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Soil Respiration and FDA Hydrolysis Following Conversion of Abandoned Agricultural Lands to Natural Vegetation in Central Korea

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Soil respiration and the hydrolysis of fluorescein diacetate (FDA) as a measure of total microbial activity were investigated in central Korea, at three sites that had been changed from abandoned agricultural lands to natural vegetation: rice field conversion to forest (RF), crop field conversion to shrub (CS), and indigenous forest (IF). Seasonal variations in soil respiration were affected by soil temperature and, to a lesser extent, by photosynthetically active radiation (PAR) and soil moisture. The mean annual rate of soil respiration (g CO_2 m^{-2} hr^{-1}) was highest at CS (0.36), followed by IF (0.29) and RF (0.28), whereas the total annual soil respiration (kg CO_2 m^{-2} yr^{-1}) was 2.82 for CS, 2.46 for IF, and 2.40 for RF. Mean annual FDA hydrolysis (μg FDA min^{-1} g^{-1} dry soil) was higher at RS (4.56) and IF (4.61) than at CS (3.65). At all three land-use change sites, soil respiration was only very weakly correlated with FDA hydrolysis.

Keywords: crop field, indigenous forest, microbial activity, rice field, soil moisture, soil temperature

Because soils are the major reservoir of terrestrial carbon (C), C storage depends on environmental and human factors. Land-use changes can affect C input and output fluxes in soils (Ross et al., 1999). In Korea, rapid industrialization and urbanization during the last several decades have resulted in huge areas of forested and agricultural lands being converted to industrial and urban purposes. In 1998, an estimated 1966 x 10^3 tons of C was released to the atmosphere due to such land-use changes and management (Lee et al., 2001). Now, the rural population is rapidly decreasing, and rice and crop fields are being abandoned, leading to changes in the natural vegetation on those sites. These changes can influence key biogeochemical rates, thereby altering soil respiration and other soil processes. Nevertheless, information is very limited concerning these changes in soil microenvironments and C dynamics following this conversion (Aweto, 1981; Knops and Tilman, 2000; Post and Kwon, 2000; Son and Lee, 2001; Son et al., 2003).

Although soil microbes contribute a significant portion to total soil respiration, few studies have been reported on the relationship between soil respiration and microbial activity (Adam and Duncan, 2001; Chapin et al., 2002; Fisk et al., 2003). Therefore, our major objective in this research was to 1) investigate seasonal variations in soil temperature and moisture, photosynthetically active radiation (PAR), soil respiration, and fluorescein diacetate (FDA) hydrolysis as a measure of total soil microbial activity; 2) determine the relationships among soil respiration, FDA hydrolysis, and environmental factors; and 3) measure the differences in soil respiration and FDA hydrolysis on three sites in central Korea that represent land-use changes during the conversion of abandoned agricultural lands to natural vegetation: rice field conversion to forest, crop field conversion to shrub, and indigenous forest.

MATERIALS AND METHODS

Study Area

Study area is on part of Mt. Kumdan near Seoul, Korea, at a latitude of 37° 27'N and longitude of 127° 14'E, and with an elevation of ca. 160 to 245 m. The climate is cool continental, with a yearly precipitation total of approximately 1300 mm, of which about two-thirds falls between June and August. During the study period, the monthly temperature averages ranged from -4.9°C (January) to 24.5°C (July).

The original vegetation had been a *Pinus-Quercus* mixed forest, but the area was then harvested and tilled for more than 30 years to produce rice and other crops (mainly vegetables). About 25 years ago, these agricultural fields were then abandoned and allowed to revert to their successional vegetation. Our study plots represented three types of land-use change in this area: 1) rice field conversion to forest (RF), 2) crop field to shrub (CS), and 3) indigenous forest (IF). The current vegetation at RF is a *Salix*-dominated mixed hardwood forest that comprises *Salix glandulosa* Seem., *Salix koreensis* Anderss., and *Acer ginnala* Max. The CS site consists of various native shrubs, including *Spiraea prunifolia* for.

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simpliciflora Nakai, *Lespedeza bicola* Turcz, and *Pueraria thunbergiana* Benth, while site IF is a *Quercus*-dominated mixed hardwood forest of *Quercus mongolica* Fisch., *Quercus variabilis* Bl., *Prunus sargentii* Rehder, and *Fraxinus rhynchophylla* Hance (Son et al., 2003). All three sites are composed of same bedrock and have a southern aspect, but they differ slightly in their slopes, with RF being relatively flat while CS and IF are located on gentle slopes. The concentrations (%) of soil organic C and nitrogen (N) at 0 to 10 cm deep are 3.26 and 0.10 for RF, 2.70 and 0.08 for CS, and 3.35 and 0.10 for IF, respectively (Son et al., 2003). A more detailed site description has been published previously (Chung et al., 1998; Son and Lee, 2001; Son et al., 2003).

Soil Respiration

Soil temperature, soil moisture, PAR, and soil respiration were measured monthly from June 2003, through May 2004, with five replicates per plot for each of the three sites. Soil temperature was measured with a probe (Barnant 90; Barnant, USA), at 10 cm, while the gravimetric soil moisture content was determined at a 0- to 10-cm depth. No soil moisture measurements were made in January and February because the soils were frozen. Soil respiration was measured daily during a 4-h period (11:00 to 15:00), using an infrared gas analyzer (EGM4; PP systems, UK) and a soil respiration chamber (15 cm inside diameter), as described by Son et al. (2003). Daily rates were calculated by assuming that the measured hourly rates represented the entire day. Each sampling date was considered the midpoint of a sampling period, so that the annual soil respiration was then calculated from the sum of all sampling periods. Concurrent with these soil respiration determinations, PAR was recorded by a Decagon Sunfleck Ceptometer (Model SF-80; Decagon Devices, USA), which was held horizontally 1 m above ground level to take readings in the four cardinal directions.

FDA Hydrolysis

The hydrolysis of fluorescein diacetate (FDA) has been widely used as accurate, sensitive, and simple method for determining total microbial activity in soil (Schnürer and Rosswall, 1982; Adam and Duncan, 2001; Nannipieri et al., 2003). However, this method has some limitations common to such assays; measuring potential rather than real microbial activities, and relying on the contributions of both extracellular and intracellular enzyme activities (Nannipieri et al., 2003). Here, soil samples were collected monthly (except January and February) with a stainless steel corer (4.5 cm diameter and 30 cm long) near the points where soil respiration also was measured. FDA hydrolysis was calculated as described by Schnürer and Rosswall (1982), and was expressed on the basis of μg hydrolyzed FDA min^{-1} g^{-1} of dry soil.

Statistical Analysis

The statistical significance of land-use change effects on soil temperature, moisture, PAR, soil respiration, and FDA hydrolysis were determined through an ANOVA of plot means (the average of five measurements per plot). The general linear model was used for all data analysis (SAS, 2000). Duncan's multiple range tests were employed to examine whether differences in soil temperature, moisture, PAR, soil respiration, and FDA hydrolysis were statistically significant for our sites. Regression analysis was used to analyze the relationships among soil respiration, FDA hydrolysis, soil temperature, soil moisture, and PAR.

RESULTS AND DISCUSSION

Soil Respiration

At individual measuring points, annual soil temperatures ranged from 0.5 to 21.8°C, with the trend being similar for all three land-use change sites: i.e., peaking in July, decreasing from August through January, and increasing again in February (Fig. 1a). In contrast, the mean annual soil temperature differed significantly among the sites, and there was a significant site x month interaction effect, with mean annual soil temperatures at CS (14.1°C) and IF (12.8°C) being higher than at RF (12.0°C). The forest floor is known to moderate extremes in soil temperatures. Moreover, temperature fluctuations are slower in wet soils because much energy is required to warm the water, which then transmits that heat deeper into the soil (Fisher and Binkley, 2000). Compared with conditions at CS and IF, the low amount of forest floor mass (Yang, 2002), fast litter decomposition (Son et al., 2003), and relatively moist soils (see below) at RF might explain these site differences in soil temperature.

In general, seasonal soil moisture content followed the precipitation pattern (data not shown), and relatively dry conditions were maintained except for the heavy rainfall in August (Fig. 1b). The mean annual soil moisture content was significantly higher at RF (34.1%) than at IF (28.5%) or CS (25.5%). Its topographic positioning and clayey soils may have influenced soil moisture conditions at RF (Son et al., 2003).

PAR was lowest in August, increasing during the fall and winter, peaking in March, then decreasing (Fig. 1c). The relatively high PARs from late fall through early spring seemed to be related to defoliation, and the low summertime PAR readings may have indicated the level of light being intercepted by the overstory canopy and understory vegetation. Mean annual PAR (μmol m^2 s^{-1}) differed significantly among sites: 265.0 for RF, 129.9

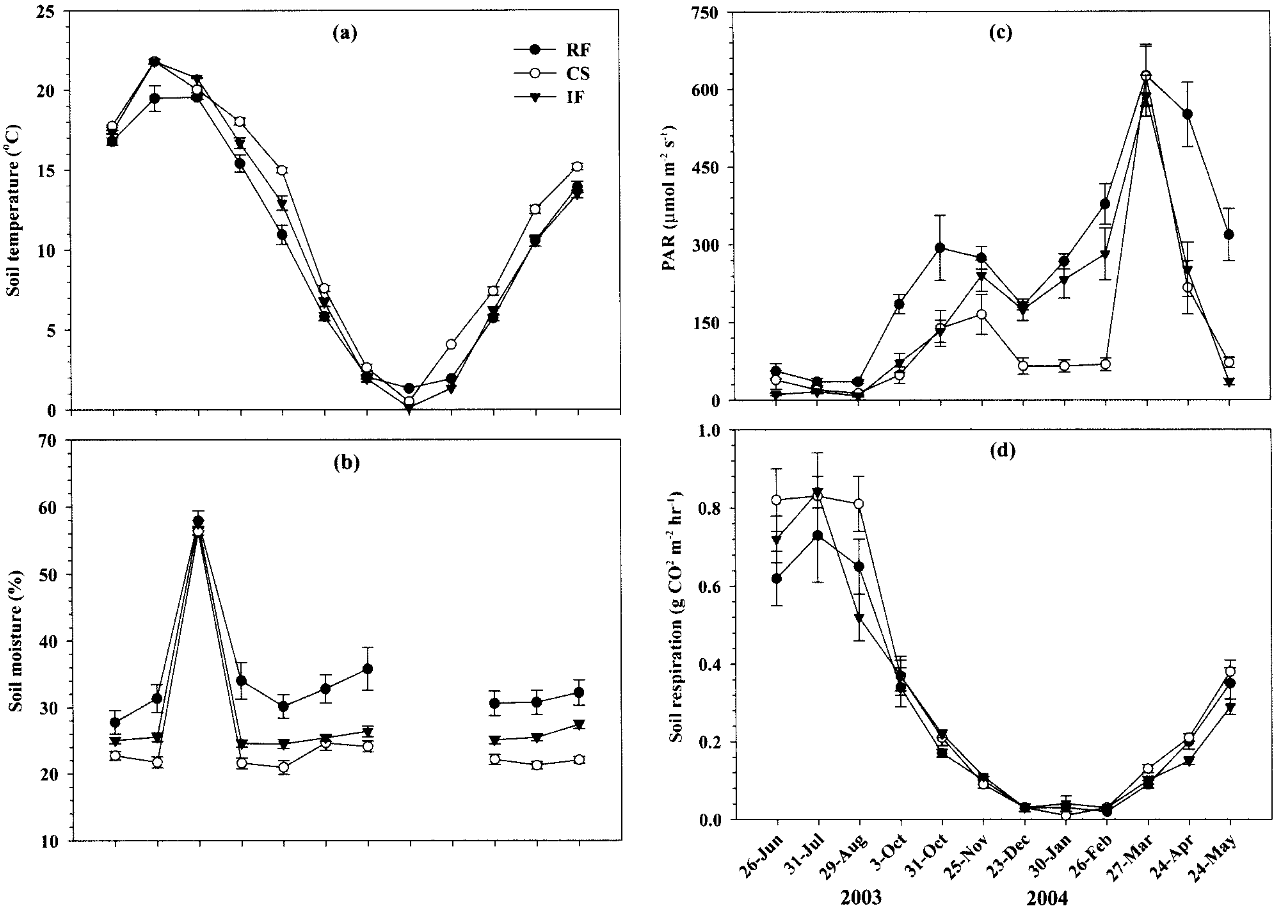

Figure 1. Seasonal soil temperature (**a**), soil moisture (**b**), PAR (**c**), and soil respiration (**d**) at three land-use change sites in central Korea. RF, rice field conversion to forest; CS, crop field conversion to shrub; IF, indigenous forest. Vertical bars represent standard errors.

Table 1. Mean annual soil respiration, total annual soil respiration, and mean annual FDA hydrolysis for three land-use change sites during the study period. RF, rice field conversion to forest; CS, crop field conversion to shrub; IF, indigenous forest. Numbers in parentheses denote the standard error. Different letters within a row indicate significant differences among the three sites.

	RF	CS	IF
Mean annual soil respiration (g CO_2 m^{-2} hr^{-1})	0.28 (0.02) b	0.36 (0.03) a	0.29 (0.02) ab
Total annual soil respiration (kg CO_2 m^{-2} yr^{-1})	2.40 (0.25) a	2.82 (0.39) a	2.46 (0.03) a
Mean annual FDA hydrolysis (μg FDA min^{-1} g^{-1} dry soil)	4.56 (0.25) a	3.65 (0.17) b	4.61 (0.18) a

for CS, and 157.3 for IF. That highest PAR at RF might have resulted from less light being intercepted because that site had the lowest basal area (Chung et al., 1998).

Annual soil respiration varied from 0.01 to 0.84 g CO_2 m^{-2} hr^{-1}, being lowest in January, increasing from February through June, peaking in July, and decreasing thereafter (Fig. 1d). This pattern was very similar to that for seasonal soil temperature (Fig. 1a), and has also been observed in other deciduous forests of Korea (Son et al., 1994; Moon et al., 2001). Mean annual soil respirations (g CO_2 m^{-2} hr^{-1}) were 0.28 ± 0.02 for RF, 0.36 ± 0.03 for CS, and 0.29 ± 0.02 for IF (Table 1). These values were slightly lower than those measured previously in this same study area (Son et al., 2003), perhaps due to interannual variations (Mathes and Schriefer, 1985; Schlentner and van Cleve, 1985; Lavigne et al., 2004). Mean soil respiration was significantly different among sites, and there was a significant month x site interaction. During most of our study period, soil respiration was highest at CS, possibly because that site also recorded higher soil temperatures (see below for relationships between soil respiration and environmental factors). Annual estimates of soil respiration (kg CO_2 m^{-2} yr^{-1}) for RF, CS, and IF were 2.40, 2.82, and 2.46, respectively (Table 1). However, this wide variation in data meant that no significant differences were calculated among sites (Son et al., 2003). Our results are within the range of 0.97 to 6.86 kg CO_2 m^{-2} yr^{-1} previously reported for deciduous forests in Korea (Lee and Mun, 2001; Moon et al., 2001), and are comparable to those recorded from other temperate deciduous forests (Ellert and Gregorich, 1995).

Table 2. Correlation coefficients for potential factors influencing soil respiration. SR, soil respiration; FH, FDA hydrolysis; ST, soil temperature; SM, soil moisture; PAR, photosynthetically active radiation.

	FH	ST	SM	PAR
SR	0.0195**	0.5902***	0.0345***	0.1634***
FH		0.0204**	0.0151**	0.0044^{ns}
ST			0.0366***	0.2516***
SM				0.0401***

, *, indicate significance at p <0.01 and 0.001, respectively; ^{ns,} indicates not significant.

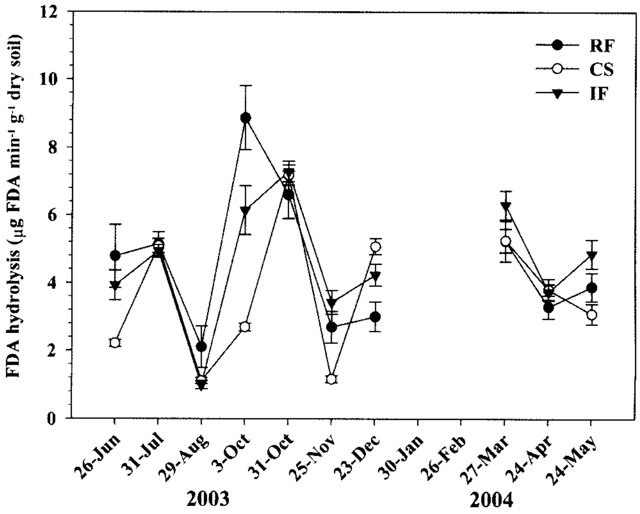

Figure 2. Seasonal FDA hydrolysis at three land-use change sites in central Korea. RF, rice field conversion to forest; CS, crop field conversion to shrub; IF, indigenous forest. Vertical bars represent standard errors.

Soil respiration largely depends upon soil temperature and moisture conditions (Carlyle and Than, 1988; Grogan and Chapin, 1999; Raich and Tufekcioglu, 2000; Yuste et al., 2003). Likewise, in our study, the patterns were similar for respiration and temperature, and a positive exponential correlation was found between those two parameters ($r^2 = 0.54$, $p < 0.001$ for RF; $r^2 = 0.60$, $p < 0.001$ for CS; $r^2 = 0.66$, $p < 0.001$ for IF). The fitted soil temperature response curve for all three sites was $S_r = 9.0339e^{(0.7272S_t)}$ where S_r is soil respiration (g CO_2 m^{-2} hr^{-1}) and S_t is soil temperature (°C) (Table 2). However, there was only a very weak correlation between soil respiration and soil moisture for the three sites ($r^2 = 0.03$, $p < 0.01$). Although soil moisture can be an important factor affecting soil respiration (Conant et al., 2000; Maier and Kress, 2000; Son et al., 2003), it likely has only a minor influence on respiration in most temperate and boreal regions (Mathes and Schriefer, 1985; Thuille et al., 2000; Widen and Majdi, 2001; Son et al., 2003).

PAR was negatively correlated with soil respiration ($r^2 = 0.16$, $p < 0.001$). This parameter reflects the interception of sunlight by deciduous overstory and understory vegetation, with high values indicating defoliation and low air and soil temperatures from fall through early spring (Lee and Mun, 2001). Likewise, low soil respiration occurred under high PAR conditions in our study. Moreover, PAR was more closely linked with soil temperature than with soil moisture (Table 2). Respiration appeared to be limited more by temperature and PAR rather than by moisture for all three sites. Nevertheless, more research is necessary about the influence of vegetation on soil respiration on those sites (Mathes and Schriefer, 1985; Weber, 1990; Wagai et al., 1998; Lee and Son, 2005).

FDA Hydrolysis

FDA hydrolysis fluctuated during the year, and differences among the three sites were inconsistent throughout that period (Fig. 2). Mean annual FDA hydrolysis (μg hydrolyzed FDA min^{-1} g^{-1} dry soil) was 4.56 for RF and 4.61 for IF, but was significantly lower, 3.65, for CS (Table 1). The lower soil moisture and PAR at CS seemed to influence the FDA hydrolysis calculated for that site (Sicardi et al., 2004) (also see below). However, other factors, such as the quantity and quality of soil organic matter and N concentration, might also caused differences in readings (Nannipieri et al., 2003). In fact, the soil organic C and N concentrations and the soil resin N availability were significantly lower at CS than at RF and IF (Son et al., 2003), and these soil chemical characteristics might have inhibited soil microbial activity at CS (Fisher and Binkley, 2000).

Soil temperature, moisture content, and organic matter are the most important properties that affect the activity, population density, and ecology of its microbiota (Stotzky, 1997). In this study, although the relationships among FDA hydrolysis, soil temperature, and soil moisture were statistically significant, those factors could explain only a very small portion of the variation in FDA hydrolysis (Table 2). Interestingly, even though microbial activity can be inhibited in either sandy or clay soils (Adam and Duncan, 2001; Nannipieri et al., 2003), our RF site showed a high degree of FDA hydrolysis, despite having a relatively high level of clay deposits because of its topographical features (Son et al., 2003).

Soil respiration was weakly correlated with FDA hydrolysis for the three sites ($r^2 = 0.02$, $p < 0.01$, Table 2; Fig. 3). The contribution of microbial activity to total soil respiration appears to depend on vegetation and soil microenvironments (Wagai et al., 1998; Raich and Tufekcioglu, 2000). Therefore, it is difficult for us to conclude that microbial activity was a minor influencing factor on soil respiration. It is also possible that, over the 25 years since our study sites began to be converted, changes have continued to occur in their vegetation, soil microenvironments, and soil biological processes (Knops and Tilman, 2000; Post and Kwon, 2000). Therefore, more detailed, long-term research is needed

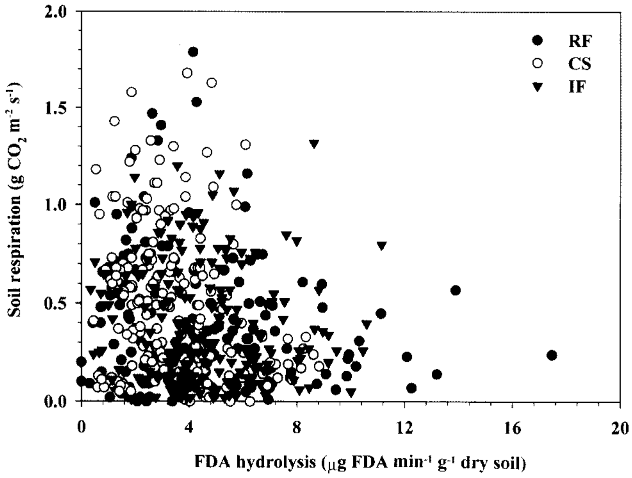

Figure 3. Relationship between soil respiration and FDA hydrolysis for three land-use change sites in central Korea. RF, rice field conversion to forest; CS, crop field conversion to shrub; IF, indigenous forest.

about the influence of land-use change on soil physical and chemical characteristics, as well as the relationship between soil respiration and microbial activity.

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