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Article

Commercial forest carbon protocol over-credit bias delimited by zero-threshold carbon accounting

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Abstract: Despite the use of commercial forest carbon protocols (CFCPs) for more than two decades, claiming ~566 $MMtCO_2e$ and a market value of ~USD $15.7 billion, comparative analysis of CFCP methodology and offset results is limited. In this study, five widely used biometric-based CFCPs are characterized, and common characteristics and differences are identified. CFCP claims of net forest carbon sequestration are compared with results of directly measured CO_2 by eddy covariance, a meteorological method integrating gross vertical fluxes of forest and soil carbon, and the only alternative non-biometric source of net forest carbon sequestration data available. We show here that CFCPs share a structural feature delimiting forest carbon values by zero-threshold carbon accounting ($gC\ m^{-2} \leq 0$), a pattern opposite to natural emissions of forest CO_2 exchange based on direct measurement and a fundamental biological constraint on net forest carbon storage (i.e., soil efflux, ecosystem respiration). Exclusion of forest CO_2 sources to the atmosphere precludes net carbon accounting, resulting in unavoidable over-crediting of CFCP project offsets. CFCP carbon results are significantly different from global forest CO_2 net ecosystem exchange population results (FluxNet2015 $gC\ m^{-2}$) at the 95% to 99.99% confidence levels, inferring an annual median error of ~247% ($gC\ m^{-2}$), consistent with over-crediting. Direct CO_2 measurement provides an urgently needed alternative method for commercial forest carbon products that has the potential to harmonize global markets and catalyze the role of forests in managing climate change through nature-based solutions.

Keywords: American Carbon Registry; California Action Reserve; California Air Resources Board; VERRA; Clean Development Mechanism; net ecosystem exchange

1. Introduction

Commercial forest carbon sequestration protocols, by design, exclude direct measurement of forest CO_2 sources and sinks, relying instead on limited forest mensuration (e.g., 6 to 12 years), proxy forest data and growth simulation models to estimate annual changes in forest carbon sequestration [1]–[5], similar to those used in the timber industry [6], [7]. Incomplete carbon accounting introduces uncertainty and risk for CFCP results, calling into question the commercial value of forest carbon offsets, emphasizing the need for improvement in CFCP methods [8]–[11]. Evaluation of CFCPs is an urgent matter considering ~ 566 million metric tons of claimed forest carbon emission reductions with a value of USD ~$15.6 billion have accumulated over the last two decades since the inception of the Kyoto Agreement [12], [13] and the Clean Development Mechanism protocol [14]. In contrast, direct independent measurement of net forest carbon sequestration, an alternative net forest carbon data method addressing the stated objective of CFCPs [15], [16], can also be determined by universally accepted eddy covariance methods resulting

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in hourly to annual changes in net ecosystem exchange for forest carbon (NEE) [17]–[21]. Importantly, NEE integrates the balance between ecosystem gross vertical fluxes of carbon stored through photosynthesis (Gross Primary Production, GPP) and that lost via respiration of soils and trees (R_{eco}; comprised of heterotrophic and autotrophic respiration) [22], (NEE = GPP + R_{eco}) [18], typically including an inventory of standing biomass and removals [23]. NEE interannual variability and corresponding R_{eco} versus GPP data for global forests provide population values and ranges reflecting known natural forest carbon dynamics [24]–[26], integrating geographic and biological factors [24]. NEE is the only independent, non-biometric alternative database freely available for comparison with CFCPs [24], [25]. Regardless of methods employed, the determination of the net reduction in atmospheric CO_2 emissions by sequestration of forest ecosystems, creating offsets (e.g., project based reductions) [27], [28] and the right to sell carbon credits (i.e., metric one ton CO_2e) [29], or offset credits [30], is the universal figure of merit for commercial purposes considered in this study, bridging the gap between science and commerce [31]. Voluntary and compliance markets transact diverse offset trading irrespective of underlying protocols [32], [33]. Scientific results may not support commercialization of carbon products (e.g., protocol, regulatory requirements) [11], [34]–[36], a topic explored in this study.

Methodological similarities and differences for the California Air Resources Board (CARB) [1], Climate Action Reserve (CAR) [37], American Carbon Registry (ACR) [38], Clean Development Mechanism (CDM) [14], [39], the Verified Carbon Standard (VERRA) [40], and the eddy covariance approach [18], [19], are described followed by analysis of available forest carbon sequestration project data. NEE global population data [25] are employed in this analysis for comparison with reported CFCP results in the universal units of gC m^{-2} $year^{-1}$, or day^{-1}. We summarize differences between methods and results, and statistically analyze the annual and/or daily values and overlapping time series for CFCPs and NEE. Results are discussed in the context of the requirements to fully account for forest carbon offsets, specifically the importance of ecosystem respiration and identifying features of CFCP data that are not reflective of natural forest carbon cycling. The impacts of incomplete carbon accounting on landholders and carbon markets are discussed, including the benefits of NEE commercialization applied to the Paris Agreement [41], [42] and policy platforms such as the Reducing Emissions from Deforestation and forest Degradation (REDD+) [43]. The limitations of NEE are addressed while improvements for CFCPs and collaboration with forest eddy covariance research are suggested.

2. Materials and Methods

2.1. CFCP Comparative information and site locations

The features for each commercial forest carbon protocol were obtained from respective websites for the CARB, CAR, ACR, CDM, and VERRA protocols. Sources of eddy covariance results expressed as net ecosystem exchange (NEE; gC m^{-2} $year^{-1}$ (y^{-1}), or day^{-1} (d^{-1})) are also provided. Table 1 summarizes the features of CFCPs and NEE methods; annotations and citations are provided in Appendix 1 (A1.Annotations). Site locations are shown in Figure 1 as excerpted from the sources in Table 1. The CFCPs have 421 projects, covering 1,214 project years. The NEE FluxNet2015 comparative data consisted of 206 sites covering 1,448 project years [25]; daily values for NEE were also acquired from FluxNet2105 (545,323 days)[25] for comparison with VERRA data, the only CFCP that employed a daily carbon data format (6,466 days). Data sources are noted for each individual protocol in Table 1.

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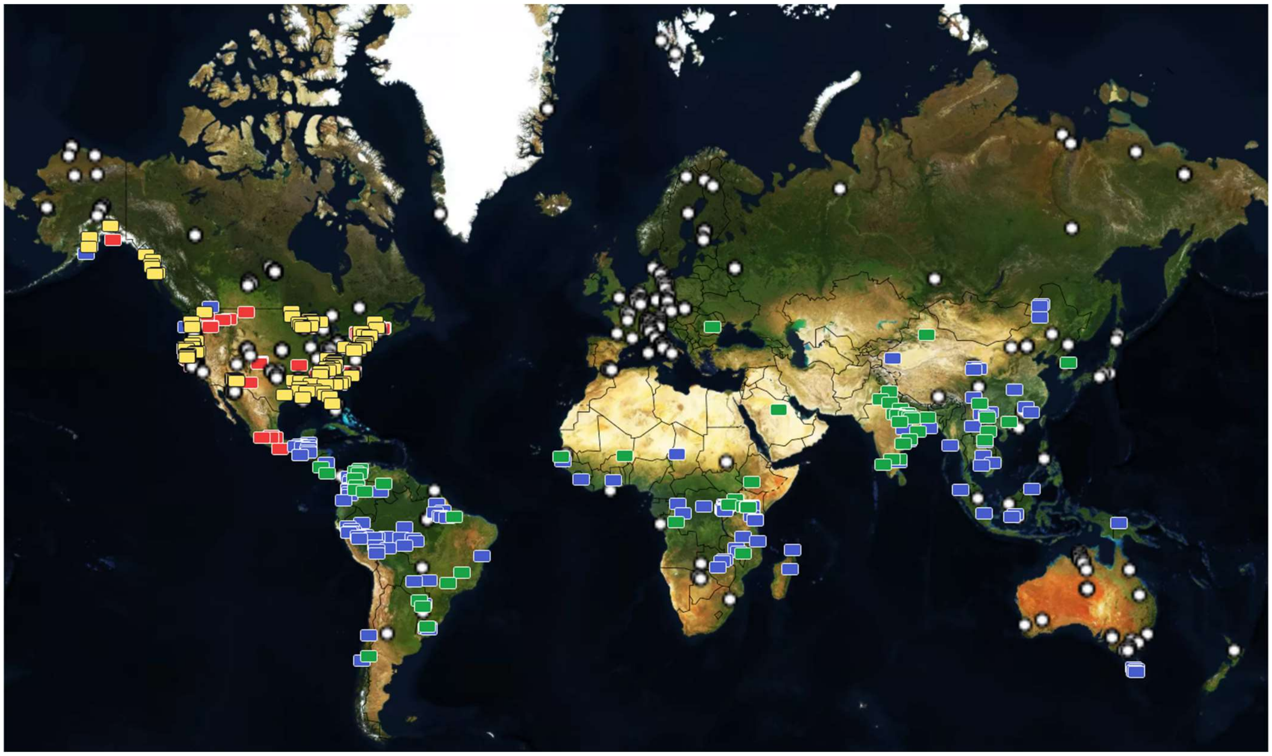

Figure 1. Site locations for data used in this study. FluxNet2015 NEE (white dots), CARB-CAR (red rectangles), ACR (yellow rectangles), VERRA (purple rectangles) and CDM (green rectangles) sites are shown. An interactive full resolution map can be found at: https://planetalphaforest.earth/map/. The online version of the map has three layers that can be turned on/off to better analyze each location. These layers show the Koppen climate classification, biome regions and a land cover division. Users can also zoom in/out and move around the online map.

2.2. Data collection

Each protocol database was built row by row by finding project areas, credits issued, dates, locations, and any information that could be relevant from each project documents. All the links and columns used are listed in Table 1. After following the protocols main links and selecting their corresponding project categories, each project documents were accessed from its link. Then, the project size was retrieved from its respective file while the offset values were copied from its own documents (CARB-CAR and ACR) or from a table (CDM and VERRA) as summarized in Table 1. According to available project data, 13% of projects analyzed were identified as REDD+ projects, while 22% and 78% from CARB-CAR were identified as avoided conversion and improved forest management projects, respectively. The CDM projects consisted exclusively of afforestation and reforestation projects.

Table 1. Data collection sources need to build each protocol dataset.

	CARB-CAR	**ACR**	**CDM**	**VERRA**

Main link	https://thereserve2.apx.com/myModule/rpt/myrpt.asp?r=111	https://acr2.apx.com/myModule/rpt/myrpt.asp?r=111	https://cdm.unfccc.int/Projects/projsearch.html	https://registry.verra.org/app/search/VCS
Project categories	"Improved Forest Management" and "Avoided Conversion"	"Forest Carbon"	"Afforestation and Reforestation"	"Agriculture Forestry and Other Land Use"
Project link	Under the column "Documents"	Under the column "Documents"	Project name	Project name
Project size document	Labeled as "Projects submittals"	Labeled as "Listing Form" or "Project Submittal"	Labeled as "Project design"	With "Description" in the name of the document
Offset tabs/ documents	Tab "Project Emission/Reductions"	"Verification Statement" documents	Table from the main link	Excel file from the main link
Offset values used	Column "Quantity of Offset Credits"	Offsets assigned plus buffer credits	Column "Reductions"	Column "Credits Quantity Issued" summed over each Retirement/ Cancellation Date".

In contrast to the data from the CFCPs, the NEE database was downloaded directly without needing to review each site individually. FluxNet2015 subsets (https://fluxnet.org/data/fluxnet2015-dataset/subset-data-product/ [25] were used as daily and annual NEE databases (spreadsheets labeled as "DD" and "YY", respectively). Columns "NEE_VUT_REF", "GPP_NT_VUT_REF" and "RECO_NT_VUT_REF" were used in calculations that involved NEE, GPP and R_{eco}, respectively. This implies that the GPP and R_{eco} used were calculated with the nighttime approach from [44], while NEE was already filtered and gap-filled with the methodology described in that publication. Instrument CO_2 measurements are made against calibrations using shared standards and reference materials [25]. Time-series CO_2 data for a site establishes the annual changes in NEE that may be directly compared to other NEE, CFCP sites, or to any established baseline [1], [26], [45]–[47]; raw data are freely accessible [25]. A non-peer reviewed version of this manuscript is available online as a pre-print accessible here: https://www.preprints.org/manuscript/202105.0151/v1.

2.3. Data availability

The protocol data that support the findings of this study are available @ https://data.world/bmarinob. FluxNet2015 NEE subset [25] can be found at (https://fluxnet.org/data/fluxnet2015-dataset/subset-data-product/). The calculations are detailed in the Methods section.

2.4. Statistical calculations

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Statistics representing a network of global flux results are accepted as a robust analytical approach to detect climate change [26]. A similar approach is used in this study to compare site populations of aggregated CFCP and NEE sites. A means two-tailed t-test was performed to evaluate if NEE data had the same mean as each of the protocol datasets (yearly: CARB-CAR, ACR, and CDM; daily: VERRA), by choosing H0: "FluxNet2015 data has the same mean as *Protocol Name*" and H1: "FluxNet2015 data and *Protocol Name* have different means". Trends in the time series were not considered. The calculation was done in Python 3.7 with SciPy 1.4.1 library using the function "scipy.stats.ttest_ind()", which returned the statistics "t" from Eq. 1 and its respective P-values. Eq. 1 requires the estimation of each sample mean (x_1 and x_2) and standard deviation (s_1 and s_2). The t-statistic follows a t-student distribution with $n_1 + n_2 - 2$ degrees of freedom, where n_1 and n_2 are the respective sizes of the samples. x_1, s_1 and n_1 correspond to the FluxNet2015 dataset, while x_2, s_2 and n_2 to the protocols.

$$t = \frac{x_1 - x_2}{\sqrt{\frac{(s_1)^2}{n_1} + \frac{(s_2)^2}{n_2}}} \quad (1)$$

Absolute and percentage errors are illustrated based on the finding that CFCPs exclude R_{eco}. The error estimation does not rely upon CFCP data but shows the unavoidable errors, and their magnitude, when R_{eco} is excluded from NEE data. For this calculation, FluxNet yearly data without missing values in both variables was used. Note that if Reco is excluded, NEE should be equal to GPP, and the errors are calculated as follows:

$$\%\ Error = \frac{GPP - NEE}{NEE} \quad (2)$$

$$Absolute\ Error = GPP - NEE \quad (3)$$

Equations 2 and 3 were preferred rather than using only R_{eco} as error for consistency with widely known error formulas that involve the difference between real and measured (or estimated) values.

2.5 Methods for the determination of forest carbon sequestration.

The two methods employed to determine forest carbon sequestration involve forest mensuration, a biometric approach typically used with models of forest growth, employed by CFCPs [1], [15], and the eddy covariance method based on direct measurement of vertical CO_2 fluxes [18], [19] (see [11] for a detailed description of the CARB-CAR and NEE methods). Both approaches are applied to existing, registered projects and based on measurement of changes in forest carbon dynamics (e.g., diameter at breast height for CFCPs, CO_2 flux for NEE). The objective of the study is to analyze offset results related to net forest carbon sequestration reported in tCO_2e or equivalent as the universal figure of merit for commercial transactions. Accordingly, the numerous methodological steps involved to create the supply chain for each CFCP and for NEE, including instrumentation, baselines, additionality, baseline corrections, and third-party verification are not considered here; an evaluation of each factor would not alter the final values published for each method. Voluntary and compliance markets transact diverse offset trading irrespective of underlying protocols [32], [33]**.** An overview of the differences for CFCPs [15], including REDD+ projects [48], [49], reports that default values and/or automatic baseline settings are widely practiced and comparable. CFCP methods imbed comparability of baselines within each protocol across methods including REDD+ projects that can be transacted in other compliance or voluntary markets, demonstrating that baselines are not a barrier to protocol comparisons. Individual project baselines across CFCP methods [2], [38], [39], [50], [51], including REDD+ are often used interchangeably [52], also consistent with [15]. The aggregated net forest carbon offset results of both approaches are analyzed in this study to determine differences in results and to identify shared protocol features responsible for the differences observed.

The data for the CFCP protocols and the NEE eddy covariance data were not selected according to specific criteria but represent the entirety of published data for a range of forest types and stand ages [25], [53] as of 2015 (i.e., FluxNet2015) for NEE and up to 2019 for CFCPs. Afforestation and reforestation projects are a minor percentage of the projects for both biometric and eddy covariance sites. The Fluxnet2015 NEE data set included forest stand ages from 0 – 10 years up to 150 – 300 years, representative of diverse global sites and multi-year observations suitable for statistical comparison [25], [26], [54], approximating similar forest projects for CFCPs. The CARB-CAR data set did not include afforestation or reforestation projects [55]. Previously reported comparative data for the Howland Forest, an Ameriflux site (US-Ho-1) and the only site where both CFCP (i.e., CARB-CAR) and NEE methods overlap, reveal large discrepancies between the methods with errors of up to 2,256% [11], [56] emphasizing the need to reconcile methodological differences to ensure integrity of commercial products and to demonstrate compliance with protocol and [15] regulatory requirements [2].

Comparative studies of biometric and eddy covariance terminology and results for annual forest carbon sequestration establish a basis for comparability [21], [23], [57]–[61]. Note that NEE is equivalent but opposite in sign to NEP (NEP = –NEE) assuming that inorganic C fluxes balance or are negligible [62]. In the case of REDD+ projects, eddy covariance is integrated with monitoring, reporting and verification (MRV) protocols, establishing methodological comparability across diverse REDD+ project types and baselines [45]–[47], [63]–[65], supporting the inclusion of REDD+ projects in this study, representing ~13% of projects analyzed and consistent with [15]. High frequency measurements for NEE detects decreasing or increasing project carbon emission scenarios averaged across hourly to annual intervals [25] that are not detectable by CFCP infrequent forest mensuration (e.g., 6 to 12 year intervals) [2]. Forest carbon changes and offsets are based on the net balance of CO_2 uptake and release between the forest and soils and the atmosphere over the project area. Project level NEE captures differing rates of uptake and release of CO_2 relative to forest cover, seasonal changes, management, and disturbances including high-severity forest fires (e.g., ~100% forest destruction) across differing project scales covered by one or more eddy covariance systems [65]–[69]. NEE data are complemented by forest inventory data resulting from plot level [70] or remote sensing methods [7]. The relationship between R_{eco} and GPP values and interannual ranges for CARB-CAR and NEE population data, irrespective of forest project location, has been reported [11], [24], providing background information relevant to the present study.

We note that limitations from eddy covariance include a high percentage of missing data, a small footprint area, or horizontal advection fluxes that are not measured [18], [71]. There are strategies to solve these problems such as using gap filling methodologies, extrapolation techniques to represent bigger areas [72], or using auxiliary towers to measure advection fluxes [73]. See [25] for a detailed description of limitations and data handling for NEE.

3. Results

A comparison of the features for each CFCP and NEE is summarized in Table 2. The dispersion of data for CFCPs and for NEE data are first characterized by box plots in gC m^{-2} y^{-1} for NEE, CARB-CAR, ACR, CDM, and in gC m^{-2} d^{-1} for VERRA (Fig. 2). Probability histograms are then employed to identify the structural features of CFCP annual net forest carbon data that delimit CFCP values to less than or equal to zero (≤ 0 gC m^{-2} y^{-1} for CARB-CAR, ACR, CDM, d^{-1} for VERRA) relative to NEE values (Fig. 3.A-D). Probability histograms are also employed to identify the NEE component, GPP or R_{eco}, that accounts for the absence of CFCP positive values relative to NEE values (Fig. 3.B,D). Lastly, a time series of annual data for CARB-CAR, ACR, and the CDM are shown relative to NEE, noting the threshold for a 5% increase over contemporaneous NEE values (Fig. 4), a figure of merit used by CARB-CAR to invalidate project offsets [74].

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3.1. Comparative Analysis of CFCP Features (Annotations Provided in Appendix 1)

Table 2 (items #1 – 22; see Appendix 1, Table A1 for annotations and citations) shows the results of a comparative analysis for the CFCP protocols and the eddy covariance method based on information sources and defining features reported in the literature as well as calculated quantities derived from published information. The CFCPs analyzed in this study employing biometric methods included CARB [1], [75], the CAR [76] (CARB and CAR employ identical protocols and are referred to herein as CARB-CAR), the ACR [77], the VERRA [78], and the CDM [79]. Project locations are shown on an interactive map: https://planetalphaforest.earth/map/, Figure 1. NEE data are provided for comparison. Referring to Table 2, items #7-10, CFCP offsets reported here covered 15,034,700 hectares (ha) corresponding to 566,434,098 offsets (tCO_2e) with an estimated value of ~$15.7 Bn USD (USD$10 tCO_2, the initial price floor for CARB-CAR offsets [53]). Verra holds 80% of the land, 50% of offsets, and 19% of revenue with an average price of US$3. In contrast, CARB-CAR holds 7% of the land, 29% of offsets, and 74% of revenue with an average compliance price of US$14.13. ACR holds 13% of the land, 20% of offsets, and 7% of revenue with an average price of US$3. CDM holds 1.7% of land reflecting exceedingly small project sizes and 0.01% revenue reflecting the lowest pricing of ~US$00.12. CARB-CAR offsets represent ~80% of offsets issued [80] compared to 20%, 42%, and 0.8% for ACR, VERRA, and CDM, respectively, emphasizing the reliance on forest carbon offsets for CARB-CAR to meet the AB-32 and AB-398 emission reduction mandates [53], [81]. CARB-CAR also hosts the highest average ratio of offsets to land area of 178.2 $tCO_2\ ha^{-1}$, ~3x, ~8x, and ~21x that for ACR, VERRA, and the CDM, respectively, (Item #11), emphasizing the differentiation of pricing for compliance versus voluntary offsets (item #12). CFCP tCO_{2e}, required to represent net greenhouse gas reductions (item #13) according to protocol standards, are expressed as $gC\ m^{-2}\ yr^{-1}$ and based on minimal forest mensuration combined with forest growth models [1], [82], are exclusive of data for soil carbon by default (e.g., soil organic matter, soil efflux of CO_2), are typically subject to desk review by selected third-party verifiers (1 – 3 years intervals), are subject to invalidation at 3- or 8-year intervals, and lack a central repository for raw data supporting CFCP (items #14 – 21). Referring to items #12-14, higher pricing for compliance versus voluntary offsets appears to be arbitrary as both offset categories are based on structurally similar CFCPs implying that offset status is vested in executive boards or similar entities [15], [16] establishing financial inequalities across forest landowner types, particularly for Indigenous Peoples.

Referring to Table 2, in contrast, the results for eddy covariance, a universally accepted atmospheric micrometeorological method (Item #22) quantifying net CO_2 vertical flux (i.e., NEE; NEE = GPP + Reco) [18], [26]), (Item #14) directly samples CO_2 and the wind field at high frequency above the forest [18], is verified against referenced independent third-party international standards [83], [84] (Item #13), offers immediate data invalidation and data removal within minutes (Items #18,19) based on remotely acquired instrumentation diagnostics or system failure flags resulting from QA/QC processing [25], provides uncertainty estimation procedures and uncertainty data [25], and affords open access to global NEE raw data repositories with standard reporting formats (e.g., QC flag (NEE_VUT_REF_QC)[85]–[88] (Item #21). Eddy covariance measurements can be replaced if they were taken under low turbulence conditions [89] or gap-filled if there were short periods of missing values (up to three months approximately [44], [90], [91]) (Item #18). Eddy covariance NEE CO_2 projects have been widely published with ~600 peer-reviewed journal articles (item #22) [26]; to our knowledge, CFCP methods, *per se*, have not been journal peer-reviewed.

In summary, considered together, the results of the analysis (items #1 – 22), show that the eddy covariance NEE method provides an alternative, directly measured universal metric for harmonizing carbon trading and markets, and can also be readily applied to the verification of CH_4 and N_2O emission reductions directly [56], [92]–[94]. However, NEE research methods clearly require technological development and cost reduction to accommodate commercial projects including scale-up of NEE data from the NEE footprint to

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larger areas, controlling for lateral flux leakage, and accounting for the uncertainties of NEE CO_2 flux data. The limitations cited are under active development by the forest research and management communities worldwide [25], [95], [96].

Table 2. Comparative Analysis of CFCP Features (Annotations Provided in Appendix 1)

	Feature	NEE[1]	CARB/CAR[2]	ACR	VERRA	CDM
1	website	Fluxnet.org	arb.ca.gov	americancarbonregistry.org	verra.org	cdm.unfccc.int
2	Registry	NA	CAR[3], VERRA[3], ACR[3]	ACR	VERRA	CDM[5]
3	First Data Year	1992	2001/2002	2009	1999	2006
4	# Projects	206	443/121	96	138	66
5	# Project Years or Days	1448 Yrs 545,323 days	519 Yrs	185 Yrs	6466 Days	67 Yrs
6	% Forestry/Land Use Projects	100%[4]	80/25	20	42	0.8
7	Land Area (ha)[5]	NA	925,252	1,887,866	11,956,885	264,697
8	Carbon Offsets (tCO_2e)[5]	NA	164,910,753	113,013,103	286,277,319	2,232,923
9	Value $10 CO2e[6]	NA	$11.7 Bn	$1.1 Bn	$2.9 Bn	$22.3 Mn
10	Ave. Price tCO_2e (2019)	NA	US$14.13[7]	US$3.00[8]	US$3.00[8]	US$0.15–0.24/tCO2e[8]
11	Ave. tCO_2/ha	NA	178.2	59.9	23.9	8.4
12	Offset Type	Compliance, Voluntary	Compliance[8], ARBOC's[9]	Compliance[10], Voluntary, VER's[8]	Voluntary, VCU's[8]	Voluntary, CERs[8]
13	Measurements gC m^{-2} yr^{-1}/d^{-1}	NEE, CO2, H2O, Energy	Net Forest Carbon[11]	Net Forest Carbon[12]	Net Forest Carbon[13]	Net Forest Carbon[14]
14	Methods NEE = GPP+R_{eco}	CO_2 Flux, Eddy Covariance (NEE = GPP + R_{eco})	Forest Biometry & Models[11], gaseous CO_2 excluded	Forest Biometry, Models[12], gaseous CO_2 excluded	Forest Biometry[13] Models, gaseous CO_2 excluded	Forest Biometry[14], Models, gaseous CO_2 excluded
15	Soil Protocol	NEE	Optional[11]	Optional[12]	Optional[13]	Optional[14]
16	Soil Default	NEE	Excluded[11]	Excluded[12]	Variable[13]	Excluded[14]
17	Third-party Verification	References, Standards[15]	Accredited by ARB[16]	Accredited by ACR[16]	Accredited by VERRA[16]	DOE[17]
18	Invalidation Criteria	Outlier Detection, filtering methods (Papale et al., 2006)	CARB +5% Overcrediting [18]/CAR[19]	None[20]	None[16]	None[16]
19	Invalidation Period	Minutes to Hours[21]	3 to 8 Years[22]	None[16]	None[16]	None[16]

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20	Biometric Survey Frequency	Research Dependent[23]	6, 12 Years[24]	10 Years[12]	10 Years[13]	5 Years[14]
21	Raw Data Repository	National, International	None	None	None	None
22	Journal Peer Reviewed Methods	~600[17]	None	None	None	None

3.2. Boxplots for Annual (NEE, CARB-CAR, ACR, CDM) and Daily (VERRA) Forest Carbon Sequestration and Statistical Analyses

Boxplots (excluding extreme outliers) shown in Figure 2 (A), for annual NEE (n = 1448), CARB-CAR (n = 519), ACR (n = 185) and CDM (n = 67), data (gC m^{-2} y^{-1}), and (B) VERRA (n = 6466) and NEE (n = 528,889), representing daily data according to the VERRA data reporting format (gC m^{-2} d^{-1}), characterizes overall data dispersion for each protocol. Horizontal lines (orange) and triangles (green) represent medians and means, respectively. The boxes represent the values between the 25th and 75th percentiles; whiskers include the numbers inside the 5th and 95th percentiles. CARB-CAR and ACR data have the largest variance, skewness towards negative values, and outliers (extreme outliers have been removed to facilitate visibility of the bulk data), relative to the annual NEE median, while the CDM is less variable, lying within the interquartile range of the NEE data. Compared with CARB-CAR and NEE dispersion, ACR mean, and SD dispersion are more extreme. The VERRA and CARB-CAR daily data distributions are correspondingly inconsistent with the NEE means and standard deviations of −257 ± 392.5, compared to −983.6 ± 3,428 and −2,798.9 ± 15,317.5, for CARB-CAR and ACR data, respectively, emphasizing the exceptionally large numerical differences between means and SDs for the datasets. Table 2 summarizes the results of two-tailed statistical analysis to accompany the dispersion data. The null hypothesis, H0, that the CFCP values are from the same population as represented by the NetFlux2015 data, is rejected at the 99.99%, 99.99%, 95% and 99.99% for CARB-CAR, ACR, CDM and VERRA, respectively. Referring to Table 2, the CFCP ≤ 0 delimit for values (note: 2 ACR positive values are reported out of 185 total values included in this analysis) constitutes the key structural feature that intricately links CFCPs. This link inevitably leads to incomplete accounting for forest carbon offset production. In addition, The CARB-CAR and ACR protocols share similarities in having higher means, ~4x and ~11x larger relative to NEE, and SDs of ~9x and ~39x larger, relative to NEE, respectively. The dispersion data also point to common methodologies and processes employed by CARB-CAR and ACR protocols, a topic beyond the scope of this study. Similarly, there is a large difference between VERRA and NEE daily data. The VERRA mean and SD are ~8x and ~27x larger than daily NEE values, respectively. The VERRA maximum value of ~0 and minimum of −4,706.3 (gC m^{-2} d^{-1}), relative to NEE values of +23.8 and −25.9 (gC m^{-2} d^{-1}) respectively, further differentiate VERRA data as not reflective of natural patterns of forest carbon dynamics and NEE. Excluding positive values unavoidably introduces carbon accounting errors resulting in an inferred median error of ~247% or −269 gC m^{-2} y^{-1} (Table A1.) over the entire FluxNet2015 database. Taken together with the statistical results suggesting that CFCP and NEE are likely drawn from different populations, the data confirm that CFCP structures and calculations delimit positive emissions to the atmosphere on an annual and daily carbon accounting basis. We emphasize that the unaccounted positive emissions represented by ecosystem respiration (R_{eco} comprised of heterotrophic and autotrophic respiration) triggers automatic debits to the net forest carbon project offset ledger resulting in unequivocal overcrediting of offsets [11], [31], [56]. Consequently, CFCP project offsets, unless proven otherwise, should be adjusted downward based on corrective measurements, or voided as the basis for valid carbon transactions, as previously reported [11], [34], [97].

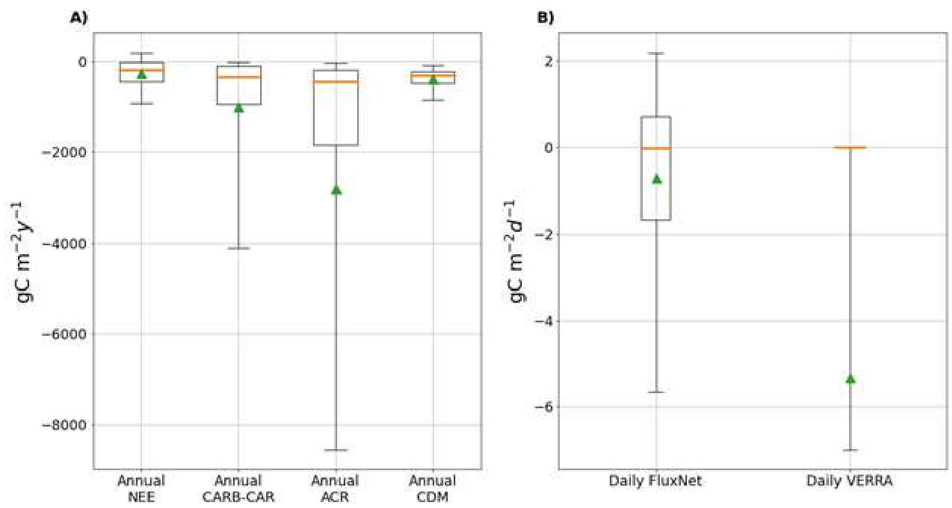

Figure 2: A) Annual boxplots in gC m^{-2} y^{-1} for FluxNet2015 NEE [25], CARB-CAR, ACR and CDM databases. B) Daily boxplots in gC m^{-2} d^{-1} for daily FluxNet2015 and VERRA databases. Mean (green triangles), median (orange lines), 1st and 3rd quartiles (box) and 5 and 95 percentiles (whiskers) are represented. The box from VERRA dataset is too small to be seen at this scale.

Table 3. Daily and yearly statistics for each dataset in gC m^{-2} y^{-1} and gC m^{-2} d^{-1}, respectively. The Means T-tests were performed between FluxNet NEE and CARB-CAR, ACR and CDM, and between FluxNet NEE and VERRA. The asterisks indicate if H0 can be rejected at 95% (*), 99% (**) or 99.99% (***) level of confidence in a two tailed t-test.

Database	FluxNet NEE	CARB-CAR	ACR	CDM	FluxNet NEE	VERRA
Frequency	Annual	Annual	Annual	Annual	Daily	Daily
Mean	-257.60	-983.61	-2,798.93	-373.72	-0.7	-5.31
Median	-182.45	-344.37	-436.16	-298.43	-0.0067	-0.0012
Min	-2505.06	-69,020.49	-204,917.54	-1,038.79	-25.9	-4706.33
Max	2129.23	0.00	675.36	-7.55	23.8	-0.00002
Sd	392.46	3428.01	15,317.54	259.64	2.49	66.69
Num	1448.00	519	185	67	528,889	24,771
t-statistic	---	7.19	6.31	2.4	---	49.5
Degrees of freedom	---	1967	1633	1952	---	601887
P-value	---	3.96 E-15	3.58 E-10	1.66 E-2	---	0.00 E0
H0 rejection	---	***	***	*	---	***

3.2. Probability Histograms for CFCPs

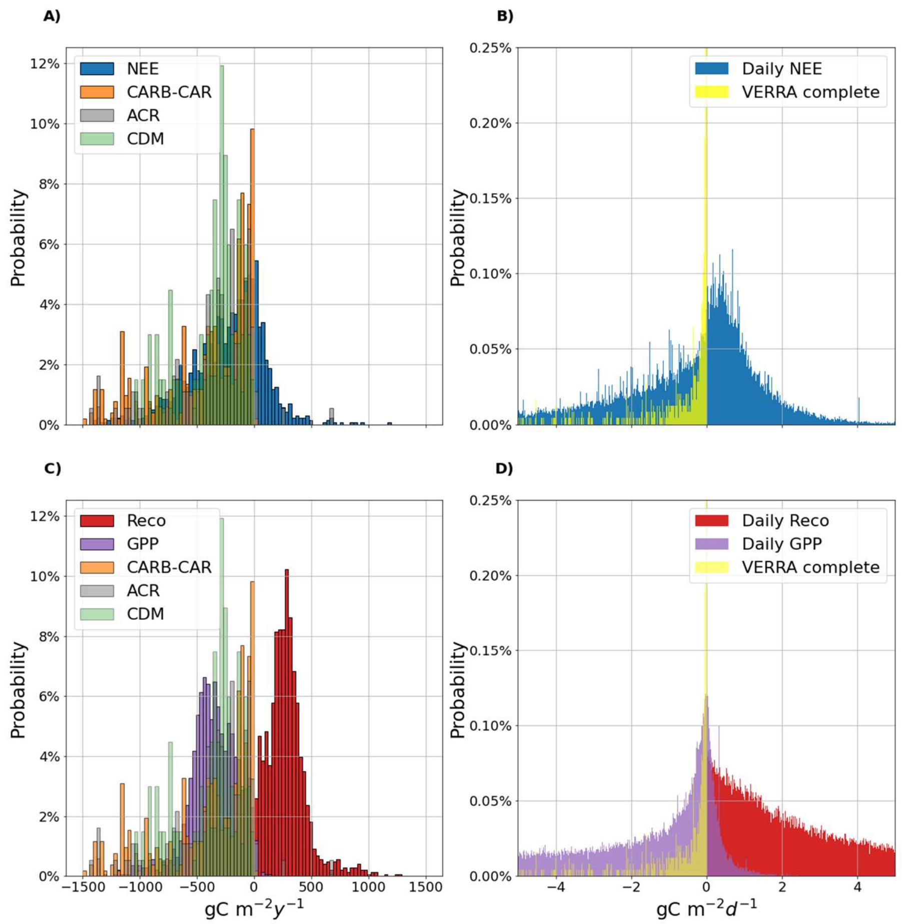

Fig. 3. CARB-CAR (orange), ACR (grey) and CDM (green) histograms in gC m^{-2} y^{-1} are shown with A) Annual FluxNet 2015 NEE (blue), and C) Annual R_{eco} (red), and GPP (purple). Only values between −1500 and 1500 gC m^{-2} y^{-1} are shown, with a bin size of 30 gC m^{-2} y^{-1}. All VERRA (yellow) histograms with B) Daily FluxNet2015 NEE (blue), and D) Daily R_{eco} (red), GPP (purple), for carbon sequestration values between -5 and 5 gC m^{-2} d^{-1}. The bin size is 0.0025 gC m^{-2} d^{-1}. Front panel histograms are slightly transparent to allow the visualization of the overlapping values from the histograms plotted on the background. Each panel histogram order, from back to front, is A) NEE (back), CARB-CAR (middle-back), ACR (middle-front) and CDM (front) B) Daily NEE (back) and VERRA complete (front) C) R_{eco} (back), GPP (middle-back), CARB-CAR (middle), ACR (middle-front), CDM (front) D) Daily R_{eco} (back), Daily GPP (middle), and VERRA complete (front).

Referring to Figure 3.A,B shows results for CFCPs compared with NEE (gC m^{-2} y^{-1}) plotted as probability histograms (A) NEE (blue), CARB-CAR (orange), ACR (gray), CDM (green), and (B) NEE (gC m^{-2} d^{-1}) (blue), VERRA (yellow). Fig. 3.C,D shows results for CFCPs compared with R_{eco} and GPP (gC m^{-2} y^{-1}) as probability histograms for (C) R_{eco} (red), GPP (purple), CARB-CAR (orange), ACR (gray), CDM (green), and (D) (gC m^{-2} d^{-1}) daily R_{eco} (red), daily GPP (purple),VERRA (yellow). The results for Fig. 3.A-D clearly shows and confirms that the probability histograms for CFCPs delimit values to ≤ 0 (gC m^{-2} y^{-1} or d^{-1}) for all protocols, with few isolated outliers as noted in the histograms, consistent with the dispersion and statistical analysis results (Fig. 2, Table 2). In particular, the results show that VERRA sharply delimits values representing daily project data with most values skewed towards zero (Fig.3.B,D), contrasting with FluxNet2015 (NEE, R_{eco}, GPP) data representing a global forest data set [25]. Thus, Fig. 3 results imply that CFCP biometric

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values and proxy model simulations do not represent the range of known NEE and corresponding R_{eco} and GPP values [24]. Exclusion of positive values explains the anomalous results for CFCPs based on the available data.

3.3. Time Series Data & 5% Overcrediting Threshold

The CARB-CAR protocol employs criteria to invalidate a project [74] if the reported net carbon sequestration is in excess of 5% of the actual project sequestration and is used here as a diagnostic figure of merit for related CFCP protocols. An analysis of the annual time series and variance for CFCP (VERRA daily data are not included) data based on estimation is compared to direct measurements of forest NEE population data, the only available non-biometric forest carbon sequestration data available. In a previous analysis, NEE values representing the known range of values for forests were used for comparison with CARB-CAR data [98]. A similar approach is used here with updated NEE FluxNet2015 values [25]. The comparison has no regulatory application. The analysis indicates when annual average CFCP data were greater than 5% relative to NEE values for the same year. Results of the analysis are shown in Fig. 4. Referring to Figure 4, the error bars are 5% of the highest yearly sequestration in each time series, which were 2015, 2019, and 2015, for CARB, ACR, and CDM, respectively, and applied to protocol values across remaining years for that protocol, as a conservative measure, and to apply the same criteria across protocols. Figure 4 shows annual data for NEE (blue), CARB-CAR (orange), ACR (yellow), and CDM (green) from 1992 to 2020; NEE values are shown as positive values. Referring to Figure 4, the CARB-CAR projects, extending beyond those reported previously [98], show no intersection between the admissible interval and the NEE measurements for any of the overlapping years (2001–2015). While the NEE data (FLUXNET 2015) do not extend beyond 2015, the CARB-CAR values for the years 2016 to 2019 are, on average, ~3x that of NEE values reported previously [98]. Mean annual ACR values recorded from 2009 to 2012 are within the NEE range, but thereafter exhibit higher average values for 2013 to 2020 than for NEE and CARB-CAR values, suggesting inconsistency in protocol application. The annual mean and SD for CARB-CAR are ~4x and ~9x that for NEE, respectively, consistent with previously reported analysis comparing CARB-CAR and NEE forest carbon sequestration results [98]. The ACR mean and SD are ~11x and ~39x that for NEE, respectively. The CDM annual values appear within the range of available NEE values and would not be considered invalid based on the 5% threshold applied to CARB-CAR and ACR. However, exclusion of positive values (Figure 3.A,C; Table 2) implies that CDM results are arguably unreliable.

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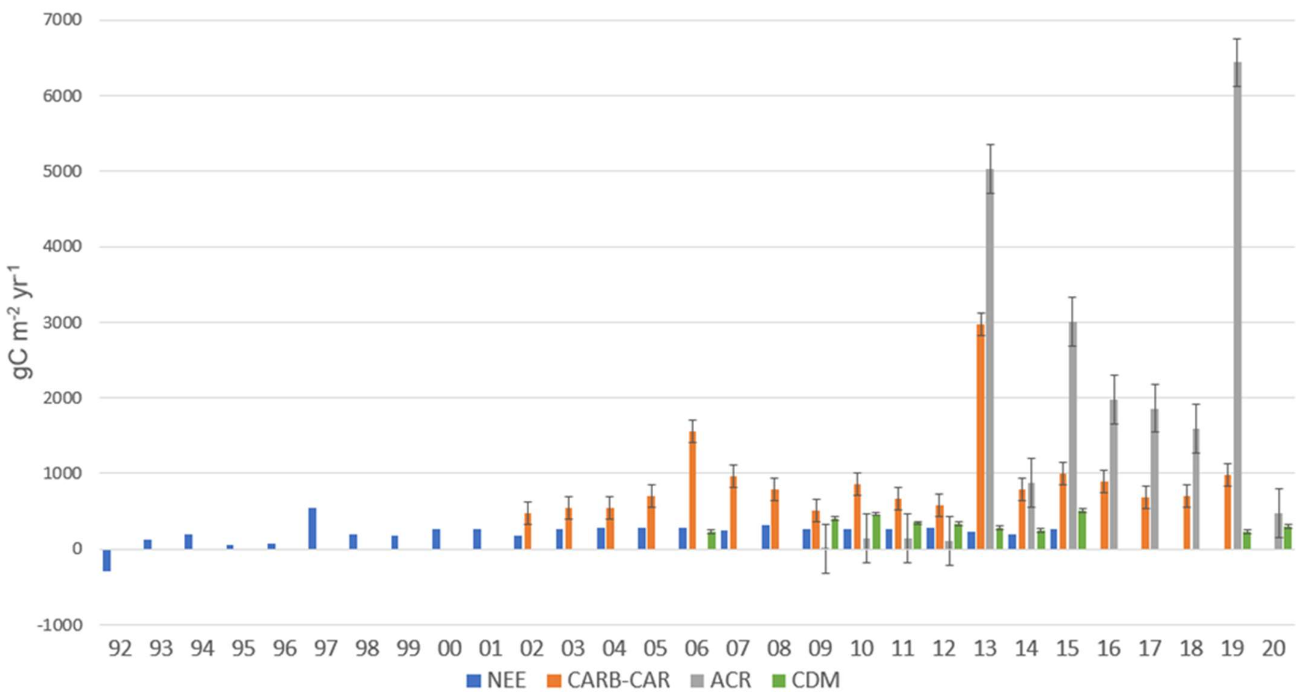

Fig. 4 NEE (blue), CARB-CAR (orange), ACR (grey) and CDM (green) yearly carbon sequestration in gC m^{-2} y^{-1}. The error bars are 5% of the highest yearly sequestration in each time series, which were 2015, 2019, and 2015 for CARB, ACR, and CDM, respectively. VERRA daily data are not shown. Positive values are sequestration by the vegetation.

4. Discussion

We have established that CFCPs, in addition to excluding direct CO_2 measurements, specifically exclude positive carbon emission values derived from biometric and/or model simulations identifying a central structural feature across the five protocols analyzed. The absence of positive values correlates with a zero-threshold for CFCP offset carbon accounting, eliminating CO_2 sources to the atmosphere unavoidably embedded in all forest ecosystems as respiration (R_{eco}). While CFCPs generally provide an option for soil carbon, it is excluded by design or default (Table 1, item #'s 15,16) [15], [98], suggesting that CFCPs do not fulfill the intended protocol objectives for a justifiable net forest carbon determination. Consequently, CFCP offsets reported as tCO_2e cannot represent net forest carbon emission reductions or achieve the methodological or regulatory objectives claimed by each protocol (Table 1, item #'s 2,13; Figures 2-4). CFCPs appear to represent a variant of methods commonly employed to document and manage timber resources [99], however, a complex and expensive regulatory system is not required for timber management. CFCPs could incorporate extensive biometric and soil respiration campaigns at substantial cost, to improve comparability with NEE methods (e.g., [21], [62]). We emphasize that comprehensive carbon accounting is required to track and commercially monetize net forest carbon sequestration, regardless of protocol and specifications, and that improvements and alternatives to CFCPs and NEE methods should be urgently considered and be subject to scientific journal peer-review [56].

Differences between NEE direct measurement and CFCP limited forest mensuration to determine net tCO_2e as the basis for commercial products must be resolved to safeguard the integrity of carbon markets. For example, in addition to offset discrepancies reported here, linkage of carbon offset results to CARB policy and regulatory terms and conditions for the CARB-CAR protocol [1] revealed inconsistencies within the carbon offset supply chain [56], a topic not typically addressed by eddy covariance studies supporting natural climate solutions [26], [100], [101], but an integral part of the offset supply chain [56]. Studies identifying deficiencies in the CARB-CAR protocol related to additionality and overcrediting of up to 30% based on discrepancies in above ground carbon accounting also support the need for improvement in CFCPs [34]–[36], [102] and are consistent with the results presented here.

The soil carbon component of forest ecosystems, typically comprising up to ~3x that for above ground carbon [103], cannot be ignored in the determination of a net carbon balance for a forest project. Moreover, temporal and spatial analysis of the soil column carbon composition is difficult to characterize [21], [31], [104], a recognized weakness of biometric forest carbon protocols [57], [60], and a challenge to CFCP improvement. Statistical comparative analysis of CFCP and NEE results is consistent with exclusion of soil respiration, accounting for up to 82% of annual net forest carbon sequestration [24], [105] resulting in an inferred median error of ~247%, based on FluxNet2015 data and consistent with overcrediting (Table A1.). An annual error of up to 2,256% relative to eddy covariance NEE results was reported for a single site, the Howland Forest, Maine, USA, [56], [106], the only site where both CFCP and eddy covariance approaches overlap. The discrepancy noted for Howland, linked in part to incorrectly monetizing initial carbon stocks as a single year of net forest carbon rather than timber volume, emphasizes the importance of evaluating compliance features that affect revenue [56], in this case over crediting, a scenario consistent with the work presented here and elsewhere [11], [34], [35]. Moreover, CFCPs are tied to multi-decadal, up to 100-year monitoring requirements (i.e., CARB-CAR), typically against an estimated, invariant and default soil carbon baseline (Table 1) [53]. Mandating estimated and invariant soil baselines is unrealistic as the soil carbon response to climate change over the coming decades and century [103] are not accounted for in CFCPs.

Following directly from the zero-threshold structure identified in this study, CFCPs lack sensitivity to detection of ecosystem switching from net carbon sink to positive source values [98], a critical capability to manage intermittent carbon sequestration [107], and to detect climate change effects on ecosystems, arguably criteria for invalidating CFCPs for these purposes. Eddy covariance monitors carbon dynamics following high severity fires that destroy forest landscapes, in some cases approximating 100% deforestation. For example, [66] reports a switch to positive emissions following deforestation and clear cut with gradual annual increases in net forest carbon sequestration towards a switch back to negative emissions, a pattern reported by similar studies [65]–[69], a scenario precluded from detection and quantification employing CFCPs.

Moreover, CFCP data do not reflect the natural patterns of time series for carbon dynamics established by global diverse eddy covariance research sites at annual or daily resolution (Fig. 3.A-D). The high interannual variance noted for NEE, for the purposes of carbon monetization, imply that direct measurement is required to capture the dynamic nature of changes in annual net forest carbon sequestration and revenue [31]. Discerning changes in annual net forest carbon from forest biometric surveys every 6 to 12 years using forest mensuration and model growth simulations are not supported by the results of this study. Considered together, we conclude that CFCPs, based on incomplete carbon accounting, are not capable of advancing forest carbon quantification methodology or technology. CFCPs cannot fulfill the requirements for verifiable financial carbon markets, or to manage and track forest carbon under changing climate scenarios including unpredictable feedbacks [108]. Indeed, CFCP results cannot be regarded as reliable, even if selected results appear reasonable, as for the CDM (Table 3), given that positive NEE values are excluded from calculating a net carbon balance. Given the enigma of persistent deforestation and the ~0.9 billion hectares of degraded forests available worldwide for large-scale restoration opportunities [109], [110], improvement in forest carbon quantification is an urgent need, and is achievable with existing, proven, direct measurement technology.

Alternative and improved forest carbon offset protocols could link the Paris Agreement through Article 6 [111], [112], REDD+ projects [43], community forests and Indigenous Peoples land management programs [113], [114]. Investors, buyers, and sellers of compliance or regulatory offsets would have access to equivalent pricing for NEE based tCO_2 trading units. Features of CFCPs including tests for additionality, baseline setting, and leakage could be applied to eddy covariance methods as needed for a specific project. However, is it increasingly clear that additionality, leakage, and setting of baselines are arbitrary, or simply based on default values [15], [16] for ease of comparison. In the case of additionality, ultimately, verification of net forest project carbon sequestration offers the most stringent test of additionality in that each tCO_2 traded is validated as "net-additional", at the project level, in reducing the atmospheric burden of CO_2. While the limitations and caveats of the statistical analyses presented here are acknowledged, specifically, the absence of multiple direct site comparisons of NEE and CFCPs, the results clearly indicate that population differences between the two approaches are statistically significant, that CFCPs do not fully account for CO_2 sources, and are likely in error for net carbon balance results. Such inconsistencies cannot be ignored and have been reported previously [11].

For example, the published sample means and standard deviations (±), for annual values of the CARB-CAR and NEE datasets reported in [11] were, respectively, −948.8 ± 1,504.8 gC m^{-2} yr^{-1} and −198.0 ± 261.6 gC m^{-2} yr^{-1} representing an extreme range of ~5× the value for CARB-CAR forest carbon sequestration mean and ~6× the standard deviation for interannual variance relative to the NEE population data [105]. The difference in mean values between the two populations was reported as significant at the 95% confidence level, rejecting the null hypothesis that the CARB-CAR population mean falls within the NEE population mean. Moreover, the mean and standard deviation of an updated NEE database [24] was reported as −156 ± 284 gC m^{-2} yr^{-1} , respectively (155 sites; 1,163 site year), supporting the comparison with CARB-CAR data and ~6× the CARB-CAR mean and ~5× the standard deviation for interannual ranges of natural and managed forest ecosystems. Similar results for CFCPs (Table 3) are observed, consistent with offset over crediting.

The NEE natural variation for diverse global forests is constrained tightly by GPP and R_{eco} providing integrated geographic and biological boundaries for NEE comparisons [24] as employed in this study and consistent with exclusion of positive CO_2 efflux to the atmosphere. For example, referring to [11], Supplement S7, a plot of GPP versus R_{eco} shows that intersecting values for the Howland Forest, Maine, USA and the Wind River, Washington State, USA, are closely linked by similar coordinates, emphasizing overlap of GPP and R_{eco} functional ranges for forests across continental scale and differing ecological zones. Likewise, tropical forests may take up more CO_2 via photosynthesis, but ecosystem respiration is also increased [24], [105], a topic addressed previously [11]. Regardless of location, CFCPs exclude data for R_{eco}, and thus cannot represent known forest carbon sequestration creating uncertainty for forest carbon trading and markets.

We acknowledge the limitations of this study lacking comparisons between direct NEE results for forest carbon sequestration and each of the CFCPs analyzed across wide geographic regions. Regardless of location, however, forest carbon sequestration is constrained by the balance of GPP and R_{eco}. Accepting NEE uncertainties (e.g., 'Methods' section), we argue that the NEE methodology for CO_2 vertical flux offers a viable alternative for creation and verification of forest carbon financial products compared to estimation and model simulation-based protocols. Moreover, in the absence of independent validation for each protocol and the CFCP protocol discrepancies reported here, the known population of NEE results offers the only available non-biometric data for independent verification of CFCP evaluation. The results presented here form the basis for ongoing comparison between CFCP and NEE results. In view of more than 600 published eddy covariance studies and the ever-expanding network of eddy covariance sites [72], [73], cooperation between CFCPs and eddy covariance research sites is desirable and may be achievable.

Finally, we suggest that CFCPs incorporate a directly measured term for ecosystem and or soil respiration to complete the carbon accounting process stated by each protocol required for verifiable quantification of net forest carbon sequestration. The frequency and biometric ensemble of measurements and associated soil respiration determinations are clearly defined for comparability of biometric and NEE carbon sequestration [21], [23], [57]–[61], and should be adopted by CFCPs.

5. Conclusions

In conclusion, forest carbon commerce is at a crossroads; it is either poised for improvement or it will remain uncertain and limited in applications to manage climate change. Given the absence of natural counterparts (R_{eco}) that intrinsically constrain net forest carbon sequestration, carbon accounting improvement of CFCPs to fill gaps is warranted and urgently needed. Regulatory requirements for forest carbon reporting cannot alter or ignore the fundamental biological processes of forest carbon dynamics. Protocols that fully account for forest carbon have the potential to catalyze integration of forest landscapes with global financial markets providing pathways to effectively manage, restore and conserve forests. Carbon trading and pricing platforms should be receptive to science-based transformation of CFCPs to verifiable net forest carbon protocols with social, economic, and diverse planetary benefits now and for future generations. Accountability and third-party validation are requirements for any forest carbon protocol applied to financial transactions. While the origin of the shared limitations of CFCPs described in this study is not clear, the effect is to exclude nature's fundamental constraint on the magnitude of forest carbon sequestration with commensurate loss of monetized CFCP offset value.

Author Contributions: Bruno D.V. Marino conceived the idea and initial writing of the manuscript. Nahuel Bautista was responsible for all numerical analyses and graphics.

Funding: This research received no external funding.

Data Availability Statement: The data are available as follows:

CARB-CAR offsets and project sizes: https://thereserve2.apx.com/myModule/rpt/myrpt.asp?r=111

ACR Data: https://acr2.apx.com/myModule/rpt/myrpt.asp?r=111

CDM Data: https://cdm.unfccc.int/Projects/projsearch.html

VERRA Data: https://registry.verra.org/app/search/VCS

FluxNet2015 Data: https://fluxnet.org/data/fluxnet2015-dataset/subset-data-product/

Summary Data: https://data.world/bmarinob

Summary of Site Locationshttps://planetalphaforest.earth/map/

Conflicts of Interest: The authors declare no conflict of interest.

Appendix

A1. Annotations for numbered reference supercripts for Table 1; all references are noted in brackets and are incuded in the bibliography.

[1] [25] NEE data source.

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[2] [51] The California Air Resources Board (CARB) and the Climate Action Reserve (CAR) share identical protocols and project listings and are identified as CARB-CAR.
[3] [16], [32] CAR, VERRA and ACR share selected project listings with CARB-CAR.
[4] [25] FLUXNET sites represent diverse terrestrial ecosystems.
[5] [79] Land area and offset totals represent data reported for each project within a protocol.
[6] A price of $10 is employed across protocols to illustrate total gross pre-tax revenue potential comparison.
[7] Approximate 2020 vintage settle prices, https://www.californiacarbon.info/.
[8] [32].
[9] [1] ARB Offset Credits, established by ARB compliance process (https://americancarbonregistry.org/california-offsets/compliance-offset-projects).
[10] [38]
[11][2], [53] Excerpt [3]: Compliance Offset Protocol U.S. Forest Offset Projects. (2015). http://www.arb.ca.gov/cc/capandtrade/protocols/usforest/usforestprojects_2015.htm. Chapter 4. Offset Project Boundary – Quantification Methodology. The GHG assessment boundary, or offset project boundary, delineates the GHG emission SSRs that must be included or excluded when quantifying the net changes in GHG emissions associated with the sequestration of carbon achieved by increasing and/or conserving forest carbon stocks.
[12] [38] Excerpt: THE AMERICAN CARBON REGISTRY STANDARD REQUIREMENTS AND SPECIFICATIONS FOR THE QUANTIFICATION, MONITORING, REPORTING, VERIFICATION, AND REGISTRATION OF PROJECT-BASED GHG EMISSIONS REDUCTIONS AND REMOVALS VERSION 6.0, July 2019; https://americancarbonregistry.org/carbon-accounting/standards-methodologies/american-carbon-registry-standard. EMISSIONS RATE OR BENCHMARK (e.g., tons of CO2e emission per unit of output) with examination of sufficient data to assign an emission rate that characterizes the industry, sector, subsector, or typical land management regime, the net GHG emissions/removals associated with the Project Activity, in excess of this benchmark, may be considered additional and credited.
[13] [40] Excerpt: 8.4 Net GHG Emission Reductions and Removals, Methodology for Improved Forest Management, Version 1.0, Date of Issue 10 August 2020; https://verra.org/methodology/methodology-for-improved-forest-management/. 8.5.1 Summary Net Emissions Reductions and/or Removals Equation The annual net carbon emissions reductions is the actual net GHG removals by sinks from the project scenario minus the net GHG removals by sinks from the baseline scenario, were then calculated by applying the leakage and uncertainty discount factors (but not the VCS permanence buffer), on an annualized basis. See also: https://verra.org/methodology/vm0012-improved-forest-management-in-temperate-and-boreal-forests-ltpf-v1-2/#.
[14] [14] Excerpt: 4. Baseline net GHG removals by sinks. 13. The baseline net GHG removals by sinks shall be calculated as follows. https://cdm.unfccc.int/methodologies/DB/C9QS5G3CS8FW04MYYXDFOQDPXWM4OE
[15] [25], [115] Detection of erroneous CO_2 products for NEE calculation (e.g., mmolCO_2 mol^{-1} CO_2) include automated flagging during QA/QC detection across NEE required variables, including spike detection; calibration of gas analyzers, typically open or closed path infrared gas analyzers are performed at each site according to the type of analyzer and project protocols.
[16] [15], [16].
[17] [32] Designated Operational Entity (DOE) accredited by Clean Development Mechanism Executive Board; (https://cdm.unfccc.int/DOE/index.html).
[18] [74] https://www.arb.ca.gov/cc/capandtrade/offsets/arboc_guide_regul_conform_invalidation.pdf. Excerpt: Overstatement of GHG Reductions or Removal Enhancements: ARB offset credits may be invalidated if ARB finds that the amount of the GHG reductions or removal enhancements that were issued credit were overstated by more than 5 percent than what the offset project actually achieved within the applicable Reporting Period.

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[19] [37] CAR non-CARB projects are subject to ±5% of measured or calculated values, however, there are no invalidation determinations.
[20] [38] A materiality threshold of ±5% is imposed on pending and completed projects, however, there are no invalidation determinations. There are no formal invalidation periods for NEE data, however, data QA/QC flags identifying instrument or data processing errors can be accessed and identified when they occur either during the high frequency CO_2 measurement or summation of flux into 30 minute or hourly fluxes, resulting automatically in a data gap for that period, or invalidation of data for that period.
[22] [53].
[23] [23], [57]–[60] Eddy covariance sites often conduct intensive biometric surveys to augment NEE determinations, for comparative analysis, or for other research purposes.
[24] [53].

Table A1. Absolute and percentage errors if R_{eco} is excluded from NEE, calculated over all site years in FluxNet database with non-missing GPP. Negative values are sequestration by the vegetation.

	Absolute error (gC m^{-2} y^{-1})	**Percentage error (% y^{-1})**
Num	1436	1436
Mean	-284	-65%
Std	181	13002%
Min	-1789	-244720%
Max	841	328977%
Percentiles		
1%	-936	-16357%
5%	-584	-2684%
10%	-469	-1086%
25%	-357	32%
50%	-269	247%
75%	-179	551%
90%	-82	1389%
95%	-42	2415%
99%	-11	11302%

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