Ecological Risk Assessment

Leaching of Dissolved Organic Carbon and Carbon Dioxide Emission after Compost Application to Six Nutrient-Depleted Forest Soils

Werner Borken,* Yi-Jun Xu, and Friedrich Beese

ABSTRACT

The objective of this study was to assess the effect of compost application on soil respiration and dissolved organic carbon (DOC) output of nutrient-depleted forest soils. An amount of 6.3 kg m⁻² mature compost was applied to the forest floor of European beech (Fagus sylvatica L.), Norway spruce (Picea abies Karst.), and Scots pine (Pinus sylvestris L.) stands at Solling and Unterlüß, Germany. Cumulative soil respiration significantly increased by 499 g C m⁻² in the spruce stand at Unterlüß and by 274 g C m⁻² in the beech stand at Solling following compost application whereas soil respiration of the other four stands was not affected. The increases in soil respiration of the two stands were explained by improved microbial decomposition of soil organic matter. The DOC concentrations and fluxes in throughfall and seepage water at 10- and 100-cm depths were determined from August 1997 to March 2000. In the control plots, cumulative DOC outputs at 10 cm ranged between 57 and 95 g C m⁻², with the highest rates in the pine stands. Compost treatment significantly increased cumulative DOC outputs by 31 to 69 g C m⁻² at 10 cm and by 0.3 to 6.6 g C m⁻² at 100 cm. The mineral soils between the 10- and 100-cm depths acted as significant sinks for DOC, as shown by much lower cumulative outputs at 100 cm of 3 to 11 g C m⁻² in the control and 6 to 16 g C m⁻² in the compost plots. Our results suggest that a single, moderate application of mature compost to nutrient-depleted forest soils has little effect on C losses to the atmosphere and ground water.

The cleaning of urban wastewater since the 19th century and the separation of organic household wastes since the late 20th century have strongly increased the production of composts. The application of mature compost is thought to improve the fertility of degraded and nutrient-depleted soils because compost can increase soil organic matter and nutrient contents, soil porosity, water holding capacity, soil microbial activity, soil microbial biomass, and plant productivity (Borken et al., 2002a; Garcia-Gil et al., 2000; Giusquiani et al., 1995; Guerrero et al., 2000; Harrison et al., 1994). Compost has also been used to encounter soil acidification because of its relatively high pH and cation exchange capacity (Hue and Licidine, 1999). Today, compost and other organic residues are widely used in agriculture, silviculture, horticulture, landscaping, and reclamation of mining areas for soil amelioration (Bulmer, 2000; Pinamonti and Zorzi, 1996; Vangronsveld et al., 1996).

Stability and maturity of compost have been identified to have strong effects on the biological and chemical properties of soils. At constant temperature and moisture, microbial activity and the release of nutrients decline exponentially with time as a result of decreasing carbon availability (Chodak et al., 2001). Microbial respiration or the CO₂ production of aerated compost is often used as an indicator for activity or stability of compost (Wu and Ma, 2002). The release of dissolved organic matter (DOM) may be also an important carbon flux and indicator that originates either from microbial or chemical degradation of organic detritus. Microorganisms may use the biodegradable fraction of DOM as an energy and nutrient source (Qualls and Haines, 1992). Chefetz et al. (1998) stressed that DOM is the most biologically and chemically active fraction of compost subjected to changes. Moreover, Chefetz et al. (1998) found that the bioavailability of DOM decreases and the amount of dissolved macromolecules related to humic substances increases with maturation of compost. Using a mature compost from municipal organic waste, Chodak et al. (2001) reported decreasing DOC to CO₂ ratios from 1.6 to 0.3 at incubation temperatures between 5 and 25°C, whereby temperature inserted a strong effect on the CO₂ production but had little effect on the release of DOC.

Little is known about the effect of compost application on soil respiration and DOC fluxes of forest soils. Not only the chemical composition but also the microbial community of compost is different to forest soils. An improved nutrient supply after compost application could stimulate the activity of many soil microorganisms in the long run and, thereby, the decomposition of soil organic matter, which may affect soil respiration and DOC fluxes. At our study sites, Borken et al. (2002a) observed a decrease in microbial respiration and microbial biomass in the O horizon, but an increase of both parameters in the upper mineral soil two years after the compost application. It is not clear if changes in fluxes
and properties of DOM have affected soil microbial respiration and biomass.

Although DOC flux rates within the soil profile are low compared with soil respiration (Borken et al., 1999), DOC may affect some important biogeochemical processes in forest soils, such as acid–base equilibrium in soil solution, mineral weathering, complexation, and leaching of metals (Kalbitz et al., 2000). Compost treatments in forests could alter many biogeochemical processes and the retention of DOM due to changes in chemical properties and increased fluxes of DOM.

The objective of this study was to investigate the effects of a single application of mature compost on soil respiration and DOC output in seepage water of nutrient-depleted forest soils. We chose European beech, Norway spruce, and Scots pine stands at two locations, Solling and Unterlüß in Germany, because these tree species are widely representative for forest ecosystems in Central Europe and because the two locations provide a good comparison in climate and soil between a mountainous and a lowland environment. We also monitored the input of DOC by throughfall to investigate site and tree species effects on hydrochemical cycling of DOC and gain a better understanding of compost effects at our study sites. Furthermore, DOC to dissolved organic nitrogen (DON) ratios of throughfall and seepage water were calculated to evaluate the effect of compost and tree species on DOM properties.

**MATERIALS AND METHODS**

The experiment was performed in European beech, Norway spruce, and Scots pine stands at Solling and at Unterlüß in Lower Saxony, Germany (Table 1). All sites are characterized by strong soil acidification with a base saturation of less than 10% in the soil profile from 5 down to 100 cm. Aluminum is the dominating exchangeable cation of the soil matrix. Recently, lime applications were used to mitigate soil pH in the O horizon and increase the base saturation of the upper mineral soil.

The 150-yr-old beech stand (SB) and the 115-yr-old spruce stand (SS) at the Solling plateau above 500 m elevation have a mean annual air temperature of 7.2°C and an annual precipitation of 1038 mm, evenly distributed throughout the year. The 103-yr-old pine stand at Solling (SP) is located at an elevation of 270 m and has a mean annual temperature of 7.5°C and an annual precipitation of 900 mm. The soils of these sites developed on 30- to 80-cm-thick solifluction deposits, overlaiding weathered Triassic Sandstone. Texture of the soils at the 0- to 20-cm depth was dominated by the silt fraction (46–58%) with varying clay and sand contents. The soils were classified as well drained to poorly drained Typic Dystrochrept according to U.S. soil taxonomy (Soil Survey Staff, 1999). Considerable amounts of organic matter in the range of 9.0 to 12.4 kg m⁻² are stored in the 5- to 8-cm-thick O horizon in the stands at Solling.

The 131-yr-old beech (UB), 90-yr-old spruce (US), and 54-yr-old pine (UP) stands at Unterlüß were close to each other at an elevation of 110 m above mean sea level (Table 1). The long-term average of mean annual air temperature is 8.4°C and the mean annual precipitation is 837 mm. The soils are developed from fluvio-glacial sand and gravel deposited over a terminal moraine during the Warthe-stadium of the Saale/Riss ice age. The soils contain about 74 to 81% sand, 16 to 23% silt, and 3 to 8% clay at the 0- to 20-cm depth. The soils have been classified as well-drained Typic Dystrochrept (Soil Survey Staff, 1999) with moder-type O horizons. The beech stand (UB) had no ground vegetation and stored 12.7 kg m⁻² organic matter in the 6- to 9-cm-thick O horizon (Table 1). The spruce stand (US) and the pine stand (UP) stored 8.6 and 7.5 kg m⁻² organic matter in the O horizon, respectively. The pine stand had a dense cover of grass and berries (Vaccinium spp.).

At all study sites, three control and three treatment plots, each of 27 m², were established within a fenced area of 500 m². In spring 1997, suction lysimeters equipped with ceramic P-80 cups were installed at 10- and 100-cm depths with four and three replicates in each plot, respectively. The lysimeters of the control plots were at least 3 m apart from the treatment plots to avoid a contamination of control seepage water with dissolved substances from the compost plots. Except for dry periods, a vacuum pressure between -0.7 and -0.3 bar, generated by a vacuum pump, ensured continuous sampling of seepage water in 1 or 2 L glass jars. Subsamples (100 mL) of seepage water were discontinuously collected from summer throughfall and seepage water were collected biweekly to monthly using 10 rain gauges installed at a height of 1 m above the forest floor. During the winter season from November to March five 10-L buckets were used to collect snow and rain. All water samples were filtered using 0.45-µm membrane filters (Schleicher & Schuell, Dassel, Germany). The concentration of DOC in seepage water and throughfall was determined using a total organic carbon analyzer (TOC 5050; Shimadzu, Kyoto, Japan) with a detection limit of <1 mg C L⁻¹. Microbial decomposition of some DOM fractions may have occurred during storage of seepage and throughfall water in the field and fridge, resulting in underestimation of DOC concentrations. The DON concentrations were calculated as total N minus NH₄-N and NO₃-N (Borken et al., 2003).

In each compost plot, 6.3 kg m⁻² (15 L m⁻²) of sieved

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**Table 1. Characteristics of the study sites.**

<table>
<thead>
<tr>
<th>Site</th>
<th>Location</th>
<th>Elevation</th>
<th>MAT</th>
<th>MAP</th>
<th>Stand age</th>
<th>C to N ratio of O horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C to N ratio of O horizon</td>
</tr>
<tr>
<td>SB</td>
<td>51°46’ N, 9°35’ E</td>
<td>504</td>
<td>7.2</td>
<td>1038</td>
<td>150</td>
<td>34</td>
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<tr>
<td>SS</td>
<td>51°46’ N, 9°34’ E</td>
<td>508</td>
<td>7.2</td>
<td>1038</td>
<td>115</td>
<td>33</td>
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<tr>
<td>SP</td>
<td>51°34’ N, 9°40’ E</td>
<td>270</td>
<td>7.5</td>
<td>900</td>
<td>103</td>
<td>33</td>
</tr>
<tr>
<td>UB</td>
<td>52°50’ N, 10°18’ E</td>
<td>117</td>
<td>8.4</td>
<td>837</td>
<td>131</td>
<td>38</td>
</tr>
<tr>
<td>US</td>
<td>52°50’ N, 10°17’ E</td>
<td>115</td>
<td>8.4</td>
<td>837</td>
<td>90</td>
<td>38</td>
</tr>
<tr>
<td>UP</td>
<td>52°50’ N, 10°16’ E</td>
<td>110</td>
<td>8.4</td>
<td>837</td>
<td>54</td>
<td>29</td>
</tr>
</tbody>
</table>

‡ SB, 150-yr-old beech stand at Solling; SS, 115-yr-old spruce stand at Solling; SP, 103-yr-old pine stand at Solling; UB, 131-yr-old beech stand at Unterlüß; US, 90-yr-old spruce stand at Unterlüß; UP, 54-yr-old pine stand at Unterlüß.

§ Mean annual air temperature.

$ Mean annual sum of precipitation.
wind speed, and solar radiation. The climatic data were ob-
tained from the weather stations in Unterlüß, Solling, and
Wahlburg-Lippoldsberg of the Deutschen Wetterdienst, Of-
fenbach.

The hydrologic simulation was accomplished based on
the water balance concept:

\[ \Sigma P_b = \Sigma I + \Sigma T + \Sigma S_i + \Delta R \]  

where \( P_b \) is the bulk precipitation, \( I \) is the interception loss, \( T \) is the transpiration, \( S \) is the seepage water at \( i \) soil depth, and \( \Delta R \) is the change in water storage of the soil. A one-
dimensional model based on Richard’s equation (Swarzen-
druber, 1969) was used to estimate the soil water flow at
various depths. Retention curves and conductivity curves of
soil water were fitted for 0-, 2.5-, 7.5-, 15-, 35-, 75-, and 100-cm depths using the functions of van Genuchten (1980) and Mua-
lem (1976). Fitted parameters of soil–water retention and con-
ductivity curves were highly correlated \((r > 0.95)\) with labora-
tory measurements of soil–water retention and conductivity
from undisturbed soil cores of each stand. The total depth of
water available for infiltration at the soil surface is the amount
of throughfall (bulk precipitation subtracted by canopy inter-
ception loss, i.e., \( P_b - I \)). Daily potential evapotranspiration
was estimated using the Penman–Monteith equation (Mon-
teith and Unsworth, 1990). The estimated potential rates of
evapotranspiration were reduced by an empirical reduction
function by Feddes et al. (1976) for the water uptake by roots.

The model results were verified by comparing predicted and
measured soil matrix potentials for all studied sites over the
period from 1997 to 1999. In the stands at Unterlüß and the
pine stand at Solling, soil matric potential at the 10-cm depth
was manually measured biweekly to monthly using five
tensiometers per stand. In addition, soil matric potentials
were recorded every 15 min at the 15-, 60-, and 120-cm depths
in 1999 in an adjacent beech stand with similar soil conditions
at Unterlüß. Soil matric potentials were recorded every 15
min at the 5-, 10-, 15-, 20-, 40-, 60-, 80-, and 100-cm depths
in the beech and spruce stand at Solling from 1997 to 2000.
Details on parameterization and calibration of the hydrologic
model are beyond the scope of this paper and will be discus-
sed in detail in a separate publication.

Data were analyzed using the SAS statistical software pack-
age (SAS Institute, 1996). A two-way analysis of variance
(ANOVA) was performed to test the significance of compost
treatment and tree species on DOC concentration and DOC
to DON ratios at 10- and 100-cm depths for the entire sampling
period using means of three replications from each site. One-
way analysis of variance (Tukey’s studentized range HSD test)
was performed using pseudo replications from the control and
compost plots to compare the effect of compost application
on cumulative soil respiration rates for each stand for the
entire sampling period. Cumulative soil respiration rates were
calculated assuming linear changes between two sampling oc-
casions.

**RESULTS**

**Effect of Compost Application on Soil Respiration**

Soil respiration varied between 11 and 158 mg C m\(^{-2}\)
h\(^{-1}\) in the control and compost plots at Solling and
Unterlüß and showed a similar seasonal pattern with
maxima during summer and minima during winter (Fig.
1a, 2a, 3a, 4a, 5a, 6a). Drought stress may have occasion-
alilly diminished soil respiration at Unterlüß in the sum-
mmer of 1997 and 1999 indicated by low throughfall and

(\(<\cdot 10 \, \text{mm}\) and mature (approximately 6 mo old) compost
(Fertigkompost; Umweltschutz Nord, Ganderkesee, Germany)
were applied to the soil surface in the summer of 1997. The
compost was produced in two steps from separately collected
organic household waste consisting mainly of plant residues
and wood shavings and, to a lesser extent, leftovers. First,
the organic waste was continuously mixed and slowly passed
through an aerated tunnel within 10 to 14 d. Microbes pro-
duced temperatures between 55 and 70°C during this intensive
composting process. Afterward, the fresh compost was stored
in piles at ambient temperature for 60 to 120 d until the self-
heating temperature of compost fell below 30°C. According
to German law, mature compost is defined as a compost with
a self-heating temperature below 30°C.

The compost had a bulk density of 0.42 g cm\(^{-1}\), with 83%
being <2 mm. The thickness of the compost layer applied to
the soil surface was about 1.5 cm. Because of the maturation
during the composting process the compost had a relatively
low organic C content of 217 g kg\(^{-1}\) and considerably high
nitrogen content of 22.8 g kg\(^{-1}\), causing a low C to N ratio
of 9.5. The total amount of C added to the soil surface through the
compost application was then 1.37 kg C m\(^{-2}\). Initial microbial
respiration of compost was 6 mg CO\(_2\)–C kg\(^{-1}\) h\(^{-1}\) at 22°C
(Borken et al., 2002a). More details about chemical and micro-
bial properties of compost and the O horizons are described
by Borken et al. (2002a).

Five cylindrical PVC columns, 30 cm in diameter and 25 cm
in height, were randomly placed in one control and one com-
post plot of each forest stand. The PVC columns were inserted
into the O horizon down to a 5-cm depth and remained in the
soil for the duration of the experiment. Soil respiration
was measured by placing a closed PVC lid over each column
and taking three gas samples from the chamber headspace
using a sampling device and evacuated glass bottles (100 mL)
after 0, 20, and 40 min of closure. Carbon dioxide concen-
trations were analyzed in the laboratory using an automated GC
system equipped with an electron capture detector (Loffield
et al., 1997). Fluxes were calculated, using the slope of the
temporal change within concentration within the chamber
head-space, based on the following equation:

\[ F = k_{CO_2}(273/T)(P/101)(V/A)(\Delta c/\Delta t) \]  

where \( F \) is the flux rate of CO\(_2\) (mg C m\(^{-2}\) h\(^{-1}\)), \( k_{CO_2} \) (0.536 mg
C mL\(^{-1}\)) is the unit conversion factor for calculating CO\(_2\) flux
rate, \( T \) is the air temperature (K), \( P \) is the atmospheric pressure
(kPa), \( V \) is the volume (L) of the headspace gas within the
chamber, \( A \) is the area (m\(^2\)) of soil within the chamber, and
\( \Delta c/\Delta t \) is the rate of change in CO\(_2\) concentration (mL L\(^{-1}\) h\(^{-1}\))
within the chamber. Flux measurements were made between
1000 and 1400 hours on each sampling date. From September
1997 to April 1998 measurements were made monthly and
from May 1998 to December 1999 biweekly. Air temperature
and soil temperature at the 10-cm depth were measured adja-
cent to each chamber at the time of the flux measurement.
Temperature was measured using a calibrated electronic ther-
mometer equipped with an NTC probe (Model 110; Testo,
Lenzkirch, Germany). The temperature and moisture depen-
dency of soil respiration in the control plots has been published
previously (Borken et al., 2002b).

Dissolved organic C outputs in seepage water at 10- and
100-cm depths were calculated for all six stands by multiply-
ing DOC concentrations of defined sampling periods with the
respective cumulative flow of seepage from a soil water bal-
ance model. This model calculated flows of seepage water on
a daily basis using air temperature, air humidity, precipitation,
wind speed, and solar radiation. The climatic data were ob-

...
low soil matric potential (Fig. 4d, 5d, 6d). Higher soil matric potentials in the stands at Solling indicated that soil respiration was less affected by drought stress compared with Unterlüß (Fig. 1d, 2d, 3d).

The application of mature compost increased soil respiration at SB (Fig. 1a) and US (Fig. 5a). While compost affected soil respiration at SB only during the first 17 mo after the amendment, a severe effect was observed in the compost plot at US throughout the experiment although the effect was stronger in 1998 than in 1999. At few occasions, the compost plot of the spruce stand at Solling (SS) showed higher soil respiration rates in the summer of 1998 (Fig. 2a). No compost effect was found at SP (Fig. 3a), UB (Fig. 4a), and UP (Fig. 6a).

Cumulative soil respiration rates ranged between 915 and 1355 g C m⁻² in the control plots and between 1235 and 1414 g C m⁻² in the compost plots at Solling and Unterlüß from August 1997 to December 1999 (Table 2). Compost application significantly \( p < 0.05 \) increased soil respiration by 274 g C m⁻² in the beech stand at Solling and by 499 g C m⁻² in the spruce stand at Unterlüß.

In the control plots, mean DOC concentrations at the 10-cm depth ranged between 20 and 92 mg L⁻¹ at Solling (Fig. 1b, 2b, 3b) and between 21 and 110 mg C L⁻¹ at Unterlüß (Fig. 4b, 5b, 6b) over the entire sampling period. Lower DOC concentrations between 2 and 17 mg C L⁻¹ were observed at the 100-cm soil depth in both study locations (Fig. 1c, 2c, 3c, 4c, 5c, 6c). The seasonal variations of DOC concentration were rather small at both depths in all stands, except the Unterlüß pine stand where the highest and the lowest concentration occurred in the summer and winter seasons, respectively.

The compost plots showed generally higher DOC concentrations than the respective control plots and ranged between 26 and 241 mg C L⁻¹ at 10 cm (Fig. 1b, 2b, 3b, 4b, 5b, 6b). The strongest compost effect at this depth was observed in the stands at SP, UB, US, and UP. The DOC concentrations were lower in the compost plots of the beech (SB) and spruce stand (SS) at Solling, suggesting that higher water flows may have decreased DOC concentrations (Table 3). The effect of compost...
application on DOC concentration decreased in most stands from 1998 to 1999, except at SS and UP.

At the 100-cm depth, DOC concentrations ranged between 2 and 38 mg C L\(^{-1}\) at 100 cm (Fig. 1c, 2c, 3c, 4c, 5c, 6c) and the highest values were observed in the Solling pine stand (10–38 mg C L\(^{-1}\)), accompanied by a large spatial variation as shown by wider error ranges (Fig. 3c). All other compost plots had a much lower range of DOC concentration from 2 to 12 mg C L\(^{-1}\).

**Dissolved Organic Carbon Fluxes of Throughfall and Seepage Water**

The Solling beech and spruce stands received the highest amount of throughfall compared with our other study sites (Table 3). Concurrently, these two stands showed the highest seepage flows at 10- and 100-cm depths. The throughfall amount in the Solling pine stand was approximately 22% lower than in the beech and spruce stands because of the lower precipitation at a 230-m elevation (Table 1). Similar throughfall inputs were measured in the three stands at Unterlüß (Table 3). Because of its lower canopy interception, the pine stand at Unterlüß had a higher throughfall input and a higher seepage output than the adjacent beech and spruce stand.

In both study locations, the beech stands showed lower cumulative DOC inputs by throughfall (15 and 11 g C m\(^{-2}\)) than the respective spruce and pine stands (22–25 g C m\(^{-2}\)), indicating a strong tree species effect on DOC leaching from the canopies (Table 2). The DOC fluxes in seepage at the 10-cm depth showed a different pattern with the highest cumulative fluxes of 91 and 95 g m\(^{-2}\) in the control plots of the pine stands. The DOC fluxes of the beech and spruce at Solling and Unterlüß were approximately 37% lower than in the pine stands. A comparison of DOC fluxes between throughfall and seepage at the 10-cm depth in the control plots revealed that the O horizon and the overlaying mineral soil were net sources of DOC in the order pine > beech > spruce, and for the same tree species, Unterlüß > Solling.

Considering all control and compost plots, a two-way ANOVA revealed strong effects of compost application (\(p < 0.002\)) and tree species (\(p < 0.002\)) on DOC outputs at 10- and 100-cm depths. Overall, the compost application increased mean DOC outputs by 46.9 mg C m\(^{-2}\) at 10 cm and by 2.9 mg C m\(^{-2}\) at 100 cm in all stands over
the entire sampling period (Table 2). Moreover, DOC outputs were higher in the pine stands than in the beech and spruce stands at Solling and Unterlüß, but no differences were observed between the beech and spruce stands. The interactions between the compost treatment and the tree species were not significant for both soil depths.

The portion of the amended compost C found in the DOC outputs ranged from 2.3 to 5.3% at 10 cm for the entire sampling period (Fig. 7). At the 100-cm depth, total cumulative DOC fluxes of the compost plots were only 0.3 to 6.3 g C m$^{-2}$ higher than those of the control plots, corresponding to a release of 0.02 to 0.46% of the applied compost C (Fig. 7). Strong reductions of DOC fluxes were found in seepage between 10- and 100-cm depths in both the control and compost plots. The mineral soil between 10- and 100-cm depths retained between 83 and 127 g C m$^{-2}$ in the compost

### Table 2. Cumulative soil respiration rates and dissolved organic carbon (DOC) fluxes (calculated for the period from 15 Aug. 1997 to 30 Mar. 2000) of throughfall and seepage water at 10 and 100 cm in the control and compost plots.

<table>
<thead>
<tr>
<th>Site</th>
<th>Control</th>
<th>Compost</th>
<th>Control</th>
<th>Compost</th>
<th>Control</th>
<th>Compost</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB</td>
<td>1075 (27)</td>
<td>1349 (46)*</td>
<td>15.3</td>
<td>57.8 (6.7)</td>
<td>88.9 (4.5)</td>
<td>3.3 (0.2)</td>
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<tr>
<td>SS</td>
<td>1088 (60)</td>
<td>1308 (85)</td>
<td>25.4</td>
<td>57.2 (7.3)</td>
<td>94.5 (5.0)</td>
<td>5.4 (0.6)</td>
</tr>
<tr>
<td>SP</td>
<td>1150 (40)</td>
<td>1235 (27)</td>
<td>25.1</td>
<td>99.6 (18.0)</td>
<td>142.4 (8.3)</td>
<td>9.1 (2.5)</td>
</tr>
<tr>
<td>UB</td>
<td>1355 (53)</td>
<td>1302 (72)</td>
<td>11.3</td>
<td>67.7 (7.5)</td>
<td>117.8 (12.6)</td>
<td>4.3 (0.4)</td>
</tr>
<tr>
<td>US</td>
<td>915 (56)</td>
<td>1414 (99)*</td>
<td>21.6</td>
<td>59.9 (9.8)</td>
<td>128.6 (15.7)</td>
<td>4.4 (0.4)</td>
</tr>
<tr>
<td>UP</td>
<td>1202 (68)</td>
<td>1133 (55)</td>
<td>24.0</td>
<td>94.5 (14.0)</td>
<td>137.0 (14.6)</td>
<td>10.6 (1.0)</td>
</tr>
</tbody>
</table>

* Significant differences in soil respiration between control and compost plots at the 0.05 probability level.
† Values are means with standard errors in parentheses.
‡ SB, 150-yr-old beech stand at Solling; SS, 115-yr-old spruce stand at Solling; SP, 103-yr-old pine stand at Solling; UB, 131-yr-old beech stand at Unterlüß; US, 90-yr-old spruce stand at Unterlüß; UP, 54-yr-old pine stand at Unterlüß.
Table 3. Water input by throughfall and modeled soil water flows at 10- and 100-cm depths at the study sites from 15 Aug. 1997 to 30 Mar. 2000.

<table>
<thead>
<tr>
<th>Site†</th>
<th>Throughfall Water flow (10 cm) mm</th>
<th>Water flow (100 cm)</th>
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<tbody>
<tr>
<td>SB</td>
<td>2417</td>
<td>1424</td>
</tr>
<tr>
<td>SS</td>
<td>2504</td>
<td>1708</td>
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<td>785</td>
</tr>
<tr>
<td>UB</td>
<td>1814</td>
<td>828</td>
</tr>
<tr>
<td>US</td>
<td>1833</td>
<td>854</td>
</tr>
<tr>
<td>UP</td>
<td>2082</td>
<td>1119</td>
</tr>
</tbody>
</table>

† SB, 150-yr-old beech stand at Solling; SS, 115-yr-old spruce stand at Solling; SP, 103-yr-old pine stand at Solling; UB, 131-yr-old beech stand at Unterlüß; US, 90-yr-old spruce stand at Unterlüß; UP, 54-yr-old pine stand at Unterlüß.

Table 4. Dissolved organic carbon (DOC) to dissolved organic nitrogen (DON) ratios of throughfall and seepage water at 10- and 100-cm soil depths in the control and compost plots from 15 Aug. 1997 to 30 Mar. 2000.†

| Site‡ | Throughfall Control Compost Control Compost
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SB</td>
<td>22</td>
<td>36.8 (1.6)</td>
<td>23.6 (0.2)</td>
</tr>
<tr>
<td>SS</td>
<td>30</td>
<td>30.2 (2.5)</td>
<td>30.3 (1.4)</td>
</tr>
<tr>
<td>SP</td>
<td>37</td>
<td>30.8 (3.5)</td>
<td>30.5 (2.3)</td>
</tr>
<tr>
<td>UB</td>
<td>24</td>
<td>55.9 (0.9)</td>
<td>37.1 (0.4)</td>
</tr>
<tr>
<td>US</td>
<td>34</td>
<td>46.4 (1.5)</td>
<td>33.7 (1.7)</td>
</tr>
<tr>
<td>UP</td>
<td>34</td>
<td>51.7 (1.4)</td>
<td>35.6 (1.1)</td>
</tr>
</tbody>
</table>

† Values are means with standard errors in parentheses.
‡ SB, 150-yr-old beech stand at Solling; SS, 115-yr-old spruce stand at Solling; SP, 103-yr-old pine stand at Solling; UB, 131-yr-old beech stand at Unterlüß; US, 90-yr-old spruce stand at Unterlüß; UP, 54-yr-old pine stand at Unterlüß.
§ Only calculated for DON concentrations of >0.3 mg L⁻¹.

Dissolved Organic Carbon to Dissolved Organic Nitrogen Ratios in Throughfall and Seepage Water

Combining the results from a previous report (Borken et al., 2003), we calculated DOC to DON ratios for throughfall and seepage water (Table 4). Mean DOC to DON ratios of throughfall were 22 and 24 in the beech stands at Solling and Unterlüß, while DOC to DON ratios ranged between 30 and 37 in the spruce and pine stands. With one exception (SS), the DOC to DON ratios of seepage water at 10 cm were generally higher compared with those in throughfall.

The compost treatment reduced the DOC to DON ratios of seepage water at 10 cm in most stands and the DOC to DON ratios were lower in the compost plots at Solling (30–37) than at Unterlüß (46–56). A two-way ANOVA revealed a significant effect of compost treatment (p < 0.001) on the DOC to DON ratios at 10 cm, but tree species as the second independent variable had no effect. Neither a compost effect nor a tree species effect was found for seepage water at the 100-cm depth. Except for the pine stand at Solling, DOC to DON ratios of seepage water at the 100-cm depth were similar in the control and treatment plots. Moreover, the DOC to DON ratios decreased from 10- to 100-cm depths in both the compost and control plots.

DISCUSSION

Effect of Compost Treatment on Soil Respiration

Recent studies on compost amendments from different soil types and geographical locations have shown that soil CO₂ release can increase after compost application (e.g., Bernal et al., 1998; Pascual et al., 1998; Sikora and Yakovenko, 1996). Our study at two locations with three different tree species showed a mixed result: soil respiration increased only in the spruce stand at Unterlüß and in the beech stand at Solling. The spruce stand at Solling showed occasionally higher rates in the growing season of 1998. Soil respiration of the other stands was not significantly affected by compost application, even during the first months after application.

The compost used in our study had an initial respiration rate of 6 mg C kg⁻¹ h⁻¹ at a temperature of 22°C and an optimum water holding capacity of 50%, which is in the range of the Oa horizons at our study sites (Borken et al., 2002a). Considering a Q10 value (i.e., the increase factor in soil respiration when temperature increases by 10°C) of 2.4 (Chodak et al., 2001) and a mean soil temperature of 7.7°C at Solling and 9.4°C at Unterlüß at the 2.5-cm depth, the added compost could have increased soil respiration by approximately 4 mg C m⁻² h⁻¹. Thus, compost respiration may have increased soil respiration by approximately 5% during the first month after application, which is too low for a significant increase in soil respiration, considering the spatial variability of the control plots.

We assume that the significant increase in soil respiration in the spruce stand at Unterlüß and the beech stand at Solling resulted from increased microbial decomposition of soil organic matter. Microbial respiration increased in the upper mineral soil of most stands; however, microbial respiration decreased or was not affected in the O horizon of the compost plots (Borken et al., 2002a). The only exception was the spruce stand at Unterlüß with a clear increase of microbial biomass and microbial respiration in the O horizon (Borken et al., 2002a). Another explanation for the increase in soil respiration could be an increase in root respiration. However, some field studies suggest that inorganic fer-
tillizations can decrease growth of fine roots and root respiration (Clemensson-Lindell and Persson, 1995; Haynes and Gower, 1995). The compost used in our study contained an initial amount of inorganic salt of 13 g kg\(^{-1}\) (Borken et al., 2002a), and it is not clear if, and to what extent, this salt fraction influenced root growth and root respiration at our sites. Overall, the compost treatment made a minor contribution to soil respiration, implying a slow process of compost decomposition and mineralization in cold temperate forests, and, therefore, a long-term beneficial effect of nutrient supply for tree growth.

**Effect of Compost Treatment on Dissolved Organic Carbon Fluxes**

Very few field studies have been conducted to identify the effect of organic residues on DOC leaching in forest soils. The results of this study demonstrate that application of mature compost can have a strong effect on DOC leaching in the soil surface, which is in agreement with the finding by Cronan et al. (1992) that a sawdust amendment increased DOC concentration in the forest floor. However, our study shows that the effect of compost on DOC leaching is largely limited as soil depth increases. Based on the amount of applied compost and its C content, the DOC leached from the compost was about 2 to 5% at the 10-cm depth and less than 0.5% at the 100-cm depth over the entire 32-mo sampling period. The strong reductions in DOC output between 10 and 100 cm in both the control and compost plots suggest that the nutrient-depleted soils at our study sites have a large capacity to adsorb or to mineralize DOC. Both the control and compost plots of the pine stands showed the highest DOC fluxes at the 100-cm depth, indicating that the risk of DOC leaching to ground water is higher under pine compared with beech and spruce stands. This may be explained by throughfall input as canopy leaching of DOC was higher in the coniferous stands than in the beech stands and by higher DOC leaching of the surface soil in the pine stands.

Although a direct release of DOC from the compost in the field was not investigated at our study sites, an accompanied laboratory study by Chodak et al. (2001) revealed that the DOC release of a similar mature compost is larger than the CO\(_2\) production at an incubation temperature between 5 and 10°C. Assuming an average CO\(_2\) production of 4 mg C m\(^{-2}\) h\(^{-1}\) from the compost applied in our study, a total CO\(_2\) flux for our studied sites would be about 90 mg C m\(^{-2}\) for the entire period from August 1997 to March 2000. This flux is more or less within the magnitude of the cumulative DOC fluxes at the 10-cm soil depth. Apparently, a large portion of the compost DOC was adsorbed by mineral soil surfaces, immobilized, and/or respired by soil microorganisms. The organic carbon content did not increase in the upper mineral soil following compost application, but the increase in total nitrogen content suggested that compost DOM was adsorbed at the 0- to 20-cm depth (Borken et al., 2002a). Particularly, mineral soils with low organic matter content and high amounts of sesqui-oxides have high capacities to adsorb DOC mainly through ligand exchange of Fe and Al oxides and hydroxides with carboxyl groups of DOC (Thurman, 1985). Kalbitz et al. (2000) reported a biodegradable part of DOM of 10 to 40% in soil solution from forest floor material. The biodegradable part of DOM from mature compost was probably very low since the respiration rate was in the same range as the respiration rates of the Oa horizon at our sites. The study by Chefetz et al. (1998) showed that the biodegradable part of DOM decreases and that the amount of stable, hydrophobic compounds increases with maturity of compost.

Not only the concentration but also the chemical properties of DOM may change through the passage of soil. Mineral soil surfaces selectively adsorb hydrophobic DOM compounds that usually contain large amounts of lignin derivatives with high C to N ratio (Kalbitz et al., 2000). Furthermore, it is believed that soil microorganisms preferentially decompose hydrophilic DOM compounds with low C to N ratio. Our study suggests that DOM from compost was strongly adsorbed by the mineral soil although the C to N ratio was probably low as the applied compost had a C to N ratio of 9.5.

Comparing control and compost plots, DOC concentrations at the 10-cm depth of the compost plots showed no or only a weak temporal trend toward lower concentrations. Hence, the DOC production from compost appeared to follow the same regulation as the DOC production from soil organic matter. In general, microbial DOC production is strongly controlled by soil temperature and soil moisture (Kalbitz et al., 2000). In our study, the compost was applied onto the forest floor and, thus, microbial DOC production may have been strongly influenced by frequent drying and wetting processes. The output of DOC at the 100-cm soil depth was higher during the wet year of 1998 and during the first three months of 2000 than in the relatively dry year of 1999. Considering the dilutional effect by higher water fluxes during the wintertime, the result may suggest a secondary role of temperature for DOC leaching. In fact, Chodak et al. (2001) reported a negative effect of temperature on the DOC to CO\(_2\) ratio, indicating that temperature has a weaker effect on DOC release than on CO\(_2\) production.

**Practical Implication of Compost Treatment in Forests**

In Germany, the legal maximum of compost application is 30 Mg ha\(^{-1}\) within three years whereby high-quality standards are required regarding the maturity of compost and its contents of heavy metals, organic contaminants, germs, seeds, and foreign materials. In contrast to agriculture practice, compost is presently not used in silviculture of most Northern and Central European countries because of the concern that the release of heavy metals, organic contaminants, and nitrogen may harm the soil biota, plant growth, and ground water quality.

We propose to apply mature compost only to 20% of the forest floor to minimize soil disturbances, simplify
the distribution of compost by machinery, and minimize operational cost. A partial compost application may not directly improve the properties of the remaining untreated forest soil; however, available nutrients from compost mineralization could be distributed by root uptake and litter production in the long term. Based upon the concept that 6.3 kg m$^{-2}$ of compost was applied to 20% of the forest floor results in a total amount of 12.6 Mg ha$^{-1}$, which is below the legal maximum in Germany. On a hectare basis, the partial compost treatment would cause an additional DOC leaching of 0.6 and 13.5 kg C at the 100-cm depth (Table 5), which is below the cumulative DOC output of the control plots (33–106 kg ha$^{-1}$) over the entire 32-mo period. Moreover, the effect of compost on DOC output showed no clear temporal trend, indicating that the release of DOC from compost is relatively constant.

CONCLUSIONS

Our results showed that surface application of mature compost increased cumulative DOC outputs at the 10- and 100-cm depths of six temperate forests during a 32-mo period. Despite the low microbial activity of mature compost, the amendment increased soil respiration in spruce and beech stands, suggesting that microbial decomposition of soil organic matter was promoted by compost in these stands. Tree species affected not only the input of DOC by canopy leaching but also DOC fluxes at the 10- and 100-cm depths. The highest DOC outputs were found in the control and compost plots of the pine stands while the beech and spruce stands showed similar outputs. The mineral soils between the 10- and 100-cm depths retained large amounts of DOC and reduced thereby the DOC outputs to the ground water. Overall, DOC outputs of our control and compost plots were in the range of other temperate forests (Zech et al., 1994; Borken et al., 1999; Solinger et al., 2001). Because a general deterioration of ground water quality by DOC leaching from forested areas has not been identified as a problem in Germany, we conclude that a single, partial application of mature compost provides little risk of ground water contamination by DOC leaching. However, compost application can deteriorate water quality in forest areas with shallow soils, like in Scandinavia, were high DOM concentrations were found in ground and surface water (Vogt et al., 2001). Long-term investigations are needed to evaluate the benefits and risks of compost treatment for entire forest ecosystems.

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![Table 5](image)

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<th>2000‡</th>
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<tr>
<td></td>
<td>kg C ha$^{-1}$</td>
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</tr>
</tbody>
</table>

† SB, 150-yr-old beech stand at Solling; SS, 115-yr-old spruce stand at Solling; SP, 103-yr-old pine stand at Solling; UB, 131-yr-old beech stand at Unterlüß; US, 90-yr-old spruce stand at Unterlüß; UP, 54-yr-old pine stand at Unterlüß.

REFERENCES


