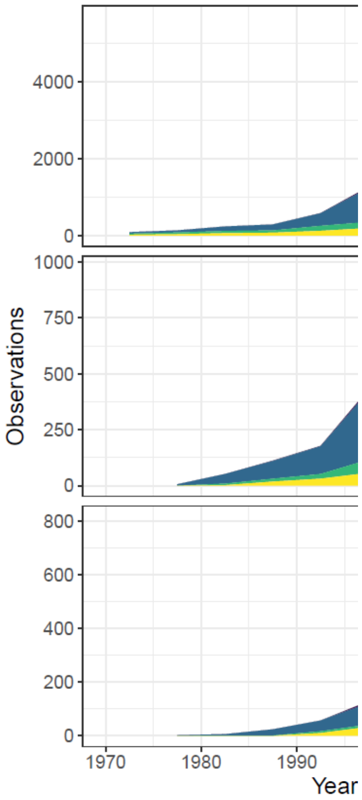

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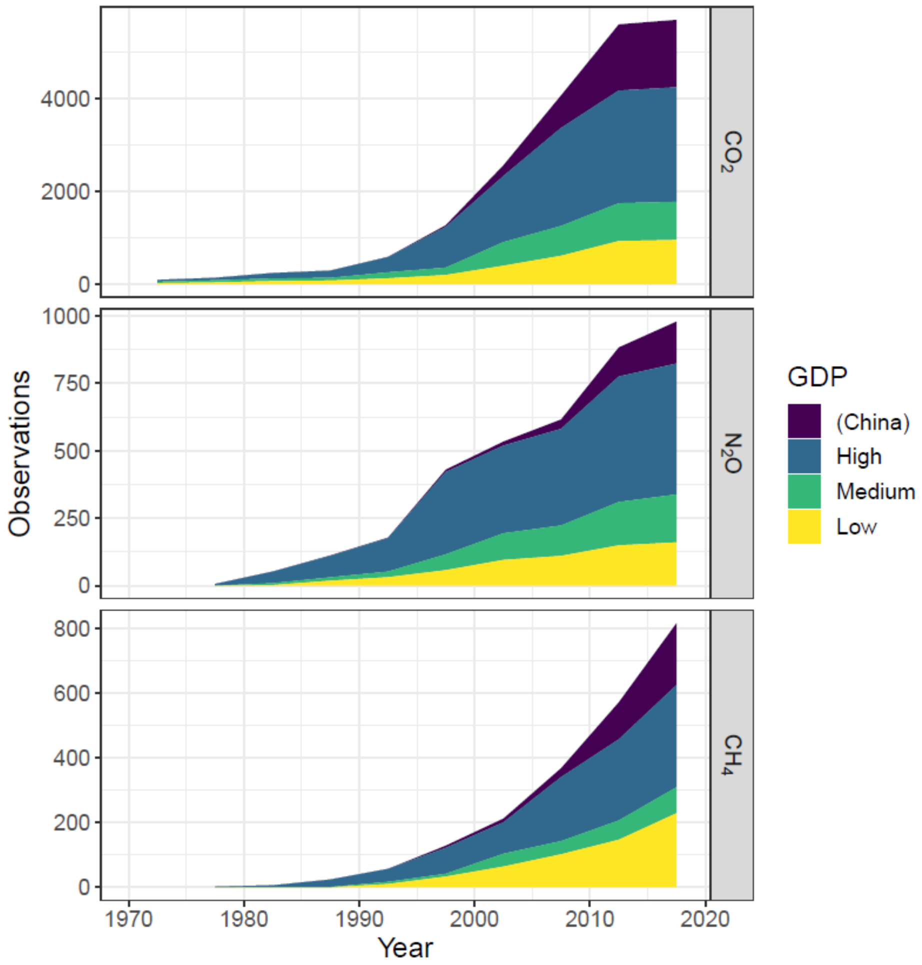

**Figure 2: Cumulative observations of annual soil-to-atmosphere flux of greenhouse gases ($CO_2$, $N_2O$, and $CH_4$) over time. An observation indicates a set of measurements that resulted in an annual flux estimate. Colors show fraction of observations made in countries with high (top third), medium, 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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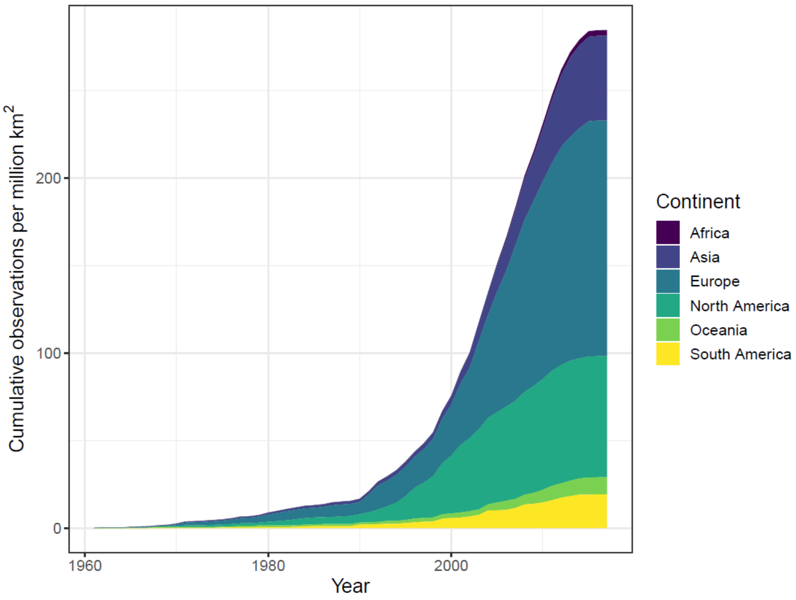


**Figure 3: Number of published soil carbon dioxide flux observations (cumulative observations per million km$^2$) in each region. An observation indicates a set of measurements conducted in a site during a certain period. Data source: Jian et al. (2021)**

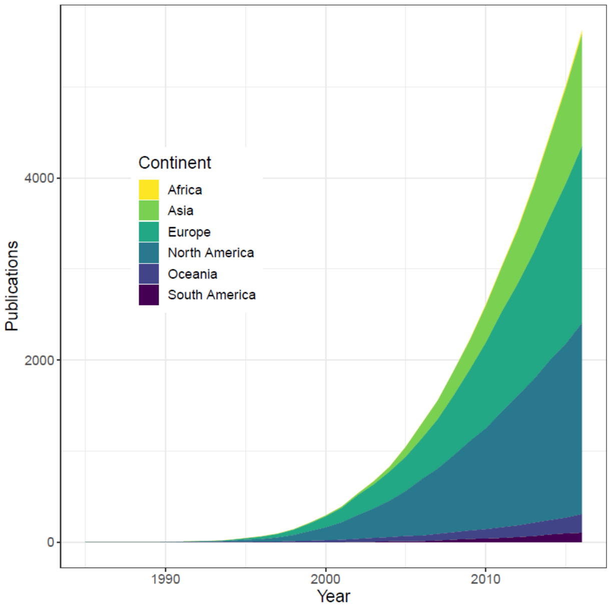
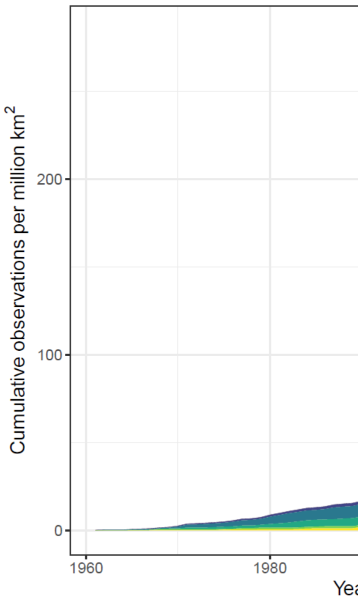


**Figure 4: Cumulative numbers of publications on eddy covariance (EC) flux research conducted in different regions from 1985 to 2016. Data source: Dai et al. (2018).**



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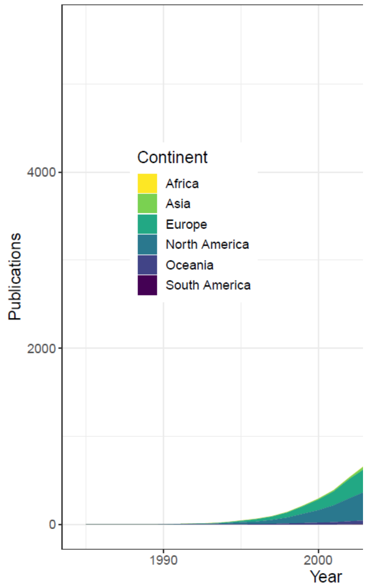

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### 3.2 Knowledge and information access

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

### 3.3 Socio-economic conditions

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

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

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

- ***Biomass carbon quantification:*** This is a critical, time-consuming and laborious task, since individual trees should be counted and measured on site, where accessibility is often very limited and harsh environments hinder progress. Trained local communities can accurately quantify it (Evans et al., 2018; Zhao et al., 2016) also through 'participatory research' or 'citizen science' initiatives (Heigl et al., 2019; Irwin, 2018; School 2 School Initiative- https://tahmo.org/school-2-school-initiative/) that have a great potential to enhance C research in developing countries (DeVries et al., 2016; Venter et al., 2015).
- ***Soil carbon quantification***: Soil C pools, soil bulk density and SOC contents are important and should be accurately determined using collected soil samples. While soil bulk density can be measured with locally available instruments (Grossman and Reinsch, 2002), alternative approaches with respect to the standard can be adopted to produce reliable SOC content data (Table 1, Gessesse and Khamzina, 2018; Apesteguia et al., 2018; Jha et al., 2014). A low-cost, field-portable reflectometer (a hardware cost of US$350) provided precise and accurate soil C estimates in central and southern Malawi (Ewing et al., 2021).

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- ***Organic matter decomposition***: Commercially available tea bags were adopted to quantify organic matter decomposition rate in various ecosystems and land-use types; they tend to be highly standardized, universally available, and cheap, and thus well-suited for global analyses of this type. Bags were buried in soils for a certain period and then decomposition quantified by the loss of weight over time (Marley et al., 2019; Djukic et al., 2018).
- ***Canopy photosynthesis phenology and parameters***: Light emitting diodes (LEDs) are a very cheap light source, but by using their inverse mode, LEDs can be used as spectrally selective light detectors (Mims, 1992). Using this principle, two or four channels of LED sensors in red and near-infrared bands have been used to monitor canopy photosynthesis, phenology, and leaf area index in grasslands (Ryu et al., 2010) and in tall deciduous and evergreen forests (Ryu et al., 2014) and the using the blue spectral band to assess fraction of canopy-absorbed light, and green leaf area index in a rice paddy (Kim et al., 2019). Digital camera images also offer key canopy structural information such as phenology (Richardson et al., 2018), gap fraction (Macfarlane et al., 2014), leaf area index and clumping index (Ryu et al., 2012), and leaf angle distribution (Ryu et al., 2010). Cameras' charge-coupled devices (CCD) work as a simple, three bands spectroradiometer (Hwang et al., 2016) that can be cheap (20-30$ for the one used in the smartphones) and if integrated with multiple LED spectral sensors can be very useful to monitor crop status, particularly important in developing countries given their limited resources in water and fertilizers.
- ***Atmospheric concentrations of $CO_2$ and $CH_4$***: Studies have used low-cost sensors to monitor atmospheric concentrations of $CO_2$ (Peltier, 2021; Shusterman et al., 2018) and $CH_4$ (Peltier, 2021; Riddick et al., 2020).
- ***Land-Atmosphere $CO_2$ and $CH_4$ fluxes***: The same low cost sensors have been used to measure $CO_2$ fluxes with chambers (Bastviken et al., 2020 and 2015; Brändle and Kunert, 2019). Cheaper technologies have been also tested in EC instrumentation e.g. using middle-cost $CO_2$ and $H_2O$ analyzers (15-25% the price, Hill et al. 2017) obtaining similar performance. Beside $CO_2$ and $H_2O$ analyzers, studies found positive signs that some instruments for EC systems such as datalogger, pressure, temperature, and relative humidity sensors (Markwitz and Siebicke, 2019; Hill et al., 2017; Dias et al., 2007) can be substituted for low-cost instruments.
- ***Remote sensing data***: The remote sensing community is increasingly moving towards open access RS data, with free and open satellite data such as Landsat, MODIS, AVHRR, and Copernicus Sentinels constellation and it provides various benefits to scientific communities, especially the ones in developing countries (Zhu et al., 2019; Rocchini et al., 2017). Often products for direct use in GHG research such gross primary production (photosynthesis), land cover change, phenology, and wildfire maps are also provided, removing the need for raw data processing (Yan and Roy, 2018; Pettorelli et al., 2017; Roy et al., 2005). Greenhouse gas satellites such as GOSAT, OCO-2, OCO-3, and TanSat that provide column $CO_2$ concentration information are an important source of information in undersampled areas (Eldering et al., 2019; Yang et al., 2019). In terms of in situ measurements there is also the tendency, at least in the developed countries, to share the data openly under licenses like the CC-BY (Creative Common). Examples are European Research Infrastructures under the ENVRI umbrella (https://envri.eu/) such ICOS, ACRTIS, LTER or the American NEON and AmeriFlux (e.g., Papale 2020).
- ***Open and free codes, software and tools***: Statistical software and visualization packages developed and adopted in scientific communities (Lowndes et al., 2017; Lausch et al., 2015) like R and Python shared under a GNU license (Hampton et al., 2015). GIS open source software such as QGIS, GRASS GIS, and SAGA GIS (Muenchow et al., 2019; Rocchini et al., 2017). GHG community software shared openly like in case

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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, ret 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 |

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|  |  |  |  |
|---|---|---|---|
|  | 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 |

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

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

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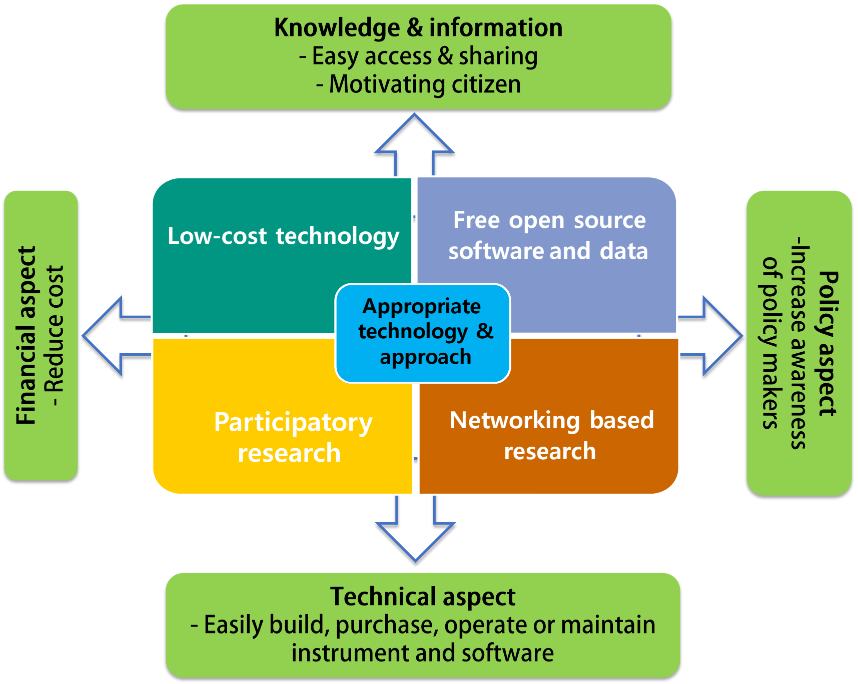

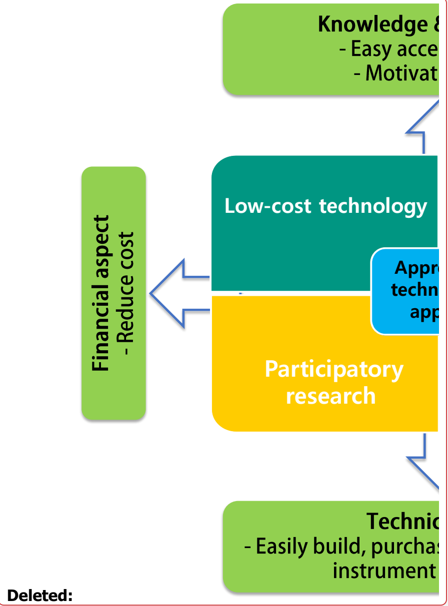
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**Figure 5: Major components of appropriate technology and approach (AT&A) and its benefits for enhancing carbon and greenhouse gas research in developing countries**

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

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

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

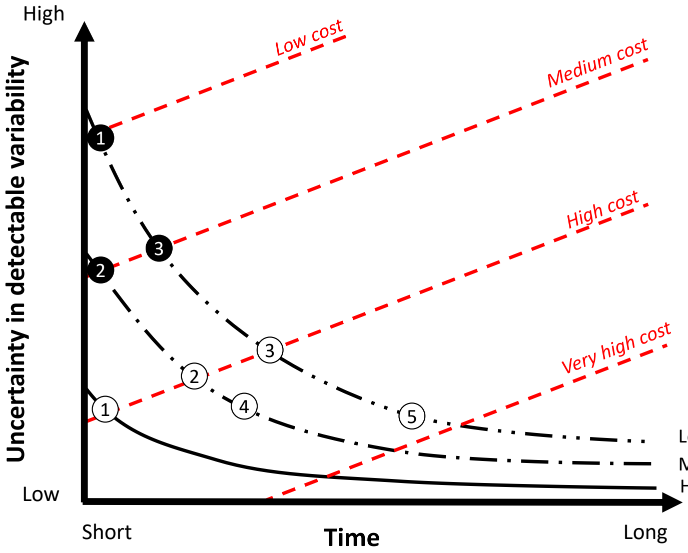

**Fig. 6: A conceptual diagram showing the uncertainty of detectable variability as a function of greenhouse gas measurement accuracy, time, and cost. Adopted from Baldocchi et al. (2018). Dashed red lines indicate different cost and black lines indicate different accuracy. The red and black lines are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

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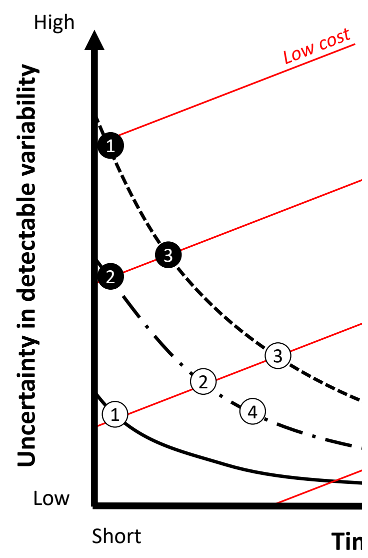

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## 6 Enhancing development and adaptation of AT&A for C and GHG research in developing countries

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

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

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

### 6.2 Promoting AT&A for C and GHG research

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

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

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## 7 Conclusions

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

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## References

Agarwal, D., Cheah, Y.-W., Fay, D., Fay, J., Guo, D., Hey, T., Humphrey, M., Jackson, K., Li, J., and Poulain, C.: Data-intensive science: The Terapixel and MODISAzure projects, Int. J. High Perform. Comput. Appl., 25, 304-316, 2011.

Al-Haj, A. N., and Fulweiler, R. W.: A synthesis of methane emissions from shallow vegetated coastal ecosystems, Global Change Biol., 26, 2988-3005, https://doi.org/10.1111/gcb.15046, 2020.

Apesteguia, M., Plante, A. F., and Virto, I.: Methods assessment for organic and inorganic carbon quantification in calcareous soils of the Mediterranean region, Geoderma Reg., 12, 39-48, 2018.

Arzoumanian, E., Vogel, F. R., Bastos, A., Gaynullin, B., Laurent, O., Ramonet, M., and Ciais, P.: Characterization of a commercial lower-cost medium-precision non-dispersive infrared sensor for atmospheric $CO_2$ monitoring in urban areas, Atmos. Meas. Tech., 12, 2665-2677, 2019.

Atickem, A., Stenseth, N. C., Fashing, P. J., Nguyen, N., Chapman, C. A., Bekele, A., Mekonnen, A., Omeja, P. A., and Kalbitzer, U.: Build science in Africa. Nature, 2019.

Bai, E., Li, S., Xu, W., Li, W., Dai, W., and Jiang, P.: A meta-analysis of experimental warming effects on terrestrial nitrogen pools and dynamics, New Phytol., 199, 441-451, 2013.

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Baldocchi, D.: Measuring fluxes of trace gases and energy between ecosystems and the atmosphere–the state and future of the eddy covariance method, Global Change Biol., 20, 3600-3609, 2014.

Bastin, J.-F., Clark, E., Elliott, T., Hart, S., van den Hoogen, J., Hordijk, I., Ma, H., Majumder, S., Manoli, G., and Maschler, J.: Understanding climate change from a global analysis of city analogues, PLOS One, 14, 2019.

Bastviken, D., Nygren, J., Schenk, J., Parellada Massana, R., and Duc, N. T.: Technical note: Facilitating the use of low-cost methane ($CH_4$) sensors in flux chambers – calibration, data processing, and an open-source make-it-yourself logger, Biogeosci., 17, 3659-3667, 2020.

Bastviken, D., Sundgren, I., Natchimuthu, S., Reyier, H., and Gålfalk, M.: Technical Note: Cost-efficient approaches to measure carbon dioxide ($CO_2$) fluxes and concentrations in terrestrial and aquatic environments using mini loggers, Biogeosci., 12, 3849-3859, 2015.

Bates, I., Chabala, L. M., Murray Lark, R., MacDonald, A., Mapfumo, P., Mtambanengwe, F., Nalivata, P. C., Owen, R., Phiri, E., and Pulford, J.: Letter to the Editor: Response to Global soil science research collaboration in the 21st century: Time to end helicopter research by Minasny et al, Geoderma, 378, 114559, https://doi.org/10.1016/j.geoderma.2020.114559, 2020.

Beillouin, D., Cardinael, R., Berre, D., Boyer, A., Corbeels, M., Fallot, A., Feder, F., and Demenois, J.: A global overview of studies about land management, land-use change, and climate change effects on soil organic carbon, Global Change Biol., https://doi.org/10.1111/gcb.15998, 2021.

Berman, E. S., Fladeland, M., Liem, J., Kolyer, R., and Gupta, M.: Greenhouse gas analyzer for measurements of carbon dioxide, methane, and water vapor aboard an unmanned aerial vehicle, Sens. Actuator B-Chem., 169, 128-135, 2012.

Bird, T. J., Bates, A. E., Lefcheck, J. S., Hill, N. A., Thomson, R. J., Edgar, G. J., Stuart-Smith, R. D., Wotherspoon, S., Krkosek, M., and Stuart-Smith, J. F.: Statistical solutions for error and bias in global citizen science datasets, Biol. Conserv., 173, 144-154, 2014.

Bockarie, M.J.: How a partnership is closing the door on “parachute” research in Africa. The Conversation, https://theconversation.com/how-apartnership-is-closing-the-door-on-parachute-research-in-africa-102217, 2019.

Bond-Lamberty, B.: Data sharing and scientific impact in eddy covariance research, J. Geophys. Res. Biogeosci., 123, 1440-1443, 2018.

Bouwman, A. F., Boumans, L. J. M., and Batjes, N. H.: Emissions of $N_2O$ and NO from fertilized fields: summary of available measurement data, Glob. Biogeochem. Cyc., 16, 2001GB001811, 2002.

Bouwman, A. F.: Direct emission of nitrous oxide from agricultural soils, Nutr. Cycl. Agroecosyst., 46, 53-70, 1996.

Brändle, J., and Kunert, N.: A new automated stem $CO_2$ efflux chamber based on industrial ultra-low-cost sensors, Tree Phys., tpz104, 2019.

Burba, G.: Illustrative maps of past and present Eddy Covariance measurement locations: I. early update. https://doi.org/10.13140/RG.2.2.25992.67844, 2019

Carbone, M. S., Seyednasrollah, B., Rademacher, T. T., Basler, D., Le Moine, J. M., Beals, S., Beasley, J., Greene, A., Kelroy, J., and Richardson, A. D.: Flux Puppy–An open-source software application and portable system design for low-cost manual measurements of $CO_2$ and $H_2O$ fluxes, Agric. For. Met., 274, 1-6, 2019.

Castell, N., Dauge, F. R., Schneider, P., Vogt, M., Lerner, U., Fishbain, B., Broday, D., and Bartonova, A.: Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates?, Environ. Int., 99, 293-302, 2017.

Charles, A., Rochette, P., Whalen, J. K., Angers, D. A., Chantigny, M. H., and Bertrand, N.: Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis, Agric. Ecosys. Environ., 236, 88-98, 2017.

Choi, C. Q.: Seven ways scientists handle technology challenges in resource-poor settings, Nature, 569, 147-149, 2019.

Collier-Oxandale, A., Casey, J. G., Piedrahita, R., Ortega, J., Halliday, H., Johnston, J., and Hannigan, M. P.: Assessing a low-cost methane sensor quantification system for use in complex rural and urban environments, Atmos. Meas. Tech., 11, 3569-3594, 2018.

Cooper, C. B., Dickinson, J., Phillips, T., and Bonney, R.: Citizen science as a tool for conservation in residential ecosystems, Ecol. Soc., 12, 11, 2007.

Cooper, C. B., Shirk, J., and Zuckerberg, B.: The invisible prevalence of citizen science in global research: migratory birds and climate change, PLOS One, 9, e106508, 2014.

Costello, A., and Zumla, A.: Moving to research partnerships in developing countries, BMJ, 321, 827-829, https://doi.org/10.1136/bmj.321.7264.827, 2000.

Dai, S. Q., Li, H., Xiong, J., Ma, J., Guo, H. Q., Xiao, X., and Zhao, B.: Assessing the extent and impact of online data sharing in eddy covariance flux research, J. Geophys. Res. Biogeosci., 123, 129-137, 2018.

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De-Arteaga, M., Herlands, W., Neill, D. B., and Dubrawski, A.: Machine learning for the developing world, ACM Trans Inf. Syst., 9, 1-14, 2018.

DeVries, B., Pratihast, A. K., Verbesselt, J., Kooistra, L., and Herold, M.: Characterizing forest change using community-based monitoring data and Landsat time series, PLOS One, 11, e0147121, 2016.

Dias, N. L., Duarte, H. F., Maggiotto, S. R., and Grodzki, L.: An attenuated eddy covariance method for latent heat flux measurements, Wat. Resour. Res., 43, 2007.

Djukic, I., Kepfer-Rojas, S., Schmidt, I. K., Larsen, K. S., Beier, C., Berg, B., Verheyen, K., Caliman, A., Paquette, A., and Gutiérrez-Girón, A.: Early stage litter decomposition across biomes, Sci. Tot. Environ., 628, 1369-1394, 2018.

Eldering, A., Taylor, T. E., O'Dell, C. W., and Pavlick, R.: The OCO-3 mission: measurement objectives and expected performance based on 1 year of simulated data, Atmos. Meas. Tech., 12, 2341-2370, 2019.

Epule, T. E.: A new compendium of soil respiration data for Africa, Chall., 6, 88-97, 2015.

Evans, K., Guariguata, M. R., and Brancalion, P. H.: Participatory monitoring to connect local and global priorities for forest restoration, Biol. Conserv., 32, 525-534, 2018.

Ewing, P. M., TerAvest, D., Tu, X., and Snapp, S. S.: Accessible, affordable, fine-scale estimates of soil carbon for sustainable management in sub-Saharan Africa, Soil Sci. Soc. Am. J., https://doi.org/10.1002/saj1002.20263, 2021.

Feng, H., Guo, J., Han, M., Wang, W., Peng, C., Jin, J., Song, X., and Yu, S.: A review of the mechanisms and controlling factors of methane dynamics in forest ecosystems, For. Ecol. Managm., 455, 117702, https://doi.org/10.1016/j.foreco.2019.117702, 2020.

Ganesan, A. L., Schwietzke, S., Poulter, B., Arnold, T., Lan, X., Rigby, M., Vogel, F. R., van der Werf, G. R., Janssens-Maenhout, G., and Boesch, H.: Advancing scientific understanding of the global methane budget in support of the Paris Agreement, Glob. Biogeochem. Cyc., 2020.

Gatica, G., Fernández, M. E., Juliarena, M. P., and Gyenge, J.: Environmental and anthropogenic drivers of soil methane fluxes in forests: Global patterns and among-biomes differences, Global Change Biol., 26, 6604-6615, https://doi.org/10.1111/gcb.15331, 2020.

Gentemann, C. L., Holdgraf, C., Abernathey, R., Crichton, D., Colliander, J., Kearns, E. J., Panda, Y., and Signell, R. P.: Science Storms the Cloud, AGU Advances, 2, e2020AV000354, https://doi.org/10.1029/2020AV000354, 2021.

Geoghegan, H., Dyke, A., Pateman, R., West, S., and Everett, G.: Understanding motivations for citizen science. Final report on behalf of UKEOF, University of Reading, Stockholm Environment Institute (University of York) and University of the West of England. http://www.ukeof.org.uk/resources/citizen-science-resources/MotivationsforCSREPORTFINALMay2016.pdf, 2016

Gessesse, T. A., and Khamzina, A.: How reliable is the Walkley-Black method for analyzing carbon-poor, semi-arid soils in Ethiopia?, J. Arid Environ., 153, 98-101, 2018.

Giller, K. E.: Grounding the helicopters, Geoderma, 373, 114302, https://doi.org/10.1016/j.geoderma.2020.114302, 2020.

Giltrap, D. L., Li, C., and Saggar, S.: DNDC: A process-based model of greenhouse gas fluxes from agricultural soils, Agric. Ecosys. Environ., 136, 292-300, 2010.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., and Moore, R.: Google Earth Engine: Planetary-scale geospatial analysis for everyone, Remote Sens. Environ., 202, 18-27, 2017.

Grossman, R. B., and Reinsch, T.G.: Bulk density and linear extensibility. In: Methods of soil analysis. Part. 4 physical methods, edited by Dane, J.H., Topp, G.C., Soil Science Society of America, Inc. and American Society of Agronomy, Inc., Madison, pp 201–254, 2002

Habib, A.: How academic journals price out developing countries. http://theconversation.com/how-academic-journals-price-out-developing-countries-2484, 2011

Hampton, S. E., Anderson, S. S., Bagby, S. C., Gries, C., Han, X., Hart, E. M., Jones, M. B., Lenhardt, W. C., MacDonald, A., and Michener, W. K.: The Tao of open science for ecology, Ecosphere, 6, 1-13, 2015.

Harden, J. W., Hugelius, G., Ahlström, A., Blankinship, J. C., Bond-Lamberty, B., Lawrence, C. R., Loisel, J., Malhotra, A., Jackson, R. B., Ogle, S., Phillips, C., Ryals, R., Todd-Brown, K., Vargas, R., Vergara, S. E., Cotrufo, M. F., Keiluweit, M., Heckman, K. A., Crow, S. E., Silver, W. L., DeLonge, M., and Nave, L. E.: Networking our science to characterize the state, vulnerabilities, and management opportunities of soil organic matter, Global Change Biol., 24, 2018.

Hartley, S., McLeod, C., Clifford, M., Jewitt, S., and Ray, C.: A retrospective analysis of responsible innovation for low-technology innovation in the Global South, J. Responsible Innov., 6, 143-162, 2019.

**Deleted:** Dieckow, J., Mielniczuk, J., Knicker, H., Bayer, C., Dick, D. P., and Kögel-Knabner, I.: Comparison of carbon and nitrogen determination methods for samples of a paleudult subjected to no-till cropping systems, Sci. Agric., 64, 532-540, 2007.¶

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Hensen, A., Skiba, U., and Famulari, D.: Low cost and state of the art methods to measure nitrous oxide emissions, Environ. Res. Lett., 8, 025022, 2013.

Hill, T., Chocholek, M., and Clement, R.: The case for increasing the statistical power of eddy covariance ecosystem studies: why, where and how?, Global Change Biol., 23, 2154-2165, 2017.

Hook, D., Adams, J., and Szomszor, M.: The Landscape of climate research funding. https://research.uarctic.org/media/1598053/digital_science_climate_research_funding_report.pdf, 2017

Houben, D., Faucon, M.-P., and Mercadal, A.-M.: Response of organic matter decomposition to no-tillage adoption evaluated by the tea bag technique, Soil Syst., 2, 42, 2018.

Hourdin, F., Mauritsen, T., Gettelman, A., Golaz, J.-C., Balaji, V., Duan, Q., Folini, D., Ji, D., Klocke, D., and Qian, Y.: The art and science of climate model tuning, Bull. Am. Meteorol. Soc., 98, 589-602, 2017.

Hubau, W., Lewis, S. L., Phillips, O. L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A., Daniels, A. K., Ewango, C. E. N., Fauset, S., Mukinzi, J. M., Sheil, D., Sonké, B., Sullivan, M. J. P., Sunderland, T. C. H., Taedoumg, H., Thomas, S. C., White, L. J. T., Abernethy, K. A., Adu-Bredu, S., Amani, C. A., Baker, T. R., Banin, L. F., Baya, F., Begne, S. K., Bennett, A. C., Benedet, F., Bitariho, R., Bocko, Y. E., Boeckx, P., Boundja, P., Brienen, R. J. W., Brncic, T., Chezeaux, E., Chuyong, G. B., Clark, C. J., Collins, M., Comiskey, J. A., Coomes, D. A., Dargie, G. C., de Haulleville, T., Kamdem, M. N. D., Doucet, J.-L., Esquivel-Muelbert, A., Feldpausch, T. R., Fofanah, A., Foli, E. G., Gilpin, M., Gloor, E., Gonmadje, C., Gourlet-Fleury, S., Hall, J. S., Hamilton, A. C., Harris, D. J., Hart, T. B., Hockemba, M. B. N., Hladik, A., Ifo, S. A., Jeffery, K. J., Jucker, T., Yakusu, E. K., Kearsley, E., Kenfack, D., Koch, A., Leal, M. E., Levesley, A., Lindsell, J. A., Lisingo, J., Lopez-Gonzalez, G., Lovett, J. C., Makana, J.-R., Malhi, Y., Marshall, A. R., Martin, J., Martin, E. H., Mbayu, F. M., Medjibe, V. P., Mihindou, V., Mitchard, E. T. A., Moore, S., Munishi, P. K. T., Bengone, N. N., Ojo, L., Ondo, F. E., Peh, K. S. H., Pickavance, G. C., Poulsen, A. D., Poulsen, J. R., Qie, L., Reitsma, J., Rovero, F., Swaine, M. D., Talbot, J., Taplin, J., Taylor, D. M., Thomas, D. W., Toirambe, B., Mukendi, J. T., Tuagben, D., Umunay, P. M., van der Heijden, G. M. F., Verbeeck, H., Vleminckx, J., Willcock, S., Wöll, H., Woods, J. T., and Zemagho, L.: Asynchronous carbon sink saturation in African and Amazonian tropical forests, Nature, 579, 80-87, 2020.

Hunt, C. W., Snyder, L., Salisbury, J. E., Vandemark, D., and McDowell, W. H.: SIPCO2: a simple, inexpensive surface water p CO$_2$ sensor, Limnol. Oceanogr. Meth., 15, 291-301, 2017.

Hurrell, J. W., Holland, M. M., Gent, P. R., Ghan, S., Kay, J. E., Kushner, P. J., Lamarque, J.-F., Large, W. G., Lawrence, D., and Lindsay, K.: The community earth system model: a framework for collaborative research, Bull. Am. Meteorol. Soc., 94, 1339-1360, 2013.

Hwang, Y., Ryu, Y., Kimm, H., Jiang, C., Lang, M., Macfarlane, C., and Sonnentag, O.: Correction for light scattering combined with sub-pixel classification improves estimation of gap fraction from digital cover photography, Agric. For. Met., 222, 32-44, 2016.

IPCC: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 688, 2014

Irwin, A.: No PhDs needed: how citizen science is transforming research, Nature, 562, 480-482, 2018.

Iyandemye, J., and Thomas, M. P.: Low income countries have the highest percentages of open access publication: A systematic computational analysis of the biomedical literature, PLOS One, 14, e0220229, 2019.

Jayathunga, S., Owari, T., and Tsuyuki, S.: Evaluating the performance of photogrammetric products using fixed-wing UAV imagery over a mixed conifer–broadleaf forest: comparison with airborne laser scanning, Remote Sens., 10, 187, 2018.

Jha, P., Biswas, A., Lakaria, B. L., Saha, R., Singh, M., and Rao, A. S.: Predicting total organic carbon content of soils from Walkley and Black analysis, Comm. Soil Sci. Plant Anal., 45, 713-725, 2014.

Jian, J., Vargas, R., Anderson-Teixeira, K., Stell, E., Herrmann, V., Horn, M., Kholod, N., Manzon, J., Marchesi, R., Paredes, D., and Bond-Lamberty, B.: A restructured and updated global soil respiration database (SRDB-V5), Earth Syst. Sci. Data, 13, 255-267, https://doi.org/10.5194/essd-13-255-2021, 2021.

Jose, V. S., Sejian, V., Bagath, M., Ratnakaran, A. P., Lees, A. M., Al-Hosni, Y. A., Sullivan, M., Bhatta, R., and Gaughan, J. B.: Modeling of greenhouse gas emission from livestock, Front. Environ. Sci., 4, 27, 2016.

Jung, M., Schwalm, C., Migliavacca, M., Walther, S., Camps-Valls, G., Koirala, S., Anthoni, P., Besnard, S., Bodesheim, P., Carvalhais, N., Chevallier, F., Gans, F., Goll, D. S., Haverd, V., Köhler, P., Ichii, K., Jain, A. K., Liu, J., Lombardozzi, D., Nabel, J. E. M. S., Nelson, J. A., O'Sullivan, M., Pallandt, M., Papale, D., Peters, W., Pongratz, J., Rödenbeck, C., Sitch, S., Tramontana, G., Walker, A., Weber, U., and Reichstein, M.: Scaling carbon fluxes from eddy covariance sites to globe: synthesis and evaluation of the FLUXCOM approach, Biogeosci., 17, 1343-1365, 2020.

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Kallimanis, A., Panitsa, M., and Dimopoulos, P.: Quality of non-expert citizen science data collected for habitat type conservation status assessment in Natura 2000 protected areas, Sci. Rep., 7, 8873, 2017.

Kay, J. E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., Arblaster, J. M., Bates, S., Danabasoglu, G., and Edwards, J.: The Community Earth System Model (CESM) large ensemble project: A community resource for studying climate change in the presence of internal climate variability, Bull. Am. Meteorol. Soc., 96, 1333-1349, 2015.

Keuskamp, J. A., Dingemans, B. J., Lehtinen, T., Sarneel, J. M., and Hefting, M. M.: Tea Bag Index: a novel approach to collect uniform decomposition data across ecosystems, Methods Ecol. Evol., 4, 1070-1075, 2013.

Kim, D.-G., and Kirschbaum, M. U. F.: The effect of land-use change on the net exchange rates of greenhouse gases: A compilation of estimates, Agric. Ecosys. Environ., 208, 114-126, 2015.

Kim, D.-G., Giltrap, D. J., and Hernandez-Ramirez, G.: Background nitrous oxide emissions in agricultural and natural lands: a meta-analysis, Plant Soil, 373, 17-30, 2013.

Kim, D.-G., Thomas, A., Pelster, D., Rosenstock, T. S., and Sanz-Cobena, A.: Greenhouse gas emissions from natural ecosystems and agricultural lands in sub-Saharan Africa: synthesis of available data and suggestions for further research, Biogeosci., 13, 4789-4809, 2016.

Kim, J., Ryu, Y., Jiang, C., and Hwang, Y.: Continuous observation of vegetation canopy dynamics using an integrated low-cost, near-surface remote sensing system, Agric. For. Met., 264, 164-177, 2019.

King, M., Pegrum, M., and Forsey, M.: MOOCs and OER in the Global South: problems and potential, Int. Rev. Res. Open Distance Learn., 19, https://doi.org/10.19173/irrodl.v19i5.3742, 2018.

Kozhirbayev, Z., and Sinnott, R. O.: A performance comparison of container-based technologies for the Cloud, Future Gener. Comput. Syst., 68, 175-182, 2017.

Lausch, A., Schmidt, A., and Tischendorf, L.: Data mining and linked open data–New perspectives for data analysis in environmental research, Ecol. Mod., 295, 5-17, 2015.

Li, S., Xu, J., Tang, S., Zhan, Q., Gao, Q., Ren, L., Shao, Q., Chen, L., Du, J., and Hao, B.: A meta-analysis of carbon, nitrogen and phosphorus change in response to conversion of grassland to agricultural land, Geoderma, 363, 114149, https://doi.org/10.1016/j.geoderma.2019.114149, 2020.

Li, X., He, H., Yuan, W., Li, L., Xu, W., Liu, W., Shi, H., Hou, L., Chen, J., and Wang, Z.: Response of soil methane uptake to simulated nitrogen deposition and grazing management across three types of steppe in Inner Mongolia, China, Sci. Tot. Environ., 612, 799-808, 2018.

Li, Z., Zan, Q., Yang, Q., Zhu, D., Chen, Y., and Yu, S.: Remote estimation of mangrove aboveground carbon stock at the species level using a low-cost unmanned aerial vehicle system, Remote Sens., 11, 1018, 2019.

Liang, A., Gong, W., Han, G., and Xiang, C.: Comparison of satellite-observed XCO2 from GOSAT, OCO-2, and ground-based TCCON, Remote Sens., 9, 1033, 2017.

Liu, L., and Greaver, T. L.: A review of nitrogen enrichment effects on three biogenic GHGs: the CO$_2$ sink may be largely offset by stimulated N$_2$O and CH$_4$ emission, Ecol. Lett., 12, 1103-1117, 2009.

López-Ballesteros, A., Beck, J., Bombelli, A., Grieco, E., Lorencová, E. K., Merbold, L., Brümmer, C., Hugo, W., Scholes, R., Vačkář, D., Vermeulen, A., Acosta, M., Butterbach-Bahl, K., Helmschrot, J., Kim, D.-G., Jones, M., Jorch, V., Pavelka, M., Skjelvan, I., and Saunders, M.: Towards a feasible and representative pan-African research infrastructure network for GHG observations, Environ. Res. Lett., 13, 085003, 2018.

Lowndes, J. S. S., Best, B. D., Scarborough, C., Afflerbach, J. C., Frazier, M. R., O'Hara, C. C., Jiang, N., and Halpern, B. S.: Our path to better science in less time using open data science tools, Nat. Ecol. Evol., 1, 1-7, 2017.

Lu, M., Yang, Y., Fang, C., Zhou, X., Chen, J., Yang, X., and Li, B.: Responses of ecosystem nitrogen cycle to nitrogen addition: a meta-analysis, New Phytol., 189, 1040-1050, 2011.

Luo, T., Hostetler, K., Freeman, C., and Stefaniak, J.: The power of open: benefits, barriers, and strategies for integration of open educational resources, Open Learning: Open Learn., 35, 140-158, https://doi.org/10.1080/02680513.2019.1677222, 2020.

Macfarlane, C., Ryu, Y., Ogden, G. N., and Sonnentag, O.: Digital canopy photography: exposed and in the raw, Agric. For. Met., 197, 244-253, 2014.

Mapfumo, P., Adjei-Nsiah, S., Mtambanengwe, F., Chikowo, R., and Giller, K. E.: Participatory action research (PAR) as an entry point for supporting climate change adaptation by smallholder farmers in Africa, Environ. Dev., 5, 6-22, 2013.

Markwitz, C., and Siebicke, L.: Low-cost eddy covariance: a case study of evapotranspiration over agroforestry in Germany, Atmos. Meas. Tech., 12, 4677-4696, 2019.

Marley, A. R., Smeaton, C., and Austin, W. E.: An assessment of the tea bag index method as a proxy for organic matter decomposition in intertidal environments, J. Geophys. Res. Biogeosci., 124, 2991-3004, 2019.

**Deleted:** Lettens, S., De Vos, B., Quataert, P., Van Wesemael, B., Muys, B., and Van Orshoven, J.: Variable carbon recovery of Walkley-Black analysis and implications for national soil organic carbon accounting, Eur. J. Soil Sci., 58, 1244-1253, 2007.¶

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Martinsen, K. T., Kragh, T., and Sand-Jensen, K.: A simple and cost-efficient automated floating chamber for continuous measurements of carbon dioxide gas flux on lakes, Biogeosci., 15, 2018.

McDaniel, M. D., Saha, D., Dumont, M., Hernández, M., and Adams, M.: The effect of land-use change on soil $CH_4$ and $N_2O$ Fluxes: A global meta-analysis, Ecosys., 22, 1424-1443, 2019.

Mims, F. M.: Sun photometer with light-emitting diodes as spectrally selective detectors, Appl. Opt., 31, 6965-6967, 1992.

Minasny, B., Fiantis, D., Mulyanto, B., Sulaeman, Y., and Widyatmanti, W.: Global soil science research collaboration in the 21st century: Time to end helicopter research, Geoderma, 373, 114299, https://doi.org/10.1016/j.geoderma.2020.114299, 2020.

Mlambo, R., Woodhouse, I. H., Gerard, F., and Anderson, K.: Structure from motion (SfM) photogrammetry with drone data: a low cost method for monitoring greenhouse gas emissions from forests in developing countries, Forests, 8, 68, 2017.

Mtebe, J. S., and Raisamo, R.: Investigating perceived barriers to the use of open educational resources in higher education in Tanzania, Int. Rev. Res. Open Distance Learn., 15, 43-66, https://doi.org/10.19173/irrodl.v15i2.1803, 2014.

Muenchow, J., Schäfer, S., and Krüger, E.: Reviewing qualitative GIS research—Toward a wider usage of open-source GIS and reproducible research practices, Geography Compass, 13, e12441, 2019.

Murphy, H. M., McBean, E. A., and Farahbakhsh, K.: Appropriate technology – A comprehensive approach for water and sanitation in the developing world, Technol. Soc., 31, 158-167, 2009.

National Academies of Sciences, Engineering, and Medicine: Improving characterization of anthropogenic methane emissions in the United States. Washington, DC: The National Academies Press. https://doi.org/10.17226/24987, 2018

Ng, W., Husnain, Anggria, L., Siregar, A. F., Hartatik, W., Sulaeman, Y., Jones, E., and Minasny, B.: Developing a soil spectral library using a low-cost NIR spectrometer for precision fertilization in Indonesia, Geoderma Reg., 22, e00319, https://doi.org/10.1016/j.geodrs.2020.e00319, 2020.

Nickless, A., Scholes, R. J., Vermeulen, A., Beck, J., López-Ballesteros, A., Ardö, J., Karstens, U., Rigby, M., Kasurinen, V., Pantazatou, K., Jorch, V., and Kutsch, W.: Greenhouse gas observation network design for Africa, Tellus B: Chemical and Physical Meteorology, 72, 1-30, https://doi.org/10.1080/16000889.2020.1824486, 2020.

Nóbrega, G. N., Ferreira, T. O., Artur, A. G., de Mendonça, E. S., Raimundo, A. d. O., Teixeira, A. S., and Otero, X. L.: Evaluation of methods for quantifying organic carbon in mangrove soils from semi-arid region, J. Soils Sedim., 15, 282-291, 2015.

Ochieng, R. M., Visseren-Hamakers, I. J., Arts, B., Brockhaus, M., and Herold, M.: Institutional effectiveness of REDD+ MRV: Countries progress in implementing technical guidelines and good governance requirements, Environ. Sci. Policy, 61, 42-52, 2016.

Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F., and Erasmi, S.: Greenhouse gas emissions from soils—A review, Geochemistry, 76, 327-352, 2016.

Ogle, S. M., Olander, L., Wollenberg, L., Rosenstock, T., Tubiello, F., Paustian, K., Buendia, L., Nihart, A., and Smith, P.: Reducing greenhouse gas emissions and adapting agricultural management for climate change in developing countries: providing the basis for action, Global Change Biol., 20, 1-6, 2014.

Pal, J. S., Giorgi, F., Bi, X., Elguindi, N., Solmon, F., Gao, X., Rauscher, S. A., Francisco, R., Zakey, A., and Winter, J.: Regional climate modeling for the developing world: the ICTP RegCM3 and RegCNET, Bull. Am. Meteorol. Soc., 88, 1395-1410, 2007.

Pang, X., Shaw, M. D., Lewis, A. C., Carpenter, L. J., and Batchellier, T.: Electrochemical ozone sensors: A miniaturised alternative for ozone measurements in laboratory experiments and air-quality monitoring, Sens. Actuators B Chem., 240, 829-837, 2017.

Papale, D.: Ideas and perspectives: enhancing the impact of the FLUXNET network of eddy covariance sites, Biogeosciences, 17, 5587-5598, https://doi.org/10.5194/bg-17-5587-2020, 2020.

Pastorello, G., Trotta, C., Canfora, E., Chu, H., Christianson, D., Cheah, Y.-W., Poindexter, C., Chen, J., Elbashandy, A., Humphrey, M., Isaac, P., Polidori, D., Reichstein, M., Ribeca, A., van Ingen, C., Vuichard, N., Zhang, L., et al.: The FLUXNET2015 dataset and the ONEFlux processing pipeline for eddy covariance data. Sci. Data, 7, 225, https://doi.org/10.1038/s41597-020-0534-3, 2020.

Pearce, J.: Teaching science by encouraging innovation in appropriate technologies for sustainable development. https://hal.archives-ouvertes.fr/hal-02120521/document, 2019

Peltier, R.E.: An Update on Low-cost Sensors for the Measurement of Atmospheric Composition, https://library.wmo.int/index.php?lvl=notice_display&id=21508. 2021.

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Petrakis, S., Seyfferth, A., Kan, J., Inamdar, S., and Vargas, R.: Influence of experimental extreme water pulses on greenhouse gas emissions from soils, Biogeochem., 133, 147-164, 2017.

Pettorelli, N., Nagendra, H., Rocchini, D., Rowcliffe, M., Williams, R., Ahumada, J., De Angelo, C., Atzberger, C., Boyd, D., and Buchanan, G.: Remote sensing in ecology and conservation: three years on, Remote. Sens. Ecol., 3, 53-56, 2017.

Pinfield, S., Salter, J., Bath, P. A., Hubbard, B., Millington, P., Anders, J. H. S., and Hussain, A.: Open-access repositories worldwide, 2005–2012: Past growth, current characteristics, and future possibilities, J. Assoc. Inf. Sci. Technol, 65, 2404-2421, https://doi.org/10.1002/asi.23131, 2014.

Pocock, M. J. O., Roy, H. E., August, T., Kuria, A., Barasa, F., Bett, J., Githiru, M., Kairo, J., Kimani, J., Kinuthia, W., Kissui, B., Madindou, I., Mbogo, K., Mirembe, J., Mugo, P., Muniale, F. M., Njoroge, P., Njuguna, E. G., Olendo, M. I., Opige, M., Otieno, T. O., Ng'weno, C. C., Pallangyo, E., Thenya, T., Wanjiru, A., and Trevelyan, R.: Developing the global potential of citizen science: Assessing opportunities that benefit people, society and the environment in East Africa, J. Appl. Ecol., 56, 274-281, 2019.

Pohl, S., Garvelmann, J., Wawerla, J., and Weiler, M.: Potential of a low-cost sensor network to understand the spatial and temporal dynamics of a mountain snow cover, Wat. Resour. Res., 50, 2533-2550, 2014.

Qiu, S., Lin, Y., Shang, R., Zhang, J., Ma, L., and Zhu, Z.: Making Landsat time series consistent: evaluating and improving Landsat analysis ready data, Remote Sens., 11, 51, 2019.

Rai, A. C., Kumar, P., Pilla, F., Skouloudis, A. N., Di Sabatino, S., Ratti, C., Yasar, A., and Rickerby, D.: End-user perspective of low-cost sensors for outdoor air pollution monitoring, Sci. Tot. Environ., 607, 691-705, 2017.

Ramirez-Reyes, C., Brauman, K. A., Chaplin-Kramer, R., Galford, G. L., Adamo, S. B., Anderson, C. B., Anderson, C., Allington, G. R. H., Bagstad, K. J., Coe, M. T., Cord, A. F., Dee, L. E., Gould, R. K., Jain, M., Kowal, V. A., Muller-Karger, F. E., Norriss, J., Potapov, P., Qiu, J., Rieb, J. T., Robinson, B. E., Samberg, L. H., Singh, N., Szeto, S. H., Voigt, B., Watson, K., and Wright, T. M.: Reimagining the potential of Earth observations for ecosystem service assessments, Sci. Tot. Environ., 665, 1053-1063, 2019.

Rashti, M. R., Wang, W., Moody, P., Chen, C., and Ghadiri, H.: Fertiliser-induced nitrous oxide emissions from vegetable production in the world and the regulating factors: A review, Atmosph. Env., 112, 225-233, 2015.

Reichstein, M., Camps-Valls, G., Stevens, B., Jung, M., Denzler, J., Carvalhais, N., and Prabhat: Deep learning and process understanding for data-driven Earth system science, Nature, 566, 195-204, 2019.

Requena Suarez, D., Rozendaal, D. M. A., De Sy, V., Phillips, O. L., Alvarez-Dávila, E., Anderson-Teixeira, K., Araujo-Murakami, A., Arroyo, L., Baker, T. R., Bongers, F., Brienen, R. J. W., Carter, S., Cook-Patton, S. C., Feldpausch, T. R., Griscom, B. W., Harris, N., Hérault, B., Honorio Coronado, E. N., Leavitt, S. M., Lewis, S. L., Marimon, B. S., Monteagudo Mendoza, A., Kassi N'dja, J., N'Guessan, A. E., Poorter, L., Qie, L., Rutishauser, E., Sist, P., Sonké, B., Sullivan, M. J. P., Vilanova, E., Wang, M. M. H., Martius, C., and Herold, M.: Estimating aboveground net biomass change for tropical and subtropical forests: Refinement of IPCC default rates using forest plot data, Global Change Biol., 25, 3609-3624, 2019.

Richardson, A. D., Hufkens, K., Milliman, T., Aubrecht, D. M., Chen, M., Gray, J. M., Johnston, M. R., Keenan, T. F., Klosterman, S. T., and Kosmala, M.: Tracking vegetation phenology across diverse North American biomes using PhenoCam imagery, Sci. Data, 5, 180028, 2018.

Riddick, S. N., Mauzerall, D. L., Celia, M., Allen, G., Pitt, J., Kang, M., and Riddick, J. C.: The calibration and deployment of a low-cost methane sensor, Atmosph. Env., 117440, 2020.

Ritchie, H.: How many internet users does each country have? https://ourworldindata.org/how-many-internet-users-does-each-country-have, 2019

Rocchini, D., Petras, V., Petrasova, A., Horning, N., Furtkevicova, L., Neteler, M., Leutner, B., and Wegmann, M.: Open data and open source for remote sensing training in ecology, Ecol. Inf., 40, 57-61, 2017.

Romijn, E., Lantican, C. B., Herold, M., Lindquist, E., Ochieng, R., Wijaya, A., Murdiyarso, D., and Verchot, L.: Assessing change in national forest monitoring capacities of 99 tropical countries, For. Ecol. Managm., 352, 109-123, https://doi.org/10.1016/j.foreco.2015.06.003, 2015.

Rose-Wiles, L. M.: The high cost of science journals: a case study and discussion, J. Electron. Resour. Librariansh., 23, 219-241, 2011.

Roy, D. P., Jin, Y., Lewis, P. E., and Justice, C. O.: Prototyping a global algorithm for systematic fire-affected area mapping using MODIS time series data, Remote Sens. Environ., 97, 137-162, 2005.

Ryu, Y., Baldocchi, D. D., Verfaillie, J., Ma, S., Falk, M., Ruiz-Mercado, I., Hehn, T., and Sonnentag, O.: Testing the performance of a novel spectral reflectance sensor, built with light emitting diodes (LEDs), to monitor ecosystem metabolism, structure and function, Agric. For. Met., 150, 1597-1606, 2010.

Ryu, Y., Berry, J. A., and Baldocchi, D. D.: What is global photosynthesis? History, uncertainties and opportunities, Remote Sens. Environ., 223, 95-114, 2019.

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Ryu, Y., Lee, G., Jeon, S., Song, Y., and Kimm, H.: Monitoring multi-layer canopy spring phenology of temperate deciduous and evergreen forests using low-cost spectral sensors, Remote Sens. Environ., 149, 227-238, 2014.

Ryu, Y., Verfaillie, J., Macfarlane, C., Kobayashi, H., Sonnentag, O., Vargas, R., Ma, S., and Baldocchi, D. D.: Continuous observation of tree leaf area index at ecosystem scale using upward-pointing digital cameras, Remote Sens. Environ., 126, 116-125, 2012.

Schimel, D., Stephens, B. B., and Fisher, J. B.: Effect of increasing $CO_2$ on the terrestrial carbon cycle, PNAS, 112, 436-441, 2015.

Shames, S., Heiner, K., Kapukha, M., Kiguli, L., Masiga, M., Kalunda, P. N., Ssempala, A., Recha, J., and Wekesa, A.: Building local institutional capacity to implement agricultural carbon projects: participatory action research with Vi Agroforestry in Kenya and ECOTRUST in Uganda, Agric. Food Secur., 5, 13, 2016.

Shcherbak, I., Millar, N., and Robertson, G. P.: Global meta analysis of the nonlinear response of soil nitrous oxide ($N_2O$) emissions to fertilizer nitrogen, PNAS, 111, 9199-9204, 2014.

Shi, S., Peng, C., Wang, M., Zhu, Q., Yang, G., Yang, Y., Xi, T., and Zhang, T.: A global meta-analysis of changes in soil carbon, nitrogen, phosphorus and sulfur, and stoichiometric shifts after forestation, Plant Soil, 407, 323-340, 2016.

Shusterman, A. A., Kim, J., Lieschke, K. J., Newman, C., Wooldridge, P. J., and Cohen, R. C.: Observing local $CO_2$ sources using low-cost, near-surface urban monitors, Atmos. Chem. Phys, 18, 13773-13785, 2018.

Silvertown, J.: A new dawn for citizen science, Trends Ecol. Evol., 24, 467-471, 2009.

Smith, P., Soussana, J.-F., Angers, D., Schipper, L., Chenu, C., Rasse, D. P., Batjes, N. H., van Egmond, F., McNeill, S., Kuhnert, M., Arias-Navarro, C., Olesen, J. E., Chirinda, N., Fornara, D., Wollenberg, E., Álvaro-Fuentes, J., Sanz-Cobena, A., and Klumpp, K.: How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal, Global Change Biol., 26, 219-241, 2020.

Sun, J., Xia, Z., He, T., Dai, W., Peng, B., Liu, J., Gao, D., Jiang, P., Han, S., and Bai, E.: Ten years of elevated $CO_2$ affects soil greenhouse gas fluxes in an open top chamber experiment, Plant Soil, 420, 435-450, 2017.

Tan, L., Ge, Z., Zhou, X., Li, S., Li, X., and Tang, J.: Conversion of coastal wetlands, riparian wetlands, and peatlands increases greenhouse gas emissions: A global meta-analysis, Global Change Biol., 26, 1638-1653, https://doi.org/10.1111/gcb.14933, 2020.

Tang, Y., Jones, E., and Minasny, B.: Evaluating low-cost portable near infrared sensors for rapid analysis of soils from South Eastern Australia, Geoderma Reg., 20, e00240, https://doi.org/10.1016/j.geodrs.2019.e00240, 2020.

Theilade, I., Rutishauser, E., and Poulsen, M. K.: Community assessment of tropical tree biomass: challenges and opportunities for REDD+, Carbon Balance Manag., 10, 17, 2015.

Theobald, E. J., Ettinger, A. K., Burgess, H. K., DeBey, L. B., Schmidt, N. R., Froehlich, H. E., Wagner, C., HilleRisLambers, J., Tewksbury, J., and Harsch, M. A.: Global change and local solutions: Tapping the unrealized potential of citizen science for biodiversity research, Biol. Conserv., 181, 236-244, 2015.

Tiago, P., Ceia-Hasse, A., Marques, T. A., Capinha, C., and Pereira, H. M.: Spatial distribution of citizen science casuistic observations for different taxonomic groups, Sci. Rep., 7, 12832, 2017.

Vargas, R., Alcaraz-Segura, D., Birdsey, R., Brunsell, N. A., Cruz-Gaistardo, C. O., de Jong, B., Etchevers, J., Guevara, M., Hayes, D. J., and Johnson, K.: Enhancing interoperability to facilitate implementation of REDD+: Case study of Mexico, Carbon Manag., 8, 57-65, 2017.

Villarreal, S., and Vargas, R.: Representativeness of FLUXNET Sites Across Latin America, J. Geophys. Res. Biogeosci., 126, e2020JG006090, https://doi.org/10.1029/2020JG006090, 2021.

Vogel, C., Steynor, A., and Manyuchi, A.: Climate services in Africa: Re-imagining an inclusive, robust and sustainable service, Climate Services, 15, 100107, https://doi.org/10.1016/j.cliser.2019.100107, 2019.

Walkley, A., and Black, I. A.: An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method, Soil Sci., 37, 29-38, 1934.

Wang, C., Jin, Y., Ji, C., Zhang, N., Song, M., Kong, D.-L., Liu, S., Zhang, X., Liu, X., Zou, J., Li, S., and Pan, G.: An additive effect of elevated atmospheric $CO_2$ and rising temperature on methane emissions related to methanogenic community in rice paddies, Agric. Ecosys. Environ., 257, 165-174, 2018.

Wang, J.-P., Wang, X.-J., and Zhang, J.: Evaluating loss-on-ignition method for determinations of soil organic and inorganic carbon in arid soils of northwestern China, Pedosph., 23, 593-599, 2013.

Warner, D. L., Bond-Lamberty, B., Jian, J., Stell, E., and Vargas, R.: Spatial predictions and associated uncertainty of annual soil respiration at the global scale, Glob. Biogeochem. Cyc., 33, 1733-1745, 2019.

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C.

**Deleted:** Wang, X., Wang, J., and Zhang, J.: Comparisons of three methods for organic and inorganic carbon in calcareous soils of northwestern China, PLOS One, 7, e44334, 2012.¶

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T., Finkers, R., Gonzalez-Beltran, A., Gray, A. J. G., Groth, P., Goble, C., Grethe, J. S., Heringa, J., ’t Hoen, P. A. C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S. J., Martone, M. E., Mons, A., Packer, A. L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M. A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., and Mons, B.: The FAIR guiding principles for scientific data management and stewardship, Sci. Data, 3, 160018, 2016.

Willcock, S., Phillips, O. L., Platts, P. J., Swetnam, R. D., Balmford, A., Burgess, N. D., Ahrends, A., Bayliss, J., Doggart, N., Doody, K., Fanning, E., Green, J. M. H., Hall, J., Howell, K. L., Lovett, J. C., Marchant, R., Marshall, A. R., Mbilinyi, B., Munishi, P. K. T., Owen, A. R., Topp-Jorgensen, E. J., and Lewis, S. L.: Land cover change and carbon emissions over 100 years in an African biodiversity hotspot, Global Change Biol., 22, 2787-2800, 2016.

Xu, M., and Shang, H.: Contribution of soil respiration to the global carbon equation, J. Pl. Physiol., 203, 16-28, 2016.

Yan, L., and Roy, D. P.: Large-area gap filling of landsat reflectance time series by spectral-angle-mapper based spatio-temporal similarity (SAMSTS), Remote Sens., 10, 609, 2018.

Yang, S., Lei, L., Zeng, Z., He, Z., and Zhong, H.: An assessment of anthropogenic $CO_2$ emissions by satellite-based observations in China, Sens., 19, 1118, 2019.

Yoo, E.-H., Zammit-Mangion, A., and Chipeta, M. G.: Adaptive spatial sampling design for environmental field prediction using low-cost sensing technologies, Atmosph. Env., 221, 117091, 2020.

Zhao, M., Brofeldt, S., Li, Q., Xu, J., Danielsen, F., Læssøe, S. B. L., Poulsen, M. K., Gottlieb, A., Maxwell, J. F., and Theilade, I.: Can community members identify tropical tree species for REDD+ carbon and biodiversity measurements?, PLOS One, 11, e0152061, 2016.

Zhou, Y., Hagedorn, F., Zhou, C., Jiang, X., Wang, X., and Li, M.-H.: Experimental warming of a mountain tundra increases soil $CO_2$ effluxes and enhances $CH_4$ and $N_2O$ uptake at Changbai Mountain, China, Sci. Rep., 6, 1-8, 2016.

Zhu, Z., Wulder, M. A., Roy, D. P., Woodcock, C. E., Hansen, M. C., Radeloff, V. C., Healey, S. P., Schaaf, C., Hostert, P., and Strobl, P.: Benefits of the free and open Landsat data policy, Remote Sens. Environ., 224, 382-385, 2019.

Zhu, Z.: Science of landsat analysis ready data, Remote Sens., 11, 2166, 2019.

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