Short communication

Effects of repeated sewage sludge application on plant community diversity and structure under agricultural field conditions on Podzolic soils in eastern Quebec

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Abstract

In Quebec, municipal sewage sludge application on agricultural lands is relatively recent and there are many concerns related to potential contamination and loss of plant productivity. This study aimed at monitoring the impacts of repeated, long-term application of sewage sludge on agricultural lands under operating field conditions. Eight paired study sites (treated and control) in three regions of the Eastern Townships (Que., Canada) were selected. Vegetation surveys were carried out twice a season for 2 years and soil samples were collected. Diversity index ($D$), yield production and percentage of weeds were measured in each field. The average number of species per site and treatment varied from 10 to 36 but the differences between control and treated plots for all sites were not significant. The diversity indices significantly varied between sites due to original soil composition differences between locations. In some cases, significant differences in diversity existed between paired treated and control fields. However, weed percentage did not necessarily vary in those same fields suggesting that change in diversity did not lead to changes in number of weeds. Soil chemical composition showed that significant variation existed between sites but not between paired fields. Correlation performed between diversity, production, weed frequency and soil parameters showed that variation in $D$ was negatively correlated with Mg and positively with pH. At the same time, the percentage of weeds was negatively associated with K, Ca and pH ($P<0.05$). Although sewage sludge produced little direct effect on the ecological parameters, analyses suggest that some soil chemical factors may affect plant diversity and percentage of weeds. These results indicate that plant community ecology may be affected by changes in environmental conditions but in a complex manner. Monitoring programs should be developed to evaluate the long-term impacts of repetitive sludge application on agricultural lands. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Environmental monitoring; Sewage sludge; Weeds; Diversity; Productivity

1. Introduction

For the last three decades in Canada, municipal sewage sludge has been used for amending/fertilizing agricultural or forest soils (Menviq, 1991). There are, however, serious concerns about potential heavy metal contamination (Logan and Chaney, 1983; Gardiner
et al., 1995; Rao and Shantaram, 1996; Vasseur et al., 1998). In most evaluation/monitoring studies, plants are used to test the potential toxicity of such amendment materials in controlled conditions (Vasseur et al., 1998). This procedure is quite rapid but does not allow for studying long-term effects on plant communities and heavy metal accumulation under normal farming operations.

In Quebec, municipal sewage sludge has been applied to agricultural soils for about 10 years. But this type of disposal actually represents less than 7% of the total sewage sludge produced in the province. Most of the sludge is currently disposed of in landfill sites. These numbers may drastically change over the next few years since the Ministry of Environment has recently recommended banning the disposal of unstabilized sewage sludge into landfill sites (BAPE, 1997, public communication). Alternatives such as land application will certainly appear more attractive to certain municipalities, mainly because of lower costs than composting and incineration.

Concerns about potential risks due to the presence of heavy metals and pathogens explain the low actual percentage of sewage sludge diversion towards agricultural and forest systems in Quebec. High levels of heavy metals can result in contamination of the habitat and modifications of the environmental conditions (e.g. soil quality) leading to changes in plant diversity (e.g. weed invasion) and productivity (Chang et al., 1992; Hooda and Alloway, 1994). Climatic conditions can also influence heavy metal accumulation into the soil and absorption rate by the plants (Vasseur et al., 1996, 1998). Since all the factors may vary at the same time in the field, controlled or laboratory tests may not effectively reflect the outcome of such treatments. Although field surveys under operating conditions have limitations, it becomes, therefore, essential to monitor the effects of such applications on agricultural lands.

As part of a continuing effort in Quebec, to better understand the potential impact of municipal sewage sludge application on agricultural ecosystems, a monitoring survey was conducted at a range of study sites. The objectives of this monitoring survey were (1) to assess changes in community structure (species composition and weed proportion) and plant productivity in hay-fields previously applied with sewage sludge, and (2) to examine if these changes could be associated with variation in soil chemical composition. The surveys were done in fields that were used for pasture during the course of the survey and were applied for at least 1 year (between the period of 1986 until 1994) with sewage sludge from the same region.

2. Materials and methods

2.1. Study sites

Eight study sites were selected in the Eastern Townships region of the province of Quebec (Canada). The study sites are situated in the range of the basswood-sugar maple (Acer Saccharum Marsh) forest ecosystem, on the Appalachian geological division (Berard and Cote, 1996). The soils are well drained loam, Podzols from glacial origin with a thick (>1 m) undifferentiated till (FAO, 1991; Berard and Cote, 1996). Soil pH varied from 4.5 to 6.0. The regional annual mean temperature is approximately 4°C and the annual precipitation is about 1000 mm with 25–30% as snowfall (Berard and Cote, 1996).

These sites had all similar farming practices. They consisted in a rotation of hay production for livestock feed, plowing and reseeding. They were selected because sewage sludge application programs had already been implemented and some farmers had received sewage sludge for a number of years. The first two sites (sites 1 and 2) were located in the municipality of Victoriaville. Sewage sludge came from the Victoriaville wastewater treatment plant where stabilized sludge originated from aerated ponds. Due to a change in type of culture, the survey of site 1 was only done in 1994. Four sites (sites 3–6) were situated in the region of Lac-Megantic. Biologically activated sludge from the municipality's treatment plant, stabilized for 21 days prior to application, was applied on those fields. Site 7 was located in the area of Sherbrooke. It received composted sewage sludge (BO-VAL, Fertival Inc., Sherbrooke), produced from sewage sludge from the treatment plant of the municipality of Sherbrooke. This secondary wastewater treatment plant produced biologically activated sludge. The application rates and frequencies as well as the basic composition of the sludge are described in Table 1. In all cases, the sewage sludge met the standards of the Ministry of Environment for land application (Menviq, 1991).
Table 1
Quantity, application frequency and chemical analysis of sewage sludge, used in the treated fields monitored in the present study

<table>
<thead>
<tr>
<th>Sites</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of applications</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Quantity of sludge applied (dry Mg ha)</td>
<td>1.8</td>
<td>1.3</td>
<td>7.5</td>
<td>14.1</td>
<td>3.2</td>
<td>9.4</td>
<td>30.4</td>
</tr>
<tr>
<td>Dry matter content in the sludge (%)</td>
<td>13.2</td>
<td>2.06</td>
<td>2.3</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>44.7</td>
</tr>
<tr>
<td>pH</td>
<td>6.6</td>
<td>6.9</td>
<td>6.4</td>
<td>6.2</td>
<td>6.4</td>
<td>6.4</td>
<td>12.3</td>
</tr>
<tr>
<td>Total Kjeldahl nitrogen (mg kg⁻¹)⁺</td>
<td>62187</td>
<td>34450</td>
<td>74964</td>
<td>74285</td>
<td>74624</td>
<td>76606</td>
<td>19688</td>
</tr>
<tr>
<td>NH₃ (mg kg⁻¹)⁺</td>
<td>2596</td>
<td>6700</td>
<td>8510</td>
<td>3254</td>
<td>5882</td>
<td>3285</td>
<td>506</td>
</tr>
<tr>
<td>Available P (mg kg⁻¹)⁺</td>
<td>23666</td>
<td>18800</td>
<td>17649</td>
<td>20198</td>
<td>18924</td>
<td>20897</td>
<td>10241</td>
</tr>
<tr>
<td>K (mg kg⁻¹)⁺</td>
<td>5525</td>
<td>2700</td>
<td>9252</td>
<td>9437</td>
<td>9437</td>
<td>878</td>
<td></td>
</tr>
</tbody>
</table>

⁺Sewage sludge samples were analyzed by certified Quebec laboratories using standards for chemical analyses (Eaton et al., 1995). Available P was analyzed using the Mehlich III method (Menviq, 1991). P=Phosphorus and K=Potassium.

2.2. Vegetation surveys

All the sites were divided into two sections: (1) control, where no sludge was applied and (2) treated, where sludge was applied according to the information given in Table 1. This experimental design was used in order to reduce heterogeneity in the data due to initial variation in soil and community composition. In each of these two sections, in June and August of the 2 years (1994 and 1995) of the survey (i.e. just before each hay-harvest) species composition was recorded. To do so, a grid of three to four transects separated by a minimum distance of 2 m was used. Vegetation was surveyed along these transects in a total of 12 quadrats of 0.09 m² (30 cm x 30 cm). The three transects were of a minimum of 20 m and separated from each other by a minimum distance of 5 m. The grid was established in the center of the field to reduce edge effects. Plant species were identified and their abundance evaluated according to the percentage cover for each species (recorded by 10% interval). Once the species were identified and their abundance measured, vegetation in the quadrat was clipped and brought back to the laboratory for the measure of plant productivity (or dry weight). The collected vegetation samples were placed in a dryer-oven at 80°C for a period of 4–5 days, then weighed.

After each mapping, plant diversity was calculated using the Simpson’s index, \( D \). It is a measure of species ‘evenness’ to provide an indication of dominance patterns (Lewis et al., 1978). The specific composition per quadrat at each mapping was used to calculate \( D \) defined as

\[
D = \sum \frac{1}{p_i^2}
\]

where \( p_i \) is the fractional abundance of the \( i \)th species. The percent cover was used as a measure of abundance. These indices were calculated per quadrat for each treatment, each harvest and each year of the survey. Then averages were used for comparison analyses. The percentage of weeds was also calculated. Species were identified as weeds according to Frankton and Mulligan (1977). These species were considered either harmful for livestock or, of less economic importance in hay fields.

2.3. Soil analysis

In June 1994, five samples of the surface horizon of soil were collected to a depth of 0–20 cm in each site. The five replicates were taken using a ‘W’ design to account for heterogeneity. The procedure was repeated in each section (treated and control) of the site (i.e. 5 samples x 2 sections x 7 sites for a total of 70 soil samples). The soil was ground to pass a 2 mm sieve and dried at room temperature (20–25°C) for two weeks before being sent for chemical analyses (Camire, Universite Laval, Que., Canada). The concentrations in organic C, total N, P (Bray II method), K, Ca, Mg, Mn, Na, Al, and pH were evaluated for each sample. Total nitrogen (including nitrates and nitrites) was determined through a digestion with sulfuric acid–salicyclic acid–Kjeltabs Mt (K₂SO₄+HgO)
solution (Tecator Digestion System 20 1005 Heating Unit linked to Tecator Autostep 1012 Controller) then sampled with Tecator Kjeltec Auto 1030 Analyser (Bremner and Madison, 1982). Organic carbon oxidized with dichromate was evaluated with Mettler DL-20 Compact Titrator equipped with a platinum electrode (oxydoreduction) (Yeomans and Bremner, 1988). Phosphorus was extracted according to the Bray II method and the concentration measured by ICP (Bray and Kurtz, 1945). Potassium, Mn, Mg, Ca, Al and Na were first extracted using a BaCl₂ 0.1 M+NH₄Cl 0.1 M solution then concentrations were estimated by ICP and titration (Mettler DL-20 Compact Titrator) (Amacher et al., 1990). Soil pH was measured using the CaCl₂ 0.01 M method.

2.4. Data analyses

In order to satisfy the normality assumption prior to statistical analyses, Simpson index, D, was arcsin-transformed and the percentage of weeds was square root-transformed. In the first step, for each year, three-way ANOVAs were performed. This first analysis gave some indication of the level of variation between the different parameters (site, treatment and harvest). However, since the main goal was to compare between paired control and treated sections of the same site, pair-wise one-way analyses of variance were performed for each site.

The association between soil composition and ecological parameters (productivity, percent cover and percent of weeds) was analyzed by calculating Pearson correlation coefficients (Rao, 1998). All statistical analyses were performed on SPSS package Version 6.1 (SPSS, 1996).

3. Results and discussion

3.1. Vegetation surveys

The surveys and mapping of 1994 and 1995 allowed for the identification of more than 36 plant species. The average number of species per site and treatment varied from 10 to 36 (Table 2). A few species such as *Poa pratensis* L., *Phleum pratense* L., *Trifolium repens* L. and *Agropyron repens* (L.) Beauv. were commonly found in all the sites. Considering all the sites, the average number of species was not statistically different between control and treated plots (P>0.05).

The Simpson diversity index (D), percent of weeds and biomass significantly varied between sites (F=13.79, 19.64 and 21.60, respectively, P=0.001). These reflect the differences in species mixture planted by the farmers. It can also be related to variation in edaphic conditions between sites. When individual pair-wise comparisons were performed between control and treated fields in a same site, there were no significant differences in diversity and dry weight (Table 2). However, in two of the June 1995 surveys, D was significantly higher in the treated field than the control of site 3, and site 7 had higher D in the control fields (data not shown). Several factors may have contributed to these differences including soil and plant spatial heterogeneity and variance in seed mixture. Such variation between pastures has been reported in several occasions (Bazzaz, 1996).

In agricultural sites, the main concern for farmers is the quality and productivity of the crop. The percentage of weeds can give a useful indication of the quality of the crop. Thus, the proportion of weeds versus economically important species in the field can greatly influence the farmer’s income and subsequently farming practices. In the present study, the mean percentage of weeds ranged from 14 to 56% of the species present in a field (Table 2). The only significant difference between treated and control field occurred in site 2 (Table 2). This high level of variation between sections and sites can be attributed to the age of the fields and cultures, the types of farming practices and the level of potential contamination.

Several studies have shown that weeds can be more resistant to soil contaminants than native or economically important species (Aniol and Gustafson, 1990). The ecology of weeds (e.g. fast germination and growth rates) allows them to establish rapidly and often more efficiently than other species. In agricultural fields, high proportions of weeds can reduce crop quality, interfere with harvesting and/or management operations, reduce land values and limit choices of crop rotation sequences (Ross and Lembi, 1983; Zimdahl, 1993). Therefore, the high percentages of weeds in some of the study sites may be detrimental for the farmer but their presence does not seem to be directly related to the addition of sewage sludge.
Table 2
Mean values per section of each study site for species number, Simpson index ($D$) plant productivity (dry weight), and percent of weeds using all the surveys of 1994 and 1995.

<table>
<thead>
<tr>
<th>Traits</th>
<th>Site 1</th>
<th></th>
<th>Site 2</th>
<th></th>
<th>Site 3</th>
<th></th>
<th>Site 4</th>
<th></th>
<th>Site 5</th>
<th></th>
<th>Site 6</th>
<th></th>
<th>Site 7</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Treated</td>
<td>Control</td>
<td>Treated</td>
<td>Control</td>
<td>Treated</td>
<td>Control</td>
<td>Treated</td>
<td>Control</td>
<td>Treated</td>
<td>Control</td>
<td>Treated</td>
<td>Control</td>
<td>Treated</td>
<td>Control</td>
</tr>
<tr>
<td>Species No.</td>
<td>18</td>
<td>18.5</td>
<td>12.5</td>
<td>11.8</td>
<td>31.2</td>
<td>29.2</td>
<td>31.5</td>
<td>25.2</td>
<td>14.5</td>
<td>17</td>
<td>18.2</td>
<td>19.5</td>
<td>11</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td>(2.8)</td>
<td>(3.5)</td>
<td>(1.3)</td>
<td>(1.3)</td>
<td>(1.9)</td>
<td>(2.5)</td>
<td>(3.3)</td>
<td>(2.6)</td>
<td>(2.1)</td>
<td>(1.4)</td>
<td>(3.2)</td>
<td>(3.3)</td>
<td>(1.4)</td>
<td>(0.7)</td>
</tr>
<tr>
<td>$D$</td>
<td>0.665</td>
<td>0.782</td>
<td>0.655</td>
<td>0.581</td>
<td>0.847</td>
<td>0.801</td>
<td>0.787</td>
<td>0.846</td>
<td>0.746</td>
<td>0.706</td>
<td>0.692</td>
<td>0.620</td>
<td>0.614</td>
<td>0.760</td>
</tr>
<tr>
<td></td>
<td>(0.306)</td>
<td>(0.183)</td>
<td>(0.200)</td>
<td>(0.168)</td>
<td>(0.074)</td>
<td>(0.150)</td>
<td>(0.208)</td>
<td>(0.116)</td>
<td>(0.095)</td>
<td>(0.134)</td>
<td>(0.186)</td>
<td>(0.196)</td>
<td>(0.265)</td>
<td>(0.122)</td>
</tr>
<tr>
<td>% weeds</td>
<td>23.8</td>
<td>14.2</td>
<td>28.9 a</td>
<td>55.6 b</td>
<td>28.4</td>
<td>33.9</td>
<td>51.6</td>
<td>37.3</td>
<td>33.5</td>
<td>33.8</td>
<td>40.4</td>
<td>33.0</td>
<td>25.4</td>
<td>23.4</td>
</tr>
<tr>
<td></td>
<td>(25.0)</td>
<td>(10.8)</td>
<td>(19.1)</td>
<td>(22.4)</td>
<td>(14.3)</td>
<td>(17.5)</td>
<td>(22.0)</td>
<td>(19.8)</td>
<td>(13.3)</td>
<td>(16.1)</td>
<td>(16.1)</td>
<td>(20.3)</td>
<td>(24.0)</td>
<td>(19.4)</td>
</tr>
<tr>
<td>Dry weight (g)</td>
<td>15.0</td>
<td>20.9 (9.9)</td>
<td>32.2</td>
<td>31.2</td>
<td>14.1</td>
<td>14.0</td>
<td>26.9</td>
<td>24.7</td>
<td>25.5</td>
<td>23.9</td>
<td>22.5</td>
<td>27.7</td>
<td>48.2</td>
<td>48.9</td>
</tr>
<tr>
<td></td>
<td>(10.1)</td>
<td>(9.9)</td>
<td>(7.4)</td>
<td>(8.5)</td>
<td>(4.6)</td>
<td>(5.1)</td>
<td>(8.6)</td>
<td>(8.9)</td>
<td>(6.4)</td>
<td>(6.7)</td>
<td>(8.4)</td>
<td>(11.3)</td>
<td>(12.4)</td>
<td>(16.5)</td>
</tr>
</tbody>
</table>

S.D. values are in parenthesis. Different letters following entries within a row and site indicate that the means were significantly different between treated and control sections.
Table 3
Mean characteristics of chemical soil analyses carried out on control and treated sections in the five study sites in 1994

<table>
<thead>
<tr>
<th></th>
<th>C (g kg(^{-1}))</th>
<th>N (g kg(^{-1}))</th>
<th>P (µg g(^{-1}))</th>
<th>K (µg g(^{-1}))</th>
<th>Ca (µg g(^{-1}))</th>
<th>Mg (µg g(^{-1}))</th>
<th>Mn (µg g(^{-1}))</th>
<th>Al (µg g(^{-1}))</th>
<th>Na (µg g(^{-1}))</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>3.97</td>
<td>24.7</td>
<td>25.85</td>
<td>0.162</td>
<td>12.68</td>
<td>0.758</td>
<td>0.046</td>
<td>0.157</td>
<td>0.058</td>
<td>5.76</td>
</tr>
<tr>
<td></td>
<td>(1.81)</td>
<td>(13.4)</td>
<td>(8.09)</td>
<td>(0.115)</td>
<td>(15.50)</td>
<td>(0.464)</td>
<td>(0.026)</td>
<td>(0.150)</td>
<td>(0.021)</td>
<td>(0.70)</td>
</tr>
<tr>
<td>Treated</td>
<td>2.27</td>
<td>16.1</td>
<td>24.60</td>
<td>0.112</td>
<td>6.03</td>
<td>0.619</td>
<td>0.040</td>
<td>0.119</td>
<td>0.044</td>
<td>5.50</td>
</tr>
<tr>
<td></td>
<td>(0.54)</td>
<td>(3.4)</td>
<td>(20.98)</td>
<td>(0.054)</td>
<td>(1.14)</td>
<td>(0.380)</td>
<td>(0.019)</td>
<td>(0.056)</td>
<td>(0.016)</td>
<td>(0.09)</td>
</tr>
</tbody>
</table>

* S.D. values are in parenthesis.

Plant productivity can also influence the willingness of a farmer to use a new type of soil amendment or fertilizer such as sewage sludge. If the results from monitoring programs, such as this one, showed that productivity was higher than without addition of soil amendment, farmers might be more willing to use such products. In the present study, however, results suggest that there was no significant increase in plant dry weight between treated and control fields. Most farmers may still accept this type of soil amendment since there is no cost associated with the application (the municipality does not charge for the product). However, other concerns such as heavy metal and pathogen contamination may limit its acceptance.

3.2. Soil properties

For most sites, there were no significant differences in soil compositions between treated and control paired-fields (Table 3). Site 1 was the only one showing significant variation for more than one soil parameter (N, C, Mg, Ca, Na, pH). These results, however, may be biased since the landowner applied lime in the spring of 1994 to increase the soil pH in the control section. In the control field of site 6, according to some discussion with the landowner, it is highly probable that the content of K is significantly higher because of wood ash application. The present concentrations of measured elements in this study are below the amounts suggested for agricultural soils (Jacobs, 1981).

Correlation coefficients between physical and ecological parameters measured in the six sites were calculated to determine whether some ecological parameters might vary in function of physical factors. Correlation coefficients show that the percent of weeds significantly \((P<0.05)\) increases with a decrease in Ca \((r=-0.631)\), K \((r=-0.657)\) and pH \((r=-0.583)\), D is negatively related to Mg \((r=-0.624, P<0.05)\), and productivity is positively correlated to Mg \((r=0.588, P<0.05)\).

Although sewage sludge produced little direct effect on plant community parameters, according to these correlation analyses, variation in plant diversity, percentage of weeds and productivity may be significantly related to variation in soil pH and other elements such as Mg and Mn. The biological interpretation of those associations may be complex and related to the types of soils and fertilizers/amendment used. It is highly possible that the type of farming practices used and how recent the manipulations such as plowing and reseeding were done can also explain these relationships. Results suggest that in the long-term, pH should be monitored. As proposed by MacLean et al. (1987) continuous application of sludge should not be allowed on lands where soil pH is low, even if sewage sludge does not contain high levels of heavy metals.

Plant diversity was negatively associated with Mg concentration in soil. Although Mg is not a limiting nutrient in soils, Pendias and Pendias (1984) noted antagonistic effects with some microelements such as, Mn, Zn, Ni, Cu, and Fe. Therefore, Mg may have become a limiting factor for some plant species, thus reducing their presence. It is also possible that some species survive and outcompete other species, reducing biodiversity. Further research would be necessary to better understand these relationships and should include longer monitoring programs.

4. Conclusions

In the present study, the results showed that little or no significant effects on plant community ecology were detected. This was true for the different types/origin of sludge using various rates and frequencies of sludge application. This low variation between
treated and control fields may be explained by the fact that in Quebec, under operating conditions, it is often difficult to reach the maximum allowable application rate. Due to climatic and/or edaphic constraints, most Quebec’s farmers cannot work on their land before mid-May. Under strict regulations (Menviq, 1991), this leaves little time for sludge application.

Further studies are still needed in this region to fully understand the interactions between sewage sludge and soil parameters. However, a recent study on pathogen contamination after sludge application in Quebec’s soils (Vasseur et al., 1996) has reported that climatic conditions such as early frosts, summer droughts and cold winters, influenced the level of assimilation and contamination of bacteria in the soils. In regions where climatic conditions are limiting and/or soils are generally acidic, monitoring is essential to evaluate the long-term impacts of sludge application.

Controlled experiments in pots or in the field are more common but have shown contradicting results (Valderes et al., 1983; Cimino and Toscano, 1993; Aitken, 1995; Gardiner et al., 1995). As it is often difficult (if not impossible) to generalize from these studies, monitoring remains an important step towards improving regulations.

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