Article

Howland Forest, ME, USA: Multi-gas flux record (CO2, CH4, N2O) establishes new forest products linked to social cost of emission in contrast to carbon limited sequestration proxies

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Absrtact: Forest carbon sequestration is a widely accepted natural climate solution, however, methods to determine net carbon offsets are limited to commercial carbon proxies and CO_2 eddy covariance research. Non-CO_2 greenhouse gases (GHG) (e.g., CH_4, N_2O) receive less attention in the context of forests, in part, due to emphasis on CO_2 and the operational requirements and cost for three-gas eddy covariance platforms. In this study, Howland forest flux tower (CO_2, CH_4) and soil flux data (CO_2, CH_4, N_2O), representing net emission reductions, are linked to their respective social costs to estimate commercial revenue if sold as a GHG social cost forest offset product (GHG-SCF). Estimated annual revenue for GHG-SCF products, applicable to realization of a Green New Deal, range from ~$120,000 covering the site area of ~557 acres in 2021, to ~$12,000,000 for extrapolation to 40,000 acres in 20240, assuming a 3% discount rate. The Howland Forest CO_2 flux record for two adjacent towers is compared to California Air Resources Board forest carbon proxy data for compliance sequestration offsets, the only project site where these approaches overlap. Overcrediting, incomplete carbon accounting with annual errors of up to 2,256%, inadequate third-party verification, and limited application to non-CO_2 GHG's are established. In contrast, direct measurement of one or more GHG's offers new forest products and revenue incentives to restore and conserve forests worldwide.

Keywords: California Air Resources Board; carbon trading; Climate Action Reserve; eddy covariance; forest carbon protocols; forest carbon supply chain; Green New Deal; Howland Forest; net ecosystem exchange; social cost of CO_2; CH_4; N_2O

1. Introduction

Uncertainty and high cost of typical commercial forest carbon offset protocols are unresolved [1]–[6], impeding widespread adoption and expansion of forest conservation projects. The main endeavor of commercial forest carbon offset trading is to assist landowners with conservation and restoration of forests based on the net carbon sequestration and carbon credit sales for a project [7], [8], while verifiably reducing net emissions. While forest restoration is recognized as a viable, economic and readily deployable nature based commercial solution to mitigate climate change [9]–[14], forest loss continues at a rate of ~10 million hectares annually from 2015 - 2020 [15]. In contrast, the forest landscape conserved by carbon protocols and trading is astonishingly small, ~0.03% of the available land for restoration of ~0.9 billion hectares [12], [15], evidence that existing methods underpinning forest carbon are not economically or ecologically viable. Forest carbon sequestration credits, typically derived from sparse forest mensuration (6- or 12-year timber inventory) [16]–[18] surveys for above ground carbon and use of multiple, carbon denominated growth models [18]–[20], by default, exclude direct measurement of GHG's, limiting in-

novative commercial applications.   In contrast, direct, hourly, in situ measurement of forest greenhouse gas (GHG) fluxes, via eddy covariance, a widely used forest research method [21], [22], resulting in net ecosystem exchange (NEE) [22]–[24], integrates vertical gross fluxes between the forest, soils and the atmosphere resulting in net forest GHG sequestration [25]–[29]. The NEE approach, reported in 600+ forest carbon and GHG studies [30], provides the foundation for commercial applications across small and large landscapes [1], [31], [32], and three-gas forest products (CO_2, CH_4, N_2O), integrating gas fluxes (tower and soil accumulation chambers) and respective social costs [33]. Emissions linked to their social cost and corresponding offset revenue potential, now and in the future, are applicable to realization of Green New Deal policies [34], that otherwise lack specificity regarding the role of forests and carbon pricing in reducing GHG emissions [35]–[37].

In the context of the Howland Forest GHG record, we bring together data and comparisons not reported previously [1] to clarify the quality and validity of forest mensuration protocols, such as those employed by the   California Air Resources Board [16] and the Climate Action Reserve [38] (CARB-CAR). The CARB-CAR data are compared to directly measured CO_2 flux [39]–[41], the only site where both commercial and research methods were employed contemporaneously across the same project area. We argue here that improved and evolving methods of quantification for forest carbon, and more broadly for GHG's, informed by forest research [42]–[45], will catalyze forest carbon programs driven by equity, fair pricing, and reduced cost of carbon project entry for landowners including Indigenous Peoples [31], [46]. The importance of non-CO_2 forest GHG's, an area of research with limited data regarding the mechanisms of forest GHG gas exchange [27], [47], is emphasized by direct measurement, applicable to climate change mitigation across diverse forest project landscapes.

Annual data for forest carbon, reported as $gC\ m^{-2}\ y^{-1}$, or equivalent units, are analyzed for two adjacent Howland Forest CO_2 flux towers (US-Ho1,2) noting differences between CARB-CAR (CAR681, CAR1161) and NEE results. The CARB-CAR third-party validation process, a critical link in the carbon offset supply chain, is reviewed for error and adherence to regulatory provisions and to assess independence of forest carbon offset validation. An example of the promise and benefits of direct GHG flux measurement is presented by monetizing the   GHG social cost for forest emissions (GHG-SCF) for the Howland forest project comprised of tower and soil accumulation chambers for CO_2, CH_4 and, or N_2O. The scalability and benefits of direct CO_2 and non-CO_2 GHG measurement are discussed to address the ~0.90 billion hectares, available globally, for restoration to support forest communities and landowners that live in and protect the forests including land protected and tenured by Indigenous Peoples. We make recommendations for improvement of the CARB-CAR and similar protocols.
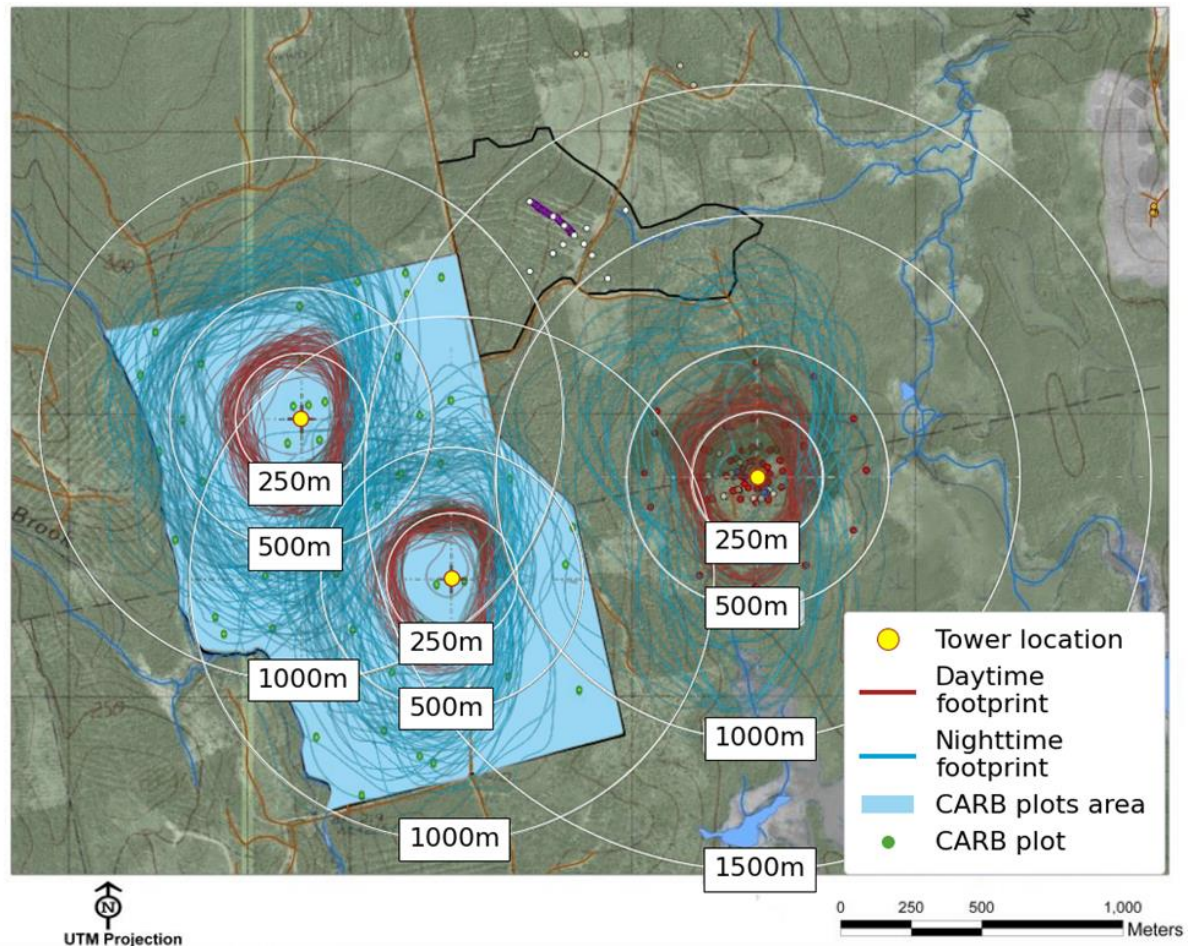
2. Materials and Methods

Site description

Figure 1. Map of the Howland Research Area. Tower locations (yellow circles; The towers are: Ho2 West, Ho1 Center, and Ho3 East), daytime and nighttime monthly climatology footprints (red and light-blue lines respectively), CARB Measurements Area (light blue area), and CARB individual plots (filled green circles) are represented. As a reference, white circles indicate the areas within 250, 500, 1000, and 1500m around each tower. Small white, purple, red, and orange dots belong to the original base map and correspond to measurements done at the Howland site, but they are not relevant to this study. The map was redrawn from https://umaine.edu/howlandforest/about/ and [17]; monthly climatology data are from [69].

The Howland Forest (Figure 1) is in central Maine at about 5 km south-west of the Howland town and 56 km north of Bangor (45.2041°N 68.7402°W, elevation 60 m above sea level). It is an area of 557 acres (~225 ha) classified as Evergreen Needleleaf Forest (ENF; Lands dominated by woody vegetation with a percent cover >60% and height exceeding 2 meters. Almost all trees remain green all year) according to the International Geosphere-Biosphere Programme (IGBP). The stands are about 20 m tall and consist of spruce-hemlock-fir, aspen-birch, and hemlock-hardwood mixtures, which were logged selectively around 1900. The region Koppen climate is Warm Summer Continental (Dfb; significant precipitation in all seasons) with mean temperature and rainfall of 6.1 °C and 990 mm, respectively. The soils are generally glacial tills, acid in reaction, with low fertility and high in organic composition. Soil drainage classes may vary widely within a small area, from well- to poorly-drained. More information can be found on its website https://umaine.edu/howlandforest/.

<u>CO_2 and CH_4 tower fluxes</u>

Howland has the second longest running flux record in the United States, dating back to 1996 (the longest belonging to Harvard Forest). These 20 years of data provide a time

series long enough for robust analyses of relationships between NEE and various environmental variables. CO_2 fluxes used in this study were measured above the canopy at a 29 m tower with the Eddy Covariance technique since 1996 (US-Ho1; "Main Tower"), from 1999 to 2004 (US-Ho2; "West Tower"), and from 2004 to 2007 (US-Ho3). US-Ho1 includes CH_4 measurements from 2012 to 2018 and it is approximately 775 meters apart from US-Ho2. The additional tower, US-Ho3, was used to monitor NEE after a shelterwood harvest. Removal of biomass from the project area was negligible for the areas represented by US-Ho1,2, while US-Ho3 experienced the planned shelterwood harvest to record changes in NEE [48].   More in-depth details about flux and footprint measurements and pre-processing can be found at [39]–[41], [48], [49]. Pre-processed data before filtering and gap-filling can be found at the AmeriFlux website (https://ameriflux.lbl.gov/sites/site-search/#keyword=Howland) or in each tower repository:

Us-Ho1: David Hollinger (1996-) AmeriFlux US-Ho1 Howland Forest (main tower), Dataset. https://doi.org/10.17190/AMF/1246061.

US-Ho2: David Hollinger (1999-) AmeriFlux US-Ho2 Howland Forest (west tower), Dataset. https://doi.org/10.17190/AMF/1246062.

US-Ho3: David Hollinger (2000-) AmeriFlux US-Ho3 Howland Forest (harvest site), Dataset. https://doi.org/10.17190/AMF/1246063.

CO_2, CH_4, and N_2O soil fluxes

An automated chamber system was used to measure soil CO_2, CH_4, and N_2O fluxes within the footprint of the US-Ho1 tower from 2012 to 2016, approximately once per hour during the snow-free period when vegetation was active (from May to November). Exact locations where the chambers were installed varied among years. Each chamber was 30.5 cm in diameter. Between measurements, the chamber top was lifted, using a pneumatic piston, off a PVC collar permanently inserted into the soil surface [41]. More details can be found at [50], [51]. The data can be downloaded from [41].

Data processing and calculations

CO_2 Eddy Covariance data was processed with REddyProc 1.2.1 [52], which filters low turbulence data using the methodology from [53] (with the 50-percentile criterion) and then fills all the gaps produced by the filtering technique or by instrument failure with a Look Up Table. The soil temperature at the lowest depth was chosen as input variable for REddyProc along with the above canopy air temperature (T_{air}), the vapor pressure deficit and the photosynthetic photon flux density divided by 0.47 as global radiation.

Ecosystem Respiration (R_{eco}), its photosynthesis (Gross Primary Productivity; GPP) and NEE are related according to the equation:

$$NEE \ = \ R_{eco} \ - \ GPP \tag{1}$$

In this study, R_{eco} was estimated with REddyProc based on the nighttime approach [21], [22], which fits the Lloyd and Taylor [54] model for respiration (Eq. 2) using only nighttime data, because NEE = R_{eco} at night, and then extrapolating the parameters R_{ref} and E_0 found in the regression to calculate daytime R_{eco} (T_{ref} and T_0 are fixed). Then, GPP is calculated with Eq. 1 [55].

$$R_{eco} = R_{ref} \ e^{\frac{E0}{Tref-T0} - \frac{E0}{T_{air}-T0}} \tag{2}$$

Afterwards, yearly NEE, R_{eco} and GPP sums were calculated in Python 3.7.7. In literature, NEE can also be expressed as Net Ecosystem Production (NEP), where NEP = NEE [56].

GHG Forest and Social Cost of CO_2, CH_4 and N_2O. Values in USD for the social cost of GHG's were adopted from the Interagency Working Group on Social Cost of Greenhouse Gases, United States Government [33]. The social cost values were applied to net emissions for US-Ho1 and for soil chamber measurements to introduce a new GHG Social Cost Forest (GHG-SCF) product that integrates the three gases into a single value of merit for holistic forest management of global warming.

Howland Eddy Covariance Footprint Data.

A composite footprint map was made by overlapping layers in Figure 1. The bottom layer consists of a satellite image showing the complete Howland Research Area redrawn from https://umaine.edu/howlandforest/about/. Then, the CARB Measurements Area with its plots were redrawn from [17] and overlapped. The top layers are the footprint monthly climatology maps that are in the Dataset S3 downloaded from https://zenodo.org/record/4015350 with their backgrounds removed and centered at each tower location. All the Howland footprints available were used (2013 to 2017 for Ho1, and 2003 to 2008 for Ho2 and Ho3). Tower locations and reference circles were highlighted for comparison.

CARB-CAR Data, Documents and Third-party Verification Review.

Table 1. CAR681 and CAR1161 Project Links*.

Project ID	CAR681	CAR1161
ARB ID	NA	CAFR5161
Project Developer	Northeast Wilderness Trust	Northeast Wilderness Trust
Project Owner	Northeast Wilderness Trust	Northeast Wilderness Trust
Project Name	Howland Research Forest	Forest Carbon Partners - Northeast Wilderness Trust - Howland Research Forest
Offset Project Operator	NA	Northeast Wilderness Trust
Authorized Project Designee	NA	Forest Carbon Partners, L.P.
Project Type	Improved Forest Management	Improved Forest Management - ARB Compliance
Status	Transitioned	Registered
ARB Project Status	Not ARB Eligible	Active ARB Project
Project Site Location	Penobscot County	Penobscot County
Project Site State	MAINE	MAINE
Total Number of Offset Credits Registered	48852	7762
Project Listed Date	12/19/2013	2/26/2015
Project Registered Date	3/13/2015	3/8/2019
Documents	View	View
Data	View	View
Project Website	www.forestcarbonpartners.com	www.forestcarbonpartners.com

CARB-CAR Forest methods exclude CO_2 measurement relying upon forest mensuration and growth models operationalized over a mandated 100-year project interval as employed by the California Air Resources Board and Climate Action Reserve [18]–[20], [57]. Howland Forest protocol data for CAR 681 and CAR 1168 results and third party

verification documentation were obtained from the Climate Action Reserve (https://www.climateactionreserve.org/) and the California Air Resources Board (https://ww2.arb.ca.gov/our-work/programs/compliance-offset-program) websites and documents available therein. Tables 1 -5 provide links to project data and document repositories, cumulative carbon credit performance reports with serial numbers, and historical summary of the CARB-CAR carbon offset supply chain for CAR 681 and CAR1161 and advances in Howland Forest carbon research.   Regulations for satisfying AB32 compliance criteria were based on the California Code of Regulations, Title 17, Division 3, Chapter 1, Subchapter 10, Article 5, Subarticle 14, Section 95977(d). Additional information on the CARB mandatory verification process can be found here: https://ww2.arb.ca.gov/our-work/programs/compliance-offset-program/offset-verification.
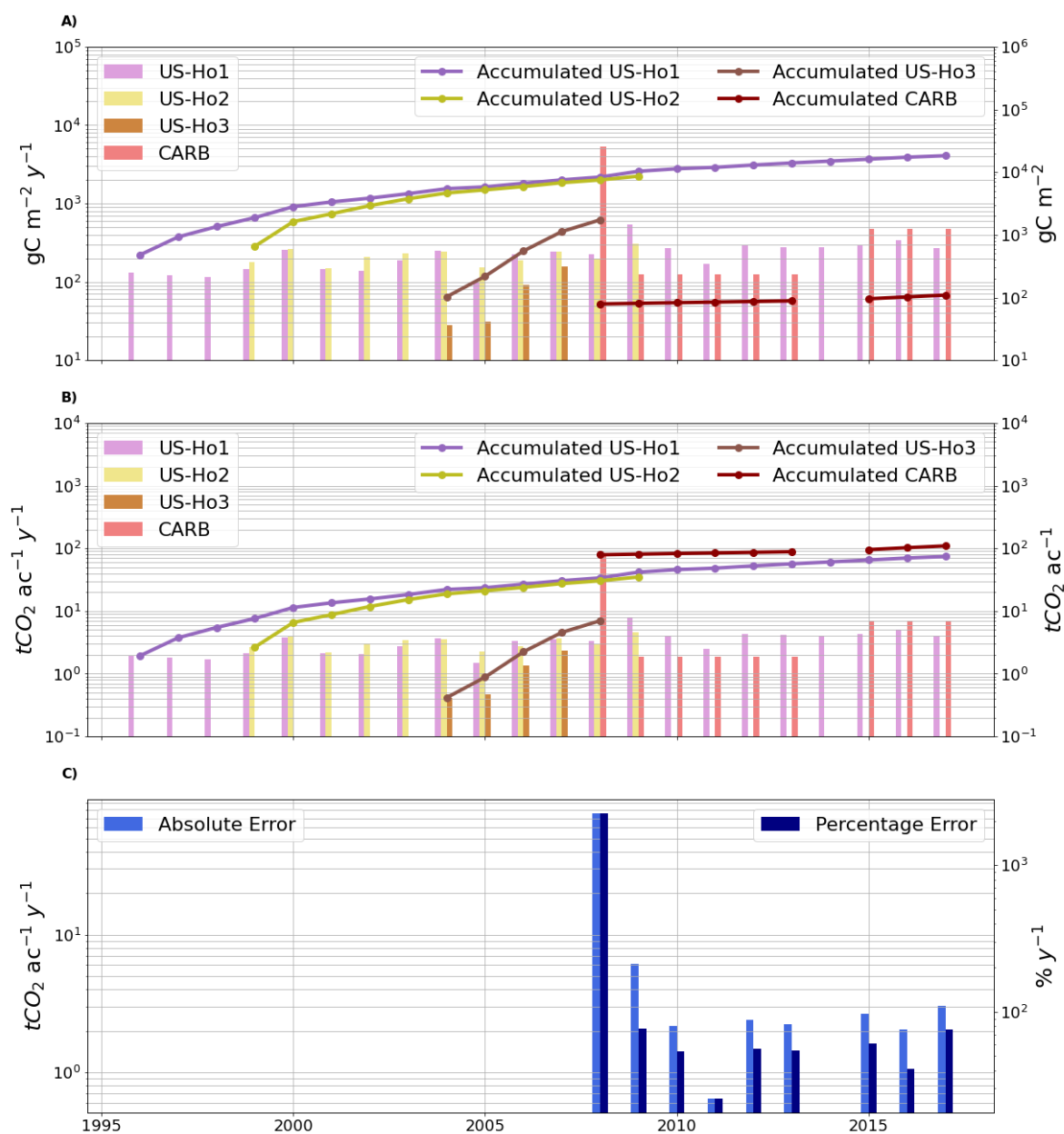
3. Results

Figure 2. Yearly NEE budgets (bars) and accumulated values (lines) for US-Ho1 (purple), US-Ho2 (green), US-Ho3 (brown) towers and for CARB (red) data in log-scale and in A) grams of carbon per square meter and B) tons of CO2 per acre. C)

Absolute and percentage CARB yearly errors if the measurements from US-Ho1 were correct, in log-scale. Negative error values were turned positive to include them in the log-scale.

Figure 2 shows NEE results for US-Ho1, 2, 3, and CARB-CAR values for the combined period of 1996 to 2017; absolute error results for the period 2008 to 2017 are shown. A) NEE gC m^{-2} y^{-1}, B) NEE tCO$_2$ acres y^{-1} (ac^{-1} y^{-1}); shown (A,B) are annual and cumulative values (years 2008 to 2013 represent CAR 681, years 2015 to 2017 represent CAR1161), C) absolute and percent errors for CAR annual project data relative to NEE overlapping data. Net carbon sequestration values are shown as positive. The mean and standard deviation for the aggregated CAR time series (2008 – 2013, 2015 – 2017) of $-768.1 \pm 1,716$ gC m^{-2} y^{-1} is ~2.7x the mean of -288.3 and ~17x the standard deviation of 95.5 gC m^{-2} y^{-1}, for Howland NEE Ho1 and Ho2 towers, respectively, consistent with exceeding the CARB 5% invalidation threshold [58] and natural ranges for reported interannual NEE variance [1], [23].   CAR681 reports a 2008 value of $-43,687.0$ tCO$_2$e, or $-5,334.7$ gC m^{-2}y^{-1}, ~19x larger than the Ho-1 NEE 2008 value of -287.1 gC m^{-2}y^{-1}, and ~32x the mean value of global forest NEE [59], establishing the CAR681 2008 value as exceeding the known natural ranges for NEE [23], [59]. Likewise, CAR681 reports an exact value of 834 tCO$_2$ (e.g., -198.0 gC m^{-2} y^{-1}) for the years 2009 to 2013 in contrast to absence of repeating values for the 20-year US-Ho1 record, documenting incapability of CAR model annual resolution and an NEE trend not observed in the natural variance of Ho1. US-Ho1 data is augmented with US-Ho2 NEE data, approximately 775 meters apart, representing ~95% of the project footprint area shared by NEE and CARB-CAR data source areas as shown in Fig 1. A two tailed t-test comparing US-Ho1 and US-Ho2 returned a t-statistic of   0.22 with an associated p-value of 0.83, thus the difference is not significant. The overlapping years are from 1999 to 2009 (10 years; at 95% the approximate t-threshold is 2.2) consistent with [40]. US-Ho3 documents the recovery of NEE after a shelterwood harvest.   The absolute and percentage error of CARB-CAR data relative to NEE data ranges from 0.65 tCO$_2$ ac^{-1} y^{-1}; 25.7% to 75.9 tCO$_2$ ac^{-1} y^{-1}, and 2,258% for the years 2011 and 2008, respectively, if US-Ho1 yearly values are taken as the correct values.
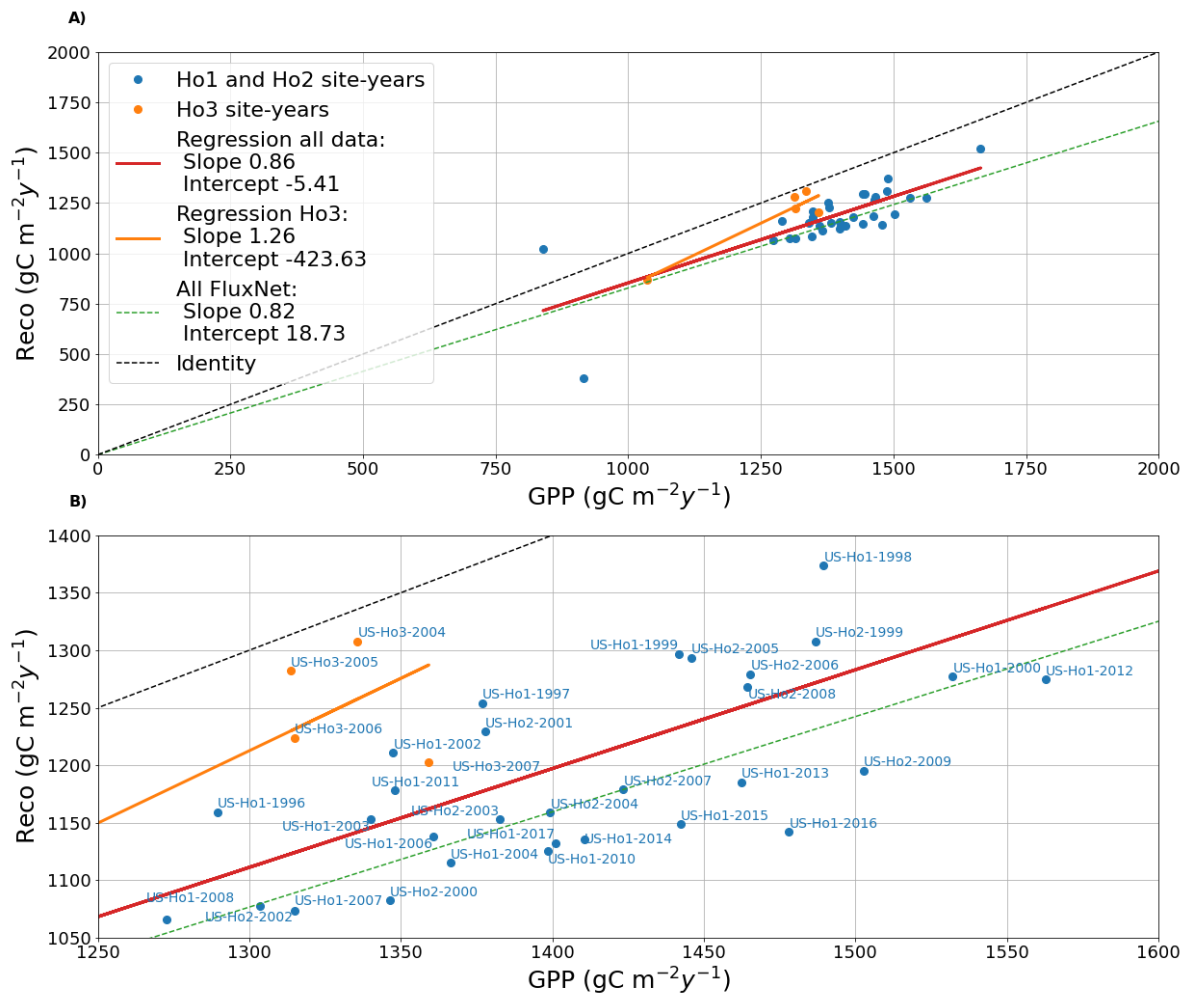
Figure 3. Yearly Reco vs GPP for US-Ho1 and US-Ho2 (blue points) and US-Ho3 (orange points). The regression lines (using all the data, red solid; using only US-Ho3 data, orange solid). The identity (black dashed) and FluxNet regression (green dashed) were added as a reference. A) Shows all the years, while B) only those in the ranges (1050; 1400) and (1250; 1600) gC m-2 y-1 for Reco and GPP, respectively.

Figure 3 shows yearly R_{eco} vs GPP for the three Howland towers (US-Ho1,2 blue points; US-Ho3 orange points) and regression lines (using all data, red solid; using only US-Ho3 data, orange solid). The identity (black dashed) and FluxNet regression (green dashed) lines were added as a reference. A) Shows all the available years, while B) shows only those in the ranges (1050; 1400) and (1250; 1600) gC m^{-2} y^{-1} for Reco and GPP, respectively. Individual years are identified in B); years with higher GPP relative to R_{eco} likely store more carbon relative to annual records for carbon sequestration shown; larger GPP is offset by larger R_{eco}. Outliers in 3-A for US-Ho1 and US-Ho2 (blue filled circles) from lowest to highest GPP are US-Ho1 (2015), US-Ho1 (2009), US-Ho3 (2008), and US-Ho1 (2001).
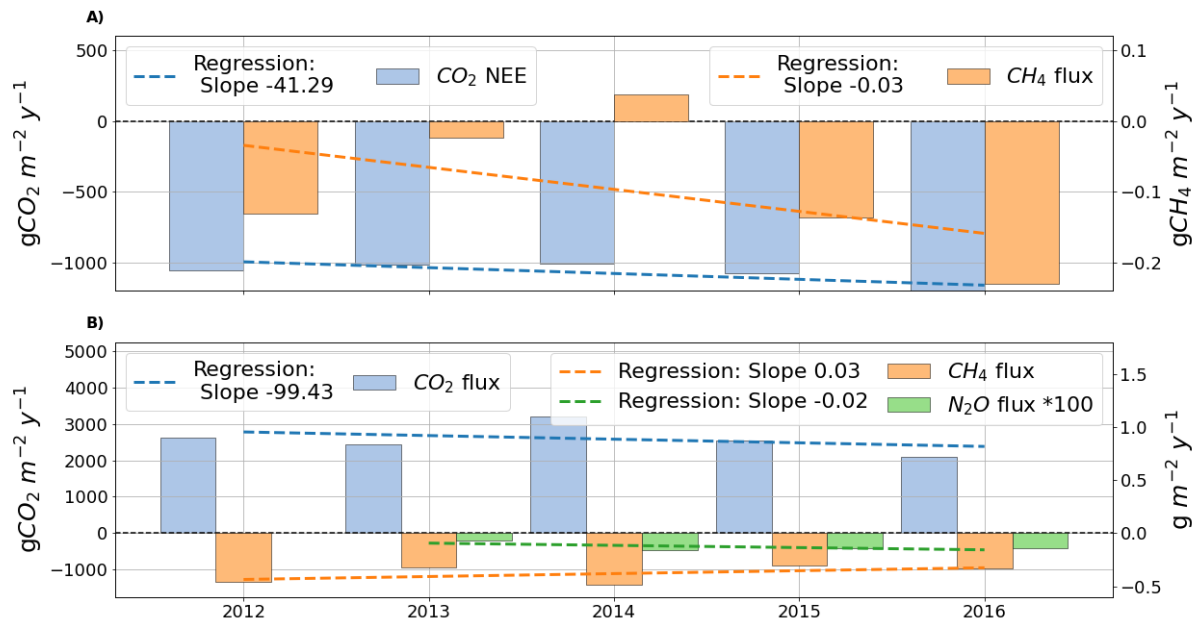
Figure 4. Yearly budgets (bars) and trends (lines) for: A) CO_2 (blue) and CH_4 (orange) fluxes measured at the top of the tower. B) Soil CO_2 (blue), CH_4 (orange) and N_2O (green) fluxes measured at chambers N° 2 (CO_2 and CH_4) and N° 10 (N_2O). Soil fluxes budgets from B) correspond only to the period May-November, while the tower fluxes from A) to the full year. In both cases, CO_2 values are represented by left Y-axes, while CH_4 and N_2O by right Y-axes.

Figure 4 shows yearly budgets (bars) and trends (lines) for: A) CO_2 (blue) and CH_4 (orange) fluxes measured at the top of the tower US-Ho1. B) Soil CO_2 (blue), CH_4 (orange) and N_2O (green) fluxes measured at chambers N° 2 (CO_2 and CH_4) and N° 10 (N_2O) [41]. Soil flux budgets from B) correspond only to the period May-November, while the tower fluxes from A) represent the full year. In both cases, CO_2 values are represented by left Y-axes, while CH_4 and N_2O by right Y-axes. The tower data for CH_4 trends to a maximum positive value of ~0.045 gCH_4 m^{-2} y^{-1} in 2014 followed by net negative fluxes in 2015 and 2016 resulting in net negative flux with CO_2 of   10.8 CO_2e. Soil chamber data for CH_4 and CO_2 do not reflect tower data. The N_2O soil chamber data are net negative resulting in a net positive flux for the soil areas sampled of 25.7 CO_2e [41], based on the limited chamber data available. Mean CO_2 and CH_4 measured at the three towers were -10.76 and -0.03 metric tons per hectare respectively, while CO_2, CH_4 and N_2O means measured at the soil chambers were 25.8, -0.13 and -0.0037 metric tons per hectare, respectively. Note, however, that the Howland forest consistently a sink for CH_4 and N_2O for the limited periods observed.
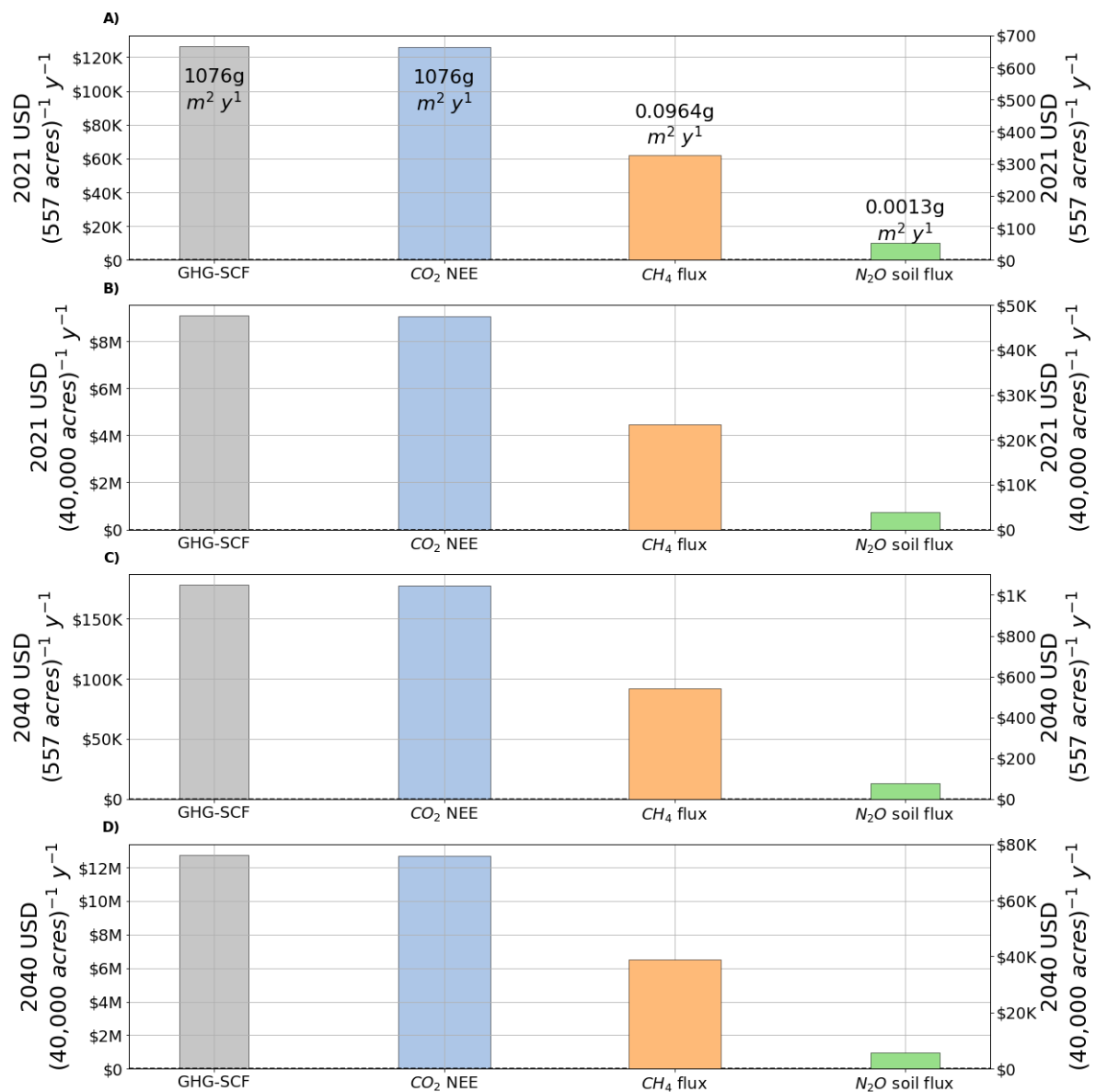
Figure 5. GHG social cost forest (GHG-SCF) yearly means (bars) for CO_2 (blue) and CH_4 (orange) fluxes measured at the top of the tower, N_2O (green) fluxes measured at chambers N° 2 (CO_2 and CH_4) and N° 10 (N_2O), and the total sum of the three (GWG Economic Value; Grey). Soil flux averages correspond only to the period May-November, while the tower means to the full year. For illustration purposes, results were extrapolated to the Howland Research Area (557 acres; panels A and C) and to 40,000 acres (panels B and D). Social cost values used were: A) and B) 52, 1500, and 19,000 USD dollars per GHG metric tonne of CO_2, CH_4, and N_2O respectively (values estimated for the year 2021). C) and D) 73, 2500, and 28,000 USD dollars per GHG metric tonne of CO_2, CH_4, and N_2O respectively (values estimated for the year 2040). In each panel, GHG-SCF Economic values and CO_2 NEE are represented by left Y-axes, while CH_4 and N_2O fluxes by right Y-axes. In panel A) yearly mean capture is annotated for each gas in g m^{-2} y^{-1} above each bar.

Figure 5 shows the monetization of the integrated average annual GHG social cost for forests (GHG-SCF), (gray bar) for the Howland Forest project (~557 acres) based on the measurement of CO_2, CH_4 and N_2O at the US-Ho1 tower, or from soil chambers, using estimates for the social cost factor for each gas. For illustration purposes only, the US-Ho1 measurements have been extrapolated to 40,000 acres to demonstrate the potential for revenue over larger forest areas. Projections account for social value estimates in 2021 and in 2040. A discount rate of 3% was applied to the values for each gas according to [33] yielding projected project average annual GHG-SCF values of $124,000 (2021 values, 557 acres) up to ~$12,200,000 (2040 values, 40,000 acres).

CARB-CAR Forest Carbon Supply Chain. Tables 1-4 describe the carbon credit supply chain for CARB-CAR. Table 1 identifies the transition of CAR681, an improved forest management project (IFM), from an early action project to an eligible ARB compliance project CAR1161 or CAFR5161 listed on 2/26/2015; total offset credits registered for both project numbers are available through the links provided. Tables 2 and 3 identify date of issue for specific vintage years and serial numbers for CAR681 and CAR1161, respectively. Table 4 lists the project documents for CAR681 and CAR1161, covering project data reporting, project design, carbon pools used in calculations and verification documents with dates of entry for each into the CARB regulatory registry. A full verification report for CAR681 credits issued was uploaded on 3/11/2015 (Item 1, SCS Global Services) completing the supply chain for CARB markets for the cap-and-trade AB32 system [16]. A full verification statement is not available for CAR1161 offsets.

Table 5 CARB-CAR, NEE Timeline. Table 5 shows the 2008 to 2019 CARB-CAR process timeline for CAR681 and CAR1161 including CAR regulatory system entry dates for offset issuance and document submission in support of offset creation, third-party validation and annual NEE data for the Howland Forest, coeval with CARB-CAR projects. Referring to CAR681, the first reporting period ending on 12-31-2013 (Year 2013), triggered an 11-month compliance period (i.e., ending 12-01-2014) for submission of a verification statement to CARB. Referring to the year 2014, the verification statement was recorded by CARB on 12/03/2014 rendering the offsets ineligible for issuance. The CAR681 timeline indicates that a timber inventory for CAR681 (and CAR1161) was completed in 2013 (raw data are not available), the same year that the project listing document (Table 4, Doc # 7) was recorded by CARB (Table 5, Year 2014). Referring to Table 5, Year 2017, the reporting period for CAR1161 offsets ended on 07/15/2017, triggering an 11-month compliance period (i.e., ending 06-15-2018) for submission of a verification statement. According to CARB documentation, the verification reporting was not uploaded to the CARB compliance registry system until 10/9/2018 rendering the 2015-2017 offsets ineligible for CARB issuance. The availability of directly measured CO_2 NEE data were available since 1996 followed by a seven year annual record of NEE in 2004 [40]. At the time of the registration of the CAR681 full verification report (3/11/2015; Document # 1, Table 5), US-Ho1 NEE data were available from [39], [40], [48], [60]–[62] covering the years 1996 to 2015 providing an independent source of forest carbon sequestration for independent evaluation of CARB-CAR data and carbon credit results. A single year of Howland NEE data, 1996, was cited, in error as described below. An accounting error is noted in the reported final Total GHG Reductions, Offset Verification Statement of 7,763 tCO_2 whereas the actual value was reported and issued as 7,762 tCO_2 (Table 3).

Table 5 Documentation of Critical Errors. Critical errors are noted in the stated interpretation and use of Howland NEE data. Referring to 2014 and 2012, the CARB-CAR documentation cites Hollinger NEE data, 1996 [39], and 2004 [40], in the Project Design Document (Table 4, Item 3, Fig. 17, p. 34) received by CARB on 12/03/2014, and a Supplemental Listing Document (Table 4, Item 12, Fig. 1, p. 9) received by CARB on 2/19/2015. The CARB-CAR documents refer to Fig. 7 of [39], [40] documenting a single year, 1996, of NEE data expressed as half-hourly net ecosystem C exchange   in micromoles $m^{-2} s^{-1}$, referring to modeled and actual NEE data [40]. The CARB-CAR PDD incorrectly states that the seasonal variation of the CAR model (v3.2) was modified based on seven years of ecosystem-atmosphere CO_2-flux measurements using the eddy covariance technique at the Howland AmeriFlux site. The Supplemental listing document repeats the same error citing and misstating the time interval of the Howland 1996 data. Both documents state, without providing details, that Table 12 (PDD, p. 34, Table 4, Document # 3) and Table 5 (Supplemental Listing), incorporates the Howland 1996 data; it is not known if the actual or modeled data were employed.

Table 2. CAR681 Project Emission Reductions and Issued Offset Serial Numbers.   1

Action	Date Issued	Status	Vintage	Quantity of Offset Credits	Quantity of Offset Credits to Buffer Pool	Issued Quantity	Reporting Period Begin	Reporting Period End	Offset Credit Serial Numbers	Buffer Offset Credit Serial Numbers
View	3/13/2015	Issued	2013	834	199	834	1/1/2013	12/31/2013	CAR-1-US-681-25-467-ME-2013-1697-1 to 834	CAR-1-US-681-25-467-ME-2013-1698-1 to 199
View	3/13/2015	Issued	2012	834	199	834	1/1/2012	12/31/2012	CAR-1-US-681-25-467-ME-2012-1699-1 to 834	CAR-1-US-681-25-467-ME-2012-1700-1 to 199
View	3/13/2015	Issued	2011	834	199	834	1/1/2011	12/31/2011	CAR-1-US-681-25-467-ME-2011-1701-1 to 834	CAR-1-US-681-25-467-ME-2011-1702-1 to 199
View	3/13/2015	Issued	2010	834	199	834	1/1/2010	12/31/2010	CAR-1-US-681-25-467-ME-2010-1703-1 to 834	CAR-1-US-681-25-467-ME-2010-1704-1 to 199
View	3/13/2015	Issued	2009	834	199	834	1/1/2009	12/31/2009	CAR-1-US-681-25-467-ME-2009-1705-1 to 834	CAR-1-US-681-25-467-ME-2009-1706-1 to 199
View	3/13/2015	Issued	2008	35,299	8,388	34,654	10/8/2008	12/31/2008	CAR-1-US-681-25-467-ME-2008-1707-1 to 34654	CAR-1-US-681-25-467-ME-2008-1708-1 to 8388
View	3/13/2015	Issued	2008	35,299	8,388	645	10/8/2008	12/31/2008	CAR-1-US-681-25-467-ME-2008-1696-1 to 645	

https://thereserve2.apx.com/mymodule/reg/TabProjectEmissions.asp?r=111&ad=Prpt&act=update&type=PRO&aProj=pub&tablename=cr&id1=681

Table 3. CAR1161 Project Emission Reductions and Issued Offset Serial Numbers   2

Action	Date Issued	Status	Vintage	Quantity of Offset Credits	Quantity of Offset Credits to Buffer Pool	Issued Quantity	Reporting Period Begin	Reporting Period End	Offset Credit Serial Numbers	Buffer Offset Credit Serial Numbers
View	3/8/2019	Issued	2017	6,910	0	6,910	7/16/2015	7/15/2017	CAR-ROC-US-1161-125-467-ME-2017-5704-1 to 5583	CAR-ROC-US-1161-125-467-ME-2017-5705-1 to 1327
View	10/9/2019	Issued	2017	852	0	852	7/16/2015	7/15/2017	CAR-ROC-US-1161-125-467-ME-2017-5852-1 to 688	CAR-ROC-US-1161-125-467-ME-2017-5853-1 to 164

https://thereserve2.apx.com/mymodule/reg/TabProjectEmissions.asp?id1=1161&ad=Prpt&act=update&sBtn=&r=111&Type=PRO&tablename=cr&aProj=pub

Table 4. CAR681 and CAR1161 Online Project Documents

Doc #	Vintage	CAR681	Document Type	Category	Upload Date	Uploaded By
1	2014	CAR-Forestry_NF_Howland_FinalVerificationReport_031115.pdf	Verification Report	Verification	3/11/2015 19:43	SCS Global Services
2	2008	CAR_NF_Howland_VerificationStatement_v3-0_120214.pdf	Verification Statement	Verification	12/3/2014 19:46	SCS Global Services
3	2008	Howland-Project-Design-Document 2014-12-02.pdf	Project Design Document	Verification	12/3/2014 1:29	Northeast Wilderness Trust
4	2008	NWT Project Developer Attestation of Voluntary Implementation_Howland.pdf	Attestation of Voluntary Implementation	Verification	5/16/2014 21:21	Northeast Wilderness Trust
5	2008	NWT Project Developer Attestation of Regulatory Compliance_Howland.pdf	Attestation of Regulatory Compliance	Verification	5/16/2014 21:21	Northeast Wilderness Trust

6	2008	[NWT Project Developer Attestation of Title_Howland.pdf](#)	Attestation of Title	Verification	5/16/2014 21:20	Northeast Wilderness Trust
7	2008	[Howland listing document submitted 121113_amended.pdf](#)	Project Submittal Form	Project Submittal	12/16/2013 22:06	Northeast Wilderness Trust
8	2008	[Map -Howland Forest Carbon v2.pdf](#)	Physical Boundary Map	Project Submittal	9/22/2010 20:53	Northeast Wilderness Trust
		CAR1161				
9	2017	[CAFR5161_OVS_16aug2019.pdf](#)	Offset Verification Statement	Verification	10/9/2019 21:49	The Climate Action Reserve
10	2017	[Howland-COP-RP1-OPDR_20190306_Final.pdf](#)	Offset Project Data Report	Verification	3/7/2019 18:05	Northeast Wilderness Trust
11	2015	[ARB IFM LISTING FORM HOWLAND_20150225_Final.pdf](#)	Offset Project Listing Information Form	Project Submittal	2/25/2015 18:59	Northeast Wilderness Trust
12*	2015	[Howland Compliance Listing Documents.zip](#)	Offset Project Listing Information Form	Project Submittal	2/19/2015 21:55	Northeast Wilderness Trust

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*Contains: 1) Supplemental Listing Document (Attachments E, F, G, H & J) no date; 2-3) Attestations, 4) ARB IFM Listing Form Howland (Completed 2/19/2015)

Covering offset 10-8-2008 to 01-01-2014, first reporting period 12/31/2015; 5) shape file

CAR681: https://thereserve2.apx.com/mymodule/reg/TabDocuments.asp?r=111&ad=Prpt&act=update&type=PRO&aProj=pub&tablename=doc&id1=681

CAR1161: https://thereserve2.apx.com/mymodule/reg/TabDocuments.asp?r=111&ad=Prpt&act=update&type=PRO&aProj=pub&tablename=doc&id1=1161

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Table 5 . Summary of Howland Timeline for CAR681, CAR1161 and Publication of US-Ho1,2,3 data.

CAR681	US-Ho1,2,3*	CAR 1161
	1996 [1]; (NEE -210 gC m^{-2} y^{-1};1996)	
	2004 [2]; (NEE - 174 ± 46 gC m^{-2} y^{-1}, 1996 - 2002) [3] (NEE forest regrowth, 2004 - 2008)	
	2007 [4]; ameriflux.com, fluxnet.org	
10/8/2008 - 12/31/2008 [VINTAGE 2008 Offsets Issued - 34,654] 10/8/2008 - 12/31/2008 [VINTAGE 2008 Offsets Issued - 645] Deed Restriction 10/8/2008	**2008**	
1/1/2009 - 2/31/2009 [VINTAGE 2009 Offsets Issued - 834]	**2009**	
1/1/2010 - 12/31/2010 [VINTAGE 2010 Offsets Issued - 834] Project Map, 9/22/2010 8:53:00 PM, NWT	**2010**	
1/1/2011- 12/31/2011 [VINTAGE 2011 Offsets Issued - 834]	**2011**	
1/1/2012 - 12/31/2012 [VINTAGE 2012 Offsets Issued - 834]	**2012**	

1/1/2013- 12/31/2013 [VINTAGE 2013 Offsets Issued - 834] Timber Inventory Howland Listing Document, 12/16/2013 10:06:00, NWT CAR681 First Reporting Period Ends 12/31/2013	**2013 [5]**	
<u>VERIFICATION</u> (1) Attestation of Title, 5/16/2014 9:20:00, NWT (2) Attestation of Regulatory Compliance, 5/16/2014 9:21:00, NWT (3) Attestation of Voluntary Implementation, 5/16/2014 9:21:00, NWT (4) Project Design Document, 12/3/2014 1:29:00, NWT (5) <u>VERIFICATION STATEMENT [VINTAGE 2008-2013]</u>, 12/3/2014 7:46:00, SCS CA Cap and Trade Regulation Section 95977(d) Deadline to Receive Offset Verification Statement, 11/30/2014	**2014**	

VERIFICATION (1) Final Verification, SCS, 3/11/2015 7:43:00 VINTAGE 2008-2013 Offsets Issued 3/13/2015	**2015**	7/16/2015-7/15/2017 [VINTAGE 2015-2017 Offsets Issued - 6,910] 7/16/2015 - 7/15/2017 [VINTAGE 2015-2017 Offsets Issued - 852] Listed 2/26/2015 2/19/2015 9:55:00 PM [Compliance Listing Documents, NWT VINTAGE 2015] 25 Feb 2015 06:59 PM [ARB IFM Listing, NWT, VINTAGE 2015]
	2016 [6] ; (NEE 188 68 gC m-2 y-1, 1996 - 2014)	
	2017	CAR1161 First Reporting Period Ends 7/15/2017
	2018	CA Cap and Trade Regulation Section 95977(d) Deadline to Receive Offset Verification Statement, 6/14/2018

	2019 [7]	3/7/2019 6:05:00 PM [VERIFICATION, Offset Data Report, NWT, VINTAGE 2015-2017] Issued 3/8/2019 6,910 Offsets Issued 3/8/2019 10/9/2019 9:49:00 PM [VERIFICATION, Offset Statement, CAR, VINTAGE 2015-2017] 852 Offsets Issued 10/9/2019

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*References to Howland Forest data publications and sources are listed in brackets.   10

[1] [39]   11

[2] [40]   12

[3] [48]   13

[4] https://ameriflux.lbl.gov/sites/siteinfo/US-Ho1#data-use-log

https://fluxnet.org/data/la-thuile-dataset/lathuile-data-summary/

[5] [62]   14

[6] https://www.osti.gov/dataexplorer/biblio/dataset/1246061   15

[7] [41]   16

4. Discussion

The three-gas flux inventory (CO_2, CH_4, N_2O) for the Howland Forest [41] demonstrates the commercial promise of expanding direct measurement of forest GHG's, an area of research with limited results [27], [47]. The Howland forest project provides an example of net GHG emission footprints coupled with external factors, such as the social cost of GHG emissions [33], [63], [64], across select areas of the Howland site. Referring to Fig. 4-A the Howland Forest was a net sink for CO_2 and CH_4, except for 2014 during the 2012 to 2016 interval for US-Ho1. Fig 4-B soil accumulation chambers were also consistently a sink for CH_4 and N_2O but a source for CO_2. While CH_4 and N_2O emissions are 11,200 (Fig. 4-A) and 828,000 (Fig. 4-b) orders of magnitude lower than corresponding CO_2 fluxes, respectively, they have higher social cost factors than CO_2 ($51) of 1,500 (29x CO_2) and 18,000 (353x CO_2), respectively, calculated for the year 2021 with a 3% discount rate [33]. Projected GHG social cost forest (GHG-SCF) offset products for the Howland project area of 557 acres and extrapolated, for illustration purposes only, to 40,000 acres for 2021 and 2040, are show in Fig 5-A-D ranging from ~$12,000 (2021, 557 acres) to ~$12,000,000 (2040, 40,000 acres). Small forest fluxes of non-CO_2 GHG's result in comparatively large revenue benefits that should not be ignored [41] and are coupled to the monetary value of the net harm to society associated with adding a small amount of a GHG to the atmosphere in a given year [33]. In principle, the GHG-SCF product includes the value of all climate change impacts, including (but not limited to) changes in net agricultural productivity, human health effects, property damage from increased flood risk natural disasters, disruption of energy systems, risk of conflict, environmental migration, and the value of ecosystem services, including forests [33]. The GHG-SCF should reflect the societal value of reducing emissions of the GHG species by one metric ton. Presently, the variables and mechanisms, such as soil composition, site land use history, species and age of trees, seasonality, rainfall, and topography, regulating forest GHG gas exchange are not well understood, emphasizing the importance of expanded monitoring for diverse forests [29], [47], [65]. Direct measurement of GHG-SCF should be integral part of the realization of green policies (e.g., Green New Deal) providing links to established policy criteria to reduce GHG emissions[33].

A combination of three-gas eddy covariance tower networks of varying heights and soil chamber measurement campaigns can be scaled-up across specific ecosystem landscapes by employing expanded ground networks, increasingly inclusive of CH_4 monitoring [44], [66]–[68], scale-aware models [69], and remote sensing data [70] available for the US and increasingly across the planet [71]. Three-gas forest eddy covariance systems employed at Howland are comprised of commercially available single and multi-gas analyzers for eddy covariance (e.g., CO_2 and CH_4, N_2O) [72], [73], also applicable to soil chamber gas analyses [41]. In contrast to the diversity of GHG direct measurements and applications for Howland, the CARB-CAR protocols identify and list CH_4 and N_2O only as sources [20]. Equations for net GHG reductions and removal enhancements cited in [20], may apply to any GHG, but are defined for CO_2, as source or sink, linked to the carbon and tree growth equations and models to satisfy the 100-year carbon baseline and tree harvest scenarios required for CARB-CAR products. Accordingly, CARB-CAR protocol uncertainties for non-CO_2 GHG's are likely higher than for CO_2 and limited to source emissions, rather than net emissions for these gases.

Expanding multi-gas eddy covariance networks can provide equitable and economically attractive green policy [35] partnerships for the ~38 million km^2 representing ~25% of the world's land surface managed or land tenured by Indigenous Peoples [46]. In contrast, the high cost and maintenance of the UN-REDD program associated with mensuration protocols and Indigenous Peoples land management and rights represent barriers to entry and economic benefits, including discount pricing for carbon offsets [74], [75]. For example, REDD carbon offset prices average ~$3.65 t$CO_2$ [76] and, if validated by the Ver-

ified Carbon Standard,   lower pricing, for example,   of ~$1.62 tCO_2 [76] is typical. In contrast,   compliance pricing is consistently higher, for example ranging from ~$12 for the Beijing pilot emission trading system offsets, to $15 for the California carbon market, to $22 for the UK carbon price floor [7]. Direct measurement of forest GHG emissions, harmonized by shared reference and standardization, equalizes pricing for voluntary-and compliance buyers [1], [31] worldwide. While eddy covariance offers an alternative to forest mensuration protocols, the main challenge for commercial applications is scale-up of single tower results to larger areas (*41, 62, 71)*, as well as errors intrinsic to the method addressed in eddy covariance applications [31], [32], [41], [77], and beyond the scope of this study.

Considering CO_2 alone, Howland Forest NEE tower data, US-Ho2, in conjunction with US-Ho1, covers ~95% of the shared project footprint area with CARB-CAR forest plots (Fig. 1). NEE values for US-Ho1 and US-Ho2 are comparable, lacking significant difference between the towers. The Howland two-tower NEE data confirm irreconcilable differences for carbon accounting relative to CARB-CAR methods consistent with previous results [1] of offset overcrediting and overpayment by ~4x relative to NEE values [1]. The aggregate CAR681 and CAR1161 time series (2008 – 2103, 2015 – 2017) were ~2.7x the mean and ~17x the standard deviation for Howland NEE over the same period, exceeding the 5% invalidation threshold cited by CARB [78] and lying outside of the natural range for 20 years of measured interannual Howland [41], [60] and NEE forest values [23], [59]. The exclusion of ecosystem respiration terms for CO_2 within the CARB-CAR protocols, critical for calculation of net forest carbon sequestration, confirm incomplete carbon accounting and likely erroneous, invalid offsets for the CARB compliance process for CAR681 and CAR1161. Absent ecosystem respiration, errors of up to 2,258% per year were calculated emphasizing the importance of complete carbon accounting, consistent with the well characterized relationship between R_{eco} and GPP (Fig. 2-A, B), and soil chamber measurements for CO_2 efflux (Fig. 5).

Referring to third-party verification to ensure the integrity and validity of the CARB-CAR forest carbon supply chain, we found that: 1) The CARB-CAR Howland project did not meet CARB reporting regulations for both tranches of Howland CARB offsets as an early action project (CAR681), or as an ARB compliance project (CAR1661), by non-compliance of offset verification reporting dates (Table 5), 2) CAR misstated actual values for a single year of NEE data (1996) [40] as 7 years of seasonal Howland NEE data in support of model adjustment for seasonal trends in tree growth. However, the CAR model (ver 3.2) excludes terms for soil carbon as ecosystem respiration, intrinsic to NEE data, and requires conversion of NEE micromoles m^{-2} s^{-1} to tree volume, a complex topic addressed by [79]. Details of model revisions and results were not provided calling the validity of model results into question, 3) The Howland NEE records, advancing annually from 1996, were available to CARB-CAR project owners, operators, and third-party verifiers (20, 24–27, 29, 32), overlapping with the supply chain process from 2013 to 2019 culminating in serialized CARB verified offsets according to the AB32 mandate [80]. The Howland US-Ho1 NEE data were not reported as an independent check of the CARB-CAR annual results, a comparison that would have constrained the natural ranges for carbon sequestration offering an opportunity to proscriptively avoid   CARB-CAR forest carbon sequestration uncertainties, 4) Howland CARB-CAR project reporting exhibits errors and lapses in recordation, similar to those reported previously [1], including numerical error, change in reporting format from annual to discretionary mixed time intervals, and non-standard model operations resulting in uncertain values, and, 5) The raw data and model outputs for the CARB-CAR project have not been made available to the public, limiting collaboration and external verification of the project results; rather CARB-CAR data and information are housed on personal computers with no central repository (Table 5, Item 10). Considering the uncertainties identified above, the CARB-CAR verification process is scientifically unjustifiable, creating avoidable offset invalidation risk for CAR681 and

CAR1161. Exclusion of direct measurement protocols for forest carbon have been recently extended within the Assembly Bill (AB)398 [81] by recommendation of a mandated Task Force to provide guidance in establishing new offset protocols, ironically ensuring that CARB forest protocols cannot advance beyond their current state of development [82].

The importance of data for forest carbon respiration to determine net carbon sequestration for Howland is emphasized in Fig. 3-A,B, showing annual steps in R_{eco} relative to GPP. Fig. 3-A,B demonstrates that for every annual interval of photosynthetic uptake of CO_2 (GPP), there is an obligatory response embodied in R_{eco} [59], or an automatic debit to stored carbon intended for carbon trading markets. US-Ho1 R_{eco} vs. GPP for 2008, the initial year of CAR681, yielding a total of 43,687 carbon credits ($-5,334.7$ gC m^{-2}y^{-1}) (Table 2), falls within the lower left quadrant of the FluxNet slope for R_{eco} and GPP values, Fig. 3-B, lower than most annual intervals. The CAR681 2008 value would require R_{eco} and GPP values of 2,667, in the case of the identity line relationship (e.g., R_{eco} = GPP; NEE = 0), clearly outside of the Ho1-3 values; requiring higher values for GPP if considering the regression line for all Ho1-3 data (red regression line). US-Ho1, 2016, showed the highest GPP relative to R_{eco} while US-Ho3 values for 2004 – 2006, exhibit high respiration relative to GPP. The US-Ho1,2 outliers (Fig. 3A) emphasize the need for high frequency monitoring as anomalous years can have disruptive impacts on project revenue [32]. US-Ho3 confirms the sensitivity of eddy covariance NEE to timber harvest and regrowth (Fig. 2-A,B), a trend not detected by CARB-CAR methods, but a requirement to test CARB-CAR modeled harvest and growth simulations (14). Eddy covariance data provide insights into carbon dynamics and related economics not possible with biometric surveys conducted every 6- to 12-years, typical for the Howland CARB-CAR protocol [17].

The CARB-CAR and similar protocols could be improved by defining measurement and model results within the Eq. 1 universal reference framework and incorporating independent field data for direct measurement of CO_2. Collaboration with forest carbon sequestration field sites represented by the National Ecological Observatory and the AmeriFlux network of eddy covariance towers [83], [84] may suggest improvements in the CARB-CAR protocol. Given the sources of uncertainty identified for the CARB-CAR verification process, improvements could be implemented in the near-term such as providing raw data availability for external users, inter-comparison of CARB-CAR with NEE data where possible, enforcing accounting standards, and adherence to consistent reporting formats.

5.0. Conclusions

The importance of verification and harmonization of net forest carbon sequestration methods cannot be overstated to manage and conserve forests. Forest carbon research is steadily advancing worldwide offering innovative applications to the commercial sector that both improve quantification and enhance pricing for carbon trading markets. Emphasis on the commercial promise for non-CO_2 GHG's is also warranted as a benefit of direct measurement for molecular flux across forest and related landscapes. The social cost of GHG's can be most effectively monetized for reduction policies with direct measurement and verifiable commercial products, an opportunity not achievable by reliance on uncertain carbon denominated estimation protocols.

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