Direct measurement of forest carbon sequestration: A commercial system-of-systems to incentivize forest restoration and management

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Forest carbon sequestration offsets are methodologically uncertain, comprise a minor component of carbon markets and do not effectively slow deforestation. We describe a commercial-scale measurement approach for determination of net forest carbon sequestration, the Direct Measurement Forest Carbon Protocol™ (DMFCP), to address forest carbon market uncertainties. The DMFCP is based on standardized methods for determination of net ecosystem exchange (NEE) of CO_2 employing eddy covariance, a meteorological approach integrating forest carbon fluxes, and employed here as the basis for quantifying carbon financial products. The DMFCP is commercialized and deployed within a System-of-Systems™ (SoS) network architecture. SoS sensor nodes, the Global Monitoring Platform™ (GMP), housing analyzers for CO_2 isotopologues (e.g., $^{13}C^{16}O_2$, $^{14}C^{16}O_2$) and greenhouse gases (e.g., CH_4, N_2O), are deployed across the project landscape capable of differentiating fossil from biogenic carbon sources and sinks. The SoS standardizes and automates GMP measurement and reporting functions resulting in reduced costs for large-scale applications. To illustrate the SoS operation, published annual NEE data for a tropical (Ankasa Park, Ghana, Africa) and a deciduous forest (Harvard Forest, Petersham, MA, USA) are used to forecast forest carbon revenue. Carbon pricing scenarios are combined with historical *in situ* NEE annual time-series to extrapolate pre-tax revenue for each project applied to 100,000 acres (40,469 hectares) of surrounding land. Based on carbon pricing of \$5 to \$36 per ton CO_2 equivalent (tCO_2eq) and observed NEE sequestration rates of 0.48 to 15.60 tCO_2eq $acre^{-1}$ yr^{-1}, pre-tax cash flows ranging from \$230,000 to \$16,380,000 across project time-series are calculated, offering landowners economic incentives to reverse deforestation. The SoS concept of operation and architecture can be extended to diverse

gas species across terrestrial, aquatic and oceanic ecosystems, harmonizing voluntary and compliance market products worldwide to assist in the management of global warming. The DMFCP reduces risk of invalidation intrinsic to estimation-based protocols such as the Climate Action Reserve and the Clean Development Mechanism that do not observe molecular CO_2. Multi-national policy applications such as the Paris Agreement and the United Nations Reducing Emissions from Deforestation and Degradation (REDD+), constrained by Kyoto Protocol era processes, will benefit from the updated scope of the DMFCP avoiding unsupported claims of emission reduction, fraud, and forest conservation policy failure.

Article

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Abstract: Forest carbon sequestration offsets are methodologically uncertain, comprise a minor component of carbon markets and do not effectively slow deforestation. We describe a commercial-scale measurement approach for determination of net forest carbon sequestration, the Direct Measurement Forest Carbon Protocol™ (DMFCP), to address forest carbon market uncertainties. The DMFCP is based on standardized methods for determination of net ecosystem exchange (NEE) of CO_2 employing eddy covariance, a meteorological approach integrating forest carbon fluxes, and employed here as the basis for quantifying carbon financial products. The DMFCP is commercialized and deployed within a System-of-Systems™ (SoS) network architecture. SoS sensor nodes, the Global Monitoring Platform™ (GMP), housing analyzers for CO_2 isotopologues[i] (e.g., $^{13}C^{16}O_2$, $^{14}C^{16}O_2$) and greenhouse gases (e.g., CH_4, N_2O), are deployed across the project landscape capable of differentiating fossil from biogenic carbon sources and sinks. The SoS standardizes and automates GMP measurement and reporting functions resulting in reduced costs for large-scale applications. To illustrate the SoS operation, published annual NEE data for a tropical (Ankasa Park, Ghana, Africa) and a deciduous forest (Harvard Forest, Petersham, MA, USA) are used to forecast forest carbon revenue. Carbon pricing scenarios are combined with historical *in situ* NEE annual time-series to extrapolate pre-tax revenue for each project applied to 100,000 acres (40,469 hectares) of surrounding land. Based on carbon pricing of \$5 to \$36 per ton CO_2 equivalent (tCO_2eq) and observed NEE sequestration rates of 0.48 to 15.60 tCO_2eq $acre^{-1}$ yr^{-1}, pre-tax cash flows ranging from \$230,000 to \$16,380,000 across project time-series are calculated, offering landowners economic incentives to reverse deforestation. The SoS concept of operation and architecture can be extended to diverse gas species across terrestrial, aquatic and oceanic ecosystems, harmonizing voluntary and compliance market products worldwide to assist in the management of global warming. The DMFCP reduces risk of invalidation intrinsic to estimation-based protocols such as the Climate Action Reserve and the Clean Development Mechanism that do not observe molecular CO_2. Multi-national policy applications such as the Paris Agreement and the United Nations Reducing Emissions from Deforestation and Degradation (REDD+), constrained by Kyoto Protocol era processes, will benefit from the updated scope of the DMFCP avoiding unsupported claims of emission reduction, fraud and forest conservation policy failure.

Keywords: 13C, 14C, carbon forest offset, eddy covariance, forest carbon finance, forest preservation, carbon products, carbon trading, biogenic carbon, fossil fuel emissions

Introduction

Forest landowners and forest communities typically lack economic incentives and social benefits to balance deforestation with conservation and preservation (Duguma et al., 2019). A constellation of factors is responsible for deforestation (Busch & Ferretti-Gallon, 2017), claiming ~50% of tropical forested landscapes (Brancalion et al., 2019; Rozendaal et al., 2019), including contested land rights, carbon project cost and requirements for landowners (Kerchner & Keeton, 2015), failure of payment for ecosystem services (PES) (Fenichel et al., 2018; Lamb et al., 2019) and as we argue here, uncertainty for forest carbon sequestration and resulting landowner revenue (Engel et al., 2015; Bruno DV Marino et al., 2019; D. Zhang, 2019). Carbon markets are primarily driven by reduction/avoidance of emissions to the atmosphere from energy production and consumption (Liddle, 2018) while investment in removal of CO_2 from the atmosphere by reforestation and conservation has not gained carbon market traction (Laurance, 2007; Gren and Zeleke, 2016) declining by ~ 72% from 2011 to 2016 (Molly Peters-Stanley, Gonzalez and Yin, 2013; Hamrick and Gallant, 2017). Discount pricing for forest carbon (e.g., < \$5 tCO_2eq, 2017: < 1\$, 2018) (K Hamrick & Gallant, 2018; Kelley Hamrick & Gallant, 2017) results in limited ecological, social and economic benefits of carbon trading to stakeholders due, in part, from risk of offset invalidation intrinsic to estimation protocols (Dunlop et al., 2019; Haya, 2019; Bruno DV Marino et al., 2019). Vendor platforms such as the Climate Action Reserve (CAR) (Brown et al., 2017) (Climate Action Reserve, 2017) and the Clean Development Mechanism (CDM) (B. Zhang et al., 2018), providing forest carbon services to landowners and large-scale policy driven programs such as REDD+ (Hein et al., 2018), are also subject to offset uncertainty, limiting effectiveness to slow and stop deforestation. Approximately 0.9 billion hectares of forests are available worldwide for large-scale restoration opportunities (Bastin, 2019; Brancalion et al., 2019), however, in addition to carbon quantification uncertainties (Bruno DV Marino et al., 2019), financing for large-scale projects has proven difficult (Foss, 2018). Complete and direct carbon accounting of forests (i.e., ecosystem assimilation and respiration of CO_2) are required to track biospheric carbon dynamics given the limited and impermanent nature of forest and soil carbon (D. Baldocchi & Penuelas, 2019; W.H. Schlesinger, 2000; William H Schlesinger, 2003). We address forest carbon accounting uncertainties by linking direct measurement of net ecosystem exchange of forest carbon fluxes (NEE) for a project with carbon market transactions in a Direct Measurement Forest Carbon Protocol (DMFCP). The objectives of the DMFCP are to effectively monetize sustainable forest management and direct revenue to landowners and communities in lieu of deforestation.

The DMFCP commercializes large-scale (e.g., 1+ million hectares), direct, *in-situ* measurement of vertical gross forest CO_2 fluxes (e.g., photosynthesis and ecosystem respiration) to determine net forest carbon sequestration or net ecosystem exchange (NEE) (D. Baldocchi et al., 2018). The DMFCP, employing a network system architecture, the SoS, and a sensor platform, the GMP, account for project carbon from measurement to monetization to sale of NEE based products as described in Figures 1 and 2. NEE has been measured in over 600 locations worldwide (FLUXNET; U.S. Department of Energy Office of Science) but has not been utilized to support commercial SoS networks for realization of verified forest carbon products and carbon market transactions. We describe The DMFCP operations of the SoS and GMP commercial platform employing NEE data from two research sites, the Ankasa Park tropical rainforest located in Ghana, Africa (Chiti et al., 2010), and the Harvard Forest deciduous forest site located in Petersham, MA, USA (Munger, 2016; Urbanski et al., 2007). The NEE time series data for each site, in combination with carbon pricing scenarios, are used to project revenue across a hypothetical areal expanse of 100,000 acres (404,685.6 hectares). We compare landowner benefits and incentives to restore forests and reverse deforestation employing the DMFCP and traditional estimation-based protocols.

Methods

Net ecosystem exchange (NEE) is a measure of the net exchange of carbon fluxes between an ecosystem and the atmosphere (per unit ground area) and is a primary metric of ecosystem carbon sink strength (Kramer et al., 2002; (D. Baldocchi et al., 2018; D. Baldocchi & Penuelas, 2019). NEE can be defined as:

$$NEE = GPP + R_{eco} \quad (1)$$

and,

$$R_{eco} = R_a + R_h, \quad (2)$$

where GPP = gross primary production or photosynthetic assimilation, R_{eco} = ecosystem respiration, R_a = autotrophic respiration by plants, and R_h = heterotrophic respiration by soil microbes. NEE can be expressed as NEP plus sources and sinks for CO_2 that do not involve conversion to or from organic carbon: −NEE = NEP + inorganic sinks for CO_2 − inorganic sources of CO_2 (Chapin et al., 2000, 2006; Lovett et al., 2006; Luyssaert et al., 2009). NEE measurements integrate (1) and (2) (Burba, 2013), consistent with the focus presented here on sequestration and monetization of biospheric carbon where CO_2 reduction/increase is a credit/debit to forest and biospheric carbon storage. For example, a negative NEE flux represents a net carbon sink into the biosphere (e.g., removal or capture of CO_2 from the atmosphere) and a positive NEE represents a net carbon source into the atmosphere from the biosphere (e.g., increase of CO_2 in the atmosphere). The sign convention accommodates the definition of a carbon credit as representing 1 tone CO_2 equivalent (CO_2eq)[ii] sequestered or captured from the atmosphere (Anja Kollmuss, 2014). We assume that loss of carbon due to fire, UV, removal of biomass and import of biomass are negligible as both project sites are protected (Ankasa Park) or managed as conserved land (Harvard Forest). NEE records reductions in photosynthesis caused by fire and deforestation should these events occur in the project areas (Goulden et al., 2006; Mamkin et al., 2019; Ney et al., 2019; Ueyama et al., 2019). Standing live carbon inventory derived from biometric and or remote sensing methods, typically would be employed to augment and cross-check project NEE data (Ouimette et al., 2018; Verma et al., 2013).

NEE data for a single tower for each site was accessed from online data sources and transformed into tones carbon dioxide equivalent per acre per year (e.g., $tCO_2eq\ acre^{-1}\ yr^{-1}$). The NEE values for both sites representing footprints of ~1-10 km^2 are used to extrapolate NEE to 100,000 acres (40,469 hectares) to illustrate potential revenue for large-scale projects. The extrapolation of NEE data is for illustration purposes only as single tower data for both sites may not be representative of larger forest areas. Extrapolated NEE values were combined with carbon prices ranging from $5 to $36 tCO_2eq to explore pre-tax revenue scenarios including definition of hypothetical carbon products underlying the projections. Cumulative tCO_2eq is based on summing the annual tCO_2eq for each annual record across the extrapolated area of 100,000 acres (40,469 hectares).

Field Sites

Ankasa Park, Ghana, Africa (Figure 3 A). The Ankasa Park eddy covariance tower (AP) (5°17′00″N 2°39′00″W: GH-Ank) is located in a wet evergreen forest in south-western Ghana (Fig. 1) (Chiti et al., 2010) within the Ankasa Conservation Area. The 62 meter high AP tower was developed and operated as part of the CarboAfrica project (Stefani et al., 2009) and was operational for four years (2011 to 2014) by the University of Tuschia, Italy. The NEE eddy covariance data for AP were retrieved, as is, from the Fluxnet2015 database as annual NEE based on the gap filled VUT_NEE_REF values (Fluxnet, 2019). The Ankasa Resource Reserve, established in 1934 (Hall and Swaine, 1981), lies within the administrative rule of the Jomoro district in the Western region of Ghana and is under the paramount chief of Beyin (Bandoh, 2010). The reserve was managed as a protected timber producing area until 1976 at which time it was designated as the Ankasa Resource Reserve (Ghana Wildlife Department, 1998, Vol. 8; (Damnyag et al., 2013). The forest area is comprised of ~500 km^2 surrounded by deforested landscapes; the area is ~90m above sea level with mean annual temperature of ~25°C. The Ankasa Resource Reserve has an average Genetic Heat Index (GHI) of 301 and forest condition score of 2 (i.e. very good forest). However, hilly portions of the reserve showed highest local GHI score of 406 (Hawthorne and Abu-Juam, 1995). These high scores in Ghana are probably amongst the "hottest" patches of genetic rarity in Africa, many of the species concerned being found elsewhere only across the border in Southern La Cote D'Ivoire. For example, Ankasa is also one of only two known localities for Ghana's sole endemic forest genus- Monocyclanthus (Annonaceae) and the other locality also falls within the type at Benso (Hall and Swaine, 1981). Generally, there is a relatively low number of valuable timber species in the Ankasa Resource Reserve which is typical of the Wet Evergreen forest type. The relatively low number of valuable timber species also occur mostly on steep slopes in the Reserve. Official records on timber logging activities in the Ankasa Resource Reserve is scanty as the object of management over years has been primarily for protection and/or resource conservation. Furthermore, poor soils of the area have, in the past, repelled commodities (i.e. cocoa) or food farmers and the population has been low for a forest area (Hall and Swaine, 1981). It is important to note that the Jomoro district where the Ankasa Resource Reserve is located experienced dramatic population fluctuations from 1960 onwards. For instance, in 1960, the estimated population was 45,162 but declined to 37,685 by 1970. The results of Ghana's 1984 population census recorded a population of 70,881. According to the 2000 population census, the population of the Jomoro district had increased significantly and it was estimated at 111,348 an increase of 54% from 1984 (Bandoh, 2010). In the very recent 2010 census, the population recorded for the district was 150,107. Nini Suhien National Park and Ankasa Resources Reserve are twin Wildlife Protected Areas that are located in the Western Region of Ghana. These areas are rich in biodiversity with about 300 species of plants recorded in a single hectare. The areas are largely unexplored but 43 mammal species including the bongo, forest elephant, 10 primate species including the endangered Dina monkey and the West African chimpanzee have been recorded (www.fcghana.org/page.php?page=268&section=32&typ=1&subs=275). Bird fauna is also rich. The reserves offer very good example of the west evergreen forest to the prospective tourist.

Harvard Forest, Petersham, MA, USA (Figure 3 B). The Harvard Forest Environmental Measurement Site (HF) tower (42.537755°N, 72.171478°W; US-Ha1) is located in the Harvard Forest Long Term Ecological Research (LTER) site in Petersham, Massachusetts. The elevation of the research area of ~16.18 km^2 ranges from 320 to 380 meters above sea level (Fig. 1a). NEE data are available online ("US-Ha1: Harvard Forest EMS Tower (HFR1)," 2019). The HF tower measurements, initiated in Oct 1991, provide the longest continuous set of flux measurements in the US (Barford et al., 2001; Urbanski et al., 2007). The mixed deciduous forest stand surrounding the tower has been regenerating on abandoned agricultural landscape since the late 1890's punctuated by a major hurricane disturbance in 1938. The Harvard NEE gap-filled dataset was read in line by line and processed using Python Libraries (Pandas, NumPy) with txt format. Year, month , day, hour and NEE data were selected for this study. NEE was determined by calculating the mean of 48 half-hour data for each day as umol CO_2 m^{-2} s^{-1}, converting the value to gC m^{-2} d^{-1}, and summing daily NEE to calculate annual NEE for each year.

DMFCP Technical Description

The DMFCP is comprised of hardware and software components designed to function as an automated commercial field sensor network, the System of Systems (B. D. V. Marino, 2013, 2014a, 2017b, 2017a, 2014b, 2014c, 2015b, 2015a, 2016b, 2016d, 2016c, 2016a; Bruno D. V. Marino, 2019). An integrated sensor platform, the Global Monitoring Platform, is positioned at each node of the network. The Software components of the SoS are configured to interact with all nodes for automated reporting of data and instantaneous third-party verification of systems, processes and results. The SoS summarizes measurements of GHG fluxes against local, regional and global reference materials for bulk and isotopic composition, providing the basis for calculation of verified tradeable GHG financial products that differentiate biogenic from anthropogenic net carbon fluxes. Additional details for the SoS, GMP and related field equipment for NEE flux determinations are described in Appendix I.

Results

Figure 4 illustrates the annual (tCO_2eq) NEE for HF (24 years) and AP (4 years) sites relative to a zero-reference baseline established by instruments at both sites and to a zero-emissions baseline defining negative (e.g., net CO_2 sequestered), positive (e.g., net CO_2 emissions released to the atmosphere) or neutral carbon balance (e.g., 0 sequestration/emissions). Annual NEE values for HF and AP were negative over the intervals shown resulting from active forest carbon sequestration or generation of carbon credits (Figure 4 A). Annual NEE for HF ranged from a minimum of −0.53 (2010) to a maximum of −9.09 (2008) tCO_2. The mean and standard deviation (SD) for the HF site for 24 years was −4.5 tCO_2 $acre^{-1}$ yr^{-1} ± 2.3 (SD). Annual NEE for AP ranged from a minimum of −6.74 (2013) to a maximum of −15.2 (2011) tCO_2. The mean and standard deviation (SD) for the AP site for 4 years was −10.2 tCO_2 $acre^{-1}$ yr^{-1} ± 3.6 (SD). The variance for annual NEE demonstrates the large interannual variance for NEE. Figure 4 (B) shows the corresponding cumulative NEE across the observational periods recorded for each site extrapolated to 100,000 acres (40,469 hectares). The HF and AP linear cumulative NEE provides insight into the potential long-term sequestration capacity of the forest landscapes. The AP NEE slope of −8.40x is 1.7 times that of the HF suggesting that in this case, the tropical wet evergreen forest site experienced consistently greater sequestration of carbon than the temperate deciduous forest, however, caveats apply in that tropical forests may not result in larger long-term carbon sinks. For example, tropical forests typically have larger gross production but a corresponding larger respiration (D. Baldocchi et al., 2018). Additionally, the two forest locations differ in stand age and history of disturbance, factors that are known to affect NEE (Hollinger et al., 2013; Ouimette et al., 2018; Urbanski et al., 2007). However, NEE provides a quantitative record of daily and annual sums of carbon sequestration characterizing the fundamental nature of derivative carbon products that cannot be replicated by proxies for forest carbon sequestration (e.g., estimation-based protocols).

Figure 5 illustrates landowner pre-tax cash flow (millions USD) relative to variable carbon pricing tCO_2eq ($5, $10, $15, $36) for cumulative NEE consisting of 24 and 4 years for the HF and AP sites, respectively. The values represent extrapolations of measured local NEE to 100,000 acres (40,469 hectares) multiplied by the annual NEE record for each site. Two cases are represented in which the landowner receives a single upfront payment (Case 1) or an upfront payment plus annual royalty on sales (Case 2). Case 1 pre-tax cash flow estimates range from upfront payments (e.g., 10%) of $230,000 to $1,670,00 and $510,000 to $3,680,000 for HF and AP, respectively, across carbon prices of $5 to $36 tCO_2eq. Case 2 pre-tax cash flow estimates range from an upfront payment (e.g., 8%) plus deferred payouts based on realized revenue from the sale of all carbon products (e.g., 6%) of $3,520,000 to $25,360,000 and $1,640,000 to $11,790,000 for HF and AP, respectively, across carbon prices of $5 to $36 tCO_2eq. A variance for the total pre-tax sales value of ± 20% of realized revenues is indicated by vertical bars to reflect uncertainty in the sale of carbon products for Case 2.

Figure 6 illustrates an example of pre-tax cash flow change for a decrease/increase in carbon sequestration strengths based on the minimum, mean and maximum values of NEE observed for each site's historical record (extrapolated to 100,000 acres or 40,469 hectares). Sequestration strength is expected to vary annually in response to rainfall and related ecological factors. We use the minimum, mean and maximum values for NEE recorded at each site to illustrate the effect of annual sequestration rate on pre-tax revenue. Project value ranges from $760,000 to $13,830,000 and from $2,140,000 to $4,860,000 across the minimum, mean and maximum values for the annual records of the HF and AP sites, respectively.

Figure 7 illustrates pre-tax cash flows for mixed carbon product types and pricing for Case 2; example product inventory and pricing for the products is indicated below each set of bars. Note that the hypothetical carbon products range in price from $12 t$CO_2$eq for compliance offsets to $50 t$CO_2$eq for carbon products with the additional element of biodiversity (e.g., conservation). Total pre-tax cash flow for Case 2 is $16,380,000 and $7,610,000 for the HF and AP sites, respectively. These data illustrate the higher potential revenue based on sale of mixed products and pricing for voluntary, compliance and regulatory markets. The vertical bars for Case 2 represent 20% variance in market uncertainty.

Discussion

The DMFCP features continuous measurement of NEE for CO_2 forest carbon projects providing a standardized universal commercial method for determination of net forest carbon sequestration. Shared calibration of instruments and reliance on a shared zero-emissions baseline ensures that results for all analyses and analyzers (e.g., GMP) within a network or between networks (e.g., SoS) are comparable. The near real-time data (30-minute average of 10 Hz CO_2 composition) for forest NEE achievable with the DMFCP offers insights into forest carbon dynamics and ecosystem function previously unavailable to landowners. Figure 1 clarifies the structure and process of the DMFCP characterized by high precision, high frequency analysis of CO_2 and other GHGs or isotopologues for both above and below ground carbon. The final result is a pooled portfolio of diverse projects and harmonized products for sale to voluntary and compliance buyers worldwide transacted as tCO_2eq (Figure 1). The SoS architecture of the DMFCP organizes and differentiates project variables consistently across forest project types. For example, the two NEE sites described in this work representing tropical and deciduous forests, when pooled, provide species and ecological diversification with respect to NEE source strength, vulnerability to climate change, among other factors (e.g., site history, soil composition, deforestation, insect damage; Barford et al., 2001) and external risks (e.g., currency value, national/sub-national environmental regulation) (Tarnoczi, 2017). The upfront and royalty revenue structure resulting from sale of DMFCP products provides financial incentive for the landowner to enter into reforestation and forest management projects in lieu of deforestation and increased disturbance due to anthropogenic activity. Long-term forest carbon projects are likely to increase harvest ages and management of forest stocking for optimal forest growth while promoting carbon benefits of active sustainable forestry (Bastin, 2019; Brancalion et al., 2019; Chazdon, 2008). Enhancement of biodiversity, food webs and cultural engagement should also accrue as forests grow (Watson et al., 2018). Private and commercial forestry operations will likely have different goals whereas the features and benefits of the DMFCP apply to both, bridging the gap between voluntary and compliance forest carbon offset markets. Project specific factors, such as annual internal sequestration strength (e.g., Figure 6), site history, location and duration can be accommodated within the DMFCP including conditions that accommodate working forests.

The hypothetical financial structure and cases for payment to landowners illustrate the pre-tax revenue potential for landowners. The potential long-term cumulative value of both sites, shown in Figures 4 B and 7, may be attractive to landowners for purposes of property valuation and cost of delayed reforestation in-line with indices for value of timber land (Ferguson, 2018; Keith et al., 2019; D. Zhang, 2019). Pre-tax revenue annual variance and risk is illustrated in the HF 2010 NEE (Fig. 2a), representing a reversal of +4.79 tCO_2eq relative to 2009, equivalent to a one-year loss of $4,790,00 ($10 tCO_2eq), but again reversed the following two years attaining -5.04 tCO_2eq and revenue of $4,510,000 ($10 tCO_2eq). Figure 6 provides estimation of upper and lower pre-tax revenue boundaries according to the minimum and maximum carbon sequestration for the two sites ranging from $760,000 to $13,830,000 and from $2,140,000 to $4,860,000 for HF (i.e., 24 years, $10 t$CO_2$) and AP (i.e., 4 years, tCO_2), respectively. Figure 6 emphasizes the revenue potential of mixed forest carbon products incorporating features of project biodiversity and allocation of offsets for specific markets. Pre-tax revenue for mixed carbon products and pricing is projected at up to $16,380,000 for the HF over the 24-year period (Figure 7). The sites described both actively sequester carbon at different rates; it is not known if these trends will reverse as a result of climate change and anthropogenic activity. The requirement for CO_2 measurement cannot be understated for determination of annual changes in NEE and for creation of annual forest carbon financial products as the NEE results from the balance of assimilation and related costs of respiration (D. Baldocchi & Penuelas, 2019; Bruno DV Marino et al., 2019). The SoS engineered architecture is scalable across large landscapes (~1 – 10 million hectares) requiring multiple GMP locations according to size of the land parcel, forest coverage, height of eddy covariance towers and data requirements (Burba, 2013); sensor architecture and engineering details will vary for each project. The cost of the DMFCP, in this scenario, are covered by sales of forest carbon products; an assumption of 100% sale, potentially subject to ± 20% of the values reported, of all carbon products is made for the purpose of this illustration for payments to landowners.

In addition to potential revenue for landowners, the DMFCP simplifies the forest carbon protocol compared to traditional approaches that differ in their methods, assumptions and allowance for discretionary revisions (A. Kollmuss & Fussler, 2015; Bruno DV Marino et al., 2019). A summary of protocol features and benefits to landowners of the DMFCP is provided in Table 1 and Figure 2. Equivalent units of tCO_2eq or units as converted are employed for the DMFCP and traditional protocols (#1). Items 2 - 5 have been covered above, defining the irreconcilable differences between direct measurement of CO_2 versus the use of proxies (i.e., CO_2 is not directly observed at any time in the estimation protocol process). Landowner revenue and time-to-revenue are key factors in landowner forest carbon project participation. Traditional protocols (e.g., CAR, CDM) require lengthy periods (e.g., 2-5 years) of fee-based project certification and registration prior to payment, limiting landowner participation (Kerchner & Keeton, 2015). In contrast, the DMFCP process provides an upfront payment and annualized payment (e.g., case 2, Figures 5, 7) in a no-fee agreement (Figure 2) available immediately according to a governing agreement (e.g., contract) that also includes no-fee listing in an open source registry (summarized by #6,7,8, Table I). The DMFCP embodied in the SoS and GMP obviates three features intrinsic to traditional protocols including estimation of a baseline (#9), tests for additionality (#10) and an invalidation period (#11) linked to compliance testing and third-party verification (#12). Direct measurement establishes forest carbon flux as either negative (e.g., CO_2 sequestration), positive (e.g., CO_2 efflux), or zero (sequestration balances efflux). It follows that a zero-emissions baseline is intrinsic to a time-series of positive/negative/zero NEE measurements (Figure 2 A) integrating forest tree species, vegetation and carbon fluxes across and within the project area including all above and below ground carbon pools (DiRocco et al., 2014) and wood that is removed from the project area. DMFCP carbon accounting is not subject to uncertainty of selection for species distribution and growth simulation models typical of traditional protocols (A. Kollmuss & Fussler, 2015). Additionality tests require a counterfactual argument (Ruseva et al., 2017) that cannot be validated and is subject to discretionary adjustment. A credit is considered additional if the emissions reduction that underpins the credit would not have occurred in the absence of the activity that generates the credit (A. Kollmuss & Fussler, 2015). In contrast, the DMFCP results in near-real time (30- minute average of 10 Hz measurements) NEE time series and trends (Dou & Yang, 2018), obviating reliance on uncertain project scenarios and an impractical prediction of future emissions against possible forest disturbance. Further, tests of net emission reduction across project areas or jurisdictions for specified periods of time are readily calculated from DMFCP results for independent projects, establishing simple numerical additionality (Figure 2 B) rules for established private and public lands. The DMFCP does not require an invalidation period (# 11) compared to estimated forest carbon offsets. In contrast to long inspection intervals for traditional forest carbon protocols (e.g., 6 or 12 years; California Air Resources Board, 2011, 2015), the DMFCP results are subject to instantaneous invalidation. The DMFCP is subject to replication of equipment and system performance standards, precision and accuracy of universal references and review of NEE from raw data to financial products at any time. The DMFCP employs a real-time wireless reporting and verification concept of operations architecture including third-party independent observers of all data developed for each SoS network (e.g., Anadiotis et al., 2019) with invalidation authority (#12). In contrast, third party validation for CAR projects, for example, is based on desk and paper reviews of unobserved CO_2 (e.g., proxies), and not readily amenable to invalidation testing and enforcement.

Once a project is in operation, a switch from carbon negative to carbon positive ecosystem function is key to project management, revenue projections and an understanding of ecosystem function in relation to climate change and anthropogenic activity. Traditional forest carbon protocols do not appear capable of determining when a forest project switches to net positive emissions to the atmosphere on an annual basis; the DMFCP NEE measurements provide this diagnostic (#13). Item #13 is also linked to demonstration of project permanence (#14) and termination of a project (#15). Traditional protocols require an arbitrary 100-year period of monitoring and maintenance for project carbon with a punitive penalty for early termination; lack of CO_2 measurement renders both of these factors indeterminate, impractical and biased against the landowner. The DMFCP employs ton-year accounting, an IPCC recognized method that does not impose an artificial time horizon for tree growth (e.g., 100 years) opening forest carbon sequestration projects to a wider range of forest project types and project intervals (Cunha-e-Sá et al., 2013; Levasseur et al., 2012). The ton-year accounting method accommodates combined budgets of CO_2, CH_4 and N_2O resulting in a comprehensive and realistic project GHG budget (Alice Courtois et al., 2019; Richardson et al., 2019), an approach that can be applied to the spectrum of projects from pure conservation to working forests and not achievable with estimation based forest carbon protocols.

Items 1 to 12 for existing protocols address two key factors favoring deforestation engagement: transaction requirements and liquidity. Forestland as a timber asset requires long periods of growth to harvest and is generally financially illiquid until harvested (Mei, 2015). It is argued here that business development of forest carbon projects, as practiced according to traditional protocols, is overly cumbersome and lengthy to establish offset transactions, and financially inviable to compete with the short time intervals of deforestation often resulting from illicit transactions (Alam et al., 2019; Tacconi et al., 2019; Tellman, 2016). In addition, with the use of satellite imagery, illegal deforestation can be detected in near real-time, with spatial resolution of ~6.5 hectare limiting potential gaming of the system and uncertainty in the sources of CO_2 flux (Hayek et al., 2018; Tang et al., 2019). Rapid set-up direct measurement, no-fee based agreements, upfront and annualized payments, discrete revenue intervals of 10 years, and reasonable exit terms align landowner business operations (private and commercial) within realistic financial frameworks with applications to culturally diverse transactional and transnational frameworks (Fenichel et al., 2018). Additional points of comparison concern the limitation of traditional protocols to accommodate the spectrum of relevant GHG's (e.g., N_2O, CH_4, PFC's, HFC's, SF_6, NF_3) (#16), isotopologues of GHG's (e.g., $^{13}C^{16}O_2$, $^{14}C^{16}O_2$) (#17), the inclusion of aquatic features (e.g., rivers, lakes ponds, wetlands, oceans)(#18) and the lack of contribution to ecosystem science and climate change studies and models (#19). Traditional forest carbon protocols (A. Kollmuss & Fussler, 2015) were developed for singular application to forests, incorporating methodology employed for timber management and primarily restricted to capturing above ground carbon. As a result, algorithms developed for forest CO_2 are not readily applicable to other GHG species and diverse biospheric landscapes. Based on the comparisons, the insuperable shortcomings of traditional protocols do not provide data that contributes to the evolving science of forest carbon sequestration, climate change studies and related model development.

The DMFCP can be applied to international emission reduction policies. For example, the expansion of measurement networks and data integration are key but unrecognized components of the Paris Agreement (Clemencon, 2016) and REDD+ (Foss, 2018). The Paris Agreement, while successful in gaining signatories of the majority of countries (Beck, 2017), lacks guidance on exactly how pledged and claimed reductions that are non-binding will be verified without actual measurement in the field (Ollila, 2019; Spash, 2016). The estimation approach remains embedded in the United Nations Framework Convention on Climate Change (UNFCCC) of 1992 (Springer, 2003) that promulgated reporting of emissions based on estimation, rather than direct measurement, an approach constraining advancement of the Paris Agreement and the REDD+. According to the UNFCCC approach, estimates of greenhouse gas emissions are inventoried and multiplied by an emission factor to yield a national emission rate for each source and each greenhouse gas (Cheewaphongphan et al., 2019; van Vuuren et al., 2009). Emissions of Kyoto gases are multiplied by the Global Warming Potential for each gas specifying the radiative efficiency as a warming agent for each gas relative to that of carbon dioxide over a 100-year time horizon (Anja Kollmuss & Füssler, 2015). The resulting estimation for national emission inventories, used by vendors and policy platforms (e.g., REDD+), are widely acknowledged as flawed and inaccurate (Jonas et al., 2019; Pacala, S., 2010). Importantly, the estimation data are not directly comparable across diverse ecosystems lacking shared standards and universal methods. The DMFCP updates the UNFCCC and REDD+ methods to validate claims of emission reduction and to determine GHG budgets across diverse ecological landscapes at the national and sub-national levels fulfilling the Paris Agreement and REDD+ goals and objectives. The DMFCP normalizes emission reduction determinations for voluntary and compliance markets bridging the gap between methods, project types and outcomes for stakeholders.

Conclusions

The DMFCP comprises a commercial standardized measurement system for the determination of net ecosystem exchange (NEE) and creation of verified forest carbon products. The SoS and GMP components can be applied to all GHG's across large-scales and diverse locations, corrects traditional carbon credit gaps in validation and recalibrates programs that rely on them such as the CAR, REDD+, CDM, and the Paris Agreement. The objective of the DMFCP is to incentivize landowners to manage forests for optimal net carbon sequestration, biodiversity enhancement and sustainable management with economic benefits. The DMFCP, coupled with policies and projects addressing the ~0.9 billion hectares of restorable landscapes, offers a viable approach to retain the Earth's natural protective capacity to sequester atmospheric CO_2 now and for future generations.

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Appendix I

System-of-Systems. Figure 1 shows an SoS sensor network as the central feature of the DMFCP. The SoS integrates GMP's deployed across the project landscape and operates according to the DMFCP. The SoS operation is supported by system operators, calibration analysts and mission data analysts responsive to environmental, regulatory and financial scenarios. The GMP functions are carried out and integrated by central reference, command and control and data processing facilities hosted remotely. A data communication and management subsystem (DCMS) controls data content of the SoS. The DCMS gathers real-time data from the GMP's and related sensors of the SoS in a central location where the data are qualified, analyzed and archived. The DCMS provides data to model analysts to calculate absolute carbon sequestration and utilize applicable models including carbon isotopes (Davidson et al., 2016; Wang et al., 2016) to characterize the spatial and temporal components of carbon sequestration across the project landscape. The DCMS provides secure digital access to data, charts, figures and images resulting from the project reporting on physical, project, financial and registered carbon. The underlying research data files may also be accessible as authorized through the DCMS. The benefits of a comprehensive data management system include ensuring data integrity, storage and security resulting in reduced risks for all stakeholders.

The Global Monitoring Platform. The GMP of the DMFCP integrates commercial off-the-shelf gas analyzers (e.g., $^{12}C^{16}O_2$, $^{16}O^{12}C^{18}O$, $^{13}C^{16}O_2$, $^{12}CH_4$, $^{13}CH_4$, $^{14}N_2{}^{16}O$, $^{15}N_2{}^{16}O$, O_2 and hydrocarbons (c2-c9)), prototypes for portable and field measurement of $^{14}CO_2$ (Galli et al. 2013; Genoud et al. 2015; McCartt et al. 2016; Fleisher et al. 2017), an eddy covariance system and micro-meteorological station creating modular, stationary and mobile base stations readily deployable upon initiation of a project. CO_2 gases are typically measured as parts per million (ppm) or expressed as isotope ratios (e.g. $^{13/12}C$, $^{14/12}C$)[iii]. The benefits of the GMP analyzer as a component of the SoS include a standardized, low cost instrument platform for the primary greenhouse gases, automated operation and data reporting in real-time with verified analyzer function through shared reference gas standards and third-party verification. The standardized, modular system is deployable across small and large landscapes (e.g., ~100 to 1,000,000+ hectares) reducing barriers to short and long-term deployment for GHG emission reduction management and verification projects. The GMP is connected to a central reference facility, a data processing facility, a command and control facility and to other GMP's in the project network. The GMP typically includes analyzers for methane (CH_4) and nitrous oxide (N_2O) in addition to CO_2 providing a comprehensive GHG budget for projects recognizing that reductions in CO_2 may be offset by increases in CH_4 and N_2O (Niklaus et al., 2016; Tian et al., 2015; Tupek et al., 2015). The flux methodology for CO_2 applies to CO_2 isotopologues including oxygen isotopic species not described here (e.g., $^{18}O^{12}C^{16}O$) (Wehr et al., 2013) and to GHG's and their isotopologues (Arata et al., 2016; Wolf et al., 2015). The GMP employs internal and shared standard reference gas modules for the CO_2 isotopologues providing standards for a reference baseline and calibration for the measured amounts of ^{12}C, ^{13}C and ^{14}C isotopic species for each GMP analyzer within the SoS sensor network. In addition, a key technology feature of the DMFCP includes synchronous measurement of third-party reference gases obtained from national and international entities such as the World Meteorological Organization, the National Oceanic and Atmospheric Association and the National Institute of Standards (e.g., "WMO"; "NOAA"; "NIST"). Such reference gases analyzed by the GMP's ensure transparency, accountability and comparability of data and resulting financial products across all GMP networks on local to global scales. The GMP will house $^{14}CO_2$ analyzer field prototypes, as available, for forest carbon projects to provide measurement of the three molecular forms of CO_2 defining the natural and anthropogenic carbon cycles. Measurements of $^{14}CO_2$ in the atmosphere, soil atmosphere and as organic carbon may also be analyzed by accelerator mass spectrometry (AMS) where applicable when a portable or field analyzer is not available.

Eddy Covariance (EC). The EC method measures gas fluxes in and out of an ecosystem (D. D. Baldocchi, 2010; Burba, 2013; Running et al., 1999). The EC method is the most accurate and direct approach available for determining the dynamic net ecosystem exchange (NEE) for a project area (Figure 1). The method is based on direct and fast measurements (e.g., 10 Hz) of actual gas transport characterized by a three-dimensional wind field in real time. The concentration of the gas of interest (e.g., CO_2, $^{13}CO_2$ and $^{14}CO_2$) is measured concomitantly resulting in flux of the gas. In the case of isotopic forms of CO_2, isoflux for each isotope is determined (e.g., $^{13}CO_2$, $^{14}CO_2$) and employed to create unique DMFCP carbon products based on a two carbon species approach ($^{13/12}CO_2$, $^{14/12}CO_2$). The EC method has been applied worldwide under remote and harsh conditions employing solar power for months without maintenance (Burba, 2013). Open or closed path gas analyzers (e.g., CO_2, CH_4, N_2O) coupled with automated flux calculation, telemetry and integrated micrometeorological sensors, for example, could be employed in DMFCP systems serving as initial base platforms readily delivered to the project site. Additional instrumentation could be integrated as specified in the project plan. EC data are analyzed by a variety of models across small and large scales to calculate NEE (Burba, 2013; Fox et al., 2009). Off the shelf bulk and isotopic analyzers for EC measurements are available from a variety of vendors (e.g., Licor Inc, Lincoln, NE, USA; Campbell Scientific Campbell Scientific Inc., Logan, UT, USA; Picarro, Santa Clara, CA, USA; Los Gatos Research, San Jose, CA, USA).

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[i] The term isotopologue refers to chemical species that differ only in the isotopic composition of their molecules or ions.

[ii] “Carbon dioxide equivalent” or “CO2e” is a term for describing different greenhouse gases in a common unit. For any quantity and type of greenhouse gas, CO2e signifies the amount of CO2 which would have the equivalent global warming impact.

[iii] The term stable isotope has a similar meaning to stable nuclide but is preferably used when speaking of nuclides of a specific element. The expression "stable isotope ratio" is used to refer to isotopes whose relative abundances are affected by isotope fractionation in nature. The stable isotopic compositions of low-mass (light) elements such as oxygen, hydrogen, carbon, nitrogen, and sulfur are normally reported as "delta" (d) values in parts per thousand (denoted as ‰) enrichments or depletions relative to a standard of known composition. The symbol ‰ is spelled out in several different ways: permil, per mil, per mill, or per mille. The term "per mill" is the ISO term, but is not yet widely used. d values are calculated by:

$$(\text{in ‰}) = (R_{sample}/R_{standard} - 1)1000$$

where "R" is the ratio of the heavy to light isotope in the sample or standard. For the elements sulfur, carbon, nitrogen, and oxygen, the average terrestrial abundance ratio of the heavy to the light isotope ranges from 1:22 (sulfur) to 1:500 (oxygen); the ratio ^2H:^1H is 1:6410. A positive d value means that the sample contains more of the heavy isotope than the standard; a negative d value means that the sample contains less of the heavy isotope than the standard. A $d^{15}N$ value of +30‰ means that there are 30 parts-per-thousand or 3% more ^{15}N in the sample relative to the standard.

Table 1 (on next page)

Comparison of features and benefits for existing forest carbon protocols and the DMFCP

Protocol features such as inclusion/exclusion of soil respiration CO_2 flux, measurement time intervals and compatibility with expanded forest carbon flux measurements of CH_4 and N_2O are compared for existing forest carbon protocols and the DMFCP. Each feature is discussed in the text.

Table 1. Comparison of DMFCP features and benefits with existing forest carbon protocols.

Item	Protocol Feature	Existing Protocols*	DMFCP	Benefit to Landowner
1	**Project tradable units**	Tons CO_2 equivalent (tCO_2eq)	Tons CO_2 equivalent (tCO_2eq), gC $m^{-2}yr^{-1}$	No change to landowner end-product for forest carbon sequestration transactions
2	**CO_2 observations by direct measurement**	No	Yes; infrared and laser based gas analyzer methods for CO_2 (10Hz)	Direct measurement of GHG's reduces risk of invalidation, increases quality of forest carbon offsets and offers management information
3	**Vertical gross and net flux observations**	No	Yes; eddy covariance methods are applied resulting in 30" averages of gross vertical CO_2 fluxes used to calculate daily/annual net carbon flux (NEE)	Direct measurement reduces risk of invalidation, increases quality of forest carbon offsets and offers management information
4	**Net ecosystem exchange (NEE) or net forest carbon sequestration**	No	Yes; vertical CO_2 fluxes are used to calculate daily, seasonal and annual NEE reported as ppm CO_2 m^{-2} $time^{-1}$	Direct measurement reduces risk of invalidation, increases quality of forest carbon offsets and offers management information
5	**Soil CO_2 flux**	No	Integrated in vertical fluxes	Complete accounting of carbon pools is required for NEE; provides data on soil ecosystem dynamics
6	**Cost to Landowner**	Substantial fees from inception to listing of carbon credits; fees increase with size of project	No direct fees from inception to listing on a registry; upfront payments and annual royalty payments may be structured within an agreement between landowner and service provider	Elimination of direct fees to intiate a forest carbon project inventivizes landowners to engage in forest carbon programs with economic, ecological and business advantages
7	**Time interval to achieve positive revenue**	Years (1-5)	Daily to yearly	Revenue to landowner is achievable, in practice, based on daily NEE but more typically would be paid annually over the long term encentivizing sustainable management; traditional protocols may require years to receive initial payment
8	**Marketing and sales of GHG offsets**	Responsibility of landowner (e.g., fee based listing on a registry); voluntary and compliance offsets are priced differently based on discretionay critieria	Projects and products are pooled into portfolios and listed in a no-fee registry for sale to voluntary and compliance buyers	Relieves landowner from handling carbon offsets once issued and from additional cost; direct measurement creates equivlanent voluntary and compliance offsets
9	**Baseline**	Estimated and uncertain; based on counterfactual arguments and proxy data; positive values are not permited or default value is used	Baseline is the zero-emissions point from which positive, negative or neutral emissions of CO_2 flux occur; the zero baseline is shared across analyzers via calibration with shared standards and references^	All NEE results are instrumentally and financially comparable providing improved management of multiple project landscapes; a measured zero baseline eliminates estimation baseline invalidation risk
10	**Additionality**	Based on uncertain counterfactual arguments regarding unobserved CO_2 or default values and other criteria	Simple mass balance of carbon (e.g., NEE) across designated areas can be summed to determine overall carbon balance, or test for differences between pooled portfolios offering measured and numerical tests of additionality	Eliminate uncertainty associated with this factor; provides near real time data for NEE and forest project management planning across additional landscapes and property ownership (e.g., municipal, private)
11	**Invalidation period and compliance testing**	Up to 8 years based on 5% invalidation rule	No invalidation period is required as validation with shared universal standards are made every 30"; invalidation can be triggered at any time instrument performance is reported as faulty	Elimination of an invalidation period will attract more project particpants and buyers of carbon project products
12	**Third party verification**	Third party validates calculations and estimation protocols; it does not include validation by independent direct measurement	Third party validation is made by independent direct measurements by an unaffiliated group as contracted in the governing agreement	Truly independent third party validation will support pricing of GHG products and market transactions as well as provide strict testing for invalid and fraudulent claims of GHG reductions
13	**Test for swtich to net positive emisions**	No	Yes; NEE identifies transitional net negative (i.e., carbon offset producing) to net positive forest carbon dynamics	Switch to positive emissions may suggest landowner management practices to attain net neutral or net negative balance
14	**Permanence**	100 year requirement	Up to 100 years but achievable in decadal increments; a100 time horizon is an arbitrary project interval	A 100 year forest carbon permanence requirement is a primary barrier to landowner participation; 10 year interval project planning allows extensions or exit and is compatible with short term financial forcasting
15	**Project exit or termination**	High penalty	Ton-year accounting is employed to adjust exit penalty based on project impact of atmospheric emissions sequestered over time	Barriers to forest carbon management are lowered when reasonable exit strategies are available based on an accepted accounting method
16	**Monitoring of CH_4, N_2O and other gases**	Not applicable	Eddy covariance can be used to determine next flux for CH_4, N_2O and other gases, similar to the method used for CO_2; eddy covariance provides a combined three-gas GHG budget for a complete GHG budget	A three-gas GHG budget may offer land owners more options to manage neutral budgets and will expand areas of project applications and increase product options
17	**Incorporate isotopolougues of CO_2 and other GHG's**	Not applicable	Eddy covariance can be used to determine net isoflux for any isotopologue, similar to the method used for CO_2 creating new product categories	Isotopologues of CO_2, CH_4 and N_2O, among others, may offer the landowner additional options to manage projects for net or negative GHG impacts and will increase the diversity of forest carbon product options
18	**Wetland, aquatic and oceanic emissions**	Not applicable	Eddy covariance can be applied to wetlands, aquatic and estaurine features and to oceanic systems	Landowners with wetland and aquatic features may benefit from their inclusion in forest GHG products; all stakeholders benefit from expanded knowledge Earth system function including oceanic GHG dynamics
19	**Contribution to forestry & atmospheric science and climate change studies and models**	Not applicable	All GHG flux data are relevant to evolving ecosystem funtion relative to climate change and human activity; all data may be incorported in climate change research and atmospheric transport models	All stakeholders benefit from understanding the mechanisms affecting forest GHG dynamics the policies

* Climate Action Reserve, Clean Development Mechanism, etc. (A. Kollmuss & Fussler, 2015)

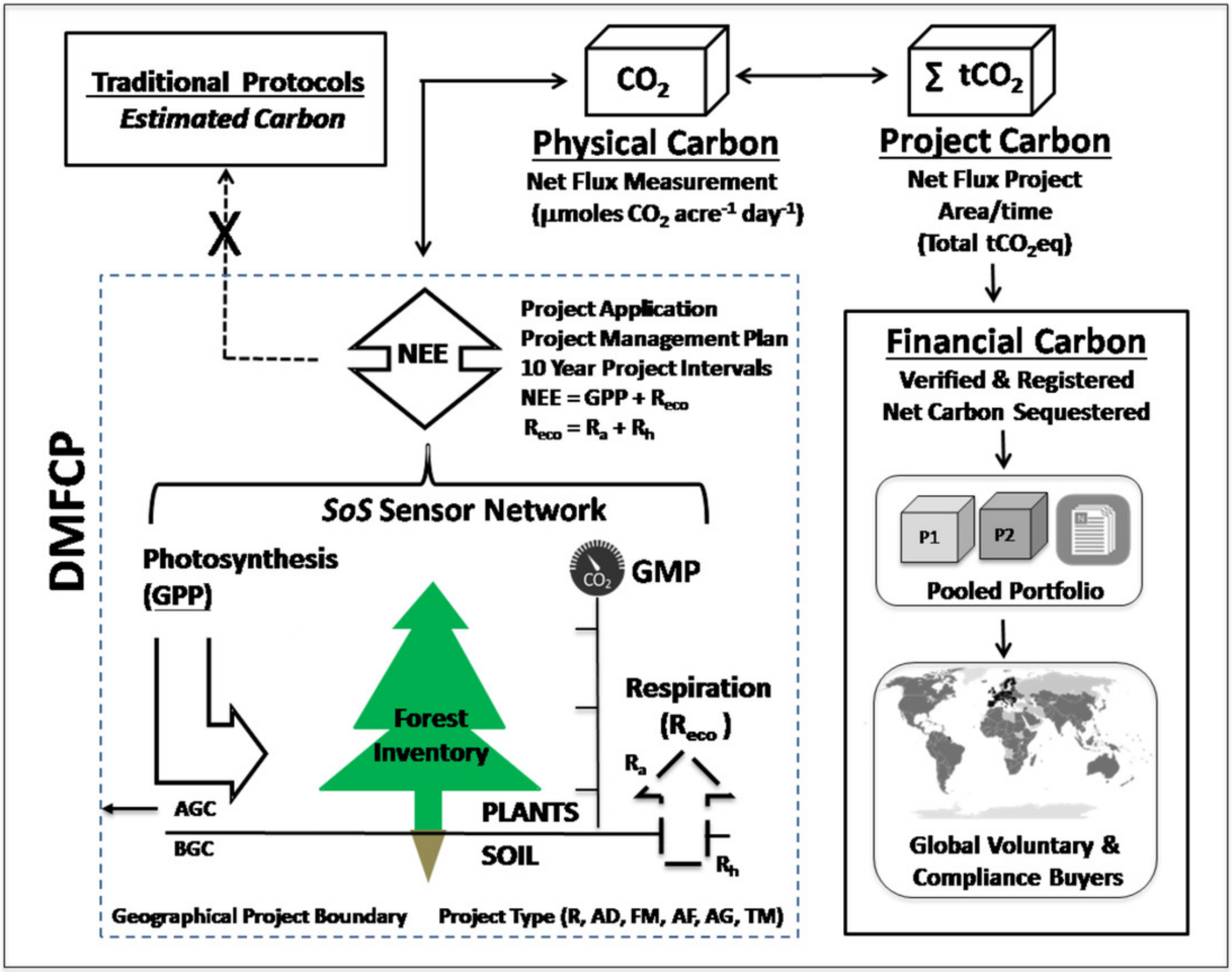
^ The DMFCP SoS and GMP's operate as an integrated autonomous system to monitor, measure and transform GHG flux data relative to local, regional and global reference materials for bulk and isotopic composition, providing the basis for calculation of verified tradeable GHG financial products that differentiate biogenic from anthropogenic net GHG fluxes (B. D. V. Marino, 2013, 2014a, 2017b, 2017a, 2014b, 2014c, 2015b, 2015a, 2016b, 2016d, 2016c, 2016a; Bruno D. V. Marino, 2019).

Figure 1

Figure 1 Showing an overview of the DMFCP structure and process

Figure 1. The Direct Measurement Forest Carbon Protocol (DMFCP) measures gross vertical fluxes of carbon forest ecosystems important for carbon trading shown as: geographical project boundary (dashed line); NEE, net ecosystem exchange of CO_2 fluxes; AGC, above ground carbon; BGC, below ground carbon; Photosynthesis, the total carbon uptake by plants or gross primary productivity (GPP); Respiration of ecosystem (R_{eco}), total sources of CO_2 released to the atmosphere from plants (AGC, R_a) and soil microbes (BGC, R_h); SoS sensor network; and, a Global Monitoring Platform (GMP). The SoS network and GMP's are deployed across the project landscape, according to an engineering plan specifying number, height and placement of sensors, to determine net ecosystem exchange (NEE) representing net forest carbon sequestration for a project. Forest carbon gross fluxes (GPP, R_{eco}) measured *in* situ and resulting in NEE is designated as *Physical Carbon*, total land area and time period of project performance are designated as *Project Carbon,* and annual accounting and registration of project carbon provides the basis (e.g., quantity of tCO_2eq available) and pricing for sale of *Financial Carbon.* Multiple projects and resulting forest carbon products are combined in a Pooled Portfolio and listed in a registry detailing project accounting and verification criteria. Pooled Portfolio carbon products, based on equivalent carbon accounting, can be sold to voluntary and compliance buyers worldwide. Pooled Portfolio products may also incorporate additional greenhouse gases (e.g., CH_4, N_2O) and isotopic forms that can be measured with precision in the field. The geographical project boundary may be comprised of local, regional or larger land areas (e.g., state, country). Project types include: R, reforestation refers to a project that plants trees on a site previously forested; AD, avoided deforestation refers to a project that prevents deforestation; FM, forest management refers

to a project that improves the net carbon sequestration; AF, afforestation refers to a project that establishes trees on land that otherwise would not be planted; AG, agroforestry refers to a project that combines forest conservation and or tree planting with agriculture; TM, timber/wood products involves sustainable harvest of timber within the project area resulting in wood products for construction and manufacturing. Traditional protocols do not directly observe CO_2 but rely on proxies and estimation. The DMFCP is formalized with standardized intake forms listing a project (e.g., project listing application) and a project management plan defining terms and conditions for carbon product operations across multiple 10-year intervals. NEE records reductions in photosynthesis caused by fire and deforestation should these events occur in the project areas. Standing carbon inventory derived from biometric or remote sensing methods will be employed to augment and cross-check project NEE data. The SoS and GMP’s operate as an integrated autonomous system to monitor, measure and transform GHG flux data relative to local, regional and global reference materials for bulk and isotopic composition, providing the basis for calculation of verified tradeable GHG financial products that differentiate biogenic from anthropogenic net GHG fluxes. (B. D. V. Marino, 2013, 2014a, 2017b, 2017a, 2014b, 2014c, 2015b, 2015a, 2016b, 2016d, 2016c, 2016a; Bruno D. V. Marino, 2019) .



Traditional Protocols
Estimated Carbon
CO_2
$\sum tCO_2$
Physical Carbon
Net Flux Measurement
(µmoles CO_2 $acre^{-1}$ day^{-1})
Project Carbon
Net Flux Project
Area/time
(Total tCO_2eq)
X
NEE
Project Application
Project Management Plan
10 Year Project Intervals
$NEE = GPP + R_{eco}$
$R_{eco} = R_a + R_h$
Financial Carbon
Verified & Registered
Net Carbon Sequestered
DMFCP
SoS Sensor Network
Photosynthesis
(GPP)
GMP
CO_2
P1
P2
Pooled Portfolio
Forest
Inventory
Respiration
(R_{eco})
R_a
R_h
AGC
BGC
PLANTS
SOIL
Global Voluntary &
Compliance Buyers
Geographical Project Boundary
Project Type (R, AD, FM, AF, AG, TM)

Figure 2

Figure 2 Showing DMFCP components and time series

Figure 2. A Features and benefits of the DMFCP comprised of the SoS and GMP's include: 1) direct field measurement of NEE (CO_2, CH_4 and N_2O) relative to a zero-emission baseline showing positive, negative or neutral GHG emission employing an SoS and one or more GMP's; a positive NEE indicates a GHG source or emission to the atmosphere from the biosphere, whereas a negative NEE indicates a CO_2 sink or emission reduction from the atmosphere and results in carbon credits or offsets , 2) *ex ante*, annual accreditation periods that can be applied to multiple GHG's, 3) exits from a landowner agreement after 10 years with a penalty according to a ton-year accounting calculation, 4) landowner benefit from initial upfront payment (t_0) and annual royalty on sales payment (t_1). (B) Multiple projects subsequent to data quality checks by a data center can be listed in a registry and grouped into pooled portfolios; verification of system performance by external third-party verifiers of reference values and calibration of GHG analyzers is performed according to operation of the SoS. Products can be purchased by voluntary and compliance buyers worldwide through multiple sales channels. The hypothetical values shown for CO_2, CH_4 and N_2O (bars) resulting from a field sensor platform are negative in year one and mixed in years 2 and 10. Simple addition of the values for each GHG for annual periods result in a positive, negative or neutral GHG balance. Multiple projects located in specified property boundaries can be grouped to address simple numerical additionality. The DMFCP process simplifies existing protocols for forest carbon sequestration (Table 1). Traditional protocols rely on proxies for CO_2 (i.e., unobserved or measured at any time in the protocol process) to establish a baseline and test for additionality. NEE records reductions in photosynthesis caused by fire and deforestation should these events occur in the project areas. Standing carbon inventory

derived from biometric or remote sensing methods will be employed to augment and cross-check project NEE data. The SoS and GMP’s operate as an integrated autonomous system to monitor, measure and transform GHG flux data relative to local, regional and global reference materials for bulk and isotopic composition, providing the basis for calculation of verified tradeable GHG financial products that differentiate biogenic from anthropogenic net GHG fluxes. (B. D. V. Marino, 2013, 2014a, 2017b, 2017a, 2014b, 2014c, 2015b, 2015a, 2016b, 2016d, 2016c, 2016a; Bruno D. V. Marino, 2019) .

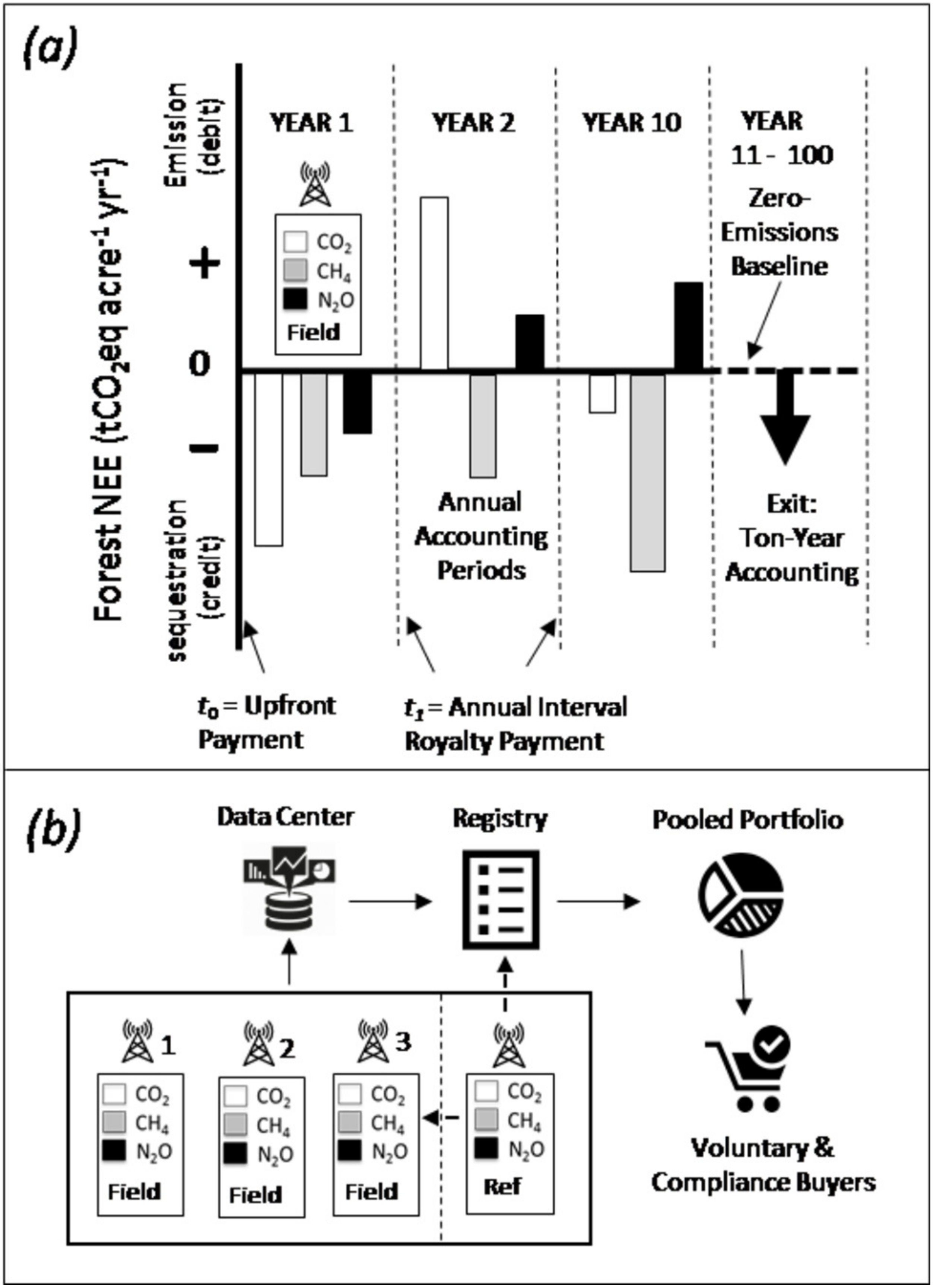

(a)
Forest NEE (tCO2eq acre-1 yr-1)
Emission (debit)
sequestration (credit)
+
0
−
YEAR 1
YEAR 2
YEAR 10
YEAR 11 - 100
Zero-Emissions Baseline
CO2
CH4
N2O
Field
Annual Accounting Periods
Exit: Ton-Year Accounting
t0 = Upfront Payment
t1 = Annual Interval Royalty Payment
(b)
Data Center
Registry
Pooled Portfolio
Voluntary & Compliance Buyers
1
2
3
Field
Ref

Figure 3

Figure 3 Locations of the eddy covariance sites analyzed in this study.

Figure 3 A. Location of Ankasa Park Tower, Ghana, Africa, (B) Location of Harvard Forest Tower, Massachusetts, USA

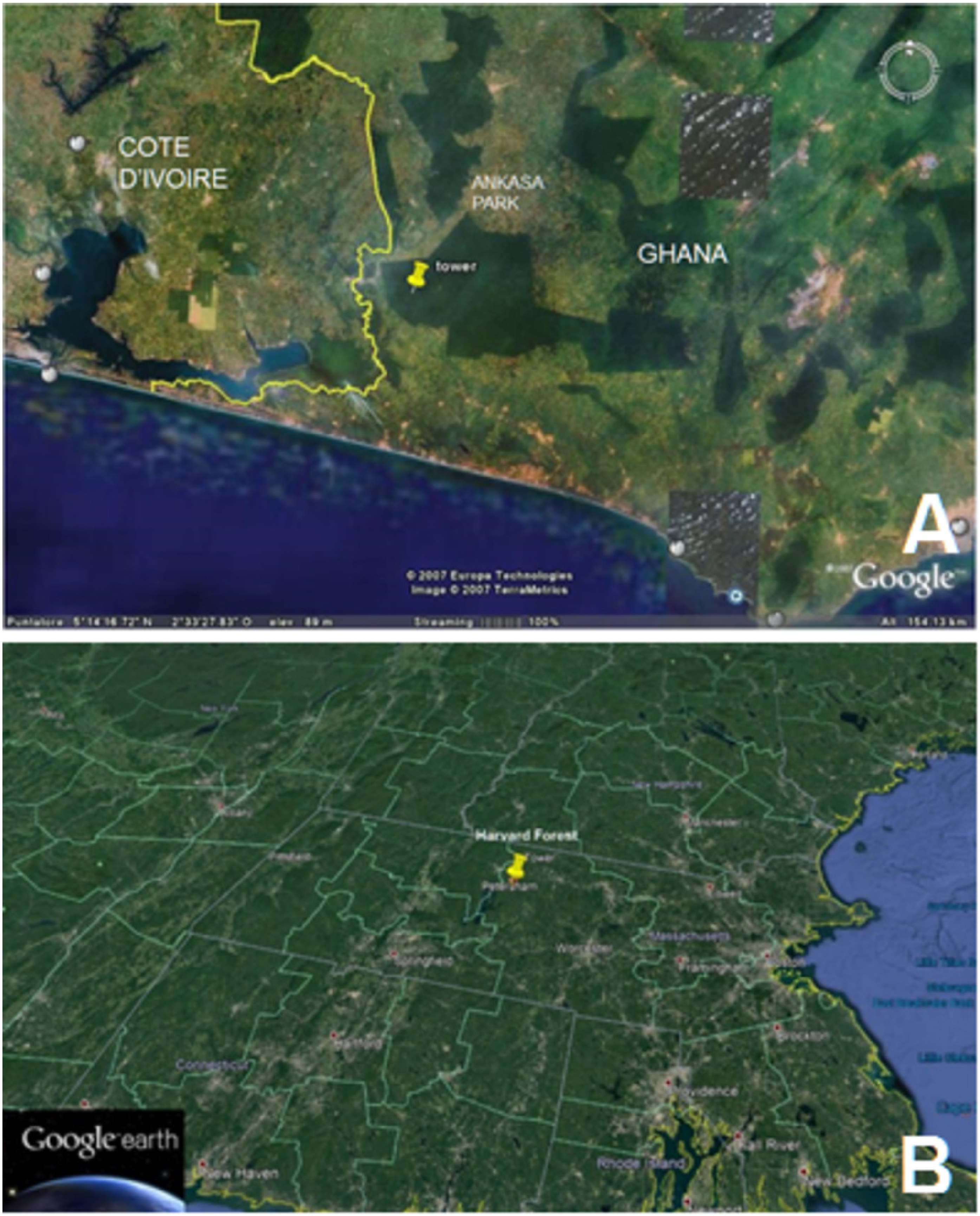

COTE
D'IVOIRE
ANKASA
PARK
tower
GHANA
© 2007 Europa Technologies
Image © 2007 TerraMetrics
Google
A
Harvard Forest
Springfield
Worcester
Framingham
Hartford
Brockton
Providence
Fall River
New Bedford
Rhode Island
New Haven
Google earth
B

Figure 4

Figure 4 Shows net ecosystem exchange for the Harvard and Ankasa times series.

Figure 4. (A) Annual NEE observed at the Harvard Forest, Petersham, MA, USA and at Ankasa Park, Ghana, Africa. (B) Cumulative NEE corresponding to annual NEE and extrapolated across 100,000 acres are employed for illustration of pre-tax cash flows.

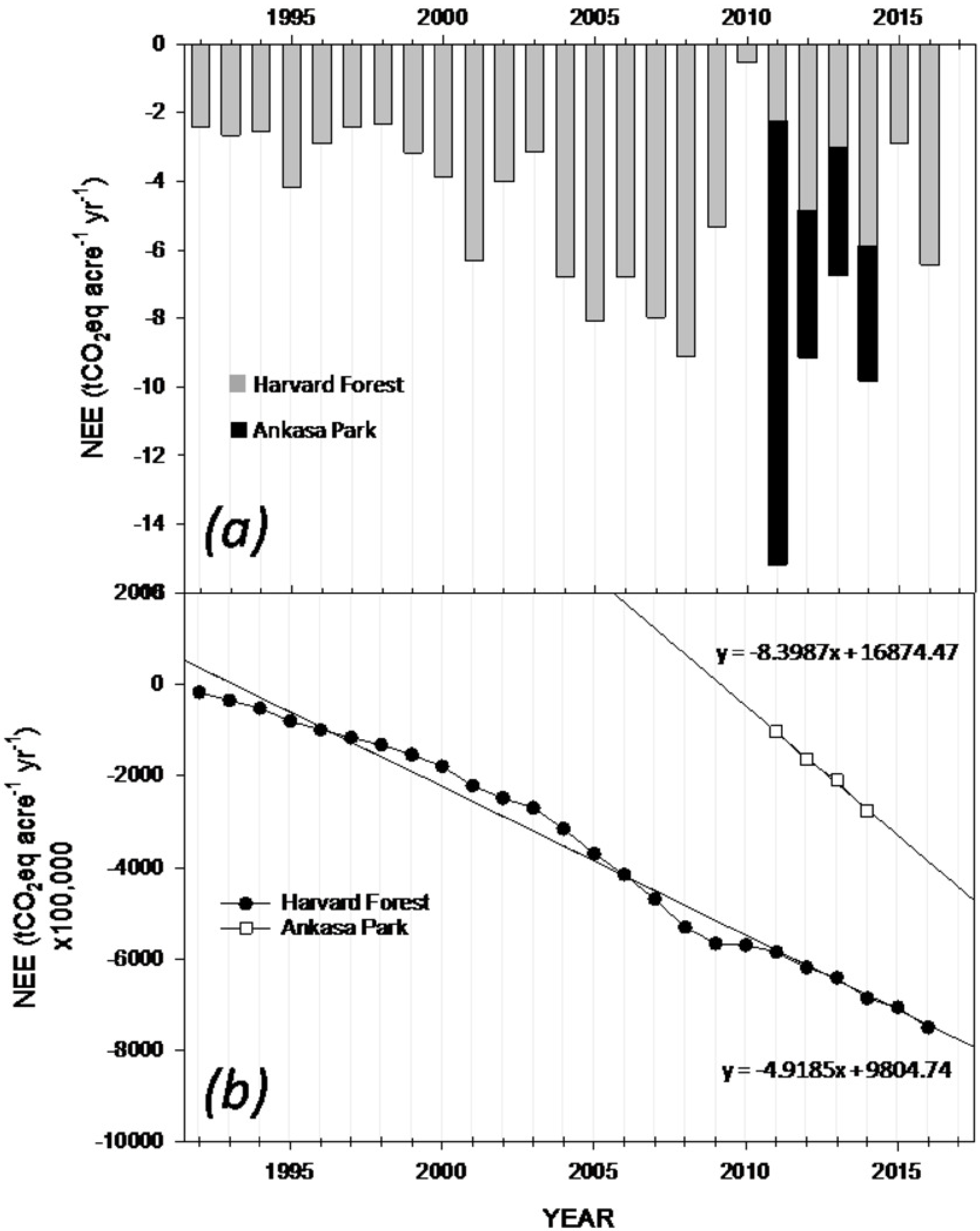

1995
2000
2005
2010
2015
0
-2
-4
-6
-8
-10
-12
-14
NEE (tCO2eq acre-1 yr-1)
Harvard Forest
Ankasa Park
(a)
2006
0
-2000
-4000
-6000
-8000
-10000
NEE (tCO2eq acre-1 yr-1) x100,000
y = -8.3987x + 16874.47
y = -4.9185x + 9804.74
Harvard Forest
Ankasa Park
(b)
1995
2000
2005
2010
2015
YEAR

Figure 5

Figure 5 shows the pre-tax cash flow for two hypothetical cases for landowner revenue associated with forest carbon management.

Figure 5. The graph depicts projected cash flows for landowners for the two cases described for Harvard Forest, USA, and Ankasa Park, Africa. Upfront payments are paid to the landowner prior to project initiation. Additional cash flows are created by selling carbon products after the initial year of monitoring (Figure 1). Case 1 (unfilled bar, Harvard Forest; filled black bar, Ankasa) shows the total pre-tax cash flow for an upfront payment of 10% of the projected annual revenue. Case 2 (light shaded bar, Harvard Forest; dark shaded bar, Ankasa) shows the total pre-tax cash flow for an upfront payment of 8% of the projected annual revenue plus deferred payouts of 6% of the realized revenue from the sale of all carbon products. The vertical bars represent the impact of a ± 20% market variance on realized revenue. These examples are provided for purposes of illustration and do not represent actual carbon products by type or cashflow.

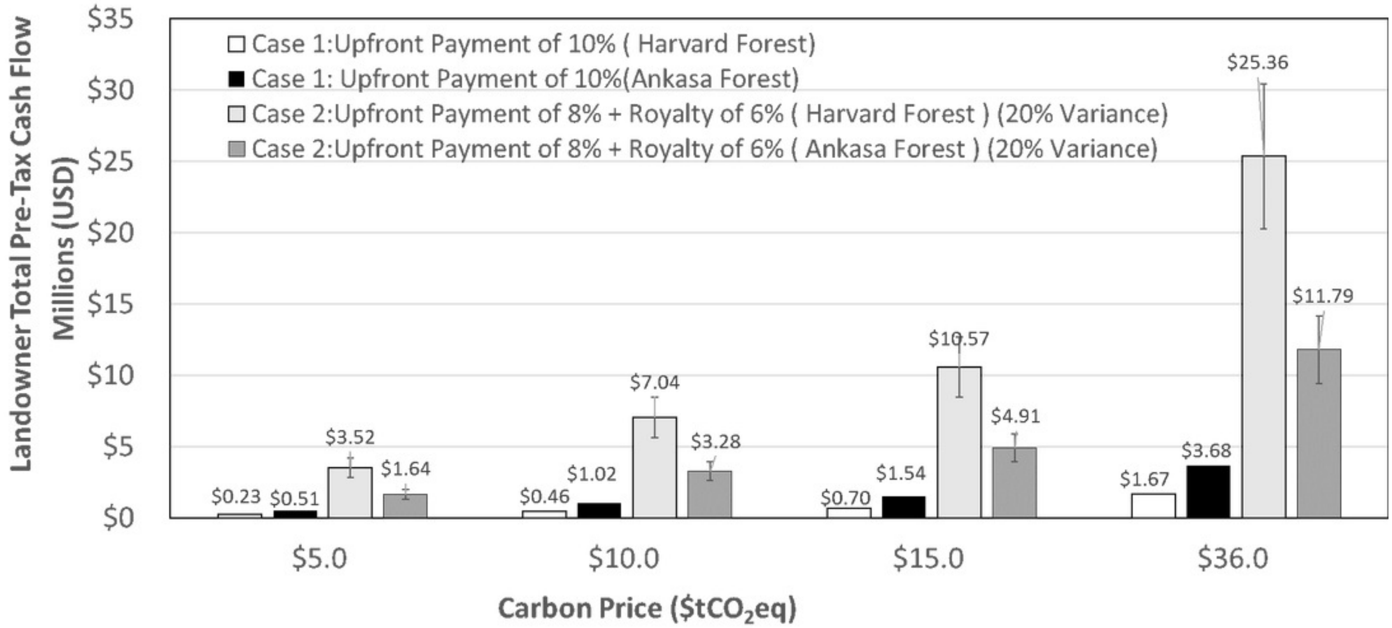

Landowner Total Pre-Tax Cash Flow Millions (USD)
$35
$30
$25
$20
$15
$10
$5
$0
Case 1:Upfront Payment of 10% (Harvard Forest)
Case 1: Upfront Payment of 10%(Ankasa Forest)
Case 2:Upfront Payment of 8% + Royalty of 6% (Harvard Forest) (20% Variance)
Case 2:Upfront Payment of 8% + Royalty of 6% (Ankasa Forest) (20% Variance)
$0.23
$0.51
$3.52
$1.64
$0.46
$1.02
$7.04
$3.28
$0.70
$1.54
$10.57
$4.91
$1.67
$3.68
$25.36
$11.79
$5.0
$10.0
$15.0
$36.0
Carbon Price ($tCO2eq)

Figure 6

Figure 6 shows projected pre-tax cash flows for the Harvard and Ankasa forest over the time series studied.

Figure 6. Landowner pre-tax cash flows are depicted based on a price of $10 per tCO_2eq across the minimum, mean and maximum values recorded for the Harvard Forest, USA (unfilled bars), and the Ankasa Park forest, Africa (filled bars), extrapolated to 100,000 acres for the historical record of each site. The vertical bars represent the impact of a ± 20% market variance on realized pre-tax revenue. These examples are provided for purposes of illustration and do not represent actual carbon products by type or cashflow.

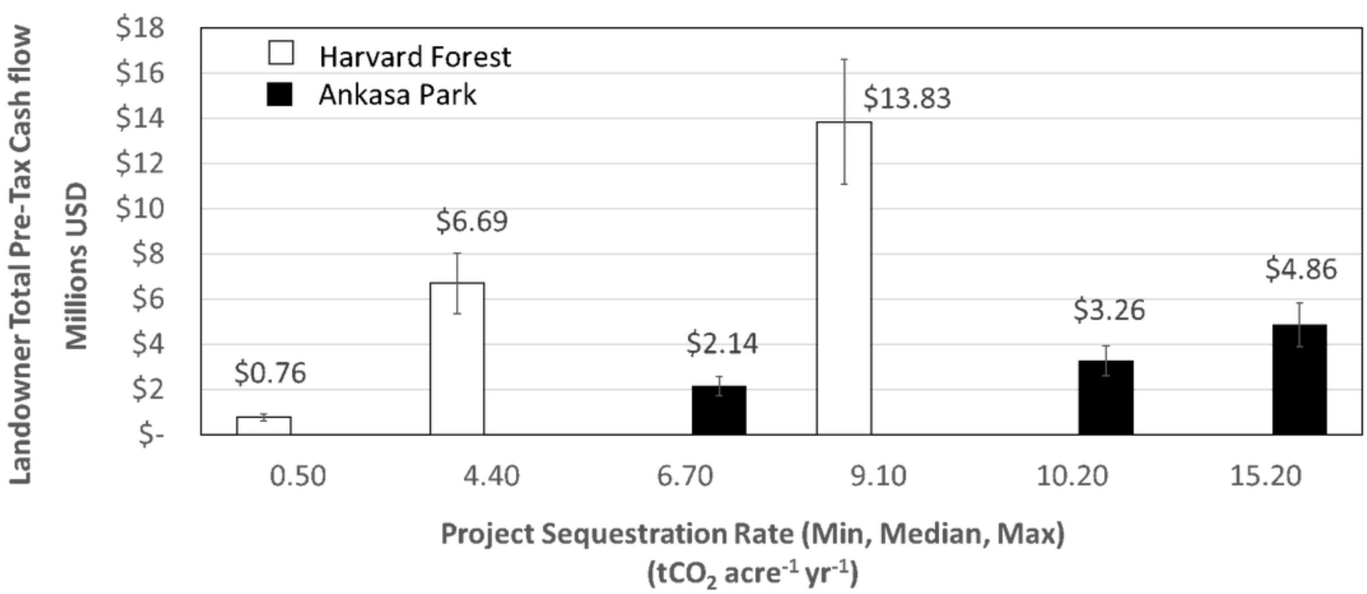


Figure 7

Figure 7 Shows hypothetical mixed carbon product types and projected pre-tax cash flows.

Figure 7. The graph shows hypothetical mixed carbon product types and projected pre-tax cash flows associated with each based on the example product inventory noted. Total pre-tax cash flow for the Harvard Forest, USA (light shaded bar), and the Ankasa Park, Africa (dark shaded bar), is $16,380,000 and $7,610,000, respectively. Both project projections illustrate the potential value of offering a mix of products and pricing to maximize revenue. Products may also incorporate additional GHG's (e.g., CH_4, N_2O), isotopic species of the GHG's, aspects of the project land and cultural features related to landownership and stewardship. These examples are provided for purposes of illustration and do not represent actual carbon products by type or price.