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ORIGINAL PAPER

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# Effects of compost, coal ash, and straw amendments on restoring the quality of eroded Palouse soil

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**Abstract** Ridgetops in the dryland farming region of eastern Washington suffer from low productivity and poor soil quality from years of erosion. Two studies investigated the effectiveness of soil amendments in restoring soil quality. Study 1 treatments were two rates of compost and a control. Study 2 treatments were compost, coal ash, wheat straw, three rates of inorganic N, and a control. A wide array of soil biological, chemical and physical parameters were measured from 1995 to 1997 and yield of spring barley, spring pea, and winter wheat were measured in different years from 1995 though 1998. In study 1, compost plus N increased barley yield and soil pH. Compost without N in study 2 increased total soil C and continued to immobilize soil N 2 years after incorporation because of the high C:N ratio of the compost. Total soil N, available P and K, some micronutrients, and cation exchange capacity were increased by the compost. Compost reduced soil bulk density and soil impedance, while increasing water-stable aggregates and improving infiltration. Coal ash slightly suppressed phosphatase activity, while tending to increase pH and soil B, and improving infiltration. Straw decreased soil bulk density and microbial activity in 1996 only. Barley grain trace element uptake, barley yield, and pea yield were uninfluenced by amendments. In 1998, 3 years after application of the amendments, winter wheat yield was significantly higher from the compost application than from any other treatments. Compost had the greatest benefit to improving soil quality and crop yield.

**Keywords** Soil quality · Microbial activity · Compost · Coal ash · Heavy metals

## Introduction

The Palouse region of eastern Washington and northwestern Idaho, USA, is a highly productive dryland farming area where wheat yields can exceed 7,000 kg ha$^{-1}$ in the high precipitation zone of 450 mm rainfall. (Papendick 1996). Between 60 and 70% of the annual precipitation normally falls between November and April. Virtually all workable land is under cultivation, and because much of the landscape is sloped as steeply as 45%, erosion rates are high, averaging approximately 31 t ha$^{-1}$ year$^{-1}$ of soil loss (USDA 1978). Consequently, there is extensive topsoil loss, especially on hilltops and ridges (Jennings et al. 1990).

The loss of topsoil reduces yield potential by reducing soil fertility and degrading soil structure (Busacca et al. 1985). Eroded clay hilltops represent approximately 10% of the land surface in the Palouse region (USDA 1978). Research published on the use of organic soil amendments in eroded soils shows that such amendments can improve soil quality and crop yield (Dormaar et al. 1986, 1988, 1997; Sun et al. 1995). The degraded area represented by hilltops is well suited for restoration efforts using soil amendments, because farmers can limit and focus their investment in applying a particular amendment to these specific landscape sites. This research was initiated to investigate the efficacy of several soil amendments in restoring eroded hilltop soil in the Palouse region.

The one-time amendments used in this study were selected on the basis of their availability to local growers, and their potential for improving soil quality. Two thousand tons per year coal ash and 15,000 t year$^{-1}$ of compost are produced on the Washington State University (WSU) campus. Wheat straw is abundantly available to farmers. Our hypothesis was that these soil amendments would improve the chemical, biological, and physical characteristics of eroded hilltop soils in the Palouse. High rates of compost were applied because its low N mineralization reduced pollution potential from NO$_3^-$ and maximized soil building properties.

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**Table 1** Chemical analysis of compost and coal ash amendments. *EC* Electrical conductivity

| Amendment | pH | EC ($dS\ m^{-1}$) | C (%) | N (%) | C:N | P ($\mu g\ g^{-1}$) | K ($\mu g\ g^{-1}$) |
|---|---|---|---|---|---|---|---|
| Ash | 11.6 | 1.34 | 13.2 | 0.27 | 48.8 | 1,587 | 1,476 |
| Compost | 8.9 | 7.0 | 29.3 | 0.92 | 31.9 | 2,700 | 7,200 |

## Materials and methods

Two field studies were conducted at two locations at the WSU Spillman Farm, 5 km southeast of Pullman (46°N, 117°W) on Naff silt loam [fine-silty, mixed, mesic Ultic Argixerolls; Donaldson (1980)].

### Study 1

Study 1 was a 1-year preliminary study using the compost amendment only. In spring 1995 compost was applied at rates of 0, 224, and 448 Mg $ha^{-1}$ in 4.9×30.5-m plots replicated 4 times in a randomized complete block design. The compost was incorporated into the soil and the entire trial area was fertilized with $NH_4NO_3$ at 90 kg N $ha^{-1}$. Barley (*Hordeum vulgare* L.) was sown on 19 June 1995. In July 1995, soils were sampled to a depth of 15 cm for soil $NH_4^+$, $NO_3^-$, and pH, using methods described in study 2 below. Barley seed yield and protein content were assessed in August 1995. Statistics were done as described for study 2.

### Study 2

#### *Field design*

This study consisted of seven treatments with four replications in a randomized complete block design. On a dry weight basis, the treatments were: 110 t $ha^{-1}$ compost from the WSU composting facility; 110 t $ha^{-1}$ coal ash from the WSU heating plant plus 90 kg N $ha^{-1}$ as $NH_4NO_3$; 22 t $ha^{-1}$ wheat straw plus 90 kg N $ha^{-1}$ as $NH_4NO_3$; 45, 90, and 135 kg N $ha^{-1}$ as $NH_4NO_3$; and a control. All treatments were one-time applications. Four randomized blocks were arranged over two adjacent, eroded hilltops (two blocks per hilltop) approximately 500 m apart. Plot size was 5×15 m for the ash, compost, and straw treatments and 3×15 m for the fertilizer N treatments and the control.

In the fall of 1995, the ash, compost, and straw amendments were surface applied and incorporated with a moldboard plow. Prior to incorporation, the coal ash and compost were 1 and 2 cm deep, respectively. The straw application was limited to 22 t $ha^{-1}$ because of its bulky structure.

In April 1996, plots were fertilized, disked, harrowed, and planted to barley. The plots received a uniform application of 17 kg P $ha^{-1}$ as $Ca(H_2PO_4)$, and inorganic N was broadcast at the rates specified for each treatment. Note that the compost and control treatments did not receive supplemental N in this study. Barley grain from this harvest was analyzed for trace elements using inductively coupled plasma atomic emission spectrometry (ICP-AES) (Issac and Johnson 1998; Gupta 1998; Soon 1998). In 1997, peas (*Pisum sativum* L.) were grown without supplemental fertilizer in any treatment. In 1998 winter wheat (*Triticum aestivum* L.) received one uniform fall fertilizer application of 41 kg N $ha^{-1}$ as anhydrous $NH_3$ and 17 kg P $ha^{-1}$ as $Ca(H_2PO_4)$ prior to seeding.

### Ash, compost, and straw amendments

The WSU power plant produced the coal ash (1:4 ratio of fly ash to bottom ash) from combustion of bituminous coal at temperatures of 800–1,000°C. WSU compost consisted of 85% by volume animal manure and bedding, 10% coal ash, and 5% food and landscaping waste. Detailed analyses of the compost were reported previously (Fauci et al. 1999). Compost was turned using a New Frontier (Clackamas, Ore.) straddle-type windrow turner, 1–3 times per week for 10 weeks. Core temperatures were maintained from 50 to 70°C. Chemical analyses of the coal ash amendment were performed at the University of Idaho Analytical Sciences Laboratory (Table 1) according to methods described below for soil. The compost amendment was analyzed by Soil and Plant Laboratory, in Bellevue, Washington. The saturation extract method was used to determine pH and electrical conductivity (EC). Percent C was determined by loss on ignition at 850°C. The difference in compost and ash weights was multiplied by 0.27 to convert the mass of lost $CO_2$ to lost C. N was measured with a LECO induction furnace. Available P was extracted with $NaHCO_3$ and determined colorimetrically. Available K was extracted with 1 M NaCl in neutral solution and determined by atomic absorption spectroscopy.

### Soil sampling and analysis

In spring 1996 and 1997, soil composites from ten subsamples were taken to a depth of 15 cm with a hand-sampler and stored in plastic bags at 4°C in the dark. C and N mineralization rates and respiration were measured in the laboratory as described by Staben et al. (1997). Phosphatase was measured according to Tabatabai (1994). In spring of 1997, earthworms were hand-separated from soil cores 15 cm in diameter and 15 cm in depth; four random subsamples were pooled for each plot. Soil analysis for routine soil nutrients other than mineral N was conducted by the University of Idaho Analytical Sciences Laboratory. Soil C and N were measured with a LECO induction furnace.

Available P and K were extracted with NaOAc. P was determined colorimetrically, and K was determined by atomic absorption spectroscopy. Soil pH was measured from unfiltered 1:1 (w/w) soil: water suspensions. EC was measured using a Hydac conductivity/temperature/pH tester. Cation exchange capacity (CEC) was determined colorimetrically after extracting samples with $NH_4OAc$ followed by NaCl. B was extracted using the hot-water method, and determined using ICP-AES. Micronutrient metals were extracted with diethylene triamine penta acetic acid (DTPA) and determined using ICP-AES.

Bulk density was measured to a depth of 7 cm using a bulk density sampler in soil at field capacity 3 days after field infiltration tests had been performed. Soil impedance (SI) was measured by manually pressing a Soil Test impedance probe to a depth of 15 cm and recording the maximum resistance indicated on the instrument. In fall 1996 and 1997, aggregate stability was determined for macroaggregates (Cambardella and Elliott 1993) from three to five 15-cm-depth soil subsamples combined from each plot in early fall 1996 and 1997. Ponded infiltration was measured in the fall of 1996 by driving ring infiltrometers of 14 cm diameter to a soil depth of 7.5 cm, infiltrating 2.5 cm of water into the soil, and then timing the infiltration of a second 2.5 cm of water (Bouwer 1986). Four infiltration measurements were taken per plot.

### Statistics

ANOVAs were completed with PROC GLM in SAS (SAS Institute 1988). The assumption of normally distributed residuals was tested with a Shapiro-Wilk statistic in PROC UNIVARIATE (SAS Institute 1990). Multiple comparisons were made with a protected least significant difference. Treatment effects were considered insignificant if the probability of rejecting the null hypothesis was <95% ($P > 0.05$). Contrasts were used to compare groups of treatments to one treatment or another group of treatments. Contrasts against "no amendment" refer to the control and 90 kg N ha$^{-1}$.

The different variances in the 1996 infiltration study were determined as follows. Infiltration times were subjected to Levene's test for equal variance in Minitab (Minitab 1994). Upon rejection of Levene's null hypothesis, at least one treatment variance was known to be different from the others, and this was considered sufficient statistical protection to proceed with pairwise comparisons of treatment variances until the differences were determined.

## Results and discussion

### Study 1

At compost application rates of 224 and 448 Mg ha$^{-1}$, soil pH significantly increased from 5.7 in the control to 6.6 and 7.2, respectively (Table 2), reflecting the high pH of the compost amendment. Soil inorganic N content was very low in all three treatments in July 1995 (3 mg N kg$^{-1}$ or less; Table 2). Although perhaps not significant biologically, statistically there was less inorganic N in the compost treatments, suggesting immobilization of N by the compost. Barley yield increased significantly from the application of 224 and 448 Mg ha$^{-1}$ of compost (Table 2). Because 90 kg N ha$^{-1}$ was applied over all plots, the yield advantage from the compost application was probably related to factors other than N.

**Table 2** Soil inorganic N, soil pH, barley yield, and barley grain protein in 1995 (study 1)

| *Compost rate* (Mg ha$^{-1}$) | Inorganic N (mg kg$^{-1}$) | pH | Barley yield (kg ha$^{-1}$) |
|---|---|---|---|
| 0 | 3.1 a | 5.7 a | 2952 a |
| 224 | 2.1 b | 6.6 b | 3877 b |
| 448 | 2.3 ab | 7.2 c | 3895 b |

### Study 2

### *Biological measures*

Soil microbial respiration in 1996 from the compost treatment was higher than from the straw treatment, which in turn was higher than from the other treatments (Table 3). In 1997, only the compost treatment had a higher rate of $CO_2$ evolution. Soil respiration activity in the straw treatment had diminished by 1997, because the labile C therein had likely been oxidized by then.

Laboratory N mineralization (90 days) from 1996 and 1997 samples showed that the compost immobilized N more than a year and a half after its soil incorporation. The low N mineralization from the compost is attributable to its high C:N ratio, the high rate of application, and the fact that no fertilizer N was added with the amendment. The straw, which had a higher C:N ratio, was incorporated at a lower rate and was amended with fertilizer N, and therefore it did not immobilize N.

Phosphatase activity was not increased by any of the treatments, although contrasts showed coal ash decreased phosphatase activity relative to unamended treatments in 1996 and 1997 (Table 3). This is consistent with the findings of Pitchel and Hayes (1990), who found that soil enzyme activity generally decreased with increasing rates of fly ash. The small quantities of inorganic P added through the fly ash increased soil extractable P in 1997 (Table 4) and could also have reduced phosphatase activity as shown by Nannipieri et al. 1978.

Earthworm mass in 1997 was not different between individual treatments, although contrasts of the amendments to unamended treatments showed that at $P = 0.10$ the straw amendment had marginally more earthworm mass than the unamended treatments (Table 3). Compost residues in the soil appeared too coarse or resilient to encourage earthworm populations. Numbers of earthworms were not significantly affected by treatments (data not shown). Earthworms affect soil quality by influencing nutrient availability, water-stable aggregation, field wa-

**Table 3** C respiration, N mineralization, phosphatase activity, and earthworm mass as influenced by soil amendments (*amend.*) in 1996 and 1997. *Values in a column* followed by the *same letter* are not significantly different from one another. *NS* Not significant ($P > 0.10$). *PNP p*-Nitrophenol

| Treatment | Respiration | | Mineralized N | | Phosphatase activity | | Earthworms 1997 (g m$^{-2}$) |
|---|---|---|---|---|---|---|---|
| | 1996 | 1997 | 1996 | 1997 | 1996 | 1997 | |
| | (mg $CO_2$-C 10 days$^{-1}$ kg$^{-1}$) | | (mg N kg$^{-1}$ 96 days$^{-1}$) | | (µg PNP g$^{-1}$) | | |
| 0 N | 66.5 c | 67.9 b | 30.85 a | 11.52 a | 408 a | 264 a | 20.2 |
| 90 kg N ha$^{-1}$ | 58.2 c | 45.3 b | 35.04 a | 16.02 a | 445 a | 274 a | 7.50 |
| Coal ash+90 kg N ha$^{-1}$ | 72.6 c | 54.2 b | 36.54 a | 17.00 a | 361 a | 218 a | 14.2 |
| Compost | 150 a | 191 a | 10.03 b | 1.93 b | 425 a | 287 a | 15.6 |
| Straw+90 kg N ha$^{-1}$ | 109 b | 72.5 b | 33.93 a | 11.87 a | 392 a | 223 a | 23.9 |
| Contrasts ($P > F_o$) | | | | | | | |
| Coal Ash+N vs. no amend. | NS | NS | NS | NS | 0.089 | 0.077 | NS |
| Compost vs. no amend. | <0.001 | <0.01 | 0.0001 | 0.0045 | NS | NS | NS |
| Straw+N vs. no amend. | 0.002 | NS | NS | NS | NS | NS | 0.100 |

**Table 4** Total soil C and N, extractable P, available K, pH, and cation-exchange capacity (*CEC*) as influenced by soil amendments in 1996 and 1997. *Values in a column* followed by the *same letter* are not significantly different from one another

| Treatment | C | | N | | P | | K | | pH | | CEC 1997 [cmol(+) $kg^{-1}$] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1996[a] | 1997[a] | 1996 | 1997 | 1996 | 1997 | 1996 | 1997 | 1996 | 1997 | |
| | (%) | | | | (mg $kg^{-1}$) | | | | | | |
| 0 N | 1.2 c | 1.3 bc | 0.20 a | 0.16 b | 3.4 b | 2.2 c | 58 b | 50 b | 5.9 a | 7.0 a | 22.4 a |
| 90 kg N $ha^{-1}$ | 1.2 c | 1.2 c | 0.20 a | 0.16 b | 3.0 b | 2.4 c | 58 b | 53 ab | 6.0 a | 6.8 a | 23.0 a |
| Coal ash+90 kg N $ha^{-1}$ | 1.6 b | 1.8 b | 0.22 a | 0. 17 b | 3.9 b | 4.4 b | 53 c | 46 b | 6.8 a | 7.6 a | 22.1 a |
| Compost | 1.9 a | 2.9 a | 0.23 a | 0.20 a | 7.3 a | 8.9 a | 69 a | 70 a | 6.4 a | 7.3 a | 23.7 a |
| Straw+90 kg N $ha^{-1}$ | 1.2 c | 1.3 bc | 0.20 a | 0.15 b | 3.0 b | 2.8 bc | 58 b | 53 ab | 6.7 a | 7.1 a | 23.5 a |
| Contrasts ($>F_o$) | | | | | | | | | | | |
| Coal Ash+N vs. no amend. | <0.01 | 0.02 | NS | NS | NS | 0.01 | 0.01 | NS | 0.04 | NS | NS |
| Compost vs. no amend. | <0.01 | <0.01 | NS | 0.01 | <0.01 | <0.01 | <0.01 | <0.01 | NS | NS | 0.08 |
| Straw+N vs.no amend. | NS | NS | NS | NS | NS | NS | NS | NS | 0.09 | NS | NS |

[a] Non-normal distribution. Log transformations of 1996 C data were unsuccessful at normalizing distribution of residuals, but 1997 C statistical analyses are based on successfully transformed data

ter-holding capacity, and water-infiltration time (Lee 1985).

### *Chemical measures*

Compost and coal ash increased soil C in 1996, although in 1997 only compost plots were significantly higher in C than either of the unamended plots (Table 4). Straw amendment did not affect C in either year. The C values may be underestimated because samples were screened through a 2-mm sieve, which excluded larger fragments of straw, ash, and compost. The higher C values in 1997 for compost may be explained by decomposition of larger organic fragments during the 1996 growing season, which would have permitted their inclusion in the 1997 sample.

Soil N in 1996 was not affected by any treatment, although levels were statistically higher in the compost in 1997 (Table 4). Extractable P was significantly higher for compost in both 1996 and 1997 which would be an asset in the eroded hilltop soils, commonly low in plant-available P (Tisdale et al. 1993). Local fertilizer recommendations suggest soil extractable P levels (NaOAc) of at least 3–4 mg $kg^{-1}$ for barley and >4 mg $kg^{-1}$ for peas (Mahler 1991a; Mahler and Guy 1992). In 1996, all plots had received a blanket application of P fertilizer, but extractable P levels were still <4 mg $kg^{-1}$ for all treatments except compost. In 1997, no P fertilizer was applied and P levels were less than 3 mg $kg^{-1}$ except for the ash and compost treatments. The ash and compost treatments were the only ones to provide adequate available P in both years. Soil available K levels >75 mg $kg^{-1}$ (NaOAc) are recommended for barley and peas (Mahler 1991a; Mahler and Guy 1992). Although none of the treatments reached that level, compost provided more K in 1996 and 1997 than did the other treatments (Table 4).

Soil pH was not influenced by any amendment, although contrasts reveal slightly higher values for ash and straw (*P*=0.045 and 0.086, respectively) than for unamended treatments in 1996 (Table 4). Although the unweathered coal ash has a pH of 11.6, previous research on WSU coal ash described the ash as poorly buffered (A. Halvorson, unpublished data), which is consistent with the small pH increase observed. However, significant increases in soil pH were observed at the two higher, spring-applied compost rates in study 1 (Table 2). All treatments had EC values <0.5 dS $m^{-1}$ (data not shown), and EC was not significantly affected by any of the amendments. Contrasts show that compost slightly increased CEC above the levels of the unamended treatments (Table 4), presumably from the presence of humified organic materials as a component of soil CEC (Brady 1990).

Both coal ash and compost increased soil B (Table 5), although levels were all within the range for soils in the region (Mahler et al. 1985). Soil B levels are best maintained above 0.5 mg $kg^{-1}$ for peas (Mahler 1991a). The increased B in those treatments was at least partly from the coal ash, which is 10% by volume of the compost mixture. Coal fly ash has been shown to increase levels of soil and plant B (Martens 1971; Furr et al. 1978; Menon et al. 1993; Salé et al. 1996). In addition, B is positively related to organic matter (Gupta 1979), and non-coal ash components of the compost may also have increased soil B in the compost treatment.

Extractable soil Zn levels in the compost, but not ash plots, were significantly higher than levels in other plots in both years (Table 5). Soil test concentrations >0.6 mg Zn $kg^{-1}$ are considered adequate for peas (Mahler 1991a). The 1997 samples showed compost treatment DTPA soil Zn in excess of 7.0 mg $kg^{-1}$, which Takkar and Mann (1978) found sufficient to cause yield reductions in wheat. However, yields were generally increased by the compost amendment in these studies. Neither Cu, Mn, or Fe were below critical levels in soil (Lindsey and Norvell 1978), nor were concentrations of these elements dramatically influenced by any amendment (Table 5).

**Table 5** Soil water-extractable B and diethylene triamine penta acetic acid-extractable micronutrients as influenced by amendments in 1996 and 1997. *Values in a column* followed by the *same letter* are not significantly different from one another

| Treatment | B | Zn | | Cu | | Mn | | Fe | |
|---|---|---|---|---|---|---|---|---|---|
| | 1997 | 1996[a] | 1997[a] | 1996[a] | 1997 | 1996 | 1997 | 1996 | 1997 |
| | (mg kg$^{-1}$) | | | | | | | | |
| 0 N | 0.24 b | 0.55 b | 3.2 b | 3.0 a | 1.8 a | 32 a | 15 a | 28 a | 36 a |
| 90 kg N ha$^{-1}$ | 0.22 b | 0.67 b | 3.5 b | 3.4 a | 1.8 a | 35 a | 18 a | 29 a | 41 a |
| Coal ash+90 kg N ha$^{-1}$ | 0.96 a | 0.71 b | 3.7 b | 2.6 a | 1.6 a | 26 a | 8 a | 23 a | 27 a |
| Compost | 0.98 a | 2.1 a | 9.6 a | 7.9 a | 1.7 a | 36 a | 15 a | 29 a | 39 a |
| Straw+90 kg N ha$^{-1}$ | 0.14 b | 0.48 b | 2.3 b | 2.8 a | 1.7 a | 33 a | 14 a | 25 a | 31 a |
| Contrasts ($P>F_o$) | | | | | | | | | |
| Coal Ash+N vs. no amend. | <0.01 | NS | NS | NS | 0.02 | 0.04 | 0.01 | 0.08 | 0.07 |
| Compost vs. no amend. | <0.01 | <0.01 | 0.01 | 0.02 | NS | NS | NS | NS | NS |
| Straw+N vs. no amend. | NS | NS | NS | NS | 0.07 | NS | NS | NS | NS |

[a] Non-normal distribution. Statistical analysis based on log-transformed data

**Table 6** Bulk density, soil impedance, and water-stable aggregates as influenced by various amendments in 1996 and 1997. *Values in a column* followed by the *same letter* are not significantly different from one another

| Treatment | Bulk density | | | Soil impedance 1997 (MPa) | Water-stable aggregates | |
|---|---|---|---|---|---|---|
| | Fall 1996 | Spring 1997 | Fall 1997[a] | | 1996 | 1997 |
| | (g cc$^{-1}$) | | | | (%>250 μm) | |
| 0 N | 1.23 a | 1.43 b | 1.27 | 0.141 ab | 12.2 a | 10.12 a |
| 90 kg N ha$^{-1}$ | 1.17 a | 1.52 b | 1.23 | 0.151 a | 11.3 a | 12.88 a |
| Coal ash + 90 kg N ha$^{-1}$ | 1.18 a | 1.40 b | 1.14 | 0.157 a | 9.6 a | 12.73 a |
| Compost | 1.10 a | 1.14 a | 1.13 | 0.121 b | 11.9 a | 17.07 a |
| Straw+90 kg N ha$^{-1}$ | 1.09 a | 1.41 b | 1.09 | 0.150 a | 15.2 a | 13.78 a |
| Contrasts ($P>F_o$) | | | | | | |
| Coal Ash+N vs. no amend. | NS | NS | NS | NS | NS | NS |
| Compost vs. no amend. | 0.087 | <0.001 | 0.071 | 0.020 | NS | 0.0192 |
| Straw+N vs. no amend. | 0.054 | NS | NS | NS | 0.0853 | NS |

[a] Least significant difference not applicable due to missing data

Environmental concerns have been raised about the disposal of industrial by-products, including coal ash, as agricultural soil amendments (Raven and Loeppert 1997; Wilson 1997). Results of the soil micronutrient analysis reveal that of the metals tested, none except for Zn in the compost-amended soil give cause for concern.

### *Physical measures*

Soil bulk density in the compost treatment was generally the lowest (Table 6). In 1996, contrasts show that the bulk density in the straw amendment was significantly lower than that of the unamended treatments ($P=0.054$). Bulk densities of spring samples taken at the end of the winter rainfall were generally higher than those of fall samples taken at the end of the dry summer season. SI, a measure of penetration resistance, for compost in spring of 1997 was lower than in unamended treatments (contrast $P=0.020$; Table 6). SI is a function of soil moisture and bulk density (Taylor and Gardner 1963). Along with soil porosity, SI is a critical factor in plant root development. Ehlers et al. (1983) have shown a negative linear correlation between SI and root growth.

Water-stable aggregation conveys information about the soil's resistance to dispersion and erosion; it is also a general indicator of favorable soil structure for rooting and water infiltration (Karlen and Stott 1994). Soil organic matter has been loosely correlated with aggregate stability (Tisdale and Oades 1982; Boyle et al. 1989), and it is reasonable to expect that organic soil amendments may exert a positive influence on this parameter. Aggregate stability measures in 1996 showed that the straw treatment resulted in a slightly greater proportion of water-stable macroaggregates than did the unamended treatments (contrast $P=0.0853$; Table 6). However, in the second year after incorporation, it was the compost amendment that improved water-stable aggregation over the unamended treatments ($P=0.0192$); the straw amendment no longer had an effect. The coal ash amendment had no influence on water-stable aggregation in either year. These results are consistent with the findings of Sun et al. (1995)

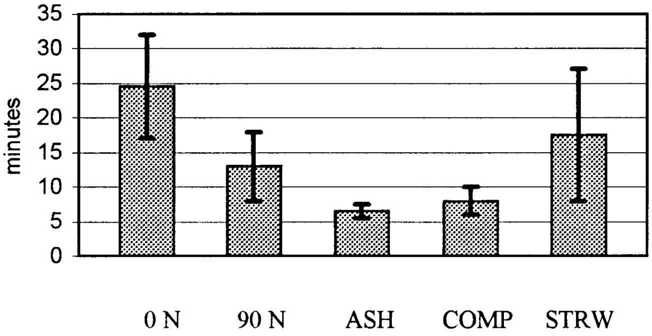

**Fig. 1** Time for 2.5 cm of water to infiltrate in 1996. Variances are not equal between treatments. *Error bars* represent 1 SD from the treatment mean

Ponded infiltration rates measured in 1996 were not significantly different due to the high variability of some treatments (statistics not shown; Fig. 1). However, the compost and coal ash treatments had the shortest mean infiltration times. Further, *F*-tests for equality of variances show that the compost and coal ash plus N treatments are less variable than unamended treatments at $P$=0.05 and $P$=0.10, respectively (statistics not shown). Therefore an application of coal ash or compost can be expected to give rapid infiltration at a more predictable rate, whereas straw-amended or unamended soils are less predictable in terms of infiltration rates. Rapid infiltration on hilltops is especially desirable because more infiltration results in less runoff and erosion.

Because the ash is not screened, it contains hard, coarse, mineral-like particles and is likely to promote infiltration by simulating a change in soil texture. Soil structure may be affected as well. The coal ash is a mix of bottom ash and fly ash, both of which have been shown to improve aeration and texture of clayey soils (Chang et al. 1977; Sell et al. 1989). Chang et al. (1977) found that hydraulic conductivity increased with additions of fly ash at rates <10%. In the present study, mixed bottom and fly ash were applied at approximately 5% of the furrow slice, so the results reported here are consistent with the observations of Chang et al. (1977).

## Crop yield and trace element content

Spring barley yields in 1996 ranged from 2,300 to 3,350 kg ha$^{-1}$, but were not significantly influenced by any treatment, although plots receiving fertilizer N yielded significantly higher than plots not receiving N (contrast $P$=0.002; Table 7). The low amount of N mineralized in the compost plots may explain the low yield in spite of improved soil physical properties and increased availability of other nutrients. In study 1, all treatments received the conventional 90 kg N ha$^{-1}$ rate of N fertilizer, which offset the N-immobilizing activity of the compost and resulted in higher crop yield.

Spring pea was grown in 1997, and no significant yield differences occurred among the treatments (Table 7). Pea yield was low in all treatments, which reflects the low productivity of hilltop sites in the region. Mahler et al. (1979) cited similar Palouse hilltop pea yields of 480 kg ha$^{-1}$ compared to bottomland yields of >2,000 kg ha$^{-1}$.

Wheat yield in 1998, 3 years after application of the amendments, was significantly greater for the compost treatment compared with the control (Table 7). Coal ash and wheat straw amendments did not influence wheat yield. The higher yield from the compost treatment presumably resulted from advantages to the crop in terms of soil fertility, soil structure, and perhaps water infiltration. Mahler (1991b) reported no benefit to winter wheat from micronutrient applications, but it is possible that the higher P levels observed in compost treatment enhanced wheat yield. The 1998 yield response to fertilizer N in the compost treatment provides further evidence that 1996 barley yields in the compost treatment were limited primarily by low availability of mineral N. In this study, the compost-induced changes to soil quality did not translate into higher soil productivity until fertilizer N was applied.

Uptake of trace elements by barley grain in 1996 was either below detection levels or was not significantly affected by the coal ash amendment or the coal ash in the compost (Table 8). Barley grain Cu was elevated slightly in the high N, coal ash, and compost treatments relative to the control. Se was elevated in the ash treatment. This

**Table 7** Crop grain yields 1996–1998 as influenced by soil amendments and N. No fertilizer was applied to the 1997 peas and the 1998 winter wheat received the same fertilizer rate for all treatments. *Values in a column* followed by the *same letter* are not significantly different from one another

| Treatment | 1996 Spring barley yield[a] | 1997 Spring pea yield | 1998 Winter wheat yield |
|---|---|---|---|
| | (kg ha$^{-1}$) | | |
| 0 N | 2316 a | 528 a | 7806 b |
| 90 kg N ha$^{-1}$ | 3174 a | 409 a | 7404 b |
| Coal ash+90 kg N ha$^{-1}$ | 3350 a | 375 a | 7462 b |
| Compost | 2194 a | 507 a | 8610 a |
| Straw+90 kg N ha$^{-1}$ | 2910 a | 450 a | 7232 b |
| Contrast ($P$>$F_o$) | | | |
| N vs. no N | 0.0022 | | |
| Coal Ash+N vs. no amend. | | NS | NS |
| Compost vs. no amend. | | NS | 0.001 |
| Straw+N vs. no amend. | | NS | NS |

[a] Non-normal distribution. Statistical analysis based on log-transformed data

**Table 8** Trace element content of 1996 barley grains. *Values in a column* followed by the *same letter* are not significantly different from one another

| Treatment | Al | As[a] | Cd[a] | Co[a] | Cr[a] | Cu | Fe | Mn | Mo[a] | Ni[a] | Pb[a] | Se[a] | Va[a] | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ($\mathrm{mg\ kg^{-1}}$) | | | | | | | | | | | | | |
| 0 | 6.6 | 0.050 | <0.15 | <0.57 | <0.50 | 5.2 a | 8.3 | 13 | 2.1 | 0.51 | <2.7 | 0.02 b | <0.52 | 26 |
| 90 kg N $\mathrm{ha^{-1}}$ | 8.1 | 0.050 | <0.15 | <0.57 | <0.50 | 5.8 b | 7.4 | 12 | 1.6 | 0.26 | <2.7 | 0.02 b | <0.52 | 25 |
| Coal ash+N | 8.8 | 0.066 | <0.15 | <0.57 | <0.50 | 6.0 b | 7.5 | 13 | 1.8 | 0.43 | <2.7 | 0.24 a | <0.52 | 28 |
| Compost | 8.9 | 0.044 | <0.15 | <0.57 | <0.50 | 5.9 b | 9.1 | 13 | 1.1 | 0.54 | <2.7 | 0.02 b | <0.52 | 24 |

[a] Analysis included data below estimated detection limit

element is deficient in the diet of cattle in the region and is often supplemented in the feed.

In conclusion, straw, coal ash, and compost affected soil quality differently. Coal ash did not consistently affect microbial properties, except by slightly suppressing phosphatase activity in both years. Coal ash increased soil pH slightly in the first year, but is not suitable as a liming agent, since by the second year, soil pH returned to the unamended level. Soil fertility was marginally enhanced for soil B and P, and infiltration properties were improved. Coal ash incorporated at 110 Mg $\mathrm{ha^{-1}}$ did not result in toxic levels of any trace elements investigated in the soil or in barley grain. Coal ash did not influence crop yield.

The straw amendment application rate was limited by its bulky structure and consequently its effectiveness in soil building properties. Most of the effects observed occurred only during the first year after incorporation, when straw reduced soil bulk density and improved the stability of macroaggregates. By the second year, microbial biomass and respiration returned to the levels of the unamended treatments. The short duration of the straw amendment effects on soil quality made it a poor choice as a soil amendment for one-time application, particularly since yield was not influenced.

Of the three amendments, compost improved the broadest spectrum of soil quality. Compost significantly increased soil pH only at high rates in study 1. It increased soil organic matter and the soil nutrient status of several potentially limiting nutrients such as P and K. Soil physical properties were most dramatically affected by the compost, which reduced bulk density and SI, while improving water infiltration and eventually increasing water-stable macroaggregates. Yield of barley was significantly increased in study 1, when supplemental N was added. In study 2, no supplemental N was added to the compost treatment, and yield of barley and pea were not affected by the compost. Barley yield appeared to be inhibited by soil N immobilization, resulting from the low N content of the compost. Eventually, the compost would have mineralized N at some time in the future. Winter wheat yield in 1998, 3 years after the amendments were incorporated, was significantly increased by the compost application because supplemental N was added in that year. Compost holds promise as an effective means of soil quality restoration on eroded slopes.

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