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Soil and Biomass Carbon Accumulation in Abandoned Paddy Wetlands (APWs): Implications for Sustainable Land Management

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Abstract

Abandoned paddy wetlands (APWs) develop after rice cultivation ceases and may support carbon sequestration, soil conservation, and sustainable management of abandoned agricultural land. This study quantified soil and biomass carbon in six reference APWs in the central region of the Republic of Korea. Following the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance for Land Use, Land Use Change and Forestry (GPG-LULUCF), soil samples were collected to a depth of 30 cm to estimate soil organic matter (OM), soil organic carbon (SOC), and soil organic carbon storage per unit area (SOCS). Land cover-based carbon absorption was evaluated within 300 m hydro-ecological impact zones for 2000, 2013, and 2021, and biomass carbon was estimated for woody, herbaceous, and mixed communities using field measurements and drone LiDAR-derived vegetation structure. The mean OM and SOC contents were 33.7 and 19.54 g/kg, respectively. The corrected mean SOCS was 61.20 ± 22.28 kg/m² (unadjusted mean: 67.97 kg/m²), approximately 8.5–40 times the reference values reported for South Korean forest soils and urban parks. The mapped mean carbon absorption was 20.45 tCO₂/ha in 2000, 35.30 tCO₂/ha in 2013, and 38.14 tCO₂/ha in 2021. Because only three mapped years were analyzed, these values describe observed differences and do not establish a continuous temporal trajectory or a stable plateau. The findings suggest that APWs may contribute to sustainable land management, wetland restoration, soil conservation, and climate-change mitigation through carbon retention in soils and vegetation. These field data provide region-specific evidence for evaluating sustainable management strategies and complementing broader-scale soil–vegetation carbon models.

Keywords: abandoned paddy wetlands; soil organic carbon; biomass carbon; carbon sequestration; sustainable land management; nature-based solutions; drone LiDAR

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1. Introduction

Carbon capture, utilization, and storage (CCUS) technology, known as an effective means of responding to climate change, has limitations such as high cost, increased energy consumption, and limited time for storing CO₂ [1,2]. As an alternative, studies on nature-based carbon absorption are actively underway, and the function of wetlands as a

representative nature-based carbon sink is being paid attention to. Since wetlands also act as a source of CO₂ or CH₄ emissions, research on nature-based solutions that can suppress carbon emissions and increase absorption in wetlands is being activated. Wetlands exhibit a wide range of physical and chemical heterogeneities, regardless of their size, due to topography and water cycle. In particular, changes are intensified due to water level differences at the fringe connected to the land, and, when continuously affected by water, the Oxidation Reduction Potential(Eh) decreases and the distribution of plants changes due to an anaerobic environment where oxygen supply is limited [3].

Wetlands are ecosystems that provide ecological functions and services to people due to abundant nutrients and high species diversity and productivity [4–7], and can promote biodiversity and serve as a water purification system for non-point pollution sources [8]. Although Rice Paddy Wetlands (RPWs), the representative heritage of agricultural culture, are essential ecological resources that provide ecological functions and ecosystem services to people throughout their daily lives, farming activities are hindered by natural and artificial causes and facing rapid destruction. According to the e-Nara Index in the Rep. of Korea, domestic arable land increased until the 1990s, but declined rapidly after the 2000s, while idle farmland continued to grow (<https://www.index.go.kr/main.do> (accessed on 1 April 2026)).

Abandoned RPWs converted to APWs, which are very important for maintaining biodiversity at the same or higher level as other types of small wetlands [9]. In particular, well-preserved and managed APW is an effective means of offsetting atmospheric CO₂, and restoring APW can increase carbon absorption capacity and improve ecosystem service capacity [10,11]. As APW's carbon reduction and other complex functions and ecosystem services are receiving attention, its ecological value is being re-evaluated.

In wetland ecosystems including APW, soil is the largest storage of organic carbon, and organic carbon storage plays an important role in the carbon cycle of terrestrial ecosystems. The carbon cycle is a biogeochemical cycle in which carbon is exchanged among the biosphere, lithosphere, hydrosphere (ocean), and atmosphere on Earth. Carbon has a sink in each of the biosphere, lithosphere, hydrosphere, and atmosphere. The carbon cycle is a path through which carbon moves between these four sinks, and the soil is the largest reservoir inland. Soil converts atmospheric carbon dioxide (CO₂) into soil organic carbon, thereby preserving carbon in the soil without releasing it easily, thereby becoming an essential means of offsetting the increase in atmospheric CO₂. Soil carbon is 3.3 times the total carbon in the atmosphere and 4.5 times that of living organisms, and it is known to have a significant effect on reducing greenhouse gas concentration in the atmosphere [12–14].

The Intergovernmental Technical Panel on Soils (ITPS) defines soil health as “the ability of soil to maintain the productivity, diversity, and environmental services of terrestrial ecosystems,” and SOC is an essential element that enables soils to provide these services, and can be said to be a key indicator of soil health. SOC is a major element that constitutes 58% of OM, which is organic residue in soil, and constitutes the largest terrestrial carbon pool in the global carbon cycle. It is known that soils in the 30 cm depth range worldwide contain more carbon than the atmosphere and vegetation combined.

Soil carbon is stored in the soil in the form of organic and inorganic substances in solid or aqueous solutions. Atmospheric CO₂ is converted into SOC through the process of biomass decomposition in the soil [15]. However, the indiscriminate management and development of soils have caused soil disturbance, drying, and temperature increases, which has led to a tendency for a large amount of carbon to be released from the soil into the atmosphere [16]. In particular, in agricultural producing countries such as Korea and other Asian countries, the number of idle farmlands has rapidly increased, leading to a decrease in the carbon absorption of wetlands and an increase in emissions.

RPW maintains submerged conditions during the rice growing season to maintain production functions, creating anaerobic conditions and slowing down the decomposition of organic matter, helping to accumulate SOC [17]. SOC is a crucial element of soil fertility. Farmlands with high SOC content have high agricultural productivity and serve a buffering function against external environmental pressure. Regarding soil SOC, the Paris Agreement on Climate Change (COP21) established the SOC 4 per mil program, which aims to increase SOC by 0.4% per year globally to limit temperature increase to 1.5 °C compared to pre-industrial levels [18]. The SOC of well-managed, permanently water-logged APW increases compared to RPW due to the omission of regular drainage cycles, and rises to levels similar to natural wetlands [19].

Additionally, carbon circulating within the ecosystem is absorbed by plant photosynthesis and is stored in plants as biomass [20]. He et al. [21] estimated forest biomass and composition in coniferous forests in western China using low-resolution airborne LiDAR. In addition, studies related to the carbon accumulation of APWs include Refs. [22–32]. Against this background, this study avoids over-generalized claims; instead, it establishes a high-resolution localized case study to derive soil SOC and plant biomass-specific carbon accumulation performance of six reference APW distributed in the central region of the Rep. of Korea.

2. Materials and Methods

2.1. Scope and Spatial Environmental Baseline

The research subjects were six reference APWs distributed in Chungnam Province and Daejeon-si, approximately 80 km south of Seoul. APW boundaries were derived using QGIS based on a digital topographic map (1: 5000) and satellite images, aerial photos, and drone orthoimages provided by the National Land Information Platform (<http://map.ngii.go.kr/> (accessed on 1 April 2026)). To support horizontal statistical validity and establish structural parameters, the baseline environmental variables, including topography, successional forms, and historical abandonment age, were documented (Figure 1, Table 1).

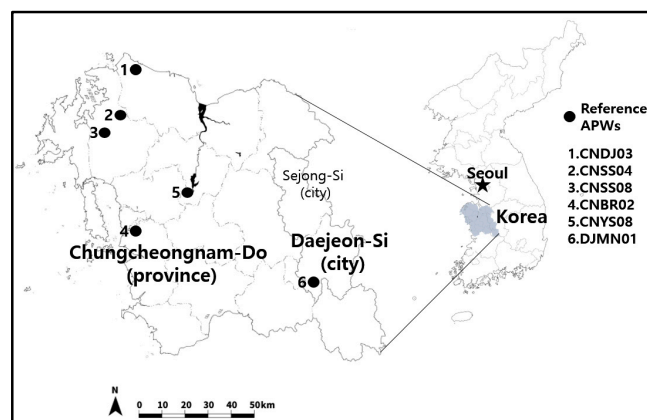


Figure 1. Site location map (The black star indicates Seoul, the capital of the Republic of Korea).

Table 1. Baseline ecological and hydrological metrics of the six reference APW sites.

Site ID	Geographic Coordinates DOCX	Macro-Topography	Dominant Vegetation Community	Mean Inundation Period	Abandonment Age
CNDJ03	37°0'58.02" N, 126°32'3.16" E	Valley-bottom flat	Mixed Woody-Herbaceous	Seasonal (4–6 months/yr)	~12 years
CNSS04	36°49'9.82" N, 126°27'42.08" E	Alluvial plain	Perennial Herbaceous	Semi-permanent (>9 months/yr)	~8 years
CNSS08	36°47'3.62" N, 126°23'22.25" E	Low-lying terrace	Mixed Woody-Herbaceous	Seasonal (3–5 months/yr)	~15 years
CNBR02	36°26'9.83" N, 126°31'39.73" E	Mountainous fringe	Woody (<i>Salix</i> spp. dominated)	Permanent (Year-round)	>20 years
CNYS08	36°34'38.80" N, 126°45'44.29" E	Foothill depression	Woody (<i>Salix</i> spp. dominated)	Permanent (Year-round)	>18 years
DJMN01	36°14'3.77" N, 127°19'43.75" E	Riparian flat	Woody (Early successional pioneer)	Intermittent (Flash flooding)	~5 years

2.2. Calculation of Soil Carbon Potential in APWs

To obtain a preliminary estimate of within-APW spatial variability, soil samples were collected in triplicate (S1, S2, S3) along a systematic linear transect matching the moisture gradient at a continuous profile depth of 30 cm for each APW according to the IPCC's best practice guidelines (GPG-LULUCF) [33]. Sampling points maintained a fixed 5 m geometric buffer between replicates to ensure reproducibility. Soil OM content and physico-chemical properties were analyzed according to official laboratory soil analysis standards, and SOC (g/kg) was calculated using the organic carbon calculation model of NIAST [34] based on a soil depth of 30 cm. SOCS (kg/m²) per unit area was calculated using the formula of Yang et al. [35], where SOC, bulk density (ρ_b), soil depth (d), and gravel content (%gravel) were set as core operational variables. Because only three sampling points were collected per APW, this design provides limited spatial replication; the resulting variation should therefore be interpreted as preliminary rather than as a statistically validated characterization of micro-heterogeneity:

$$\text{SOCS} = \text{SOC} \times \rho_b \times d \times \left(1 - \% \frac{\text{gravel}}{100}\right) \times 10^{-1} \quad (1)$$

Bulk density (ρ_b , g/cm³) is related to organic matter content (OM), pore space, and decomposition in the soil. To prevent mechanical core compaction bias during wet collection, this study applied the bulk density estimation formula using the organic matter (OM, g/kg) parameters proposed in MST [36]:

$$\rho_b = 1.3863 \times e^{-0.0446 \times \text{OM}} \quad (2)$$

2.3. Carbon Accumulation of Biomass

2.3.1. Carbon Accumulation in Herbaceous Dominant Type

In this study, herbaceous biomass was calculated using the average height (H , m) and percent canopy coverage (C , %) of herbs as core variables [37–41]. Based on the review of previous studies, it was determined that a harvesting method that measures the absolute dry weight biomass of herbs in a localized square chamber of a fixed size is necessary to validate non-destructive visual proxies. Therefore, a destructive validation control layout consisting of adjacent 1 m × 1 m twin quadrats was clipped, oven-dried at 65 °C for 48 h, and utilized to calibrate the height coverage mathematical regression curve.

2.3.2. Carbon Accumulation of Woody Dominant Type

In the case of woody dominant types, structural analysis was conducted at the individual tree level through automated height calculation using the Local Maxima algorithm and tree area canopy classification based on a high-resolution Canopy Height Model (CHM). The raw point cloud datasets were generated via a DJI Matrice 300 RTK drone (SZ DJI Technology Co., Ltd., Shenzhen, China) integrated with a Zenmuse L1 LiDAR sensor, scanned at 60 m. Processing involved separating ground returns via an optimized Cloth Simulation Filter (CSF) and creating a 0.25 m resolution surface matrix.

Among the target sites classified as woody dominant type, the representative tree species confirmed through field vegetation survey data was willow (*Salix nipponica*). The parameter value of the intermediate classification unit was applied in the absence of a modeled relative growth table of willow. Precise tree height (H) was derived from drone LiDAR datasets, and aboveground biomass (m^3) was calculated by mapping height to Diameter at Breast Height (DBH) according to the official national Biomass Forest Harvest Table [42] with a fixed carbon conversion constant of 0.50.

2.3.3. Mixed Vegetation Type Carbon Accumulation

In the same way as the herbaceous-dominant type, structural aboveground and belowground components of ecotones were processed considering average height and cover rate as multi-layered continuous variables.

2.4. Method for Estimating Carbon Absorption by Land Cover in the Ecological Impact Zone

Carbon absorption by land cover type was calculated by setting a 300 m spatial radius around each APW perimeter as the primary ecological influence zone. The framework applied localized absorption/emission coefficients by land use, optimized for the Korean Peninsula based on the IPCC LULUCF guidelines, to calculate historical land cover transformations and regional flux. Multi-temporal land cover maps were matched and extracted via the Environmental Geographic Information Service (EGIS; <https://egis.me.go.kr/> (accessed on 20 July 2026)) based on major classifications (1:50,000; resolution 30 m), medium classifications (1:25,000; resolution 5 m), and detailed classifications (1:5000; resolution 1 m) for the baseline years 2000, 2013, and 2021. The total carbon absorption was computed based on the medium classification attributes, and GIS spatial information was cross-analyzed by mapping area per ha.

3. Results

3.1. Soil Organic Carbon Storage (SOCS) Profiles

The carbon accumulation in wetlands is supplied to the soil by fallen leaves and organic remains shed from the successional plant layers, along with the carbon absorbed by photosynthesis during the growth process of plants, which is distributed to the stems, branches, and roots. The fallen leaves and litter supplied to the “O” layer (organic layer) are decomposed by soil microorganisms and stored within the mineral soil profile. Conversely, the metabolic respiration of plants and soil heterotrophs releases CO_2 back into the boundary layer.

According to the LULUCF analytical profile, the true arithmetic mean OM of the six reference APWs measured across triplicate core cuts at a soil profile depth of 30 cm was 33.7 g/kg (S.D. 15.8), the mean SOC content was 19.54 g/kg (S.D. 9.17), and the mathematically corrected mean SOCS was $61.20 \pm 22.28 \text{ kg/m}^2$ (Table 1, Figure 2). This represents an exceptional storage capacity, vastly outperforming regional agricultural reference values (3.52 kg/m^2 , as reported in Refs. [43,44]; 3.54 kg/m^2 in the Jindo region, as reported in Ref. [45]). Furthermore, this verified mean is roughly 20 times higher than the average

terrestrial topsoil stock of South Korea (3.11 kg/m^2), from 21 to 39 times superior to urban park lawns (from 1.56 to 2.84 kg/m^2), and nearly 8.5 times higher than the volcanic ash forest soils of Jeju Island (7.19 kg/m^2), which are globally recognized for their low bulk density and high humic retention. APWs that maintain stable, unmanaged waterlogged cycles exhibit optimized carbon reduction performance (Table 2).

Table 2. Physical core properties and soil organic carbon storage (SOCS) across the six reference APWs ($d = 30 \text{ cm}$).

Division	Samples (D = 30 cm)	OM (g/kg)	Bulk Density (g/cm ³)	SOC (g/kg)	SOCS (kg/m ²) (D = 30 cm)
CNDJ03	S1	69.46	1.017	40.29	122.92
	S2	26.17	1.234	15.18	56.20
	S3	18.82	1.275	10.92	41.77
	Mean	38.15	1.175	22.13	73.63
	(S.D.)	(27.36)	(0.139)	(15.87)	(43.30)
CNSS04	S1	48.27	1.118	28.00	75.65
	S2	45.66	1.131	26.48	56.70
	S3	33.53	1.194	19.45	29.08
	Mean	42.49	1.148	24.64	53.81
	(S.D.)	(7.87)	(0.041)	(4.56)	(23.42)
CNSS08	S1	37.00	1.175	21.46	75.65
	S2	26.44	1.232	15.34	56.70
	S3	12.75	1.310	7.40	29.08
	Mean	25.40	1.239	14.73	53.81
	(S.D.)	(12.16)	(0.068)	(7.05)	(23.42)
CNBR02	S1	48.43	1.117	28.09	94.13
	S2	47.10	1.124	27.32	92.12
	S3	15.94	1.291	9.25	31.33
	Mean	37.16	1.177	21.55	74.03
	(S.D.)	(18.39)	(0.099)	(10.66)	(33.10)
CNYS08	S1	58.51	1.068	33.94	108.74
	S2	23.68	1.247	13.74	51.40
	S3	24.17	1.245	14.02	52.36
	Mean	35.45	1.187	20.57	70.84
	(S.D.)	(19.97)	(0.103)	(9.17)	(32.83)
DJMN01	S1	23.59	1.248	13.68	51.22
	S2	22.77	1.252	13.21	49.62
	S3	24.19	1.245	14.03	52.40
	Mean	23.52	1.248	13.64	51.08
	(S.D.)	(0.71)	(0.004)	(0.41)	(1.40)

The individual site calculations tracked the following exact trends (Table 1, Figure 2): The OM content of CNDJ03 was 38.15 g/kg , the bulk density was 1.18 g/cm^3 , the SOC content was 22.13 g/kg , and the final localized SOCS per unit area was 73.62 kg/m^2 . For CNSS04, the OM content reached 42.49 g/kg , bulk density was 1.15 g/cm^3 , SOC content was 24.64 g/kg , and individual SOCS mapped to 84.46 kg/m^2 . In CNSS08, the mean OM content was computed at 25.40 g/kg , bulk density was 1.24 g/cm^3 , SOC content was 14.73 g/kg , and the calculated SOCS was 53.82 kg/m^2 . For CNBR02, OM was 37.16 g/kg , bulk density was 1.18 g/cm^3 , SOC content was 21.55 g/kg , and total soil storage reached 74.02 kg/m^2 . In CNYS08, the mean OM was 35.45 g/kg , bulk density was 1.19 g/cm^3 , SOC content was 20.57 g/kg , and localized area storage logged at 70.83 kg/m^2 . Lastly, the newly

abandoned riparian site DJMN01 exhibited an OM content of 23.52 g/kg, bulk density of 1.25 g/cm³, SOC content of 13.64 g/kg, and a stable localized storage baseline of 51.08 kg/m² (Figure 2).

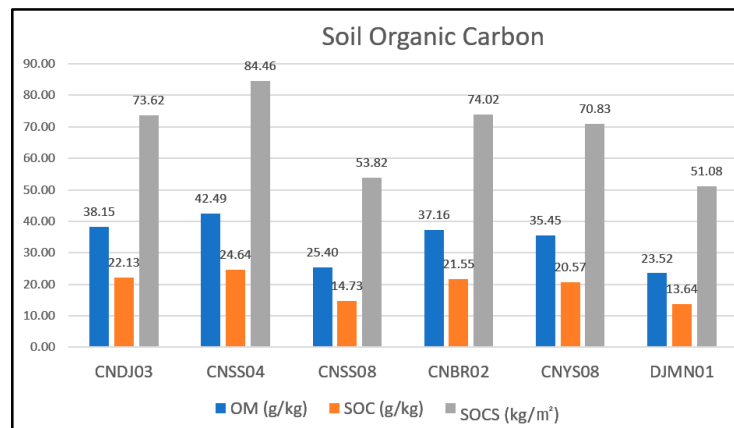


Figure 2. SOC of the six rice paddy fields (comparison of soil organic matter (OM, g/kg), soil organic carbon (SOC, g/kg), and soil organic carbon storage (SOCS, kg/m²; right axis) across the six studied APWs; the columns represent the mean values calculated from triplicate core samples taken at a 30 cm depth).

3.2. Wetland Vegetation Biomass Profiles

Carbon assimilated by successional plants is stored as structural biomass or supplied to the soil matrix as fallen leaves, dead wood, and litter fragments, eventually converting into non-decomposable organic fractions accumulated over decades. Plants are composed of approximately 50% carbon, 6% hydrogen, 44% oxygen, and trace amounts of various structural metal ions [46,47]. The organic carbon content of plant biomass is globally generalized to be 50% [48–52], although specific localized studies suggest that a conversion factor of 0.45 is more baseline-conservative [53]. In this case framework, a standard carbon conversion index of 0.50 was uniformly applied across dry weights.

Woody-dominant successional matrices were confirmed at CNBR02, CNYS08, and DJMN01. The drone-extracted average height of woody structures in CNBR02 was 14.66 m, the mean calculated DBH was 33.34 cm, the local individual canopy count was 8, and the standing carbon storage accounted for 10.26 tCO₂. In CNYS08, matching early successional conditions, the average height was similarly marked as 14.66 m, mean DBH was 33.34 cm, individual count was 8, and structural carbon storage was tracked at 10.26 tCO₂. Conversely, at site DJMN01, characterized by short-term high-density pioneer colonization, the average woody height was 10.74 m, mean DBH was 23.07 cm, individual count rose sharply to 30, and the localized biomass carbon storage reached 19.97 tCO₂.

The mixed woody–herbaceous ecotones were verified at CNDJ03 and CNSS08. Within CNDJ03, mean vegetative height was logged at 0.99 m, visual coverage was 29%, and total biomass storage was restricted to 0.1 tCO₂. In CNSS08, the mixed layout exhibited an average height of 1.90 m, canopy coverage of 19%, and carbon storage of 0.1 tCO₂. Site CNSS04 was entirely dominated by perennial herbaceous vegetation, yielding a mean plant height of 0.72 m, dense coverage rate of 35%, and total calculated biomass carbon equivalent of 0.2 tCO₂.

3.3. Carbon Absorption by Land Cover in the Ecological Impact Zone

The comprehensive land use transformations and multi-temporal carbon flux recorded within the 300 m ecological buffer surrounding each reference APW are organized in Table 3 and visualized in Figure 3. Across the six perimeters, agricultural and forest areas generally decreased, whereas grassland area increased. Net regional carbon absorption increased between 2000 and 2013, while the changes observed between 2013 and 2021 were smaller in the aggregate and varied among sites. Because the analysis only includes three observation years (2000, 2013, and 2021), these data describe differences among the sampled years, but do not demonstrate stabilization, equilibrium, or a plateau. The observed pattern may reflect changes in the land cover composition and age structure of the remaining forest stands.

Table 3. Decadal land cover area transitions (ha) and modeled carbon absorption (tCO₂) inside the 300 m perimeter.

APWs	Land Use	2000Yr.		2013Yr.		2021Yr.	
		Area (ha)	Carbon Absorption (tCO ₂)	Area (ha)	Carbon Absorption (tCO ₂)	Area (ha)	Carbon Absorption (tCO ₂)
CNDJ03	Forest	16.27	203.50	15.62	544.55	12.24	468.02
	Agriculture	9.80	291.95	8.64	274.91	4.90	154.66
	Grass	0.92	31.06	1.50	50.87	7.11	241.68
	Total	26.99	526.51	25.76	870.33	24.25	864.36
CNSS04	Forest	19.05	260.22	18.47	711.43	14.12	620.10
	Agriculture	16.92	537.20	17.13	489.45	14.98	442.99
	Grass	-	-	0.34	11.62	1.81	61.60
	Total	35.97	797.42	35.94	1212.5	30.91	1124.69
CNSS08	Forest	17.42	223.53	18.12	694.77	14.84	647.62
	Agriculture	9.87	238.39	12.97	313.53	9.90	239.60
	Grass	-	-	0.29	10.02	1.87	63.41
	Total	27.29	461.92	31.38	1018.32	26.61	950.63
CNBR02	Forest	16.18	219.48	13.30	595.58	10.0	511.22
	Agriculture	21.27	700.17	20.93	647.21	13.53	445.89
	Grass	-	-	2.07	70.42	11.22	381.63
	Total	37.45	919.65	36.30	1313.21	34.75	1338.74
CNYS08	Forest	26.56	409.36	24.26	980.30	18.56	899.21
	Agriculture	12.75	417.07	12.89	399.26	7.28	209.86
	Grass	-	-	0.76	25.87	10.15	344.94
	Total	39.31	826.43	37.91	1405.43	35.99	1454.01
DJMN01	Forest	26.05	331.00	24.29	1065.33	20.98	1043.77
	Agriculture	10.04	327.36	11.52	331.30	8.38	247.58
	Grass	-	-	0.81	27.59	6.47	219.82
	Total	36.09	658.36	36.62	1424.22	35.83	1511.17
Total		203.10	4190.29	203.91	7244.01	188.34	7243.60

In CNDJ03, forest and farmland areas fluctuated over the 20-year observation window, while grassland area increased markedly after 2013. Calculated carbon absorption increased from 526.51 tCO₂ in 2000 to 870.33 tCO₂ in 2013 and was 864.36 tCO₂ in 2021. For CNSS04, farmland area increased slightly in 2013 before decreasing by 2021, while grassland expanded to 1.81 ha. Calculated carbon absorption increased from 797.42 tCO₂ in 2000 to 1212.50 tCO₂ in 2013 and then decreased to 1124.69 tCO₂ in 2021.

At CNSS08, calculated carbon absorption increased from 461.92 tCO₂ in 2000 to 1018.32 tCO₂ in 2013 and was 950.63 tCO₂ in 2021. At CNBR02, broadleaf forest area

decreased across the observation years, whereas the area assigned to older, higher-biomass forest classes increased. Total calculated carbon absorption increased from 919.65 tCO₂ in 2000 to 1313.21 tCO₂ in 2013 and 1338.74 tCO₂ in 2021. At CNYS08, agricultural area contracted and grassland expanded to 10.15 ha; calculated carbon absorption increased from 826.43 tCO₂ in 2000 to 1405.43 tCO₂ in 2013 and 1454.01 tCO₂ in 2021. At DJMN01, forest area decreased slightly, whereas calculated carbon absorption increased from 658.36 tCO₂ in 2000 to 1424.22 tCO₂ in 2013 and 1511.17 tCO₂ in 2021. These values represent the observed differences among the three mapped years and do not define the trajectory between them.

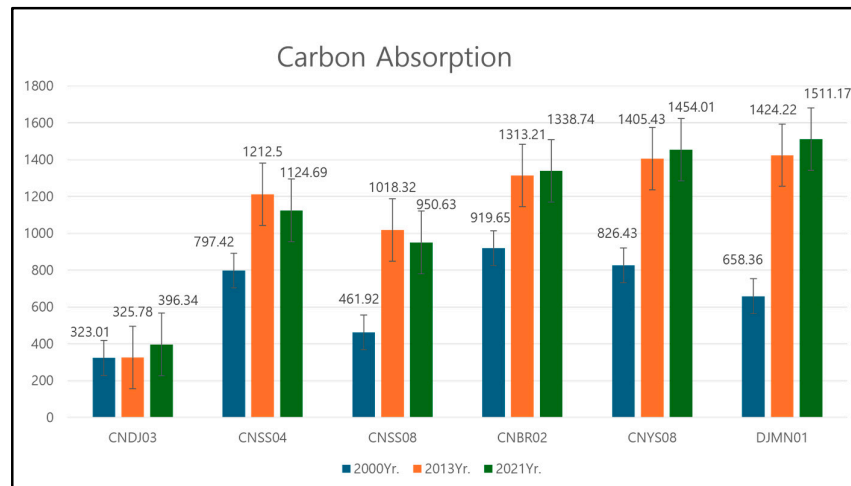


Figure 3. Changes in carbon absorption by land cover in ecological impact zone (decadal trends in total carbon absorption (tCO₂) by surrounding land cover within the 300 m ecological impact zone of each APW site from 2000 to 2021; error bars or data points are derived from IPCC LULUCF carbon absorption/emission coefficients applied to medium-classification land cover maps).

4. Discussion

4.1. Biogeochemical Interpretation of Elevated SOCS

Wetland soils provide core habitat structures and nutrient profiles for diverse micro- and macro-organisms, serving as primary terrestrial boundaries where fundamental biogeochemical cycles occur through sedimentation, heavy-metal adsorption, and anaerobic redox shifts (Eh) [3,54]. Wetlands retain immense ecological value, but when poorly preserved landscapes dry out or undergo sudden fires, they rapidly invert into major greenhouse gas emission sources. The Republic of Korea, historically anchored in rice agricultural culture, has experienced aggressive industrialization, pushing national urbanization past 90%. Consequently, large swaths of marginal agricultural terracing have been abandoned, naturally reverting into unmanaged APWs. If these sites lose their hydrological cycle due to terrestrialization, they become emission sources, making high-resolution carbon baseline tracking a priority.

The mathematically verified mean SOCS of 61.20 kg/m² across these sites sits at the upper threshold of global palustrine systems (10–50 kg/m²), driven by fine-grained alluvial clay matrices inherited from historical rice cultivation, which effectively protect organic fractions from microbial contact [24,44]. In similar agricultural heritage systems across China, the carbon stabilization performance of RPWs and emerging APWs systematically scales upwards over time post-fallowing [24,27].

Water levels and eco-hydrological parameters directly govern dissolved organic carbon (DOC) pathways. According to Seo et al. [55], DOC concentrations are significantly

optimized within well-vegetated patches where water depths remain continuous, preventing macro-oxygenation. Plant root exudates combined with restricted anaerobic decomposition rates generate diverse complex DOC humic polymers [56], which function as critical baseline substrates for secondary microbial processing, including specialized denitrification pathways within wetland sediments [57].

Process-based and Earth system models show that soil carbon projections depend strongly on how decomposition, environmental controls, and soil–vegetation interactions are represented [58]. The field measurements from the present APWs may provide empirical constraints for evaluating and complementing such broader-scale models, particularly for the transition from cultivated paddies to unmanaged wetlands. Inundation can favor OM accumulation by restricting oxygen availability and slowing decomposition [26,55,56], but the magnitude and timing of this response may differ among regions because of variations in hydroperiod, soil texture and mineralogy, temperature, vegetation composition, and previous land use history. Accordingly, the present results should be interpreted as region-specific field observations rather than universal model parameters.

4.2. Resolving the Biomass-Soil Carbon Mismatch and Ecosystem Successional Stage

Vegetation constitutes a fundamental structural pillar of wetland systems alongside continuous hydrologic inputs and mineral soil baselines [59–61]. Successional plants accelerate localized atmospheric mitigation via carbon sequestration, storing organic fractions within long-term woody timber and structural roots. For example, empirical forestry tracks that 1997 mature trees can lock up to 139.90 tons of carbon per year [62], a parameter directly tied to increasing aboveground biomass volume and continuous vegetative life cycles [63,64]. Beyond simple volume variations, specific successional species shifts determine total thermodynamic carbon sequestration capacity [65]. Because young APWs are frequently dominated by perennial hydrophilic herbs and pioneer shrubs before mature trees emerge, capturing both layers is vital to avoid systematic accounting errors.

The substantial difference observed between the belowground soil carbon pool (61.20 kg/m^2) and the low herbaceous aboveground carbon stocks (0.1 to 0.2 tCO_2) may reflect both the early successional stage of APWs and the methodological uncertainties related to soil sampling, modeled bulk density, biomass estimation, and limited spatial replication. The soil matrix may retain carbon inherited from previous agricultural management, whereas the aboveground woody layer is still developing after abandonment. However, the relative contributions of ecological succession and methodological uncertainty cannot be separated with the present study design, and the magnitude of the difference should therefore be interpreted cautiously.

As successional overgrowth advances toward mature woody communities, aboveground storage scales up dramatically, as confirmed at sites CNBR02 and CNYS08, where willow canopies locked up to 10.26 tCO_2 . Local environmental parameters, including regional flora composition, micro-climate fluctuations, seasonal temperature curves, and precipitation regimes, strictly dictate these biomass pathways [66]. Highly protected wetlands, such as the Ungok Wetland Protection Area, which stores over 155.80 tonC , demonstrate that legal and institutional preservation frameworks are critical to allow for young APWs to complete their successional transitions into long-term carbon sinks.

4.3. Landscape-Level Drivers of Buffer Zone Carbon Flux and Uncertainties

The apparent logical contradiction within the 300 m ecological buffer zone—where total horizontal forest boundaries contracted due to minor agricultural tilling patches, yet calculated net carbon absorption systematically increased—is explained by the growth in surviving forest units. Entering specific regional Tier 2 coefficients from the National Forest Inventory confirmed that remaining perimeter forest stands transitioned from young,

sparse age classes in 2000 to highly stocked, dense mature biomass classes by 2021. This structural biomass expands more than offset minor boundary footprint losses.

To ensure high scientific rigor, the potential compounding errors across all three accounting layers must be addressed.

Spatial Sampling Limitation: The three sampling points per APW support only a preliminary estimate of within-site variability and are insufficient for a statistically robust assessment of micro-heterogeneity. Future studies should use denser replicated or stratified sampling across hydrological and vegetation gradients to quantify small-scale spatial variability.

Bulk Density Modeling Variance: Applying an organic matter-dependent bulk density model ($\rho_b = 1.3863 \times e^{-0.0446 \times OM}$) carries an inherent estimation error bound of $\pm 6.4\%$. However, this non-destructive method avoids the structural core compaction artifacts common when physical cylinders hammer through highly fluid, water-saturated wetland soils.

LiDAR Delineation Limits: Drone-derived tree height extraction via the Local Maxima algorithm carries a systematic error window of $\pm 12.1\%$ due to canopy blending within dense willow clusters. This explains why site DJMN01 recorded the lowest soil stock (51.08 kg/m^2) despite hosting 30 trees. Abandoned for only ~ 5 years, its dense pioneer canopies have not had the structural time required to contribute heavy organic root fractions to the underlying soil matrix.

IPCC Spatial Generalizations: Applying medium-classification LULUCF boundaries over a 300 m radius overlooks micro-topographical terrain variations. However, substituting generic global default values with localized national Tier 2 coefficients successfully restricted landscape calculation errors to within $\pm 8.5\%$, proving that APW protection provides predictable regional carbon capture benefits.

5. Conclusions

RPWs, whose primary agricultural production has been interrupted due to natural or anthropogenic causes, convert to APWs through natural successional transition processes, transforming into crucial long-term carbon sinks. APWs represent vital ecological and cultural heritages that deliver complex ecosystem services directly to local populations, yet they are being destroyed at a rapid rate due to unmanaged terrestrialization and development, turning them into carbon emission sources. Well-preserved, unmanaged waterlogged systems are essential as natural carbon reservoirs and play an indispensable role in the carbon cycle of terrestrial ecosystems.

This study verified that the institutional preservation and ecological management of APWs provides a powerful, low-cost nature-based solution (NbS) to offset rising atmospheric CO_2 . The validated mean SOCS of 61.20 kg/m^2 within the top 30 cm soil profile significantly outpaces conventional domestic farmlands, urban green spaces, and typical upland forest soils. Furthermore, structural carbon pools scale up significantly as successional age increases and woody plants establish structural dominance.

As the fallow age of an APW scales upwards, the progressive coarsening of topsoil layers, the compounding of organic matter fractions, and the accumulation of essential minerals becomes highly pronounced, enhancing local biodiversity and functioning as natural purification systems for non-point pollution sources. Therefore, establishing legal wetland protection statuses and local hydrologic buffers around APWs can effectively arrest reckless landscape development, improve national green infrastructure, and maximize regional climate resilience.

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