# Carbon sequestration patterns in the replanted areas of the Sudbury barrens

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**Abstract**

Due to industrial pollution by the mining industry and deforestation, much of the forest cover in the Sudbury region had been disturbed or destroyed by the 1960's. Starting in 1978 after a major reduction in $SO_2$ emissions a replanting initiative commenced on the Sudbury 'barrens'. In recent years how these forested sites are recovering has become increasingly important as concerns over carbon cycling increases due to the problems of global warming. This project is examining how the carbon pools are recovering, due to re-vegetation, across different areas of the Sudbury region. Sampling took place over the summer and fall of 2002 with mineral soil cores taken to a depth of 20cm at 14 sites. Sampling was done in five age classes, planted in 1979, 1983, 1987, and 1993 respectively and at 3 non-restored sites. Sampling was also done for the forest floor layer and the vegetative components which were divided into tree, shrub and herbaceous layers. Ecosystem carbon showed significant gains in the replanted areas. The oldest site (planted 1979) had a total carbon pool of 106.5 $\pm$ 6.16 Mg C $ha^{-1}$, compared to an adjacent non-restored site with 35.54 $\pm$ 6.47 Mg C $ha^{-1}$ in the carbon pool. The majority of change came via the tree level vegetation which was significantly correlated with age (r =0.921) and contributed up to 59% of the total carbon pool at the oldest site. The litter layer was also a significant contributor to the increase in the total community carbon pool contributing up to 12.37 Mg C $ha^{-1}$ and up to 16% of the total. Mineral soil carbon was highly variable across the region with different areas showing distinct patterns in their carbon levels. However, no regional pattern was observed with age of the replanting site.

## Introduction

The Sudbury region of Ontario, Canada has had a long and successful history of mining and smelting going back over the past 100 years (Beckett *et al*., 1995). The economic success of these operations has come at a cost, for as a result this area is one of the most disturbed ecosystems in Canada and is an example of extreme human impact upon the environment (James and Courtin, 1985).

These activities, along with forest fires and logging, led to the creation of nearly 20,000 ha of completely barren land and another 80,000 ha of semi-barren landscape (Gunn et *al.*, 1995). These areas were highly eroded with the remaining soil pockets being highly acidified. Vegetation consisted of communities with very little trophic structure and few species (James and Courtin, 1985).

Beginning in 1978, a large-scale program of repairing the industrial damage was initiated. Starting with liming and grassing of the barren areas, followed by replanting of mainly native coniferous tree species, this program has led to over seven million trees having been planted over 17,000 hectares of the barren and semi-barren landscapes surrounding the Sudbury smelters (VETAC 2001). The two main species of conifer planted in the region are Jack Pine (*Pinus banksiana*) and Red Pine (*Pinus resinosa*). In recent years, as the ecosystem has recovered and sulphur dioxide emissions have dropped, White Pine (*Pinus strobus*) and Black and White Spruce (*Picea mariana* and *Picea glauca*) have also become a major component of the replanting effort, but Jack and Red Pine continue to be planted in large numbers.

As these replanted stands mature and grow they change the ecosystem from a barren almost tundra like system (James and Courtin, 1985) to a forest system that closely resembles the natural ecology of the region. Along with providing positive changes in the ecosystem such as slowing erosion, reducing runoff, lowering evaporation and serving as a nutrient and moisture sink, the replanting of these areas has altered the carbon sink patterns of the region. The growth of the trees, the formation of a litter and humus layer and modification of the mineral soil layer would all suggest the region is accumulating carbon across the region. This accretion of carbon is of increasing interest due to the effects of global climate change and the need to better describe the sources and sinks of $CO_2$.

The present study was an attempt to gain some understanding of the current carbon sink patterns in the replanted areas of the Sudbury barrens. The study concentrated on areas planted with Jack and Red Pine as they have been planted

throughout the restoration program allowing for temporal changes to be considered.

## Materials and methods

### *General*

The Sudbury, Ontario region lies approximately 400km north of Toronto and 75km north east of Lake Huron at 46$^{o}$ 30' N, 81$^{o}$ 00' W . The region is located on the southern edge of the Pre-Cambrian shield consisting of undulating topography with rock outcroppings, glacial till deposits and numerous lakes (Beckett *et al*., 1995). The climate of the Sudbury region is continental, and under the influence of the nearby Great Lakes system. The average annual precipitation is 899.3 mm of which 274.4 mm comes in the form of snow. The mean annual temperature is 3.7 $^{o}$C, with a range of –13.7 $^{o}$C in January to 19 $^{o}$C in July. The natural vegetation of the region consists of Red and White Pine and hardwoods like Sugar Maple (*Acer saccharum*) and Yellow birch (*Betula alleghaniensis*) characteristic of the Great Lakes-St. Laurence forest. Additionally, species from the southern edge of the boreal forest such as Jack Pine and White Spruce are found as the region lies in the ecotone between the two forest zones. Within the immediate area of the Sudbury smelting operations three additional plant communities are found. Described by Amiro and Courtin (1981) the barren, maple transition and birch transition communities reflect the anthropogenic effects on Sudbury ecology.

### *Site Description*

Fourteen study sites were selected within the Sudbury region, all of them within the formerly barren areas as described by McCall *et al*. (1995) (Figure 1). The sites picked had to meet a number of criteria: they had to occur on areas that were limed prior to planting; they had to have only been planted during one year, or at maximum in two consecutive years; and they had to consist primarily of Red or Jack pine. Restoration sites were picked in four age categories of 9, 15 19 and 23 years since their establishment. Additionally, three non-reclaimed sites were sampled to establish a baseline for carbon levels. Of these 14 sites, 4 are located in the in the region surrounding the Falconbridge smelter: FAL0, FAL93, FAL87 and FAL83 (Figure 1), with each site named for its location and year of planting (Site names ending in 0 are non-replanted sites). All of these sites occurred on flat to gently rolling terrain with deep sandy soils. Five sites are located in the area surrounding the former Coniston smelter: CONU, CON93a, CON93b, CON83 and CON79. These sites are more variable in nature, CON93a, CON93b and CON0 are on slope and ridge tops, each having highly variable soil depths, and areas of exposed rock. CON83 and CON79 occur on more even terrain but still have areas where the bedrock occurs near or at the surface. The final five sites are located in the region surrounding the INCO Copper Cliff smelter: INCO0, INCO87a, INCO87b, INCO83b and INCO83a. These sites are also highly variable in nature, with shallow soils and large areas of exposed rock, moreover INCO0 and INCO87a are located on INCO property right next to active slag dumping operations. The one exception is INCO83a, which is located in a slight sloping valley, with relatively deep soils.

### *Methods*

Sampling took place during the summer and early fall of 2002. At each site 30 sample points were selected within the areas where tree planting had occurred. At each sample point a soil core was taken to a depth of 20 cm in the mineral soil using a copper pipe with an interior diameter of 3.8 cm, the core were then transported to the Laurentian University Arboretum where they were air dried and stored until analysis.

Soil samples were passed through a 2-mm sieve to remove course fragments. An approximately 7.5-8.5g sample from each core was then oven dried at 80$^{o}$C to a constant mass. Moisture content of the soil was then calculated as the weight lost during this process, and the oven dried weight of the core was calculated by multiplying the weight of the air dried core by the percent weight of the oven dried sample. Bulk density of the <2mm soil fraction was calculated by dividing the oven dried core weight by the core volume minus the volume occupied by the course fragments. Organic matter concentration was determined using the loss on ignition (LOI) method using a muffle furnace at 500$^{o}$C for 15hrs (Bagatto and Shorthouse 1999). Carbon concentration for the mineral soil was then

estimated by multiplying the OM concentration by 0.5 (Nelson and Sommers, 1996).

The forest floor layers (L,F,H) were collected at each site, except the 3 untreated sites where they were not present, using a 25cm x 25cm frame. 30 samples were collected at each site in the same location as the soil cores. The samples were then air-dried before being dried to a constant weight at 70$^{o}$C and weighed. The samples were then ground in a Wiley mill until they passed through a 1mm screen. A 3.5 g sub-sample was then analysed for organic carbon content using the same procedure as in the mineral soil.

At each sample point the point quarter method was used to gather DBH and height measurements for overstory level vegetation and to calculate stand density. This data was converted to above ground biomass measurements using the equations of Alban and Laidey (1982) for jack and red pine, while Ker (1984), Harding and Grigal (1985) and Ter-Mikaelian and Korzukhin (1997) were used for minor tree species. Carbon concentration was estimated at 48% based on other studies (Foster and Morrison, 2002), (Johnston *et al*., 1996). Below ground biomass for the overstory vegetation was estimated at 20% of above ground biomass. This value is at the low end of accepted values for Coniferous forest species which are usual between 20-30% (Cairns *et al*., 1997; Retzlaff *et al*., 2001; Snowden *et al*., 2000; Vogel and Gower, 1998). However, shallow rooting depth (<20cm) at most sites would suggest a lower than average below ground biomass.

Aboveground shrub and herbaceous biomass was determined by marking off 10 1m x 1m or 25cm x 25cm plots per site respectively. In each square the vegetation was clipped at the soil surface and weighed. Shrub strata was described as all woody species less than 3cm DBH or 2m in height. Total shrub biomass was assumed to be 2.5 times the aboveground biomass (Johnston *et al*., 1996) and carbon estimates were made by multiplying the weights by 0.48. Overall herbaceous biomass was assumed to be 3 times above ground biomass. Carbon content was taken as 0.45 of weight (Vogel and Gower, 1998).

Statistical analysis was done using XLSTAT version 6.0 (Addinsoft, 2002). Spearman correlation coefficients were found in order to look for relationships between site components. Tukey multiple comparison tests were performed on the mineral soil and forest floor results to examine site differences. Relationships between stand age and other community components were explored using both linear and non-linear regression equations.

## Results

### *Community Carbon Pool*

Overall estimates of the community carbon pools ranged from a high of 106.5 + 6.16 Mg C*ha$^{-1}$ at Site CON79 to a low of 35.54 $\pm$ 6.47 Mg C*ha$^{-1}$ fat site CON0 (Table 1). The mineral soil contributed the vast majority (91%) of the carbon to the community pool at site CON0 and was the dominant component at all the non-reclaimed sites (FAL0: 89%, INCO0: 85%). The mineral soil remained the largest carbon contributor until it was replaced by the aboveground tree component at site CON79 contributing 29% and 49% respectively. The combined tree carbon pool was at a maximum at site CON79 where it contributed 59% of the total pool. Of the planted sites FAL93 had the lowest contribution by trees at only 4%.

The shrub layer and herbaceous layer both made small contributions to the overall community carbon pool. Herbaceous contributions were highest in the non-reclaimed sites where they ranged from 4% (CON0) to 12.5% (INCO0) of the community pool and lowest at FR93 where they made up 0.1% of the carbon pool. Shrub contributions were highest at CON0, FAL87 and INCO87a all at 4.5%. This was in contrast with site INCO83a where no shrub layer was recorded.

The forest floor (L,F,H) contributed between 6 and 16% to the total carbon pool in replanted sites with its largest contribution being at INCO87a. The three non-reclaimed sites all had no forest floor in their carbon pools.

### *Aboveground Vegetative pool*

The total above ground vegetative (AG) carbon pool was at its largest at site CON79 where it contributed 53.11 Mg C ha$^{-1}$ to the community carbon pool, it was lowest at site FAL93 where it was only 2.98 Mg C ha$^{-1}$ (Figure 2). The AG carbon pool was significantly correlated with the age of the stand (0.921) and this was mainly due to the influence of the tree level vegetation, which was even more closely correlated at 0.962 (Table

2). This relationship was explored using both linear and non-linear regression. To improve the lower end of the regression tree values from a 6yr old planting site were included in the analysis. Regressions were performed on a carbon per tree basis, as well as carbon/ha to eliminate stand density differences. The linear regressions had $R^2$ values of 0.752 for carbon per ha and stand age and this $R^2$ value rose to 0.839 if carbon per tree was used (Figure 3a-b). The non-linear regression analysis produced logistic curves that had a $R^2$ values of 0.9 and 0.98 for carbon per tree and carbon per ha respectively (Figure 3c-d).

The tree layer was dominant in all the replanted sites ranging from 98.6% of the AG carbon pool at CON79 to 56.41% at FAL93. In the non-reclaimed sites it represented only a small fraction of the AG carbon pool between 0 and 2.5%.

The shrub layer reached its highest carbon values in the 15yr old sites where they averaged 2.34 Mg C $ha^{-1}$ or 16.5% of the vegetative pool. In terms of percent it reach a maximum at site FAL93 where it represented 41% of the AG carbon pool while it did not have any contribution at site INCO83a (0%). The shrub layer did not correlate significantly with age or any other measured parameters (Table 2).

The herbaceous layer was the major contributor to the AG carbon pool at the non-reclaimed sites, where it made up between 46% (CON0) and 95.5% (FAL0) of the pool. It still made a substantial contribution to some of the mid-aged replanted sites, INCO87b at 9% and INCO87a at 8% of the carbon pool. One 19yr old site, FAL83 also had a substantial herbaceous layer contribution of 5%. The herbaceous layer is significantly negatively correlated with tree carbon at -0.543 (Table 2), it also had a negative correlation with stand age, -0.532, but this was not significant at $p<0.05$.

### *Mineral Soil*

The top 20cm of the mineral soil layer did not show any pattern in its organic carbon content in relation to the age of the site since replanting (Figure 4). This lack of a pattern is reflected in the soil properties, where low bulk density or shallow soil often offsets high carbon concentration (Table 3). The Site with the highest level of mineral soil carbon was INCO83a with 44.87 $\pm$2.52 Mg C $ha^{-1}$, the lowest soil carbon levels were found at site INCO87a at 27.97 $\pm$ 2.51 Mg C $ha^{-1}$, the sites averaged 35.02 Mg C $ha^{-1}$. The Tukey's multiple comparison test separated the mineral soil results into two groups with sites INCO83a and FAL93 having significantly higher mineral soil carbon than sites CON93a, CON83b and INCO87a (Figure 4), with all other sites falling into both groups. The mineral soil also did not show any significant correlation with any of the other site parameters (Table 2).

**Table 3**: Soil Properties of the 14 Sudbury sampling sites (BD = bulk density).

| Sites | BD g $cm^3$ | Carbon g $kg^{-1}$ | Soil Core Depth cm |
|---|---|---|---|
| CON79 | 1.07 | 1.82 | 18.70 |
| CON83 | 1.04 | 1.53 | 19.33 |
| FAL83 | 1.02 | 1.70 | 20.00 |
| INCO83b | 1.05 | 2.35 | 16.30 |
| INCO83a | 0.81 | 3.40 | 18.65 |
| INCO87b | 0.82 | 4.06 | 12.80 |
| FAL87 | 1.14 | 1.72 | 20.00 |
| INCO87a | 1.03 | 1.93 | 16.23 |
| CON93a | 1.08 | 2.09 | 16.47 |
| FAL93 | 1.12 | 1.82 | 20.00 |
| CON93b | 1.02 | 1.90 | 17.33 |
| INCO0 | 0.83 | 2.62 | 16.23 |
| FAL0 | 1.19 | 1.79 | 19.87 |
| CON0 | 1.14 | 2.01 | 16.79 |
| Average | 1.03 | 2.20 | 17.76 |

### *Forest Floor*

The Tukey multiple comparison test performed on the forest floor data found that there were five significant groupings (Figure 5). The breaks were highly dependent on the age of the planting and this is reflected in the significant correlation (0.948) between age of the planting and the mass of the forest floor carbon (Table 2). The forest floor carbon levels were also highly correlated with tree carbon (0.875) and total aboveground vegetative carbon (0.869). The linear correlation performed between age of the planting and the accumulation of the forest floor layer shows a significant increase in forest floor carbon averaging 0.54 Mg C $ha^{-1}yr^{-1}$.

## Discussion

When examining the community carbon pool, above and below ground tree biomass proves to be the main contributor to the carbon gains across the study sites, increasing at approximately

1.74 Mg $ha^{-1}$. This dominance is in line with other studies of afforested land (Vesterdal *et al*., 2002; Johnston *et al*., 1996). It was expected that both the shrub layer and the herbaceous layer would decrease in mass with increasing stand age. This would be a result of the canopy closing which typically reduces understory productivity (Peek *et al*., 2001). The shrub layer however, did not significantly correlate with stand age and because of the variability in the measurements none of the sites were significantly different from each other. This may be a result of the relatively young age of most of the sites and variability in stand density. The herbaceous level, while it was not significantly correlated to stand age, did have a significant negative correlation with the tree component, which is closely tied to age. While the loss of the two understory components from the vegetative carbon pool would slow the overall increase in carbon storage, the net effect would still be highly positive as they only represent a small component on existing Sudbury barren sites compared to the gains from the growth of the trees.

One problem occurring when the sites are compared is the fact that the sites were planted in very different manners. The study sites planted around Falconbridge are planted in a similar manner to forest plantations, while at other sites the plantings occur in small pockets where the soil was not eroded away. These pockets may only occupy 20-30% of a given area while the rest is a mixture of exposed rock, bare soil and grass. This means that the carbon levels stated for the tree components at some sites are four times higher than their value would be if examined across the whole site and not just in the replanted areas.

Another problem is the biomass equations used in the study were developed in areas that did not experience the massive anthropogenic forces of the Sudbury region. While the growth pattern of the trees in Sudbury is similar to control sites (Beckett *et al*. 1995), there may be a need in the future to develop regional biomass equations.

The forest floor is the other component that is providing a significant sink for carbon across the study sites. Representing the major change in the soil system it is highly linked to age and the tree biomass of the system. This link was lost at one site in particular, CON83. At this site the litter layer was a lot thinner than expected (Figure 5) for the biomass and age of the site. The reasons for this anomaly are unclear as many factors may be contributing to this situation. Litter build-up is highly correlated to site conditions and the nutrient status of the soils (Vesterdal *et al*., 1998). Additionally this site also has lowest carbon concentration in the mineral soil layer at 1.53% (Table 3).

The lack of a pattern in the mineral soil carbon measurements was not particularly surprising, because of the history of the region. Most of the sites examined have experienced large amounts of erosion. This has resulted in soil been concentrated in pockets across the replanting sites. These pockets contain not only old carbon remaining form the former forest system but often have charcoal deposits left from the fires that afflicted the region. This makes soil conditions highly variable from site to site (Table 3.) and comparisons between sites difficult.

As in most other studies sampling was done to a fixed depth in the soil. Some authors have suggested the need to examine soils that are undergoing changes in land use, such as reforestation, by sampling to a greater depth to compensate for decreases in bulk density (Ellert and Bettany, 1995; Vesterdal *et al*., 2002). The only location where this might be possible in Sudbury is near the Falconbridge smelter where soil conditions are more homogeneous. The bulk density of the oldest planting, FR83, was 17% lower than the non-replanted site, FRU, while the soil carbon pool was 21% lower (Table 1). Even assuming the additional depth added to FR83 had the same carbon content as the top 20cm, the replanted site would still have a slightly lower carbon concentration.

While some studies have found that soil carbon increases over time following afforestation, (Johnston *et al*., 1995; Jug *et al*., 1995) this study on Sudbury contaminated soils did not support this. One problem is that many of these studies concentrate on the conversion of arable land to forest, which is unlike the Sudbury situation. It has also been theorised that the increase in carbon inputs to the mineral soil is currently being offset by the reestablishment of soil decomposers as site conditions improve. Conversely the carbon inputs from the trees could be reaching the forest floor layer and remaining in this component because of site conditions such as

metal contamination or low pH keeping the decomposition rate low. Detailed studies of the decomposition rates at these reclaimed sites would be needed to answer these questions.

***Conclusions***

This study did show a general increase in the community carbon pool as replanted areas increase age. While the tree biomass was the major source of increasing carbon values. The forest floor was also a major component in the overall-increasing trend. The shrub and the herbaceous layers were not major contributors to the increasing carbon stock and tended to decrease over time. The mineral soil carbon pool proved to be highly variable across the Sudbury region because of heterogeneous site conditions and no regional trend was apparent with age. If an age effect is occurring detailed long-term studies may be needed

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**Table 1**. Mean (± standard error) carbon content (Mg ha$^{-1}$) for tree level, shrub, herbaceous, forest floor and mineral soil components of the community carbon pool across the 14 Sudbury barrens sites

| .Site | Aboveground Tree | Belowground Tree | Shrub | Herb | Forest Floor | Mineral Soil | Total |
|---|---|---|---|---|---|---|---|
| CON79 | 52.36 ± 5.87 | 10.47 ± 1.17 | 0.51 ± 0.51 | 0.24 ± 0.17 | 12.37 ± 0.77 | 30.53 ± 1.09 | 106.5 ± 6.16 |
| CON83 | 30.5 ± 2.65 | 6.1 ± 0.53 | 0.93 ± 0.46 | 0.49 ± 0.17 | 6.83 ± 0.54 | 28.30 ± 2.06 | 73.19 ± 3.47 |
| FAL83 | 23.24 ± 2.52 | 4.65 ± 0.50 | 1.07 ± 0.41 | 1.25 ± 0.90 | 9.11 ± 0.62 | 33.68 ± 2.88 | 73.04 ± 4.03 |
| INCO83b | 28.19 ± 3.27 | 5.64 ± 0.65 | 1.43 ± 0.48 | 0.83 ± 0.19 | 11.77 ± 1.32 | 33.12 ± 2.90 | 81.04 ± 4.64 |
| INCO83a | 33.19 ± 2.57 | 6.64 ± 0.51 | 0.00 | 0.55 ± 0.36 | 12.36 ± 0.58 | 44.87 ± 2.52 | 97.60 ± 3.69 |
| INCO87b | 12.53 ± 1.24 | 2.51 ± 0.25 | 2.01 ± 0.64 | 1.39 ± 0.50 | 6.96 ± 0.61 | 39.07 ± 4.42 | 64.55 ± 4.71 |
| FAL87 | 8.76 ± 0.87 | 1.75 ± 0.17 | 2.49 ± 0.98 | 0.65 ± 0.24 | 4.35 ± 0.56 | 37.83 ± 2.41 | 55.93 ± 2.82 |
| INCO87a | 12.35 ± 1.35 | 2.47 ± 0.27 | 2.52 ± 1.00 | 1.24 ± 0.45 | 8.92 ± 1.07 | 27.97 ± 2.51 | 55.58 ± 3.25 |
| CON93a | 6.75 ± 0.73 | 1.35 ± 0.15 | 1.5 ± 0.63 | 0.58 ± 0.17 | 3.71 ± 0.45 | 29.93 ± 2.01 | 43.88 ± 2.29 |
| FAL93 | 1.68 ± 0.17 | 0.34 ± 0.03 | 1.24 ± 0.23 | 0.06 ± 0.06 | 3.24 ± 0.47 | 40.26 ± 2.58 | 46.87 ± 2.64 |
| CON93b | 10.53 ± 1.28 | 2.11 ± 0.26 | 0.84 ± 0.49 | 0.58 ± 0.13 | 2.79 ± 0.29 | 28.04 ± 3.36 | 44.92 ± 3.65 |
| INCO0 | 0.07 ± 0.02 | 0.02 ± 0.01 | 0.76 ± 0.53 | 5.79 ± 2.31 | 0.00 | 39.44 ± 3.25 | 46.14 ± 4.02 |
| FAL0 | 0.00 | 0 | 0.22 ± 0.11 | 4.58 ± 2.75 | 0.00 | 40.74 ± 2.92 | 45.54 ± 4.01 |
| CON0 | 0.08 ± 0.01 | 0.02 ± 0.01 | 1.58 ± 0.55 | 1.42 ± 0.55 | 0.00 | 32.37 ± 6.42 | 35.54 ± 6.47 |

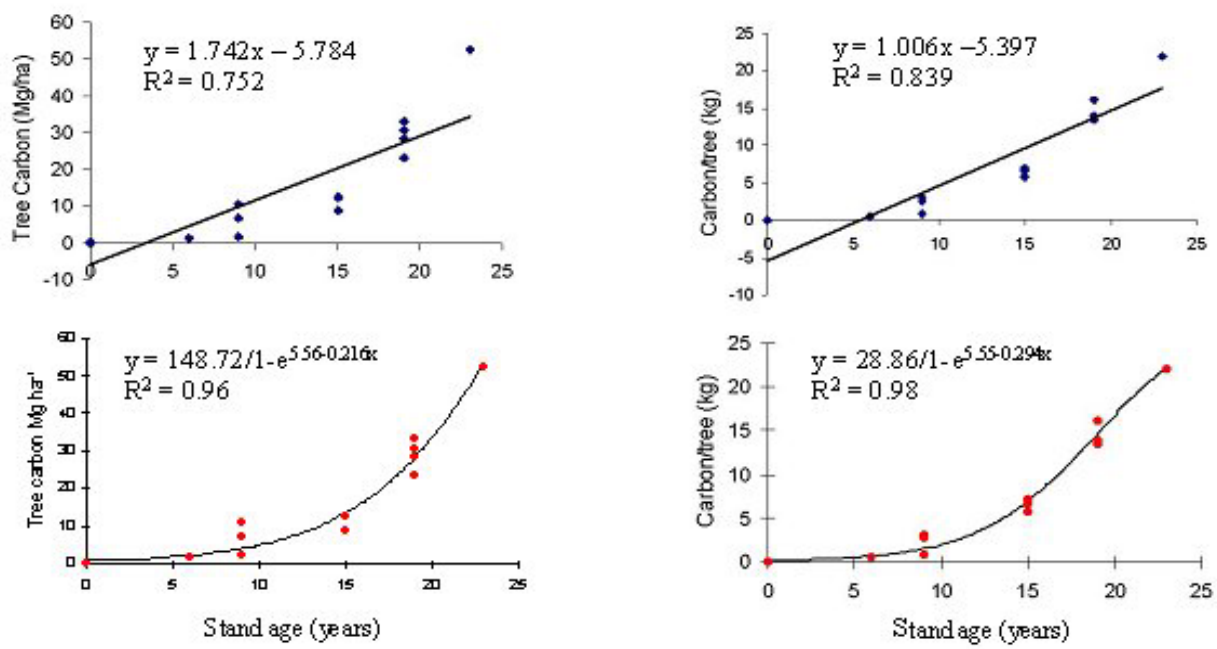


**Figure 3.** Tree level carbon concentrations at different stand ages at the replanted sites of the Sudbury barrens. (a) tree carbon ha$^{-1}$; (b) carbon tree$^{-1}$; (c) non-linear tree carbon ha$^{-1}$; (d) non-linear carbon tree$^{-1}$. One non-replanted site was excluded from regression (c) (see text).

**Table 2**. Spearman correlation coefficients for measured parameters in the14 Sudbury barren sites, (AG = aboveground carbon pool). (Correlations in bold significant at the 0.05 level).

| Spearman correlation coefficients | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Forest Floor | Tree Strata | Age | Soil | Herb Strata | Shrub Strata | AG |
| Forest Floor | 1.00 | | | | | | |
| Tree strata | **0.921** | 1.00 | | | | | |
| Age | **0.948** | **0.962** | 1.00 | | | | |
| Soil | -0.108 | -0.244 | -0.178 | 1.00 | | | |
| Herbaceous strata | -0.449 | **-0.543** | -0.532 | 0.200 | 1.00 | | |
| Shrub strata | -0.029 | -0.147 | -0.090 | -0.389 | 0.158 | 1.00 | |
| AG total | **0.885** | **0.956** | **0.921** | -0.257 | -0.381 | -0.240 | 1.00 |

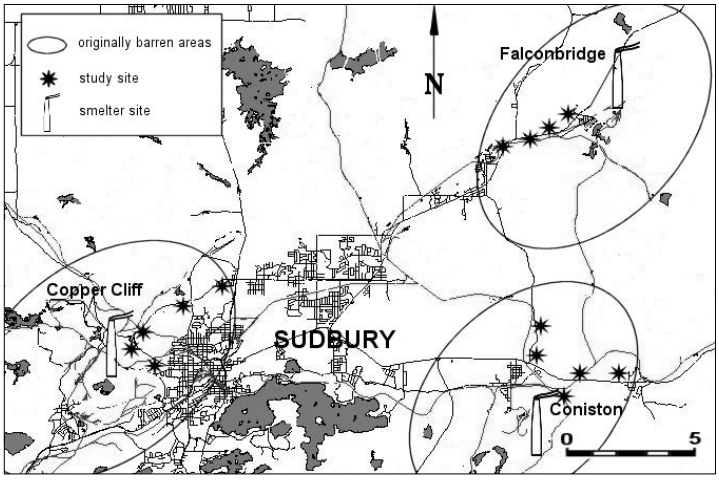


Figure 1:Locations of study sites in the Sudbury region and the three major smelters in the region along with their surrounding barren areas. Note: the entire area covered by the map is with the semi-barren zone.

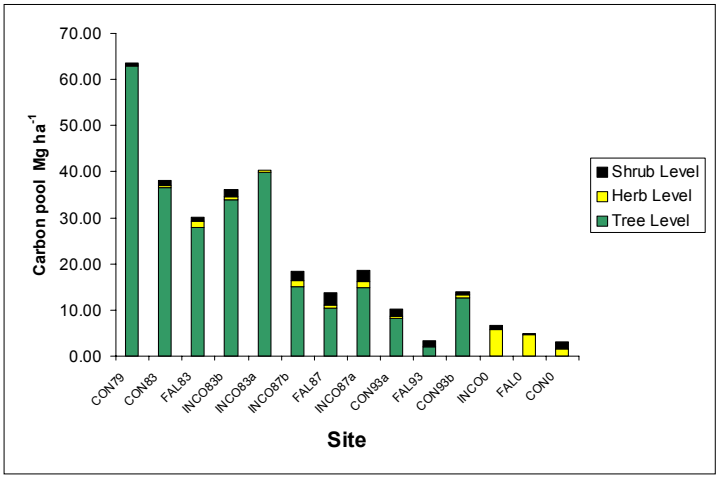


Figure 2. Aboveground vegetative carbon pool at the 14 sites across the Sudbury barrens comprised of the tree, shrub and herbaceous layer. Error bars are the SE of the above ground vegetative carbon pool.

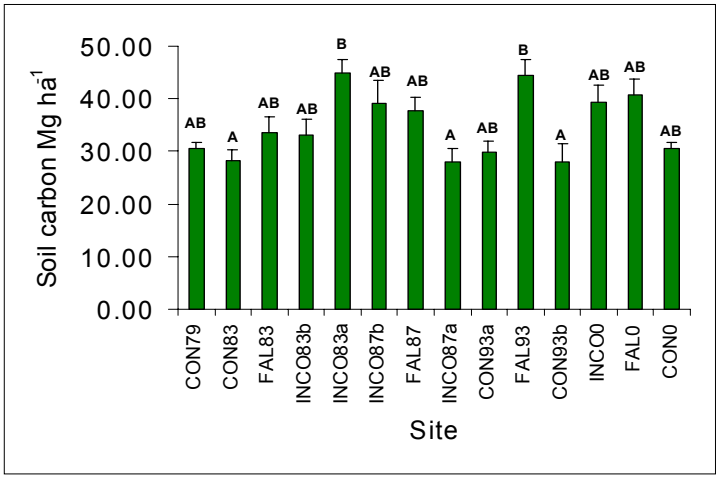


Figure 4. Mean organic carbon content in the top 20cm of the mineral soil at the 14 Sudbury barren sites. Different letters indicate significant differences between sites found by Tukey's HSD. Bars indicate standard errors of soil carbon content.

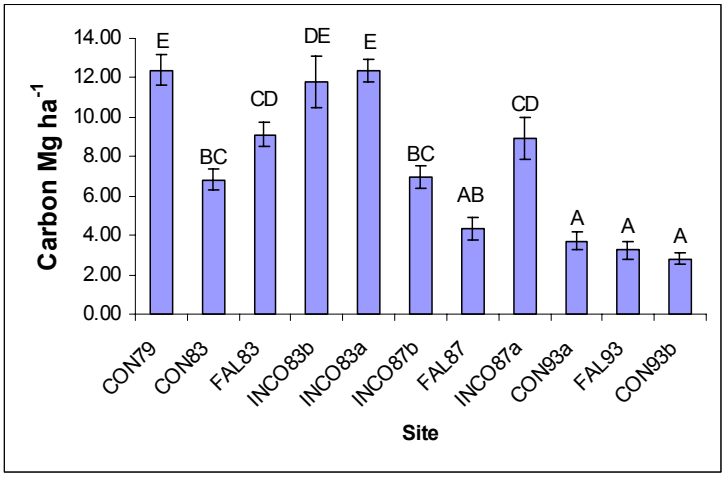


Figure 5. Mean carbon content in the forest floors of the 14 Sudbury barren sites. Different letters indicate significant differences between sites found by Tukey's HSD. Bars indicate standard errors of soil carbon content