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Exploring Explainable Range of *In situ* Portable CO_2 Sensor Signatures for Carbon Stock Estimated in Forestry Carbon Project

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Credible information regarding carbon stock is the fundamental underlying basis for forestry carbon trading. The current measurement, reporting, and verification (MRV) system uses various emission/absorption factors derived from biomass and land use/cover. However, this MRV system does not take into consideration the actual reduction in atmospheric CO_2 concentration induced by the CO_2 uptake of the above-ground biomass, which is closely related to the effects of on-site topographical factors on the capability of CO_2 uptake of the above-ground biomass. This raises questions about the reliability of the actual atmospheric CO_2 reduction of carbon stock presented in a project design document (PDD). The explainable range of 'ambient' CO_2 concentrations measured using nondispersive infrared (NDIR) sensors from the ground level was evaluated to explore how the amount of carbon stock presented in the PDD reflects the variation in ground CO_2 density in terms of the topographical above-ground biomass. Ground CO_2 was measured using NDIR portable sensors at 182 points (August–September 2018) according to the World Data Centre for Greenhouse Gases (WDCGG) method. NDIR sensor signatures provide tangible quantitative values (correlation coefficient, R^2 = 0.28) for differentiating the interactive relationships between the carbon stock presented in the PDD as a dependent variable and a set of independent variables (topographical above-ground biomass). It is shown that the sensor signal is not a measure of the amount of carbon accumulated in the above-ground biomass itself but is seriously affected by the surrounding topographical terrain parameters (low solar radiation, solar duration, slope, and elevation). The results of this study provide a valuable reference for verifying the measurable range of carbon concentrations in the atmosphere, which fluctuate according to the carbon absorption capability of the above-ground biomass in forestry carbon project sites.

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1. Introduction

The United Nations forestry carbon project requires a measurement, reporting, and verification (MRV) process to determine how much CO_2 can be reduced and this information is presented through a formal and explicit document called the project design document (PDD). The MRV process is performed to present objective data regarding the amount of greenhouse gases (GHGs) reduced by forestry carbon projects through the MRV process for GHG emission and removal. This process is a prerequisite for implementing forestry carbon trading. In general, the MRV process uses an existing or new methodology approved by the United Nations Framework Convention on Climate Change (UNFCCC) to meet the local specific circumstances of the project. This process involves the *in situ* destructive sampling of five carbon pools [above-ground biomass (e.g., stems, bark, and leaves); below-ground biomass (roots of all sizes); dead wood; leaf litter; and soil organic carbon (SOC)] defined in the IPCC Good Practice Guidance (GPG). Samples with constant weights are oven-dried to determine the proportion of dry matter (biomass) used to estimate the carbon content. However, in reality, it is not possible to apply this destructive method to the entire forestry project area. As an alternative, it is common to estimate carbon stock using default coefficients (e.g., stem diameter of a tree).

However, the existing MRV process for the PDD is limited for verifying the actual CO_2 density reduced through forestry carbon projects since it focuses on the accuracy of data acquisition and the correct application of the methodology approved by UNFCCC. It is impossible to introduce incentive or compensation schemes based on the reduced carbon content because there is no scientifically reliable verification method for the performance of forest carbon projects.(1) To overcome the limitations of the current MRV system for the PDD, it is necessary to use the CO_2 concentration data measured at project sites as fundamental evidence for MRV.(2) If a portable carbon measurement device can be used to correlate the CO_2 data measured from the ground with the carbon uptake documented in the PDD, it can be an alternative tool to overcome the limitations of MRV based on carbon emission factors and to assess carbon footprints based on land cover at specific points.

Theoretically, carbon stock changes in forests predominantly occur with uptake through plant photosynthesis. Hence, increases in forest carbon stocks over time are equated with a net removal of atmospheric CO_2.(3) Thus, the carbon stock in the forest can be estimated directly on the basis of gas flux rates to and from the atmosphere.(3) Several previous studies were performed to explore the interactive correlations between forest carbon stocks versus the changes in net CO_2 fluxes using nondispersive infrared (NDIR) sensors. Zweifel *et al.* found that the atmospheric CO_2 fluxes measured with NDIR sensors closely correlated with the stem radius changes in a subalpine Norway spruce forest in the Swiss Alps from 1998 to 2008, which represented the carbon stock from the above-ground biomass on annual (adj. R^2 = 0.85) and monthly (adj. R^2 = 0.53) scales.(4) There are also long-term observations of the atmospheric carbon concentration derived from the increase in the amount of the above-ground biomass in reforested areas.(5,6)

However, no studies have been performed to verify the interactive relationship between in situ portable CO_2 sensor signatures (unit: ppm) and the carbon stock (unit: ton) specified in the PDD for forestry carbon project sites. It is expected that an *in situ* portable CO_2 sensor can realistically differentiate the amounts of carbon absorption changes depending on local specific forest conditions (e.g., species, age, and density) at the project site. The purpose of this study is to investigate the relationship between the ground CO_2 concentration measured using a portable CO_2 meter and the carbon absorption data presented in the PDD. The experimental investigation for a case study will focus on obtaining quantitative evidence for how *in situ* measurement equipment can be used for the MRV process of the PDD for potential customers who want to undertake the forest carbon business. The results of this study can be used as an important evidential reference for confirming the error range to be considered when using NDIR sensor signatures for the MRV process for the forest carbon business.

2. Materials and Methods

The study area Yuga-Myeon is situated in the southeastern part of South Korea between latitudes 35° 40’ 39.42 N and 35° 40’ 45.51 N and longitudes 128° 27’ 47.25 E and 128° 28’ 00.36 E. It is part of the western district (administrative district) of Daegu Metropolitan City, which is the third most populous city in South Korea (Fig. 1). This study area consists of five zones planted with different species. Figure 1 shows the boundaries and locations of the individual zones (Zones 1–5) and 182 CO_2 field survey points. Forest restoration was performed by planting a single species at each subplot (within 0.5 ha) in 2015 as presented in

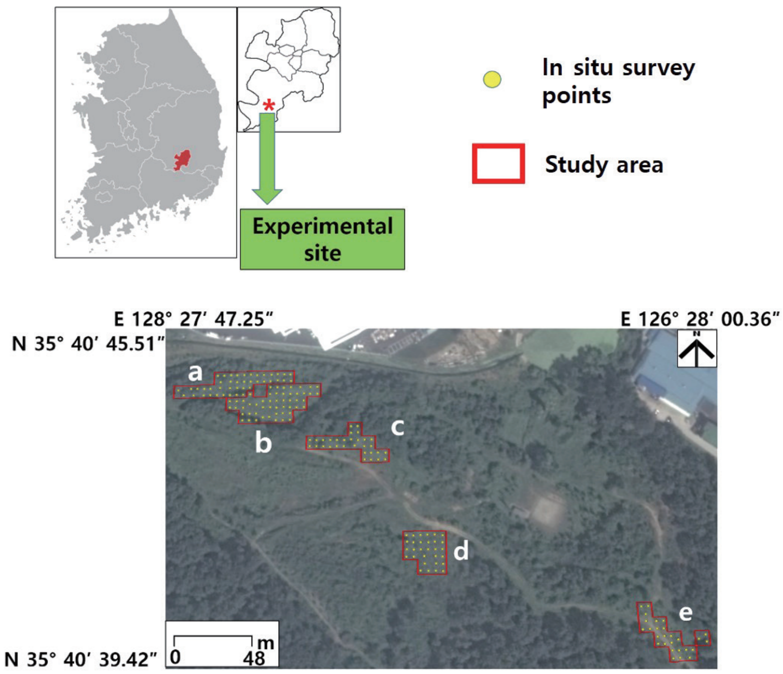


Fig. 1. (Color online) Location of study area and its Google earth image (taken on 03.06.2016). (a) Zone 1 (*Prunus armeniaca*), (b) Zone 2 (*Chionanthus retusus*), (c) Zone 3 (*Cypress*), (d) Zone 4 (*Liriodendron*), and (e) Zone 5 (*Mono maple*).

Fig. 1 and Table 1. Various topographical characteristics (e.g., aspect, slope, solar radiation, and solar duration) that affect plant growth and CO_2 uptake can be observed in this study area since the area is located on the hills. Diverse species are densely located within a small area (0.02 km^2) with trees with identical specifications (e.g., tree age of 5 years, tree height, and root collar caliper) planted at the same time. Because the study area (0.02 km^2) is relatively small, it is affected equally by the same exogenous variables such as climatic factors (e.g., rainfall and temperature). There are no specific emission sources such as human settlements, roads, and livestock farms around each zone that could affect the CO_2 uptake capacity of plants. Thus, this area seems to be suitable for performance evaluation to explore the interactive relationship between the carbon stocks presented in the PDD and the topographical above-ground biomass at forestry carbon project sites.

There are various exogenous variables such as temperature and wind that may affect the measurements of a portable sensor. The World Data Centre for Greenhouse Gases (WDCGG) method is used internationally as a standardized method to collect reliable data. In this method, the CO_2 concentration is monitored every 30 s using CO_2 NDIR sensors and hourly CO_2 concentration data are generated in a specific period such that measurement disturbances by local CO_2 sources are short.(7–9) NDIR sensors in WDCGG stations measure the intensity of infrared radiation passing through a "sample" cell relative to that of the radiation passing through a reference cell. Sample air, pumped from inlets located away from the measurement station, and standard gas flow alternately through the sample cell. CO_2 abundance is reported as dry-air mole fraction (μmol mol^{-1}) and abbreviated as ppm on the WMO CO_2 mole fraction scale.(7) Plant respiration occurs at various parts including stems, branches, and leaf stomata. Therefore, unlike in WDCGG stations that monitor the ambient CO_2 concentration, CO_2 should be measured at various altitudes starting from below 10 cm under the tree tip at the carbon forestry project sites to observe the CO_2 flux occurring in the leaves of an actual plant after the implementation of the forestry carbon project. However, the CO_2 flux in the soil was not measured in this study because trees were planted densely within a 0.02 km^2 region with the same soil type. In addition, the data were generated in ppm at a 1.5-m-long ground level every 30 s according to the WDCGG standard with TESTO 480 (Fig. 2).(10)

The carbon absorption coefficient applied in the PDD is mainly calculated on the basis of the above-ground biomass by the destructive gravimetric method (oven drying).(3,11) However, the

Table 1
Planted tree status in study area.

Species: Zone number	*Prunus armeniaca* (Zone 1)	*Chionanthus retusus* (Zone 2)	*Cypress* (Zone 3)	*Liriodendron* (Zone 4)	*Mono maple* (Zone 5)
Number of trees planted	50	135	75	50	70
Tree specification*	H 1.4 (m) × R 5.0 (cm)	H 2.3 (m) × R 6.0 (cm)	H 1.6 (m) × R 6.0 (cm)	H 4.0 (m) × R 10.0 (cm)	H 3.5 (m) × R 6.0 (cm)
Number of seedlings per 100 m^2	9	18	15	10	14

*The tree specifications are as follows:
H (tree height) is the length of the tree from the uphill side of the stem on the ground surface to the stem tip.
R (root collar caliper) is the diameter of the part of a plant where the stem and roots meet.

(a) (b)

(c)

Fig. 2. (Color online) Image of CO_2 measurement meter; IAQ probe (a: CO_2), 16 mm Vane Measurement Probe (b: velocity), and Model 480 (c).

most important factors that affect the CO_2 uptake are topographical parameters (such as slope, elevation, and solar radiation) related to nutrients and water stress for the experimental area. To identify the effects of topographical factors on the CO_2 uptake of the above-ground biomass, we geographically calculated the topographical above-ground biomass using the ordinary least squares (OLS) method at individual measurement points. In processing the topographical above-ground biomass, we set the ground CO_2 density and topographical factors as explainable variables and the PDD carbon stock as the independent variable. Thus, the topographical above-ground biomass contains the carbon stock, which reflects the CO_2 uptake capacity differentiated by the surrounding topographical factors in the measurement points at the forestry carbon project site.

An *in situ* CO_2 density survey was carried out at the specific time (11–13 h) and season (08.01–09.30.2018), during which photosynthetic activity and plant growth are vigorous and the atmosphere is stable after the rainy season.(2,10) Wind velocity strongly affects the accuracy of CO_2 measurement.(12) It is essential to validate the CO_2 measurement accuracy by comparing the wind speed measurements between portable instruments and standardized wind measurements at national meteorological telemetry stations. The minimum observed velocity was 0.0 m/s, the maximum velocity was 5.4 m/s, and the mean velocity was 1.9 m/s at national meteorological telemetry stations located near each CO_2 measurement site during the survey period. The mean velocity at the *in situ* survey points was 0.6 m/s, with a minimum of 0.01 m/s and a maximum of 1.6 m/s. The difference in velocity between the *in situ* data and the national meteorological telemetry station data was 1.3 m/s, showing a deviation similar to those in previous studies.(2,13)

We selected the measurement points (182 points) (Fig. 3) that show different normalized difference vegetation indexes (NDVIs) to explore the topographical above-ground biomass in terms of the CO_2 uptake and the capability of the above-ground biomass. NDVI is a graphical

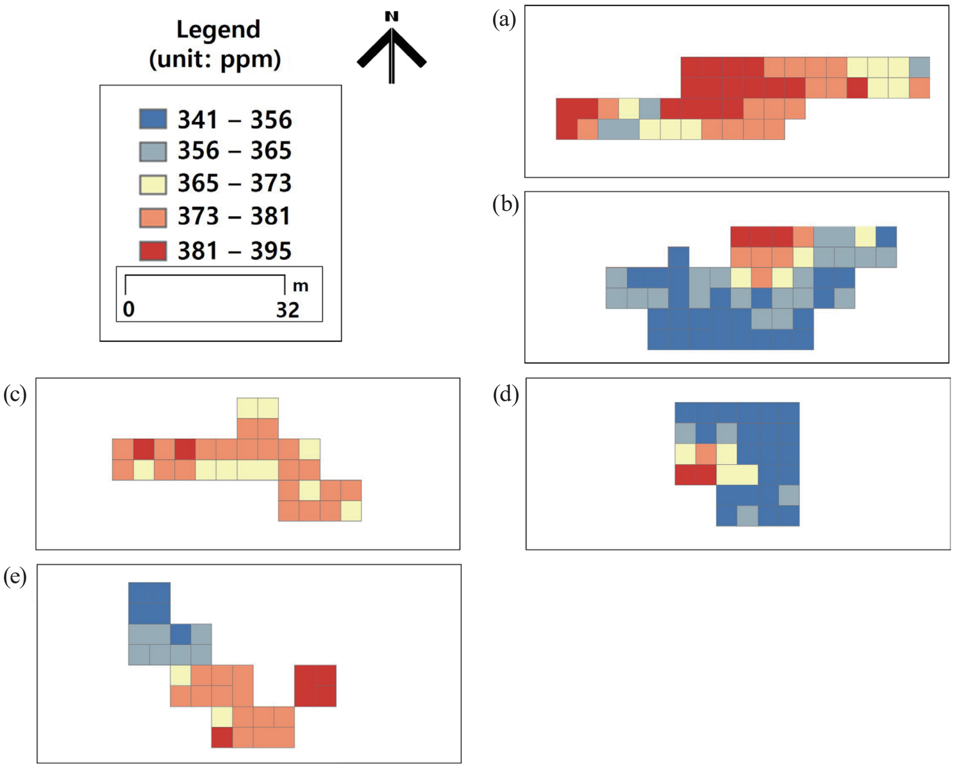


Fig. 3. (Color online) *In situ* CO_2 measurement map of the study area. (a) Zone 1 (*Prunus armeniaca*), (b) Zone 2 (*Chionanthus retusus*), (c) Zone 3 (*Cypress*), (d) Zone 4 (*Liriodendron*), and (e) Zone 5 (*Mono maple*).

indicator that quantifies vitality and the existence of vegetation. In other words, if the NDVI is close to +1, the area is covered with dense leaves and has a wide canopy leaf area with high leaf vitality. On the other hand, when the NDVI is close to zero, a low leaf density and a narrow canopy leaf area with low leaf vitality are observed.

The KOMPSAT-2 satellite used in this study is equipped with a multispectral camera with a spatial resolution of 1 m in the panchromatic mode and a spatial resolution of 4 m in the multispectral mode. Multispectral imagery with a spatial resolution of 4 m was used to extract the NDVI.(14) The cell size of the triangulated irregular network (TIN) data was set correspondingly to the satellite imagery (4 m). The solar radiation and sunlight duration were calculated for individual measurement points during the measurement period. Daily cumulative values of solar radiation and sunlight duration were extracted using the data on solar altitude, azimuth angle, and zenith angle provided by the Astronomy and Space Science Information and the Area Solar Radiation tool in Arc GIS 9.3.

3. Results and Discussion

The higher the amount of carbon stock presented in the PDD, the lower the ground CO_2 density that should appear according to the PDD MRV hypothesis. In other words, the PDD carbon stock and ground CO_2 density should have a negative (−) correlation. However, the PDD carbon stock and ground CO_2 density were not consistent in this study. For instance, *Cypress* (Zone 3) showed the highest carbon stock (747.6 kg/C) in the PDD, but its CO_2 concentration was the second highest (375.5 ppm) (Fig. 4). *Prunus armeniaca* (Zone 1) and *Liriodendron* (Zone 4) had the same carbon stock in the PDD. However, the measured CO_2 concentration of *Prunus armeniaca* (Zone 1) was 19.3 ppm higher than that of *Liriodendron* (Zone 4). *Liriodendron* (Zone 4) showed the lowest carbon stock (249.4 kg/C) in the PDD and the lowest CO_2 concentration (375.5 ppm) (Fig. 4).

We used OLS for estimating the topographical above-ground biomass using the PDD carbon stock (dependent variable), *in situ* CO_2 concentration (independent variable), and topographical factors (independent variables) to evaluate the performance of the portable *in situ* CO_2 sensor in differentiating the interactive relationship between the carbon stock in the PDD and the topographical above-ground biomass at the forestry carbon project site (Fig. 5). The R^2 of OLS was 0.28 between the PDD carbon stock and the topographical above-ground biomass. This means that the explainable range of topographical above-ground biomasses could explain 28% of the PDD carbon stock. The capability to sequester atmospheric CO_2 from the above-ground biomass is strongly affected by topographical factors that induce variations in water stress, and nutrient scarcity, and the impediment or enhancement of CO_2 uptake. The topographical above-ground biomass was adequate in *Chionanthus retusus* (Zone 2) and *Mono maple* (Zone 5) with regard to identifying its interactive relationship with the carbon stock in the PDD (Table 2). The topographical factors at Zone 2 weakly impacted the differentiation of the PDD carbon stock versus the CO_2 uptake capability (Fig. 5). In contrast, *Cypress* (Zone 3) and *Liriodendron* (Zone 4) showed the largest deviations between the PDD carbon stock and the topographical above-ground biomass (Fig. 5). The PDD carbon stocks at Zones 3 and 4 were greatly overestimated

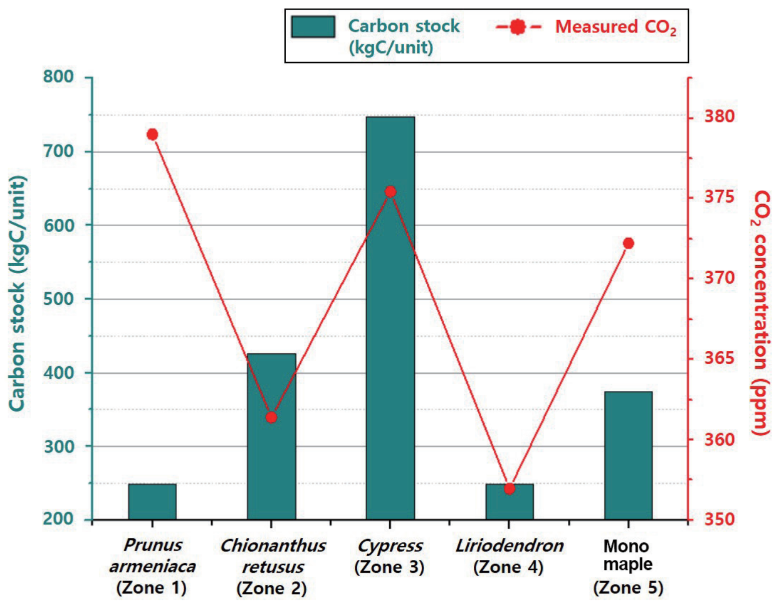


Fig. 4. (Color online) Distribution trends for carbon stock in PDD versus in situ survey CO_2 concentration.

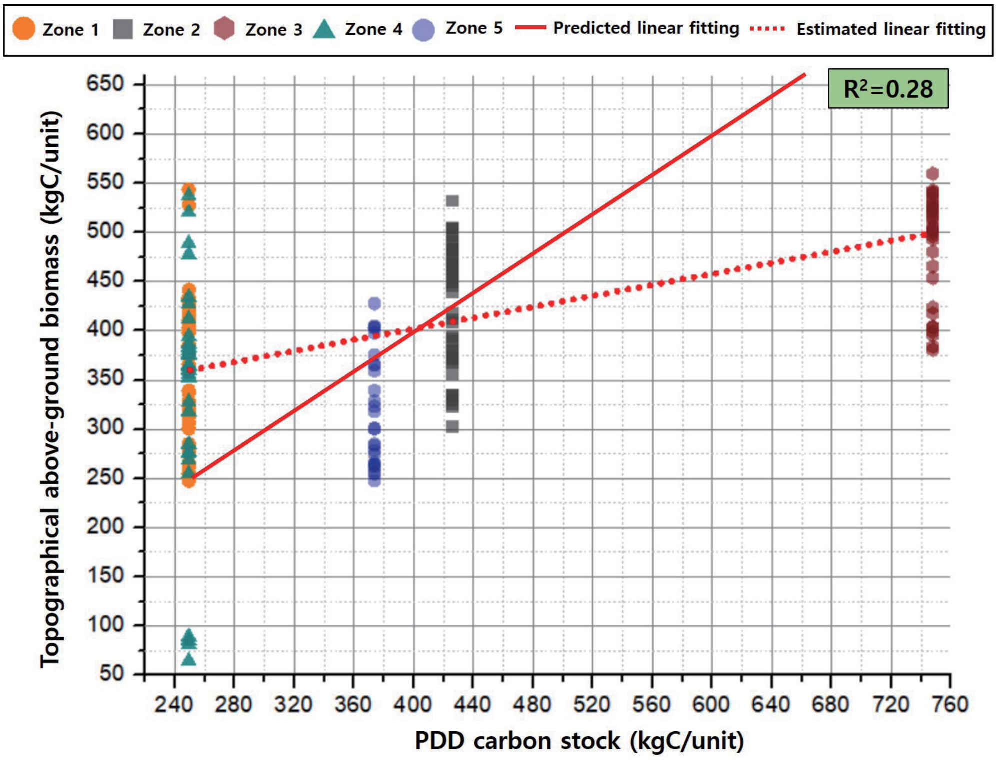


Fig. 5. (Color online) Comparison of PDD carbon stock and topographical above-ground biomass detected using CO_2 NDIR sensors and topographical factors (NDVI, aspect, elevation, solar radiation, solar duration, and slope).

(Zone 3) or underestimated (Zone 4) compared with the topographical above-ground biomass. This means that the topographical factors are the major factors affecting the CO_2 uptake capacity from the above-ground biomass in these two areas.

The CO_2 uptake capability of trees is mostly attributable to the above-ground biomass, especially the leaves. The CO_2 uptake capacity from leaves varies according to the available nutrients and the water stress derived from *in situ* topographical factors. There are three indicators that represent the CO_2 uptake capability of the above-ground biomass: (1) leaf vitality, (2) leaf density, and (3) canopy leaf area. These indicators can be observed quantitatively using the NDVI, which contains the combined information for these three indicators.[15,16] The NDVI for Zone 3 is comparably lower (0.42), whereas that for Zone 4 is the highest (0.54) among the areas evaluated (Table 2; Fig. 6). Zone 3 had a lower NDVI (Table 2; Fig. 6) owing to excessive incident-light and light intensity inflows, which caused drought stress and nutrient loss, and inhibited plant growth (Table 3; Fig. 7). Zone 4 had adequate incident-light and light intensity inflows, which promoted the growth and CO_2 uptake capacity of the above-ground biomass (Table 3; Fig. 7).

The results of this study are consistent with those of previous studies showing little correlation between the interactive growth rate of the carbon stock in forests and the atmospheric CO_2 density.[17] Rocha *et al.* (2006) reported an inconsistent relationship (p-value: 0.241) between the variability of the carbon stock present in the tree ring and the atmospheric CO_2 fluxes detected using NDIR sensors from an old-growth boreal forest in central Manitoba

Table 2
Performance evaluation of portable CO_2 NDIR sensors in detecting PDD carbon stock.

Species: Zone number		*Prunus armeniaca* (Zone 1)	*Chionanthus retusus* (Zone 2)	*Cypress* (Zone 3)	*Liriodendron* (Zone 4)	*Mono maple* (Zone 5)
Carbon stock (kgC/unit)		249.4	426.0	747.6	249.4	373.8
CO_2 (ppm)		377.1	361.3	375.5	357.8	371.3
Topographical factors	NDVI (index)	0.37	0.49	0.42	0.54	0.41
	Aspect (direction)	247.2 (SW)	216.5 (SW)	220.6 (SW)	198.8 (S)	164.7 (SE)
	Elevation (m)	55.5	20.5	42.2	59.8	74.9
	Solar radiation (MJ/m^2)	2582.3	928.8	2026.8	1137.2	3064.7
	Solar duration (h)	11.7	2.8	5.6	5.9	9.5
	Slope (°)	55.3	58.6	58.7	62.1	43.0
Performance evaluation (portable NDIR sensors vs PDD carbon stock)		×	○	×	×	△

○: well-matched zone between carbon stocks in the PDD versus CO_2 data obtained from CO_2 NDIR sensors.
△: ambiguously matching zone between carbon stocks in the PDD versus CO_2 data obtained from CO_2 NDIR sensors owing to topographical factors under field conditions.
×: zone where there is no crosslink between the carbon stocks in PDD versus CO_2 data obtained from CO_2 NDIR sensors.

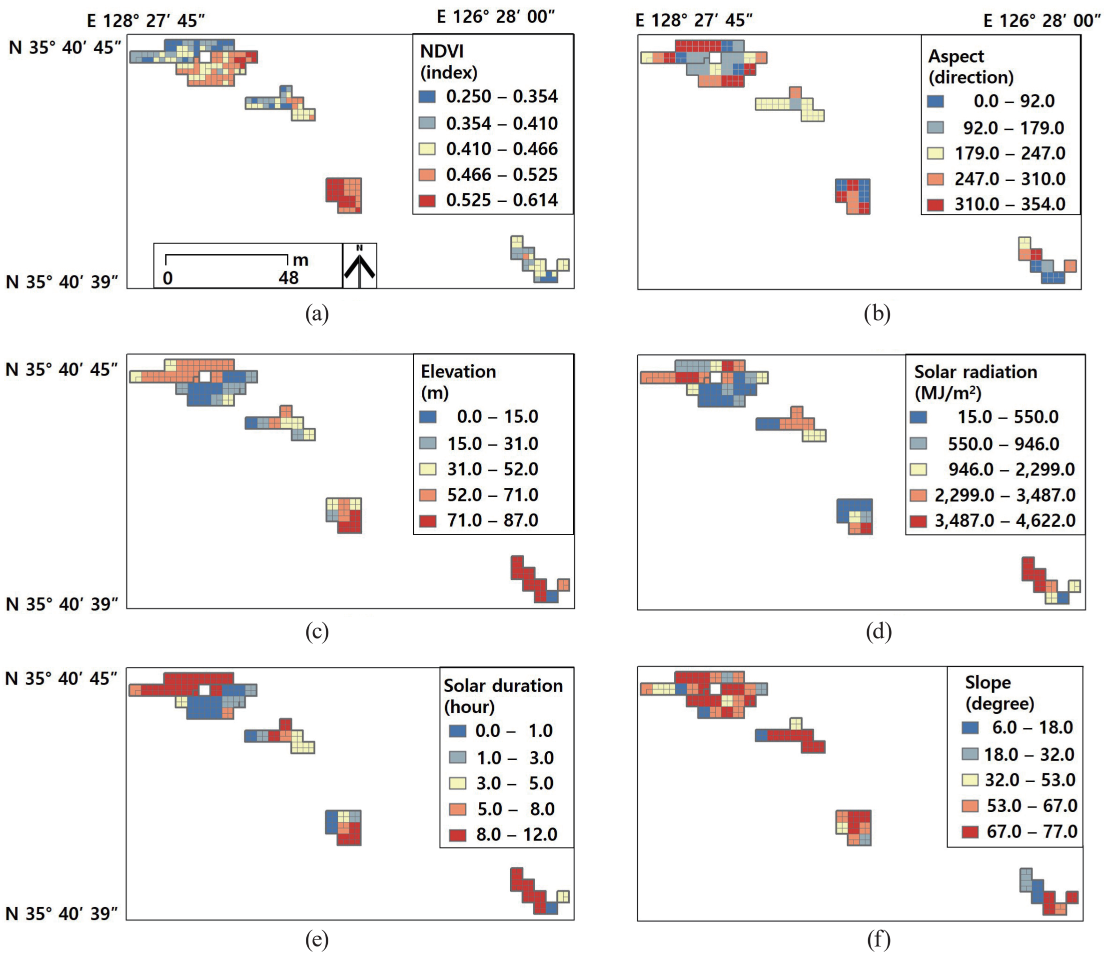
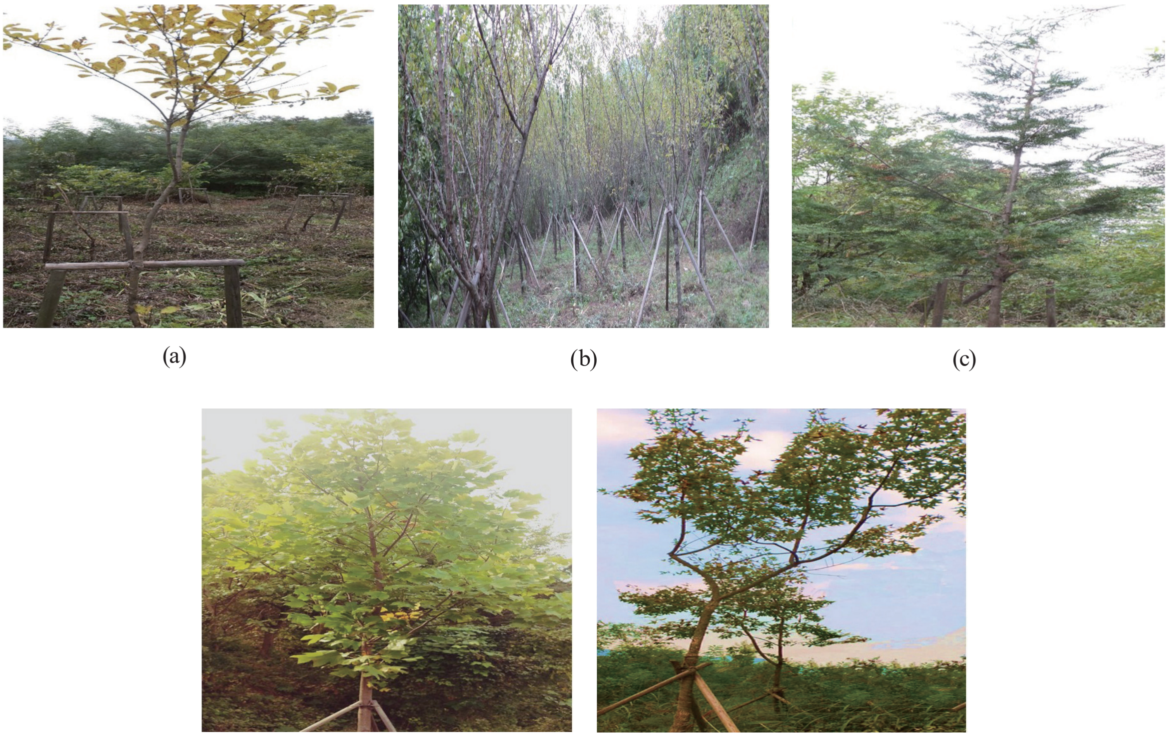


Fig. 6. (Color online) Distribution map of topographical characteristics of individual zones and OLS results. (a) NDVI, (b) aspect, (c) elevation, (d) solar radiation, (e) solar duration, and (f) slope.

Table 3
Ground conditions for above-ground biomass, which affect the carbon concentration.

Category	Site condition				
Factors that affect above-ground biomass photosynthesis	*Prunus armeniaca* (Zone 1)	*Chionanthus retusus* (Zone 2)	*Cypress* (Zone 3)	*Liriodendron* (Zone 4)	*Mono maple* (Zone 5)
Leaf vitality	×	○	△	○	×
Leaf density	×	△	×	○	△
Canopy leaf area	×	△	×	○	△

○: zone with high CO_2 uptake from leaf photosynthesis because of a factor that positively affects leaf photosynthesis.
△: zone with intermediate CO_2 uptake from leaf photosynthesis owing to ambiguous conditions for a factor, which require further assessment of their positive and negative impacts on leaf photosynthesis.
×: zone with poor CO_2 uptake from leaf photosynthesis because of a factor that negatively affects leaf photosynthesis.



(a) (b) (c)

(d) (e)

Fig. 7. (Color online) On-site photographs of individual species in study areas. (a) *Prunus armeniaca* (Zone 1), (b) *Chionanthus retusus* (Zone 2), (c) *Cypress* (Zone 3), and (d) *Liriodendron* (Zone 4), and (e) *Mono maple* (Zone 5).

(the Northern Old Black Spruce Site) from 1968 to 2004.[18] The discrepancy between the PDD carbon stock and the topographical above-ground biomass determined using the NDIR sensor is due to the different measurement methods used, as shown in Table 4. The NDIR sensor can detect CO_2 uptake variations for the above-ground biomass owing to changes in various topographical parameters and interactions between variables that affect the changes in the rate of photosynthesis in the above-ground biomass.[19,20] Although the CO_2 signal detected by the NDIR sensor contains information on actual CO_2 reduction and emission from the forestry carbon project site, the PDD carbon stock is not only based on historical data but also does not

Table 4
Comparison between portable NDIR CO_2 sensors and sensor used to calculate carbon stock in PDD.

Category	Portable CO_2 NDIR sensors [21,22]	PDD carbon stock [3,11]
Possibility to consider topographical terrain variables	Measurement of topographical effect on carbon absorption capacity of trees	Focused on above-ground biomass
Sensor type	Physical	Chemical/biological
How to measure	Infrared spectroscopy Real-time direct measurement	Gravimetric method Indirect and statistical method
Operating temperature	0 to +40 °C	Oven drying of biomass (e.g., root, soil, and trunk) at 60 to 105 °C for 24 to 48 h

take into account various topographical parameters of the forestry carbon project site (Table 4). This study was carried out within a short survey period of 60 days, and the measurement points were decided to be located at regions that could be accessed within a short time owing to the limit of the survey period. Because of the limitations of the surveying personnel and equipment, it was not possible to measure several points at the same time. It was also not possible to control external factors such as wind speed change.

4. Conclusions

This study is the first attempt to explore the explainable range of *in situ* portable CO_2 sensor signatures in view of the fact that the existing research data do not indicate an interactive relationship between carbon stock growth and actual decreases in ground CO_2 concentration at forests reforested through the forestry carbon project. The correlation of the *in situ* portable CO_2 sensor signatures measured on the ground with the carbon stock presented in the PDD was found to be 0.28, which indicates interactive relationships between the carbon absorption factors calculated through *in situ* destructive sampling for the five carbon pools and the actual decreases in ground CO_2 concentration. It was confirmed that the explainable ranges for the two instruments were relatively underestimated compared with previous studies, and this should be taken into consideration when using *in situ* portable CO_2 sensor signatures. The results of this study (explainable range of *in situ* CO_2 sensor signatures: 28%) can provide valuable references for setting the uncertainty range in the MRV process for the PDD carbon stock. In this study, we confirmed that NDIR portable sensors can be used to explore the fluctuations in ground CO_2 concentration owing to various topographical characteristics of the ground. Furthermore, this study is meaningful in offering a starting point to discuss this question and addresses concerns as to whether NDIR portable sensors can be used as MRV tools for the forest carbon business.

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