New Forests, July 2019, Volume 50, Issue 4, pp 555–572
DOI: 10.1007/s11056-018-9678-9

The effect of tree planting density on the relative development of weeds and hybrid poplars on revegetated mine slopes vulnerable to erosion

Arnaud Remaury[(1)], Marie Guittonny [(1)*] and Jane Rickson[(2)]

1. *Research Institute on Mines and Environment (RIME),* Université du Québec en Abitibi-Témiscamingue (UQAT), 445 boul. de l'Université, Rouyn Noranda, QC, J9X 5E4

2. *Cranfield University,* College Road, Cranfield, MK43 0AL, Bedfordshire

*Marie Guittonny (Corresponding author)
Tel. 001-819-762-0971 ext.2563   Email: Marie.Guittonny@uqat.ca

Keywords

Erosion pin method, fast-growing plantation, tree and weed competition, mine revegetation, root length density, vegetation cover.

Abbreviation list

RLD: Root length density

T: Control treatment without planted trees or hydroseeding of herbaceous species

T1m: Treatment with tree planting at 1x1m spacing, without hydroseeding

T2m: Treatment with tree planting at 2x2m spacing, without hydroseeding

T4m: Treatment with tree planting at 4x4m spacing, without hydroseeding

T2mH: Treatment with tree planting at 2x2m spacing, with hydroseeding

Acknowledgements

This research was funded by Canadian Malartic and the Natural Sciences and Engineering Research Council of Canada (NSERC) through a CRD grant (grant number RDCPJ 462610-13). The authors thank A. and H. Jobin, C. Mirault and undergraduate summer students (namely C. Frénette-Vallières, S. Gervais, M. Rajot, L. Boivin, A. Beaulieu, P. Castro Y Neves, and Y. Goudreau) for assistance in fieldwork, as well as C. Pednault and D. Thellend from Canadian Malartic for fieldwork coordination at the mine site. We also thank the four anonymous reviewers who helped to improve the manuscript with constructive comments.

Abstract

In reclaimed waste rocks slopes, the soil cover spread for revegetation is prone to erosion. This soil needs to be immediately protected from soil erosion by above and belowground vegetation. The seeding of fast-growing herbaceous species used in agriculture is generally used on waste rock slopes to control erosion, but these compete with planted trees for resources needed for growth. The aim of this study was to assess the ability of an alternative to these herbaceous species (i.e. fast-growing hybrid poplars) to mitigate soil losses in the short-term. However, the growth of poplars could be impaired by competition from weeds' colonization. Tree planting density was expected to change competition levels among trees and between trees and weeds, so influencing above and belowground vegetation development and hence effectiveness at controlling soil erosion processes.

Five treatments were installed in 2013: 1x1, 2x2, 4x4 meter spacing of hybrid poplars; 2x2 meter spacing, with hydroseeding of fast-growing herbaceous plants; and a control plot with no tree planting or hydroseeding. The planting of hybrid poplars did not decrease soil losses compared to the control plot, regardless of the tree planting density. Weed development through natural colonization occurred in all the non-hydroseeded plots and was more effective at soil erosion control in the short-term than planted trees. The selected clone of hybrid poplar coped well with any competition from weeds for water, since 100% of trees survived after three years and since the non-hydroseeded plots produced greater length of roots per soil volume (root length density, RLD) for the poplars compared with the weed species. As early as the first year, the hydroseeded plots showed the highest RLD and a complete cover of vegetation which effectively controlled soil erosion compared to the control plots. However, both treatments with increased competition levels (i.e. highest

tree planting density and hydroseeding treatment) showed less aboveground tree biomass. On the hydroseeded plots, where interspecific competition with weeds was the highest, a greater increase in root length was seen during the third year after planting. After three years, canopy closure was achieved in the 1x1 meter spacing treatment, which reduced weed cover.

Introduction

Waste rock management can be considered as one of the most important environmental liabilities for mining companies (Aubertin and Bussière 2013; Bussière 2007; Spitz and Trudinger 2008), especially in the case of open pit mines, which generate a larger amount of waste rocks than underground mines (Dudka and Adriano 1997). Waste rocks (i.e. all material removed from the mine pit other than topsoil, subsoil or ore) are dumped in stockpiles, often several tens of meters high, containing millions of tonnes of material, constituting the most visible component of the project landscape footprint. At mine closure, waste rock piles must be reclaimed with appropriate methods to avoid soil, air and water contamination. Reclamation of these waste rock piles includes revegetation, which is a legal requirement in several countries around the world.

Tree planting can help to integrate reclaimed waste rock piles with natural forested landscapes. Moreover, revegetating mine wastes with tree cover can reduce the negative impacts of habitat loss and fragmentation on ecosystem services (Fahrig, 2003). Thus, trees have been used extensively worldwide to revegetate surface mine sites (Macdonald et al 2015). To increase the chances of successful establishment, waste rock slopes of non-acid-generating material can be covered with soil, but this soil is often poorly structured and highly vulnerable to erosion by rainfall and surface runoff.

Seeding mixtures of grasses and legumes commonly used in agriculture is the most common practice adopted to control the erosion of soil covers used on waste rock slopes (Skousen and Zipper 2010). Their quick and complete development of ground canopy cover (Andreu et al. 2008) minimizes the time when bare slopes are subjected to potentially erosive rainfall or snowmelt. Indeed, even when plant cover is still low, the canopy can reduce raindrop size, velocity and energy, so reducing the risk of soil particle detachment by rainsplash (Morgan and Rickson 1995).

However, herbaceous weeds are known to compete with planted trees for light, nutrients and water resources (Groninger et al. 2004, Siipilehto 2001) and may decrease tree productivity at the critical establishment phase. Planting native trees without herbaceous seeding may decrease this competition, but the limited development of tree canopy cover in the first years after planting can allow erosion processes to occur, leading to soil degradation and associated loss of tree productivity. Planting trees that grow faster than native trees could protect the soil against erosion more rapidly, whilst also integrating the reclaimed waste rock piles into the forested landscape. However, trees may remain less effective than weeds in controlling soil erosion since their canopy is further from the soil surface and their cover at the ground level is lower compared to weeds (Morgan and Rickson 1995).

Fast-growing trees such as hybrid poplars can be artificially established on waste rocks with soil cover (Larchevêque et al. 2014). In the ecozone of the boreal humid forest, weeds can quickly colonize hybrid poplar plantings (Ann et al. 2008). Since poplars can be very sensitive to competition from weeds for water and nutrients during the first years of establishment (Jassal et al. 2013; Shock et al. 2002; Stanturf et al. 2001), and since weed control is difficult on reclaimed mine slopes, weed colonization may limit hybrid poplar productivity. Conversely, weed colonization could contribute to soil erosion control.

In plantations, the development of both tree and weed species is related to the degree of competition for resources. Tree growth after planting will depend on the above and belowground biomass production of early colonising weeds (Hoomehr 2012). Tree size and spacing will in turn impact the composition and production of weed species (interspecific competition) (Scholes and Archer 1997). Increased shading associated with denser planting hinders the development of light-demanding, weedy species (De Keersmaeker et al. 2004). Furthermore, planting trees at low densities (i.e. low intraspecific competition) may favor an increase in biomass in the aboveground shoot component (DeBell et al. 1996). Intraspecific competition (i.e. competition between weeds and planted trees) can have greater effects than interspecific competition, especially for hybrid poplar (Marino and Gross 1998). Below ground, root growth and the specific root length of early succession species like hybrid poplar are decreased by competition for space with weed roots (Messier et al. 2009). Friend et al. (1991) showed that under high plantation densities (1x1m spacing), poplar roots cover an area six times greater than the canopy. Each root system overlaps with one another, increasing root density and creating a soil/root matrix which encourages water infiltration, increased soil cohesion and thus mitigation of soil erosion. Plant roots, ground cover and canopy cover are three different components of vegetation that can influence erosion processes (Morgan 2005).

The present study will specifically deal with waste rock slopes covered with topsoil in a boreal forest area. The main research objective was to study if planting fast-growing poplars on slopes without the traditional seeding of agricultural grasses and legume species allowed faster tree growth, while decreasing soil losses. More specifically, we compared the effect of three planting densities of hybrid poplars (1×1, 2×2, 4×4m, i.e. differing inter- and intraspecific competition levels) on above- and belowground vegetation development for three years after planting. A control treatment without planting was also set up. The effect of tree planting density on soil losses was investigated, especially in the first year after planting, when the soil is expected to be most vulnerable to erosion. One treatment (tree spacing at 2m × 2m) included hydroseeding of fast-growing herbaceous species to compare it to natural colonization by weeds. The three following hypotheses were tested: 1) Hybrid poplar planting will decrease soil losses in the first year after planting compared to a control treatment of bare soil without planting or hydroseeding; 2) Combining tree planting and hydroseeding will result in the lowest tree growth (due to interspecific competition), but also to the lowest soil losses (due to greater weed development above and below ground); 3) Increasing tree planting density will decrease weed development as well as aboveground tree growth (due to intraspecific competition).

Methods and materials

Site description

The study site is located at the Canadian Malartic mine (48°06’47”N, 78°07’58”W) in the Abitibi region of Quebec, Canada. Canadian Malartic is an open pit gold mine with low grade ore. The ore extracted is mineralized greywacke and represents a small fraction of the mined material, which generates a large amount of waste rock. Analysis of the waste rock revealed low sulphur contents (less than 1%) with trace metal concentrations lower than Quebec regulatory thresholds for residential land (Gouvernement du Québec 2016). The site belongs to the white birch bioclimatic domain which occupies the southern portion of the boreal zone (Saucier et al. 2009). The experimental plots are surrounded by forest stands which include jack pine (*Pinus banksiana* Lamb.*),* black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenb.), trembling aspen (*Populus tremuloides* Michx.*),* white birch (*Betula papyrifera* Marsh.), tamarack or eastern larch (*Larix laricina* (Du Roi) K. Koch), and balsam fir (*Abies balsamea* (L.) Mill.). In this boreal region, the growing season typically begins in mid-May and ends in early October, with a mean temperature during the three warmest months (June, July, and August) of around 18–19°C. The mean annual temperature is 1°C, and the mean number of frost-free days is 80. Mean annual precipitation is around 900 mm (Government of Canada 2004).

Experimental design

The experimental plots were separated by 4m-wide buffer zones without trees. The design consisted of 15 experimental plots measuring 8 x 12m in a randomized complete block design. Five treatments were randomly distributed in 3 replication blocks and were monitored over three years of growth (2013, 2014 and 2015) (Figure 1): Plots with 1x1m tree spacing (T1m); Plots with 2x2m tree spacing (T2m); Plots with 4x4m tree spacing (T4m); Plots with 2x2m tree spacing and hydroseeding (T2mH); Plots without trees or hydroseeding (T, control plot).

Substrates

Tree planting took place in May 2013 on 33% slopes (7 m elevation, west to south-west slope orientation) covered with 50cm of overburden topsoil. The overburden topsoil is a planosol (FAO, 2015), sourced from a swamp area above the mine pit that had been previously colonised by conifers. The topsoil consists of dark (organic-rich) soil layers (O and A horizons) that had been set aside prior to the excavation of the open-pit. It had been stockpiled for 30 to 36 months before use in 7 m high piles with a 2.5:1 slope. The overburden topsoil is characteristic of the clay belt of Northeastern Ontario and Northwestern Quebec (Harper et al. 2003). In May 2013, the topsoil was dumped by trucks in the upper part of the waste rock slope and spread downslope with a mechanical shovel, avoiding soil compaction.

Soil samples were collected during tree planting in May 2013 (Table 1), with one sample (0-10cm depth) per plot for chemical characterization. Soil and waste rock characteristics did not show evidence of toxicity. Soil nutrient analyses were conducted on sieved (2 mm mesh), finely ground, oven-dried (at 50 °C) samples to constant weight by the Lakehead University Centre for Analytical Services (Thunderbay, ON, Canada). Total nitrogen (N) and sulphur (S) were determined by the Dumas combustion method (CNS 2000, LECO Corporation, Mississauga, ON) and organic carbon (C) by the thermogravimetric method (LECO TGA, Missisauga, ON).

A conversion factor of 1.72 was used to convert organic carbon to organic matter (Nelson and Sommers 1982). Following HNO_3-HCl digestion, sample concentrations of total P, K, Ca, Mg, Na, Al, As, B, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Sr, and Zn were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES, Vista PRO, Varian

Canada, Mississauga, ON). Available-P was determined colorimetrically on sodium bicarbonate extracts of the soil samples (Olsen 1954). Bulk pH was determined from saturated soil pastes, while soil electrical conductivity was determined from a 1:2 (soil:water) extract. Soil texture was determined using the hydrometer method (Bouyoucos, 1962).

Tree planting

Hybrid poplars (*Populus maximowiczii A. Henry* × *Populus balsamifera L. (M × B)* - clone 915319) were planted on all plots in May 2013. The trees were locally-sourced and were provided by the Ministère des Ressources naturelles du Québec (MRN). The hybrid was selected for its potentially high resistance to drought stress (Larchevêque et al. 2011a). The trees were clonally propagated, one-year-old whips (i.e. 1-m long cuttings), which were planted directly into the soil to a depth of 30 cm. A fertiliser comprising 15 g ammonium nitrate (34.5-0-0) and 15 g triple superphosphate (0-45-0) was applied near the base of each tree in a 15 cm deep slit made with a spade, 20 cm from the tree (van den Driessche 1999). Trees were planted in the lower half (lowest 12 metres) of the slope with the intention of improving the slope's mechanical stability (Styczen and Morgan 1995). In the upper half of the slope, two lines of fast-growing willows (*Salix miyabeana* Seemen) were planted at a high density, and hydroseeding was applied on the upper-most 2 metres of the experimental plots to control water run-off and soil erosion in this vulnerable zone. Hydroseeding consisted of spreading a mixture of water, seeds and fertilizer onto the soil surface with a high-pressure hose. The fertilizer comprised 8% N, 32% P and 16% K, di- and mono-ammonium phosphates and potassium chloride at 750 kg/ha. The seed mix comprised *Lotus corniculatus* (15 %), *Trifolium repens* (7 %), *Trifolium hybridum* (3 %), *Trifolium pratense* (10 %), *Avena sativa* (11 %), *Lolium perenne* (12 %), *Poa pratensis* (15 %), *Festuca rubra* (15 %) and *Sorghum bicolor* (12 %), applied at a rate of 100g/ha.

Root sampling

The auger core sampling method was used to study the root system morphology (Reubens et al. 2007) in the surface soil prone to erosion (0-10 cm depth). This method is considered to be an efficient method of assessing root length density (i.e. the length of roots per unit volume of soil, RLD - expressed in $cm.dm^{-3}$) in the top soil layer (Reubens et al. 2007). Core samples were collected around a selected tree in each plot during six measurement campaigns (May, July and October 2014 and 2015). The tree selected in the spring was located in the centre of the plot. Then, in the summer and fall sampling period, the tree on the right or left hand side of the plot respectively was selected. Six (in 2015) to eight (in 2014) cores per tree were taken, based on a Voronoï polygon (Snowdon et al. 2002). The edges of a square were placed in the middle of the distance between the sampled tree and its neighbours. This square was then separated into four smaller squares with the sampled tree at the corner of the four squares. Coring was performed in the squares on the right and above the sampled tree, the other to the left and below the sampled tree. Cores were collected randomly at three distances from the tree: one core from the most distant area from the tree, another from the closest area, and one to two cores from the intermediate area. The auger diameter was 8 cm (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands). The target core depth was 10 cm, but ranged from 8 to 14 cm. Each core depth was noted in order to calculate the corresponding core soil volume. Where the auger could not penetrate the ground sufficiently, coring was performed in an adjacent location. Cores were stored at 4°C until analysis.

For each core sample, the roots and organic residues were washed using tap water and then scanned (8 bits per pixel grey levels images). The woody and non-woody plant roots were separated after washing, based on colour and architecture. As the planted poplars were clearly the dominant woody species on the plots (there were very few woody weeds present), we assumed that any woody roots were poplar roots. These were darker (brownish) than the non-woody roots, and more rigid when bent by hand. The root scans were analysed using WinRhizo software (regular version, Regent Instruments Inc., Quebec, Canada). This is considered to be the most widely recognised software in plant stress research (Pang et al. 2011), giving information on root length, area and volume, and classifying these parameters according to the root diameter. The proportion of fine roots (diameter <2mm) to total root length was calculated. The software also calculates the root length density, expressed in $cm.dm^{-3}$. This is a vital parameter for expressing root development (Pierret et al., 2000). Roots were then separated into fine (diameter <2mm) and coarse sizes, oven dried and weighed to obtain root biomass. From the biomass data, the specific root length of the fine roots was determined by dividing the root length by the dry mass of the fine roots. This ratio is an indicator of root growth (Zhang et al. 2015), carbon allocation (Pimentel Rosado et al. 2011) and the plant's ability to take up water and nutrients (Besharat et al. 2010, Ostonen et al. 2007, Pimentel Rosado et al. 2011).

Weed vegetation cover

The non-destructive, point intercept method was used to assess weed cover (Jonasson 1983). A sharp rod (5mm diameter) was vertically dropped every 10 cm on a transect line (5 m long, *i.e.* 50 reading positions). Transects were set up approximately 6.5 m downslope from the first line of poplars and then 50 cm below the closest trees. At each rod position, the presence of each plant species was noted to obtain weed cover percentage, as well as information on whether the cover comprised litter or vegetation (alive or dead). Such measurements were carried out in spring (May 2014 and 2015), in summer when the weed cover was greatest (July 2014 and 2015), and in fall (September 2013, 2014, and 2015).

Tree canopy development

All trees were measured at planting for maximum height, stem basal diameter and mortality. A similar plantation inventory was carried out in the fall in 2013, 2014, and 2015. In the fall, maximum tree crown width (diameter) was measured perpendicularly to the slope (D_1) and along the slope (D_2) for 6 randomly selected trees per plot; these two diameters were used to estimate the projected canopy area by considering the canopy as an ellipsis ($area=\pi*D_1*D_2/4$). The plot % canopy cover was calculated by multiplying the mean of these 6 canopy area values by the number of trees by plot, divided by the plot area × 100. Tree biomass was calculated from the allometric equation developed by Benomar et al. (2012) for the same poplar clone and in the same region of Abitibi-Témiscamingue: $B=0.28*DBH^{1.79}$; where B = biomass (kg dry mass tree^{-1}) and DBH = diameter at breast height (cm).

Soil erosion measurements

The erosion pin technique allows identification of “ground advance” (deposition of soil material) and “ground retreat” (erosion of soil material) (Haigh and Gentcheva-Kostadinova 2002, Loughran 1989). This method is recognized as being well suited to the present study conditions and to meet the stated research objectives (Haigh 1977; Stroosnijder 2005). Soil erosion was monitored by taking comparative measurements of the soil surface position using erosion pins in the spring, summer and fall in 2013, 2014 and 2015. The spring measurements took place just after all the snow at the experimental site had melted (except in 2013) and the fall measurements took place just before the first snow, making 7 data collection campaigns.

Erosion pins are nails or metal rods inserted into the soil, at locations where disturbance from the weather (e.g. frost heave) or incidental trampling is unlikely. Haigh (1977) recommends installing the pins perpendicular to the slope gradient and notes the precise millimetre-scale accuracy of the method. The pins used in the present study were 70 cm long metal rods (0.6 cm diameter) inserted 40 to 50 cm deep into the soil on 4 m transects (4 pins per plot) superposed on the 5m-transects used for the weed cover measurements. Over the measurement period, visual inspection of the experimental plots showed no apparent change in the soil surface level. Indeed, there was no rill or gully erosion present. The exposed height of the pin when facing upslope was taken to indicate the degree of soil erosion. The soil loss (or gain if sediment deposition occurred) between two measurement dates was derived from these measurements.

Statistical analysis

Statistical analysis was performed using the R package (R Core Team / version 3.2.3 / 2015) at the 0.05 significance level. A randomized block analysis of variance (block as random factor) with repeated measures was carried out in order to identify if a significant difference between the treatments (treatment as the only fixed factor analysis) occurred for the studied parameters: soil erosion (cm), mean root diameter (mm), root biomass (g), fine root to total root length proportion (%), root length density (cm/dm^3), weed percentage cover (%), poplar canopy percentage cover (%), tree height (m) and tree diameter (cm). A multiple comparison of means was conducted with a paired t-test (Holm) to specify which pairs of treatments were significantly different. Pearson's correlation coefficients (r) were used to assess the strength of the relationship between soil erosion and RLD, weed cover, and poplar canopy cover.

Results

Tree survival and aboveground growth

Tree survival was close to 100% on all planted plots, three years after planting. Tree height was greater in October 2014 for T1m than T2mH ($p<0.001$) and T4m ($p<0.01$) (Figure 3). T1m had the highest height/diameter ratio (10% higher) among the four planted treatments over the two years ($p<0.001$, results not shown). T1m also had a lower aboveground biomass compared to T2m ($p<0.001$) and T4m ($p<0.01$) in 2015 (Figure 4). T2mH had a lower height (30 cm less) and aboveground biomass (0.2 kg less) than T2m and T1m after two years, and when compared to all other treatments after three years ($p<0.001$, Figure 4). The differences in tree height between T2mH and other treatments increased over time. Poplar canopy cover increased with planting density in the second (2014) and third year (2015) after planting ($p<0.001$, Figure 4) and reached 100% in the third year for T1m. When comparing T2m and T2mH, hydroseeding decreased tree canopy cover by around 15% ($p<0.001$, Figure 4) in the second year after planting, but this effect declined by the third year after planting. By then, the difference in canopy cover between T2m and T2mH was no longer significant.

Weed cover

The development of herbaceous species was more rapid in the T2mH plots, with weed cover being significantly greater (× 2.5 to 4 times) in September 2013 ($p<0.01$) and May

2014 ($p<0.01$) than for all other treatments (Figure 5). However, the development of the weed cover from naturally colonising species after planting resulted in a comparable aboveground cover for all treatments by the end of the growing season in 2014 and 2015 (Figure 5). The weed cover was similar between the treatments where no hydroseeding took place (including the control plot without trees), except in July 2015 where T1m showed the lowest weed cover ($p<0.001$).

Poplar and herbaceous root development

RLD was the most useful parameter to discriminate the differences between the treatments during the first three years after planting. By contrast, mean root diameter and root biomass were similar among treatments. Sampled roots with a diameter less than 2 mm accounted for the largest part of the total root length (93%) by the end of the study. The hydroseeded treatment T2mH showed a significantly higher herbaceous RLD on all sampling dates ($p<0.001$) compared to the other treatments which were naturally colonized (Figure 6b). Poplar RLD was significantly higher in T1m compared to all other treatments at all six sampling dates, except when compared to T2mH and T2m in July 2015 ($p<0.001$, Figure 6a). In 2014, the increase of RLD in T1m was proportional to the increase in tree density associated with the treatments (×3 and ×10 compared to T2m and T4m, respectively) while in 2015, T2m and T4m RLDs were closer to T1m RLD (which was ×2 and ×5 compared to T2m and T4m, respectively). The seasonal variation (May-October) was greater for T1m during the second year of growth and for T2mH during the third year of growth. From the third year of growth, poplar RLD in T2m became significantly higher than in T4m ($p<0.05$). T4m and T2mH showed a greater specific fine root length (SRL) of the poplars by October 2015 compared to the other treatments ($p<0.001$).

When combining herbaceous and tree species RLD, T2mH presented the highest total RLD over all sampling periods. The contribution of herbaceous roots to total RLD decreased over time for all treatments, particularly in the T2mH, where the tree / herbaceous species roots ratio increased from 0.07 (October 2014) to 0.7 (October 2015) (Table 2). Herbaceous roots remained dominant (ratio <1) after three growing seasons in both T2mH and T4m. The T1m treatment had the second most extensive total root development due to the contributions of the many closely spaced trees. Finally, in October 2015 T1m had a significantly higher mean diameter of poplar roots compared to T2m ($p<0.01$), T2mH and T4m ($p<0.001$), and a lower proportion of fine roots compared to all other treatments ($p<0.001$) (i.e. the length of the roots with a diameter less than 2 millimetres/total root length (results not shown)).

Soil erosion

From the first erosion pin measurement in July 2013, two different changes in soil surface level were observed: soil loss during the spring snowmelt between October 2013 and June 2014, and soil deposition during the summer rainfall between June and October 2013, and between June and October 2014. Hence, for the analysis, the data were separated into two time periods associated with either soil loss or soil deposition.

The treatment T2mH showed the lowest soil loss during the first year after planting, which was three times lower than the control treatment (T) ($p<0.001$, Figure 2). The three other treatments (T1m, T2m and T4m) had intermediate soil losses, not significantly different from T2mH and T (Figure 2). Subsequent measurements in May 2015 showed lower soil loss rates than in 2014 (due to less snowmelt), but all treatments had similar soil losses.

Similarly, soil deposition analysis from June to October 2015 did not reveal any statistically significant results.

Correlations between soil loss rates and explanatory data (i.e. poplar and weed cover, and RLD) were carried out, but no significant correlations were found between the variables ($p<0.05$).

Discussion

Tree survival was 100% for all planted treatments three years after planting and the planted trees showed similar or better growth rates compared to data collected from other hybrid poplar plantations under boreal conditions (Larchevêque et al. 2011b; Larchevêque et al. 2010; Larocque et al. 2013). This result confirms the ability of the selected hybrid poplar to acclimatize on waste rock slopes, despite the rapidly draining environment and strong competition for water expected for some of the tested treatments. There was no planting shock.

Contrary to the first hypothesis, planting of fast-growing trees in areas colonized by weeds did not decrease soil losses. In the two first years after planting, weed colonization resulted in similar cover and root development in all plots without hydroseeding, whether planted with trees or not. Indeed, the non-hydroseeded plots were rapidly colonized by weeds by the second year of the experiment, which may have decreased erosion rates (Pohl et al. 2009). No effect of tree planting density was found on soil losses because similar weed cover protected the soil. This highlights that in our study, soil erosion rates were mostly influenced by weed cover. Trees were less able to control erosion, maybe due to the slow development of tree roots and canopy closure.

Comparison of T2m and T2mH confirmed the second hypothesis. As predicted, greater weed development (both above- and below ground) from the start of planting in T2mH, inhibited tree development in terms of height and stem diameter. Indeed the herbaceous species were competitive for soil water and N (Boothroyd-Roberts et al. 2013) and this interspecific competition can result in delayed tree growth. Accordingly to Marino and Gross (1998), the aboveground biomass of poplars is more limited by competition from weeds compared to competition from similar tree species.

Belowground, tree root contributions to the total RLD increased over time for all the treatments, especially for the hydroseeded treatment, even if herbaceous roots remained dominant in this treatment. Messier et al. (2009) showed that competition for space with the roots of herbaceous species reduces poplar root growth in the short term (i.e. first growing season), as well as specific root length. In our study however, poplar specific root length increased in the treatment with the higher level of competition from weeds (i.e. the hydroseeded treatment) by the third growing season. It is possible that in the longer term, pioneer trees like poplars can acclimatize to competition for space with weed roots through increased root growth and SRL. However, since hybrid poplars of differing parental lineages can have differing abilities to cope with increased resource stress (for example water, Larchevêque et al. 2011a), their ability to compete with weeds in the root zone could vary with different clones. In Larchevêque et al (2011a), a B×M poplar clone similar to the one used in the present study responded to increased water stress by increasing root growth. In the fast-draining waste rock slopes of the present study, increased SRL in the hydroseeded plots could indicate the ability of the tested poplar to get acclimatized to the increased interspecific competition for water. Indeed, increased SRL and decreased root diameter were reported by Comas et al. (2003) as well-known indicators of plant acclimation to water stress. Contrary to this, interspecific competition actually increased the root diameter of planted poplars in the present study. It thus seems that unlike what was observed for biomass production above ground, poplars may have adapted better to competition for water from weeds, than from conspecifics below ground.

As expected, the hydroseeded treatment was the most effective at controlling soil losses after snowmelt in the first year after planting, when the soil was most vulnerable to erosion. As erosion rates will be higher on newly constructed slopes, based on our results it would be useful to combine tree planting with mulching and/or seeding a grass and legume mix to protect the soil (Dyrness 1975). However, before combining herbaceous seeding with tree planting, mitigating the negative effects of greater interspecific competition between herbaceous species and trees should be considered. Fields-Johnson et al. (2009) demonstrated that combining trees with low-growing, less-competitive groundcover mixes caused less erosion than a conventional mix containing grasses and legumes. One of the five steps recommended by the Forestry Reclamation Approach (FRA) for successful reforestation of degraded land includes the use of ground covers that are compatible with growing trees (Burger et al. 2005). On this point, the same authors explained the importance of seeding "grasses and legumes that are slow-growing and have sprawling growth forms" in order to limit both soil erosion and competition with trees.

The degree of aboveground vegetation cover directly depended on tree spacing. Varying tree planting density controlled competition intensity among trees, but also affected light penetration and associated weed development, which influenced stand dynamics. The time to reach tree canopy closure depended on planting density, the initial plot canopy cover and the increase in canopy diameter. Three years after planting, the highest density planting gave 100% ground cover, while the lowest density planting had better lateral growth, but only partial plot coverage (20%), because of the wide spacing of the trees. The lowest planting density showed a slightly lower rate of height growth the second year after planting, possibly due to the strategy of carbon allocation by the poplars. For some species, tree height can be positively correlated to stand density (Nilsson 1994). A short distance between the trees implies limited access to photosynthetic radiation, high water and nutrient competition, and a strategy to invest energy in height growth rather than diameter growth, which was evidenced by a greater H/D ratio for T1m trees. Due to the lower diameter growth and according to the third hypothesis, the greatest planting density produced the lowest tree aboveground biomass; however, lower density treatments (T2m and T4m) produced similar aboveground biomass, showing that spacing trees at 2x2m allows low levels of intraspecific competition and no limited access to resources for poplar development during the first three years after planting. Below ground, root length density increased with planting density, but this mirrors the increase in the number of trees (i.e. no additional root length production due to increased intraspecific competition). Increasing planting density results in spreading and overlapping root systems (Friend et al. 1991). Moreover, the increase in root length over time for each growing season (i.e. slope of the curves) was similar for all non-hydroseeded treatments. Finally, regarding interspecific competition with naturally colonizing weeds, in treatments without hydroseeding, planted poplar roots were dominant in terms of root length density compared to the colonizing weeds after 3 years, regardless of the tree spacing.

In T2mH and T1m, analysis showed the interaction between above ground weed and tree growth: interspecific competition reduced the tree canopy development in T2mH, while complete tree cover after three years reduced weed development in T1m due to light competition. Indeed, light is an important limiting factor for the establishment of weed plants, with canopy closure reducing its development or stopping its growth completely (Burger et al. 2009; Klinka et al. 1996). After the second year of growth, the proportion of herbaceous roots decreased in T1m because of canopy closure. In the T2mH treatment, herbaceous roots were partially replaced by tree roots in the second year, and tree root length density showed a steeper increase in the third year compared to the plots with less interspecific competition. This evolution shows that interspecific competition may stimulate more poplar root production than intraspecific competition. Moreover, the colonizing weeds and tree growth may change the relative proportion of weed and tree roots throughout the development of the plantation.

Conclusion

Hybrid poplar successfully revegetated waste rock slopes and coped well with interspecific competition for water in environments where weed control is difficult. Greater interspecific competition induced a shift in resource allocation as fine root production of poplar (RLD, SRL) was stimulated, while aboveground biomass and canopy extension were decreased. The greatest planting density (1×1m) reduced weed cover over time and the associated interspecific competition for resources. On the other hand, greater intraspecific competition increased tree height for the heliophile poplar and increased its root diameter, which is thought to be less efficient in acclimatization to possible water stress. In our study, competitive interactions with weeds or with conspecifics thus resulted in differing responses of the above- and belowground growth of poplars.

On waste rock slopes with soil cover, erosion rates after the first year were reduced more by weeds rather than by poplars. Increasing the planting density of fast-growing hybrid poplars did not significantly reduce erosion rates in the short-term compared to the bare soil. Consequently, increased spacing between trees is recommended to maximize above-ground growth. The use of a good quality topsoil favoured weed colonization by the second year after planting, which could advantageously replace traditional herbaceous seeding in mitigating soil erosion, while reducing competition with planted poplars.

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Tables

Table 1. Initial soil and waste rock characteristics. Mean (standard error, SE); N = 15, except on waste rock. All values are expressed on a dry matter basis.

	Unit	Overburden topsoil	Waste rock	Regulatory threshold** (residential lands)
pH		5.9 (0.2)	6.7 to 9	
EC*	$mS.cm^{-1}$	0.4 (0.1)		
OM*	%	20 (3)		
total N	%	0.6 (0.3)		
total P	$g.kg^{-1}$	0.6 (0.02)		
total S	%	0.3 (0.05)		
total Ca	$g.kg^{-1}$	10 (1)	15	
avail. K*	$g.kg^{-1}$	0.1 (0.005)		
avail. Mg*	$g.kg^{-1}$	0.6 (0.04)		
avail. Na*	$mg.kg^{-1}$	22 (2)		
Olsen-P	$mg.kg^{-1}$	1.1 (0.5)		
avail. Cu*	$mg.kg^{-1}$	7.4 (0.4)		
avail. Fe*	$g.kg^{-1}$	0.3 (0.03)		
avail. Mn *	$mg.kg^{-1}$	75 (10)		
avail. Zn *	$mg.kg^{-1}$	4.5 (0.4)		
total Al	$g.kg^{-1}$	14 (0.8)	9.5	
total As	$mg.kg^{-1}$	6.2 (1.9)		5
total B	$mg.kg^{-1}$	3.5 (0.7)		
total Ca	$g.kg^{-1}$	10 (0.7)		
total Cd	$mg.kg^{-1}$	0.24 (0.09)	0.2	0.9
total Co	$mg.kg^{-1}$	5.1 (1.9)		20
total Cr	$mg.kg^{-1}$	217 (34)	123	85
total Cu	$mg.kg^{-1}$	50 (2)	25	50
total Fe	$g.kg^{-1}$	28 (1.4)	24	
total K	$g.kg^{-1}$	4.6 (0.6)	10	
total Mg	$g.kg^{-1}$	14 (1.4)	10	
total Mn	$mg.kg^{-1}$	404 (23)	372	1000
total Mo	$mg.kg^{-1}$	3.7 (0.6)		6
total Na	$g.kg^{-1}$	0.2 (0.04)	0.2	
total Ni	$mg.kg^{-1}$	94 (10)	57	50
total Pb	$mg.kg^{-1}$	76 (22)	31	40
total S	$g.kg^{-1}$	3.4 (0.9)		
total Sr	$mg.kg^{-1}$	101 (5)		
total Ti	$g.kg^{-1}$	0.95 (0.08)		
total Zn	$mg.kg^{-1}$	96 (7)	63	120

*OM, organic matter; EC, electrical conductivity; avail., available. **Gouvernement du Québec (2016)

Table 2. Tree / herbaceous Root Length Density (RLD) ratio and total RLD in October 2014 and October 2015 by treatment (T1m: trees at 1x1m spacing, T2m: trees at 2x2m spacing, T4m: trees at 4x4m spacing, T2mH: trees at 2x2m spacing combined to hydroseeding of fast-growing herbaceous species). Means, with SE in parentheses.

	Tree / herbaceous RLD ratio		**Total RLD ($cm.dm^{-3}$)**	
	2014	**2015**	**2014**	**2015**
T1m	3.38	13.73	1448 (361)	1599 (408)
T2m	0.49	1.48	954 (247)	1308 (211)
T2mH	0.07	0.76	2076 (656)	2351 (337)
T4m	0.26	0.51	611 (212)	968 (170)

Figure captions

Fig. 1 Picture of the tree planting and experimental design. (a) Site photograph including three of the experimental plots (T2m, T2mH and T1m), two months after planting (July 2013). The black arrows indicate the position of the erosion pins for soil loss measurement. (b) One replication block of the experimental design: black dots represent trees, red crosses the position of the erosion pins. Depending on the spacing, 12 (T4m), 35 (T2m) or 117 (T1m) trees were present in each plot

Fig. 2 Mean soil losses in cm by treatment (T1m: trees at 1x1m spacing, T2m: trees at 2x2m spacing, T4m: trees at 4x4m spacing, T2mH: trees at 2x2m spacing combined to hydroseeding of fast-growing herbaceous species, T: control without trees or hydroseeding), during the 2014 spring snow melt one year after planting. (N=12). Bars denote SE. Means that do not differ at the 0.05 level are noted with the same letter (a < b)

Fig. 3 Mean poplar height in cm by treatment (T1m: trees at 1x1m spacing, T2m: trees at 2x2m spacing, T4m: trees at 4x4m spacing, T2mH: trees at 2x2m spacing combined to hydroseeding of fast-growing herbaceous species) for the first, second and third year after planting (T1m: N=351; T2m and T2mH: N=105; T4m: N=36). Bars denote SE. Means that do not differ at the 0.05 level are noted with the same letter for each year (a < b)

Fig. 4 (a) Aboveground biomass (kg dry mass) and (b) Plot canopy cover (%) two and three years after planting by treatment (T1m: trees at 1x1m spacing, T2m: trees at 2x2m spacing, T4m: trees at 4x4m spacing, T2mH: trees at 2x2m spacing combined to hydroseeding of fast-growing herbaceous species) (T1m: N=351; T2m and T2mH: N=105; T4m: N=36). Bars denote SE. Means that do not differ at the 0.05 level are noted with the same letter at each date (a < b < c)

Fig. 5 Mean weed cover (%) by treatment (T1m: trees at 1x1m spacing, T2m: trees at 2x2m spacing, T4m: trees at 4x4m spacing, T2mH: trees at 2x2m spacing combined to hydroseeding of fast-growing herbaceous species, T: control without trees or hydroseeding) along three years after planting (N = 3 transects). Means that do not differ at the 0.05 level are noted with the same letter at each date (a < b<c)

Fig. 6 (a) Mean poplar (N = 18) and (b) herbaceous Root Length Density (RLD) (N = 24) by treatment (T1m: trees at 1x1m spacing, T2m: trees at 2x2m spacing, T4m: trees at 4x4m spacing, T2mH: trees at 2x2m spacing combined to hydroseeding of fast-growing herbaceous species, T: control without trees or hydroseeding) over three growing seasons since planting. Bars denote SE. Means that do not differ at the 0.05 level are noted with the same letter at each date (a < b)

The effect of tree planting density on the relative development of weeds and hybrid poplars on revegetated mine slopes vulnerable to erosion

Remaury, Arnaud

2018-08-31

Arnaud Remaury, Marie Guittonny and Jane Rickson. The effect of tree planting density on the relative development of weeds and hybrid poplars on revegetated mine slopes vulnerable to erosion. New Forests, Volume 50, Issue 4, July 2019, pp. 555-572

https://doi.org/10.1007/s11056-018-9678-9