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Impacts of paper sludge and manure on soil and biomass production of willow

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ABSTRACT

Land application of organic wastes to short rotation woody crops (SRWC) can reduce the environmental impacts associated with waste disposal and enhance the productivity of biomass production systems. Understanding the potential impacts of organic amendments however, requires the examination of changes in soil characteristics and plant productivity. This study was conducted to evaluate the effect of paper sludge and dairy manure on biomass production of shrub willow (*Salix dasyclados* SV1) and to determine the impacts of these amendments on soil chemical properties. Treatments included urea, dairy manure and paper sludge separately and in combination, and a control. These materials were applied in the summer of 2005 to two fields of SV1 at different stages of growth: An old field with one year old shoots on a 10 year old root system and a young field which was beginning regrowth after being coppiced at the end of its first growing season. Foliar nutrient concentrations and soil chemical properties were analyzed at the end of the second growing season after treatment application to determine plant response to the fertilization regimes and to determine the effects of fertilization on soil characteristics. Fertilization did not increase biomass production in either field. However, application of the N-poor paper sludge did not reduce yield either. In general, fertilization did not influence soil or foliar chemistry, although there were some exceptions. The lack of response observed in this study is probably related to the nutrient status of the site or losses of applied nutrients.

1. Introduction

The production of short rotation woody crops (SRWC) is projected to be an important source of renewable energy in the coming decades [1,2]. Shrub willow (*Salix* spp.) is an ideal SRWC candidate because it is easy to propagate, has a short breeding cycle, can resprout after multiple harvests, and produces high yields within a few years. Average annual biomass yields in shrub willow biomass crops systems range from 10 to 15 dry Mg ha^{-1} [3–6], but biomass yields can be as high as 27–30 Mg ha^{-1} when crops are fertilized and irrigated [3,7–9]. Maintenance of site conditions over multiple rotations

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requires that nutrients removed in harvested woody biomass be replenished. According to Adegbidi et al. [3], an annual biomass production of 15–26 Mg ha^{-1} annually removes 75–100 kg ha^{-1} of nitrogen (N), 10–12 kg ha^{-1} of phosphorus (P), and 25–40 kg ha^{-1} of potassium (K) in the woody biomass. Kopp et al. [9] obtained an annual biomass yield of up to 16.3 Mg ha^{-1} with the annual application of 336 kg ha^{-1} of N, 112 kg ha^{-1} of P and 224 kg ha^{-1} of K, respectively. Hytonen [10] observed an increase in willow biomass production due to fertilization at annual rates of 100–200 kg ha^{-1} of N, 20–40 kg ha^{-1} of P and 100–200 kg ha^{-1} of K. These studies indicate that nutrient additions to willow production systems can influence biomass yields under certain conditions [11].

The cost of commercial fertilizer is an important component of the inputs needed for the production of willow biomass crops. An analysis of willow biomass crop production in New York State indicated that fertilizer can make up 10–20% of the cost of production over seven rotations [12]. Nitrogen fertilizer input into willow production systems in the US has been estimated to account for 37% of the non-renewable fossil energy input to these systems [13]. By relying on commercial N fertilizers, these systems indirectly require significant inputs of fossil energy and thus decrease both their potential environmental and economic benefits [2,12]. Replacing inorganic commercial fertilizers with organic wastes such as municipal biosolids, paper mill sludge, wastewater and animal manure can increase the farm gate net energy ratio of a willow biomass production system from 1:55 to 1:83 [13] and produce yields comparable to those attained with inorganic sources of N [5]. For example, the application of wastewater sludge to willow biomass crops led to significant increase in biomass productivity on treated plots and recycled residues [14]. In some cases, little or no yield response to fertilization has been reported in willow biomass crops and forestry experiments due to adequate site availability and internal cycling of acquired nutrients [15–17]. Nielsen [18] applied sewage sludge to willow plantations in amounts equivalent to 300 and 600 kg N ha^{-1} and reported that sludge application did not affect biomass production.

Due to increased public concerns about environmental issues and reluctance of farmers to use some organic waste streams for food crop production, SRWC systems have become attractive means for utilizing organic wastes because they direct heavy metals away from the human and animal food chain. The application of organic wastes to SRWCs can provide multiple benefits by making productive use of the waste material as well as providing needed plant nutrients. Organic amendments can also influence various qualities of soil, such as cation exchange capacity (CEC) [19] and improve soil physical properties such as organic matter content and bulk density and water holding capacity [20]. Organic amendments are less expensive and have a lower carbon footprint than commercial fertilizers, yet they have the same potential to supply SRWC systems with the necessary nutrients, particularly on marginal sites where nutrients may be limited. They also help to reduce production costs and to address problems associated with organic waste disposal.

A potential source of organic material for soil amendments is solid waste from the pulp and paper industry. About 85% of the 5.5 million Mg of paper mill sludge produced annually in the U.S. is a byproduct of primary clarification treatment [20–22]. This material consists of expanded fibers of pulverized wood, which is rich in lignin and unused cellulose but low in N and P [23,24]. Disposal of this material presents a problem for the pulp and paper mills. More than half of this primarily organic byproduct is disposed of in landfills or lagoons [25,26]. This method of waste disposal is costly and faces increasingly stringent environmental regulations [27,28]. The regulatory and economic climate favors the treatment of this material through land application to forestry and agricultural systems [29]. Using paper mill sludge as a soil amendment on farmland is an attractive alternative, because it allows for some cost recovery, improves soil properties and recycles some of the carbon into soil [30,31].

A major drawback to the use of paper sludge on SRWC is its low N content [32]. With large contributions of plant fibers, the elemental composition of paper sludge is relatively high in C (30–50%) and low in N (0.1–4%) [32–34]. This high C:N ratio could have detrimental effects on crops [24] by immobilizing soil N [35,36]. Application with a complementary high N organic waste material such as animal manure may relieve these deficiencies while maintaining the soil-building properties of organic residues from paper mill sludge [28]. Animal manure is commonly used as a soil amendment in agricultural systems. Manure has relatively high concentrations of N, typically around 5% of dry matter for dairy cattle and around 9% for swine manure [37], making it a good source of N.

In this study, we explored the use of two common organic wastes, pulp and paper mill sludge and dairy cattle manure, and a combination of the two as soil amendments in a willow biomass crop production system. The primary objective of this study was to compare the effects that sludge and manure applications have on biomass production, foliar nutrient concentrations and soil chemical properties with the effects of commercial fertilizer (urea) and untreated plots. It was hypothesized that: 1) The application of sludge and manure would increase plant growth and biomass production similar to that of commercial fertilizer relative to the control, and 2) sludge and manure treatments would increase CEC, organic matter and the concentration of nutrients in the soil and plant foliage.

2. Materials and methods

2.1. *Description of study sites and experimental design*

The effects of the application of pulp and paper mill sludge and cattle manure on plant growth, biomass production and soil chemical properties were assessed on a willow biomass production system at the State University of New York, College of Environmental Science and Forestry (SUNY ESF) Genetics Field Station in Tully, NY (42° 47′ N, 76° 07′ W). The soil at the site is a Glossoboric Hapludalf of Palmyra series [38]. The parent material is a gravelly sandy outwash derived from limestone, sandstone and shale. Topographically, the site is located on a glacial outwash terrace with a gentle slope of 0–3%. The soil is porous and is well to excessively well drained.

Six treatments were applied, consisting of four organic treatments, one commercial fertilizer (urea), and a control with no additions (Table 1). A target total N application rate of 100 kg ha^{-1} was used for all treatments except the high manure

(MH) treatment, for which the target was an available N application rate of 100 kg ha^{-1}, and a mixed treatment which included paper sludge and manure. Available N in manure was taken as ammonia-N plus 35% of organic N [39]. Due to differences in dry matter and N content between preliminary samples and applied material, actual N application rates differed from the target rates. The treatments were applied in a randomized design with four replications in late July and early August 2005. Two fields of a shrub willow variety (*Salix dasyclados*; SV1) at different growth stages were used: 1) an old field (OF) that was beginning its second year of aboveground regrowth on a 10 year old root system, and 2) a young field (YF) which was beginning regrowth after being coppiced at the end of its first growing season. In each field, 24 permanent treatment plots consisting of four double rows (each double row 0.75 m wide, with 1.5 m between double rows and 0.6 m between cuttings) were established. Each treatment plot measured 7.30 × 8.92 m. A section of the two double rows in the center of each treatment plot, measuring 21.93 m^2, was used as the measurement plot for data collection.

2.2. Organic amendments

The paper sludge was from a plant that recycles paper in central New York State. Sludge samples were stored at 4 °C until analysis could be completed. Moisture content was determined by drying samples at 105 °C, and total N was determined by the macro-Kjeldahl method. Total P and concentrations of metals were determined via inductively-coupled plasma emission spectroscopy following microwave digestion. Sludge was delivered to the field site and stored in a large pile under plastic tarps during application. Dairy cattle manure was collected from an 800-head farm in central New York State. The farm used wood shaving as bedding, and manure was handled as slurry. Manure was analyzed for the same constituents as the sludge. Raw manure was stored in covered tanks during application. Application was done manually by distributing the materials as evenly as possible within each treatment plot. Laboratory procedures used for chemical analysis of the organic materials followed Wilde et al. [40].

2.3. Plant growth and biomass production

Growth and biomass production were assessed at the end of each growing season. In the old field, measurements were collected in 2004, 2005, and 2006, providing pre-treatment data from one year (2004), and post-treatment data for two years. Only post-treatment measurements were made in the young field, in 2005, 2006, and 2007. Each year, the height of the tallest stem in each stool in the measurement plots was measured from its origin to its apex using a measuring pole. Stem diameters were measured at 30 cm height for all stems in the measurement plots. Biomass production was estimated by developing allometric equations following the procedures in Arevalo et al. [41]. To do this, diameters of thirty stems covering the measured range of diameters (3–45 mm) were cut and oven dried at 60 °C to a constant mass and then weighed. The relationship between the diameter at 30 cm height and biomass (dry weight) was quantified using a nonlinear regression equation, which was used to estimate dry biomass production. The weight of all stems in the measurement plot was then summed and scaled to provide standing biomass in Mg ha^{-1}.

2.4. Foliage sampling and analysis

Foliar analysis was used to assess plant response to the fertilization regimes and the nutrient status of the plants. Exactly 100 fully developed leaves from the third quarter of the plant canopy were collected in each plot in early September of the second growing season after fertilization (2006). All plots within each field were sampled on the same day. The collected leaves were oven dried at 65 °C to constant mass, after which dry weight was measured. Dried samples were ground in a Wiley mill to pass through a 1 mm mesh sieve. Foliage N concentration was determined using the macro-Kjeldahl method. Exactly 1 g of ground sample was dry-ashed and the ash was digested with a 6 mol/L HCl solution. The digested solution was used for the analysis of the macro-nutrients and exchangeable ions including Ca, K, Mg, S and P via inductively-coupled plasma emission spectroscopy.

2.5. Soil sampling and analysis

Soil samples were collected for chemical analysis in 2004 prior to application of treatments, and at the end of the second growing season post-treatment in 2006. Samples were collected from three regularly spaced locations to include within- and between-row samples within each treatment plot. Samples were collected in 15 cm increments to a depth of 60 cm. All plots within each field were sampled on the same day. Samples from the three locations within a treatment plot were mixed thoroughly to provide a single composite sample. Soil samples were air dried and then passed through a 2 mm sieve. Total N was determined with the macro-Kjeldahl method. Extractable P was

Table 1 – Fertilization treatments applied to the shrub willow (*Salix dasyclados* SV1) crops.

Code	Treatment	Amendment	N application rate (kg total N ha^{-1})	Amendment application rate (Mg as-applied material ha^{-1})
CT	Control	None	0	0
CF	Commercial fertilizer	Urea	100	0.22
ML	Low manure	Dairy manure	87	26
MH	High manure	Dairy manure	130	38
PS	Paper sludge	Paper mill sludge	120	73
SM	Sludge + Manure	Paper Sludge + Dairy Manure	250	73 (sludge) 38 (manure)

determined by extracting with 0.002 N H_2SO_4 and then measuring the P concentration on a spectrophotometer. Organic matter and ash content were determined by loss-on-ignition. Concentrations of all exchangeable ions including K were determined via inductively-coupled plasma emission spectroscopy following ammonium acetate (2 mol L^{-1}) extraction. Soil pH was measured in a 1:2 (w:v) slurry with deionized distilled water. All the laboratory procedures used for chemical analysis of soil and foliar nutrients followed Wilde et al. [40]. Cation exchange capacity was calculated as the sum of all exchangeable cations plus exchangeable acidity, which was determined by titration [42].

2.6. *Data analysis*

The effects of the fertilization treatments on stem height, biomass production, foliar and soil chemical characteristics were analyzed by analysis of variance (ANOVA), followed by the Tukey test to compare individual treatments, with $\alpha = 0.05$. Height, yield, foliar, and soil data from each field were analyzed independently because of the differences in the age of both the root system and the aboveground growth. Stem height and biomass yield within each field were analyzed separately for each year. For the OF pre-treatment data were available from 2004. To account for intrinsic differences among individual treatment plots in the OF, plot measurements from 2005 to 2006 were normalized prior to statistical analysis by dividing by 2004 pre-treatment values. Similarly, changes in soil properties from pre-treatment data of 2004 to the post-treatment data of 2006 were normalized by subtracting 2004 values from those from 2006. All statistical results presented below for post-treatment OF yield and height, and all post-treatment soil properties are based on these normalized values. Statistical analyses were carried out using Statistical Analysis System 9.2 (SAS) [43] and R version 2.12.1 [44].

3. Results

3.1. *Organic amendments*

Chemical characteristics of the organic materials indicate that, on a dry matter basis, the manure contained higher levels of the macro-nutrients N, P, K, Mg and S than did the sludge, while Ca concentration was higher in the sludge (Table 2). On a dry matter basis, concentrations of metals were generally similar in manure and sludge. One exception was Cu, which was higher in manure (Table 2). The concentrations of metals in both materials were well below the maximum levels permitted for land application.

3.2. *Plant growth and biomass production*

Generally, the treatments had no significant effects on stem height or biomass production in either field. However, in the OF, stem height was lower in the PS plots than in CF and MH plots (Figs. 1 and 2). In the OF, mean biomass production at the end of the second growing season after fertilization (2006, three year old aboveground plants) ranged from 32.3 odt ha^{-1} in MH to 36.3 Mg ha^{-1} in SM treated plots (Fig. 2a). Yields were lower in the YF, where mean biomass production after three years of aboveground growth (2007) ranged from 27.0 Mg ha^{-1} in PS treated plots to 31.6 Mg ha^{-1} in MH treated plots (Fig. 2b).

Table 2 – Chemical characteristics (mean and standard error) of the organic wastes used as amendments for the willow (*Salix dasyclados* SV1).

Element	Macro-nutrients (g kg^{-1}, dry basis)	
	Manure	Sludge
Total N	35 (0.1)	3.0 (0.40)
P	8.3 (0.72)	0.44 (0.045)
K	33.0 (2.9)	0.47 (0.096)
Mg	0.76 (0.056)	0.36 (0.048)
Ca	23 (5.8)	49 (6.0)
S	0.54 (0.050)	0.21 (0.010)

		Manure	Sludge
Dry matter	% Total mass	9.6 (1.3)	56 (7.8)
Organic Matter	% Dry matter	81 (0.25)	69 (0.66)
Ammonia	% Total N	49 (1.8)	–

	Micro-nutrients (mg kg^{-1}, dry basis)		
	Regulation[a]	Manure	Sludge
Cd	85	<1	1.4 (0.73)
Cu	4300	400 (130)	82 (9.4)
Pb	840	<10	61 (30)
Mo	75	8.0 (1.1)	6.0 (0.67)
Ni	420	17 (1.1)	18 (2.5)
Zn	7500	390 (27)	250 (29)

a US maximum permissible concentration (ceiling concentration) in land-applied biosolids (Protection of the Environment 2010). Two-tailed *t*-tests indicated that measured concentrations were all below US ceiling concentrations (assuming log-normal distribution, $\alpha = 0.01$).

3.3. *Foliar mass and nutrient element concentrations*

Leaf mass and the concentrations of N, P, and S were all higher in the old field than in the young field, while the opposite was true for Ca, Mg, and K (Figs. 3 and 4). Mean leaf mass in the old field ranged from 0.26 to 0.27 g, and was not affected by fertilization (Fig. 3). Mean leaf mass in the YF ranged from 0.085 to 0.11 g, and was significantly lower in PS treated plots than in control plots and SM plots (Fig. 3). In the OF, foliar N, P, K, Mg, and Ca concentrations did not show any significant response to fertilization (Fig. 4). However, the urea treatment appeared to increase S concentration, compared to control treatments (Fig. 4f). In the young field, fertilization affected only foliar P concentration, which was depressed in CF plots relative to control plots (Fig. 4b).

3.4. *Soil chemical properties*

Soil chemical properties below the top 15 cm were not influenced by the fertilization treatment, therefore only the data from the top 15 cm depth is presented and discussed. In general, soil concentrations of Ca and Mg increased over time in both the OF and YF (Figs. 5 and 6). Organic matter concentration increased in the YF. Concentrations of N, P, K, and CEC

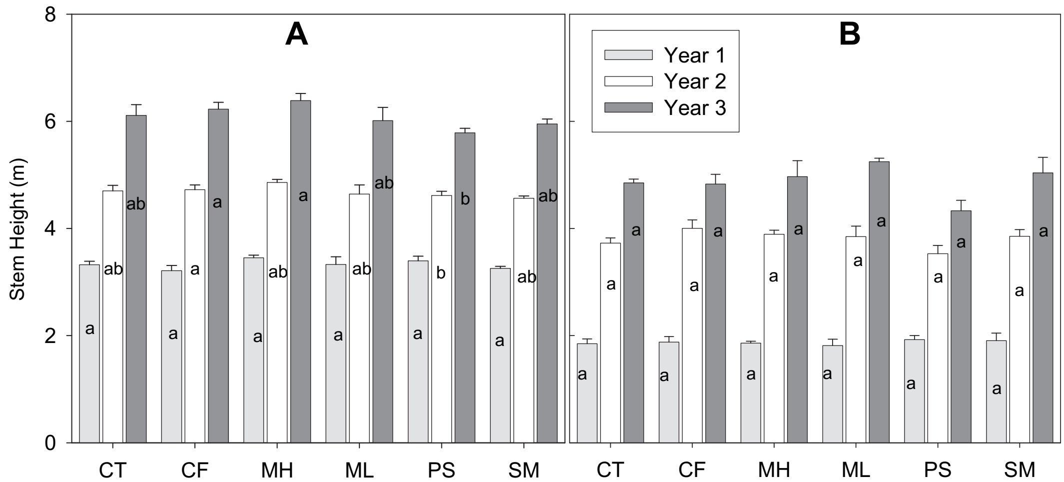

Fig. 1 – Stem height (mean and standard error) of the shrub willow (*Salix dasyclados* SV1) in the old field (A) and the young field (B) treated with urea fertilizer and four organic amendments. Means within the same field and year with the same letters are not statistically different based on the Tukey test ($\alpha = 0.05$).

and pH did not consistently change. The effect of fertilization on these changes was evaluated by comparing measured changes among the treatments. Soil concentrations of some cations increased in response to fertilization in the OF but not the YF. Concentrations of Mg increased in response to the ML treatment, relative to the MH and PS treatments. Concentrations of Ca increased in response to SM treatment relative to CT and CF treatments. In the YF, CEC appeared to be depressed in the PS treatment relative to ML. Fertilization did not influence changes in N, P, or other nutrients, and did not influence changes in pH in either the old or young fields.

4. Discussion

4.1. *Plant growth and biomass production*

In this study, fertilization with organic and inorganic sources of nitrogen did not have any significant effect on aboveground biomass production. Adegbidi et al. [3] previously conducted an organic amendment study in the same field that was used for the old field trial and found greater biomass production in organic amended plots. However, they observed relatively high yields even in the non-fertilized plots and attributed it to the site being naturally good agricultural soil. Although fertilization did not affect biomass production in our study, the biomass yields are similar to those reported by Adegbidi et al. [5]. The lack of significant effects of fertilization on biomass production in this current study and higher production levels obtained earlier at the same site [5], therefore suggest that the soil at this experimental site is good and not limited by nutrient availability. Since this site is well to excessively well drained, biomass production could be limited by water availability rather than nutrients. Consequently these factors may have obscured any response of the crop to fertilization in the present study.

The timing of amendment application also may have influenced the response to fertilization. Fertilizer application

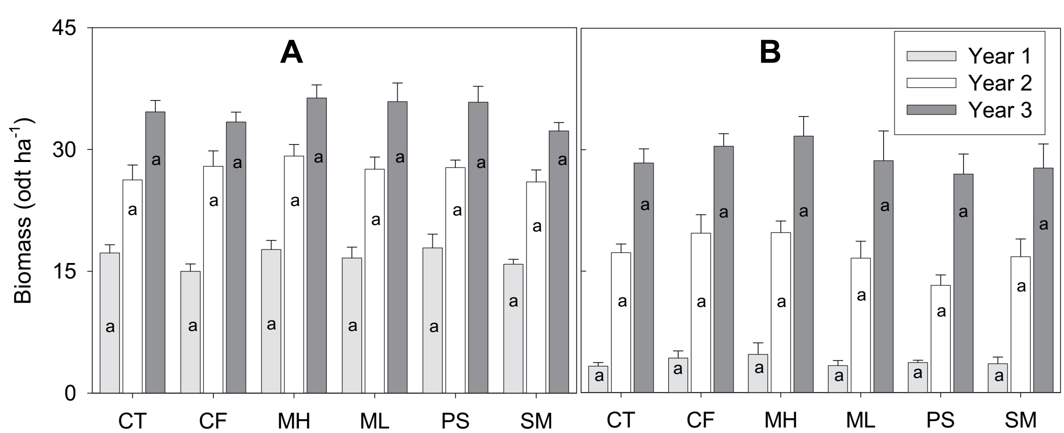

Fig. 2 – Biomass yield (mean and standard error) of the shrub willow (*Salix dasyclados* SV1) in the old field (A) and the young field (B) treated with urea fertilizer and four organic amendments. Means within the same field and year with the same letters are not statistically different based on the Tukey test ($\alpha = 0.05$).

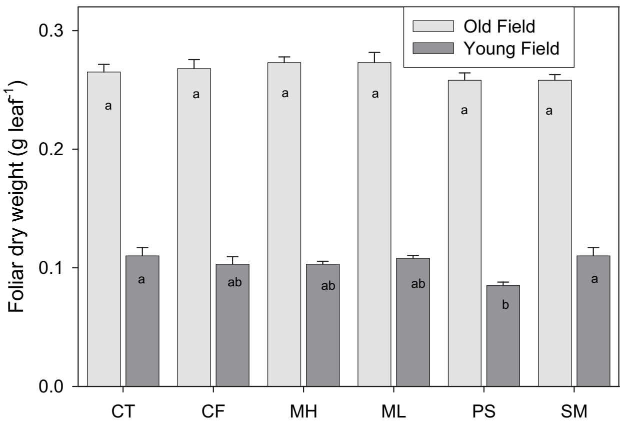

Fig. 3 – Leaf dry weight (mean and standard error) of the shrub willow (*Salix dasyclados* SV1) in the old field and the young field treated with urea fertilizer and four organic amendments. Means within the same field with the same letters are not statistically different based on the Tukey test ($\alpha = 0.05$).

occurred well into the 2005 growing season, and therefore added nutrients were not available for early growth, which would reduce the potential impact of fertilization on yield measured later that year. Conversely, Adegbidi et al. [5] applied amendments in May. Moreover, the warm (mean temperature around 23 °C), dry weather (most days were rain-free) during the application period may have contributed to loss of N through ammonia volatilization. Volatilization of ammonia from urea and manure can represent a significant loss of N (up to 40% of N for urea and up to 70% of manure ammonia), and a lack of rainfall after application can exacerbate volatilization [45,46].

Most experiments that showed positive response of biomass production to fertilization were conducted on sites that were considered to be nutrient limited. For example, Labrecque and Teodorescu [7] compared the growth of two willow species at different sites and observed that increase in yield due to fertilization was greater in sandy (poor) soil than in clay (good) soil. This finding emphasizes the point that where plants have access to soil nutrients, they don't show growth response to applied fertilizer. Hytonen [47] stated that willows' response to fertilizer in terms of productivity is more important on poor sites than on rich sites. He found that on sandy and poor sites, the application of organic fertilizers is very important in the establishment of willow crops. A response to fertilization, however, does not imply greater productivity. Although Labrecque and Teodorescu [7] observed positive response of willow to fertilization on sandy (poor) soils, they reported that greatest productivity was obtained from the fertilized plots in clay (good) soil. In willow coppice systems, first rotation biomass productions are generally low but increase with subsequent harvests [6,48–50]. The differences in production between the YF and OF reflect this condition, with production across all the treatments being 20% greater in the OF. Differences in production were greatest in the PS treatment (33%) and lowest in the CF treatment (9.8%). Aboveground production in the OF occurred on a well established root system, while in the YF both aboveground biomass and below ground systems were being developed.

Since willow biomass crops are perennial systems with fairly tight nutrient cycling, the need for external input of nitrogen may decrease after the first cutting-cycle in willow biomass production systems [51]. The lack of a yield response to fertilization in the OF could be explained by this reason since the root system was about 10 years old at the time of this study. The decomposition of foliage and root litter over the years has therefore contributed to the internal nutrients of the site. Ingestad and Agren [51] reported that decomposition of litter is a major source of plant nutrients, and that, with time, complementary supply of fertilizers is needed only for the replacement of the nutrients removed by stem harvest and that internal recycling of nutrients could result in a decreased demand of externally applied nutrients. Adegbidi [52] reported that the litter of three year old unfertilized shrub willow (*S. desyclados* SV1) contained 2.13% N and added 80.3 kg N ha^{-1} yr^{-1} to the soil via litter fall. Rytter [53] also found that due to rapid fine roots turnover rates, 34–69 kg N ha^{-1} yr^{-1} was cycled back into the soil from three year old willows. According to Alriksson et al. [54], the need for N fertilization decreases over time as the quantity of N derived from internal nutrient cycling due to decomposition of leaf litter and root turnover increases. He also estimated that, in the third and fourth growing season, 27% and 48%, respectively, of the total N demand can be supplied by reusing nitrogen applied in previous growing seasons.

Although there were no statistical differences among the treatments, it is worth noting that application of paper sludge did not substantially reduce biomass yields in either the old or young fields. At the end of the second growing season after fertilization (2006), mean yield in the OF plots treated with PS (35.8 Mg ha^{-1}) was not significantly different from control plots (34.6 Mg ha^{-1}). For YF, the mean yield for three year old willow in the PS plots (27.0 Mg ha^{-1}) was slightly lower than for control plots (28.4 Mg ha^{-1}), but again, this difference was not statistically significant. This suggests that the application of paper sludge to SRWC systems may be a feasible approach for disposal of sludge and to increase soil organic matter. Repeated inputs of high C:N ratio material is expected to significantly reduce N availability eventually, but simultaneous application of manure or other amendments with high N availability may reduce this problem. Additional research is needed to more precisely quantify short- and long-term effects of paper sludge application on SRWC systems.

4.2. *Foliar nutrient response to fertilization*

Foliar nutrient concentration has been used as an indicator of plant response to fertilization because it is a function of available nutrients for uptake and the factors that influence uptake by plants [55]. In this study, the fertilization treatments generally did not affect foliage nutrient concentrations compared to the control. This lack of a response can be explained partly by the relatively high internal nutrient cycling in the fields used for this study (especially for the OF).

Kopinga and van den Burg [55] have identified foliar nutrient concentrations that should support normal growth for three willow species (*Salix viminalis*, *Salix alba*, and *Salix triandra*). They suggested that the following nutrients concentrations in leaves

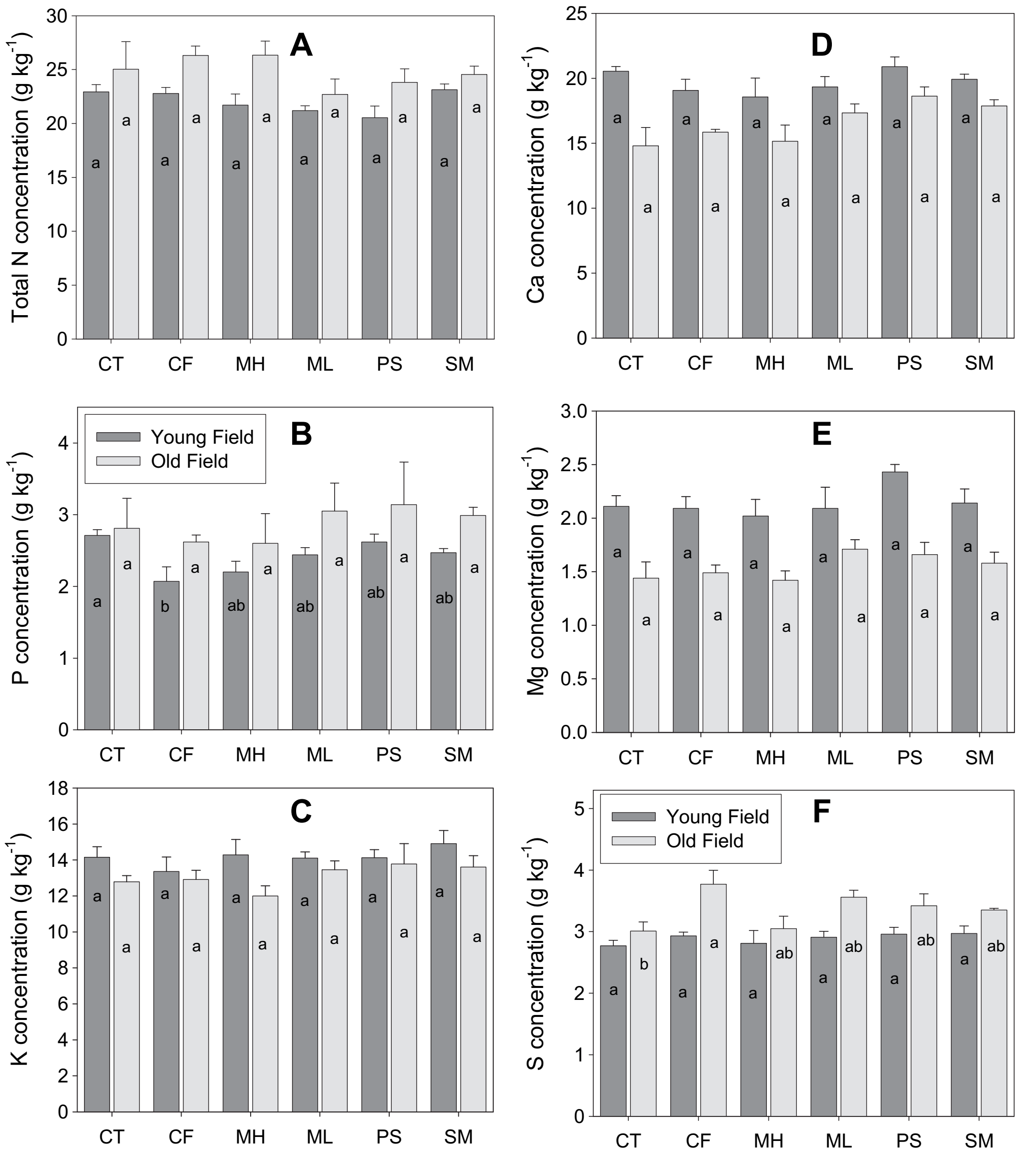

Fig. 4 – Foliar elemental concentrations (mean and standard error) of the shrub willow (*Salix dasyclados*; SV1) in the old field and the young field treated with urea fertilizer and four organic amendments. Means within the same field with the same letters are not statistically different based on the Tukey test ($\alpha = 0.05$).

promote normal growth: 23–30 g kg^{-1} N; 1.7–2.1 g kg^{-1} P; 8.5–19 g kg^{-1} K; and 1.7–3.0 g kg^{-1} Mg. Comparing these ranges to the results of this study, the mean foliar N concentrations for the plants in OF (22.7–26.3 g kg^{-1}) can be considered to be in the optimal range for all treatments. In YF, however, only SM had a mean foliar N concentration (23.1 g kg^{-1}) within the optimal range for normal growth. The mean foliar N concentrations for CT and CF were 22.9 and 22.8 g kg^{-1} respectively, which was lower than the lower limit of 23 g kg^{-1} given by Kopinga and van den Burg [55].

The overall mean foliar N concentration for all treatments in this study (20–26 g kg^{-1}) are lower than foliar N concentration values reported by Labrecque and Teodorescu [7], and Rytter and Ericssion [56] for *S. viminalis*. Labrecque and Teodorescu [7] reported that fertilization with municipal sludge induced a significant increase in foliar N. The mean foliar P concentrations for both fields ranging from 2.07 to 3.14 g kg^{-1} were slightly above the optimal values while K and Mg values were within the optimal range for normal plant growth indicated by Kopinga and van den Burg [55]. The limited response of foliar nutrients to the applied fertilizers in this study is another indication that the site used for this study was not limited by nutrient availability [5].

4.3. *Soil chemical properties*

The soil pH and CEC of both fields in this study indicate that the soils were moderately acidic and have a good availability of base cations. Contrary to published results, which demonstrate that sludge application increases organic matter content of soil [20,57], in this study the increase in soil organic matter content was no greater in fertilized plots than in the

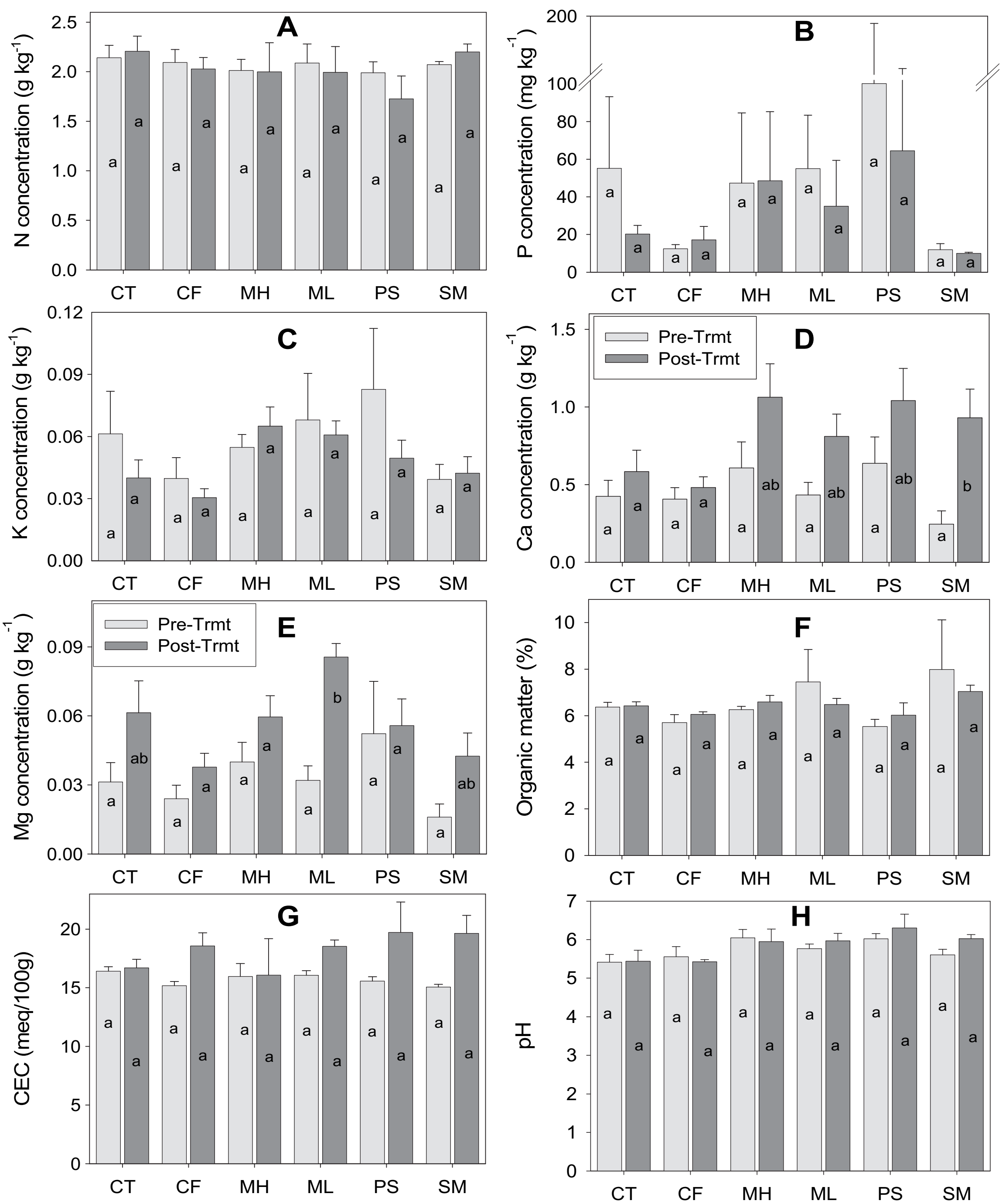

Fig. 5 – Soil chemical characteristics (mean and standard error) in the top 15 cm of the old shrub willow (*Salix dasyclados*; SV1) field treated with urea fertilizer and four organic amendments. Means within the same treatment era (pre- or post-treatment) with the same letters are not statistically different based on the Tukey test ($\alpha = 0.05$).

control plots, and therefore cannot be attributed to sludge or manure application. The increase in organic matter content observed in this study could have been caused by litter fall and root turnover. Litter fall from unfertilized three year old willow has been reported to added 90% organic matter to the soil annually Adegbidi [52].

The addition of nitrogen to the soil through the organic amendments and urea did not have any significant effect on total soil N. Since the mass of N applied was small compared to total soil N, it is not surprising that differences were not detected. Mean P concentration in the unfertilized soil was about 20 g kg^{-1}, suggesting that P is not a limiting nutrient at the site. In an earlier study done at the same site, Adegbidi et al. [5] found that organic amendments significantly increased soil organic matter, pH and concentrations of N, P and Ca relative to un-amended soil.

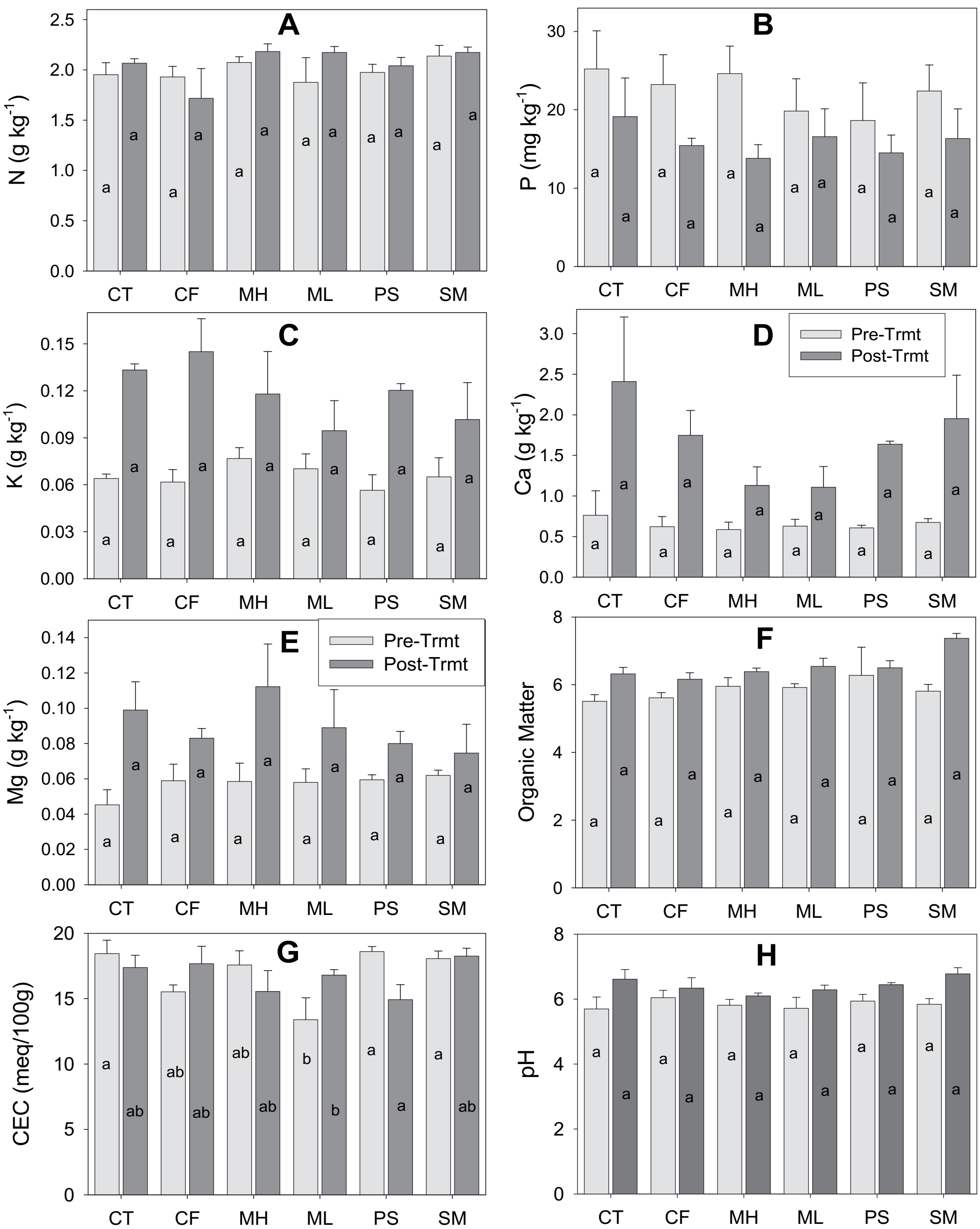

Fig. 6 – Soil chemical characteristics (mean and standard error) in the top 15 cm of the young shrub willow (*Salix dasyclados*; SV1) field treated with urea fertilizer and four organic amendments. Means within the same treatment era (pre- or post-treatment) with the same letters are not statistically different based on the Tukey test ($\alpha = 0.05$).

5. Conclusion

Our results demonstrate that response to fertilizer applications in short rotation willow coppice systems may not be significant in soils that have high internal nutrient supply. The lack of response observed in our study may be related to the high soil quality of the experimental site, or loss of nutrients through volatilization. However, even the low N paper sludge did not significantly reduce biomass yield, supporting the use of this type of waste as a soil amendment for short rotation willow coppice systems. Additional research is needed to assess the effects of paper sludge application on productivity on low quality sites, and over longer time periods.

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