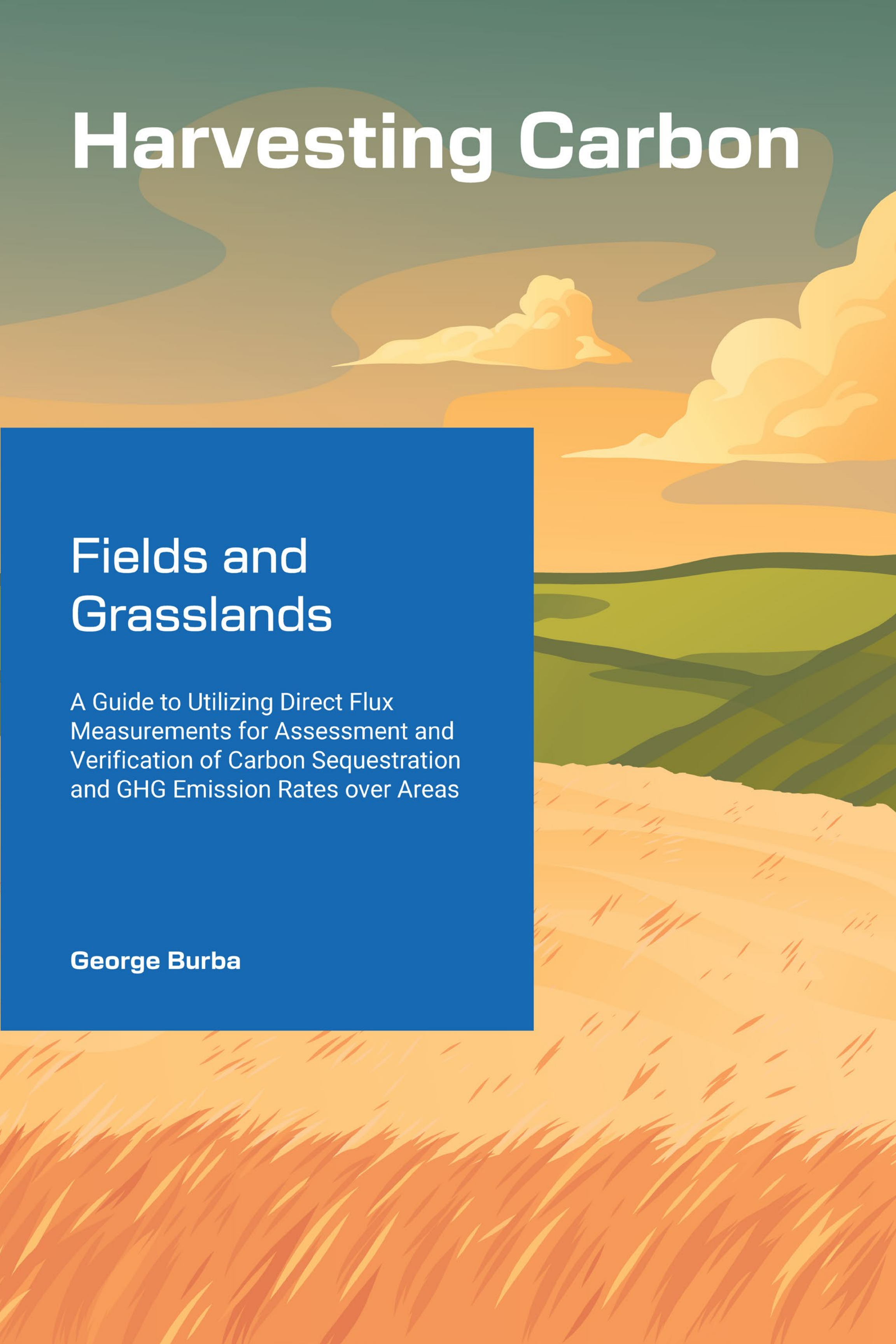
Harvesting Carbon



Fields and Grasslands

A Guide to Utilizing Direct Flux Measurements for Assessment and Verification of Carbon Sequestration and GHG Emission Rates over Areas

George Burba

Harvesting Carbon

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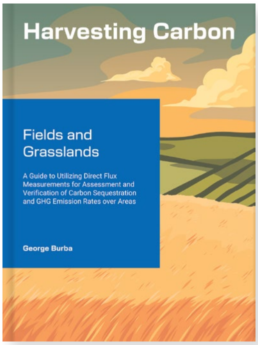
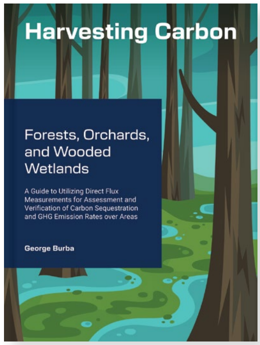
A Guide to Utilizing Direct Flux Measurements
for Assessment and Verification of Carbon
Sequestration and GHG Emission Rates over Areas

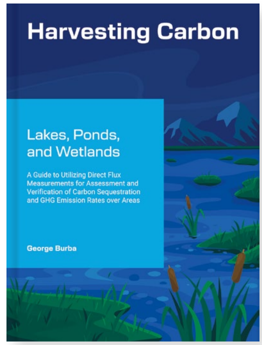
George Burba

LI-COR®

“Harvesting Carbon: Fields & Grasslands. A Guide to Utilizing Direct Flux Measurements for Assessment and Verification of Carbon Sequestration and GHG Emission Rates over Areas” is the first guide in a 3-part series.







Note: This guide provides a general plain-language framework for carbon credit verification using direct flux measurements. Adaptations for special cases and additional requirements may be necessary based on specific project guidelines, regional regulations, and stakeholder requirements. For comprehensive academic guidance, please refer to Burba, G., 2022. Eddy Covariance Method for Scientific, Regulatory, and Commercial Applications. LI-COR Biosciences, Lincoln, USA: 702 pp. ISBN: 978-0-578-97714-0.

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Introduction

As carbon markets evolve from primarily volunteer, goodwill, and advertising paradigms into a commodity-like trading paradigm, the measurement, monitoring, reporting, and verification of the traded quantities (MMRV) also evolves from approximations to actual measurements. The process is somewhat equivalent to moving from estimating the quantity of gold or grain based on the size of the heap to placing it on the actual scales.

Traditionally used approximate carbon estimates such as emission factors, regional-scale modeling, and infrequent observations of partial carbon pools (aboveground biomass without roots or soil, soil carbon without roots or aboveground biomass, etc.)[1-7] can now be augmented, and sometimes replaced, by an approach continuously monitoring the entire carbon pool (aboveground biomass, roots, soil) using direct in-and-out-of-the-air measurement methods[8-24].

In such methods, the real-time transport of GHGs, including CO_2, in-and-out of the atmospheric air is actually measured with a device, in oppose to modelling or approximation from some other parameters. It accounts for the number of molecules of CO_2 added to or removed from the air by the underlying surface in real time[8, 25].

Among such direct methods, the eddy covariance flux method[25-29] comes as the most widespread in academic carbon sequestration/emission measurements. It has been used widely over the past 40 years[30-41], capturing all relevant carbon pools continuously over areas ranging from a few single hectares to tens of thousands of hectares, with 30-60 min time resolution, at over 2100 measurement locations around the globe[42-93] (Fig. 1).

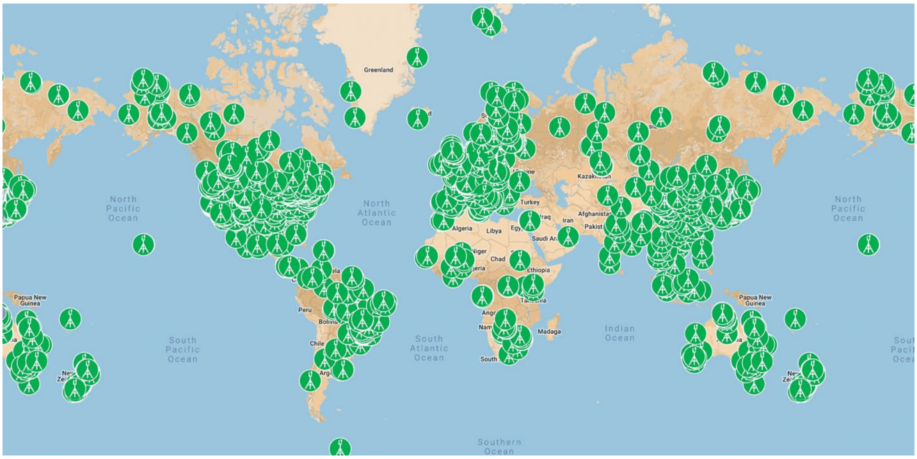

Figure 1. The locations of 2155 past and present flux stations making direct flux measurements[42] using the eddy covariance method.

Properly maintained and accurately processed continuous direct flux measurements have fundamental advantages over traditionally used techniques[24-29]:

- Significantly surpass present field techniques in terms of time resolution, spatial coverage, component coverage, and overall accuracy.
- Allow continuous automated real-time tracking of the carbon sequestration/emission over the area and all carbon pools with an uncertainty of approximately 15-20% every 30 minutes.
- Provide the ability to immediately see and quantify the effects of extreme weather, droughts, other natural processes, and human intervention, and develop remedies, mitigation, or insurance provisions.
- Provide the ability to immediately see and quantify the effectiveness of carbon management (Fig. 2), such as fertilizer application, biochar treatment, cover crop, irrigation regiment, tillage practice, or microbial inoculation, enabling effective carbon management on daily-to-weekly and longer scales.
- Help a detailed understanding of the carbon exchange at the land use level (Fig. 3), enabling the development of new field-specific carbon management techniques tailored for specific time periods in each specific land use. New added-value carbon products can be developed and tested instantly.
- Allow dynamic simultaneous baselining through paired sites, with a control site in an untreated area providing a baseline against which the outcomes of mitigation actions in treated areas can be compared and quantified.

- Enable standardization across multiple types of land use, such as crops, grasslands, forests, wetlands, lakes, deserts, oils and gas fields, marine and urban environments, using the exact same approach.
- Provide a much more defensible final carbon number than traditional measurements which sample partial carbon pools at a few selected spots every 1-5 years.

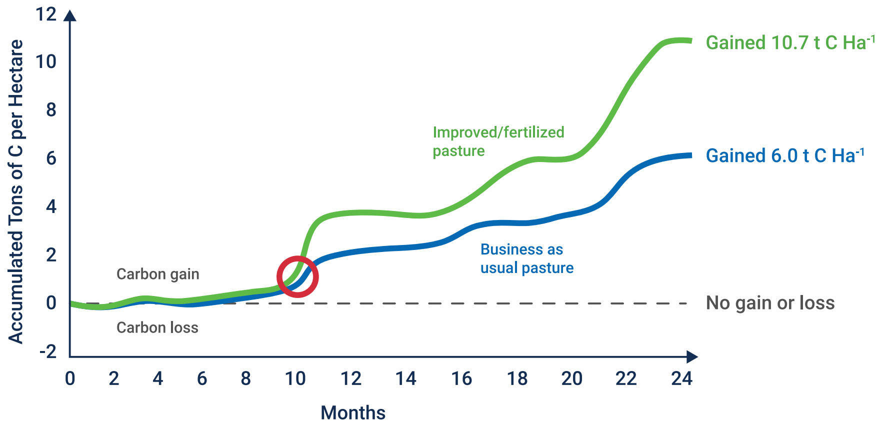

Figure 2. A real-life example[94] of the immediate effect of fertilizer application leading to 1.8x carbon sequestration by a fertilized pasture vs an unfertilized control, observed days after the fertilization. Such a level of tracking and quantifying the effectiveness of carbon management is completely out of reach for traditional MMRV methods.

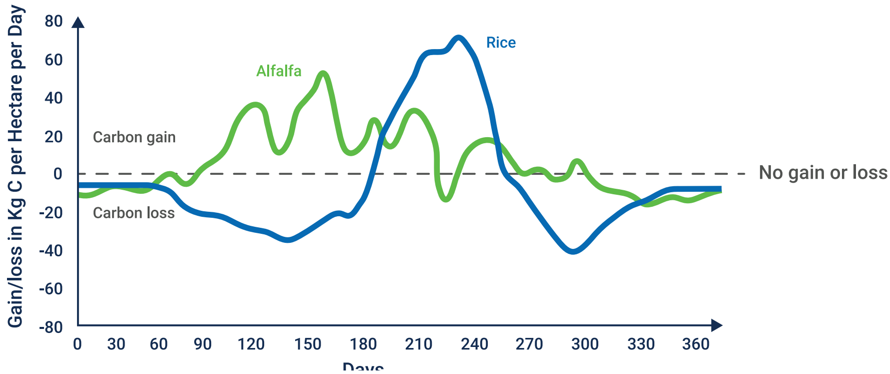

Figure 3. A real-life example of continuous tracking of daily rates of carbon gains and losses in traditionally managed alfalfa and rice fields[95]. Distinct differences between two land uses, and periods for potential improvements through carbon management for each of the two land use types, are easily identified. Again, as with Fig. 2, such performance is completely out of reach for traditional MMRV methods.

The key challenges of using a direct flux approach come from the higher upfront cost of the equipment and installation, the continuous maintenance of the flux station, and the need to quality control the data before the integration into a final MMRV value.

This guide will help maximize the advantages and minimize disadvantages of the direct flux measurements, tailor-fit them to the specific location to provide the highest quality of data, and optimize costs and time required for equipment maintenance, data quality control and analysis.

Overall, this guide will help significantly optimize costs and de-risk the direct MMRV system to help create premium site-specific management-specific carbon solutions.

Objective and Scope

The objective of this guide is to help carbon and climate entrepreneurs, investors, and regulators with the development of a standardized framework for their MMRV systems and protocols by enhancing the accuracy and resolution, in time and space, of carbon sequestration measurements and carbon credits verification by using direct flux measurements.

It outlines the minimal set of essential steps for planning, installation, data collection, processing, quality control, and reporting requirements for projects seeking to establish or verify carbon sequestration rates, and generate related credits, based on the quantification of fluxes of CO_2 and other GHGs directly in and out of the air.

The guide is specifically designed to take maximum advantage of LI-COR solutions (methodology, instrumentation, and software) tailor-fit to achieve the most accurate GHG flux measurements at the optimized upfront and operational costs, de-risk MMRV systems, and help create premium carbon products at reasonable cost.

Pre-Planning and Cost Optimization

1

The guide below describes standard scenarios for using direct flux measurements for the assessment and verification of carbon dioxide sequestration and emission rates over areas. Measuring other gas species has very similar and often identical requirements to those of CO_2.

Using direct flux measurements in a multitude of non-standard scenarios (e.g., complex terrain, custom equipment, very small or large areas, etc.) is entirely possible but may require additional steps. The non-standard scenarios are outside the scope of this guide. However, the guide lists essential pointers for typical non-standard scenarios and key references for further information.

If desired, LI-COR Professional Services (LPS) can be contracted at any stage to help plan and execute the projects of various difficulties, from standard to highly complex, including site installation and maintenance, direct support and management, and final data preparation.

1.1 De-risking the project and minimizing the costs

Flux stations (Fig. 4) are very similar to automated weather stations (AWS) often found near airports, schools, mountain passes, etc. However, in addition to weather parameters, flux stations measure GHG, water vapor, and heat fluxes, and have a few additional requirements and related costs.

Figure 4. Solar-powered eddy covariance flux station operating in a prairie in Eastern Nebraska.

The short-term upfront costs are the hardware and installation of the flux station. These have to be balanced against long-term costs that include station access and maintenance, and any subscriptions to software and data services (data cleaning, filling missing data, and data integration).

Optimized and amortized over a project's lifetime, the costs of the direct measurements over the entire carbon pool become comparable or lower than properly implemented traditional approximate estimates of partial carbon pools (aboveground biomass without roots or soil, soil carbon without roots or aboveground biomass, etc.).

To minimize overall costs over the duration of the project, and to de-risk the project from failure, the following key items should be considered and optimized during the planning and budgeting stage:

- Area coverage
- Installation, power, and data access
- Accessibility of the site for maintenance
- Maintenance over duration

Area coverage: A flux station covers an upwind area of roughly 50-100 times its height above the vegetation. So, depending on the size of the area of interest and available infrastructure, it may be beneficial to have either one tall tower or several short ones.

If the flux station height exceeds approximately 10-15 m height, the tower construction costs grow exponentially and special permits may be required to service the equipment, so often multiple 3-5 meter tall tripods or telescopic poles would cover the same area, and be cheaper and easier to service, than one 20-30 m climb-up tower or a scaffold.

However, if a tall structure is already available, it may make sense to take advantage of this, place instrumentation on such a tower, and use the fluxmapping technique[96-99] to get high spatial resolution fluxes.

Installation, power, and wireless access: The installation of a 3-7 m tripod or telescopic pole is significantly less expensive than the tall tower, and typically requires very little or no regulations or specialized training. The installation of scaffold towers up to 10-15 m in height is more expensive but still can be done by local construction professionals. The installation of a scaffold or anchored tower over 10-15 m height may require permitting, access roads, professional crew, significant safety regulations, and specialized tall-tower training. During pre-planning, these installation options should be balanced against area coverage.

When only CO_2 and CH_4 are measured, the power can nearly always be provided by solar panels. One should plan on smaller or fewer panels in sunnier places and large or more panels in overcast environments. Solar power calculations allow the sizing of the panels during pre-planning[100]. The sizing can be discussed with LI-COR Technical Support or outsourced to LPS.

When N_2O measurements are added to the flux station, solar or wind power will not be practical at the site due to the very significant power requirements of the presently available instruments, and either grid power should be planned for the site, or a different direct method[8,25] should be used to estimate the N_2O emission rates. Such approaches are outside the scope of this guide and can be discussed with LI-COR Technical Support or outsourced to LPS.

Wireless remote access is highly desirable and recommended for reliably operating a flux station and providing high-quality carbon product. Wireless remote access allows immediate alerts if data collection is interrupted, helps diagnose the exact cause, and dispatch maintenance accordingly.

In special cases, when wireless access cannot be provided by standard cellular coverage, radio, and satellite access can be set up in a manner that minimizes data charges. In all cases, data access options and costs shall be evaluated in the pre-planning stage and weighed against other factors.

Accessibility of the station for maintenance: The key to achieving the best MMRV certainty with flux stations is to keep the station operating with minimal data gaps. This typically can require bi-weekly to bi-monthly station services (cleaning equipment, inspecting cables, etc.) subject to local conditions.

Depending on the number of stations, and driving distances to the stations, this may require a small fraction of a full-time equivalent (FTE) for a single station and up to 1-2 FTE for 5-10 stations.

Very remote stations are often serviced by a part-time local contractor, which saves a significant amount of time and money in travel costs over time. These can be people without any specialized technical background such as high-school students or retirees.

1.2 Maintenance over duration

Maintenance over the duration of the project[25] is the key to minimizing data gaps and maximizing the accuracy of the final carbon product, and it's the main de-risking tool. At the same time, it is one of the significant expenditures in the project. The plan needs to be developed at the pre-planning stage to account for all logistics, costs, and FTE requirements, in order to significantly optimize the costs of the project and maximize product quality.

The maintenance plan for a flux station is very similar to that of a traditional Automated Weather Station. In all cases, the site should be maintained at least once per two months, with the following steps:

- Inspection of diagnostic flags and overall data quality (e.g., reasonable numbers for temperature, humidity, fluxes)
- Inspection and cleaning of instrumentation and sensors (windows, mirrors, domes, etc.)
- Inspection and cleaning of solar panels
- Inspection of battery bank capacity
- Inspection of cables and connectors for cracks, corrosion, and other visible damage
- Inspection of the area immediate to the station for major disturbances
- Inspection and replacement of filters and pumps if needed per factory manual
- Replacement of internal chemicals on a half-yearly or yearly basis per factory manual
- Temporary replacement of the devices requiring yearly or bi-yearly calibrations with spares, and reconfiguration of newly calibrated devices if needed
- If a station does not have remote data access, the data should be downloaded manually and sent for further processing

A single site may require at least a year of operation to establish a baseline for the specific location and land use. Paired sites may require at least a year of operation to quantify the differences between business-as-usual and a new treatment.

So, depending on the location and site access, contracting some or all of the maintenance services may be more cost-effective than hiring own FTE. Three main choices of contractors are available:

- Local unskilled contractor, such as a high-school student or a retired person. This type of contractor is most economical and can handle routine inspections and cleaning but not equipment replacements or simple repairs.
- Local high-end contractor, such as a nearby university. This type of contractor can handle nearly all maintenance items, as well as some of the data processing items, and often in exchange for a medium cost in combination with using the same flux data for their scientific purposes.
- Professional services. This type of contractor can handle all aspects of maintenance, as well as site installation, and data handling. This may be the premium option but is also most likely to provide the best data coverage,

- maximum data privacy, and the most reliable long-term solution. LI-COR offers a variety of such services under LI-COR Professional Services (LPS) contracts that can include partnering with local resources.

1.3 Summary of optimizing data coverage and costs

Optimization for maximizing data quality and minimizing costs over the duration of the project can utilize the following iterative decision-making steps:

- Select the largest continuous available areas of the land use of interest
- Rate prospective sites by size from largest to smallest
- Rate them on topography from flat to complex
- Rate them on patchiness, from more uniform to most patchy
- Rate them on appropriate land use history from best to worst
- Make note of existing power, and other infrastructure closeness and availability
- Rate prospective sites on distance for the maintenance services from closest to furthest
- Rate them on wireless data access availability and reliability from best to worst
- Optimize costs: examine expenses for one or few taller towers with larger coverage areas, and compare these expenses versus many shorter stations with smaller coverage area each; include construction/installation costs and ongoing maintenance into such a decision
- Select a set of specific candidate sites for MMRV monitoring

Site Selection

2

A set of the candidate project sites identified in the pre-planning stage shall be examined, and the most suitable site(s) shall be selected based on the criteria listed in Stage 2.1-2.6.

Google Earth, Bing Aerial, satellite images, or other comparable maps indicating the site location, GPS coordinates of the site in WGS84 World Geodetic System, and wind rose at the selected site, shall be added to the chain of decisions, documented for regulatory compliance or potential audit, and added to Pre-implementation report (project description) described in Stage 7.1.

2.1 Land Use

The land use, crop type, grassland management regime, etc. should correspond to the project's specifications. For example, if a project specifies characterizing the carbon sequestration from irrigated maize, dryland maize shall not be used as a measurement site. The degree of acceptable patchiness and required uniformity of land use plots will be addressed in Stage 2.4.

Paired sites: For paired sites, where business-as-usual baseline compared to a new carbon management, the sites shall be of a similar land use history, and ideally should have comparable soils and climatic conditions. For example, if one of the two paired sites was under several years of corn-soybean rotation on a 1.2 m soil in a humid subtropical climate, the other site should not have a several-year history of being used as a pasture on a 0.4 m soil in a cold semi-arid climate.

2.2 Plot Size

Standard flux measurements work best over areas that are larger than 200 m x 200 m, and ideally, equal or larger than 300 m x 300 m. For the standard case, the site shall be selected to be at least 200 m x 200 m, and with all else equal, the preference should be given to larger plots.

Flux stations cover an upwind area of 50-100 times its height above the vegetation, so measuring larger plots can be done by simply raising the measurement height. Standard LI-COR equipment allows measurements up to 5 m above the soil surface, and depending on vegetation height, covering up to 500 m x 500 m plots.

Larger areas, up to 20 km x 20 km, will require either the use of a taller structure, such as a pole, lattice, truss, or scaffold tower, or multiple tripod stations.

Paired sites: Where business-as-usual baseline compared to a new carbon management, the sites shall have similar area coverage. For example, if one of the two paired sites has a 3 m tripod over a 0.5 m tall grassland, covering up to 250 m upwind, the other site shall not be located on a 25 m tower covering nearly 2500 m upwind.

Special cases: In special cases, plots smaller than 200 m x 200 m can be measured using a combination of prevailing wind directions in the area and/or fluxmapping technique[96-99]. In a separate set of special cases, very large areas can be covered using radio and cell phone towers, or by using interpolation techniques[8,101-102] based on remote sensing and weather data. Both of these cases are outside the scope of this guide but the applicability of these approaches for a specific site can be discussed with LI-COR Technical Support or outsourced to LPS.

2.3 Topography

Research-grade flux measurements are done over all kinds of terrains including the most complex urban and mountain regions[25]. However, for MMRV purposes, it is much safer and less cumbersome to find the classical sites that are less complex in topography.

Standard flux measurements work best on flat terrains and consistent slopes. Data from such sites could be computed using standard software, and would not require additional stations in the same area or additional calculations to correct for the complexity.

For a standard case, the site for the flux station shall be selected on a flat terrain or a consistent slope, and shall not be placed on a sharp peak or in a deep ravine (Fig. 5). The sites with flatter topography shall have priority over sites with complex topography.

Paired sites: For paired sites, where business-as-usual baseline compared to new carbon management, the sites shall have approximately the same topography, sun exposure, soil thickness, etc. For example, if one of the two paired sites is located on a 10-degree southern slope, the other site shall not be placed on the 10-degree northern slope.

Special cases: In special cases, fluxes from complex terrains can be measured using specially designed station placement and data processing. These approaches are outside the scope of this guide but can also be discussed with LI-COR Technical Support or outsourced to LPS.

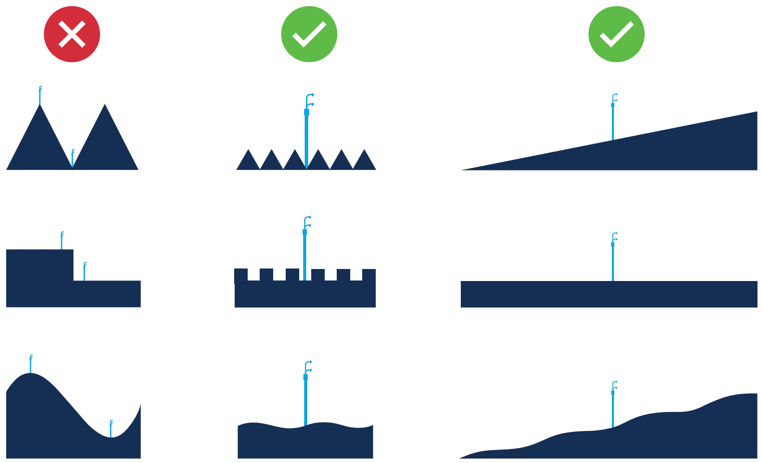

Figure 5. Typical examples of unacceptable and acceptable types of terrains and slopes for direct measurements using flux stations.

2.4 Uniformity

There are no perfectly uniform sites, but some sites will be more uniform and others will be patchier (Fig. 6). The more uniform site is easier to work with in terms of future data coverage and should be a priority when selecting the location.

The site shall not have a significant presence of the vastly contrasting systems. For example, the grassland site of one management can have small patches of a grassland site with different management, but shall not have a grass-free cattle yard or a suburban landscape intertwined with the grass-covered areas.

For standard cases, a more uniform site shall be selected over a patchier site.

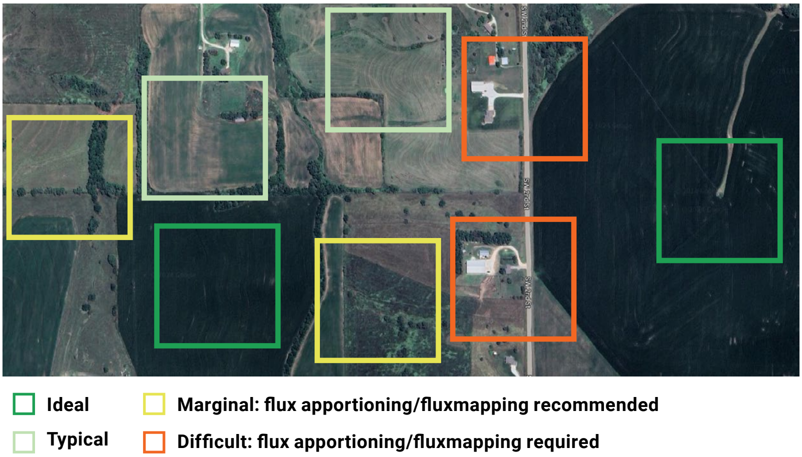

Figure 6. Examples of perfectly uniform ideal sites, typical standard sites, marginally acceptable sites where flux apportioning/fluxmapping is recommended, and difficult sites where flux apportioning/fluxmapping is required.

Paired sites: For paired sites, where business-as-usual baseline compared to new carbon management, the sites shall have approximately the same uniformity and composition. For example, if one of the two paired sites is located in an area with 95% grassland and 5% roads, the other site shall not be placed in an area with 80% grassland, 15% agricultural fields, and 5% urban area.

Special cases: In special cases, fluxes from patchy areas can be measured using flux apportioning and/or fluxmapping techniques[96-99]. These approaches are outside the scope of this guide but can be discussed with LI-COR Technical Support or outsourced to LPS.

2.5 Wind distribution

For each 30-60 min measurement interval, the flux station sees the fragment of an upwind area stretching 50-100 times the instrument height, effectively ‘scanning’ the measurement plot depending on the wind direction.

The wind rose (a plot with the wind direction distribution; Fig. 7) shall be constructed for the area based on the data from a nearby airport, school, or other facility, or based on a tiled weather product by a national weather service or local Mesonet.

It is critical to select a wind rose location as close to the candidate site as possible, with actual wind direction measurements having priority over a tiled weather product or a model.

Such wind distribution shall be related to the shape of the candidate site. The sites where stations can be placed to cover most of the site most of the time shall be selected over the sites with partial coverage.

For the standard case, the ideal site would allow placing the station at the center of the site with winds covering most of the site most of the time.

Paired sites: For paired sites, where business-as-usual baseline compared to new carbon management, the sites shall have approximately the same wind distribution in relation to the shape of the site. For example, if one of the two paired sites is a square shape with most winds coming from East and West, the other site shall not be an East-West extended oval with most winds coming from North and South.

Special cases: If there are no good candidates with strong coverage most of the year, the wind rose shall be constructed by seasons or vegetation growth stage, and the site selection shall favor the sites with good coverage during the most active season.

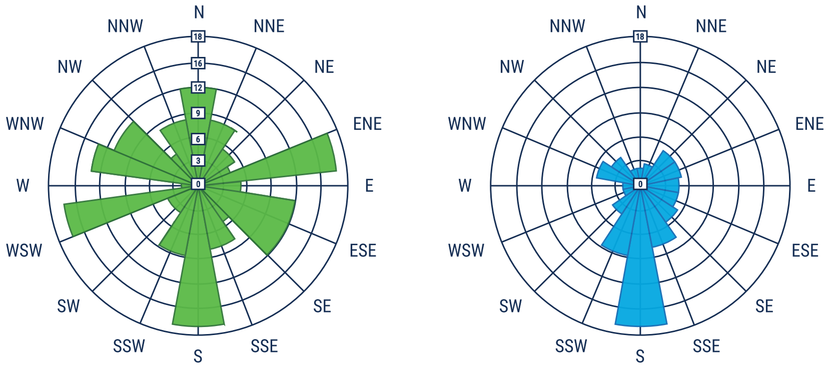

Figure 7. Examples of wind roses. On the left, winds come from various directions: ideally, such a site should be large enough to place the station in the center of the site so no data is lost due to unfavorable wind directions. On the right, most winds come from the South: such a site can be smaller in size and the flux station may be placed closer to the downwind (northern) edge of the site, but some data loss due to non-southern winds will occur.

2.6 Other considerations

The considerations below should have been largely addressed during the pre-planning stage. However, it is recommended to have a final iteration of such considerations to ensure the optimal selection of the site.

Power considerations: with criteria described in 2.1-2.5 being equal, the site with better solar/wind power conditions or easier grid power access shall be selected over the site with a more difficult power solution. This will help minimize data gaps and increase the quality of the final carbon product.

Wireless/remote access considerations: with criteria described in 2.1-2.5 and power access being equal, the site with better wireless coverage or remote access shall be selected over the site with more difficult remote data access. This will help minimize site visits, maintenance costs, and data gaps to ensure the higher quality of carbon products.

Physical access considerations: with all the criteria described above being equal, the site with easier physical access shall be selected over the site with more difficult access. This will help reduce the costs of site visits, and maintenance time.

Active site management considerations: particularly for agricultural fields and actively managed grasslands (including grazing, prescribed burn, etc.), with all the criteria described above being equal, the site with easier coordination between ongoing measurements and site management shall be selected over the site with more difficult coordination. This will help reduce the data gaps due to agricultural and other site management operations.

Paired sites: For paired sites, where business-as-usual baseline compared to new carbon management, the sites shall be selected such that they have approximately the same maintenance visit times to assure that data coverage is in sync at both paired sites and the data gaps match. For example, if one of two paired sites is serviced every first week of the two-month period, the other site shall also be serviced in the same week, or at least in the adjacent week, but not in the fourth week of the two-month period.

Special cases: Extremely remote sites with little or no power solutions, remote data access, or physical access can be and have been used for flux measurements. These will require special planning and equipment, significant expense, and typically significant training of the local maintenance person. These are outside the scope of this guide but can be discussed with local technical organizations and LI-COR Technical Support, or outsourced to LPS.

Hardware and Software Selection

3

The selection of the hardware and software, including dated versions, shall be documented for regulatory compliance or potential external audit, and added to the pre-implementation report (project description) described in Stage 7.1.

3.1 Available instrumentation and software

The following hardware choices provided by LI-COR are suitable for MMRV via direct flux measurements:

LI-720 CO_2/H_2O Flux Sensor: This is the lowest-cost, lowest-power, easiest to install, and most automated solution[103] capable of providing CO_2 sequestration/emission rates, underlying raw data (to satisfy transparency criteria and for potential audits), and key weather parameters (photosynthetically active radiation, wind speed and directions, air temperature and humidity, and atmospheric pressure) needed for quality control and filling the missing data.

This option, designed specifically for long-term commercial monitoring, will likely provide optimal configuration for most MMRV projects.

The instrument can be used stand-alone as a part of a user-supplied system, or as a part of a Carbon Node where solar power, wireless access, tripod or pole mounting, and cloud data storage are provided as a package, and data services (cleaning, filling data gaps, and aggregating) are provided as a service.

LI-7500DS CO_2/H_2O Analyzer combined with 3D Sonic Anemometer: This is a research-grade system based on the longest-running commercial open-path gas analyzer[25,104] deployed in numerous national and international flux observation networks (AmeriFlux[44], AsiaFlux[45], CARN[48], CERN[49], ChinaFlux[50], LTER[63], OzFlux[68], Parallel41[70], etc.)

It will require an additional Biomet Module[25,105] to provide key parameters needed for filling data gaps. The setting up and data processing of this system will be more complex than the first option. However, this option is backed by multiple national and international tests and research protocols developed from the early 2000s onward, and can used in combination with LPS.

LI-7200RS CO_2/H_2O Analyzer combined with 3D Sonic Anemometer: This is a premium, most highly resolved, research-grade system[25,106-107], providing minimal uncertainty of the 30-min flux measurements compared to open-path systems, and allowing extended operation in foggy and rainy environments.

It is an official standard of large-scale permanent national and international CO_2 flux observing facilities, such as ICOS[13,54] in Europe (Integrated Carbon Observation System, created by the EU Commission and funded by member countries) and NEON65 in the US (National Ecological Observatory Network, funded by NSF), after such facilities carefully tested various competing systems[108, 109]. It is also a part of their official measurement protocols[34,37,110].

This system will require an additional Biomet Module[25,105] to provide key parameters needed for filling data gaps. Setting up this system will also be more complex than the first option. The maintenance of this system is more complex than both 1st and 2nd options. LPS may be available for installation and data services with this option.

It is also important to consider that the instrument configuration for the LI-720 system or Carbon Node is preset, and has little room for error. However, configurations for LI-7500RS and LI-7200DS have recommended settings described in the respective manuals[111,112], but allow for significant flexibility regarding variables and rates, additional modules, and multiple choices of sonic anemometer models[25]. These potential combinations and options are outside the scope of this guide, can be briefly reviewed here[25, 124], and can be discussed with LI-COR Technical Support.

The selection of the data collection software is prescribed by the selection of the instrumentation listed above. However, the data processing, QC/QA, and integration software does have several options.

EddyPro Processing Software: This is the recommended software for raw data processing, converting fast data collected by the instruments into fluxes, and assigning quality flags. This software is a standard for most national and international flux networks, and is the most reliable, vetted, cited, and used software globally[25,113-116]. It does not compromise on intensive iterative calculations, the code is open, and versions are fully traceable. The configuration files with exact processing steps are automatically stored with each 30-60 min flux data file, to allow easy replication and auditing.

SmartFlux: SmartFlux[25,37,117] is a field microcomputer operating with LI-7500DS and LI-7200RS models that runs a subset of the EddyPro software configurable for specific models. SmartFlux devices also control instrument clocks via GPS, integrate and synchronize data sets, and compress and store data for remote access.

FluxSuite: FluxSuite[25,118-120] is a web-service connected to a network of SmartFluxes to allow monitoring the results from many stations, setting up alerts, and storing and accessing the computed fluxes. FluxSuite does not modify the data, and is used for site management and data sharing.

Tovi: Tovi[121-123] is an analytical software that works with EddyPro and SmartFlux results to further QA/QC the flux data, fill the missing gaps, visualize measurement footprints, and compute and integrate the final carbon product. As with EddyPro, Tovi stores configuration files with exact QA/QC and integration steps, and relevant reference publications, automatically to allow for easy replication and auditing.

Carbon Node: Carbon Node[103] is a complete (hardware, communication, and software) flux station, with a telescoping mast up to 5 m tall. Carbon Node includes an IoT module operating with the LI-720 sensor, and closely follows the EddyPro processing subset code configured for this specific model, computing 30-minute fluxes in real-time. It also performs daily cryptographic hashing to ensure the utmost security of the raw data. The output from the Carbon Node is similar to the output from a SmartFlux, and all applicable variables are aligned with FLUXNET standards.

LI-COR Cloud: LI-COR Cloud operates with the Carbon Node and utilizes many functions similar to FluxSuite and Tovi, but is now embedded into the web application. The processing within the Cloud is tightly controlled, and has strict standards for provenance, automated documentation, and raw data archive for easy replication and auditing.

Custom untested codes, closed black-box software, and any other untraceable or non-replicable codes, shall not be used for the collection, processing, QA/QC, analysis, and integration of flux data.

The LI-720 or Carbon Node shall be the default option due to its level of automation, low power, and low maintenance. However, there are two likely scenarios where other selections will take priority:

1. Existing research-grade station utilized in collaboration with another institution. With universities and networks operating many hundreds of flux stations, there is a good reason to partner with an existing research station for MMRV of local land use. In such cases, the station may already have LI-7500DS or LI-7200RS devices, but it shall be required to verify that the processing software and steps used by these stations are in compliance with the criteria described above, and are traceable and auditable.

2. Site with remarkable fog density or rain or snow frequency. In such cases, a combination of the LI-7200RS and Gill Anemometer is recommended to reduce gaps in the data created by fog or precipitation.

Table 1 presents a summary of each of the three solutions, as well as criteria suitable for MMRV via direct flux measurements.

	LI-720	LI-7500DS	LI-7200RS
Timing/synchronization protocol	GPS/PTP-like RTC	GPS/PTP	GPS/PTP
Response time for gas transport	Fast	Fast	Fast
Flux resolution	High	High	Very High
Ease of installation	Easy	Moderate	Moderate
Ease of maintenance	Easy	Easy	Moderate
Power requirements	Low	Low	Moderate
Automation level	High	Moderate	Moderate
Carbon Node operation	Yes	SmartFlux planned	SmartFlux planned
Computing software	Eddy-Pro-like	EddyPro	EddyPro
Analytical software	LI-COR Cloud	FluxSuite/ Tovi	FluxSuite/ Tovi
Calculation transparency	Full	Full	Full
Data QA/QC transparency	Full	Full	Full
Data gaps filling transparency	Full	Full	Full
Traceability: raw to final number	100%	100%	100%
Ease of Independent audit	Easy	Easy-to-Moderate	Easy-to-Moderate

Table 1. Essential categories and criteria for instrumentation suitable for MMRV via direct flux measurements: examples of three suitable solutions from LI-COR. The LI-7700 CH_4 gas analyzer is not shown as this guide is focused on CO_2.

Paired sites: Regardless of the choice, for paired sites, where business-as-usual baseline compared to new carbon management, the selection should aim for having the identical instrumentation and software configured in the identical manner.

Special cases: In special cases, such as working with an existing research-grade flux station, the equipment intercomparison and inter-calibration shall be performed between the two sites. These are outside the scope of this guide but can be discussed with LI-COR Technical Support or outsourced to LPS.

3.2 Custom instrumentation considerations

The lucrative nature of the growing carbon market spurred the development of multiple low-cost solutions and services purporting to provide the same high-quality carbon product as research-grade systems described above and used in the global research networks[25, 43-76].

Selection for the instrumentation shall be based on the actual performance of the devices and systems (as described above and in publications[12,25]) to assure that technology transfer of direct flux measurement methods from academia to carbon markets is done using appropriate hardware, and without degrading the quality of the carbon product.

Selection of the software shall be based on the tested and documented performance, openness of the source code, and transparency and traceability of each processing and QA/QC step. Software shall ensure that independent audits can examine individual steps and replicate the final carbon product starting with the raw data.

For example, the low-cost devices that have slow response time, too slow to capture gas transport, or use slow or undisclosed time protocol, thus requiring 50-250% corrections, shall not be used instead of higher-end research-grade or monitoring-grade devices with typical correction of 5-25%.

Paired sites: For paired sites, where business-as-usual baseline compared to new carbon management, the selection should aim for having the instrumentation where large correction or excessive modelling do not lead to the error bars overlapping the averages from both treatments, and rendering both treatments statistically the same. If custom instrumentation is used, the models, setup, and configuration need to be nearly identical between the two sites.

Special cases: In special cases, such as measuring CH_4 and/or N_2O alongside CO_2, the custom equipment may need to be carefully selected, set up, and configured for the additional GHG gases. This can be done relatively easily by a non-professional using the LI-7700 CH_4 analyzer, but not most other devices available on the market. These cases are outside the scope of this guide but can be discussed with LI-COR Technical Support or outsourced to LPS.

Station Setup

4

The flux station shall be installed at the site selected in Stage 2 and equipped with instrumentation selected in Stage 3. The details of station setup and configuration shall be documented for regulatory compliance or potential external audit, and added to the Monitoring report described in Stage 7.2.

4.1 Location within the measurement site

For standard measurements, the flux station shall be installed in the middle of the site selected in Stage 2 such that the station measures fluxes from the land use of interest from all or most wind directions[25].

The exact placement should avoid having a large, disturbed area in the immediate vicinity of the station such as a building, dense fencing, road, bare soil, or vastly different vegetation cover. Smaller disturbances within the 1-2 m radius around the station are allowed but should be minimized.

The placement should also avoid having vastly contrasting land use areas within the footprint of the station (50-100 times the measurement height above the vegetation), especially in the prevailing wind directions. For example, the grassland site of one management can have small patches of a grassland site with different management upwind from the station, but shall not have a large pond or an animal pen.

Some flexibility in the placement of the station can be achieved by trading off the instrument height. Flux stations cover an upwind area of 50-100 times its height above the vegetation, so if the site is large enough, the station can be placed off-center to avoid major disturbances upwind of the station, and bring the station closer to a power source or an access road.

In all cases, the preferred placement of the station within the site should be such that major disturbances of vastly contrasting land use areas are placed in the least frequent wind directions from the station.

Google Earth, Bing Aerial, satellite images, or other comparable map indicating the station location, GPS coordinates to at least 4th decimal in WGS84 World Geodetic System, wind rose at the site, and wide-angle photos of the station from N, W, S, and E directions shall be made, and added to the Monitoring report described in Stage 7.2.

Paired sites: For paired sites, where business-as-usual baseline compared to new carbon management, the sites shall have approximately the same placement within their respective sites. For example, if one of the two paired sites is located in the middle of the plot, the other site shall not be placed on the downwind edge of the plot.

Special cases: In special cases, such as very small plots or sites with major disturbances in an upwind direction, the station can be placed on the downwind edge of the plot in relation to the prevailing wind. Depending on wind distribution, such cases may require more than one station per plot. In another set of special cases, when using footprint apportioning or fluxmapping techniques[96-99], the site placement within the area may be guided by the distribution of plots of interest in a larger non-uniform area. Such cases are outside the scope of this guide but can be discussed with LI-COR Technical Support or outsourced to LPS.

4.2 Instrument placement height

For standard flux measurements, the minimum measurement height above short canopies should be at least 1 m above the vegetation top, and ideally equal to, or more than, 1.5 m. At the same time, the measurement height has to be 50-100 times less than the upwind length of the area of interest[25].

In all cases, if the size of the plot and uniformity of surrounding areas allow, the higher instrument placement shall have priority over the lower instrument placement to decrease corrections and improve the quality of the measurements:

- For example, a flux station placed in the center of an 800 m x 800 m field of the uniform 0.5 m soybean crop (Table 2), could strictly speaking have instrumentation as low as at 1.5-2.0 m height (1.0-1.5 m above vegetation top).
- However, a much better placement height would be around 4.0 m, as such high placement will minimize corrections and provide the most defensible results while still seeing the same field even when it is fallow with no crop (vegetation height of 0 m).
- If surrounding fields are also under the soybean managed in a similar manner, there can be a further advantage of putting the instruments even higher, up to 8.4 m above the soil surface.

For standard measurements, the instrument placement height remains a relatively flexible number, and optimal placement is very much dependent on the specific conditions at the site[25].

In most cases, the instrument height should be close to the recommended number or recommended maximum listed in Table 2, but it shall never exceed the absolute maximum listed in the table.

On the lower end, the instrument height should not be below the recommended minimum without a very good cause[25], and it shall never be lower than the absolute minimum listed in Table 2.

Paired sites: For paired sites, where business-as-usual baseline compared to new carbon management, the sites shall have approximately the same instrument placement height above the canopy top. For example, if one of the two paired sites has instruments placed 1.5 m above the canopy top, the other site shall not have instruments placed 4.5 m above the canopy top. The exception is if the new management has a completely different canopy. In such a case, the instrument placement height should be selected to allow approximately similar area coverage at both sites.

Special cases: In special cases, when using footprint apportioning or fluxmapping techniques[96-99], the instrument height may be much smaller or much larger than 1/50th or 1/100th of the plot radius. These approaches are outside the scope of this guide but can be discussed with LI-COR Technical Support or outsourced to LPS.

PLOT SIZE, m	CANOPY HEIGHT, m	0	0.5	1	1.5	2	2.5	3
		INSTRUMENT HEIGHT, m						
Marginal 200 x 200	Absolute min	1.0	1.5	2.0	2.5	3.0	3.5	4.0
	Recommended*	**2.0**	**2.4**	**2.7**	**3.1**	**3.4**	**3.8**	**4.1**
	Absolute max	2.0	2.4	2.7	3.1	3.4	3.8	4.1
Good 400 x 400	Absolute min	1.0	1.5	2.0	2.5	3.0	3.5	4.0
	Recommended*	**2.0**	**2.4**	**2.7**	**3.1**	**3.4**	**3.8**	**4.1**
	Absolute max	4.0	4.4	4.7	5.1	5.4	5.8	6.1
Excellent 800 x 800	Absolute min	1.0	1.5	2.0	2.5	3.0	3.5	4.0
	Recommended*	**4.0**	**4.4**	**4.7**	**5.1**	**5.4**	**5.8**	**6.1**
	Absolute max	8.0	8.4	8.7	9.1	9.4	9.8	10.1
Excellent 1000 x 1000	Absolute min	1.0	1.5	2.0	2.5	3.0	3.5	4.0
	Recommended*	**5.0**	**5.4**	**5.7**	**6.1**	**6.4**	**6.8**	**7.1**
	Absolute max	10.0	10.4	10.7	11.1	11.4	11.8	12.1
Excellent 1600 x 1600	Absolute min	1.0	1.5	2.0	2.5	3.0	3.5	4.0
	Recommended*	**8.0**	**8.4**	**8.7**	**9.1**	**9.4**	**9.8**	**10.1**
	Absolute max	16.0	16.4	16.7	17.1	17.4	17.8	18.1
Excellent 5000 x 5000	Absolute min	1.0	1.5	2.0	2.5	3.0	3.5	4.0
	Recommended*	**25.0**	**25.4**	**25.7**	**26.1**	**26.4**	**26.8**	**27.1**
	Absolute max	50.0	50.4	50.7	51.1	51.4	51.8	52.1
Excellent 10000 x 10000	Absolute min	1.0	1.5	2.0	2.5	3.0	3.5	4.0
	Recommended*	**50.0**	**50.4**	**50.7**	**51.1**	**51.4**	**51.8**	**52.1**
	Absolute max	100.0	100.4	100.7	101.1	101.4	101.8	102.1

Table 2. Lookup table with approximate ranges of instrument height placed above the soil surface for a centrally placed station over a square-shaped or circle-shaped uniform plot.

**Recommended number is for general guidance only: actual placement height highly depends on the size and shape of the plot, dynamic changes in vegetation height throughout the year, and land use type adjacent to the measurement plot.*

4.3 Instrument orientation

Instruments on the stations shall be oriented such that most of the physical obstacles (instrument's own structures, other instruments, supporting arms and booms, poles, tower, solar panels, etc.) are located in the least frequent wind direction[25], according to the wind rose constructed for the site in Stage 2.5.

Specifically, the vertical wind speed measurement path shall be free of any disturbances, and shall be oriented in such a way that the potential disturbances to the wind flow are located in the least frequent wind direction (Fig. 8).

For slopes with inclination angles less than 10 degrees, the vertical wind speed measurement can be oriented per gravity. For slopes with steeper inclination, the vertical wind speed measurement needs to be oriented perpendicular to the mean inclination angle of the slope in order to be perpendicular to the mean wind flow at the site.

Close-up photos of the instruments on the tower should be made, and added to the Monitoring report described in Stage 7.2.

Paired sites: For paired sites, where business-as-usual baseline compared to new carbon management, the sites shall have approximately the same instrument orientation in relation to their wind distribution. For example, if both sites have little to no winds from the SSE direction, both sites should have most of the physical obstacles placed SSE of the instrumentation.

Special cases: In special cases, when a horizontal boom is used with many flux instruments placed in a row, the boom shall be perpendicular to the most frequent wind direction, such that all paths of vertical wind speed measurements meet the same prevailing wind at the same time. This arrangement is not ideal but sometimes may be required, and can be further discussed with LI-COR Technical Support or outsourced to LPS.

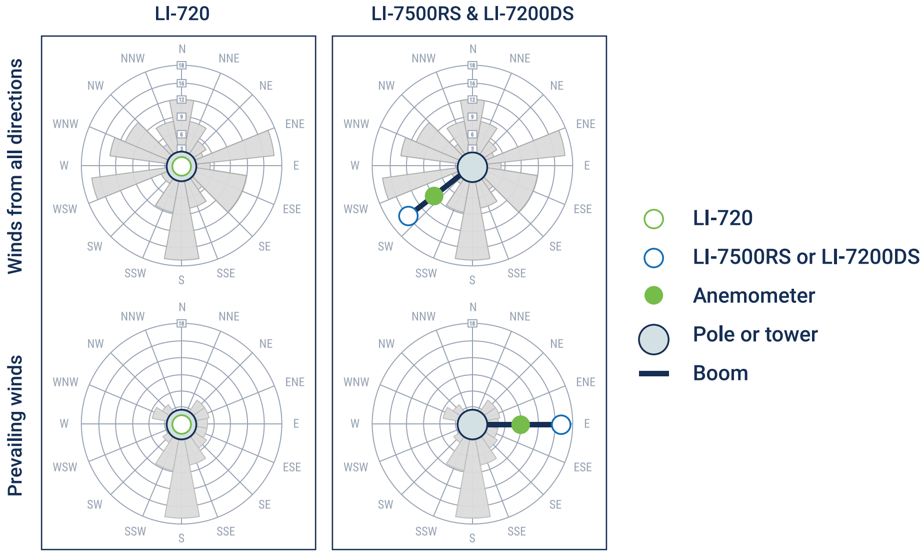

Figure 8. Examples of instrument orientation at the sites with omnidirectional winds and sites with prevailing wind directions for LI-720, LI-7500DS, and LI-7200RS flux stations.

4.4 Instrument configuration

Although typically pre-set at the factory and mostly automated, instrument configuration shall be checked before and during the field deployment, and a copy should be saved for the record. This information shall be entered into the system software during installation and updated if the configuration changes.

Factory calibration shall be performed prior to field deployment, and the calibration certificate shall be saved for the record. Both shall be dated, and added to the Monitoring report described in Stage 7.2.

The configuration for the LI-720 system or Carbon Node is fully preset, and has little room for error. The configurations for LI-7500DS and LI-7200RS have recommended settings described in the respective manuals[104-106], but allow for significant flexibility regarding variables and rates, additional modules, and multiple choices of sonic anemometer models[25]. These potential combinations and options are outside the scope of this guide, can be reviewed here[25,124], and can be discussed with LI-COR Technical Support or outsourced to LPS.

Open-source precision time protocol (PTP) or GPS/PTP-like real-time clock (RTC) protocol shall be used for the best possible time alignment of various data streams in the instrumentation. NTP, and slower protocols, as well as closed-source unverifiable protocols, shall be avoided.

Depending on the instrument model, the cabling, wireless access, and other technical installation steps should follow the procedures described in the manufacturer's use manual for the specific model.

Paired sites: For paired sites, where business-as-usual baseline compared to new carbon management, the sites shall have nearly identical instrument configuration. For example, if one site uses LI-7200RS with 10 Hz data collection with a 17 lpm sampling flow, another site should not use 20 Hz data collection with an 11 lpm sampling flow.

Special cases: When custom instruments are used at the flux station, it is essential to consult a professional. Errors over 1000% and data gaps lasting for months, and even years, have been recorded when custom instrumentation was not configured properly; even when run by national agencies and major universities. Such configurations should be discussed with LI-COR Technical Support or outsourced to LPS.

4.5 Initial checks

For the first two weeks after the installation, three sets of parameters shall be checked on a daily basis: data quality, status of remote access, and battery power drain (if on solar or wind power). Such checks will rapidly reveal if there are any issues with the site installation, and help diagnose and resolve most such problems.

Data quality should include checking for system notifications and quality flags in the data. These automated notices are the first indicators if something is not operating normally. The user manual will list system notifications and quality flags for specific instruments or software.

If there are no system notifications or bad flags, the weather parameters shall be checked for physically plausible ranges for a particular season or location. Temperature, humidity, wind speed, and atmospheric pressure should all be examined. For example, temperatures should not exceed 60°C or be below -60°C in general, but should be between 20°C and 35°C on a warm summer day in the middle latitudes.

If the weather parameters also look good, then the fluxes should be examined:

- First, sunlight intensity should be reviewed either by looking at the Net Solar radiation (Rn) or Photosynthetically Active Radiation (PAR). Both should have a bell-like shape on clear days following the normal sunlight intensity (Fig. 9). However, on cloudy and overcast days, both Rn and PAR can have very different irregular shapes. Daytime Rn or PAR are typically shown as positive numbers, while nighttime Rn values are negative and PAR values are zero.

- Then, sensible heat flux (H) shall be examined. The H shows the amount of heat going from the surface and into the air, and should follow the Rn or PAR. Depending on the sign convention of the software, the H can be a positive or negative number. Nighttime H has typically the opposite sign than the daytime H.

- Next, latent heat flux (LE) shall be examined. The LE shows the amount of energy used to evaporate water from the surface and into the air, and should also follow the Rn or PAR. Depending on the sign convention of the software, the LE can be a positive or negative number. Nighttime LE is typically near-zero.
- Finally, CO_2 flux (Fc) shall be examined. With a green healthy vegetation, the Fc shall follow Rn or PAR as well, and have opposite signs during daytime and nighttime. However, with no vegetation or dead vegetation, Fc can have the same sign during day and night following the Rn or PAR or can simply be near zero.

After checking all of the above, the status of remote access shall be examined to make sure the data transfer is happening correctly. This can be done by looking at the file transfer records making sure all expected files are transferred and are of the expected size, opening the files and checking them for corruption, making sure the transfer time is normal, and checking that each file has the expected number of rows.

Finally, the battery power drain shall be checked at the sites with solar or wind power and a battery bank, to make sure the system does not slowly drain the batteries. For sites with grid power, the quality of the power can also be examined in the first few days after the installation.

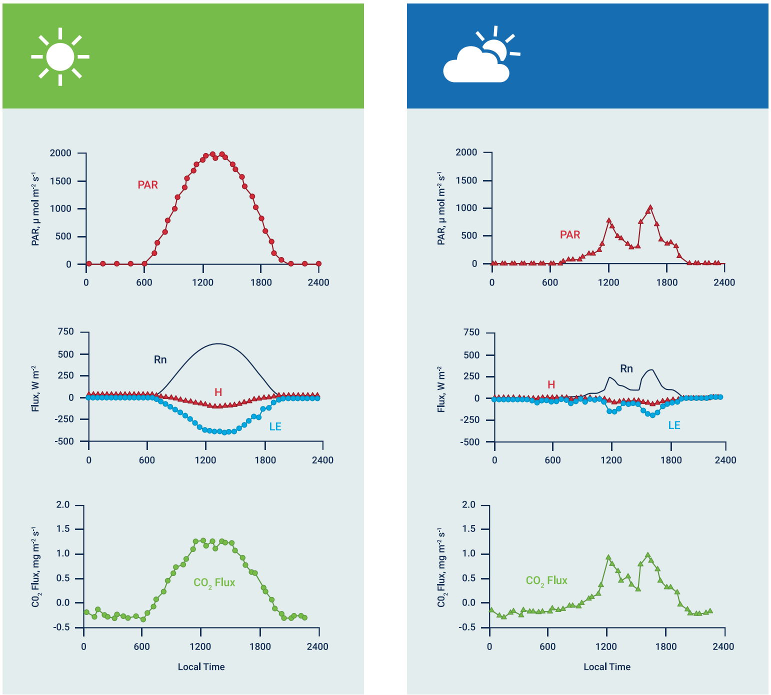

Figure 9. Examples of normally-looking fluxes on sunny and cloudy days during summer with green vegetation[25].

Data Collection

5

The flux station shall be maintained in working order to ensure continuous data collection. The station configuration, raw data, maintenance and field logs shall all be updated and kept for regulatory compliance, transparency, and traceability, as well as potential audits. These shall be added to the Monitoring report described in Stage 7.2.

5.1 Ongoing monitoring

After the initial data check in Stage 4.5, the ongoing results shall be checked at least bi-weekly to ensure consistent data quality.

Regardless of the choices in Stage 3, the LI-COR systems will generate daily summaries with quality assessment, as well as instant notifications of issues at the site. These notifications shall be evaluated, and site maintenance provided in order to prevent gaps or inaccuracies in the data.

For standard measurements, data shall be collected for a minimum recommended period of one year to capture seasonal variations and to obtain statistically robust estimates. For treatment studies, the monitoring period may be reduced to the duration of the treatment.

Paired sites: For paired sites, where business-as-usual baseline is compared to a new carbon management, the ongoing monitoring shall be conducted at similar time frames to avoid mismatching gaps at one site vs another.

Special cases: In special cases, when the study site is extremely remote, and no wireless connection is available, the summaries and notifications are not possible. In such cases, it is recommended to have physical bi-weekly downloads of the data from the station by a local contractor who can then send them electronically for inspection.

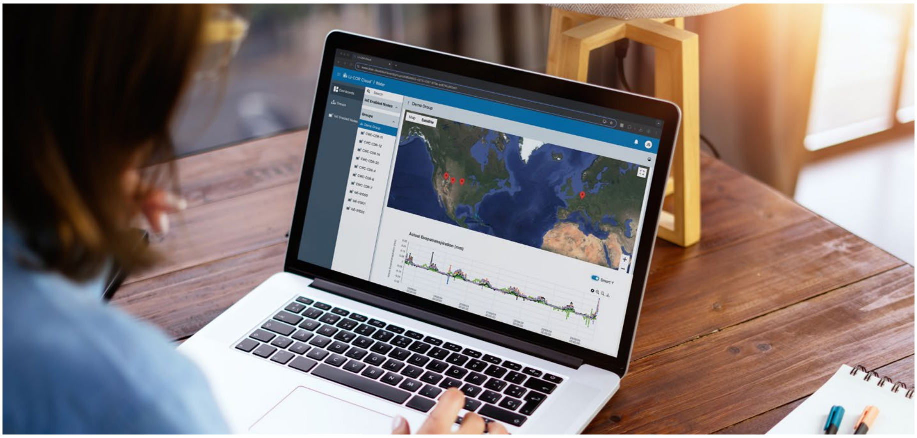

Figure 10. Example of ongoing station monitoring of the flux station using LI-COR Cloud software.

5.2 Ongoing station maintenance

After initial maintenance at Stage 4, the ongoing maintenance shall adhere to the plan developed in Stage 1.2. In the first week, the station shall be checked every other day. In the first month, the station should be checked at least bi-weekly. After the first month, the maintenance schedule shall be adjusted depending on site conditions such as dustiness, precipitation frequency, likelihood of salt deposition, etc.

In all cases, the site should be maintained at least once per two months, with the following steps:

- Inspection diagnostic flags and overall data quality (e.g., reasonable numbers for temperature, humidity, fluxes)
- Inspection and cleaning of windows, mirrors, and other measuring elements
- Inspection and cleaning of solar panels
- nspection of battery bank capacity
- Inspection of cables and connectors for cracks, corrosion, and other visible damage
- Inspection of the area immediate to the station for major disturbances
- Inspection and replacement of filters and pumps if needed per factory manual
- Replacement of internal chemicals on a half-yearly or yearly basis per factory manual, which may include user calibration check

- Replacement of devices requiring yearly or bi-yearly factory calibrations with spares, and reconfiguration of the spares if needed
- Logging time of the visit and all the above steps in the electronic or physical field log

Paired sites: For paired sites, where business-as-usual baseline compared to new carbon management, the ongoing maintenance shall be conducted at similar time frames to avoid mismatching data gaps at one site vs another.

Special cases: In special cases, when the study site is extremely remote it is recommended to hire and train a local contractor who can provide the routing maintenance over the yearly period, except for replacement of the devices for factory calibrations.

Figure 11. Visual inspection of flux station's cables and connectors for cracks, corrosion, and other visible damage.

5.3 Keeping field logs and other documentation

Site maintenance visit logs, documented changes in station setup or configuration, documented changes in land use or site management (agricultural operations, cattle grazing, prescribed burn, etc.), and other field log documentation, as well as the entirety of the collected raw data, shall be updated and kept for regulatory compliance, transparency, and traceability, in the form easily accessible to the audit or replication. These shall be added to the Monitoring report described in Stage 7.2.

All LI-COR software have provisions to streamline this process. Tovi and Cloud software track every processing and analytical step and allow saving the configuration in an external file. Such files need to be saved every time the configuration is changed. LI-COR Cloud documents the processing and reports the provenance for potential replication and audit, while raw data integrity is protected by daily cryptographic hashing to ensure the utmost security. EddyPro does not require any special tracking because it stores its configuration with every 30-60 minute flux data file.

If using professional services, the above shall be requested as a part of the contract agreement.

Data Processing and Quality Control

6

Document all configurations and data processing steps, including algorithms, software used, assumptions made, and the raw and processed data. These shall be updated and kept for regulatory compliance, transparency, and traceability, as well as potential audits. These shall be added to the Monitoring report described in Stage 7.2.

6.1 Data processing

For standard measurements, raw data will be processed into 30-min flux data automatically on-site, using established and well-documented EddyPro Software[25,113,114] run on a SmartFlux computer for LI-7500DS and LI-7200RS systems[25,104-112]. The configuration, the actual code, and the processing steps are all transparent, recorded and saved during the process, and open to inspection and replication.

For the LI-720, the processing code closely follows the EddyPro subset configured specifically for the LI-720 sensor, open to audit and replication in a similar fashion to the EddyPro outputs.

The processing automatically filters raw high-frequency data to remove spikes, outliers, and flags non-turbulent periods using established data quality control procedures, performs flux calculations, applies frequency and density corrections, and computes quality flags for each 30 min period, according to ICOS and AmeriFlux standards.

The processing software requires manual inputs of a few user-specific data, such as instrument height, vegetation height, orientation of the system, etc. Such inputs shall be done during installation and prior to station operation, so they will be automatically recorded with processing configuration for each 30-minute period. It is important to inspect these inputs to avoid human error and the need for recalculation.

With rapidly growing tall vegetation (such as corn, reed, or elephant grass) the vegetation height may need to be adjusted every few weeks. This shall be recorded and entered into the processing configuration, dated, and saved for the record. Similarly, the records shall be created dated, and saved in the rare cases when the measurement height may need to be adjusted. For example, in a small field with tall vegetation after the harvest.

Paired sites: For paired sites, where business-as-usual baseline compared to new carbon management, the sites shall have nearly identical processing configuration except for small differences in site-specific inputs.

Special cases: In special cases, customized processing may be required for non-standard sites, highly unusual weather regimes, or unique experiment designs. Customized processing is outside the scope of this guide but can be discussed with LI-COR Technical Support or outsourced to LPS.

6.2 Quality control

Data quality control shall exclude all bad data according to data quality flags[125,126] reported by the EddyPro flux processing program[113,114]. It shall also include plausible range inspection and exclusion of the data outside such a range.

These are done automatically for the Carbon Node on LI-COR Cloud, and can be done semi-automatically for the LI-7500RS and LI-7200DS systems using the data management software Tovi. Both approaches provide a history of changes for further documentation.

Occasional outlier data points shall be excluded manually after careful visual inspection. The utmost care should be taken to avoid excluding data points without strong physical reasoning, such as for example, relative humidity over 100%, negative wind speed, or 70°C temperature in winter.

Finally, occasional outliers shall be examined against field logs (Stage 5.3) and removed due to site events such as site maintenance, changes in station setup or configuration, active site management (agricultural operations, cattle grazing, prescribed burn, etc.), and other field activities affecting the measurements.

LI-COR 2-day training for the personnel[127] responsible for data QC/QA at LI-COR's Lincoln, Nebraska, headquarters is highly recommended to ensure reliable QC/QA. Alternatively, LPS can be utilized to provide such training onsite. Finally, a research organization experienced in data QC/QA can be contracted to complete the data QA/QC procedure.

All data exclusions shall be done such that the original uncleaned data are preserved and remain available for potential audit or inspection. Data QC/QA procedures, including plausibility ranges and reasons for manual data exclusion, shall be documented and kept for the record.

Paired sites: For paired sites, data QA/QC procedures should be done in a nearly identical manner. Small differences in plausibility ranges or manual point removal are acceptable, but should be minimized.

Special cases: In special cases, when customized processing was required for non-standard sites, highly unusual weather regimens, or unique experiment designs, the QA/QC procedure may need to be customized. This can be discussed with LI-COR Technical Support or outsourced to LPS.

6.3 Filling data gaps

Missing data shall be filled by established gap-filling techniques[25,121,122], using methods such as regression-based models or climatological approaches, as well as more sophisticated tools[128-129]. Averages shall not be used to fill the data gaps, as this will bias the results towards the periods with the least gaps, typically sunny middays.

Filling the data gaps is done automatically by the Carbon Node on the LI-COR Cloud, and can be done semi-automatically for the LI-7500RS and LI-7200DS systems using the data management software Tovi[121,122]. Both approaches utilize the well-established, tested, and verifiable gap-filling procedures[130], and provide a history of changes for further documentation.

Analytical techniques to determine the uncertainties, including those created by gap-filling procedures, can be done using Monte-Carlo and other methods[129-138], but these are not required if the described above tools have been used for gap-filling. If desired, LPS can be contracted to provide assistance with gap-filling related flux uncertainties.

Paired sites: For paired sites, where business-as-usual baseline is compared to a new carbon management, the gap-filling approaches shall be identical to avoid biasing the results.

Special cases: In special cases, when customized processing and data QA/QC were required for non-standard sites, highly unusual weather regimens, or unique experiment designs, or in case of very large gaps, the gap-filling procedure may need to be customized. This can be discussed with LI-COR Technical Support or outsourced to LPS.

6.4 Integration

After data have been properly cleaned and missing data have been gap-filled, the integration shall be done in time and space.

When using LI-COR Cloud or LPS, this step will be done automatically. However, when using LI-7500RS or LI-7200DS systems, or custom devices or software, the integration will need to be done manually.

Integration in time: Integration in time shall be computed as a cumulative sum of all the gap-filled data available from the site. One has to be careful with units when creating the cumulative sum.

For example, CO_2 flux from the station can be reported in micromoles of CO_2 per m^{-2} s^{-1} every 30 minutes. One shall first convert this number to a total flux over a 30-minute period:

$$\mathbf{X\ \mu mol\ CO_2\ m^{-2}\ s^{-1} = X{*}1800\ \mu mol\ CO_2\ m^{-2}\ 30\ min^{-1}} \qquad \mathbf{[1]}$$

These 30-minute numbers can then be summed up over the entire period of time.

Likewise, fluxes are sometimes reported every 60 minutes. One then shall first convert this number to a total flux over a 60-minute period:

$$\mathbf{X\ \mu mol\ CO_2\ m^{-2}\ s^{-1} = X{*}3600\ \mu mol\ CO_2\ m^{-2}\ 60\ min^{-1}} \qquad \mathbf{[2]}$$

These 60-minute numbers can then be summed up over the entire period of time.

After the sum over the entire period has been computed in flux station units, the number can be converted into other popular MMRV units, that are better understood by the MMRV professionals.

The conversion from typical flux station units (μmol CO_2) to typical MMRV units (t CO_2) can be done as follows:

$$\mathbf{X\ \mu mol\ CO_2\ m^{-2}\ p^{-1} = 0.00000000004401{*}X\ t\ CO_2\ m^{-2}\ p^{-1}} \qquad \mathbf{[3]}$$

Where *p* is the period of time.

The look-up Table 3 lists conversion factors for other frequently used units. For example, if the total sum of all half-hourly fluxes over the entire year of measurements was 100000000 μmol of CO_2 m^{-2} y^{-1}, this number can be converted to tons of CO_2 m^{-2} y^{-1} as follows: 100000000 μmol CO_2 m^{-2} y^{-1} = 0.0044 t CO_2 m^{-2} y^{-1}.

Depending on the units and periods, the following additional information may be useful for the proper integration in time:

- 1 mol CO_2 = 44.01 g CO_2 = 12.0027 g C-CO_2, where C-CO_2 is amount of carbon contained in CO_2

- The total over the period does not have to be computed as a rate per standard time period (e.g., per hour, day, or year), but can be computed as a sum over the actual non-standard period by summing up all gap-filled data over that period
- Most current MMRV protocols operate on a yearly basis, so the yearly rate/ yearly sum will likely have to be used for further integration in space

Integration in space: After integration in time has been completed, the integration in space shall be computed as a conversion of the cumulative total over the land use area.

The conversion from typical flux station area units (m^2) to typical MMRV area units (ha) can be done as follows:

$$\mathbf{X\ t\ CO_2\ m^{-2}\ p^{-1} = 10000{*}X\ t\ CO_2\ ha^{-1}\ p^{-1}} \qquad \textbf{[4]}$$

The look-up Table 4 lists conversion factors to other frequently used units. For example, if the total time-integrated sum was 0.005 tons of CO_2 m^{-2} y^{-1}, it can be converted to tons of CO_2 per hectare as follows: 0.005 t CO_2 m-2 y^{-1} = 50 t CO_2 ha^{-1} y^{-1}.

Final reported number: Most current MMRV protocols operate on a basis of actual land use area characterized by the measurements, so the standard units per area will need to be converted to represent the actual land use area.

For example, if a station reported an uptake of 1 t CO_2 ha^{-1} y^{-1} over the grassland area of 3 hectares, the total reported uptake would be 3 tons of CO_2 over that land use area per year.

Paired sites: For paired sites, where business-as-usual baseline compared to new carbon management, the sites shall have identical integration periods and areas. For example, if one of two paired sites was integrated over 365 days and an area of 1 hectare, the other site shall also be integrated over 365 days and an area of 1 hectare.

Special cases: In special cases, when using footprint apportioning or fluxmapping technique[96-99], the integration process may differ from the one described above. This is outside the scope of this guide but can be discussed with LI-COR Technical Support or outsourced to LPS.

Flux Units	MMRV Units			
	t CO_2 $m^{-2}d^{-1}$	t CO_2 $m^{-2}y^{-1}$	t C-CO_2 $m^{-2}d^{-1}$	t C-CO_2 $m^{-2}y^{-1}$
10 µmol CO_2 $m^{-2}s^{-1}$	0.000038	0.0139	0.000010	0.0038
10,000 µmol CO_2 $m^{-2}h^{-1}$	0.000011	0.0039	0.000003	0.0011
1,000,000 µmol CO_2 $m^{-2}d^{-1}$	0.000044	0.0161	0.000012	0.0044
100,000,000 µmol CO_2 $m^{-2}y^{-1}$	0.000012	**0.0044**	0.000003	0.0012

Table 3. Conversion *in time* of typical flux station units to typical MMRV units over the periods of one second (s), hour (h), day (d), and year (y). C-CO_2 is the amount of carbon contained in CO_2.

Flux Units	MMRV Units		
	t CO_2 $km^{-2}y^{-1}$	t CO_2 $mile^{-2}y^{-1}$	t CO_2 $ha^{-1}y^{-1}$
0.00001 t CO_2 $m^{-2}d^{-1}$	3650	9453	36.5
0.005 t CO_2 $m^{-2}y^{-1}$	5000	12950	**50.0**
	t C-CO_2 $km^{-2}y^{-1}$	t C-CO_2 $mile^{-2}y^{-1}$	t C-CO_2 $ha^{-1}y^{-1}$
0.00001 t C-CO_2 $m^{-2}d^{-1}$	995	2578	10.0
0.005 t C-CO_2 $m^{-2}y^{-1}$	1364	3532	13.6

Table 4. Conversion in *space* of typical flux station units to typical MMRV units over the areas square kilometer (km), square mile (mile), hectare (ha).

Reporting and Documentation

7

The goal of the reporting phase is to ensure that data on carbon flux measurements is accessible to various users, customers, and stakeholders. This process promotes transparency and allows for independent checks of the provided data.

Stakeholders involved in the project are required to create, maintain, and keep all the documentation described in Stages 1-6, and attach it to pre-implementation and monitoring reports for regulatory compliance or potential external audit.

Four types of reports[139] are essential:

1. **A report before the project begins:** Pre-implementation Report, or Project Description
2. **A report at the start of the project:** Initial report
3. **Reports every six months:** Ongoing reports
4. **A report at the end of the project:** Final report

7.1 Pre-implementation report

This report shall encompass a comprehensive description of the project:

- Geographical boundaries: The precise location and geospatial map as outlined in Stage 2, satellite images of the area, and other related documentation from Stages 1 and 2
- Temporal boundaries: The duration of the project, including the duration of baseline measurements if any
- Business as usual management records: A summary of the historical activity data for the different sites to be evaluated, including detailed land cover and land use description
- Intervention scenario records: The spatial boundaries and identification of the alternative treatments or management, and a summary of the projected activity data concerning the implementation of such practices
- De-risking and cost optimization description and maintenance plan created in Stage 1

- Initial options, criteria for selection, and final site selection recommended in Stage 2
- Initial options, criteria, and final hardware and software selection done in Stage 3
- Any additional documentation produces for the record in stages 1-3

7.2 Monitoring reports

Initial report must include:

- The summary of the site installation
- Wide-scale and close-up photos of the station and instrumentation
- Documents with exact instrument and software configuration on the date of installation
- Raw and processed data from the first 2 weeks of operation
- List of changes to original installation, configuration, or maintenance plan resulting from first 2 weeks of operation
- Any additional documentation provided in Stages 4.1-4.4

Ongoing reports should contain:

- Raw and processed data from the period of operation
- List of changes to installation, configuration, or maintenance plan during the reported period
- List of changes to land use or carbon/land management during the reported period
- Any additional documentation produced in Stages 5 and 6

Final report shall cover:

- The adjusted and updated information from the Pre-implementation report (Sec 7.1)
- The adjusted and updated information from the Initial report (Sec 7.2)
- List of changes to installation and configuration throughout project duration
- List of changes to land use or carbon/land management throughout the project duration

- List of changes to the maintenance plan throughout the project duration
- List of changes to processing, QA/QC, and gap-fill procedure throughout project duration
- The final summary of cleaned and gap-filled data (Sec 6.3)
- The final summary of integrated, geotagged data (Sec 6.4)
- Any additional hand-off information important for carbon sequestration analysis, MMRV, or carbon credit-issuing entity
- Any additional documentation produced in Stages 1-6

Independent Review, Verification, Auditing

8

All reports, both initial and monitoring, need to be reviewed and endorsed by a professional specializing in direct flux measurements. This professional should be trained and accredited by a recognized and certified university or other institutions or organizations with deep expertise in direct flux measurements.

Independent Review: The review and endorsement certify the accuracy of the information provided, including site selection, station setup, data collection, processing, QA/QC, and integration procedures. A brief CV of the professional, showcasing their experience (which could be academic and/or professional), should be attached.

Verification: Verification refers to the independent process of checking the accuracy and reliability of the reported information or the procedures used to generate that information[139]. This process provides feedback on measurement/monitoring methods and procedures, leading to improvements in reporting. It also provides quality assurance and quality control that enhances the use of direct flux measurements for MMRV. Verification must be conducted independently of monitoring and reporting processes. Individuals or companies unaffiliated with project owners shall be responsible for verification.

Auditing: Auditing may be done by periodically subjecting the reports to spot-checking by external reviewers from an independent organization or regulatory entity. This is done to establish completeness and reliability. Verification helps to ensure accuracy and conformance with any established procedures, and to provide meaningful feedback for future improvement.

Certification: LPS can be utilized to provide training and certification for the portion of the project dealing with direct flux measurements done by the flux station over a specific area (Fig. 12).

LI-COR and LPS cannot provide the certification, verification, or auditing related to the entire project, including the appropriateness of chosen sites for carbon MMRV baseline, implemented carbon management methods, high-resolution flux mapping, scaling of flux measurements between the flux stations, conversion of carbon numbers to carbon credits, etc.

However, LPS can be contracted as part of the project management to connect the stakeholders to organizations and companies that can provide such services.

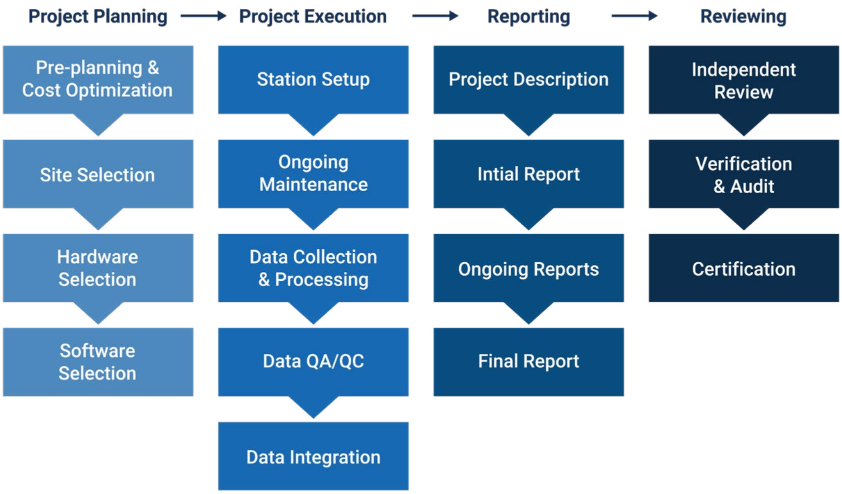

Figure 12. Outline of the planning and execution workflow utilizing direct flux measurements for assessment and verification of carbon sequestration and GHG emission rates over crops and grasslands.

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Key Plain-Language Terminology

The list below contains simple operational plain-language explanations, helpful for practical understanding in the context of this Guide. These are not the complete scientific or legal definitions.

Allometric measurements: relating the size or shape to some other characteristic; for example, approximating the carbon content of the forest by measuring tree height and diameter.

Analyzer: or gas analyzer, the device that measures gas concentration.

Anemometer: a device that measures wind, including vertical motions.

AWS: automated weather station, a typical weather station that can be found near an airport, school, or mountain pass.

Direct measurements: measurements where an entity of interest is actually measured with a device, in oppose to modelling or approximation from some other parameters.

Direct flux measurements: direct measurements of the transport of gasses or heat between the surface and the air, when the concentration of the entity and speed of the vertical transport in-and-out of the atmospheric air are directly measured with devices, in oppose to modelling.

Fields and Grasslands: here we define these as any dryland areas with canopy height below approximately 4 m, ranging from deserts to elephant grass, but excluding giant bamboo.

Flux: the rate of vertical transport of GHGs, water vapor, or heat into and out of the atmospheric air; flux from the surface into the air is often called emission or release; flux from the air into the surface is often called sequestration, removal, or uptake.

Flux station: a station similar to AWS, but measuring fluxes in addition to weather parameters.

Footprint: or fetch, the area covered by flux station measurements.

Eddy covariance: measurement method typically deployed by flux stations.

Emission: release of gas from the surface and into the atmospheric air.

Exchange: emission or uptake of entity between the surface and the atmospheric air.

FTE: the full-time equivalent of time required to accomplish a task, FTE=1 is 40 hours per week.

GHG: greenhouse gas; CO_2 = carbon dioxide; N_2O= nitrous oxide; CH_4 = methane.

LI-COR Technical Support: complimentary services provided to assist customers with issues related to their LI-COR products.

LPS: LI-COR Professional Services, fee-based consulting, project management, instrument leasing, installation, maintenance, and data services.

Mesonet station: a fully equipped research-grade Automated Weather Station.

MMRV: or MRV, refers to measurement, monitoring, reporting, and verification. Here, the term MMRV is used most broadly, in oppose to one of the specific process definitions used by various regulatory and carbon trading agencies.

NEE: net ecosystem exchange, amount of CO_2 removed from the air or added into the air by a surface area.

Sequestration: removal of gas from the atmospheric air, typically used for long-term removal; similar term 'uptake' is typically used with short-term or undefined-term removal.

Soil core: a continuous soil sample taken with a soil probe to a specific depth.

QA/QC: Quality assurance/quality control.

Uptake: removal or sequestration of gas from the atmospheric air by the surface.

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