

Article

Land Use Alters the Plant-Derived Carbon and Nitrogen Pools in Terraced Rice Paddies in a Mountain Village

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Abstract: In Japan, terraced paddies in mountain villages are symbolic of the traditional landscape, but they are gradually being abandoned. To compare plant-derived C and N among land uses, we compared adjacent forest floor (FF), agricultural paddy (AP), and post-agricultural paddy (PP) sites. Long-term litter accumulation could explain the significantly higher litter C and belowground biomass C in FF than in AP and PP. The low-density-fraction (LF) soil C was significantly higher in FF than in PP and better reflected land use than the whole-soil C. The AP soil held more N than FF and PP at 20–30 cm, associated with higher LF soil N. Periodic tillage in AP maintains the LF soil N, but N supplied to the surface soil reduced with depth following abandonment. Differences in recycling of organic matter and nutrients among land uses are crucial to plant-derived C and N contents of soil.

Keywords: land use; paddy; soil carbon; agricultural abandonment

1. Introduction

The production of rice (*Oryza sativa* L.) is a major agricultural land use in the temperate regions of East Asia. In mountain villages, terraced paddies are symbolic of the traditional landscape, along with forests. The landscapes formed of terraced paddies and their surroundings (such as levees and adjacent secondary forests) harbor high biodiversity maintained by conventional agricultural practices [1–3]. However, most paddies in mountain villages have gradually been abandoned or fallowed because of a rapid decrease in the farming population [4].

In northern Japan, rice is grown with continuous flooding during spring and summer and drainage before harvest in autumn [5]. The crop residues are later turned into the soil. Paddy field abandonment ends flooding and soil turning. The change from submerged to drained conditions may hasten the decomposition of crop residues, but also enhance carbon (C) sequestration, because the fast development of root systems incorporates C rapidly into the soil [6]. Thus, the balance between conditions that determine organic matter (OM) build up and decomposability are crucial to C and nitrogen (N) dynamics after abandonment. The low-density fraction (LF) of soil is composed mainly of partially decomposed plant fragments that are not associated with mineral particles [7]. In general, litter is transported into the soil via the LF [8]. The study of dominant plant species can help to explain the transport of plant-derived OM into soil [9]. However, little information is available on the differences in plant-derived C and N among different land uses.

Terraced paddies abut forests and grasslands, and Japanese cedar (*Cryptomeria japonica*) plantations are common in our study area. Their dense canopy blocks sunlight, and only sunflecks reach the forest floor to support limited species. The shift to grassland following paddy abandonment

provides an opportunity to investigate the soil response to aeration and the shift of plant cover. As well as providing food security, paddies maintain soil and water resources, preserve biodiversity, and ensure the viability of rural communities [10]. Long-term fallowing and abandonment of paddies reduces these services.

The aim of this study was to investigate the effects of land use on plant-derived C and N pools. Land use influences above- and belowground C availability by determining the quantity and quality of leaf litter that is incorporated into the soil. To understand plant nutrient use and litter C and N accumulation, we compared mineral and labile soil C and N among forest floor (FF), post-agricultural paddy (PP), and agricultural paddy (AP) sites.

2. Materials and Methods

2.1. Site Description

The study site was located in a village in Tokamachi city, southeastern Niigata Prefecture, Japan (37°03' N, 138°37' E) (Figure 1). Most of the terraced paddies cover slopes formed by ancient landslides on unconsolidated tertiary sediments [10]. The fields are composed of gray upland Gleysol with a fine texture. The local people believe that the terraces were established about 500 years ago. The maximum snow depth in winter exceeds 2 m.

We focused on the differences in C and N stocks among three land uses: FF, AP, and PP ($n = 4$). Previous study suggested that soil organic matter was linked with fields situated at the lower slope positions of a terrace sequence [11,12]. Experimental plots matched for elevation were established at 441, 431, 427, and 420 m of sea levels in A–D (Figure 1) to avoid imbalance of soil fertility among land uses. Aerial photographs (<http://mapps.gsi.go.jp/maplibSearch.do#1>) show that the area of abandoned fields has increased markedly in the last 20 years in this region. FF is dominated by *Cryptomeria japonica* forest, and PP by perennial grasses such as *Miscanthus sinensis*, both typical of such regions in Japan. The survey point in FF was set on the forest floor. Rice cv. Koshihikari is generally grown in AP sites. To reveal differences in plant-derived C and N and the effects of land use on plants composition and soil, we selected flat sites to avoid the influence of soil erosion and the heterogeneity of soil properties.

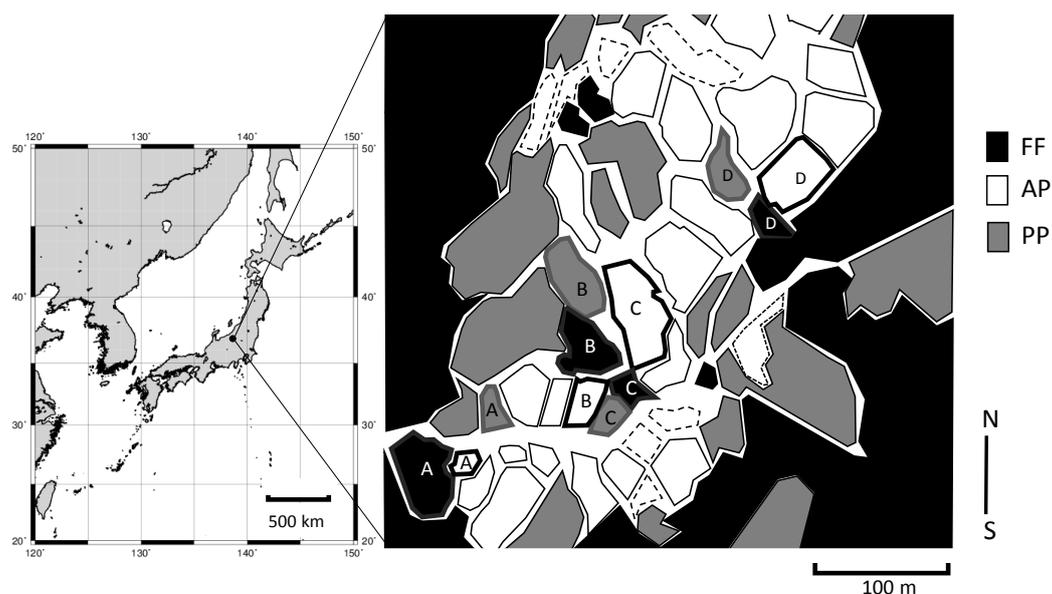


Figure 1. Layout of the study fields. Fields with the same letter (A–D) have the same elevation. Dashed lines indicate upland crop fields. FF, forest floor; AP, agricultural paddy; PP, post-agricultural paddy.

2.2. Estimation of Soil and Plant C and N

Samples were obtained from the study site in October 2014. Soil and BG biomass samples in three replicate were collected at depths of 0–5, 5–10, 10–15, 15–20, and 20–30 cm with a 40-mm-diameter linear soil auger (04.04.00.40.C and 0.1.10.11.C; Eijkelkamp Co., Giesbeek, The Netherlands). The conventional tillage depth in the region is 15 cm [5], and Japanese paddy soils have an effective plow layer for soil C of 30 cm [13]. Processes of C and N estimation is shown in a schematic diagram (Figure 2). Air-dried samples were passed through a 2.0-mm sieve to remove stones and to pick up roots and weighed to estimate the BG biomass, since fine roots of less than 2 mm diameter often cannot be distinguished empirically from soil organic matter or litter [14]. The low-density fraction (LF) of OM is normally occluded by soil mineral particles and aggregates [7]. To extract it, we placed each air-dried sample in a centrifuge tube with 25 mL of sodium polytungstate solution (1.60 g cm^{-3}), mixed it on a shaker table at 150 rpm for 120 min, and centrifuged it at 3500 rpm for 30 min, and drew it out of the floating LF after oven-dry [15].

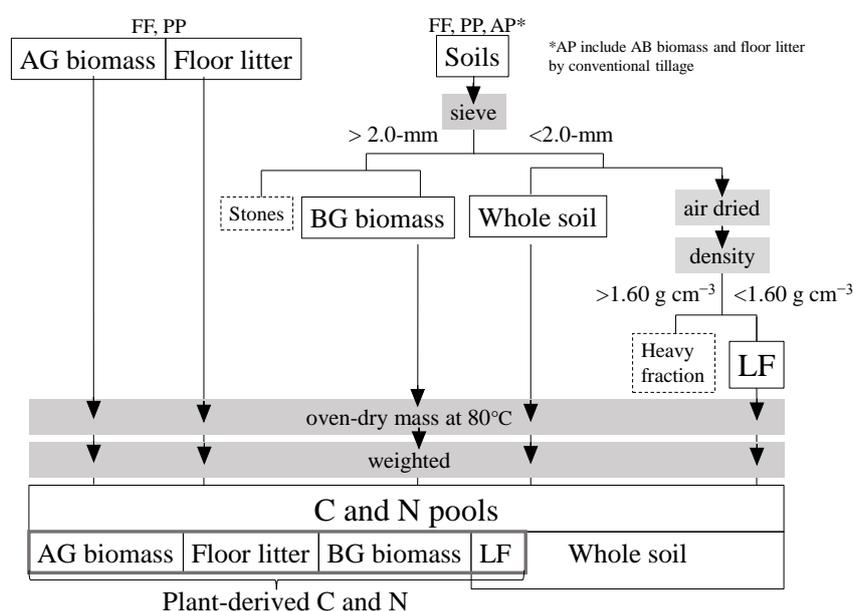


Figure 2. Schematic diagram of C and N estimation.

We harvested the aboveground (AG) biomass in three quadrats ($0.5 \times 0.5 \text{ m}$) per plot and collected litter from the soil surface in three quadrats ($0.3 \times 0.3 \text{ m}$) per plot in FF and PP in October 2014 to estimate the AG and BG biomass production from the peak value of biomass. Standing dead vegetation was removed by clipping at ground level by hand, and the dominant vegetation type of the abandoned fields was decided from the dry weight of each species [16]. We did not estimate woody part of AG and BG biomasses in FF.

The C and N contents of floor litter, AG biomass, and BG biomass were estimated from their concentrations and the mass per area (kg m^{-2}). Samples were oven-dried at $80 \text{ }^\circ\text{C}$ for at least 48 h and ground into a fine powder. Samples were weighed ($\sim 100 \text{ mg}$ of soil and $\sim 10 \text{ mg}$ of plant matter), and C and N concentrations were determined by the dry combustion method using an NC analyzer (Sumigraph NC-22; Sumika Chemical Analysis Services Ltd., Tokyo, Japan). The soil C concentration (g C kg^{-1}) was multiplied by the corresponding equivalent soil mass to obtain the C pool (kg m^{-2}) at each sampling depth, and the C pools were summed to calculate the total C pool. The use of equivalent soil mass can avoid errors associated with compaction or expansion of the soil. To account for changes in bulk density and compaction, C contents are reported on a volumetric basis. Carbon pools (kg m^{-2}) in each soil layer were calculated by the minimum equivalent soil mass approach instead of the simple

bulk density method [17]. The LF dry mass was expressed as a percentage of the total soil mass. The C and N concentrations of LF were multiplied by the corresponding equivalent soil mass to obtain soil LF-C and LF-N (kg m^{-2}). We similarly calculated BG biomass from the BG biomass density at each sampling depth.

2.3. Statistical Analysis

All statistical analyses were performed in R v. 3.2.5 software (R Foundation for Statistical Computing, Vienna, Austria). One-way analysis of variance (ANOVA) in conjunction with Dunnett's test was performed to identify differences in plant and soil traits among land uses in R with the 'multcomp' package. The Shapiro–Wilks and Bartlett's tests were used to test normality and homogeneity of variance.

3. Results

3.1. Plant Species Composition and Biomass

Dominant species in the AG biomass were *Cayratia japonica*, *Houttuynia cordata*, *Miscanthus sinensis*, and *Sasa nipponica* in FF; and *Artemisia indica*, *Cayratia japonica*, and *Miscanthus sinensis* in PP (Appendix A). *Cayratia japonica* dominated in both FF and PP, and was the only dominant species that depended on position. By AG biomass, 61% of plant matter in FF had N concentration of 2.0% to 2.5% (Figure 3a). By number of species, the N concentration was independent of land use; 45% and 41% of species had an N concentration of 1.5% to 2.0% in both FF and PP (Figure 3b).

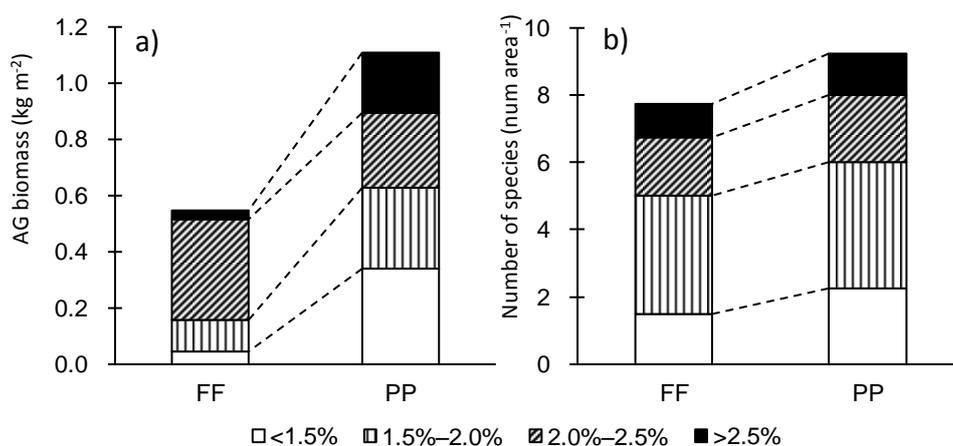


Figure 3. Distribution of plant N on (a) AG biomass basis and (b) species number basis at forest floor (FF) and post-agricultural paddy (PP) sites.

3.2. Soil C, N, and Belowground Biomass at Each Soil Depth

Soil C did not differ significantly with land use at any depth (Figure 4a). Soil N did not differ significantly with land use at 0–20 cm, but it was significantly higher in AP than in FF and PP at 20–30 cm (Figure 4b). The vertical distributions of C and N in the LF did not parallel the changes in the whole soil in any land use (Figure 4c,d). LF soil C and N gradually decreased with soil depth in FF and PP, but gradually increased in AP. LF soil C was significantly higher in FF than in AP and PP at 0–5 cm, but LF soil C and N were significantly higher in AP than in PP at 20–30 cm. Belowground biomass C and N in FF were more than double those ($P < 0.05$) in AP and PP at 0–5 cm (Figure 4e,f).

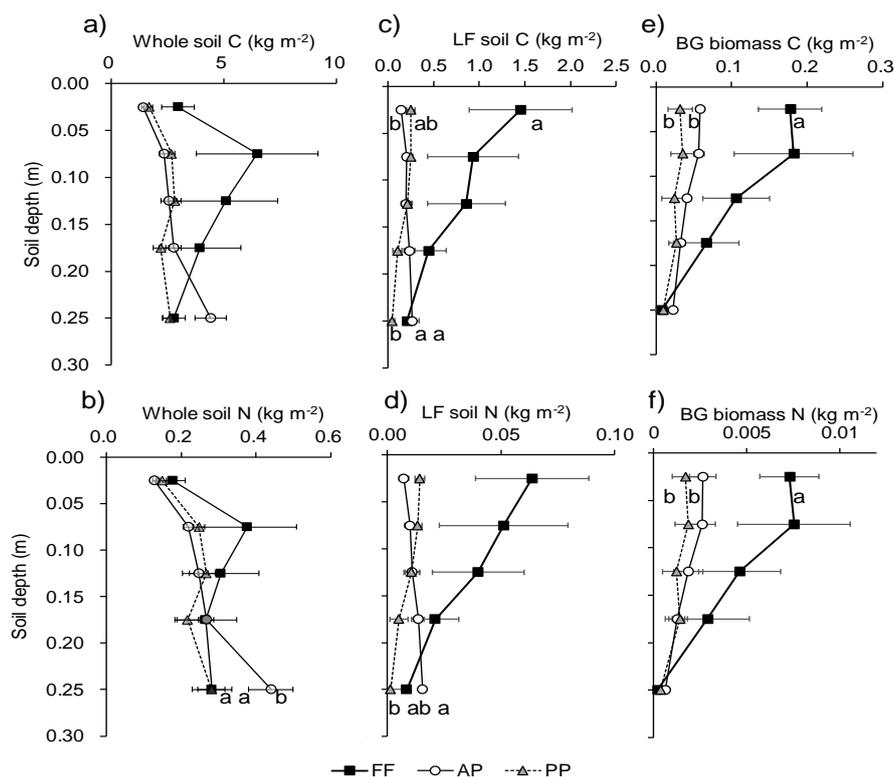


Figure 4. Differences in (a,b) whole-soil C and N, (c,d) soil LF C and N, and (e,f) BG biomass C and N among land uses by depth. Points with the same letter at the same depth are not significantly different ($P < 0.05$). FF, forest floor; AP, agricultural paddy; PP, post-agricultural paddy.

3.3. Total C and N

The amount of floor litter C in FF was $3.6 \times$ that in PP (Table 1, $P < 0.05$), but the amount of floor litter N was not significantly different. Although AG biomass was independent of land use, BG biomass C was significantly higher in FF than in AP and PP ($P < 0.05$). Since the results of whole-soil C and N varied widely, no significant differences between land uses could be detected. The LF soil C was significantly higher in FF than in PP at 0–30 cm ($P < 0.05$) and better reflected the difference in land use than the whole soil C. The composition of N at 0–30 cm showed no significant difference among land uses.

The N content was associated with C in floor litter, AG biomass, and BG biomass (Appendix B). The ratio of N to C in floor litter was marginally higher in FF ($34.0\% \pm 4.8\%$) than in PP ($24.9\% \pm 1.1\%$; $P = 0.061$) (data not shown). The association of C with N in the whole soil did not parallel that in LF among land uses (Figure 5): in the whole soil, the ratio of N to C was especially high in AP.

Table 1. Carbon (C) and nitrogen (N) contents of litter, AG biomass, BG biomass, whole soil, and low-density fraction (LF) by land use (mean \pm standard error of the mean, $n = 4$).

	Floor Litter		AG Biomass		BG Biomass		Whole Soil		Soil LF						
C															
FF	0.36	a	± 0.09	0.25	a	± 0.09	0.54	a	± 0.15	21.3	a	± 7.59	3.90	a	± 1.63
AP	–	–	–	–	–	–	0.13	b	± 0.01	13.5	a	± 1.59	1.05	ab	± 0.19
PP	0.10	b	± 0.06	0.50	a	± 0.06	0.21	b	± 0.06	12.0	a	± 1.20	0.86	b	± 0.14
N															
FF	0.011	a	± 0.005	0.012	a	± 0.005	0.023	a	± 0.008	1.0	a	± 0.16	0.18	a	± 0.08
AP	–	–	–	–	–	–	0.007	a	± 0.001	1.7	a	± 0.19	0.06	a	± 0.01
PP	0.004	a	± 0.004	0.022	a	± 0.004	0.009	a	± 0.003	1.2	a	± 0.11	0.04	a	± 0.01

Note: Values followed by the same letter within a column and element are not significantly different ($P < 0.05$).

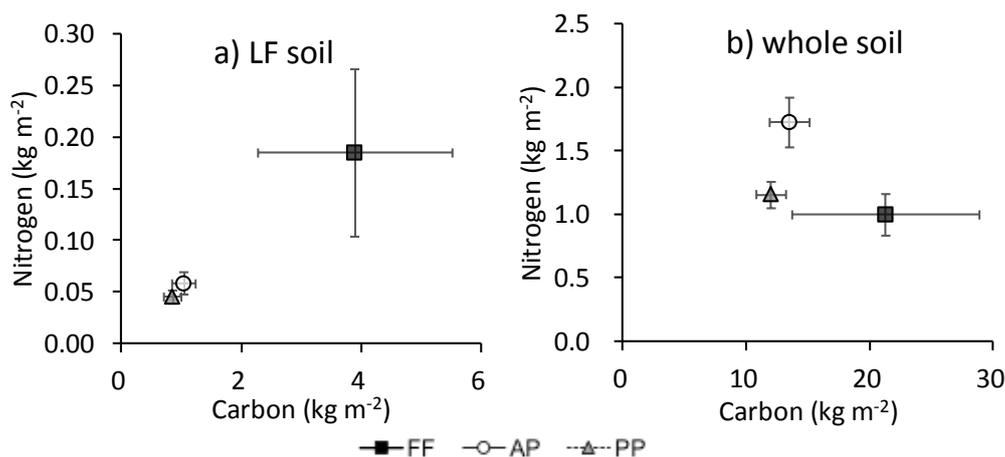


Figure 5. Relationship between C and N contents (kg m^{-2}) in (a) LF and (b) whole soil. Bars show standard error of the mean ($n = 4$).

4. Discussion

4.1. Plant-Derived C and N in Forest Floor Litter and Abandoned Paddies

AG biomass and litterfall in forests are major sources of C transfer into the soil through decomposition. Significantly higher floor litter C in FF than in PP indicates slower decomposition and/or faster accumulation in FF (Table 1). In a mature *Cryptomeria japonica* forest, annual litterfall C was 0.27 kg m^{-2} [18]. Therefore, litter production C as the sum of this plus AG biomass C from grasses is about 0.8 kg m^{-2} , indicating that the total litter production in PP was more than that in FF. Although previous study showed elevated N availability in PP support litter decomposition [19], Figure 3b and Table 1 both showed low N availability in PP in our study. Long-term accumulation could contribute to the significantly higher floor litter C and BG biomass C in FF than in PP (Table 1).

LF soil C better reflects the recycling of plant-derived OM than whole-soil C and N [7,15]. Whole-soil C did not differ among land uses despite the differences in the LF soil C (Table 1) because of its large variations in FF at 0–20 cm (Figure 4). A previous study suggested that LF soil C was more sensitive to land use or environmental change than the heavy-fraction soil C [20]. During long-term abandonment, OM inputs and root activity increase AG + BG biomass, enhancing the formation of soil aggregates and the accumulation of soil C [9,21]. Significantly higher LF soil C and N in some soil layers in FF in our study suggest long-term OM accumulation. AG biomass was higher in PP than in FF (Figure 3a), but the LF soil C input was less in PP than in FF at 0–5 cm (Figure 4b). The C in litter may be slow to move into the mineral soil in the early stages following abandonment [15]. A steady state following the conversion from cropland to grassland may be reached after more than 150 years [22]. Although our results show that abandonment did not increase the C and N pools (Table 1), the ecosystem will not reach a steady state quickly. Previous studies have indicated that soil C accumulation after paddy abandonment increases at poorly drained low land sites [23,24] and decreases at well-drained mountainous sites [25,26]. Abandoned upper terraced paddies are exposed to the atmosphere, while the lower slope position usually maintains high groundwater levels [27]. The gentle C increase after land use was caused by our mountainous fields at the upper part of terraced paddies, supporting the previous studies [25,26].

4.2. Crop-Derived C and N

Through the regional OM cycle, terraced rice paddies are likely to help sustain soil stability. Our results show that abandonment reduced LF soil C and N at 20–30 cm. Whole-soil N at 20–30 cm was highest in AP, in agreement with the higher LF soil N at 20–30 cm than in FF and PP (Figure 4b,d). The lower soil N in PP indicates that plant-derived N cannot compensate for the soil N reduction at

20–30 cm after abandonment. This may be a consequence of the length of time it takes for C and N to move down through the soil profile; not enough time has passed since abandonment to see a clear result in PP. In fertilized paddies, crop residues may stimulate nutrient cycling and lead to a positive feedback of C and N in the paddy ecosystems. Although annual crop residue application can move N into the soil, abandonment cannot increase soil N at 20–30 cm. Plant-derived N may not be enough to increase the soil N pool [15]. Furthermore, the decrease in the whole-soil N over time could be attributed to the exposure of easily oxidizable N in soil following abandonment [28]. Environmental changes from submerged to un-submerged conditions can lead to drastic decreases in whole-soil and LF N.

Our results indicate that the LF of soil can show some differences in plant-derived C among land uses. Further research on the availability of other nutrients is still needed, and more complex ecological questions require continued development of our understanding of C and N recycling from different sources in forests, active paddies, and abandoned paddies. It is well known that the soil C pool plays an important role in determining soil chemical properties—including pH, nutrient availability, and nutrient cycling—and buffers against sudden fluctuations. From the viewpoint of sustainable management of soil C and N, it is necessary to review the functions of terraced rice paddies during land use change.

4.3. Possible Effect of Agricultural Abandonment on Nutrient Cycling

In temperate agricultural landscapes in Japan, some perennial grasses (e.g., *Phragmites australis*, *Miscanthus sinensis*, *Miscanthus sacchariflorus*) come to dominate within about five years after abandonment of paddy fields [29]. In our study area, giant perennial *Miscanthus sinensis* dominated in PP (Appendix A). In temperate East Asia, giant perennial *Miscanthus* grasses can achieve high yields with low inputs of N [10,30]. An increase in leaf area has less effect in increasing the productivity of *Miscanthus* than of other grasses [31]. Although a low rate of N cycling is associated with low biomass productivity in abandoned agroecosystems [32], *Miscanthus sinensis* might be able to compensate for the N reduction. This might be one reason for the lack of significant differences in soil N between AP and PP (Table 1), especially in the surface layer. Litter C and N inputs are strongly associated with plant growth traits to maximize resource gain or to conserve nutrients [33]. Because successional stages differ depending on climatic and local environmental conditions such as soil water content, light, or adjacent land use [34], further research is needed for clarifying the potential effects of abandonment on ecosystem nutrient cycling for sustainable use of paddy fields.

5. Conclusions

This study investigated the effects of land use on plant-derived C and N pools in terraced rice paddies. To compare plant-derived C and N among land uses, we compared adjacent forest floor, agricultural paddy, and post-agricultural paddy sites in a mountain village in Japan.

Floor litter C in forest floor was 3.6× that in post-paddy. Furthermore, significantly higher LF soil C and N in some soil layers in forest floor suggested long-term organic matter accumulation. Agricultural abandonment did not increase the C and N pools, the ecosystem will not reach a steady state quickly in the last 20 years in our study. The gentle increase after the abandonment of terraced paddies is caused by the geographic character in mountainous, supporting the previous studies. Lowland paddies may show the different proceeding in increasing C after the abandonment.

LF soil C and N gradually decreased with soil depth in forest floor and post-paddy, but gradually increased in agricultural paddy. Terraced agricultural paddies are likely to help sustain soil C and N stabilities in a mountain village.

In post-paddy, plant-derived N cannot compensate for the soil N reduction associated with low biomass productivity. However, successional vegetation might be possible to compensate for the N reduction. Further research is needed to elucidate potential effects of abandonment on ecosystem nutrient cycling in consideration of various patterns of vegetation succession.

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Author Contributions: Seiji Shimoda designed the study, and contributed to analysis and interpretation of data, and wrote the initial draft of the manuscript. Tomoyo F. Koyanagi contributed to interpretation of data, and critically reviewed the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

AG	aboveground
AP	agricultural paddy field
BG	belowground
C	carbon
FF	forest floor
LF	low-density fraction
N	nitrogen
OM	organic matter
PP	post-agricultural paddy field

Appendix A

Table A1. Plant species at forest floor (FF) and post-agricultural paddy (PP) sites.

		Area	A	B	C	D	A	B	C	D
		Land Use	FF	FF	FF	FF	PP	PP	PP	PP
Life	Family	Species								
Annuals	Asteraceae	<i>Bidens frondosa</i>					100		42	
Annuals	Balsaminaceae	<i>Impatiens noli-tangere</i>	77							
Annuals	Commelinaceae	<i>Commelina communis</i>					4			
Annuals	Fabaceae	<i>Amphicarpaea bracteata</i> subsp. <i>edgeworthii</i>	42	12	5		7			
Annuals	Fabaceae	<i>Desmodium paniculatum</i>	10							
Annuals	Fabaceae	<i>Vigna angularis</i> var. <i>nipponensis</i>		31			85			
Annuals	Poaceae	<i>Digitaria ciliaris</i>				17	7			
Annuals	Poaceae	<i>Oplismenus undulatifolius</i>				15				
Annuals	Polygonaceae	<i>Persicaria longiseta</i>					3			
Annuals	Polygonaceae	<i>Polygonum thunbergii</i>		12			58	506	4	266
Perennials	Apiaceae	<i>Hydrocotyle ramiflora</i>				2			3	
Perennials	Apiaceae	<i>Oenanthe javanica</i>					1			
Perennials	Asteraceae	<i>Artemisia indica</i>					89		20	544
Perennials	Asteraceae	<i>Petasites japonicus</i>					86			2
Perennials	Houttuynia	<i>Houttuynia cordata</i>		97			110	2		17
Perennials	Fabaceae	<i>Pueraria lobata</i>								
Perennials	Onagraceae	<i>Oenothera odorata</i>				1				1
Perennials	Plantaginaceae	<i>Plantago asiatica</i>				1				
Perennials	Poaceae	<i>Eragrostis ferruginea</i>					11			5
Perennials	Poaceae	<i>Miscanthus sinensis</i>	8	35	268	34	325	713		
Perennials	Poaceae	<i>Sasa nipponica</i>	734			4				
Perennials	Polygonaceae	<i>Reynoutria japonica</i>	44	6						
Perennials	Equisetaceae	<i>Equisetum arvense</i>					18			
Perennials	Thelypteridaceae	<i>Thelypteris palustris</i>	17	9	213				286	
Perennials	Vitaceae	<i>Cayratia japonica</i>	2	37	649	24		325	482	29
Perennials	Vitaceae	<i>Vitis ficifolia</i> var. <i>lobata</i>					42			

Black: dominant species in biomass; gray: species present.

Appendix B

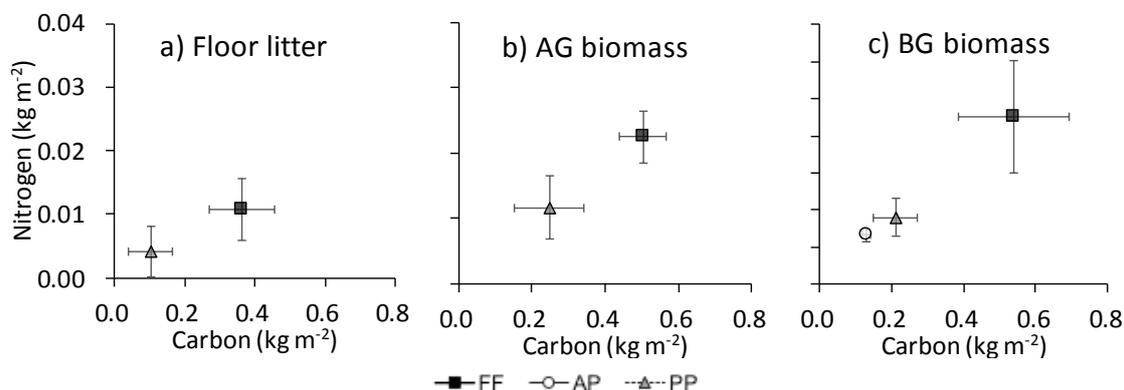


Figure A1. Relationship between C and N contents (kg m^{-2}) in (a) floor litter, (b) AG biomass, and (c) BG biomass. Bars show SEM ($n = 4$).

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