Improvements in Soil C and N Compositions After 40 and 80 Years of Reforestation in Subtropical Low Mountain Forests

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Abstract Reforestation is an important step toward recovering soil quality and wildlife habitats that are degraded due to deforestation. However, little is known about how soil C and N compositions in subtropical forests evolve after decades of reforestation. This study comprehensively evaluated the differences in soil C and N fractions in 40- and 80-year-old secondary (reforested) coniferous forests and a natural broadleaf forest. Although reforestation with coniferous plants appeared to increase soil organic matter and labile C levels, the ratio of soil labile C to total organic C was lower in the reforested coniferous forests than the natural broadleaf one. The trend in the labile N to total N ratio as coniferous reforestation progresses follows that of C. Furthermore, the percentage of recalcitrant C as total soil organic C was higher in the reforested coniferous forests than the natural broadleaf one. This feature of C composition in reforested coniferous forest causes environmental stress to microbes (as indicated by a high metabolic quotient) in the forest, even several decades after reforestation of a former broadleaf forest site. Results from this study demonstrate that it takes a very long time for reforestation with coniferous vegetation to restore the soil chemical properties of the previous natural forest.

1. Introduction

The forest ecosystem covers 31% of global land area (FAO, 2011) and provides habitats and valuable ecosystem services such as carbon (C) sequestration (Humpenöder et al., 2014). However, deforestation and land use changes have reduced the global forest cover (Flynn et al., 2009; Hurtt et al., 2006), biomass production, and soil and water qualities (Lal, 2004) over the last few decades. Reforestation has become an important way to recover soil quality and wildlife habitats that have degraded due to the adverse impacts of deforestation (FAO, 2010; Richter et al., 1999).

Soil biochemical and chemical properties respond to reforestation, though it may take a long time for them to return to natural conditions (Chodak & Niklińska, 2010). For example, it was shown that soil C and N contents in a karst region increased and environmental stress to soil microorganisms (i.e., metabolic quotient, qCO2) decreased as reforestation progressed (Hu et al., 2016). These improvements in soil properties can be related to the type of tree used for reforestation (Mo et al., 2016). The tree type in a plantation also affects soil conditions such as microbial community (Ushio et al., 2008), soil nutrients, and mycorrhizal fungi community (Holste & Kobe, 2016). Oulehle et al. (2007) found lower soil pH in coniferous than broadleaf forests because of their different litter qualities.

Disturbances from human activity during forest conversion could increase soil bacterial diversity more in a reforested coniferous plantation than a natural broadleaf forest (Lin et al., 2011). In addition, Chang et al. (2016) showed that total fungal content, fungi to bacteria ratio, and Gram-positive to Gram-negative bacteria ratio were higher in a reforested coniferous plantation than a nearby natural broadleaf forest soil, and they attributed this to the quality of the soil organic matter (SOM). These changes in soil microbial communities could be linked to changes in soil physicochemical properties and the litter quality of plants (Arunachalam et al., 1996; Chang et al., 2016; Singh et al., 2000). Indeed, several studies have shown degraded soil C and N contents after reforestation. Lu et al. (2014) found that soil total organic carbon
Table 1: Coniferous and Broadleaf Forests in the Study Area

| Site         | Age (Year) | Plants                                                                 | Litter mass (g m⁻²) | Litter C (%) | Litter N (%) |
|--------------|------------|------------------------------------------------------------------------|----------------------|--------------|--------------|
| BROAD-Nat    | >200       | Cryptocarya chinensis (Hance) Hemsl., Litsea acuminatae (Blume) Kurata, Prunus phaeosticta (Hance) Maxim., and Lithocarpus amygaldifolius (Skan) Hayata | 727 ± 311 a          | 41.2 ± 4.3 a | 1.39 ± 0.12 a |
| CONIF-80     | 80s        | Calocedrus formosana (Florin) Florin, Randia cochininchensis (Lour.) Merr., Schefflera octophylla (Lour.) Harms, and Prunus phaeosticta (Hance) Maxim. | 778 ± 404 a          | 38.7 ± 2.7 ab | 1.38 ± 0.15 a |
| CONIF-40     | 40s        | Cunninghamia lanceolata (Lamb.) Hook., Styrax formosana Matsum., and Schefflera octophylla (Lour.) Harms | 342 ± 69 a           | 34.2 ± 3.6 b | 1.45 ± 0.18 a |

Note: Values with the same letters in each column are not significantly different at p = 0.05 based on the Tukey’s HSD comparison.

*Plant species in the three studied sites were identified and previously published in Chang et al. (2016).
Soil samples were collected from CONIF-40, CONIF-80, and the natural broadleaf forest in July 2010 (summer) and February 2012 (winter). Five plots (50 × 50 m each) were established at each forest site 50 m apart along a transect line as designed in Jien et al. (2009). Three soil core samples (8 cm in diameter and 10 cm deep) were randomly taken from each plot (after the litter was removed) and mixed into a composite sample in a plastic zipper bag. All samples were stored at 4°C until the analysis.

2.2. Soil KCl- and HW-Extractable C and N

KCl and HW extraction methods (Chen et al., 2005) were used to examine soil NH$_4^+$, NO$_3^-$, soluble organic N (S$_{ON}$), and soluble organic C (S$_{OC}$) contents. For the KCl extraction, 5-g air-dried soil from each composite sample was weighed and placed in a 250-ml conical flask with 50 ml of 2 M KCl. Then, the flask was shaken for 60 min at 150 rpm. The aqueous extracts were then filtered with Whatman No. 5 filter papers (Whatman Inc., Buckinghamshire, UK) to test their chemical contents. For HW extraction, 6-g air-dried soil samples were weighed and placed in a 50-ml centrifuge bottle with 30-ml distilled deionized water. The bottle was heated in a 70°C water bath for 18 hr and then shaken for 5 min at 150 rpm. All shaken bottles were centrifuged at 12,000 × g for 10 min, and aqueous extracts from the slurry were filtered with the same filter papers for analysis.

NH$_4^+$ content in the extract was analyzed by an indophenol method with a spectrophotometer (UV-1201, Shimadzu Corp., Kyoto, Japan). NO$_3^-$ in the extract was analyzed by the cadmium reduction method.
(O’Dell, 1993) with a flow injection analyzer (SP-8001, Metertech Inc., Taipei City). The extract was digested into NO$_3^-$ by a persulfate method to determine soil TDN (Sollins et al., 1999) and then analyzed with the same flow injection analyzer as previously described. The SbON concentration was calculated by subtracting NO$_3^-$ and NH$_4^+$ contents from the TDN content. SbOC content was measured with a TOC analyzer (1010, O. I. Analytical, Texas, USA).

Total C and N contents in litter were analyzed using a Fisons NA1500 elemental analyzer (ThermoQuest Italia, Milan, Italy).

2.3. Determination of Acid-Hydrolyzable and Recalcitrant C Contents

Two-step acid hydrolysis was used to quantify acid-hydrolyzable C pool I (AHPI-C), acid-hydrolyzable C pool II (AHPII-C), and recalcitrant C pool (RP-C) contents in soil samples (McLauchlan & Hobbie, 2004; Rovira & Vallejo, 2002). Briefly, 0.5-g air-dried soil was weighed out from each composite sample, mixed with 20 ml of 5 N H$_2$SO$_4$ and hydrolyzed at 105°C for 30 min in Pyrex flasks with Allihn condensers. The solution containing AHPI-C was centrifuged at 20,000 × g for 10 min and then decanted from the sample.

The remaining residue was mixed with 2 ml of 26 N H$_2$SO$_4$ overnight and shaken at 150 rpm at room temperature. Then, the concentration of H$_2$SO$_4$ in the sample was diluted to 2 N and hydrolyzed at 105°C for 3 hr and then centrifuged at 20,000 × g for 10 min, and the solution containing AHPII-C was decanted from the sample. The remaining residue, considered RP-C, was flushed with 30-ml deionized water and dried at 60°C.

Figure 2. Hot water-extracted concentrations of soil soluble organic C (a), soluble N (b), NH$_4^+$ (c), NO$_3^-$ (d), and total dissolved N (e) in the top 10 cm of soil in the broadleaf forest (BROAD-Nat) and 40- (CONIF-40) and 80-year-old (CONIF-80) coniferous forests.
Table 2

| Season | Vegetation | TOC (%) | TN (%) | PMN (μg N/g soil/d) | AHPI-C (mg/g soil) | AHPII-C (mg/g soil) | RP-C (mg/g soil) | Cmic (μg C/g soil) | Nmic (μg N/g soil) | Soil respiration (μg/g soil/h) | qCO2 (mg CO2-C/g microbial-C/h) |
|--------|------------|---------|--------|---------------------|--------------------|---------------------|-----------------|------------------|------------------|---------------------------|-----------------------------|
| Winter | BROAD-Nat  | 2.6 ± 0.3 | 0.2 ± 0.0 | 78.6 ± 16.4 | 12.8 ± 1.4 | 2.4 ± 0.3 | 15.4 ± 4.0 | 763.3 ± 77.6 | 119.4 ± 8.2 | 3.2 ± 0.5 | 4.2 ± 0.6 |
|        | CONIF-80   | 3.3 ± 0.6 | 0.3 ± 0.0 | 78.5 ± 8.4  | 15.8 ± 2.0  | 2.8 ± 0.5  | 20.7 ± 3.7  | 748.3 ± 83.9  | 121.4 ± 10.5 | 3.5 ± 0.6 | 4.7 ± 0.6 |
|        | CONIF-40   | 3.8 ± 0.5 | 0.3 ± 0.0 | 78.7 ± 6.9  | 16.9 ± 1.5  | 3.5 ± 0.5  | 26.4 ± 6.4  | 812.9 ± 138.6 | 117.4 ± 10.7 | 4.7 ± 1.2 | 5.8 ± 1.2 |
| Summer | BROAD-Nat  | 3.5 ± 0.2 | 0.3 ± 0.0 | 68.8 ± 7.5  | 18.1 ± 0.7  | 3.6 ± 0.2  | 19.7 ± 0.2  | 1668.6 ± 111.2 | 139.9 ± 9.1  | 8.2 ± 0.8 | 4.9 ± 0.4 |
|        | CONIF-80   | 3.2 ± 0.7 | 0.2 ± 0.1 | 60.2 ± 11.7 | 14.4 ± 2.3  | 3.8 ± 0.9  | 19.7 ± 0.6  | 1314.2 ± 30.5 | 94.5 ± 11.0  | 6.3 ± 0.8 | 4.8 ± 0.5 |
|        | CONIF-40   | 4.1 ± 0.8 | 0.3 ± 0.1 | 68.5 ± 22.1 | 19.8 ± 1.9  | 4.6 ± 1.1  | 30.1 ± 0.8  | 1167.9 ± 156.1 | 111.5 ± 12.2 | 6.5 ± 1.5 | 5.5 ± 1.2 |

Note: Data are mean ± SD. Significant results at p < 0.05 are shown in Table 3.

2.4. Soil Microbial Biomass C and N, Basal Respiration, and Mineralizable N

Soil microbial biomass C (Cmic) and N (Nmic) were analyzed with a chloroform-fumigated extraction method (Witt et al., 2000). Soil basal respiration was estimated from the average CO2 flux rate during a 3-day incubation after 7 days of pre-incubation, using an alkali method (Gömöryová et al., 2009; Huang et al., 2014). About 10-g fresh soil was weighed out from a composite sample and placed in a plastic tube; then, the tube was kept in a 250-ml serum bottle. The soil was adjusted to 60% water-holding capacity. The serum bottle was pre-incubated at 25°C for 7 days so that the microbial community could recover to the same stage as it was when the soils were collected, as suggested by other previous studies (Hamer et al., 2007; Zhou et al., 2016). We acknowledge that the determined soil basal respiration rates may not be the same as the soil CO2 flux collected with static chambers in situ. After pre-incubation, the plastic tube (with soil inside) was removed and carefully placed into another 250-ml serum bottle with a beaker at the bottom containing 20 ml of 0.05 M NaOH. The serum bottle was capped and incubated at 25°C for 3 days. After incubation, BaC2 was added and the 20-ml NaOH solution in the beaker was titrated using 0.05 M HCl with phenolphthalein. Basal respiration was calculated based on the CO2 produced during the incubation. The microbial quotient (qCO2) was calculated as the basal respiration per unit of microbial biomass.

Total potential mineralizable N (PMN) content was determined using a waterlogging incubation method (Keeney & Bremner, 1966). Briefly, 5-g air-dried soil was weighed out from the composite samples and placed in a 250-ml centrifuge bottle with 25-ml distilled deionized water. Then, the bottle was incubated and shaken at 150 rpm in a dark incubator (LM-509RD, Yihrder Technology, Shinbei City, Taiwan) at 40°C for 7 days. After incubation, 25 ml of 4 M KCl was injected into the bottle, and the bottle was shaken for 1 hr at 150 rpm. The bottle was centrifuged at 12,000 × g for 20 min; then, the solution was decanted to determine the NH4+ concentration, and the difference in NH4+ concentrations between incubated and non-incubated soil samples was used to calculate the PMN.

2.5. Statistical Analyses

Differences in soil nutrients among the three forests and two seasons were tested for significance by two-way analysis of variance (ANOVA) to evaluate the influence of reforestation age, plant types, and seasons on the changes in soil C and N fractions. Principal component analysis (PCA) was used to determine the soil properties with the most variation among BROAD-Nat, CONIF-40, and CONIF-80. Two-way ANOVA and PCA analyses were conducted using JMP v11 (SAS Inst., Cary, NC, USA). Significance was set to p < 0.05.
### Table 3

**Difference in Soil Biochemical Properties for Samples Collected in the Three Forest Types and Over Two Seasons by Two-Way Crossed Factorial Analysis**

| Factor          | Site effect | Season effect | Interaction effect (site × season) |
|-----------------|-------------|---------------|-----------------------------------|
| TOC             | 40Y > 80Y = Nat | n.d.          | n.d.                              |
| TN              | 40Y > 80Y = Nat | Summer > winter | Nat                              |
| $S_{0}\text{OC}_{\text{KCl}}$ | n.d.         | Summer > winter | n.d.                              |
| $\text{NH}_4^+_{\text{KCl}}$ | 40Y > 80Y = Nat | Summer > winter | n.d.                              |
| $\text{NO}_3^-_{\text{KCl}}$ | 40Y > 80Y = Nat | n.d.          | n.d.                              |
| $S_{0}\text{ON}_{\text{KCl}}$ | n.d.         | n.d.           | n.d.                              |
| $\text{TDN}_{\text{KCl}}$ | 40Y > 80Y = Nat | Summer > winter | n.d.                              |
| $S_{0}\text{OC}_{\text{KCl}}/\text{TOC}$ | Nat ≥ 80Y > 40Y | Summer > winter | n.d.                              |
| $S_{0}\text{ON}_{\text{KCl}}/\text{TN}$ | n.d.         | Winter > summer | Nat                               |
| $S_{0}\text{OC}_{\text{HW}}$ | n.d.         | Summer > winter | n.d.                              |
| $\text{NH}_4^+_{\text{HW}}$ | n.d.         | Summer > winter | n.d.                              |
| $\text{NO}_3^-_{\text{HW}}$ | 40Y > 80Y = Nat | n.d.          | n.d.                              |
| $S_{0}\text{ON}_{\text{HW}}$ | 40Y > 80Y = Nat | n.d.          | n.d.                              |
| $\text{TDN}_{\text{HW}}$ | 40Y > 80Y = Nat | Summer > winter | n.d.                              |
| $S_{0}\text{OC}_{\text{HW}}/\text{TOC}$ | Nat > 80Y > 40Y | Summer > winter | 40Y                               |
| $S_{0}\text{ON}_{\text{HW}}/\text{TOC}$ | n.d.         | n.d.           | Nat                               |
| PMN             | n.d.         | Winter > summer | n.d.                              |
| $C_{\text{mic}}$ | Nat > 80Y = 40Y | Summer > winter | Nat > 80Y = 40Y                    |
| $N_{\text{mic}}$ | Nat > 80Y = 40Y | Summer > winter | 80Y = Nat                         |
| Basal respiration | n.d.         | Summer > winter | 80Y = Nat                         |
| $q\text{CO}_2$  | 40Y > 80Y = Nat | n.d.          | n.d.                              |
| AHPI-C          | 40Y > 80Y = Nat | Summer > winter | Nat                               |
| AHPII-C         | 40Y > 80Y = Nat | Summer > winter | Nat                               |
| RP-C            | 40Y > 80Y = Nat | n.d.          | n.d.                              |
| AHPI-C/TOC     | n.d.         | n.d.           | n.d.                              |
| AHPII-C/TOC    | n.d.         | Summer > winter | n.d.                              |
| RP-C/TOC       | 40Y > 80Y = Nat | n.d.          | n.d.                              |

*Note: No difference (n.d.); 40-year-old coniferous plantation (40Y); 80-year-old coniferous plantation (80Y); and natural broadleaf forest (Nat).*

### 3. Results

#### 3.1. Soil-Extractable C and N

For the KCl extraction, $\text{NH}_4^+_{\text{KCl}}$, $\text{NO}_3^-_{\text{KCl}}$, and $\text{TDN}_{\text{KCl}}$ contents were higher at the CONIF-40 site than the BROAD-Nat or CONIF-80 sites (Figure 1 and Table 3). Although $S_{0}\text{OC}_{\text{KCl}}$ was not statistically different among the three forest sites, the $S_{0}\text{OC}_{\text{KCl}}/\text{TOC}$ ratio (labile C/TOC) was higher in the BROAD-Nat forest than the CONIF-80 one and lowest in the CONIF-40 forest. A similar trend was observed for the $S_{0}\text{ON}_{\text{KCl}}/\text{TN}$ ratio, though the differences among the three forest sites were not significant (Figure 1 and Table 3).

For the HW extraction, $\text{NO}_3^-_{\text{HW}}$, $S_{0}\text{ON}_{\text{HW}}$, and $\text{TDN}_{\text{HW}}$ contents were higher in CONIF-40 than BROAD-Nat and CONIF-80 (Figure 2 and Table 3). The $\text{NH}_4^+_{\text{HW}}$ and $S_{0}\text{OC}_{\text{HW}}$ were similar among the three forest sites. Similar to the KCl extraction, the $S_{0}\text{OC}_{\text{HW}}/\text{TOC}$ ratio (labile C/TOC) was lower at CONIF-40 than BROAD-Nat and CONIF-80. The effect of coniferous reforestation on the $S_{0}\text{ON}_{\text{HW}}/\text{TN}$ ratio was the same as for the $S_{0}\text{OC}_{\text{HW}}/\text{TOC}$ ratio, though it was not statistically different among the three forest sites.

Most C and N fractions from the KCl and HW extractions were lower in the winter than the summer by similar magnitudes for all three forest sites. The soil $S_{0}\text{ON}_{\text{KCl}}/\text{TN}$ ratio in the BROAD-Nat soil seemed to be very sensitive to seasonal changes, with lower values in the winter. The $S_{0}\text{OC}_{\text{HW}}/\text{TOC}$ ratio decreased in the winter more severely in the CONIF-40 site than in the other two sites. In addition, the $S_{0}\text{ON}_{\text{HW}}/\text{TN}$ ratio also had a larger decrease in the winter at the BROAD-Nat site than the other two sites.

#### 3.2. Soil Acid-Hydrolyzable and Recalcitrant C

The AHPI-C, AHPII-C, and RP-C were all higher in CONIF-40 than BROAD-Nat and CONIF-80 (Tables 2 and 3). The RP-C/TOC ratio was higher in CONIF-40 than CONIF-80 and BROAD-Nat. The AHPI-C/TOC tended to be highest in BROAD-Nat, followed by CONIF-80 and CONIF-40, though there was no significant difference among the three forest sites (Figure 3 and Table 3). The AHPII-C/TOC ratios were similar at all three forest sites. Furthermore, AHPI-C and AHPII-C contents were both higher in the summer than the winter. The AHPI-C in the BROAD-Nat soil also appeared to be remarkably sensitive to seasonal changes and much lower in the winter.

#### 3.3. Soil Microbial Biomass C and N, Soil Basal Respiration, and Mineralizable N

Soil microbial biomass C and N were considerably higher in BROAD-Nat than CONIF-80 and CONIF-40. In addition, the metabolic quotient ($q\text{CO}_2$) was higher in CONIF-40 than CONIF-80 and BROAD-Nat, though soil basal respiration rates were similar among all three forest sites (Tables 2 and 3). Both soil basal respiration and $q\text{CO}_2$ were lower in the winter than summer. The basal respirations decreased more in the winter in the CONIF-80 and BROAD-Nat soils than in the CONIF-40 ones. The $q\text{CO}_2$ content was more sensitive to seasonal changes in the BROAD-Nat soils than in the CONIF-40 and CONIF-80 soils.

#### 3.4. Principal Component Analysis

The first (PC1) and second principal components (PC2) of the PCA explained 67.6% and 14% of the soil variations, respectively, in the winter (Figure 4), and 54.9% and 20.5% of the soil variations, respectively, in the summer (Figure 5). For the winter sampling, among all the soil chemical properties, those related to the KCl...
and HW extraction comprised the major components of the PC1 and were positively linked to CONIF-40 soil, reflecting the higher KCl- and HW-extracted C and N in CONIF-40 soil than in CONIF-80 and BROAD-Nat soils observed in the study. The labile C/TOC and labile N/TN ratios composing PC2 were positively linked in BROAD-Nat soils in the winter.

Similarly, in the summer, the KCl- and HW-extracted soil N and C were also the major components that comprised the PC1 and PC2, and the arrows of KCl and HW extracts were positively related to CONIF-40 soils and negatively related to CONIF-80 soils. In addition, the AHPI-C/TOC ratio was positively correlated to BROAD-Nat soils in the summer.

Figure 3. Soil $S_{OC\text{KCl}}/\text{TOC}$ (a), $S_{ON\text{KCl}}/\text{TN}$ (b), $S_{OC\text{HW}}/\text{TOC}$ (c), $S_{ON\text{HW}}/\text{TN}$ (d), labile C pool I to total organic carbon (AHPI-C/TOC) ratio (e), labile C pool II to total organic carbon (AHPII-C/TOC) ratio (f), and recalcitrant carbon to total organic carbon (RP-C/TOC) ratio (g) in the top 10 cm of soil in the broadleaf forest (BROAD-Nat) and 40- (CONIF-40) and 80-year-old (CONIF-80) coniferous forests.
Figure 4. Plots of the two first principal components (PCs) from the principal component analysis of soil biochemical properties in samples collected from three forest sites in the winter (CONIF-40: 40-year-old coniferous plantation; CONIF-80: 80-year-old coniferous plantation; BROAD-Nat: natural broadleaf forest).

Figure 5. Plots of the two first principal components (PCs) from the principal component analysis of soil biochemical properties in samples collected from three forest sites in the summer (CONIF-40: 40-year-old coniferous plantation; CONIF-80: 80-year-old coniferous plantation; BROAD-Nat: natural broadleaf forest).
4. Discussion

This study showed that, even after long-term reforestation using a coniferous forest on a cutover of a broadleaf forest, soil labile C and N fractions in the reforested soils may not return to their natural conditions. The litter and SOM from coniferous plants typically contain higher aromatic C and alkyl C than those from broadleaf forests (Jien et al., 2011), which makes this litter and SOM resistant to decomposition and benefits of C and N accumulation in soils (Chang et al., 2016). This explains the higher soil TOC and TN contents and the lower labile C to TOC ratio in the conifer forest sites than the natural broadleaf one. The similar soil C and N fractions between CONIF-80 and BROAD-Nat sites imply that soil chemical properties in the reforested coniferous plantations would ultimately reach a stage of succession similar to those of the natural forest, despite having different plant types.

Soil soluble N from compounds like NH$_4^+$-KCl, NO$_3^-$-KCl, and TDN$_{KCl}$ was higher in CONIF-40 than either BROAD-Nat sites, and this could be linked to the fact that young forests have more young leaves than do old forests. Soil organic C is not polar and therefore dissolves better in HW than under ion exchange (Shiau et al., 2017; Shiau & Chiu, 2017). Therefore, $S_{0}OC_{HW}$ concentrations were higher than those of $S_{0}OC_{KCl}$ at all three studied sites, and $S_{0}OC_{HW}$ is typically considered to reflect the labile portion of soil C better than $S_{0}OC_{KCl}$ (Shiau & Chiu, 2017).

The differences in litter qualities provided by the coniferous and broadleaf forests also influenced the acid-hydrolyzable C contents among the soils of the three studied sites. Because coniferous litter is more resistant to decomposition, the RP-C/TOC ratio was high in the CONIF-40 site, implying that SOM is dependent on the properties of plant litter (Kleber, 2010). The reforested coniferous areas had lower ratios of labile C or N to total C or N and higher RP-C/TOC ratio than native broadleaf ones; this concurs with the observation that soil microbial biomass is lower in secondary coniferous plantations than in natural broadleaf forests (Chang et al., 2016). Moreover, the soil AHPI-C, AHPII-C, and RP-C contents in CONIF-80 were similar to those in BROAD-Nat, indicating that it may take a very long time for reforested soil organic C composition to reach that of natural forests.

In the summer, high temperatures and soil water content increase the microbial biomass of forest soils (Chang et al., 2016; Liu et al., 2012), leading to accelerated SOM decomposition (Swift et al., 1979). This explains why higher HW- and KCl-extracted C was observed in the summer for all three forest soils.

Metabolic quotient (q$_{CO2}$) is a useful a posteriori indicator for determining the ecological efficiency of soil microbial communities (Anderson & Domsch, 1990; Degens, 1998). The low microbial biomass C and N contents but high q$_{CO2}$ values in the CONIF-40 soil imply that microbes in this soil were under greater stress than those in the CONIF-80 and BROAD-Nat soils, similar to the trend from microbial phospholipid fatty acids (PLFA) analysis by Chang et al. (2016). This may be explained by significantly lower labile C and N to total C and N ratios in the CONIF-40 than CONIF-80 and BROAD-Nat soils, which may have created an adverse environment for microbial growth.

5. Conclusions

This study demonstrates that soil labile C and N contents are significantly affected by the type of plant used for reforestation. Reforesting a broadleaf forest with a coniferous plantation increased the overall soil C and N concentration, but percentages of soil labile C as total organic C decreased because coniferous plants have a more recalcitrant litter quality than broadleaf plants. The recalcitrant litter quality in coniferous forests decreased the soil C and N qualities and created an adverse environment for soil microbial communities in the coniferous plantation soils. Although environmental stress to microbial communities can be alleviated after long-term reforestation, the environmental stress that comes with using conifers for reforestation may last for decades. Thus, although reforestation may quickly provide ecosystem services such as wildlife habitats (as mentioned in section 1), soil chemical composition may require decades or even longer to return to natural conditions after reforestation.

Conflict of Interest

The authors declare no conflict of interest.
Data Availability Statement

The data supporting this study can be accessed in the National Taiwan University Scholars (https://scholars.lib.ntu.edu.tw/handle/123456789/435478).

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