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Effects of Pear Orchards on Carbon Reduction

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Additional index words: direct harvesting, carbon uptake, carbon emission, management, regression model

Abstract

This study quantified storage and annual uptake of carbon from pear trees through a direct harvesting method, and calculated annual carbon emissions from pear cultivation. Individual trees in three study orchards were sampled to include the range of stem diameter sizes. The study measured biomass for each part including the roots of sample trees to compute total carbon storage per tree. Annual carbon uptake per tree was quantified by analyzing the radial growth rates of stem samples at ground level. Annual carbon emissions from management practices such as pruning, mowing, irrigation, fertilization, and pesticide and fungicide use were estimated based on maintenance data, interviews with managers, and actual measurements. Regression models were developed using stem diameter at ground level (D) as an independent variable to easily estimate storage and annual uptake of the carbon. Storage and annual uptake of carbon per tree increased as D sizes got larger. Pear trees with D sizes of 10 and 20 cm stored 7.5 and 46.5 kg of carbon and annually sequestered 0.6 and 3.0 kg, respectively. Storage and annual uptake of carbon per unit area in study orchards were 8.75 t/ha and 0.61 t/ha/yr, respectively, and annual carbon emissions were 3.86 t/ha/yr. Thus, the carbon emissions were 6.3 times greater than the annual carbon uptake. The study explored useful strategies for low-carbon orchard management to improve carbon reduction effects, including efficient uses of water, pesticides, fungicides, and fertilizers. This study breaks new ground by including measured root biomass of pear trees and a detailed inventory of carbon emissions from their maintenance.

There has been rising interest in and demand for low-carbon agricultural production. Efforts to reduce carbon emissions have been made in various ways worldwide, and Korea also set the goal to reduce national carbon emissions by 30% compared to business as usual (BAU) by 2020 (Greenhouse Gas Inventory and Research Center, 2012). Recently, the country has adopted an agricultural carbon offset scheme that provides carbon emission rights equivalent to the reduction amount for farmers that decrease their carbon emissions using green agricultural technology, and is implementing a certification system for low-carbon agricultural products that reduce carbon emissions in the production process (Ministry of Agriculture Food and Rural Affairs, 2011).

The significance of trees as a source of carbon uptake to respond to climate change is increasing rapidly. Research both overseas and in Korea has focused mostly on the carbon uptake of forest trees (Birdsey, 1992; Milne and Brown, 1997; Song et al. 1997; Jo and Ahn, 2000; Korea Forest Research Institute, 2010a) and urban trees (Nowak, 1994; Jo and Cho, 1998; McPherson, 1998; Jo, 1999a; McPherson and Simpson, 2000; Jo and Ahn, 2001; 2012; Jo, 2002; Nowak and Crane, 2002; Korea Forest Research Institute, 2010b; Park and Kang, 2010; Jo et al., 2013; Jo et al., 2014a). However, there have been few studies on carbon uptake by trees of varying age on farmlands such as orchards and fields, even though Jo et al. (2014b) recently studied the carbon reduction effects of apple trees through direct harvesting.

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Like the plantation effect provided by landscape trees, orchards can take up carbon, but orchard trees, which are cultivated for production, may reduce carbon differently than general landscape trees. In other words, the cultivation of fruit trees either directly or indirectly emits carbon to the atmosphere due to the need for management practices such as pruning, mowing, fertilization, irrigation, and the use of pesticides. Carbon emissions from cultivation offset part of the carbon uptake by trees (Jo, 1999b). Determining the emissions is necessary for understanding carbon flow of orchards and quantifying net carbon uptake. However, little is known about carbon emissions related to fruit tree cultivation in Korea.

The area occupied by orchards in Korea was 150,000 ha in 2014, which is about 9% of the country's total farmland area, and the main fruit trees in cultivation were apple, pear, peach, grape, citrus, and plum (Statistics Korea, 2014). Pear orchards accounted for a relatively broad area among cultivated fruit trees with 14,000 ha (Statistics Korea, 2014), which is approximately 9% of the total orchard area. The purpose of this study was to quantify carbon storage and uptake through direct harvesting of pear trees (*Pyrus pyrifolia* Nakai), which are typical fruit trees in Korea, and calculate the carbon emissions related to cultivated pear tree maintenance. The study also explored some strategies for low-carbon orchard management to improve carbon reduction effects. Carbon storage in this study refers to the total amount accumulated over many years as the trees grew, whereas carbon uptake refers to the amount of uptake by the trees in one year.

Materials and Methods

Selection of Study Orchards and Trees for Digging.

Three commercial orchards in Chuncheon, Korea (referred to as orchards 1, 2, and 3) were selected for tree harvesting and management monitoring. The cultivar was mostly 'Niitaka', with some 'Wonwhang' and 'Whasan'. An in-situ survey of each of the study orchards was conducted, and 20 trees with the typical pear tree form were selected for digging. Sample size of trees for digging was a compromise between two conflicting concerns: the high cost and difficulty of purchasing trees and the need for a sufficient number of specimens, including a range of trunk diameters at ground level (D) in the study orchards. The variety of pear trees cultivated in the study orchards was mostly Niitaka, with some Wonwhang and Whasan also included.

Digging and Fresh Weight Measurement.

To avoid damaging adjacent trees at harvest, trees were dug in mid-July 2014, and fresh weights of each part such as stem, branch, leaf, fruit, and root were measured. Therefore, trunk diameter for trees of similar sizes growing adjacent to the specimens, were measured until late October, the end of growth by attaching a diameter growth measuring tool (8L05042, Shinill Science, Korea), and reflected the fluctuations of carbon storage and carbon uptake equivalent to D increment compared to the digging period in July. When digging the trees, the size of each tree including D, crown width, and tree height was measured. Physical and chemical characteristics of the soils under the trees were analyzed using the soil analysis method of the Korean Institute of Agricultural Science and Technology (2000). Digging and fresh weight measurement were conducted with partial reference to the biomass survey/analysis standard method of the Korea Forest Research Institute (2007), and the specific methods are as shown in Table 1.

Dry Weight Specimens and Measurement.

To calculate dry weight compared to fresh weight, we collected specimens to convert to dry weight for each part and measured the fresh weight of the specimens on site to an accuracy of 10 g. The stem was separated at 1m intervals, and disks of 5–10 cm thickness were collected from the central part at

Table 1. Methods of digging and fresh weight measurement for various parts of tree specimens.

Component	Method
Tree size	Stem diameter was measured to 0.1 cm at ground level with a caliper Crown width was measured to 0.1 m in duplicate at 90° with a measuring tape Tree height was measured to 0.1 m with a measuring tape after digging
Root	Roots were dug with a backhoe and all broken roots were collected They were separated from the stem at ground level with a sawing machine They were washed with a high-pressure jet and then weighed to 10 g
Stem	The stem was weighed to 10 g after cutting out all branches with a sawing machine
Branch/leaf	Branches were weighed to 10 g after separating all leaves from them by hand, and leaves were also weighed to 10 g
Fruit	Fruits were weighed to 10 g after separating them from all branches by hand

0.5, 1.5, 2.5, and 3.5 m. As for branches, we sampled 1–2 kg evenly mixed with thick, medium, and thin branches. Roots were divided into stump and other parts, and 1–3 kg of these were collected. We also randomly sampled 1 kg each of leaf and fruit. Stem disks for D growth analysis were immediately put into a double vinyl bag, and carried to the laboratory.

The specimens for dry weight conversion were dried in an oven (US-1202 DH, Vision Scientific, Korea) at 85℃ to constant weight, and the dry weight was measured to an accuracy of 0.01 g on an electronic scale (FX-3200, AND, Japan). The ratio of dry weight to fresh weight of each sample was calculated and used to estimate the dry weight (hereafter referred to as biomass) for the part and tree total.

Development of Regression Models for Carbon Storage and Uptake.

Regression models were developed to estimate carbon storage according to the growth of a tree, deriving an allometric equation to calculate the biomass change related to tree size and applying a carbon content ratio. Carbon content of three samples per tree was analyzed for stem, bark, branch, leaf, fruit, and root, using the dry ashing method (Korean Institute of Agricultural Science and Technology, 2000; Kang et al., 2009). Linear and nonlinear models were developed, where D, tree height, and crown width were included as independent variables to estimate carbon storage.

Tree age and annual D growth rate of the tree specimens were analyzed using the stem disks collected from the ground level. The D growth rate was obtained by averaging the measurements from the four directions of each disk. By calculating the annual increase in biomass based on the D growth rate and converting it to the amount of carbon, we developed regression models to easily estimate carbon uptake according to the growth of a tree. That is, we used the annual D growth rate to obtain the previous year's D, and applied this D variable to the biomass allometric equation to quantify the previous year's biomass. The previous year's biomass was subtracted from the current year's biomass to calculate the annual biomass increment and carbon uptake. Since leaf and fruit return carbon to the atmosphere every year through decomposition and consumption, they were deducted from the annual increase in biomass. The most suitable regression models and variables to estimate carbon uptake were identified by linear and nonlinear approaches with D, tree height, and crown width as independent variables.

Management Inventory and Carbon Emission Estimation.

To estimate carbon emissions from pear cultivation, management practices were investigated by obtaining management data from the study orchards, conducting interviews with managers, and recording some measurements. Management inventories included: 1) frequency, amount, and energy consumption of pruning, 2) frequency, amount, and energy consumption of mowing, 3) frequency, time, amount, and tools of irrigation, 4) frequency, type, amount, and tools of fertilization, and 5) frequency, type, amount, tools, and energy consumption of pesticide use. To compare and supplement the management inventory data, we conducted an investigation of 38 orchards nationwide (hereafter referred to as orchard 4) in addition to the three study orchards. The inventory data were statistically analyzed using Microsoft Office Excel 2010.

Among management practices, the amount of pruning, mowing, irrigation, fertilization, and pesticide application were measured by monitoring the study orchards. Fresh weight of pruning was measured to an accuracy of 10 g by collecting branches pruned in winter and summer (except leaf and fruit) for 30 trees selected at regular D intervals. Branches of approximately 1 kg were randomly sampled at 10 locations per tree to quantify pruned biomass per tree through the aforementioned method. Then, the most suitable regression model base on a test of statistical significance and goodness-of-fit was selected to estimate carbon emissions equivalent to the amount of pruning for a tree by D size. Fresh weight of mowing was measured to an accuracy of 10 g by establishing 2×2 m quadrats at 6 locations per orchard and collecting vegetation mowed in each quadrat. Mowed vegetation of about 1 kg was randomly sampled from each quadrat to obtain average mowed biomass per unit area, and the biomass was converted to a carbon emission estimate by multiplying by 0.45 (Olson, 1970; Ajtay et al., 1979; Jo and McPherson, 1995). The average amount of irrigation was estimated by measuring the amount of water collected per unit time at 6 locations per orchard with a beaker marked with volume gradations. Application rates of fertilizers and pesticides were measured to an accuracy of 10 g by type on the day they were applied.

Direct energy consumption for pruning, mowing, pesticides, and fungicides was converted to carbon emissions by applying the emission factor of 0.57 kg of carbon per 1 L of gasoline (Climate Insight Knowledge Portal, 2010). For direct and indirect energy consumption by irrigation, fertilization, pesticides, and fungicides, the relevant emission factor did not exist in Korea; thus, carbon emissions were estimated using the factor reported by Pitt (1984), Wells (2001), and Lal (2004). That is, we applied emission factors of 0.024 kg C/kg for irrigation, 1.23 kg C/kg for nitrogen fertilizer, 0.20 kg C/kg for phosphate fertilizer, 0.15 kg C/kg for potassium fertilizer, 3.79 kg C/kg for pesticides, and 3.38 kg C/kg for fungicides. Here, direct emissions refer to fossil fuel consumption including the operation of tools within the study orchards, and indirect emissions indicate fossil fuel consumption in the manufacturing process of applied fertilizers, pesticides or fungicides.

Results and Discussion

Growth Environment and Biomass.

The city of Chuncheon where orchards 1, 2, and 3 are located in a temperate zone in the central inland (east longitude 127°31′–127°47′, north latitude 37°41′–38°05′) of the Korean Peninsula, characterized by a continental climate with wide seasonal temperature variations. Based on the meteorological data observed at the Chuncheon Meteorological Office (Korea Meteorological Administration, 2014), the average annual temperature in the last 10 years (1995–2014) was 11.3℃, and the highest and lowest temperature was 34.9℃ and -18.9℃, respectively. The average annual precipitation was 1,471.9 mm, and sunshine hours were 1,997.2 h.

Table 2 summarizes the soil physical and chemical characteristics. Soil texture was sandy clay loam or loamy sand. The chemical properties were as follows: pH 4.6–5.7, organic matter 1.4–3.2%, total

Table 2. Physical and chemical characteristics of soils for three test orchards[z].

Study orchard	Soil texture	pH	OM (%)	TN (%)	Ava. P (mg/kg)	EC (cmol+/kg) K+	Ca2+	Mg2+	CEC (cmol+/kg)
1	SCL	5.7	1.4	0.07	977.2	0.27	0.98	0.65	2.6
2	LS	5.3	3.2	0.17	1633.0	0.84	0.72	1.72	4.1
3	SCL	4.6	2.6	0.14	1179.0	1.06	0.95	1.72	4.5
Standard[y]	SL-CL	6.0-6.5	2.5-3.5	-	200-300	0.3-0.6	5.0-6.0	1.5-2.0	10-15

[z] Orchards 1, 2, and 3 are located at Cheonjeon-ri and Saam-ri in Chuncheon (the same with Table 6 and Fig. 2). OM: Organic matter, TN: Total nitrogen, Ava. P: Available P_2O_5, EC: Exchangeable cation, CEC: Cation exchange capacity, SCL: Sandy Clay Loam, LS: Loamy Sand, SL: Sandy Loam, CL: Caly Loam.

[y] Source: Korean Institute of Agricultural Science and Technology (2006).

nitrogen 0.07–0.17%, available phosphate 972.2–1633.0 mg/kg, exchangeable K^+ 0.27–1.06 cmol+/kg, and cation exchange capacity 2.6–4.5 cmol+/kg. According to the optimum soil standards of orchards provided by the Korean Institute of Agricultural Science and Technology (2006), orchard 1 was below the optimum range in most components except K^+, while orchards 2 and 3 were below the optimum range in components other than organic matter, available phosphate, K^+, and Mg^{2+}.

The range of various tree parameters was 3.5 – 21.6 cm for D, 2.8 - 4.9 m for tree height, 0.7 - 4.8 m for crown diameter, 6 – 22 years for tree age, 0.7 - 1.0 cm/yr for annual D increase and average annual D increase was 0.85 ± 0.21 cm/yr. Total biomass of the trees tended to increase nonlinearly with D growth and ranged from 0.5–70.2 kg (Fig. 1). The biomass allocation rate per part varied more or less among the trees, but stem was the highest and averaged 45.1%, followed by root with 29.1%, branch with 15.6%, leaf with 7.1%, and fruit with 3.1%.

The biomass expansion factor of the above-ground parts (stem, branch, leaf, and fruit) compared to stem averaged 1.59±0.04, and the ratio of underground part/above-ground part was 0.40±0.02. The biomass expansion factor of pear trees was lower than 2.65 reported for apple trees (Jo et al., 2014b), but the ratio of underground part/above-ground part was similar to 0.41 for apple trees. Compared to the case of landscape trees (Jo and Ahn, 2012), the biomass expansion factor

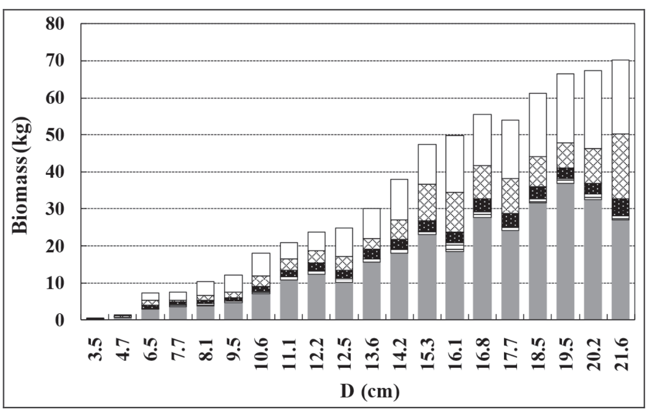

Fig. 1: The relationship between biomass of various pear tree organs and trunk diameter (D).

☐ Root, ⊠ Banch, ■ Leaf, ⊟ Fruit, ■ Stem of pear trees was similar to or slightly lower than 1.60 for *Prunus yedoensis* and 1.71 for *Acer palmatum*. Meanwhile, the ratio of underground part/above-ground part for pear trees was similar to 0.39 for *Acer palmatum* and 0.43 for *Prunus yedoensis*.

Carbon Storage and Uptake.

Mean carbon content of pear trees was 55.4±0.1% of biomass, with no significant difference ($P > 0.05$) among the tree parts, such as wood and leaf. Therefore, biomass was converted to carbon storage and uptake multiplying by 0.55. Previous researchers (Pingrey, 1976; Chow and Rolfe, 1989; Song et al., 1997) reported that the average carbon content of wood and leaf of trees was approximately 50% of biomass, but other recent studies (Lee and Park, 2007; Kang et al., 2009) revealed that the carbon content is about 55%, and thus applying 50% may cause an underestimation of the amount of carbon. The carbon content of pear trees in this study was quite similar to the latter, and may be comparatively verified later by applying various carbon analysis methods. The regression models to quantify carbon storage and uptake of pear trees are shown as follows.

Carbon storage (kg) = $e^{-4.0410 + 2.6305 \ln D*}$ (D unit is cm) [1]

Carbon uptake (kg/yr) = $(e^{-4.6358 + 2.1071 \ln D}) - (e^{-4.8653 + 1.9104 D})*$ (equation to estimate pruned carbon) [2]

The regression models were statistically significant ($P < 0.0001$) through F test, and had a high goodness-of-fit with $R^2 = 0.97$ and 0.98, respectively. R^2 of pruning regression model was 0.95. The regression coefficients were significant at a 1% level. This study attempted to derive regression models that include not merely D but also tree height and crown width as independent variables. However, the regression coefficients for tree height or crown width were not significant at a 5% level, but the F value was significant and R^2 was fairly good. Although the regression models for tree height were statistically significant, it is difficult to accurately measure tree height in the field; thus, the error of estimation may be larger than that for regression models using only D (Whittaker and Marks, 1975; Park and Lee; 1990). The regression models developed in this study can be easily used to estimate the carbon storage and uptake of pear trees, as they require only D measurement. The regression model for carbon uptake includes the equation that subtracts carbon emissions associated with annual pruning.

Fig. 2 shows carbon storage and uptake by D estimated with aforementioned regression models. Carbon storage increased with increasing D growth for the D range studied. As the D increased by 2 cm, the carbon storage of pear trees increased from a minimum of 1.3 times to a maximum of 2.9 times. Compared with apple trees (Jo et al., 2014b),

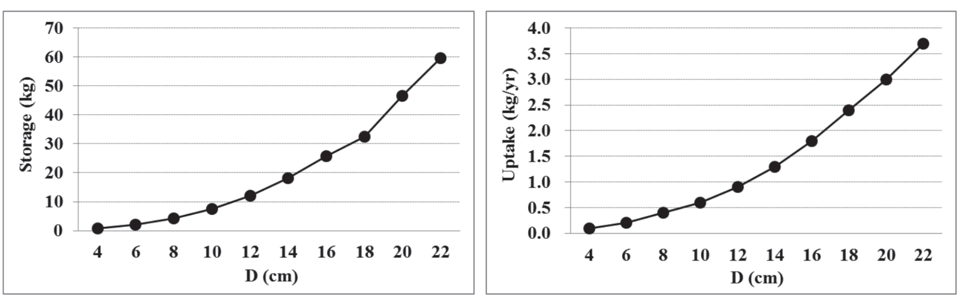

Fig. 2: Carbon Storage and uptake per tree with varying trunk diamenters (D).

carbon storage of pear trees was similar or lower for the same D of 14 cm or smaller; but for D ≥ cm, it was greater than that of apple trees by a maximum of 1.3 times. Compared with landscape trees, carbon storage of pear trees showed quite a difference from *Acer palmatum* and *Prunus yedoensis*. For example, carbon storage for D of 10 cm was equivalent to 48–82% that of *Acer palmatum* and *Prunus yedoensis*. The lower carbon storage in pear trees could be associated with the annually repeated pruning for production efficiency. Consumption of 10 L of gasoline emits approximately 5.7 kg of carbon into the atmosphere (Climate Insight Knowledge Portal, 2010). A pear tree with the D of 10 cm stored an amount of carbon equivalent to that emitted by burning about 13 L of gasoline.

Carbon uptake increased along with D growth, and the difference in carbon uptake between D sizes also tended to increase along with increasing D, similar to carbon storage. As the D increased from 2 to 4 cm, the carbon uptake increased from 0.1 to 0.2 kg/yr and as D increased from 20 to 22 cm, carbon uptake increased from 3.0 to 3.7 kg/yr. Carbon uptake of pear trees equaled 33–87% that of apple trees (Jo et al., 2014b), for trees with D ≤ 14 cm, but for trees with D ≥ 16 cm, it was greater than that of apple trees by a maximum of 1.7 times. The carbon uptake of pear trees after the annual pruning was subtracted showed quite a difference from that of landscape trees. For example, carbon uptake of pear trees with D = 14 cm was equivalent to 27–33% that of *Acer palmatum* and *Prunus yedoensis*. A pear tree with the D = 10 cm acted as a carbon sink that annually offset carbon equivalent to that emitted by burning about 1.0 L of gasoline.

Management Practice and Carbon Emission. The pruning frequency in this study was 1–2 times each year. Trees may have been pruned while dormant and in summer. Trees in orchard 1 were pruned only in winter, whereastrees in orchard 4 were pruned more frequently done in winter, with 63.4% of the 38 samples. The annual pruning biomass measured per pear tree averaged 2,237.7±273.8 g/yr. All pruned branches were used as compost in orchards 1, 2, and 3, and were used as compost (79.2%) or incinerated (20.8%) in orchard 4. Gasoline consumption per pruning event and carbon emissions per year from operating the pruning equipment (TD600G, Mitsubishi, Japan) for each tree were 14.3 ml and 16.3 g/yr in orchard 3 (Table 3), and 13.9 ml and 12.7 g/yr in orchard 4, respectively. In orchards 1 and 2, the trees were pruned with hand saws and scissors, which do not involve fossil fuel consumption.

All study orchards were weeded with a mechanical weeder without applying herbicides. The frequency of mowing was 3–6 times per year, mostly in summer with one additional mowing in spring and fall.

Table 3. Annual carbon emissions (g carbon/tree) for various culturalmanagement practices in four commercial pear orchards.

Management	Study orchard			
practice	1	2	3	4[z]
Pruning	0.0	0.0	16.3	12.7
Mowing	80.8	75.0	48.9	70.4
Irrigation	10,960.3	9,394.6	9,811.2	15,130.4
Fertilization	233.1	0.0	0.0	312.3
Pesticide	340.1	141.8	271.2	329.9
Fungicide	319.1	136.8	257.7	319.3
Total	11,933.4	9,748.2	10,405.3	16,175.0

[z]Average from 38 samples except orchards 1, 2, and 3.

The annual mowing biomass per unit area was 297.5–350.2 g/m^2, most of which was used as compost. Gasoline consumption per mowing event and carbon emissions per year from operation of the weeder for each tree were 23.6 ml and 80.8 g/yr in orchard 1, 26.3 ml and 75.0 g/yr in orchard 2, 28.6 ml and 48.9 g/yr in orchard 3, and 28.7±2.3 ml and 70.4 g/yr in orchard 4, respectively. The annual carbon emissions were 1.1–1.7 times greater in orchard 1, where the mowing frequency was higher than in other study orchards.

The annual frequency of irrigation was 6–20 times. The duration of irrigation per event was approximately 0.8 hours in orchard 1, 1.5 hours in orchard 2, 5 hours in Orchard 3, and 3.4±0.3 hours in orchard 4. Sprinkler irrigation was used in orchards 1, 2, and 4, whereas orchard 3 was drip irrigated. The amount of irrigation measured per tree averaged 724.9±85.3 ml/min for sprinkler irrigation and 67.0±13.0 ml/min for drip irrigation. Thus, sprinkler irrigation consumed approximately 11 times more water than drip irrigation. The amount of water applied per event and carbon emissions per year per tree were the highest in orchard 4 with 39.7±3.2 L and 15,130.4 g/yr, respectively, followed by orchard 1 with 32.6 L and 10,960.3 g/yr, and orchard 3 with 20.4 L and 9,811.2 g/yr. Orchard 2 had an irrigation amount of 65.2 L greater than orchard 4, but the lowest carbon emissions at 9,394.6 g/yr due to having the lowest irrigation frequency.

The annual frequency of fertilization was 2 times in orchard 1 and 2.5±0.2 times in orchard 4. The amount of fertilizer applied per tree, per application in orchard 1 was 85.8 g of N, 37.5 g of P, and 26.8 g of K, whereas in orchard 4 it was 90.9±5.8.0 g of N, 29.9±2.9 g of P, and 34.7±3.7 g of K. Orchards 2 and 3 used compost instead of chemical fertilizers. The fertilization amount in orchard 1 was almost similar to the fertilization standard set by the Korean Institute of Agricultural Science and Technology (2006). In orchard 4, the phosphate amount was 85% of the fertilization standard, but the amount of nitrogen and potassium was 1.1–1.4 times greater than the standard. Annual carbon emissions from fertilization were 233.1 g/yr in orchard 1 and 312.3 g/yr in orchard 4. The carbon emissions based on the fertilization standard were 218.5 g/yr. Thus, following the standard will reduce the carbon emissions.

Pesticide application was highest in orchard 1 with 13 applications, followed by orchard 4 with 12.2±0.7 applications, orchard 3 with 10 applications, and orchard 2 with 8 applications. Gasoline consumption per tree for the power sprayer was highest in orchard 3 at 51.4 ml, followed by orchard 2 with 42.1 ml, orchard 4 with 41.3±5.5 ml, and orchard 1 with 39.4 ml. The pesticide application rate per time per tree was highest in orchard 4 at 4.0 g. But annual carbon emissions from pesticide use were greatest at 340.1 g/yr in orchard 1, as it had the highest frequency. Application rate per time of and carbon emissions per year from fungicides were 4.3 g and 319.3 g/yr, respectively, in orchard 4, indicating that they were 1.2–2.3 times higher than the other study orchards excluding orchard 1. Pesticides used most frequently in this study were imidacloprid, acetamiprid, and etofenprox to prevent moths, mites, and aphids, while the dominant fungicides were tebuconazole and dithianon to prevent brown spots and anthracnose.

The standard pesticides suggested by the Korea Crop Protection Association (2011) is safe and limits the annual application frequency to 3–5 times and the application rate per time to 2.3 g for each tree. The annual carbon emissions per pear tree from this standard are 42.6 g/yr for pesticides and 38.0 g/yr for fungicides, but all study orchards except for orchard 2 emitted 2.9–4.6 times more carbon for both pesticides and fungicides. It is necessary to abide by the application standard of pesticides and fungicides to reduce management costs and carbon emissions.

Carbon Budget and Low Carbon Management.

Carbon storage and uptake per unit area of orchard area was 7.80 t/ha and 0.55 t/ha/yr in orchard 1, 10.94 t/ha and 0.74 t/ha/yr in orchard 2, and 7.69 t/ha and 0.54 t/ha/yr in orchard 3, respectively (Fig. 3). Annual carbon emissions per unit area from management practices were 4.36 t/ha/yr in orchard 1, 3.74 t/ha/yr in orchard 2, 3.72 t/ha/yr in orchard 3, and 5.82 t/ha/yr in orchard 4. Irrigation accounted for 91.9–96.4% of the carbon emissions, followed by pesticide and fungicide use with 2.9–5.5%, fertilization with 1.9–2.0%, mowing with 0.4–0.8%, and pruning with 0.1–0.2%. The carbon emissions were variable depending on the management intensity and method of each study orchard. Summing up orchards 1, 2, and 3, the carbon storage and uptake were 8.75 t/ha and 0.61 t/ha/yr, respectively, and the carbon emissions were 3.86 t/ha/yr. Thus, the carbon emissions were 6.3 times greater than the carbon uptake, even though the carbon storage was equivalent to 2.3 times the carbon emissions.

Ultimately, low-carbon management strategies are required to enhance the carbon reduction effects of pear orchards. Of the management practices, irrigation was the greatest source of carbon emissions, and energy consumption from spray irrigation was 11 times greater per unit time than drip irrigation. Therefore, it is desirable to reduce carbon emissions by adopting drip irrigation. The use of pesticides and fungicides should follow the aforementioned application standard (Korea Crop Protection Association, 2011). Biological control is an alternative to control mites and aphids that frequently occur in pear orchards. As for fertilizers, it is necessary to abide by the aforementioned fertilization standard (Korean Institute of Agricultural Science and Technology, 2006), or use the elaborate soil test service provided by technical officials to apply the recommended amount of fertilizers based on soil analysis. As for mowing, it is desirable to minimize the operation of weeders that consume fossil fuels. Cultivating green manure crops such as milk vetch, barley, and rye can reduce the need for mowing by preventing the in-

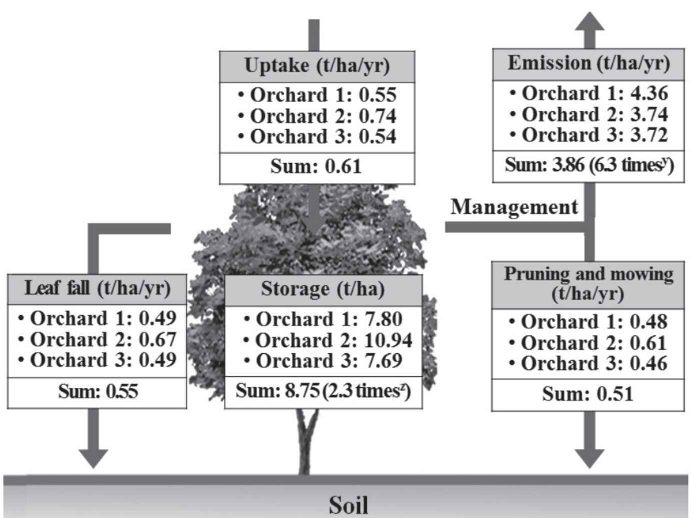

Fig. 3: Carbon budgets in study orchards 1, 2, and 3.
[z] Carbon storage vs. emissions.
[y] Carbon emissions vs. uptake.

vasion of weeds. The crops may also reduce the need for chemical fertilizers by supplying soil organic matter. Pruned branches should be used as compost and mulching materials to promote carbon accumulation in the soil instead of being incinerated. If drip irrigation and fertilization standard is adopted for the study orchards with sprinkler irrigation, estimated annual carbon emissions are expected to be 0.48–0.61 t/ha/yr. This change in management practices would result in a reduction of carbon emissions by as much as 86.0–87.2%, and a maximum carbon uptake 1.5 times greater than the estimated carbon emissions. Improving orchard management will likely change pear orchards from a source of carbon emissions to a source of carbon uptake.

This study played a pioneering role in overcoming the difficulty and complexity of quantifying the effects of orchards on carbon reduction through direct harvesting including root digging. The main challenges were the difficulty in purchasing pear trees for logging among the trees cultivated as an income source, the digging of the trees and the fresh weight measurement of each part, and the long-term drying process of multiple fresh weight specimens and carbon content analysis. Low carbon industry is a major concern worldwide given the need to satisfy the increasing demand for low carbon products in trade markets. These research findings are expected to be internationally useful, as they provide the practical information necessary for quantifying the carbon uptake and emissions involved in orchard production. This study also provides actual measurement data regarding growth characteristics of pear trees that have been little known until now, such as biomass expansion factor, underground part/aboveground part ratio, and D growth rate. The limitation of this study in quantifying carbon storage and uptake is that it was limited to a specific region due to the difficulty in purchasing pear trees for digging, as orchard owners were uncooperative when it came to digging the cultivated trees and requested high costs. It is necessary to verify the research findings and build relevant data by conducting additional experimental studies on different cultivation environments.

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