Survival and Growth of Willows on Biosolid Covers Over Ni-Cu Tailings

by Eric Wilcox

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ABSTRACT:

The growth of biofuel willows was examined in covers of biosolid materials over top of Ni-Cu mine tailings at Vale (Copper Cliff, ON) and Xstrata Nickel (Onaping, ON). The Vale site had a pulp and paper biosolid cover, while the Xstrata Nickel site had a municipal compost cover. The Vale biosolids were of two ages, Vale Old applied in 2008 and Vale New, applied in 2011. These biosolid covers had been applied to provide a physical barrier to the tailings and act as growing medium for biofuel crops. In the spring 2011, four different types of biofuel willows were planted in latin squares at both Vale and Xstrata Nickel sites, namely *Salix miyabeana* variety 64, *Salix miyabeana* variety 67, *Salix sachalinensis*, and *Salix viminalis*. The objectives of this study were to determine (i) which of the two biosolid covers is optimal, and (ii) which willow species has the best overall survival, performance and health, over the summer 2012. Performance measurements included branching and height, while heath characteristics assessed included chlorosis, curling of leaves, shedding of leaves, and insect damage. All biosolid covers had a relatively neutral surface pH, despite strongly acidic tailings at Vale and slightly acidic tailings at Xstrata. The moisture content of the surface of the biosolids differed during a drought period, with it being highest at the Vale New site and lower and similar at the Vale Old and Xstrata site. Varieties had good survival, except for *Salix viminalis,* which had few surviving individuals. The three remaining willows varieties had similar growth and health within sites. The Vale new site had the best height growth, potentially related to the moister soil conditions, while the Xstrata site had the most branching, potentially related to shading from thick annual weeds. The effect of different biosolids covers could not be easily assessed due to site differences, especially weed density. *Salix viminalis* cannot be recommended as a biofuel species because it failed on all aspects of performance and health. However, both varieties of the *Salix miyabeana* as well as the *Salix sachalinensis* are viable sources of biomass for future projects.

ACKNOWLEDGEMENTS:

I would like to thank Dr. Daniel Campbell for his constant support and help throughout this past year, especially the last few months. I do not know where I would be without his input. I would also like to thank Dr. Peter Beckett and Mike Soenens, who put in some very long days in the field. This was not asked for but much appreciated. Also, Dr. Gerard Courtin, I would like to thank you for all your time throughout the school year. Your endless advice and support made this whole experience much more enjoyable. I would also like to thank Joe Fyfe and Lisa Lanteigne for making this whole project possible. Last but not least, I would like to thank Kelly Moore, who was always ready to help with any task at any time.

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INTRODUCTION

One of the biggest concerns with metal mining is the large amount of waste that is produced to obtain a small amount of a desired metal. Tailings form a major component of these metal mine wastes. Ore is crushed and ground finely and the desired metals are separated (Stoltz & Greger, 2002), leaving fine-textured tailings, which must be disposed of. Given the low content of desirable metals in some ores and the fact that the volume of material increases as the ore is ground, large volumes of tailings can be produced (Stanislaw & Domy, 1997). The composition of tailings varies tremendously, but they often contain high levels of residual metals and/or generate acid, which can be deleterious to the environment and even to human health (Nicholson et al, 1989). Mining companies must therefore build extensive tailings containment facilities and prevent their migration off site.

Tailings provide little to no fertility for plants attempting to colonize these facilities, because of their acid generation and an abundance of heavy metals (Williamson & Johnson, 1981). The groundwater and air can also be seriously impacted by the composition of the tailings (Lindsey et al, 2011). Groundwater contamination threatens the drinking water for nearby communities and puts the health of the streams, rivers and lakes in jeopardy. Wind erosion of tailings is also a problem, producing dust pollution, which requires control measures. Owing to these issues, the reclamation of tailings areas is essential and often mandatory through government regulations (Cao, 2007). Besides these legal obligations, the reclamation of tailings facilities can also improve public relations with nearby communities and build or maintain a social license to operate (Cao, 1989).

A priority in most reclamation projects is an attempt to create a physical barrier between the tailings and the outside environment. The objective of the barrier is to stop or reduce the amount of air and water that comes in contact with the tailings, thereby decreasing oxidation reactions with metals. If the tailings are sulphur-rich, a physical barrier can also limit the generation of acid rock drainage. In addition, the barrier also helps prevent dust pollution emanating from the tailings (Nicholson et al, 1989).

An organic cover is optimal because organic matter consumes oxygen which limits the oxygen flux down to the tailings (Cabral et al, 2000). In the upper layer of the cover, the material decomposes under aerobic conditions. The layers below this generally decompose under anaerobic conditions, this process consumes oxygen. These processes essentially trap the oxygen throughout the cover. In the end, this limits the oxidation of the sulphide rich tailings below (Peppas et al, 2000). If the cover becomes saturated with water the oxygen diffusion rate will decrease quite significantly (Peppas et al, 2000). Furthermore, since organic covers absorb water , and the plants they support transpire much of the excess water at least during the growing season, organic covers can also limit the amount of water that reach the tailings (Peppas et al, 2000; Lock et al, 2010). Therefore organic covers can potentially limit oxygen and water ingress into the tailings. Materials known as biosolids can be used as a barrier as well as a growth amendment. Biosolids are organic-rich materials derived from a wide variation of sources, including; treated sewage waste, municipal waste such as compost, and even treated industrial waste such as pulp and paper sludges (Dampier et al, 2002). Many biosolid covers like compost and pulp and paper biosolids, contain a high abundance of organic matter as well as essential nutrients. For example, the deinking process of pulp and paper sludge often involves the addition of nitrogen and phosphorus, both important plant nutrients (Cabral et al, 2000; Camberato et al, 2005). High concentrations of organic matter will allow the cover to retain a high amount of moisture. Biosolids can be used in agriculture because they contain many nutrients, improve cation exchange capacities as well as soil moisture holding abilities (Dampier et al, 2002). However, some biosolids can also contain elevated levels of heavy metals, so their use in agriculture is limited and strictly controlled (Illera et al, 2000). As a result, many biosolids are simply landfilled or incinerated (Benitez et al, 2001).

The use of biosolids for mine reclamation has many advantages. First, these materials are used in a constructive way that will eventually benefit the environment. The spreading of these biosolids on mine tailings reduces the amount of waste entering landfills and incinerators (Carter-Whitney et al, 2009). Second, biosolids provide a fertile medium in which plants can grow. Even if there are elevated levels of some metals, the high organic content of biosolids restricts their availability to plants (Park et al 2011). Third, having established a physical and oxygen barrier between the surface environment and the tailings, the lack of oxygen will actually create reducing conditions thereby preventing acid generation and improving groundwater quality (Cabral et al, 2000). Fourth, biosolids and the plants they support can absorb moisture and therefore these covers may act also as a hydrologic barrier, limiting the amount water entering tailings (Peppas et al, 2000). Finally, the use of biosolids over tailings converts seemingly useless land to valuable land for agriculture or silviculture.

Agriculture is a potential valuable use of the land. However, as noted above, many biosolids can contain high concentrations of heavy metals (Smith, 2009), and the underlying tailings also contain high concentrations of heavy metals. As such, any crop that is grown on covers of biosolids will likely not be suitable for human consumption due to tissue metal tissue, or at least face the perception of tissue metal content in these crops. A potential option is to grow biofuel crops on these reclaimed tailings sites, so not for human food consumption (Pulford & Watson, 2003).

Biofuel crops are grown worldwide. They can be generally described as a form of energy that is produced by living organisms, in this case, plants. The entire biomass can be harvested and pelletized, or components can be processed further into combustible fuel through the breakdown and fermentation of carbohydrates in the plant tissue. Some plants that have high oil content are converted to biofuel by transesterification, a process that converts natural fats found in the plant tissue into methyl alcohol. An advantage is that most biofuels are derived from plant material (a renewable resource). Biofuels are also found to burn much cleaner than fossil fuels. Common plants that are used in biofuel production are: corn, canola, switchgrass, and woody plants such as willows (Crawford et al, 2012). There is a growing concern in over utilizing very healthy fertile land for growing crops that will be manufactured into biofuel instead of using these areas for food production. Growing biofuel crops on reclaimed mine lands would completely avoid this concern. Therefore, a good option for a reclamation crop is planting vegetation that has biofuel potential.

Willow species (*Salix* sp.) have been commonly used in restoring degraded wetlands, and more recently used in contaminated site reclamation. Willows grow very quickly in comparison to other perennial crops. They also form very large root systems over a relatively short period of time. This relates back to the water flux down to the tailings. The root system will absorb a larger amount of water than other plants. Willow species are also capable of up taking large amounts of heavy metals, with little negative effect on the overall health of the plant (Boyter et al, 2008; Kuzovkina and Quigley, 2005). Another advantage of willows is that as a whole they are ideal for restoring an ecosystem.

Willow species also happen to be one of the most promising biofuel prospects in the world. Even on contaminated degraded lands the biomass production of willows is still significant enough for biofuel (Kuzovkina & Quigley, 2004). With the addition of a biosolids cover, there should be an increase in crop yield. The biosolids will provide more nutrients as well as retain more moisture throughout the profile (Kuzovkina & Quigley, 2004). The fact that willow species provide the lower labour costs of a perennial crop makes them a very attractive option for mining companies.

The broad goal of this particular study was to determine which biofuel willow species have the greatest survival, health and productivity on different biosolids over nickel-copper tailings in Sudbury, Ontario. A second goal was to determine which biosolids materials, either municipal composts or pulp and paper sludges were optimal as a cover for the growth of biofuel willows. At one site, biosolids differed in age and depth, so a third objective was to determine whether depth and age of the cover affects its overall ability as a growth amendment.

METHODS

Study areas

The study was conducted at two Ni-Cu tailings facilities: The Vale facility near Copper Cliff, ON (46.3^{o}N 81.0^{o}W) and the Xstrata Nickel tailings facility near Onaping, ON (46.61^{o}N 81.43^{o}W; Figure 1).

The old and the new Vale study sites were adjacent to each other (Figure 2) on oxidized tailings; fresh tailings have not been added to site in over 10 years (Hargreaves et al, 2012). The tailings on the sites have a high sulphur content, so they had an extremely acidic pH of 2.78. They have high levels of Ca, Fe, Mg, Mn, P, and K; and levels of Ni and Cu exceed CCME soil quality guidelines for agricultural soils (Hargreaves et al, 2012; Table 1).

Figure 1. Location of the sites studied in the vicinity of Greater Sudbury: A:Vale at Copper Cliff ; B: Xstrata at Onaping. Base map from Yahoo Maps.

The biosolids used at the Vale tailings facility were comprised of pulp and paper material from the Domtar paper mill in Espanola, ON. The biosolids were spread on the tailings at Vale old in 2008 and at Vale new in 2011. The biosolids at the Vale old site were spread to an approximate depth of 100cm. The site was then reworked in 2011 to eliminate ice wedges that had formed in the cover. The cover was spread to a new depth of about 50 to 60cm over a 0.5 hectare area. The Vale new site was covered with the same biosolids material more recently at a more sporadic depth ranging anywhere between 30 and 60cm over an approximate 0.5 hectare area. The biosolids at application had high organic matter content with a circumneutral pH (MIRARCO, 2011; Table 2). Certain metals, including Cd, Cu, Ni and Zn exceeded CCME guidelines in these biosolids.

The Xstrata tailings facility site (Figure 3) consisted of Ni-Cu tailings with an approximate 100cm thick cover of desulpherized tailings, also called desulphurized slimes. The tailings had a circumneutral pH in contrast to the Vale tailings (Smith, 2012; Table 3). It also had elevated levels Ca, Fe, Mg, Mn, P, and K; and Ni and Cu again exceeded soil quality guidelines. The biosolids used as an additional cover here were comprised of municipal compost waste that was transported from the Greater Toronto Area (GTA). The compost cover was spread at a relatively constant depth of 50 to 60cm over an area of approximately 0.5 ha. The compost had lower levels of metals, below the CCME guidelines. The compost was not taken from the Sudbury area because of its generally high metal content (Smith, 2012).

Figure 2. Location of the Vale Copper Cliff tailings facility, with a close-up in the inset map. The study site is shown with a red star on the inset map (base map from Google Earth).

Table 1. pH and total concentrations of selected elements in tailings at the Vale Copper Cliff site (Hargreaves et al, 2012), as compared to the CCME soil quality guidelines for agricultural soils (CCME 2013). Values in tailings that exceed guidelines are highlighted in bold.

	Tailings mg kg^{-1}	Guideline mg kg^{-1}
pH	2.78	-
Cd	0.015	1.4
Ca	14002	-
Co	10.3	40
Cu	**292**	63
Fe	65850	-
K	3615	-
Pb	32.5	70
Mg	4538	-
Mn	486	-
Ni	**174**	50
P	488	-
Zn	159	200

Table 2. Total concentrations of elements at different depths in the Vale new cover, based on results from 2010 (Vale Appendices, MIRARCO 2011), as compared to the CCME soil quality guidelines for agricultural soils (CCME 2013). Values that exceed guidelines are highlighted in bold.

	Concentration (mg kg^{-1})			Guideline (mg kg^{-1})
	0-15 cm	15-30 cm	30-45 cm	
Al	6497	6195	5416	
As	2.22	2.37	1.50	12
Ca	91100	92300	83200	
Cd	**7.26**	**7.39**	**6.52**	1.4
Co	7.71	7.29	7.00	40
Cr	27.1	25.7	21.9	64
Cu	**150**	**119**	**114**	**63**
Fe	12200	11000	10300	
K	2488	2300	2067	
Mg	4889	4691	4384	
Mn	2122	2093	1932	
Ni	**61.2**	**57.7**	**64.0**	50
P	2581	2635	2185	
Pb	13.5	12.4	11.3	70
Sb	<0.32	0.43	<0.32	20
Se	187	142	150	1
V	16.9	15.3	14.0	
Zn	**543**	**558**	**441**	200

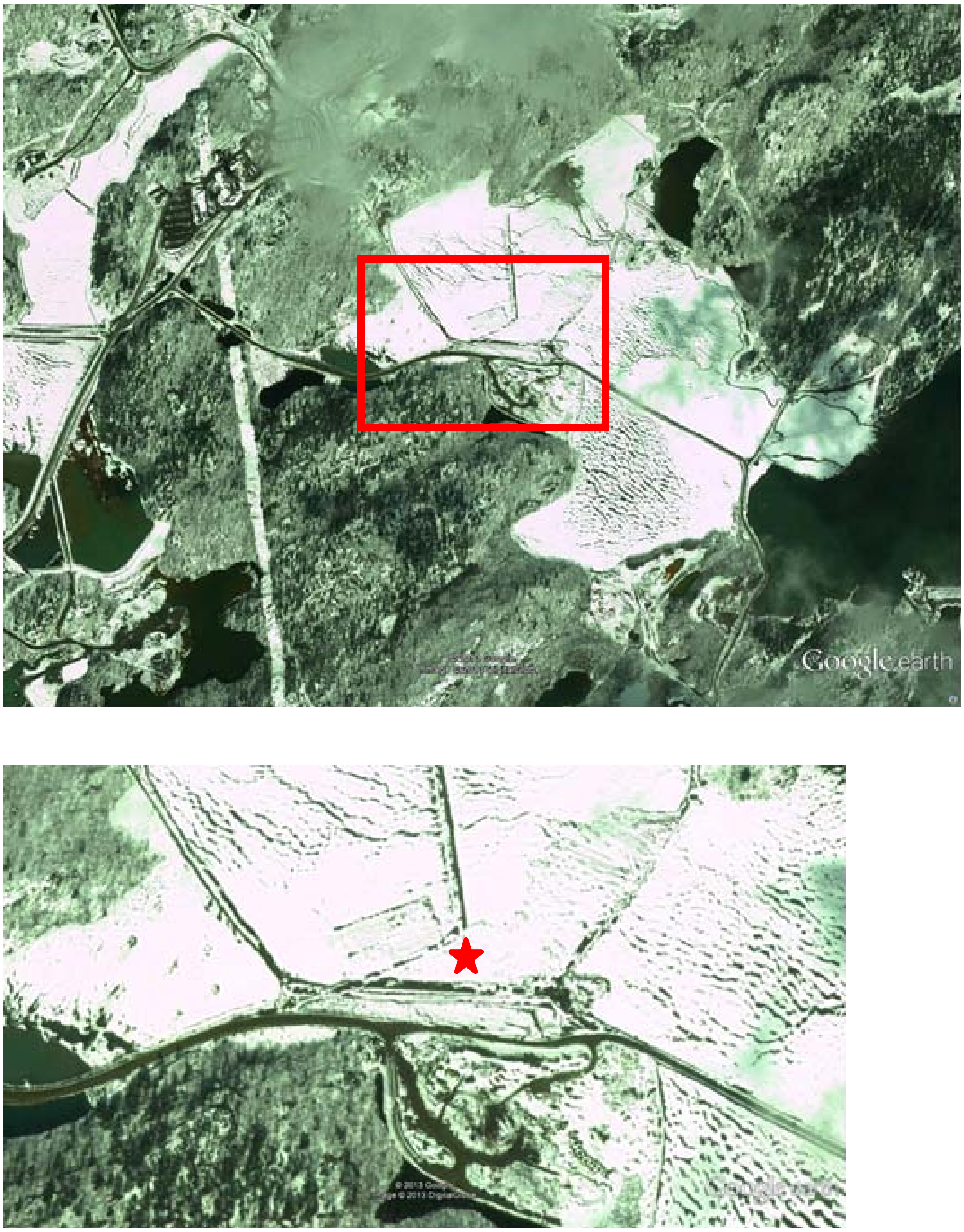

Figure 3. Location of the Xstrata Strathcona tailings facility, with a close-up in the inset map. The study site is shown with a red star on the inset map.

Table 3. pH and total concentrations of selected elements at increasing depths in the compost biosolids cover profile at the Xstrata site as compared to the interface and the underlying tailings (Smith, 2012). The data are also compared to the CCME soil quality guidelines for agricultural soils (CCME 2013). Values that exceed guidelines are highlighted in bold.

	Concentration (mg kg^{-1})							Guideline
	0-15cm	15-30cm	30-45cm	45-60cm	60-75cm	Interface	Tailings	mg kg^{-1}
pH	6.14	6.35	6.44	6.64	6.5	6.53	6.91	
Ca	28100	35500	42800	44800	42800	44000	2030	
Cu	47.3	75.3	54.5	44	45.6	48.9	**355**	63
Fe	12500	11400	1000	10600	11400	11200	34900	
K	2140	2660	3180	3780	3700	3840	6780	
Mg	8860	9620	10600	11600	9790	11300	14400	
Mn	391	398	455	429	434	446	514	
Ni	23.6	20.9	11.2	11.3	9.43	26.1	**903**	50
P	1340	1570	1720	1790	2320	1780	704	
Zn	149	150	366	171	191	145	72.8	200

Study design and planting

The experiment was set-up in a latin square format with two squares at Vale old, two squares at Vale new and three squares at Xstrata. The square consisted of 4 rows and 4 columns (16 plots). Plots were planted with four treatments of biofuel willow varieties. The four varieties were non-native and consisted of *Salix miyabeana* 64, *Salix miyabeana* 67, *Salix sachalinensis,* and *Salix viminalis*. *Salix miyabeana* 64 and 67 as well as *Salix sachalinensis* are native to northeastern Asia and were chosen based on a recommendation from forestry Canada. *Salix viminalis* is a European variety and was chosen because it is used extensively for biofuel in Europe. Each plot contained two double rows of 15 willows a piece making for a total of 60 willows per plot (Figure 4). The double rows were planted with about 1.25m of space between them and 0.75m between rows. The 15 willows were evenly spaced within each row. The four varieties were planted across all sites between the last week of May and the first week of June, 2011. Before planting, the biosolids were cultivated to destroy any germinating weeds; no herbicide was used as this could have affected the growth and health of the willows. The different varieties were planted by hand, using cuttings, following general guidelines (Abrahamson et al, 2002). The willows were pre-cut in lengths ranging from 5cm to 25cm depending on variety. A metal post/probe approximately the diameter of the willow shoots (~2cm) was used to make a hole to allow for easy, efficient planting. Willow cuttings were submerged approximately two thirds into the ground, with buds facing up. The soil was then packed down around the base of the plant to insure stability.

The willows grew for one year, meaning they were not cut back in the fall harvest which is normally done (Abrahamson et al, 2002). This was not done in this experiment because of the possibility of damage over the harsh winter months of this region. From April 6th to 12th of 2012,

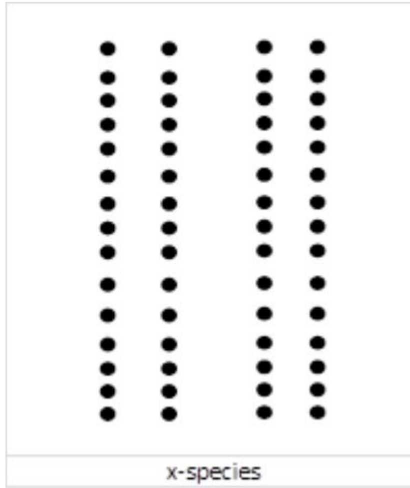

Figure 4. Planting layout of each individual plot within a latin square at all sites.

All varieties at all three sites were cut to a height of approximately 2cm. All sites were now ready for the growing season.

Methods for Summer 2012

pH and conductivity were recorded once during the growing season at all three sites, for each plot. Slurries were made with approximately 30 mL of soil placed into a clean plastic beaker. The beaker then was filled with distilled water, mixed, and let to stand for approximately 3-5 minutes. The instrument (YSI® multimeter) was calibrated for pH using a three point calibration method to insure optimal accuracy. A pH was measured, recorded, and then the instrument was washed with water prior to the next pH reading. The slurries were then discarded and the beaker cleaned. Conductivity was then measured on the same slurry, after being calibrated for conductivity using three different conductivity standard solutions.

Water content of surface soils was determined twice in September 2012. Soil samples were taken to allow for an evaluation of volumetric moisture content. The surface layer of soil was sampled using a short cylindrical corer, 100g volume instrument. These samples were then taken back to the lab and weighed fresh, then dried at 105^{o}C for at least 24 hours, and reweighed. Water content was determined as the weight loss during drying relative to the fresh mass.

Near the end of the growing season the willow crop were analysed for survival, growth and overall health. Seven different aspects were studied: survival, height, branching, chlorosis, curling of leaves, shedding of leaves, and insect damage. Survival rate was measured as a percentage of the total crop (of each Species/variety) that survived at each site. This is determined by counting the number of surviving willows and dividing by the number that were originally planted.

Height and branching characteristics were measured on eight willows per plot, selected at random, if sufficient individuals were present. The height of the surviving plants was simply measured by using a tape measure and measuring from the base of the stem to the tip of the longest branch. The number of branches of surviving plants was determined by only counting the branches growing from the base of the stem.

The percentage of surviving willows that exhibited signs of chlorosis, leaf curling, leaf shedding, and insect damage was also evaluated. This was also done by again evaluating up to 8 willows per plot, selected at random. Chlorosis, leaf curling and leaf shedding were studied on a yes or no basis as a percentage. For example, the number of willows showing signs of chlorosis divided by the number of willows analysed at the site. Therefore a 43% rate of chlorosis of the Salix *miyabeana* 64 species at the Vale old site equals to approximately 83 out of the 192 willows analysed, having chlorosis. Insect damage was evaluated slightly different than the other health characteristics. This was also measured as a percentage, but on three different levels, low, medium and high damage.

Once all the data was collected, statistical analyses were performed using SPSS 19 and Excel. Survival of species was not analyzed statistically, but simply plotted. For height and number of branches, the data was analysed using ANOVA, with sites, columns and rows of the latin squares and willow species as independent variables. Site was considered as a random effect, while row and column of the latin squares and the willow varieties were fixed effects. A restricted model was used for the ANOVA, without interactions.

RESULTS

The soil surface pH had a neutral to slightly alkaline state (pH 7-7.5) at all sites (Figure 5). The conductivity was also very similar at Vale old and new biosolid sites, but was lower at Xstrata (Figure 6). The summer of 2012 was very dry. By September, the water contents were very low at the Vale old site, with only 15-20% water content at the surface across both dates (Figure 7). However, water content was almost double at the new Vale site with water contents of 30-40%.

The survival rates were quite similar at Vale old and new (Figure 8). *Salix miyabeana* 64, *Salix miyabeana* 67 and *Salix sachalinensis* were similarly successful, but *Salix viminalis* almost completely died out. However, survival differed greatly between sites. Vale new and old had similar survival (70-90%), however the new Domtar material (Vale new site) slightly outperformed the old Domtar (Vale old site) material. The Xstrata site had by far the least survival, and again, survival appeared to be similar across varieties. The Xstrata site also by far had the highest density of weeds, although weed density was not quantified. It was visibly obvious that the Xstrata willows were starved of moisture and nutrition (Figure 9 and 10).

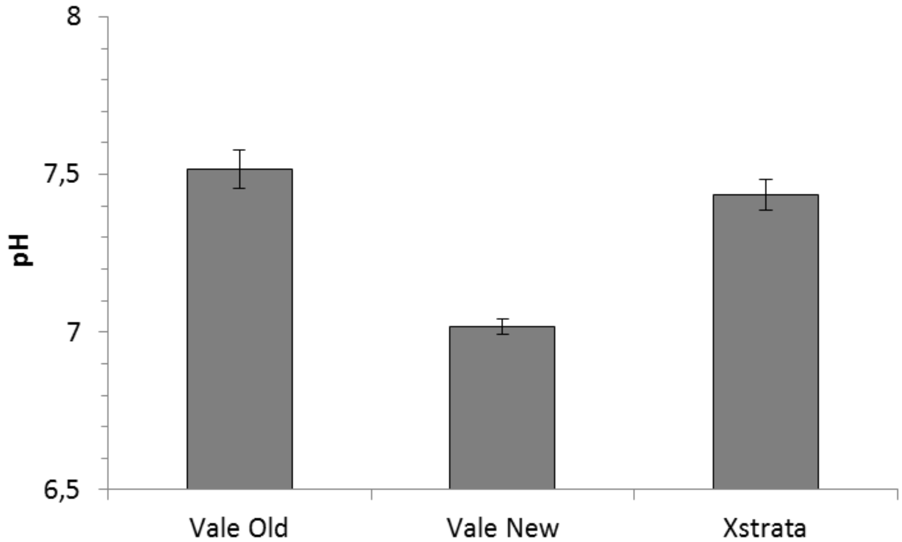

Figure 5. pH of surface biosolids at Vale old and new sites as well as the Xstrata site (mean ± SE; Vale old n = 32, Vale new n= 32, Xstrata n= 48).

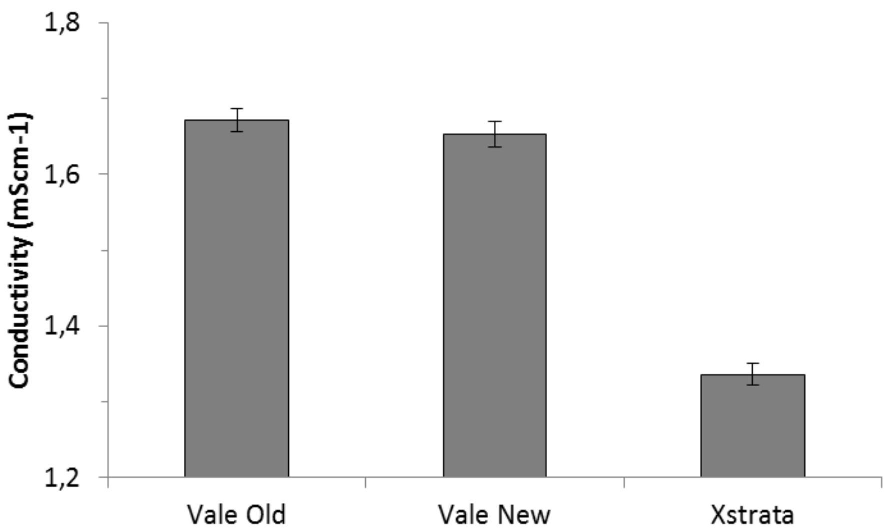

Figure 6. Conductivity of surface biosolids at Vale old and new sites as well as the Xstrata site (mean ± SE; Vale old n = 32, Vale new n= 32, Xstrata n= 48).

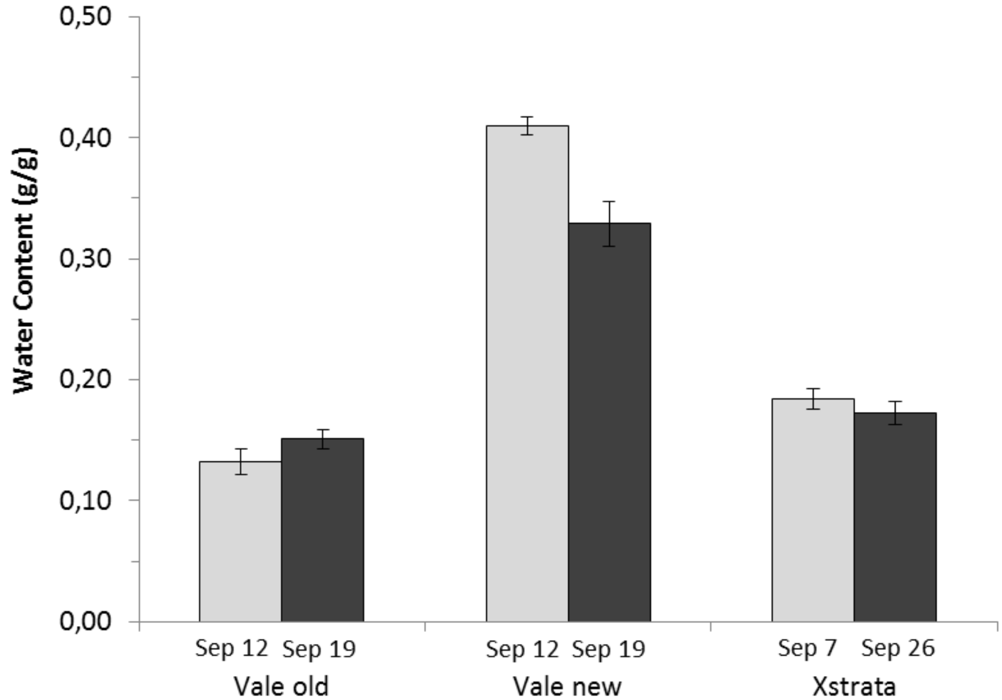

Figure 7. Water content of biosolids at the old and new Vale and the Xstrata site on two sampling dates in September 2012 (mean ± SE; Vale old *n* = 32, Vale new *n* = 32, Xstrata *n* = 48). Note that Xstrata sampling dates differ from Vale sampling dates, as shown on the X axis.

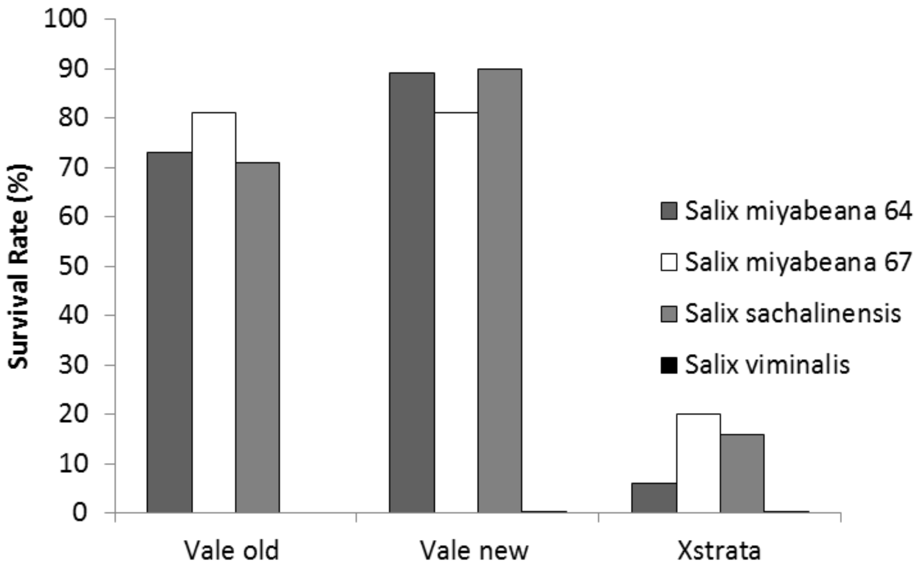

Figure 8. Percentage of surviving willows per variety at each biosolid site (Vale new *n* = 480; Vale old *n* = 480; Xstrata *n* = 720).

Figure 9: Weeds covering the biofuel willow plot at the Xstrata site in early July, 2012. Willows could not be seen amongst the weeds.

Figure 10. Biofuel willows at the Vale old site in early July, 2012. Note the relatively thin weed density compared to the Xstrata site.

Salix miyabeana 64 and 67 as well as the *Salix sachalinensis* were relatively equal in height at all sites ($P = 0.53$; Table 4, Figure 11). The few surviving willows of the *Salix viminalis* were under 50cm and by far the smallest of the 4 varieties. However, willows had large differences in height between sites ($P < 0.001$; Table 4). Willows at Vale old and Xstrata were similar in height, at 75-95 cm, but the Vale new site (new Domtar) had the tallest willows, averaging between 125-135 cm tall. The difference in height between the two Vale sites was striking. Branching again did not vary with species ($P = 0.12$; Table 5; Figure 12). Surprisingly and in contrast to the height results, the willows on the Xstrata site had greater branching on average than both Vale sites, which were not significantly different.

Chlorosis was highly evident in the few surviving *Salix viminalis* (Figures 13). Both varieties of the *Salix miyabeana* as well as the *Salix sachalinensis* had similar chlorosis. The willows at Vale old and new were quite equal at around 20-40%, but the Xstrata willows were most affected by chlorosis out of all three sites, with 50-70% showing some signs of chlorosis.

Leaf curling was sporadic throughout the entire willow population at all three sites, but was almost double at the Xstrata site (Figure 14). It often occurred in drier areas of the plots and was quite abundant in the latter part of the drought period of the growing season. With precipitation, some plants recovered. Leaf curling also seemed to be more abundant in taller willows (>100cm) than shorter willows (<100cm). Shedding of leaves appeared to be correlated with curling of leaves and was also greatest at the Xstrata site (Figure 15). Also like curling the shedding of leaves seemed to be more common in taller willows than shorter willows.

The last health characteristic that was studied was insect damage. With the exception of *Salix viminalis*, insect damage did not seem to differ between species (Figure 16). The level of insect damage at Vale old and new was very equal and was obviously most abundant at Xstrata.

Table 4. ANOVA table of the effects of variety, site and latin square position on the height of willow species. *Salix viminalis* was excluded from the analysis due to extremely low survival. Significant effects are in bold ($P < 0.05$).

Source	df	SS	MS	*F*	*P*
Site	**2**	**35129**	**17564**	**58.5**	**<0.0001**
row	3	1163	388	1.3	.285
column	3	527	176	0.6	.627
Variety	2	385	193	0.6	.530
Error	65	19526	300		

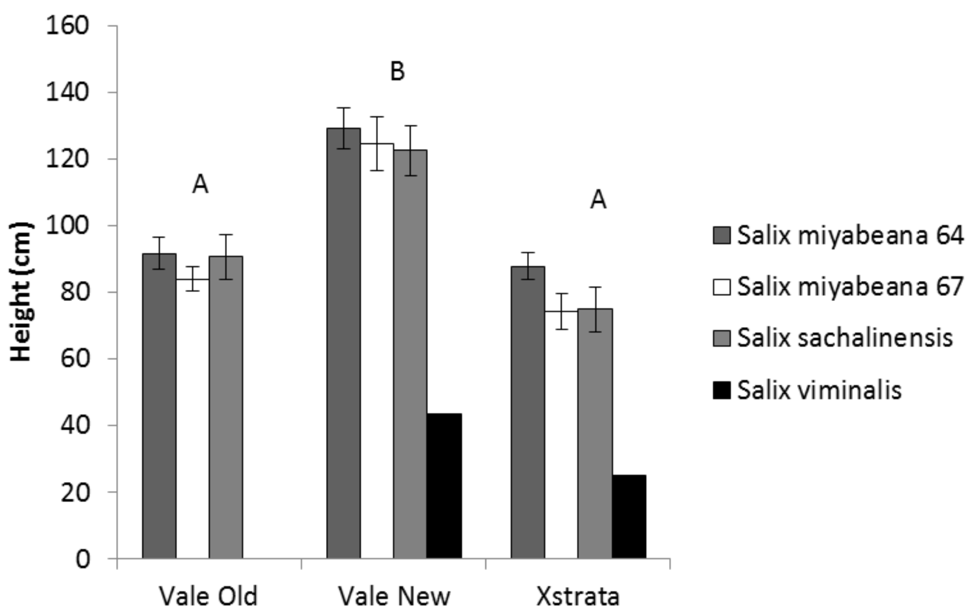

Figure 11. Height of all willow varieties on Vale old and new as well as the Xstrata site (mean ± SE; Vale old n = 192, Vale new n= 192, Xstrata n= 240). Capital letters indicate significant differences between sites across species based on Tukey's test ($P < 0.05$) on all willows except *S. viminalis*.

Table 5. ANOVA table of the effects of variety, site and latin square position on the number of branches of willow species. *Salix viminalis* was excluded from the analysis due to extremely low survival. Significant effects are in bold ($P < 0.05$).

Source	df	SS	MS	*F*	*P*
Site	**2**	**17.07**	**8.53**	**15.2**	**<0.0001**
Row	3	2.49	0.83	1.5	0.228
column	3	3.41	1.14	2.0	0.118
Variety	2	0.14	0.07	0.1	0.879
Error	66	36.96	0.56		

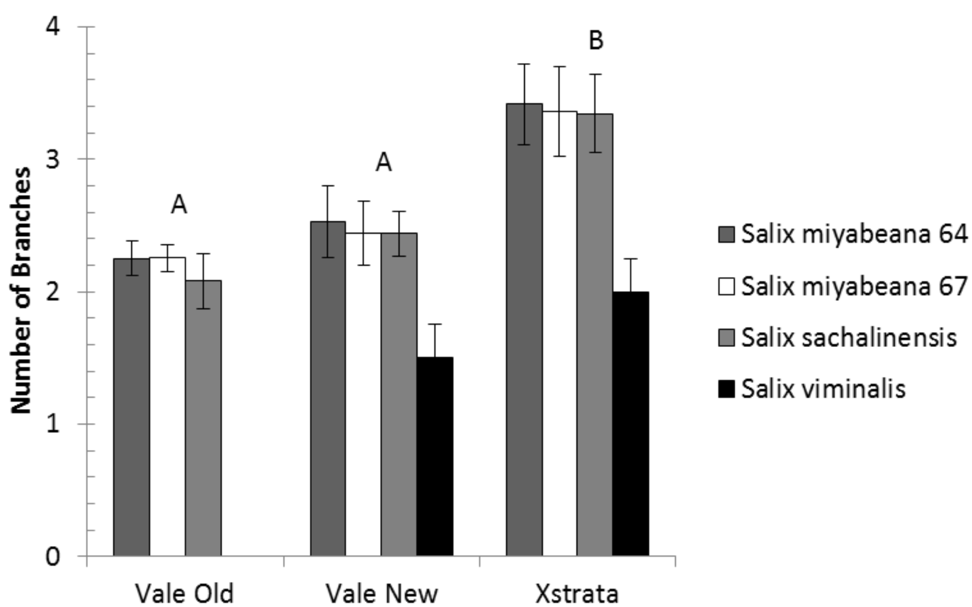

Figure 12. The number of branches per plant at the Vale and Xstrata sites (mean ± SE; Vale old n = 192, Vale new n= 192, Xstrata n= 240). Capital letters indicate significant differences between sites across species based on Tukey's test ($P < 0.05$) on all willows except *S. viminalis*.

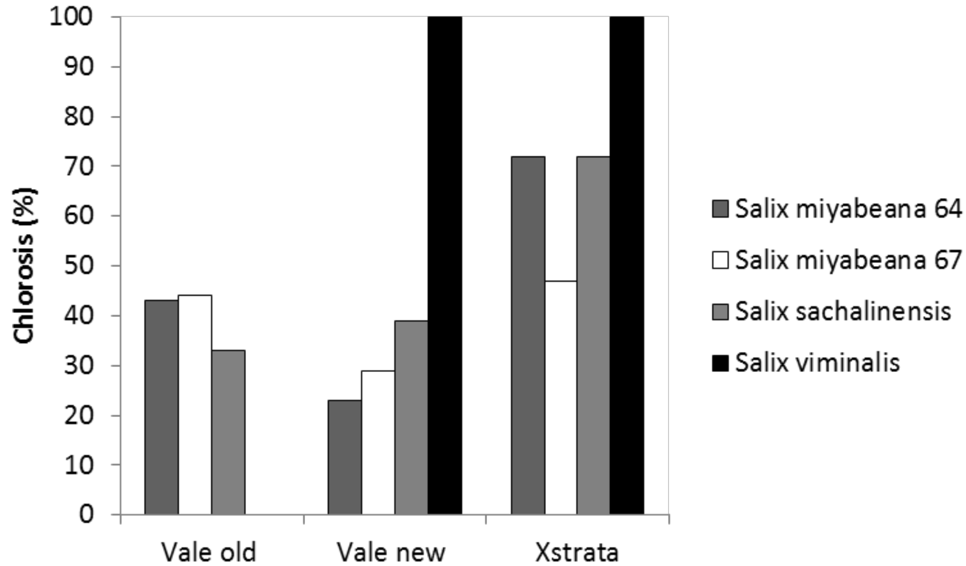

Figure 13. The percentage of studied willows that showed characteristics of chlorosis (Vale old n = 192, Vale new n= 192, Xstrata n= 240).

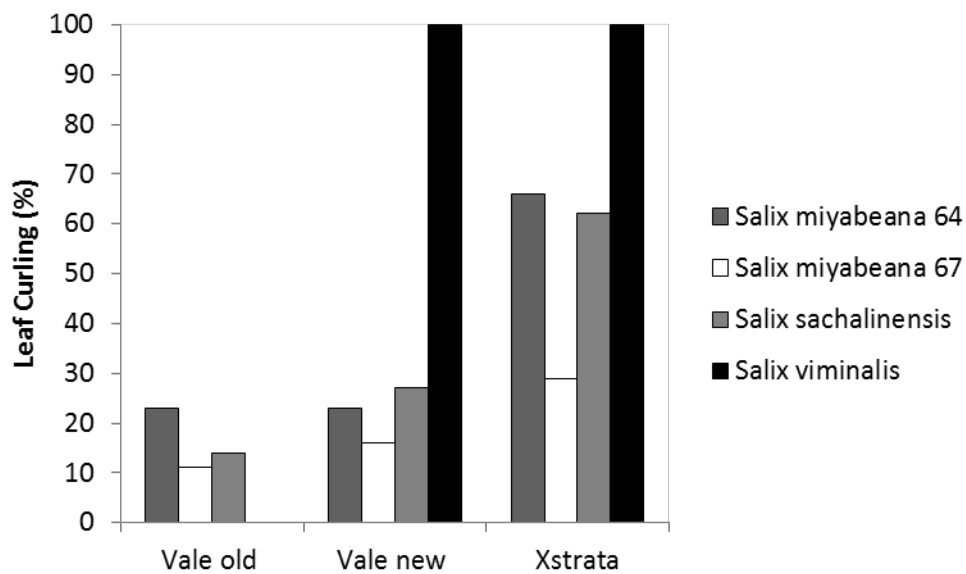

Figure 14. Percentage of studied willows that had obvious curling in their leaves (Vale old n = 192, Vale new n= 192, Xstrata n= 240).

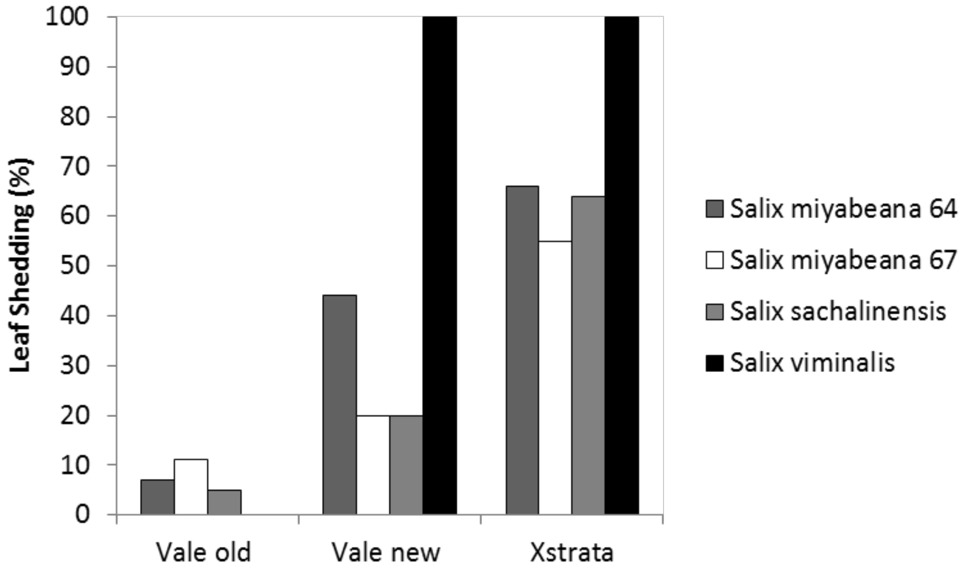

Figure 15. Percentage of studied willows that showed shedding of the leaves at Vale old and new as well as the Xstrata site (Vale old n = 192, Vale new n= 192, Xstrata n= 240).

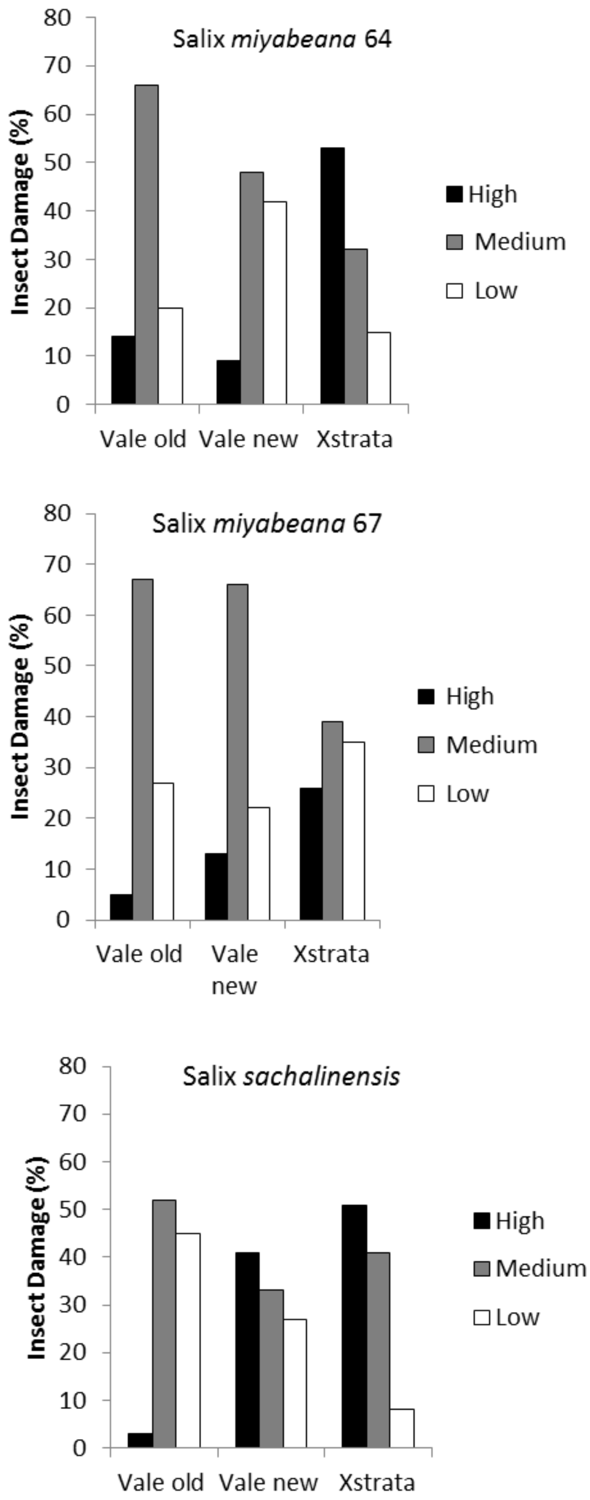

Figure 16. The level of insect damage in the four Salix varieties when grown on biosolids at the three study sites. Note that *Salix viminalis* is not included ibecause of the extremely low survival.

DISCUSSION

Weed density was likely the cause of an extremely low survival rate at the Xstrata site over the course of the 2012 growing season. This was likely due to the weed population out competing the willow population for moisture and nutrients in the compost biosolid cover, as occurs frequently in tree plantings (Zeleznik & Zollinger, 2004). The analysis of health characteristics such as chlorosis, leaf shedding and leaf curling support this assumption. The willow population at Xstrata was also decimated by insect damage, which could have also been related to the high weed density combined with the low height of the willows.

The lesser weed density at both Vale old and Vale new was likely one of the reasons why the willows at these sites succeeded in both survival and health characteristics. Apart from the weed density, the water content of the pulp and paper biosolid cover on the Vale new site was greater than the Vale old site. This could be a result of the newer material having the ability to hold more moisture. Another reason could be that initially the location of Vale new may have contained more moisture before application of biosolids. When comparing the water content between the Vale old and Xstrata sites, they appear to be quite similar. However, the samples were taken on different dates. This combined with the dense weed population at Xstrata would make it difficult to determine completely which cover had the greatest water retention ability from this data alone.

Other aspects of the biosolid covers, such as pH and conductivity were encouraging. Both the pulp and paper and compost biosolids appeared to accomplish their initial objective of establishing a physical barrier. This was the most noticeable at the Vale sites where the surface pH was increased from 2.78 (Table 1) at the tailings to approximately 7.5 at the Vale old site and 7 at the Vale new site at the surface of the cover (Figure 5). Also based on the water content, both biosolid types clearly limited the water flux down to the tailings (Keller et al, 2011; Lock et al 2010).

Another interesting result from this study was comparing the branching of willows at all three sites. Surprisingly, Xstrata was the significant site for this aspect when compared to Vale old and Vale new. This could once again be owing to the weed population. A hormone in plants called auxins allows the plant to react to external conditions and adapt to them (Schachtman and Shin, 2007). In this case the high weed density allowed for little sunlight to reach the willows. This possibly forced the plant to branch out and grow wider in search of sunlight. The Vale willows may have had less branching on average because of the lesser weed density on the two sites. This allowed the Vale old and new willows to grow completely vertical and straight into the sunlight in most areas of the site (Schachtman and Shin, 2007).

Comparing the maximum mean height of the willows at all three sites was another interesting data set of the study. The Vale new site was the most significant with Vale old and Xstrata being very similar to each other on average. A reason for the Vale new site having willows significantly taller than that of Vale old and Xstrata, could relate back to the higher water content of the Vale new biosolids. Once again the poor performance in this category for the Xstrata willows could likely be related to the weed population out competing the willow population for moisture and nutrients (Zeleznik & Zollinger, 2004). This in turn may have stunted the growth of the surviving willows at the Xstrata site. The cause of the shorter willows at Vale old in comparison to Vale new could have simply been the hot and dry growing season combined with the lower water content of the Vale old cover.

From analysing the results obtained over the 2012 growing season, several conclusions can be made. First of all, the Salix *viminalis* was extremely unsuccessful at all three sites. Owing to this, the *viminalis* species should not have a cardinal role in future projects of this nature. Other than the *viminalis*, both varieties of Salix *miyabeana* (64 and 67) as well as the Salix *sachalinensis* were all quite successful. These willow species are therefore viable for future projects, going by the results from this study.

Second, the weed density at the Xstrata site was a major factor. This likely skewed the results of the study, in turn making the pulp at paper biosolids appear to be the optimal cover. However, this likely is not the case as the willows on both Vale sites had much better growing conditions simply because of the lesser weed population. Due to this, there cannot be a complete decision as to which of the two biosolid types are optimal.

The last partial conclusion that can be made from this study is that the age of the biosolids seems to affect the overall performance of the cover. The depth of the cover does not affect performance, to an extent. This may have been proven when comparing the two Vale sites. The new biosolids produced healthier willows with more biomass than the old biosolids even though they were applied at an overall shallower depth. However, this objective was not a significant part of the study, therefore a solid conclusion cannot be made. That being said, there is good reason for this hypothesis to be further studied.

From these conclusions, there are recommendations to be made for future projects. Given that weed growth at Xstrata was a major issue, a form of weed control or herbicide use should be considered. There is a possibility of the herbicide negatively impacting the willow population. However, given the survival data from this study, weed growth is just has much of a concern. This study demonstrated that both cover types do provide a sufficient growing medium for biofuel crops. It was also proven that while Salix *viminalis* was unsuccessful, both Salix *miyabeana* 64 and 67 as well as Salix *sachalinensis* are viable choices for future projects.

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